PACIFIC EARTHQUAKE ENGINEERING RESEARCH CENTER

Report of the Tenth Planning Meeting of NEES/E-Defense Collaborative Research on Earthquake Engineering

Disaster Prevention Research Institute
December 11-13, 2013
Kyoto University

Convened by

NEES Operation Center

and

Hyogo Earthquake Engineering Research Center, NIED

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PREFACE

Following an agreement between the Japan Ministry of Education, Culture, Sports, Science and Technology (MEXT) and the U.S. National Science Foundation (NSF), the First Planning Meeting for NEES/E-Defense Collaboration on Earthquake Engineering Research was held in 2004. This meeting laid the groundwork for an initial joint research program related to improving understanding of seismic effects and reducing the seismic vulnerability of bridges and steel buildings. The emphasis of the program was to conduct experimental research using the George E. Brown, Jr. Network for Earthquake Engineering Simulation (NEES) equipment sites and the three-dimensional full-scale earthquake testing facility (E-Defense) of the National Research Institute for Earth Science and Disaster Prevention (NIED). To formalize the “first-phase” collaboration, two Memorandums of Understanding (MOU) were executed, one between NSF and MEXT in September 2005 and the other between the NEES Consortium Inc. (NEES Inc.) and NIED in July 2005. In order to continue the collaboration to the “second phase,” the latter MOU was updated in May 2010 by the NEES Operation Center (NEEScomm) and NIED, to continue collaborative activities through 2015.

Before updating the MOU between NEEScomm and NIED, two meetings were held. The First Planning Meeting for the Second Phase of the NEES/E-Defense was held in January 2009 to discuss the need for and benefits of continued NEES/E-Defense collaboration. This meeting identified a number of important topics of mutual interest to the U.S. and Japan that would benefit from continued research collaboration and sharing of NEES and E-Defense resources. In addition, a follow-up meeting to discuss details of the next phase of collaboration was recommended. In response, the Seventh Planning Meeting of NEES/E-Defense Collaborative Research on Earthquake Engineering was convened in September 2009 to review the efforts and accomplishments of the past four and one half years and to discuss mechanisms for collaboration for the coming years.

Following these two meetings, the Eighth and Ninth Planning Meetings of NEES/E-Defense Collaborative Research on Earthquake Engineering were convened during September 17 and 18, 2010 and August 26 and 27, 2011, respectively, These meeting were attended by leading researchers from both countries as well as representatives from NSF, MEXT and other government agencies. In the plenary and breakout sessions of the meeting, participants from the U.S. and Japan discussed progress and future plans for NEES/E-Defense collaboration. Because of the closure of E-Defense during the upgrade of the facility that occurred at the end of 2012 and beginning of 2013, a joint planning meeting was not held in 2012.

This report contains a summary of the Tenth Planning Meeting that was convened at the Disaster Prevention Research Institute of Kyoto University during December 11 and 13, 2013.

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ACKNOWLEDGMENTS

The Joint Technical Coordinating Committee for the NEES/E-Defense Collaborative Research Program in Earthquake Engineering would like to thank the meeting participants for making the meeting a success by generously sharing their time, experience and ideas. The participants agree that the cordial and harmonious atmosphere at the meeting, and the candid and thoroughgoing discussions signal an outstanding future for NEES/E-Defense Collaboration.

The meeting was held at the Disaster Prevention Research Institute (DPRI) of Kyoto University, in Uji, Japan. During a field trip to the Hyogo Earthquake Engineering Research Center, National Institute for Earth Science and Disaster Prevention (NIED), in Miki, Japan, the participants were able to learn firsthand about the upgraded capabilities of E-Defense and witness a test of an 18-story tall, one-third scale model of a steel moment resisting frame building. The participants would like to express their gratitude to DPRI and NIED for planning the meeting and making their facilities available.

The meeting was hosted by DPRI including making local arrangements. The support of Prof. Masayoshi Nakashima and the staff and students of his group in DPRI contributed enormously to the success of the meeting.

Many participants from the U.S. and Japan attended the meeting using their own travel funds. Travel support for a significant number of the U.S. participants was made possible by NSF Award No. CMMI-0958774 (Coordinating Workshops for the NEES/E-Defense Collaborative Research Program in Earthquake Engineering (Phase 2) and Cooperative Agreement No.CMMI-0402490, and subsequent amendments and supplements, between the U.S. National Science Foundation and the NEES Operation Center. This support is greatly appreciated.

The findings, recommendations and conclusions contained in this report are the consensus views of the meeting participants, and do not necessarily reflect opinions of any one individual or the policy or views of the National Science Foundation, the National Earthquake Hazards Reduction Program, the NEES Operation Center or other organization in the U.S., nor of the Ministry of Education, Culture, Sports, Science and Technology, National Institute for Earth Science and Disaster Prevention (NIED), the Hyogo Earthquake Engineering Research Center or the Disaster Prevention Research Institute in Japan.

CONTENTS

SUMMARY AND RESOLUTIONS

The Tenth Planning Meeting for the NEES/E-Defense Collaborative Research Program in Earthquake Engineering was among the largest held to date, and attended by 61 participants from the U.S. and 53 from Japan. There was great interest on both sides in the research that had been carried out in the past two years, and in the potential for future collaborative research. The upgrade of the E-Defense shaking table was appreciated by all, and will permit many new and important lines of research to be conducted that were not possible before.

The report includes the recommendations and resolutions reached by the participants. The appendices contain the list of participants, the meeting program and schedule, the materials presented during the plenary sessions, the minutes of the Joint Technical Coordinating Committee, and reports summarizing the specific recommendations developed by the individual working groups where participants discussed in detail various scientific and engineering challenges that should be addressed during the remainder of the second-phase NEES/E-Defense collaboration, as well as recommendations regarding the need and scope of a third phase.

Issues Discussed

The tenth joint NEES/E-Defense planning meeting was organized to:

1. Discuss results, refine research plans and strengthen collaboration for current NEES/E-Defense projects,
2. Discuss current gaps in knowledge and identify high impact research efforts that would benefit from collaborative NEES/E-Defense research planning,
3. Discuss mechanisms for enhancing and extending the excellent collaboration already established between researchers in the U.S. and Japan in the field of earthquake engineering, and
4. Based on the foregoing and the accomplishments to date, consider the desirability of extending the program to the next phase (Phase 3).

In the meeting, the background of US-Japan collaboration related to earthquake engineering was reviewed, as was the background and scope of the NEES/E-Defense Collaborative Research Program in Earthquake Engineering. The previous development of the "Resilient City" as the overarching meta-theme for Phase 2 research activities was also discussed. As part of the scope of the Resilient City meta-theme, scientific challenges and specific research needs were previously identified for the following six topics: Buildings, Nonstructural Elements, Transportation Systems, Lifelines including Geotechnical Issues, Computational Simulation, and Monitoring.

The major upgrade to the E-Defense shaking table was described. As a result of the upgrade, E-Defense can simulate earthquake records with the duration of more than three minutes, like those experienced in the March 2011 Tohoku earthquake. Many new opportunities to investigate the effect of earthquake duration, especially for motions containing significant long period content, are made possible by these enhancements. Recent research on steel structures, base isolated structures, and other systems were also discussed. Several suggestions were made by E-Defense for future collaboration, including special efforts by joint U.S. and Japanese research teams to synthesize, analyze and interpret data already obtained in past tests.

Five working groups then met. In keeping with the Resilient City meta-theme, the working groups focused on:

a. New materials and new technologies for reinforced concrete buildings,
b. Understanding and improving resilience of structural steel buildings
c. Present and Future of base-isolation and vibration control,
d. Critical Issues on geotechnical engineering and underground structures, and
e. Enhancement of monitoring and condition assessment.

In preparation for the meeting the Japanese and U.S. working group co-conveners had solicited input from the working group members and other researchers. Following these discussions the participants gathered for a plenary discussion of the findings and recommendations of the working groups, and to develop overall recommendations and resolutions for the meeting.

Each of the working groups also considered overarching issues related to evaluating and improving capabilities for numerical simulation, data exchanges, and opportunities for payload projects, such as those involving nonstructural components, sensors, and development and calibration of numerical models.

The list of participants and the agenda of the meeting are shown in Appendices I and II. A summary of recent work on the upgrade of E-Defense facility is presented in Appendix III. The working group summary reports and minutes of Joint Technical Coordination Committee (JTCC) are shown in Appendices IV and V. The papers presented during the meeting are presented in Appendices VI to XI, in the order of Plenary Session, RC Working Group, Steel Working Group, Protective Systems Working Group, Geotechnical Engineering Working Group, and Monitoring Working Group. The Working Group Summary Presentations can be found in Appendix XII. The meeting also featured a “Student Activities Program” in which 18 students from Japan and United States participated in an extensive series of technical and social activities. The summary of the program is presented in Appendix XIII.

Resolutions

Based on the presentations, discussions and deliberations, the participants of the Tenth Planning Meeting of the NEES/E-Defense Collaborative Research on Earthquake Engineering formulated and unanimously adopted the following specific resolutions:

NEES/E-Defense Collaboration should continue without interruption into Phase 3. The participants agree that the first and second phases of the NEES/E-Defense Collaborative Research Program in Earthquake Engineering were a resounding success and demonstrated the effectiveness of joint U.S. – Japan research in addressing high priority problems of mutual interest. Given an assessment of the current state of knowledge in the light of recent large earthquakes in Japan and elsewhere, it is believed that a third phase of the NEES/E-Defense program is needed and beneficial, Specific reasons for the third phase include: (1) the rapidly growing realization of the importance of the Resilient City meta-theme concept to both the U.S. and Japan, (2) the smooth and effective collaboration already established between NEES and E-

Defense, (3) the new capabilities made possible by the upgrades to the E-Defense shaking table, and (4) the significant opportunities to leverage the unique other equipment, intellectual and personnel resources offered by NEES and E-Defense. It is strongly believed that NEES/E-Defense collaboration by the U.S. and Japan provides the strongest mechanism to accelerate the pace of discovery and development in engineering needed to realize the goals of the earthquake disaster resilient city.

Projects suggested by working groups (a) to (e) are suitable for NEES/E-Defense Collaboration. Based on extensive discussions during the plenary and breakout sessions, the participants believed that the five project areas discussed by the working groups provide an excellent and broad-based framework for pursuing high priority research of mutual interest to the U.S. and Japan. The breakout session summarized in Appendix IV highlight the technical challenges raised by each of these problem areas and the social and engineering benefits of the research proposed. Special opportunities are possible related to conducting payload projects, improving numerical simulation, and so on, and these should also be pursued to enhance the outcomes of the NEES/E-Defense collaboration.

Regular planning meetings are needed. It was agreed that it is important that regular joint planning meetings be held to plan future tests, and accelerate exchange of information resulting from the joint NEES/E-Defense research. A near-term planning meeting is desired to refine research directions, identify additional topics, if any (e.g., nonstructural components, lifelines and transportation systems, numerical simulation, multi-hazard, etc.), and implementing procedures for Phase 3. In addition to annual planning meetings, joint technical sub-committees should be established on each of the five project areas plus numerical simulations to (1) identify the appropriate characteristics of the research to be performed, (2) establish research goals of the major joint test programs, (3) recommend needed ancillary and payload tests and analyses, (4) facilitate collaboration and (5) share the information obtained and promote dissemination of research findings and their use in education and practice.

Efforts should be increased to take advantage of currently available data. Significant efforts have been undertaken to carry out the tests that have been conducted at E-Defense and to analyze the data to validate underlying theories, improve analytical simulations tools and models, and develop recommendations and guidelines that impact engineering design and evaluation. However, there is believed to be value in expanding the scope of such evaluations. There are two approaches that were recommended: (i) having groups of U.S. and Japanese researchers examine data from individual tests, and perhaps more importantly compare and contrast data obtained from multiple tests and numerical analyses; and (ii) implement interoperability such that certain data from E-Defense is accessible to U.S. researchers and Japanese researchers have access to the NEES data as well (for example, using the prototype system developed between the U.S. and the SERIES project in Europe). These efforts are thought to have a high value for relatively modest cost. Some assistance in translating descriptive information in the data and documents may be helpful to this effort.

Efforts should be made to facilitate exchange of personnel. It is desired to increase collaboration by identifying existing and perhaps initiating new mechanisms that would enable exchange of researchers from the U.S. to Japan, and from Japan to the U.S. In particular, it is recommended that exchange of students and junior researchers to participate in particular efforts focusing on synthesizing, analyzing and interpreting available data, or participate in planning and conduct of tests would be highly beneficial.

Efforts to increase involvement design professionals and dissemination of findings to various stakeholders should continue. It is clear that there is a significant benefit of involving design professionals in the formulation of research plans, conduct of research and interpretation of findings. Greater involvement would be expected to increase the value and impact of the research. Various means have successfully transferred research findings to regulatory and building officials, code agencies, professional engineers, financial service organizations, owners, and the public. Expanding these efforts are expected to accelerate the adoption and impact of the research findings.

Funding agencies are encouraged to provide needed resources. Given the importance of the research proposed, and the benefits of leveraging resources available in the U.S. and Japan, appropriate funding agencies in the U.S. and Japan are encouraged to provide adequate funding and other support needed to realize the benefits of the second phase of the NEES/E-Defense collaboration.

Closure

The participants believe that the Tenth Planning Meeting of the NEES/E-Defense Collaborative Research Program on Earthquake Engineering was highly successful, and that NSF and MEXT should be congratulated for providing the earthquake engineering community with cutting-edge tools that will substantially accelerate progress towards the important goals of earthquake loss reduction. The attendees agree that the cordial and harmonious atmosphere at the meeting, and the candid and thoroughgoing discussions signal an outstanding future for NEES/E-Defense Collaboration.

The participants also appreciate and heartily thank the Disaster Prevention Research Institute and the Hyogo Earthquake Engineering Research Center for their efforts in hosting this successful meeting.

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APPENDIX II: PROGRAM AND SCHEDULE

Time	Title	Presenters	Chairs
DAY1			
9:00 – 9:20	Registration		
9:30 – 9-45	Opening@Kihada Hall Greeting from Japan Greeting from U.S.	Japanese Host President of NIED Director of DPRI Program Director of NSF President of NEES	Nakashima & Mahin
9:45 – 10:15	A history of U.S./Japan collaboration on EE	Nakashima	Ramirez & Kajiwara
	An overview of current U.S./Japan collaboration (NEES/E-Defense)	Mahin	Ramirez & Kajiwara
10:15 – 11:00	Recent activities of E-Defense	Kajiwara	Nakashima & Mahin
11:00 – 11:30	Identification of workshop themes – Resilient City		Nakashima & Mahin
	Session grouping		Nakashima & Mahin
11:30 – 12:00	Lunch (Box lunch provided)		
12:00 – 16:30	Tour to E-Defense – Collapse test of a high-rise steel building (Briefing in limousines)		
	A rapid summary of E-Defense test (videos)		
17:30 – 19:30	Banquet at DPRI @Restaurant Kihada		
DAY2			
9:30 – 10:00	Instructions to session discussion@Wood Hall		Pauschke
10:00 – 12:00	Concurrent session: RC structures@Wood Hall	Presentations	Kusunoki & Ghannoum
	Concurrent session: Steel structures@Seminar Room 1	Presentations	Okazaki & Mosqueda
	Concurrent l session: Protective systems@Seminar Room 2	Presentations	Ikago & Christensen
	Concurrent session: Geotech and underground structures@Seminar Room 4	Presentations	Tamura & Stewart
	Concurrent session: Monitoring@Seminar Room 5	Presentations	Kurata & Lynch

12:00 – 13:00	Lunch (Kyoto Univ. Cafeteria)		
13:00 – 17:00	Concurrent session: RC structures@Wood Hall	Discussion	Kusunoki & Ghannoum
	Concurrent session: Steel structures@Seminar Room 1	Discussion	Okazaki & Mosqueda
	Concurrent l session: Protective systems@Seminar Room 2	Discussion	Ikago & Christensen
	Concurrent session: Geotech and underground structures@Seminar Room 4	Discussion	Tamura & Stewart
	Concurrent session: Monitoring @Seminar Room 5	Discussion	Kurata & Lynch
DAY3			
9:30 – 12:00	Concurrent session: RC structures@Wood Hall	Group report preparation	Ghannoum & Kusunoki
	Concurrent session: Steel structures@Seminar Room 1	Group report preparation	Mosqueda & Okazaki
	Concurrent l session: Protective systems@Seminar Room 2	Group report preparation	Christensen & Ikago
	Concurrent session: Geotech and underground structures@Seminar Room 4	Group report preparation	Stewart & Tamura
	Concurrent session: Monitoring@Seminar Room 5	Group report preparation	Lynch & Kurata
12:00 – 13:00	Lunch (Kyoto Univ. Cafeteria)		
13:00 – 15:00	Session reports: @Wood Hall (1) RC (2) Steel (3) Protective systems (4) Geotech & underground (5) Monitoring	 Ghannoum Mosqueda Christensen Stewart Lynch	
15:00 – 15:20	Break		
15:20 – 15:50	Resolution		Mahin & Nakashima
15:50 – 16:00	Closure	Ramirez & Kajiwara	Mahin & Nakashima

APPENDIX III: POTENTIAL ROLES OF THE UPGRADED E-DEFENSE

by Kenichi Abe [*1] and Koichi Kajiwara [*2]

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Key words: Line performance, long duration shaking, bypass valve, accumulator, wide range period motion, discharged oil volume

1. Introduction

E-Defense operates the world's largest and most advanced 3-D shake-table. Under the full payload of 1,200 tonf (2690 kips), the table can reproduce the most severe ground motion recorded during the 1995 Hyogoken-Nanbu earthquake amplified by a factor of 1.3. During the eight years since its inauguration in April 2005, E-Defense has carried out as many as 60 experimental programs.

Figure1 compares the performance line of E-Defense (in solid red line) against that of the now discontinued Tadotsu shake table. The original E-Defense emphasized a very different performance range from the Tadotsu shake table which was capable of producing high acceleration motions in the short period range. The shake table tests at E-Defense focused primarily on the range enclosed by the blue ellipse, which correspond to inland or near-field ground motions. The focus so far has been on high velocity motions in the period range between 0.2s and 2.0s and lasting less than one minute. Such motion addressed the research needs for structural behavior leading to failure. On the other hand, E-Defense was not designed to produce motions in the long period range. The limitation was in the sheer volume of pressurized hydraulic fluid. Therefore, E-Defense was not suited for producing the long period-long duration motions that characterize massive earthquakes caused by big oceanic trenches. In the past, E-Defense compensated for this limitation by eliminating the vertical component of such motion and producing only its two horizontal components. In some projects, the horizontal motion was amplified by inserting a layer of rubber bearings, with or without dampers, between the table and the specimen. The horizontal-only motion, with the aid of motion-amplifying device, was used to clarify how the upper stories of high-rise buildings may function during long period-long duration motions.

The March 11, 2011, earthquake off the Pacific Coast of Tohoku earthquake alarmed Japan with the need to address resilience of our cities against a broader range of ground motions. The massive, moment magnitude 9.0 earthquake was caused by a fault rupture that continued over 170 seconds and spread strong tremors over the entire eastern Japan. For example, the motion lasted for 10 minutes in the Tokyo metropolitan area. In the near-field areas of Miyagi, Fukushima and Iwate Prefectures, strong motions lasting over 3 minutes were recorded. The Tohoku earthquake produced motions characterized by long period components and long duration. Many scientists expect an even stronger, long period-long duration motion to threaten the metropolitan areas of Japan in the near future. Therefore, urgent research needs have been highlighted by the Tohoku earthquake. Unfortunately, the original E-defense was not equipped with the capacity to produce the strong motions recorded during the Tohoku earthquake in their entirety. The limitation was primarily in the net supply of pressurized hydraulic fluid. In 2012, E-Defense was upgraded in order to resolve the limitation.

2. Upgrade Measures

In order to address new research needs, the capability of E-Defense, as illustrated in Fig. 1, needed to extend towards longer periods. The shake table is controlled by ten horizontal actuators, five each in the X and Y directions, and fourteen vertical actuators. Each of the ten horizontal actuators is equipped with three servo valves, each of which consumes a maximum oil volume of 15kl/min, to produce strong motions with a velocity pulse as large as 2.0m/s Each of the fourteen vertical actuators is equipped with one of such servo valve. Dual measures were adopted to upgrade E-Defense. First, new accumulators were added to increase the total supply of pressurized hydraulic fluid. Second, a bypass function was installed in actuators that need not be loaded to produce the long period-long duration motions. Without the second measure, the E-Defense system will demand several times the amount of fluid (20kl) that is supplied by the original accumulators. In other words, the second measure was essential to make the upgrade economically feasible. As indicated by the performance line in Fig.1, the required acceleration performance in the long-period domain is rather small, and therefore, production of these motions does not required all actuators to be loaded. Due to the savings in fluid consumption by the bypass function, the target performance might be achieved by a mere 20 % increase (4kl) in accumulator capacity.

Figure2 indicates the upgrades installed along the oil flow diagram. Bladder type accumulators were adopted for the new accumulators. The bladder type is efficient and they have been in use for the main flow shut-down valves adjacent to the shake table. Piston-type accumulators, which form the original accumulator system, could not be adopted because of lengthy approval procedures demanded by the high pressure gas act of Japan. 360 units of bladder-type accumulators, each of which discharge 11 liters of fluid, were combined to achieve a total volume 4kl.

A bypass functions was installed in selected actuators. The bypassed actuators are load free and merely follow the motion of the loaded actuators. The fluid saved by the bypass function is concentrated to drive the loaded actuators. The result is increased efficiency in the use of the pressurized fluid towards meeting the demand of long period-long duration motions. As shown in Fig.3, 3 bypass valves were installed in each of the 3 middle actuators in the X and Y directions, respectively (X2 to X4, Y2 to Y4). These six actuators can be used in either loaded or unloaded state. The four corner actuators are not equipped with bypass valves and are always used in the loaded state. In the vertical direction, one bypass valve was attached to the single servo valve of actuators Z6 and Z13. While the four corner actuators are always used in the loaded state, 4 spare bypass valves have been constructed for possible installation in the remaining six actuators. Consequently, the bypass system can be added to a maximum of 16 actuators. The 8 corner actuators, 2 each in the X and Y directions and 4 in the Z direction, will always be used in the loaded state. Thirty-seven different patterns of fluid supply are possible by altering the combination of loaded and unloaded actuators. In association with these upgrades, the hydraulic control system as well as the table control system was modified.

3. Result of Upgrade

Table 1 compares the fluid consumption of the shake table system before and after the upgrade. The table lists three motions recorded by the K-NET array during the Tohoku earthquake (at stations Sendai, Iwanuma, Furukawa), a simulated motion from a scenario Tokai-Tonannkai earthquake (Sannnomaru), and a near-field motion recorded from the 1995 Kobe earthquake (JR-Takatori). While all three Tohoku motions are characterized by long duration and wide period range, Furukawa is distinguished by the dominance of components in the 4-second range, while Sendai is dominated by short-period motions. If all actuators are loaded, the Tohoku motions and Sannomaru require a fluid volume exceeding the original capacity of 20 kl. In fact, Furukawa and Sannomaru require more than twice the original capacity. The original capacity of 20 kl is the volume required to reproduce the JR Takatori motion amplified by a factor of 1.3. However, after the upgrade that involved increase in accumulator capacity to 24 kl and the bypass function that enable selective use of pressurized fluid, all five motions can be reproduced by an appropriately selected bypass pattern. Fig. 4 shows the simulated fluid consumption as a function of time. Furukawa consumes the largest volume among all motions recorded by the K-NET array during the Tohoku earthquake. 49.1kL is required to reproduce the Furukawa motion with all actuators loaded. Pattern 2v, which bypasses four horizontal actuators and two vertical actuators, reduces the required volume to 21.7 kl. As demonstrated by this example, the bypass function is extremely efficient for this particular objective.

The force and acceleration limit decreases with payload. Table 2 shows the relationship between payload and acceleration limit. The penalty of payload is greater when a larger number of actuators are used in the unloaded state. The vertical limits in brackets are the limits reduced due to simultaneous action of the limiting overturning moment of 15,000 tonf×m (110,000 kip-ft) and full payload. The limit must be checked carefully before adopting the bypass system for tall and heavy specimens.

Theoretically, when an appropriate bypass pattern is adopted, table shaking can continue as long as pressurized fluid circulates the hydraulic system. However, the shaking duration is limited by the 2^{20} step limit defined in the computer code. If the table is controlled in a 0.001-second (1,000Hz) increment, then the shaking duration is limited to 17.48 minutes.

4. Conclusion

E-Defense was originally designed to produce motions up to a maximum velocity of 2.0m/s under the full payload of 1,200 ton-force. Such motions represent the largest near-field ground motions caused by in-land earthquakes. The capability has been used effectively to advance our understanding of the seismic behavior of our infrastructure. The test data from E-Defense projects has significantly contributed to progress earthquake engineering in Japan.

In 2012, E-Defense was upgraded to extend its capability in the long-period range. Now, E-Defense can produce a wide range of three-dimensional, long period-long duration motion, including the motions recorded from the Tohoku earthquake. E-Defense will continue to play a key role to resolve advanced earthquake engineering issues.

5. Acknowledgements

The upgrade of E-Defense was funded by the grant for facilities construction from the Ministry of Education, Culture, Sports, Science and Technology (MEXT) in Japan. We would like to express our gratitude to MEXT for their continuing support. We also thank Associate Professor Taichiro Okazaki of Hokkaido University for proof reading this document.

Table1 Fluid Consumption Before and After Upgrade

Motion's Name	Before Upgrade		After Upgrade		
	Fluid Consumption (kL)	Acc. Capacity (kL)	Bypass Pattern	Fluid Consumption (kL)	Acc. Capacity (kL)
Sendai	23.2	20	No Bypass	23.2	24
Iwanuma	31.7		Pattern 1	23.3	
Sannomaru	42.5		Pattern 2	23.6	
Furukawa	49.1		Pattern 2v	21.7	
JR Takatori	14.5		No Bypass	14.5	

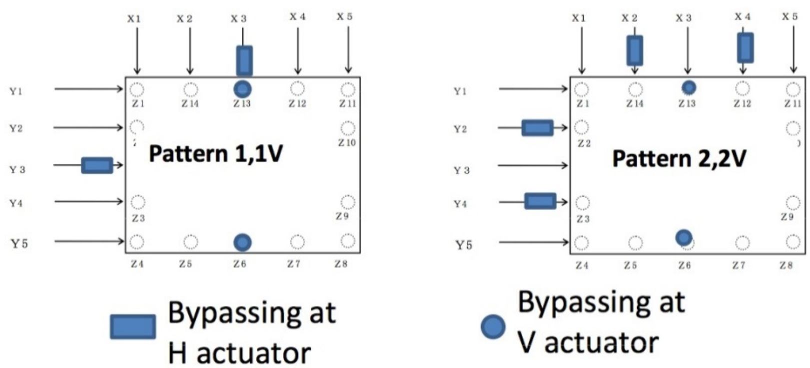


Table 2 Decrease of maximum acceleration due to payload

Payload (tonf)	Maximum Acceleration (G)							
	Horizontal direction				Vertical direction			
	Number of unloaded actuators				Number of unloaded actuators			
	0	1	2	3	0	2	4	6
0	1.7	1.4	1.0	0.7	2.3 [1.7]	1.9 [1.1]	1.6 [0.5]	1.5 [0.4]
600	1.2	1.0	0.7	0.5	1.7 [1.2]	1.4 [0.8]	1.2 [0.4]	1.1 [0.3]
1200	0.9	0.9	0.5	0.4	1.5 [1.0]	1.2 [0.6]	1.0 [0.3]	0.8 [0.2]

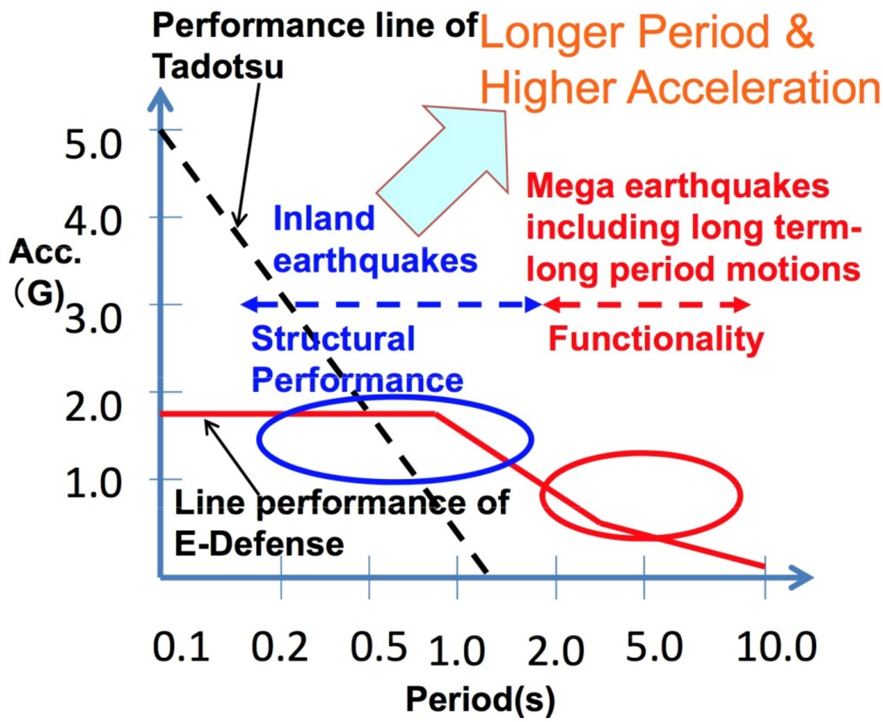


Fig. 1 The performance line of E-Defense and its usage fields.

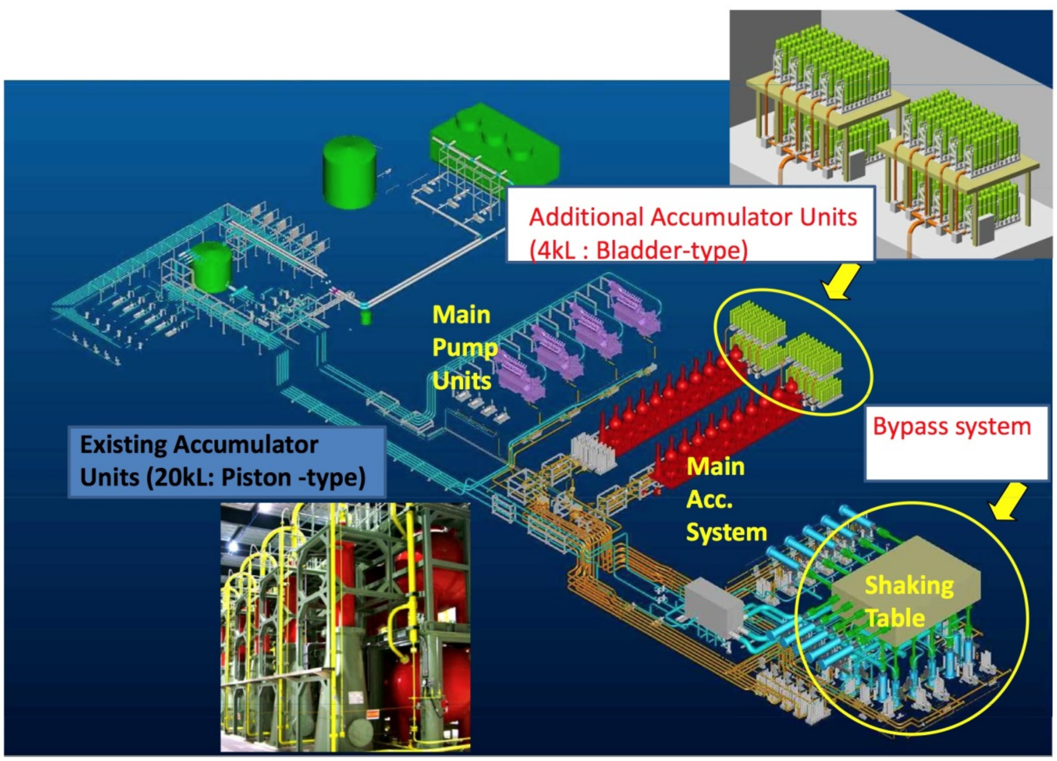


Fig. 2 The oil flow pass and its renewal areas.

Appendix III

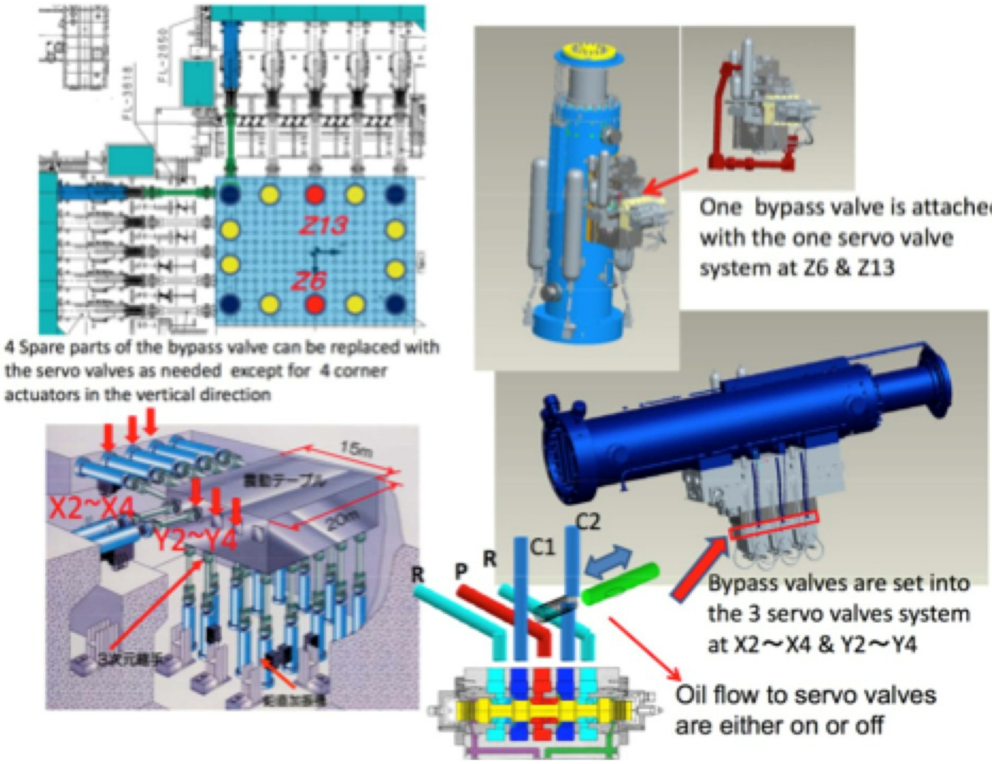


Fig. 3 Bypass valves with H and V actuators.

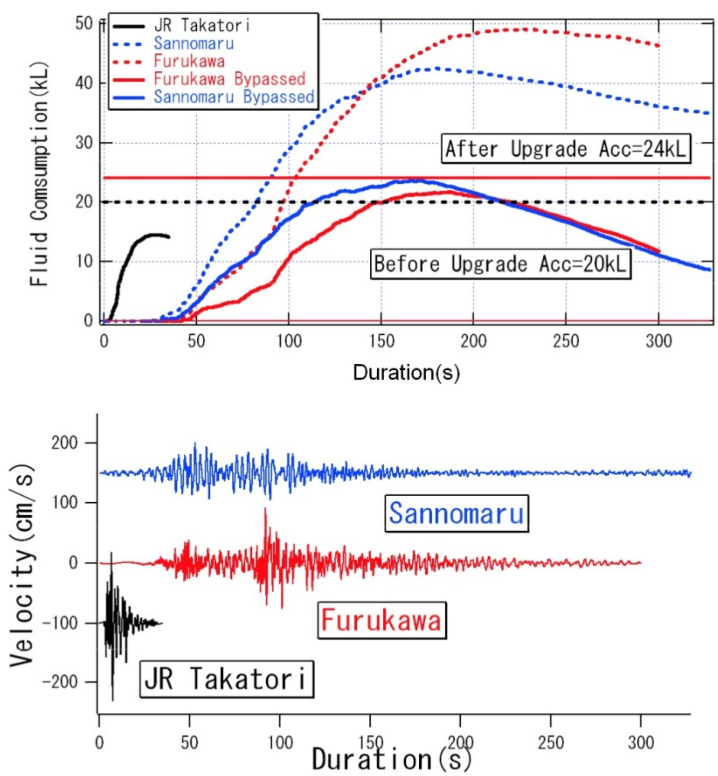


Fig. 4 Trend of fluid consumption during shaking.

APPENDIX IV: WORKING GROUP SUMMARY REPORTS

RC Working Group

Working Group: High performance reinforced concrete structures

Moderators: Wassim Ghannoum (University of Texas at Austin) and Koichi Kusunoki (Yokohama National University)

Recorder: Andreas Stavridis (University at Buffalo, SUNY)

Members (in alphabetical order of last names): Anna Birely (Texas A&M), Gregory Deierlein (Stanford University), Marc Eberhard (University of Washington), Kenneth Elwood (University of British Columbia, Vancouver), Hiroshi Fukuyama (Building Research Institute), Wassim Ghannoum (University of Texas at Austin), Toshimi Kabeyasawa (Earthquake Research Institute, University of Tokyo), Hideo Katsumata (Obayashi Co. Ltd.) Koichi Kusunoki (Yokohama National University), Masaki Maeda (Tohoku University), Yasuhiko Masuda (Obayashi Co. Ltd.), Tomohisa Mukai (Building Research Institute), Minehiro Nishiyama (Kyoto University), Julio Ramirez (Purdue University), Yasushi Sanada (Osaka University), Hitoshi Shiohara (University of Tokyo), Lesley Sneed (Missouri S&T), Andreas Stavridis (University at Buffalo, SUNY), John Wallace (University of California, Los-Angeles)

Presentations:

All participants gave a short presentation introducing themselves and their research interests. Additional presentations were given to outline possible collaboration topics

- Minehiro Nishiyama, Yasushi Sanada: R/C E-Defense test
- Koichi Kusunoki: Near to midterm collaborations: SSI E-Defense test
- Tomohisa Mukai: Database Project, CIB Roadmap
- Hitoshi Shiohara: Research Needs for the Future
- Kenneth Elwood: Near to Midterm Collaboration Topics

Recommended Efforts to Increase Effective Collaboration:

It is strongly recommended to have a group meeting at least one per year to share the new knowledge and current situations in both countries to achieve a fruitful collaboration. Face-to-face meetings are essential. Earthquake engineering and earthquake damage prevention is the research against nature. We, U.S. and Japan, face the same hazard and have a long history of teamwork to tackle the problems. In order to maintain the collaborative history, personnel exchanges between U.S. and Japan are highly needed. Longer term personnel exchanges such as embedding researchers into research projects in both countries are highly recommended to achieve more comprehensive exchanges of ideas and information.

E-Defense tests of reinforced concrete (RC) structures are planned in years 2014 and 2016. It is recommended to NSF and NEES to provide funding for U.S. researchers to visit E-Defense during the shaking table tests to share the outputs of the test and to have the meeting there.

Additional workshops are needed to tackle the two highest priority research topics that were identified in this workshop: 1) Database exchange, expansion, and analysis, and 2) Resiliency of RC wall systems to extreme events.

Recommended High Priority Research of Mutual Interest to the U.S. and Japan:

The discussions held during the breakout session demonstrated unanimous agreement between the Japanese and U.S. participants that strong collaboration would allow us to achieve the 'Resilient City' objective within a more rapid time frame.

Collapse of deficient concrete structures is often attributed to the majority of deaths during major earthquakes. In addition, given that a large portion of the building stock is comprised of RC buildings, a large portion of the cost attributed to major seismic events arises from damage to RC structures. Therefore, to achieve the 'Resilient City" objective, it is crucial to improve the damage and collapse performance or RC buildings subjected to earthquake demands.

The following research topics have been identified as high-priority items for addressing pressing challenges that are limiting the resilience of concrete structures in the face of extreme earthquake events.

a) Improving understanding and definition of limit-states of RC structural members

The seismic design methodology is shifting from mandating prescriptive detailing to performance-based design (PBD) that requires improved evaluation of member and building behavior during an earthquake. The shift to PBD is largely driven by the desire to achieve better performance in structures during major events. For existing deficient RC buildings, improved performance up to the life-safety performance objective is typically the target in remediation efforts. For "modern" RC buildings, improved performance beyond the currently prescribed life-safety performance objective is increasingly being sought.

In PBD, a structure is idealized through a computer model that is defined using modeling parameters (MP). The analytical model is then subjected to various loading scenarios and damage is estimated from the model. The estimated damage is compared with acceptable damage levels defined through acceptable limit-states or acceptance criteria (AC). Accurate modeling parameters and acceptance criteria as well as improved analytical tools are therefore essential to the effectiveness of the PBD methodology. Significant experimental research has been conducted in both the U.S. and Japan relating to the definition of MP and AC for RC members and structures. Test results have however not been sufficiently analyzed to extract intermediate limit-states that occur prior to the ultimate failure state. Such intermediate limit-states are needed to define acceptance criteria for stricter performance objectives in standards and guidelines.

It is recommended that databases of experimental test results be built to define modeling parameters and acceptance criteria for various RC members. A database exchange program is recommended between the U.S. and Japan that would allow researchers from each country to access a larger data set. Joining efforts and exchanging techniques for defining and extracting modeling parameters and acceptance criteria would enhance the final products of both countries. The constructed databases should include intermediate damage and limit-states of members that occur prior to failure. Of particular interest are databases for vertical elements that are critical to the stability and performance of a structure (i.e., columns and walls).

It is further recommended to consider joint efforts in developing advanced analytical models for RC members subjected to extreme events. Such analytical models could utilize data gathered through the database effort and are key to the success of the PBD methodology in reducing the vulnerability of RC structures to extreme events.

b) Improving the seismic behavior of RC structural systems subjected to extreme events

Beyond improving our understanding of member behavior, an improved understanding of the full system behavior of buildings is essential to the PBD methodology. The upgraded E-Defense shaking table provides a unique facility to test full-system benchmark tests. Supplementing the E-defense shaking table tests are data obtained from monitored structures during earthquakes (such as during 2011 Tohoku Earthquake). Based on shaking table tests conducted on the E-Defense shaking table and several monitoring datasets recorded during large earthquakes such as the 2011 Tohoku Earthquake, the current numerical simulation techniques and models of structures do not always reproduce observed system behaviors accurately. At the heart of the discrepancies is the current limited understanding of member interactions in structural systems such as slab and gravity system effects on the lateral strength behavior of RC buildings. Complicating matters further is the coupling of seismic demand to seismic capacity of structures.

It is recommended to investigate the effects of 3-D system response on building seismic performance; particularly for collapse prone non-seismically designed buildings. Issues such as localized damage that lead to severe load redistributions and increased torsional demands need to be investigated to improve assessment of structural seismic performance and demands. Particular emphasis should be given to developing methods for evaluating the residual capacity of collapse-vulnerable systems such that after-shock vulnerability could be better assessed. In support of such efforts, it is recommended to develop enhanced structural monitoring techniques from which benchmark data could be obtained from large-scale shaking table tests and earthquakes.

It is also recommended to explore RC structural systems of conventional construction that are resistant to damage in the face of extreme seismic demands. Such systems could be identified using damage data collected through the proposed database work. It is recommended to conduct component testing to improve on the detailing of identified damage-resistant members. A full-scale building test should follow on the E-defense shaking table to validate the damage-resistant nature of the improved detailing at the system level.

c) Development a new seismic evaluation method under extremely large input

The 2011 Tohoku Earthquake revealed the importance of accurate estimation of building behavior under large input motions. Of particular interest is improving capabilities of estimating the collapse potential of structures subjected to an earthquake event that is greater than the earthquake level defined in building codes. Effects of long duration motion on strength loss and damage accumulation are of particular concern in extreme and unexpected events. In order to achieve a new and acceptable seismic evaluation methodology under extremely large input motion, the following items need to be investigated;

- New limit state definition for collapse stage
- Re-evaluation of the limit states of structural members
- New analysis modeling to take the effect of “negative slope” into account
- Re-evaluation of the building collapse scenario
- New modeling of structural members with so-called “non-structural” members such as wing wall and spandrel walls to control the seismic damage

d) Development of damage-free or limited-damage RC structures of innovative design

The structural engineering field is increasingly moving towards reducing damage and downtime in RC structures that result from major earthquakes. Thus in the long term, the concept of damage-free or limited-damage RC structures in the face of high seismic demand may be worth pursuing. If such systems are to be achieved, the structural engineering community needs to develop systems that will sustain very limited damage during major earthquakes and will be cost effective. Envisioned limited-damage innovative structural systems could be comprised of post-tensioned members, rocking walls, and fuses.

e) Payload on upcoming E-Defense shaking table collapse tests

In the near term, two series of the E-Defense tests with R/C structures are planned. One is planned in the year of 2014, and the specimen is 6-story R/C structure (scaled down by 1/3) fixed to the table to investigate the behavior of R/C structures at the collapse stage. Another test is planned in the year of 2016, and the specimen is 3-story R/C frame structure (scaled down by 1/3) on piles in a soil layer on the E-Defense shaking table to discuss the effective input motion and behavior of soil and structure at the collapse stage.

Potential payload projects could include: 1) evaluating analytical simulation tools in light of test results and 2) non-destructive damage evaluation using innovative instrumentation or techniques applied to conventional instrumentation.

WORKING GROUP SUMMARY REPORTS

<u>Steel Working Group</u>

Working Group: Advanced Steel Structures

Moderators: Taichiro Okazaki, Gilberto Mosqueda

Members (in alphabetical order of last names): Maikol Del Carpio Ramos (University of New York at Buffalo), Ahmed Elkad (McGill University), Larry Fahnestock (University of Illinois at Urbana-Champaign), Julie Fogarty (University of Michigan), Maria Garlock (Princeton University), Yoshihiro Kimura (Tohoku University), Chinmoy Kolay (Lehigh University), Dimitrios Lignos (McGill University), Xuchuan Lin (University of Tokyo), Judy Liu (Purdue University), Jason McCormick (University of Michigan), Gilberto Mosqueda (University of California, San Diego), Isao Nishiyama (Building Research Institute), Taichiro Okazaki (Hokkaido University), Fuminobu Ozaki (Nagoya University), James Ricles (Lehigh University), Tomohiro Sasaki (NIED), Atsushi Sato (Nagoya Institute of Technology), Daiki Sato (NIED), Barb Simpson (University of California, Berkeley), Toru Takeuchi (Tokyo Institute of Technology)

Discussions:
The session opened with self-introduction of all participants, followed by presentations from each side. The presenters and topics are listed below.

Dimitrios Lignos "Current Research on the Collapse Assessment of Steel Buildings Subjected to Extreme Earthquake Loading"

Yoshihiro Kimura "Proposal of new column support system to prevent yielding of columns"

Atsushi Sato "Deformation capacity of beam-columns"

Daiki Sato & Tomohiro Sasaki "Experimental Study on Large-frame structures, an ongoing E-Defense Project"

Toru Takeuchi "Rocking frames"

Maria Garlock "Evaluating resilience within a multi-hazard context"

Barb Simpson "Vulnerability and retrofit of older braced frames"

Jim Ricles "Self-centering steel frame systems and supplemental passive damper systems"

The U.S. and Japan researchers identified the following four themes as possible areas for collaboration in the near and mid-term. Focused discussion groups were organized in the afternoon session on these four topics with assigned moderators and recorders reporting a summary of each session to the group:

1. *Collapse assessment of steel structures (experimental simulation and numerical prediction)*
   Chairs: Yoshihiro Kimura and Jason McCormick, Recorder: Julie Fogarty
2. *Rocking systems*
   Chairs: Toru Takeuchi and Maria Garlock, Recorder: Kolay Chinmoy
3. *Response control for improved functionality*

Chairs: Dimitrios Lignos and Jim Ricles, Recorder: Maikol Del Carpio Ramos

4. *Evaluation and retrofit of older steel structures*

Chairs: Atsushi Sato and Larry Fahnestock, Recorder: Barb Simpson

Discussions in each of the four themes addressed immediate research needs and research needs for the next 5 to 10 years with particular emphasis on topics of common interests to both U.S. and Japan. The discussion identified how the advancement of research could be effectively addressed and accelerated by U.S.-Japan collaboration, in particular through the use of E-Defense and NEES experimental facilities. Interest was particularly high for themes (1) and (2). Themes (3) and (4) were also of high-priority to both sides with clear benefits to collaboration, but some substantial differences were identified with respect to design and construction practices in both countries.

Overarching research needs were identified from the discussions. The research needs, each lying within the meta-theme of 'Resilient Cities', are listed below.

A. Immediate occupancy and damage-free performance under multi-hazard scenarios. The research needs apply to existing structures and new construction and to structural as well as nonstructural systems.

B. Consideration of beyond design basis events. This requires the understanding and the ability to simulate structural behavior from onset of damage to collapse.

C. Consideration of multi-hazard loading. Following earthquake shaking, structural systems can be subjected to aftershocks, fire, and tsunami loads, which should be considered in the design of resilient infrastructure.

It was agreed that continued dialogue is essential to further refine the research plans and begin execution of the research. In the short term, there exists an immediate opportunity to collaborate on the collapse assessment of steel structures, building on the recent tests on a tall steel building that was witnessed by the meeting participants. In addition, three long term high-priority research proposals were identified.

<u>Recommended High Priority Research of Mutual Interest to the U.S. and Japan:</u>

(1) Title: Simulation of the Seismic Response of Steel Structures through Collapse

Description: Building on the series of steel frame collapse tests conducted at E-Defense, including the 1/3-scale 18-story steel moment resisting frame structure tested to collapse during the meeting, there exists an immediate opportunity to evaluate current numerical tools to predict structural response from the onset of damage to collapse. The recent test series at E-Defense as well as previous testing of low-rise buildings provide an unprecedented set of data to validate system level modeling of steel frame structures. The need for additional component tests such as columns under combined axial load and lateral displacements as well as large scale subassemblies that capture the interaction of these components was identified.

Scientific merit: In order to better quantify the life-safety risk posed by current structural systems, numerical tools are needed to adequately predict structural behavior from the onset of damage to collapse. Research needs include improved component models that adequately capture the strength and stiffness degradation and their effect on the structural system response under a wide range of loading conditions. While many past studies have focused on beam-to-column connections, data examining column behavior under combined high axial loads and lateral drifts is more limited. The system level test at E-Defense can be complemented by testing large-scale columns at NEES facilities as well as hybrid simulations of frame subassemblies to better understand these members contribution to the collapse margin of a frame. The combined series of component, subassembly and system tests can provide the necessary data to better understand the behavior of steel structural members under various types of loading conditions and the development of validated system level models. Future modeling efforts should focus on high-fidelity mechanics-based models as opposed to spring-based models to more effectively capture expected behavior under a wide range of loading conditions.

Broader impact: Reliable numerical tools for collapse prediction are essential to better quantify the collapse safety margin of structural systems designed to current standards as well as the risk posed by existing buildings. These tools are needed to identify vulnerable buildings and effective retrofit strategies as well as for rational recommendations for the design of new structures. Reliable collapse assessment of structures was also identified as a key research needs within the following proposed collaborative projects.

(2) Title: Evaluation and Retrofit of Deficient Structures

Description: This project addresses the large number of structurally deficient structures that exist in both the U.S. and Japan. In the U.S., a large number of braced frames exist in both moderate and high seismic regions (and are currently still designed and constructed in moderate seismic regions) that are not specifically detailed for seismic events, and thus are expected to exhibit limited ductility. In Japan, a large proportion of buildings constructed prior to 1981 were designed for significantly smaller earthquake loads than what is required today in design. In particular, braced frames constructed in this era were designed with little consideration for ductility. In both countries, the largest concern for structural deficiency of seismic load resisting systems is in braced frames. Therefore, this project will conduct a series of component, subassembly, and system testing to collapse of full-scale braced frames. Component tests will be performed using the advanced capabilities at the NEES facilities; the focus of these tests will be on framing action (including the stiffening effect of gusset plates) at extremely large deformations, columns under high axial loads and lateral drifts, and column base connections. Two full-scale braced frames will be tested at E-Defense, one with U.S. design and detailing, and one with Japanese design and detailing. Focus will be placed on quantifying the contribution of frame action, especially after buckling of braces. The project will provide answers to the long debate on how frame action, which is neglected in design, may supply reserve capacity, particularly as the system approaches collapse. The significantly improved knowledge of deficient structures will be used to develop possible retrofit strategies. A third full-scale frame will be tested at E-defense to validate the proposed retrofit and design strategies.

Scientific merit: By addressing the global behavior of a system governed by low ductility limit states, the research will advance our ability to assess collapse of steel structures. Experimental and numerical studies will be performed to examine the failure hierarchy, formation and impact of soft stories, and the reserve capacity (or back-up strength) of components of the structure that are not designed for lateral load resistance. The full array of experimental data, from component level behavior at NEES facilities to dynamic response of a full system through shaking at E-Defense, will establish a database to calibrate and verify numerical models. The data will be well suited to establish high-fidelity modeling for collapse simulation starting from failure of components, followed by torsional behavior of the system triggered by sudden loss of stiffness, damage concentration, and ending with gravity bringing down the system.

Broader impact: The research information and data will be used to assess, and improve as needed, current evaluation strategies for existing structures. Two different categories of retrofit strategies will be proposed. One is pragmatic, low cost strategies that target life safety and collapse prevention performance. The other is advanced and high performance strategies that target immediate occupancy. Consequently, by providing means to reduce the number of structures that are not expected to perform adequately under strong ground shaking, the project will directly impact the urgent need to improve the resiliency of our cities.

(3) Title: Resilient Steel Rocking Systems for Extreme Events

Description: The project will develop and validate advanced steel rocking frame systems that target immediate occupancy and damage-free performance under multi-hazard scenarios. The focus will be on rocking systems that incorporate 1) a spine element that prevents damage concentration at a weak story and 2) a self-centering mechanism to achieve immediate occupancy and functionality of the building even after extreme earthquake events. The research will combine extensive numerical simulation and hybrid simulation at NEES facilities to address component-level behavior, and a full-scale shake-table test at E-Defense, including nonstructural elements, to demonstrate how the concept can be implemented.

Scientific merit: If appropriately implemented and detailed, rocking systems have the potential to achieve high resiliency against a very wide variety of earthquake ground motions. Issues to be addressed includes: appropriate detailing of architectural finishes and nonstructural elements, serviceability of the building, resiliency of the gravity system, effective floor systems to collect and deliver inertia to the rocking systems, multi-hazard performance (including fire), application to mid and high rise (more than 6 stories) buildings considering higher mode effects, cost analysis, and collapse resistance against maximum considered events. After addressing individual issues at the component level, the research will culminate with a full-scale test at E-Defense to validate the concept using a full three-dimensional structure and three ground motion components.

Broader impact: The project will build upon the focused research conducted over the last decade and implementation examples (a number of buildings exist that implement the rocking system concept to some degree) to develop a probability-based, performance-based design methodology, applicable to seismic upgrade of existing buildings as well as to new construction. This design methodology will encourage rapid and widespread application of the rocking frame concept. The expected outcome of the project is to enable cost-effective, highly resilient structural systems.

Opportunities for Payload Projects:

Within the experiments proposed above, there will be unique opportunities for payload projects such as instrumentation schemes for health monitoring, including non-structural components to identify structural systems that minimize damage to these systems as well as the development of protective installation strategies, and development of methods to minimize interaction between structural system undergoing rocking motions and the remainder of the structure.

WORKING GROUP SUMMARY REPORTS

Protective Systems Working Group

Working Group: Protective systems

Moderators: Kohju Ikago (Tohoku University); and Richard Christenson (University of Connecticut)

Recorder: Brian Phillips (University of Maryland)

Members (in alphabetical order of last names): Tracy Becker (DPRI / McMaster), Richard Christenson (University of Connecticut), Hiroki Hamaguchi (Takenaka Corporation), Su Hao (ACII, Inc.), Kohju Ikago (IRIDeS, Tohoku University), Eric Johnson (University of Southern California), Koichi Kajiwaro (NIED, E-Defense), Dorian Krausz (University of California, Los Angeles), Stephen Mahin (University of California, Berkeley), Ryota Maseki (Taisei Corporation), Narutoshi Nakata (Johns Hopkins University), Marios Panagiotou (University of California, Berkeley), Brian Phillips (University of Maryland), Keri Ryan (University of Nevada, Reno), Eiji Sato (NIED, E-Defense), Kan Shimizu (Kajima Corporation), Toru Takeuchi (Tokyo Tech), and Osamu Yoshida (Obayashi Corporation).

Presentations:

Name	Title	Topic
Becker, Tracy	Tall Building Isolation and Hybrid Testing of Isolated Systems	-Tall building base-isolation -RTHS of base-isolated structure
Christenson, Richard	Testing Magneto-Rheological (MR) Fluid Dampers Advances in Real-Time Hybrid Simulation	-MR Dampers -RTHS -Geographically distributed RTHS
Hamaguchi, Hiroki	What is Takenaka?	-New sliding isolation device -Comparison of U.S. and Japanese design
Hao, Su	Design and Calculation for Seismic Response in Curved Bridges and a Digital Shaken-Table Test (DTSS) for Bridges	-Influence of horizontally curved segments on bridge collapse -Numerical modeling of bridges
Ikago, Kohju	International Research Institute of Disaster Science (IRIDeS)	-Long period ground motions -Rotary TMD
Johnson, Eric	NEESR Planning: Toward Experimental Verification of Controllable Damping Strategies for Base Isolated Buildings	-Testing at multiple scales -Leveraging shake table, HS, and RTHS testing
Maseki, Ryota	Dynamic Loading Experiment of Full-Scale Oil Damper for Seismic Isolation Against Large Velocity Excitation	-Semi-active base isolation -Hybrid damper design -E-Defense test of damper under large velocities
Nakata, Narutoshi	Development of Experimental Methods (Hybrid Simulation, Shake Table Testing and Effective Force Method)	-Force feedback control of actuators -Effective force testing
Panagiotou, Marios	Using Base Isolation and Rocking for Earthquake Resilient Design of Structures in Near Fault Regions	
Phillips, Brian	NEES/E-Defense Planning Meeting Research Summary	-Actuator control for RTHS -Large scale NEESR RTHS project
Ryan, Keri	Future Directions in Seismic Protective Systems Research	-E-Defense test of 5-story steel moment frame -Comparison of isolation devices

		-New passive isolation system
Sato, Eiji	My Previous Shaking Tests	-Shake table tests of semi-active isolation system -E-Defense test of medical facility -E-Defense test of 4-story eccentric RC structure
Shimizu, Kan	NEES/E-Defense Meeting 2013	-New semi-active oil damper
Yoshida, Osamu	Self-Introduction and Research Proposal	-Active base-isolation -Collision with moat wall

Recommended Efforts to Increase Effective Collaboration:

The discussions held during the breakout session identified strong agreement between the Japanese and U.S. participants that protective systems, with the specific application of base isolation, provide an excellent opportunity to establish meaningful and synergistic medium and long-term NEES/E-Defense and U.S.-Japan collaborative research related to earthquake engineering and the notion of the resilient city. The challenges and associated research needed to address these challenges were discussed on the second day of the workshop and recommended research of mutual interest to the U.S. and Japan was identified.

It was noted that there are many strong collaborative efforts already in place in the form of: (1) the use of E-Defense on NEES projects, (2) direct collaboration between E-Defense and NEES, and (3) payload projects on E-Defense projects. The most effective way to increase collaboration is by exploring additional opportunities that do not require a large amount of funding or commitment. Ideas proposed include test beds, reusing existing data from NEES/E-Defense experiments, and the exchange of research personnel.

Test beds: There is a strong push to create a test bed that may include one or more of the identified areas of common research interest. A few ideas were proposed, including a modular test bed where you can mix and match components to suit the interest of the researcher. For example, a researcher could choose a U.S. building or Japanese building, near-fault pulses or long-period ground motions, active or semi-active control, etc.

A modular approach will allow for multiple experiments. Test bed experiments can be of increasing complexity and held at different laboratories, including small-scale RTHS, large-scale RTHS, small-scale shake table tests, and large-scale shake table tests. For example, one laboratory can propose a shared experimental setup as a module for the community to propose new devices or control designs. This approach will increase the number of collaborators without a large time or funding commitment. Final tests could be conducted at E-Defense, perhaps as a payload test for funding reasons.

The benefit of a test bed is that researchers can study the device that they are interested in without designing a complete structure or selecting appropriate ground motions. The parameters will all be community selected and approved, providing a great starting point for conference and journal papers. Due to many evaluation criteria, the test bed should be seen as a design tradeoff problem rather than a competition.

Data Sharing: For collaborative NEES/E-Defense tests, the data goes directly to NEEShub. Purely Japanese E-Defense tests may not be available publically. A committee is needed to discuss how to make data available to the public and in an English language format. Not doing so is a loss of opportunity.

Beyond laboratory experiments, there is a wealth of field data on base-isolated buildings. These can be used to calibrate models and assess structural performance in as-built structures. However, both the U.S. and Japan, private companies own most buildings and are not open to sharing data. Some university buildings (e.g., Tohoku University and Tokyo Tech) have test bed buildings with instrumentation and data available. These types of field data test beds can be promoted by both U.S. and Japanese researchers.

Exchange of Personnel: Exchanging people is a good way to ensure ideas and data are shared. Graduate students can be included in collaborative efforts through existing funding mechanisms such as EAPSI (NSF), JSPS, Monbusho, etc. These programs facilitate the exchange of students for short research visits.

Recommended High Priority Research of Mutual Interest to the U.S. and Japan:

Protective systems are inherently intended to ensure resilience in a system with design objectives that go beyond life safety to provide continued operation. With this goal in mind and based on individual research presentations during the second day of the workshop, recommended high priority research topics of mutual interest to the U.S. and Japan were identified: (1) performance of protective systems to extreme (long-period, long-duration, near-field) ground motion, (2) performance and application of protective systems for vertical ground motion, (3) characterization and performance of protective system components, and (4) design and performance of protective systems for tall / slender / high rise buildings.

1) Performance of protective systems to extreme (long-period, long-duration, near-field) ground motion.
The 2011 Tohoku Earthquake with unique long-period and long-duration ground motion generated concerns with current protective systems. In terms of base-isolation systems, such ground motion may cause resonance of the bearing systems, excessive heat generation, and low-cycle fatigue. Researchers need to design systems to be effective for both likely earthquake scenarios and extreme events.

Scientific Importance: For long-period isolation with long-period motion, a better understanding of the effects on structure contents (e.g., piping, interior walls) is needed. Large displacement can also lead to moat wall impact; researchers need to clarify potential damage to structure, bearings, and nonstructural elements. Also, the capabilities of semi-active control devices to adaptively provide optimal performance can be shown for a wide array of potential ground motions.

Societal Benefit: Protecting the structures from extreme ground motions is critical to protect life-safety and minimize economic losses. There are many base-isolated structures which need to remain functional even after an earthquake.

Relation to the context of "resilient cities": Intact infrastructure is vital to the recovery of a city and a society, as well as the emotional well-being of the survivors.

2) Performance and application of protective systems for vertical ground motion.
Participants of the workshop are concerned that "traditional" base-isolation hardware might not provide effective protection for nonstructural components and essential equipment from the high frequency, vertical component of excitation that can be significant relative to the horizontal motion. Furthermore, vertical vibrations are coupled to horizontal motion just as horizontal

motion is coupled to vertical vibrations. Such considerations need to be made when understanding vertical ground motion.

Scientific Importance: At a very basic level, vertical vibrations add axial force demands to base-isolation bearings. Furthermore, the influence of vertical shaking on performance of nonstructural components and contents needs to be more clearly understood. Significant amplifications in the vertical vibrations are observed as they propagate from the base through the structure to the floor slabs. These vertical vibrations are also significantly influenced by soil-structure interaction. It was noted that a coupling of horizontal and vertical modes affects torsionally or vertically irregular buildings, further complicating the problem. A better understanding of these complex phenomena is required to propose mitigation strategies by isolation or damping at the base or at the floor level.

Societal Benefit: Damage and failure of nonstructural components and content disruption can be a life-safety issue, or cause substantial economic losses.

Relation to the context of "resilient cities": The mitigation of vertical vibration is important for protective system applications, which are chosen by owners to meet higher performance objectives such as continued operation. Sensitive power and hospital equipment may be susceptible to vertical vibration damage, hindering response and recovery efforts.

3) Characterization and performance of protective system components.
A better understanding of the individual system components will allow for accurate design of structural performance and plan for potential failure. There are many performance based design approaches and philosophies; for example, in an extreme event, should the base-isolation bearings fail or should the building fail? The bearings are protecting the structure, but perhaps something should be done to protect the bearings. It takes time to replace the bearings, and there is a concern for aftershocks after an extreme main event.

Scientific Importance: Through a more accurate characterization of the performance of protective system components, the system-level behavior can be better understood. When focusing on the components, long-term issues related to robustness and maintenance of the device should be included. Devices should be able to function for the lifespan of the building or be easily replaceable or maintained. Furthermore, the practicality of device must be considered.

Societal Benefit: With better models and understanding, devices can be presented to engineering community with confidence. More devices will provide more options for performance-based design to meet unique client and society needs.

Relation to the context of "resilient cities": Incremental developments in protective devices get researchers closer to the grand challenge of earthquake resilient structures. Component characteristics can have a strong impact on critical structures. Improvements to component's characteristics maintain operability of critical structures and lifeline. Replacing protective system components can cause significant inoperability and downtime.

4) Design and performance of protective systems for tall / slender / high-rise buildings.
In light of the 2011 Tohoku Earthquake and recent tests at E-Defense, there is a concern that tall buildings are more vulnerable than previously thought. It may be possible to retrofit these buildings using base-isolation, though many concerns remain. High-rise buildings are very heavy and may be difficult to lift for retrofit. A few alternative explored include strengthening the bottom few levels and placing isolation plane above ground or retrofitting columns one by one (such as using concrete to encase steel column) then adding base-isolators.

Scientific Importance: Presently, seismic isolation systems are applied to tall/slender/high-rise buildings. Questions remain regarding the performance of these isolation systems in regard to uplift and the compressive buckling of bearings. Large scale testing of tall/slender/high-rise buildings containing seismic isolation devices might address such concerns.

Societal Benefit: Performance improvement of tall/slender/high-rise buildings would contribute to better business continuity and sustainable society of large part of urban areas.

Relation to the context of "resilient cities": Tall/slender/high-rise buildings containing high performance seismic protective devices can serve as a shelter in a severe seismic event. Earthquake resilient tall/slender/high-rise buildings eliminate the business disruption of large regions in the vicinity of the building and large CO_2 waste that occurs when a damaged building has to be demolished after an earthquake.

Additional areas of interest that overlap with high priority items.
During discussions, additional areas of research interest were identified that overlap with the high priority items.

Special buildings: Special facilities such as servers, chip-making facilities, and high-tech manufacturing facilities have design requirements that are more stringent than typical structures. For example, high accelerations may damage expensive equipment, requiring active control to minimize accelerations. Industry partners might be interested in this area of collaboration.

Historical buildings and cultural heritage sites: These structures may need to be retrofit in a noninvasive manner, perhaps using base isolation.

Occupants: Experiments tend to neglect the human component, even if they consider nonstructural components. Furthermore, beyond the initial event, there may be some degree of excitation where people may be so frightened that they will not reenter the structure or will feel unsafe.

Perfect / absolute isolation: The challenge was presented to make an earthquake proof structure that is operable after an extreme event. Many issues have to be considered, such as soil structure interaction and uplift. Existing technologies can be combined, with robust active control identified as a promising area.

Elastic versus inelastic superstructure: The question was raised if it is possible to control or avoid inelasticity of the superstructure. Moreover, if it were possible, should inelasticity be avoided? There is concern in the U.S. about having the superstructure yield. But U.S. code allows for yielding before MCE earthquake. This brings up a point as to why inelastic behavior is allowed. But, no matter what is done, under a big earthquake, yielding may be inevitable, so it should be designed to happen in a favorable manner. It was noted that base-isolator bearings filter the ground motion to the superstructure, which can be used to maintain nominally elastic behavior.

Passive control versus semi-active and active control: The costs and benefits of structural control alternatives were debated among the group. A good building may be designed for 50 years, but be expected to last 100+ years. Semi-active and active control systems are susceptible to increased maintenance in terms of the sensor and computer systems that will likely break down before the structure has surpassed its useful life. Even active-mass dampers for wind applications require costly maintenance. On the other hand, the forces we design for now are twice as much as they used to be. Down the road, design criteria may change. With semi-active and active control, we can easily change control strategies (stiffness, base shear, etc.) without replacing physical devices, saving on replacement cost.

Opportunities for Payload Projects: (list)

- Nonstructural components
- Soil-structure interaction tests
- Human perception of earthquake response
- Validation of RTHS to large-scale shake table tests
- Different devices & control algorithms

Opportunities and needs for advancing capabilities of numerical simulation: (list)

- Adequate modeling of components and interaction of components during extreme loading
- Validation of component and system level models using E-Defense

WORKING GROUP SUMMARY REPORTS

Geotechnical Engineering Working Group

Working Group: Geotechnical Earthquake Engineering and Engineering Seismology

Moderators: Jonathan P. Stewart (UCLA) and Shuji Tamura (Kyoto University)

Recorder: Ramin Motamed (University of Nevada, Reno)

Members (in alphabetical order of last names): Scott A. Ashford (Oregon State University), Shideh Dashti (University of Colorado), J. David Frost (Georgia Institute of Technology), Shunji Fujii (Taisei Corporation), Hideki Funahara (Taisei Corporation), Kenneth Gillis (University of Colorado), Youssef MA Hashash (University of Illinois), Susumu Iai (Kyoto University), Takahito Inoue (NIED), Hisatoshi Kashiwa (Osaka University), Yohsuke Kawamata (NIED), Anne Lemnitzer (UC Irvine), Lelio Mejia (URS Corporation), Saburoh Midorikawa (Tokyo Institute of Technology), Atsushi Mikami (The University of Tokushima), Ramin Motamed (University of Nevada, Reno), Shoichi Nakai (Chiba University), Naohiro Nakamura (Takenaka Corporation), Ellen M. Rathje (University of Texas, Austin), Nicholas Sitar (UC Berkeley), Jonathan P. Stewart (UCLA), Shuji TAMURA (Kyoto University), Tetsuo Tobita (Kyoto University), Kohji Tokimatsu (Tokyo Institute of Technology)

Presentations:

- Shuji Tamura and Jonathan Stewart. Session overview. Preliminary research priorities for Japan-U.S. collaboration in Geotechnical Earthquake Engineering and Engineering Seismology
- Yohsuke Kawamata. Possible future researches using E-Defense shake table
- Saburoh Midorikawa. Site amplification factors derived from strong motion records of the 2011 Tohoku, Japan earthquake.
- Ellen Rathje. Validation of nonlinear site response from KiK-net array data
- Naohiro Nakamura. Earthquake response analysis using nonlinear energy transmitting boundary
- Atsushi Mikami. Empirical approach using Japanese data including evaluation of kinematic soil-structure interaction
- Nicholas Sitar. Performance of improved ground during earthquakes
- Shoichi Nakai. Analysis of liquefaction damage and development of its countermeasure.
- Tetsuo Tobita. Next Generation of Physical Model Testing with Generalized Scaling Law
- Hisatoshi Kashiwa. Simulation analysis of damaged structure supported by piles in heavily damaged zone during the 1995 Kobe earthquake
- Ken Gillis, Shideh Dashti, Youssef Hashash. Centrifuge testing of soil-structure interaction for underground structures. Use of tactile sensors.
- Shunji Fujii. Monitoring of foundations and shaking table test on the E-Defense
- Ramon Motamed. Shaking table testing related to piles and lateral spreading.
- Hideki Funahara. Dynamic interaction between pile foundation and liquefied ground. Shaking table tests and effective stress analyses
- J. David Frost. Exploiting interfaces for enhanced seismic subsurface characterization and infrastructure performance
- Kohji Tokimatsu. Potential topics for U.S.-Japan collaboration.

Summary:

The research discussed within our session supports the broad objective of engineering "Societal Sustaining Systems." We considered the critical research needs in areas related to engineering seismology and geotechnical earthquake engineering. Specific areas of research that support this objective pertain to hazard characterization, ground failure, and mitigation. Moreover, we discussed the degree to which U.S.-Japan collaboration is essential to realizing research objectives and E-Defense and NEES facilities can support the research.

Recommended Efforts to Increase Effective Collaboration:

- Improve clarity in data sharing protocols (both sides) and perhaps revisit those protocols that unnecessarily restrict data access in joint experiments.
- Fund research to interpret existing data & perform applicable simulations. This could be facilitated with jointly funded graduate student fellowships on the U.S. and Japan sides.
- Consortium of U.S. and Japanese testing facilities to streamline access to equipment.

Recommended High-Priority Research:

Societal Sustaining Systems

1. Multi-hazard risk characterization. Examples include mainshock/aftershock sequences and rain or tsunami following earthquakes. The critical issue is what is the relative impact of the subsequent event (aftershock, rain, tsunami) as a result of the degraded state of the system following the mainshock.
2. System response in an urban environment. Soil-structure interaction (including kinematic effects, energy dissipation of foundation systems, and modeling requirements). Impact of tightly-packed structures in a dense urban environment – effects on foundation damping and foundation input motions.
3. Performance of distributed systems during earthquakes. Issues with these systems include the fragility of a single segment, correlation of damage across segments, and vulnerability to system functionality if individual segments fail. Example systems include levees, transportation systems, pipelines, energy transmission systems, etc. Role of alternate ground failure mechanisms in system performance (liquefaction, cyclic softening, seismic compression, response of organic soils).

Hazard Characterization

4. Regional variations in site response. What are the fundamental factors causing variations in Vs30-scaling and nonlinearity by region? What site parameters, beyond Vs30, should be considered to capture these regional effects?
5. Is site response predictable from 1D analysis? Role of geologic complexity. Methods for large-strain site response. Appropriate damping levels. Challenges associated with existing data from KiK-net and K-NET arrays.
6. Site response for the vertical component of ground motion.
7. Estimation of Vs30 from proxies for the application of GMPEs in regions without seismic velocity data

Ground Failure

8. Next generation liquefaction (NGL):

a) Development of community liquefaction triggering and effects database
b) Models for liquefaction triggering and effects derived from this database
c) Physical model testing to support aspects of the models not constrained by data (e.g., effects of high overburden stress).

9. Prediction of site response for sites that experience liquefaction (e.g., LEAP project).
10. New site characterization techniques, including surface wave methods, improved cone penetration testing and other types of penetrometers.

Mitigation

11. Soil improvement. Use field performance data, including recent cases from Japan and NZ where improved ground did not do as well as expected, to guide the design of future physical model tests and related analysis.
12. Mitigation of foundations for existing structures

For each research topic, we consider its anticipated impact, the importance of U.S.-Japan collaboration, and the testing scale, with the result shown in Figure 1.

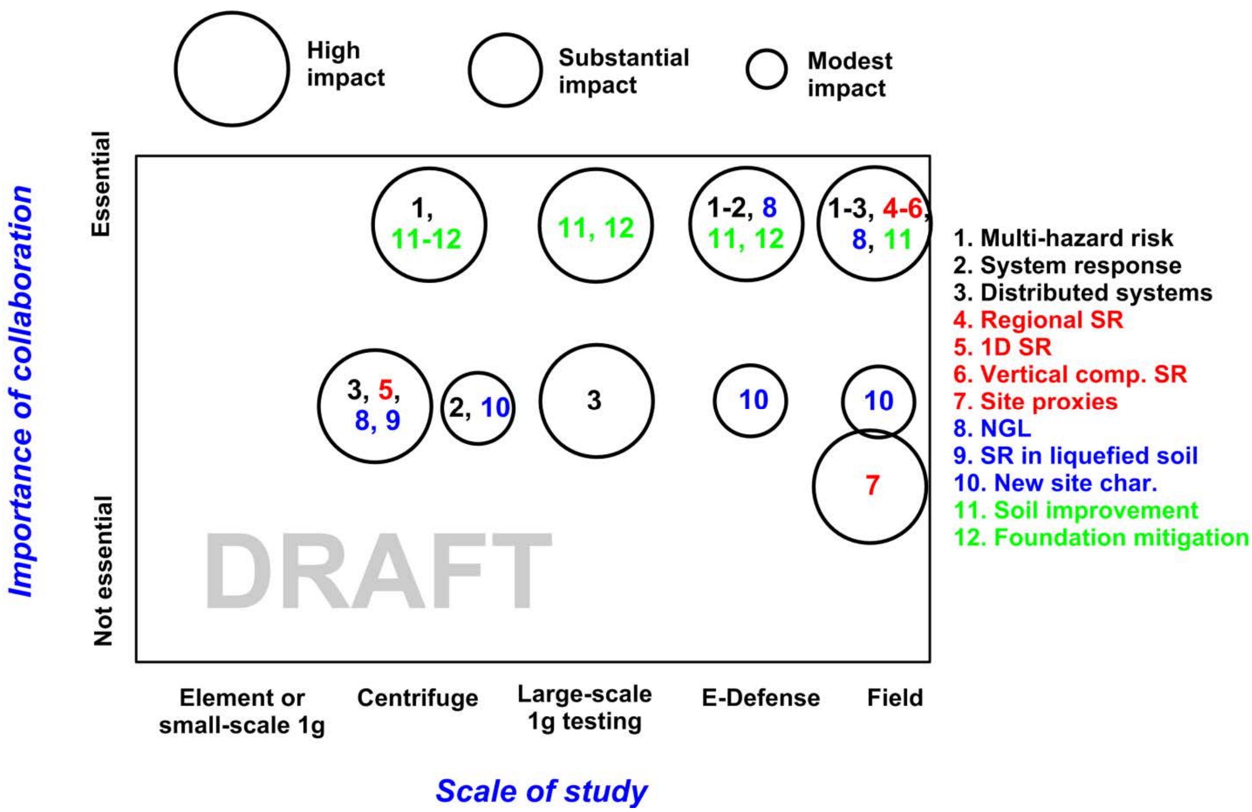


Figure 1. Schematic illustration of proposed research tasks in geotechnical earthquake engineering and engineering seismology plotted in space that indicates the type of data required for the study (abscissa) and the importance of U.S.-Japan collaboration (ordinate). The potential impact of the study is indicated by the size of the circle.

WORKING GROUP SUMMARY REPORTS

Monitoring Working Group

Working Group: Monitoring

Moderators: Masahiro Kurata (Kyoto University), Jerome P. Lynch (University of Michigan)

Recorder: Kenneth J. Loh (University of California Davis)

Members: Shirley Dyke (Purdue University), Tomonori Nagayama (University of Tokyo), Anne Kiremidjian, Stanford University, Akira Nishitani (Waseda University), Yoshihiro Nitta (Ashikaga Institute of Tech), Kincho Law (Stanford University), Sean O'Connor (University of Michigan), Shamim Pakzad (Lehigh University), Jennifer Rice (University of Florida), Wei Song (University of Alabama)

Presentations:

"NEES/E-Defense Collaborative Earthquake Research Program 10th Planning Meeting: Rebooting U.S.-Japan Joint Research on Earthquake Engineering" by Masahiro Kurata (DPRI, Kyoto University)

"Network for Earthquake Engineering Simulation" by Shirley J. Dyke (Purdue University)

"Monitoring Systems for Intelligent Infrastructures: Design, Sensing and Data Analytics" by Anne Kiremidjian (Stanford University)

"Cyber-infrastructure for Monitoring" by Kincho H. Law (Stanford University)

"Wireless Cyber-Physical System Frameworks for Enhancing Civil Infrastructure Resiliency" by Jerome P. Lynch (University of Michigan)

"Condition Evaluation of Infrastructure through Monitoring: Practical Applications" by Tomonori Nagayama (Tokyo University)

"Direct Sensing of Inter-story Drift Displacements for Buildings" by Akira Nishitani (Waseda University)

"Structural Health Monitoring for Local Element" by Yoshihiro Nitta (Ashikaga Institute of Technology)

"Resource Efficiency for Wireless Sensing using the Telegraph Road Bridge Testbed" by Sean M. O'Connor (University of Michigan)

"SHM Research within NEES / E-Defense" by Shamim N. Pakzad (Lehigh University)

"NEES – E-Defense Monitoring Session" by Jennifer A. Rice (University of Florida)

"Application of Model Updating in Structural Performance Evaluation" by Wei Song (The University of Alabama)

Recommended Efforts to Increase Effective Collaboration:

The working group was unanimous in its belief that the human network has been and will continue to be the key ingredient to the success of U.S.-Japan collaborations. To reinforce this already strong human network, it is proposed that a student-oriented exchange program focused on studying hazard mitigation and resilient cities be revived. In addition, the human network should be expanded to include social scientists and other stakeholders relevant to the resiliency of urban communities.

To advance research collaborations, the U.S.-Japan community should prioritize the development of interoperable experimental data repositories generated by NEES and E-defense.

Specific to the focus of the working group, perhaps datasets of greatest relevance to SHM should be prioritized for release. While data access is a necessary step to joint collaboration, to create a true virtual testbed, efforts should concentration on facilitating access to tools that can be used to process data stored in a common data repository.

To accelerate the creation of next-generation monitoring technologies, the working group proposes that a separate solicitation in which both U.S. and Japanese teams could seek join funding for payload projects.

Finally, to truly tackle the technical and non-technical challenges of resilient cities, it is proposed that the U.S. and Japanese research communities focus on two seismically-active testbed cities, one in each nation (e.g., Los Angeles and Tokyo). A research program should be created to leverage existing and to create new opportunities to deploy regional-scale instrumentation in these cities to study *in situ* community resiliency. In addition to instrumentation deployment, regional-scale simulations can be performed so that the response of both cities to an equally destructive earthquake can be compared between the two urban environments.

Recommended High Priority Research of Mutual Interest to the U.S. and Japan:

The working group organized its effort to identify high priority research topics of mutual interest to the U.S. and Japanese research communities spanning from the individual infrastructure component-scale (*e.g.,* a building) to the regional scale (*e.g.,* a mega-city).

Sensing and Identification of SHM-aided Limit States for Ductile Structures

A previously missing link between earthquake-resistant design and structural health monitoring (SHM) is a framework that explicitly connects design criteria with the information generated by sensing systems. The grand challenge is to create and sense damage limit states in strong non-linear region after the initiation of strength deterioration with the aid of sensors and sensing systems. The research challenges include the identification of damage limit states with novel SHM technologies and leveraging the NEES/E-Defense data archive of large-scale tests. Design verification tests using densely-instrumented large-scale test beds. Accomplishing this grand challenge will yield opportunities to account for the potential ductility and redundancy in structural systems for post-event safety evaluation and reduce downtime before re-occupation of damaged structures.

Scientific Importance:

- ❑ Identification of damage limit states will enable rapid damage assessment
- ❑ Damage limit state analysis can be performed within a probabilistic framework
- ❑ Novel sensing technologies will enable direct damage quantification of damage limit states
- ❑ Assessment of reliability in damage limit states will empower decision-making

Societal Benefit:

- ❑ Structural-engineer-friendly SHM index
- ❑ Incorporation of the potential residual ductility and redundancy in structures during post-event analysis
- ❑ Reduced downtime with rapid structural safety assessment
- ❑ Greater benefits to infrastructure owners that offset cost of the deployment of SHM systems
- ❑ Increase in public confidence in infrastructure safety and post-event decision-making

Ready-to-Deploy Sensor-based Decision Support System for Post-event Infrastructure Re-occupancy

Rapid recovery is critical for achieving next-generation resilient communities and for minimizing the adverse socioeconomic impact following a severe earthquake. The grand challenge is to devise new technologies, computational methods, and probabilistic tools for making reliable decisions regarding the immediate re-occupancy and use of infrastructure systems and their intended functionalities. A broad community of stake holders would be engaged to accelerate the transfer of research findings to practice. The research challenges include: developing verified sensing technologies for measuring specific damage modalities (including their initiation and propagation) before, during, and after an earthquake; mining and utilizing existing test data for algorithm and model verification; designing test beds aimed at assessing different structural health monitoring methods applied to different classes of structures; and assessing structural performance, operational capabilities, and rehabilitation priority. The decision support system for re-occupancy and continued operations should incorporate uncertainties while still provide definitive actions that are aligned with the needs and expectations of engineers, owners, facility managers, and stakeholders.

Scientific Importance:

- ❑ Design and optimize sensors and algorithms for characterizing damage initiation and propagation
- ❑ Create test beds for assessing SHM technologies and methods when applied to different classes of structures or construction methods
- ❑ Implement validated models for prediction of structural response to different excitations
- ❑ Develop probabilistic decision-making framework that integrates structural resistance and demand

Societal Benefit:

- ❑ Significantly enhance the resiliency of large urban environments following major earthquakes
- ❑ Reduce socioeconomic impact of major events
- ❑ Improve psychological well-being
- ❑ Enhance functionality and operations of disaster-impacted regions
- ❑ Dedicate shelter and recovery resources to areas of greatest need
- ❑ Prioritize repairs and rehabilitation efforts

<u>City-scale Monitoring for Assessing and Advancing Urban Resiliency</u>

To take on the scientific and technological challenges associated with creating truly resilient cities, existing experimental programs should be expanded to include a focus on city-scale response (physical and social) to natural hazard events. Monitoring technologies, in conjunction with advance simulation tools, can be used to provide a more comprehensive view of how infrastructure systems and human populations respond to earthquakes. Incorporation of emerging information sources, such as crowd-sourcing, remote sensing, and social media, will enhance regional-scale responses. In the context of future NEES/E-defense research collaborations, specific focus should be paid on the development of monitoring technologies that can learn and track the physical weaknesses and vulnerabilities that may exist at points of connection of infrastructure systems. Experimental programs should also be devoted to the testing aimed at understanding how component performance impacts the performance of the infrastructure system or network of which that component is a part. Simulation tools can be used to further advance how decision makers can rapidly utilize monitoring data to assess system fragilities and to allocate resources immediately after the event in the ensuing days and weeks.

Scientific Importance:

- ❑ With fundamental knowledge in the infrastructure system interdependency lacking, experimental testing and computer simulation will:

Advance sensing methods and data aggregation systems for monitor points of system connection

Create simulation tools to model the mechanisms of cascading failures in infrastructure systems
Optimize data-driven decision-support systems for allocation of emergency response at the regional-scale

Societal Benefit:
- Identify pre-event weaknesses in city-scale systems for hardening to ensure global system performance and to eliminate cascading failures
- Rapidly assess health of urban physical infrastructure post-event:

Allocate emergency response resources
Enhance the operations of first responders
- Minimize time to full regional and global economic recovery of region and social impact

Opportunities for Payload Projects:
The working group identified the creation of a large-scale testing program that is open to the broader research community for the purposes of identifying damage limit states in seismically loaded structures. The specific attributes of this program include:
- Test specimens designed to illuminate specific damage mechanisms at local and global length scales
- Open access to the research community to validate novel sensor technologies
- Intelligent sensors for real-time agent software migration of embedded damage detection algorithms
- Create datasets for blind assessment of damage detection algorithms (in addition to the research, consider supplemental student competition possibilities)
- Assess the reliability and durability of sensors and sensing systems

With the establishment of this research program, a diverse stakeholder community should be fully engaged:
- Involve visual inspectors to evaluate tested specimens to identify optimal ways of combining SHM data with visual inspections for re-occupancy decisions
- Quantify the benefits of SHM systems for cost-benefit analyses

Opportunities and needs for advancing capabilities of numerical simulation:
Once the aforementioned testbed has been established, data generated would enhance the simulation of regional responses to earthquakes, especially the performance of physical infrastructure under ground motion. The following computation opportunities would be available for the research community to advance resilient communities:
- Reduce the uncertainty inherent in numerical models of structures, especially structures responding in their nonlinear response regime, through advance online or real-time model-updating techniques
- Agent-based simulation of societal response to earthquakes over varying time-scales

APPENDIX V: MINUTES OF JOINT TECHICNAL COORDINATING COMMITTEE

Date and Time: 9:30 AM – 10:45 AM, December 13
Place: Room N307, DPRI, Kyoto University
Participants: Joy Pauschke, Koichi Kajiwara, Julio Ramirez, Stephan Mahin, Masayoshi Nakashima, Lelio Mejia, Takahito Inoue

Issues Discussed:
1) Summary of past ten years
2) Possibility of Phase III (next five years)
3) Next meeting

Resolutions:

Close and carefully tailored collaboration for the past ten years had greatly contributed to the advancement of NEESR research and E-Defense research.

Achievement of NEES/E-Defense for the past ten years is worthy of a summary. A special session in 16WCEE, to be held in 2017 in Chile, may be a vehicle to make such a summary.

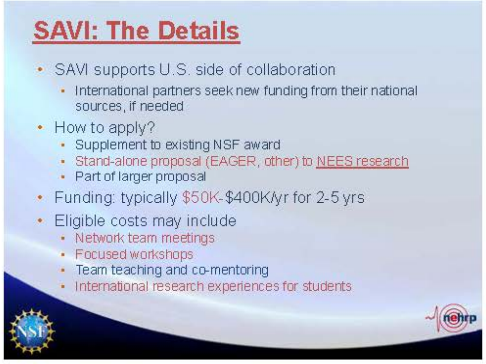
The effort shall continue in the future and to this end the plan for Phase III, which is to start in 2015, should be laid out at the earliest convenience possible. Continuing exchanges of ideas as well as the establishment of face-to-face planning meetings are encouraged.

JTCC learned that NIED is planning multiple large-scale tests for the coming few years, and the tests can serve as the objects that are jointly examined by the Japanese and U.S. researchers. NIED is encouraged to share the test plans with the U.S. researchers so that they can prepare for the collaboration. NIED is also asked to show the price list regarding the use of E-Defense by U.S. researchers.

NEES/E-Defense meetings shall continue on an annual basis, and the next target is the summer to fall of 2015 dependent on availabilities of researchers in the two countries.

APPENDIX VI: PRESENTED PAPERS IN PLENARY SESSION

Introductory Remarks from NSF ◆ Joy Pauschke



An Overview: U.S.-Japan Research Earthquake Engineering ◆ Masayoshi Nakashima

An Overview – US-Japan Joint Research Earthquake Engineering

December 11, 2013

Masayoshi Nakashima

Disaster Prevention Research Institute
Kyoto University

A Partial History of US-Japan on Earthquake Engineering for Past Forty Years

US-Japan joint Program Utilizing Large Scale Testing Facilities (1975 – 2000)
(Sponsors: NSF and Japanese Ministry of Construction)

RC buildings (Phase I), steel buildings (Phase II), masonry buildings (Phase III), pre-cast buildings (Phase IV), composite structures (Phase V), and smart structures (Phase VI).

NEES/E-Defense Project (2005 – present)
(Sponsors: NSF and MEXT)

Two Distinguished Leaders to Initiate and Promote US-Japan joint Program

Joe Penzien
UC Berkeley

Damaging Quakes

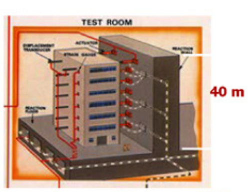
1964 Niigata
1968 Tokachi-oki
1971 San Fernando
1978 Miyagiken-oki

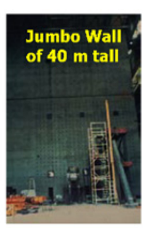
Hajime Umemura
Univ. of Tokyo

"Ume-san" & "Joe-san" friendship and mutual-trust over many years (with much *Sake*) was the source of US-Japan collaboration.

My Juvenile Reminiscence
JTCC (Joint Technical Coordinating Committee) Meeting at Tsukuba

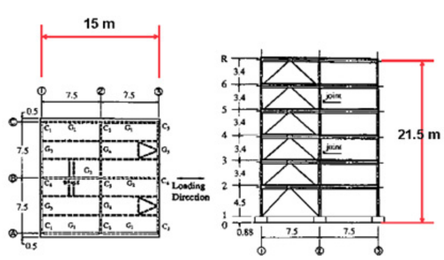
US-Japan joint Program Utilizing Large Scale Testing Facilities (1975 – 2000)

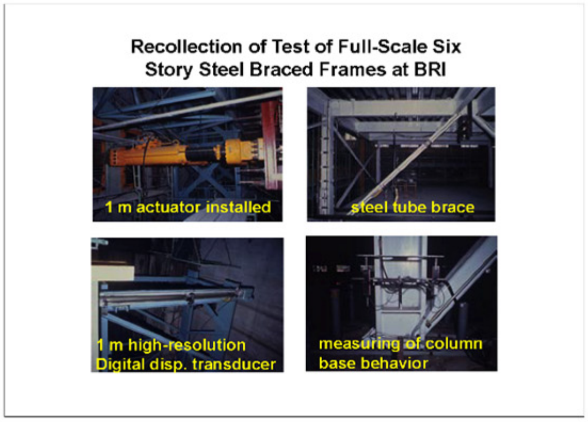


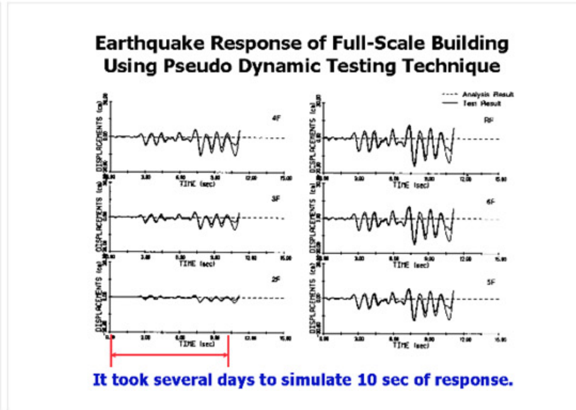


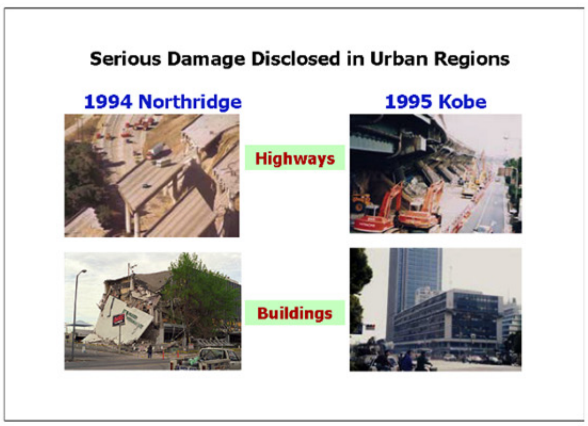
Jumbo Testing Facilities at Building Research Institute (built in 1980)

Pseudo Dynamic Test on Full-Scale Six Story Steel Braced Frames (1983-1985)



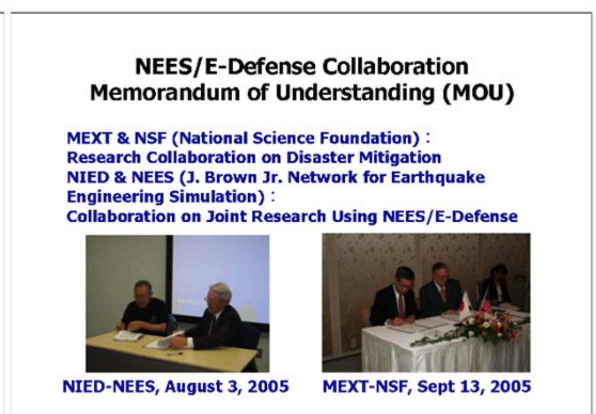

Recollection of Test of Full-Scale Six Story Steel Braced Frames at BRI
1 m actuator installed
steel tube brace
1 m high-resolution Digital disp. transducer
measuring of column base behavior


Earthquake Response of Full-Scale Building Using Pseudo Dynamic Testing Technique
It took several days to simulate 10 sec of response.


Serious Damage Disclosed in Urban Regions
1994 Northridge
1995 Kobe
Highways
Buildings


Construction of Large-Scale Experimental Facilities for Earthquake Engineering Research
E-Defense
Ready in April, 2005
NEES
Ready in October, 2004


Planning Meetings
First
Second
Third
Fifth


NEES/E-Defense Collaboration Memorandum of Understanding (MOU)
MEXT & NSF (National Science Foundation) :
Research Collaboration on Disaster Mitigation
NIED & NEES (J. Brown Jr. Network for Earthquake Engineering Simulation) :
Collaboration on Joint Research Using NEES/E-Defense
NIED-NEES, August 3, 2005
MEXT-NSF, Sept 13, 2005

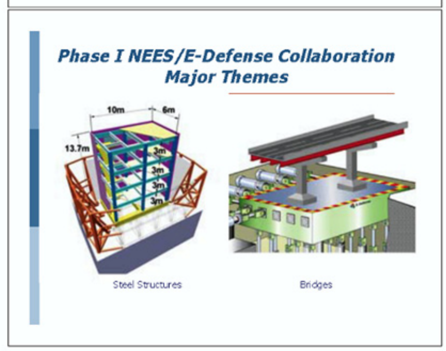
Appendix VI

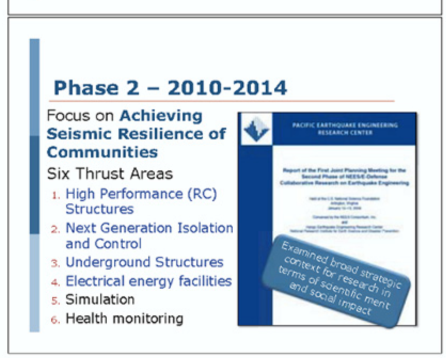
A History of Planning Meetings

Planning Meetings

First	April, 6 to 8, 2004 at Kobe
Second	July 12 to 13, 2004 at Washington DC
Third	January 17, 2005 at E-Defense
Fourth	August 2 to 3, 2005 at E-Defense
Fifth	September 27 to 29, 2006 at E-Defense
Sixth	September 28 to 30, 2007 at E-Defense
(Workshop for Second Phase of NEES/E-Defense)	
	January 12 to 13, 2009 at Washington DC
Seventh	September 18 to 19, 2009 at E-Defense
Eighth	September 17 and 18, 2010 at E-Defense
Ningh	August 26 and 27, 2011 at E-Defense

Overviews on NEES/E-Defense Collaboration on Earthquake Engineering ◆ Stephen Mahin





Phase 2 – 2010-2014

Focus on **Achieving Seismic Resilience of Communities**

Six Thrust Areas

1. High Performance (RC) Structures
2. Next Generation Isolation and Control
3. Underground Structures
4. Advanced Steel Buildings
5. Simulation
6. Health monitoring

NEEStips project (Keri Ryan, UNR)

Triple Pendulum Friction Bearings

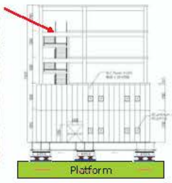
LRB with Linear Crossover Sliders

Fixed Base Structure

Phase 2- High Performance Buildings + Isolation and Control

December 2010 August 2011

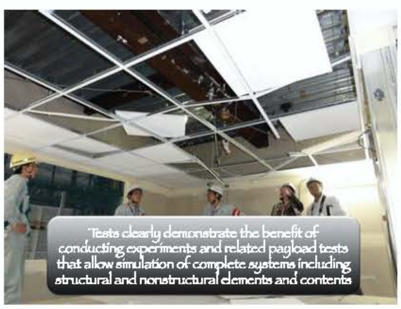
Conventional and self-centering RC precast buildings



"New" zero damage isolation

NEEStips project (Keri Ryan, UNR)

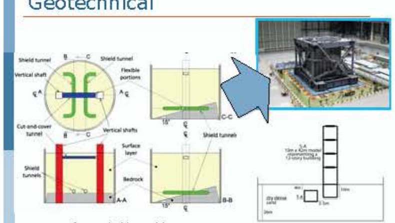
Payload tests:
Nonstructural components: Ceilings, partitions, cladding, fire sprinklers
Staged office, hospital and lab occupancy



Collaboration key to advancement in Earthquake Engineering Engineering

NEES/E-Defense Planning Meetings

Underground Structures and Geotechnical



E-Defense Shaking Table Tests

NEESR Centrifuge Tests

Building codes are minimum standards for public safety

- Stated purpose:
  - Provide minimum provisions for design and construction of structures to resist effects of seismic ground motions
  - "...to safeguard against major structural failures and loss of life, not to limit damage or maintain function."

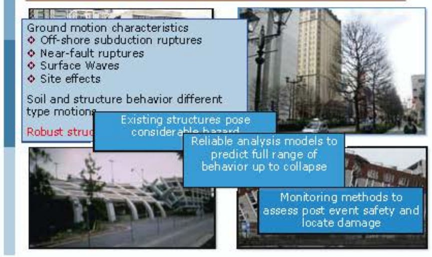
Designed to protect life in extreme event, but damage expected

Building codes do not provide earthquake proof structures

- Stated purpose:
  - Provide minimum provisions for design and construction of structures to resist effects of seismic ground motions
  - "...to safeguard against major structural failures and loss of life, not to limit damage or maintain function."

Designed to protect life in extreme event, but damage expected

Damage potential of subduction zone, near-fault and other events

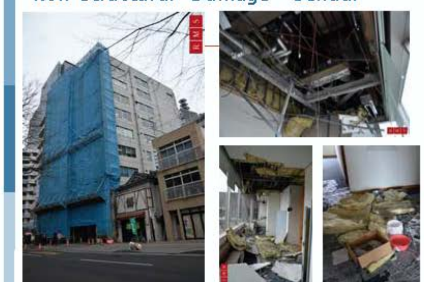


Engineering Effective in Reducing Loss of Life

Sendai, Japan

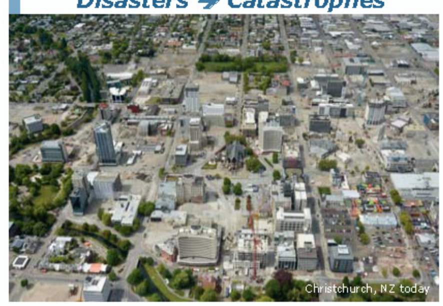
Structural damage due to ground shaking was relatively light for new structures even in regions of heavy shaking

"Non-Structural" Damage - Sendai

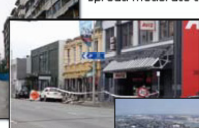


Nonstructural Elements Also Pose Life Safety Concerns

Disasters → Catastrophes



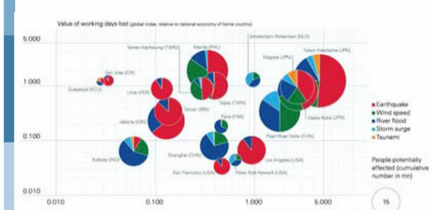
Structures Should Not Be Considered Individually: Disaster vs Catastrophe

Natural disasters cause wide-spread moderate to severe damage that may strain ability of a community to respond

Widespread damage can have substantial long-lasting social, economic and cultural impact on the well-being and vitality of a city and nation

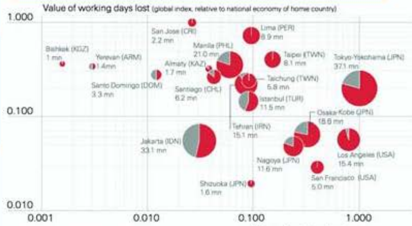
Potential Loss of Work Caused by Natural Disasters



SwissRE: Mind the Risk, 2013

Appendix VI

Potential Loss of Work Caused by Natural Disasters: Earthquake Only



SwissRE: Mind the Risk, 2013

10th NEES/E-Defense Planning Meeting: Goals

- Strengthening and extending collaboration
- Help refine plans for near-term research
- Identifying appropriate high priority problems and projects for future collaboration having high impact benefits
- Identify opportunities for rapid dissemination of findings

Moving ahead

- E-Defense provides a unique facility of mutual benefit to the U.S. and Japan
- Collaboration of experts from the US and Japan can accelerate progress to reduce tremendous social and economic consequences of earthquakes and related natural disasters.

- Collaboration leverages limited resources.

Special Project for Reducing Vulnerability for Urban Mega Earthquake Disasters ◆ Masayoshi Nakashima

Special Project for Reducing Vulnerability for Urban Mega Earthquake Disasters (2012 – 2016)
Budget for 2012: 6 million USD

(II) Maintenance and recovery of functionality in urban infrastructures

December 11, 2013

Masayoshi Nakashima
Disaster Prevention Research Institute (DPRI)
Kyoto University

Lessons to Earthquake Engineering Community

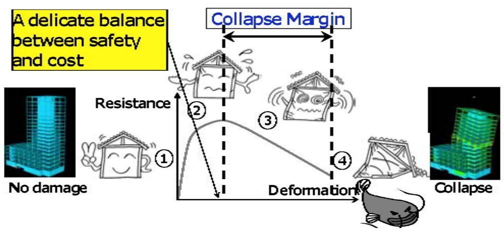
(1) Response to earthquakes beyond what is considered in structural design
(2) Continuing business and prompt recovery

Specific Engineering Research Needed

(A) Quantification of collapse margin of high-rise buildings
(B) Monitoring and prompt condition assessment of buildings

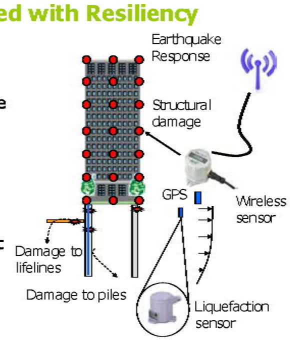
Engineering Research Need Associated with Resiliency

(1) Quantification of Collapse Margin: To make a consensus to the response to earthquakes that go beyond one considered by codes, we shall quantify the performance of each structure up to complete.



Engineering Research Need Associated with Resiliency

(2) Technologies for Enhanced Health Monitoring: To make our society more resilient, we need more advanced sensing and monitoring technologies by which we can detect damage and/or evaluate state of safety immediately.



Special Project for Reducing Vulnerability for Urban Mega Earthquake Disasters (2012 – 2016)
Budget for 2012: 6 million USD

Objective/Scope: Based on lessons learned from 2011 Tohoku earthquake, urgent, comprehensive research is to conduct for minimizing loss of urban disasters against large ocean ridge earthquakes along Nankai Trough and near fault earthquakes that would hit metropolitan regions. To carry out this research, a trans-disciplinary research team has been formed, consisting of earth science, structural engineering, and social sciences.

Prediction
(I) Prediction of earthquake damage to metropolitan regions

Responses
(III) Advancement of capacity for urban disaster responses

Prevention
(II) Maintenance and recovery of functionality in urban infrastructures

40

Research Objectives

Objectives of Research:
① Quantification of collapse margin of urban buildings
①−1: Steel high-rise; ①−2: RC high-rise
② Monitoring and condition assessment of buildings
②−1: Superstructure; ②−2: Soil and underground; ②−3: Interactive SSI system
③ Monitoring and response evaluation of SSI
③MeSO-net observation

Experiences on "Special Project for Earthquake Disaster Mitigation in Tokyo Metropolitan Area (2007-2011)"	Trans-disciplinary research team that considers "national interest", "advanced research", and "timely transfer to practice"

Appendix VI

Work Sharing and Annual Plan

	2012	2013	2014	2015	2016
①-1 Steel Collapse	Element test		Simulation		
	E-Defense test				
				Evaluation	
①-2 RC Collapse		Element test	Simulation		
	Test planning		E-Defense test		
				Evaluation	
②-1 Monitoring Super-structure	Methodologies			Evaluation	
	System development				
		Verification (①-1, ①-2)			Verification
	Survey			Evaluation	
②-2 Monitoring Soil	Survey				
	Element test			E-Defense	Verification
		System development			Evaluation
②-3 Monitoring SSI	Survey	Simulation			
	Planning			System development	
					E-Defense
③ SSI and Monitoring in Actual Buidings	Deployment and observation				
		Simulation			Verification
			Estimation of shallow earth structures		
					Evaluation

Research Team

Oversight Committee

Headquarters
- DPRI, Kyoto U. (M. Nakashima, PI)
- E-Defense, NIED (K. Kajiwara, Vice-PI)
- Kobori Institute (N. Koshika, Secretary)

Research Team
- ①-1:S
- ①-2:RC
- ②-1:
- ②-2:
- ②-3:
- ③:MeSO-net

Research Team

Oversight Committee

Head-quarters

①-1: Steel collapse
PI: Kajima (M. Takahashi)
Co-PIs: Shimiz, Kobori, Kyoto U. (K. Suita), E-Defense

①-2: RC collapse
PI: Obayashi (H. Katsumata)
Co-Pis: Shimiz, Kyoto U. (M. Nishiyama), E-Dfense

②-1: Monitoring superstructure
PI: Shimiz (T. Saito)
Co-PIs: Kajima, Obayashi, Nagoya U. (J. Tobita), E-Defense

②-2: Monitoring soil-foundation
PI: Taisei (S. Fuji)
Co-Pis: Kobori, Kyoto U. (S. Tamua), E-Defense

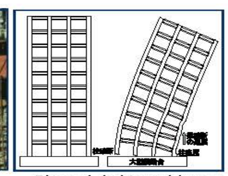
②-3: Monitoring SSI System
PI: Kobori (H. Okano)
Co-Pis: Kyoto U. Shimiz, Taisei, Taeknaka, Yokohama U. (K. Kusunoki), E-Defense

③: MeSO-net
PI: Takenaka (K. Kobayashi)
Co-PIs: Univ. Tokyo (S. Sakai), Kyoto U., E-Defense

①-1 Collapse Margin of Steel High-Rise Buildings

Background:
Higher performance has been considered in the design and construction of high-rise buildings, but the performance under extreme earthquake events that are beyond the code consideration shall be quantified in light of 2011 Tohoku earthquake and damage.

Steel damage disclosed in 1995 Kobe

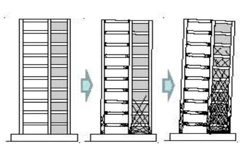


Planned shaking table test

①−2 Collapse Margin of RC Buildings

Background:
Many residential buildings are made of RC. Their performance, notably under long-period ground motions, shall be evaluated; damage growth and loss of functionality shall be characterized; and collapse margin shall be quantified.

Collapse example (in Turkish earthquake of October 2011), with significant death toll



Planned shaking table test under repeated exitation

②-1 Monitoring for Superstructures

Background:
To ensure business continuity and prompt recovery to normal life, technologies related to health monitoring and condition assessment should be enhanced. Deployment of sensors, acquisition of data, and prompt assessment on damage location and severity shall be developed.

Visual inspection by engineers

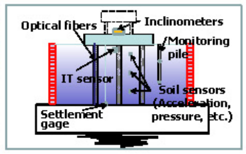
- Time consuming
- Shortage after events
- Invisibility due to interior/exterior finishes

Damage Assessment System

➋-2 Monitoring – Soil and Foundation

Background:
Prompt condition assessment for soils, foundations, and underground lifeline systems is a key for earthquake disaster response, but invisibility has made it extremely difficult. A condition assessment system using various sensors deployed in the soil shall be developed.

Pile damage in soil during 1964 Niigata; damage disclosed after twenty years during rennovation.



Planned shaking table test for soil-foundation system

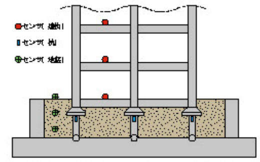
➋-3 Monitoring – Soil-Structure Interaction (SSI) System

Background
To assess the condition as a total system, sensoring techniques that interactively combine data on super-structures, foundations, and soils shall be advanced; and associated condition assessment technologies shall be developed.

Differential settlement

Damage to pile head

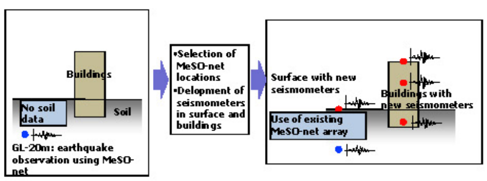
Damage in the middle of pile



Planned shaking table test for SSI system

➌ Observation Using MeSO-net

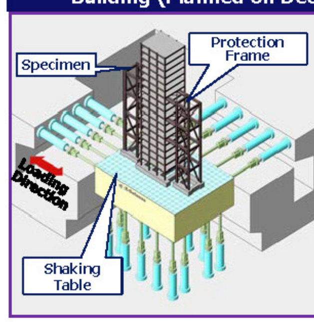
Background:
Evaluation of structure as SSI system shall be promoted, and to this end, realistic data that reflect SSI system shall be collected. Use of MeSO-net system that has been deployed in metropolitan regions is most useful.



Earthquake observation in current system

Real-time observation of SSI system using MeSO-net arrays

Shaking Table Test for Collapse of Steel High-Rise Building (Planned on December 2013)



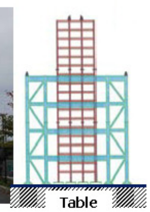
■ Shaking Table
Use of E-Defense

■ Specimen
A height of 25 m adopted in light of E-Defense allowable limit (27 m)

■ Protection Frame
Developed to protect collapsing specimen as well as to serve as a frame to lift specimen

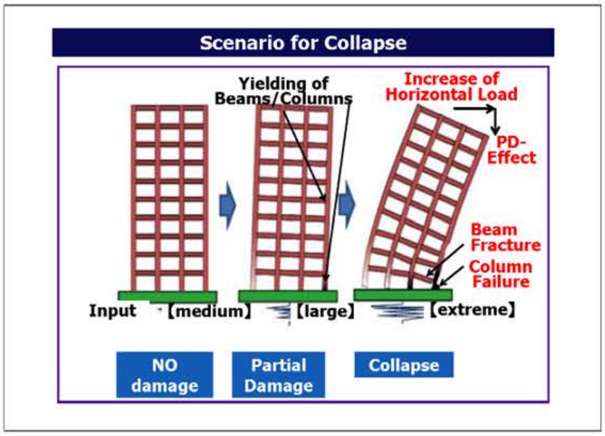
■ Input Motion
Synthesized motion considering simultaneous ruptures of three troughs

Construction of Collapse Specimen (October 8, 2013)

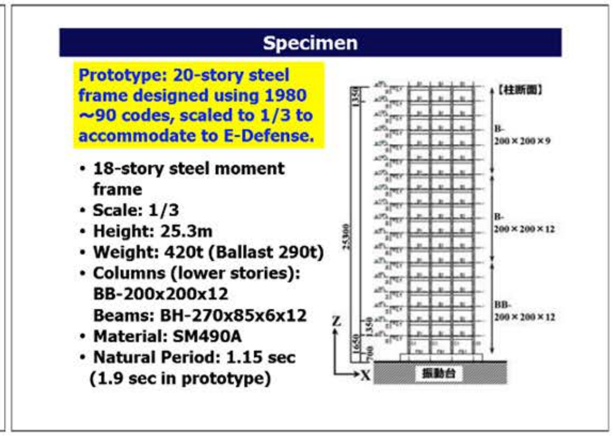


Construction of Collapse Specimen (November 15, 2013)

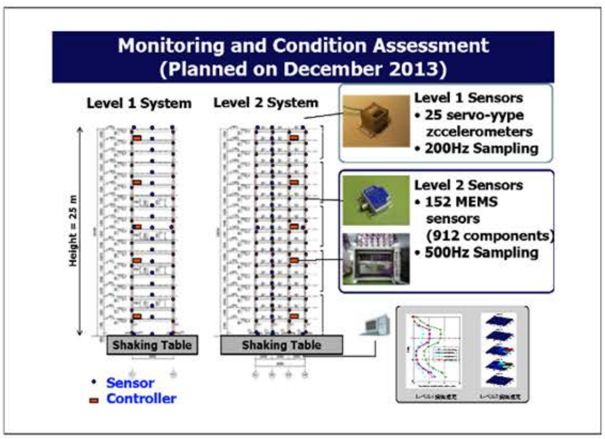
Appendix VI



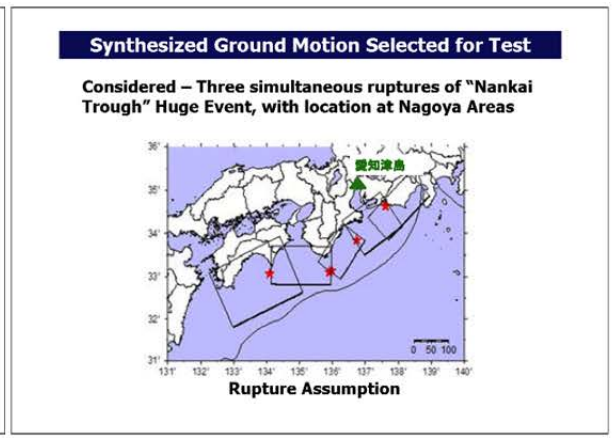
Scenario for Collapse
Yielding of Beams/Columns
Increase of Horizontal Load
PD-Effect
Beam Fracture
Column Failure
Input 【medium】 【large】 【extreme】
NO damage
Partial Damage
Collapse



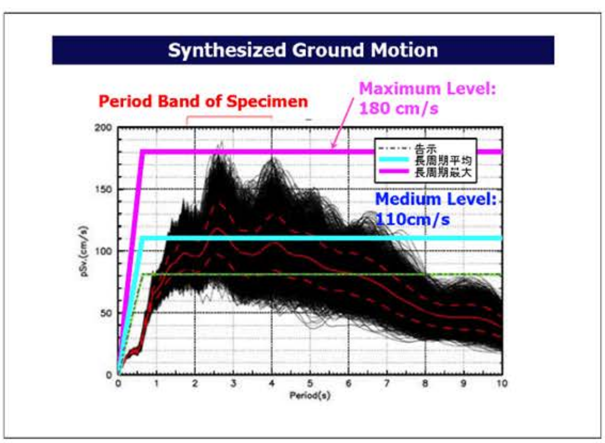
Specimen
Prototype: 20-story steel frame designed using 1980 ~90 codes, scaled to 1/3 to accommodate to E-Defense.
• 18-story steel moment frame
• Scale: 1/3
• Height: 25.3m
• Weight: 420t (Ballast 290t)
• Columns (lower stories): BB-200x200x12
Beams: BH-270x85x6x12
• Material: SM490A
• Natural Period: 1.15 sec (1.9 sec in prototype)
【柱断面】
B-200×200×9
B-200×200×12
BB-200×200×12
25300
振動台



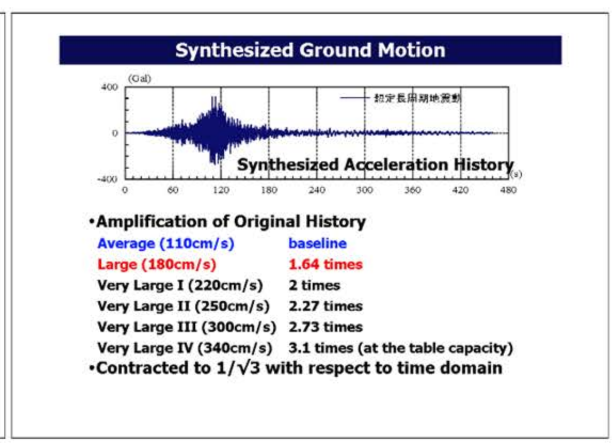
Monitoring and Condition Assessment (Planned on December 2013)
Level 1 System
Level 2 System
Level 1 Sensors
• 25 servo-yype zccelerometers
• 200Hz Sampling
Level 2 Sensors
• 152 MEMS sensors (912 components)
• 500Hz Sampling
Height = 25 m
Shaking Table
Shaking Table
• Sensor
Controller



Synthesized Ground Motion Selected for Test
Considered – Three simultaneous ruptures of "Nankai Trough" Huge Event, with location at Nagoya Areas
愛知津島
0 50 100
Rupture Assumption



Synthesized Ground Motion
Period Band of Specimen
Maximum Level: 180 cm/s
Medium Level: 110cm/s
告示
長周期平均
長周期最大
pSv(cm/s)
Period(s)



Synthesized Ground Motion
(Gal)
Synthesized Acceleration History
•Amplification of Original History
Average (110cm/s) baseline
Large (180cm/s) 1.64 times
Very Large I (220cm/s) 2 times
Very Large II (250cm/s) 2.27 times
Very Large III (300cm/s) 2.73 times
Very Large IV (340cm/s) 3.1 times (at the table capacity)
•Contracted to 1/√3 with respect to time domain

Schedules

倒壊したときの観客への安全性を考慮し、最大級の入力ではあるが、崩壊する可能性が極めて低いケースを視察・見学用に選定

実験日	Sv* (h=5%)	想定するレベル	推定被害	備考
12/9	40cm/s	告示極稀地震の1/2相当	弾性	
	81cm/s	告示極稀地震相当	一部塑性化	
	110cm/s	三連動・愛知での平均レベル	塑性化進展	
12/10	110cm/s	同2回目	塑性化進展	
	180cm/s	三連動・愛知での最大レベル	下層階で一部劣化	公開実験
	180cm/s	同2回目	劣化進展	
12/11	220cm/s	三連動・愛知での最大超え1	劣化進展、大変形	倒壊用
	250cm/s	三連動・愛知での最大超え2	劣化進展、大変形	倒壊用
	300cm/s	三連動・愛知での最大超え3	劣化進展、大変形	倒壊用
	340cm/s	三連動・愛知での最大超え4	劣化進展、大変形	倒壊用

＊縮尺前実大モデルでの入力地震動レベル

Recent Activity of E-Defense ◆ Koichi Kajiwara

Recent Activities of E-Defense

Koichi Kajiwara

Director, Department of Disaster Mitigation Research /
Hyogo Earthquake Engineering Research Center (E-Defense),
National Research Institute for Earth Science and Disaster Prevention

December 11, 2013
The 11th NEES/E-Defense Planning Meeting, Kyoto, Japan

E-Defense research staff

Before starting my presentation, I introduce E-Defense research staff here:

- Koichi Kajiwara, Director
- Takahito Inoue, Deputy Director
- Taizo Matsumori and Eiji Sato, Leader and Head, Operation Office Team
- Researchers: Matsumori, E. Sato, Nakamura, Nagae, Tabata, Yamashita
- Research Fellows: Tani, Aoi, Kawamata, Sasaki, D. Sato, Tagawa, Tosauchi

Presentation contents

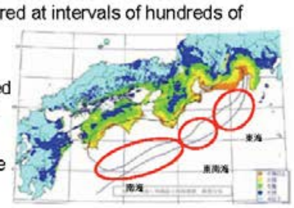
Today I present the following topics;

- scenario change of anticipated Nankai Trough earthquakes due to the 2011 Great East-Japan Earthquake Disaster,
- E-Defense recent tests and plans,
- E-Defense upgraded performance,
- recent E-Defense shake-table tests, and
- future E-Defense research plan and direction.

Anticipated Nankai Trough earthquakes (*before* the 2011 Great Disaster)

In 2003, the Central Disaster Management Council anticipated Nankai Trough large-scale earthquakes as follow:

- Anticipated earthquakes were based on historical earthquake events occurred at intervals of hundreds of years.
- The assumed possible epicenter zone was based on the knowledge of the plate shape.
- The estimated magnitude was 8.4.

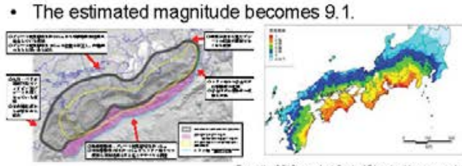


From the website of Central Disaster Management Council, Japan

Anticipated Nankai Trough earthquakes (*after* the 2011 Great Disaster)

After the disaster, a working group of the Central Disaster Management Council reconsiders Nankai Trough earthquakes:

- Any possibility based on scientific knowledge is taken into account to anticipate earthquakes.
- The assumed possible epicenter zone widens and deepens.
- The estimated magnitude becomes 9.1.

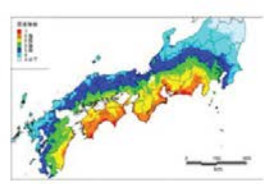


From the 2013 report of Central Disaster Management Council, Japan

Anticipated Nankai Trough earthquakes

The working group estimates the damage as follows. This is the severest case;

- casualties can be ~323,000,
- structures collapsed and burned can be ~2,386,000, and
- economic loss can be 1.7 trillion dollars in disaster areas, additional 500 billion dollars nationwide.



From the 2013 report of Central Disaster Management Council, Japan

E-Defense recent tests in FY2012

Next I introduce the recent tests in the fiscal years 2012 and 2013

Between April to October 2012, E-Defense carried out following five tests:

- The 1st test is on vibration characteristics of base-isolated small structures under long-period earthquakes
  ...for a house-builder project.
- The 2nd test is on piping systems in a facility
  ...assumed as an energy plant.

E-Defense recent tests in FY2012

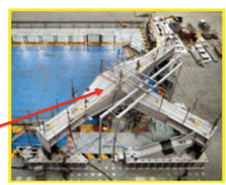
Between April to October 2012, E-Defense carried out five tests:

- The 3rd test is on *a 1/4-scaled, 20-story RC building under long-period ground motions*
  ...for the project of Ministry of Land, Infrastructure, Transport and Tourism (MLIT).
- The 4th test is on evaluation of seismic performance of traditional wood houses.

E-Defense recent tests in FY2012

Between April to October 2012, E-Defense carried out five tests:

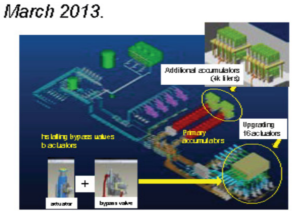
- The 5th test is on safety assessment of base isolators against long-period, long-duration earthquakes
  ...to evaluate rubber bearings.



E-Defense recent tests in FY2012

Between April to October 2012, E-Defense carried out five tests.

After these five tests, MEXT and NIED upgraded the E-Defense performance between October 2012 and March 2013.



E-Defense recent tests in FY2012

Between April to October 2012, E-Defense carried out five tests.

After the five tests, MEXT and NIED upgraded the E-Defense performance.

After the upgrade work finished, E-Defense conducted the following test in March and April 2013:

- This is the test on evaluation of response of base-isolators against long-period, long-duration earthquakes.

E-Defense recent tests in FY 2013

By November 2013, E-Defense completed following three shake-table tests:

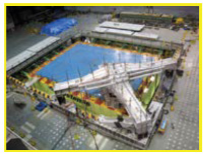
- The 1st test is on passive base isolators of a structure
  ...to development of next-generation base-isolation system.
- The 2nd test is on safety assessment of a steel structure damaged by previous earthquakes.

Appendix VI

E-Defense recent tests in FY 2013

By November 2013, E-Defense completed following three shake-table tests:

- The 3rd test is <u>on safety assessment of base isolators against long-period, long-duration earthquakes</u>
  ...to evaluate lead dampers and oil dampers.



E-Defense test plans in FY 2013

By November 2013, E-Defense completed three shake-table tests:

In the rest of the fiscal year 2013, the following two tests will be conducted at E-Defense:

- The 1st test is on <u>quantification of margin of high-rise-steel-structure failure</u>

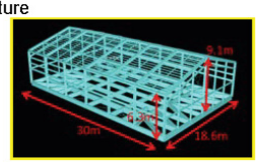
  <This is the Professor Nakashima and major construction company's test.>

E-Defense test plans in FY 2013

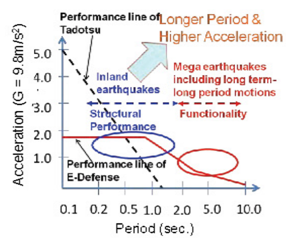
By November 2013, E-Defense completed three shake-table tests:

In the rest of the fiscal year 2013, the following two tests will be conducted at E-Defense:

- The 2nd test is on wide-area suspension ceiling for a large-space structure
  ...that is underway now.



E-Defense upgraded performance

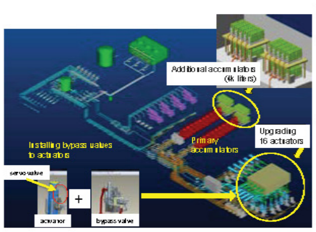


After the 2011 Great Disaster, E-Defense requires the following functions to produce the recordings and scenarios;

- simulating long-duration, long-period accelerations.

<u>MEXT and NIED installed additional facilities for E-Defense upgrade</u> completed in March 2013.

E-Defense upgraded performance



This upgrading work installed these two systems;

- 4 kilo-liter additional accumulators (original is 20 kilo liters), and
- bypass valves to servo valves that cut off their function when unneeded.

It makes <u>the table possible to simulate 2011-earthquake recordings and future scenarios.</u>

E-Defense upgraded performance

This table shows E-Defense upgraded performance in terms of specimen's mass on the table and number of inactive actuators;

Specimen's mass (ton)	Maximum acceleration (G = 9.8m/s²)							
	Horizontal direction (*x*, *y*)				Vertical direction (*z*)			
	Number of inactive actuator(s)				Number of inactive actuator(s)			
	0	1	2	3	0	2	4	6
0	1.7	1.4	1.0	0.7	2.3	1.9	1.6	1.5
600	1.2	1.0	0.7	0.5	1.7	1.4	1.2	1.1
1,200	0.9	0.7	0.5	0.4	1.5	1.2	1.0	0.8

「A unit of number in the table is gravitational acceleration, 1G = 9.8m/s2」

Recent E-Defense shake-table tests

- This is the collaboration research between NIED and Hyogo Prefecture in October 2013.
- The objective is to observe influences of a future Nankai Trough earthquake on a 1995-Kobe-Earthquake damaged structure.
- The specimen was a 3-story, steel-frame building, shaken under one-dimensional input motions.

Recent E-Defense shake-table tests

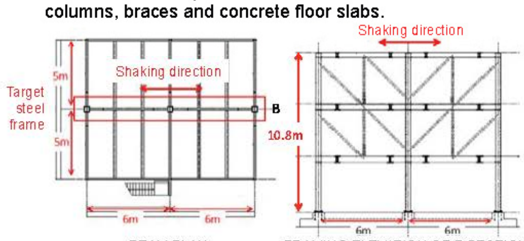
The following pictures show the specimen:

- Its design is based on the new Japanese Building Design Code before the 1995 Kobe Earthquake.

Recent E-Defense shake-table tests

The following pictures show the specimen:

- It's assumed as a part of a steel structure that consists of columns, braces and concrete floor slabs.



BEAM PLAN

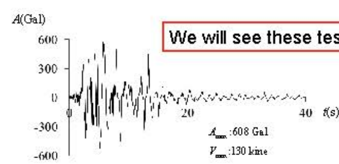
FRAMING ELEVATION OF B SECTION

Recent E-Defense shake-table tests

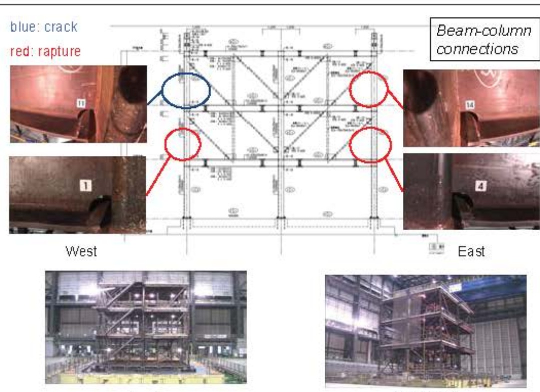
To the specimen, following input motions were applied:

- The JR Takatori Station record in the 1995 Kobe Earthquake: Its 40%, 60%, 80% and 100% North-South components were applied.

We will see these test results from now.



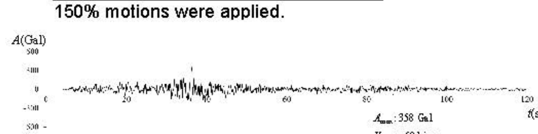
Unit: Gal = m/s², kine = m/s



Recent E-Defense shake-table tests

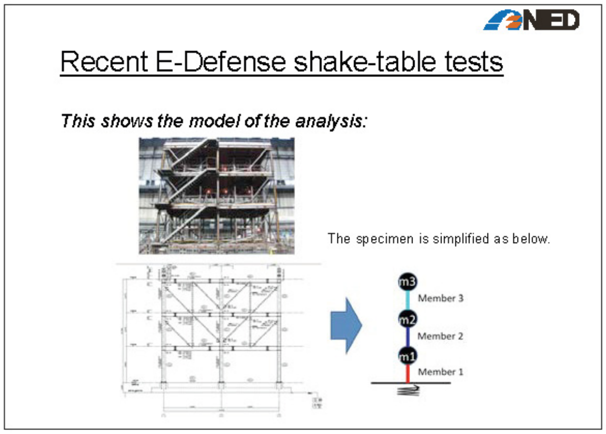
To the specimen, two types of input motions were applied:

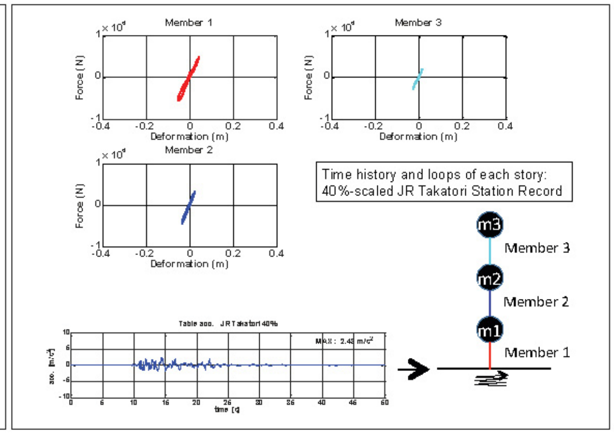
- The other is the scenario ground motion of the Nankai Trough Earthquake, which 100% scaled were applied before 40% scaled JR Takatori Station.
- After JR Takatori Station record shakes, Its 50%, 100% and 150% motions were applied.

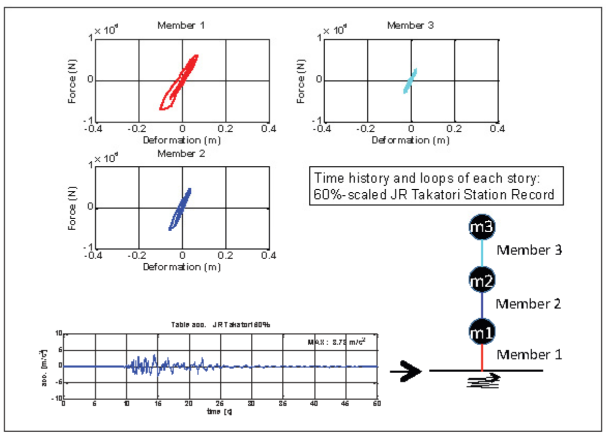


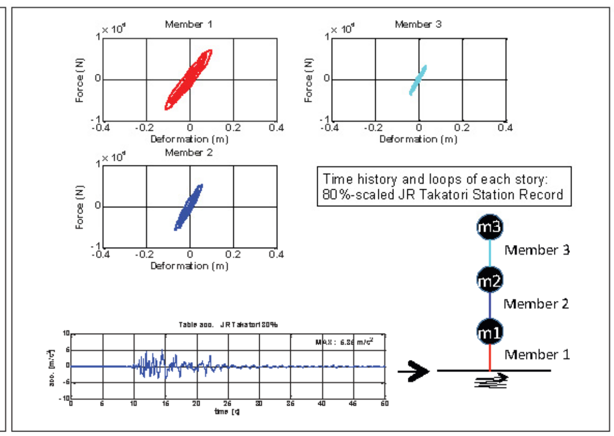
Unit: Gal = m/s², kine = m/s

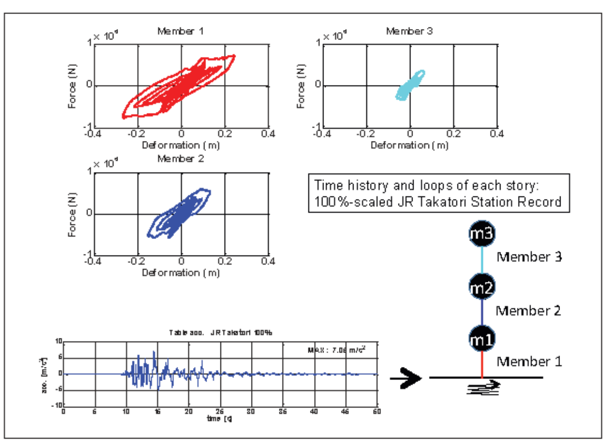
Appendix VI

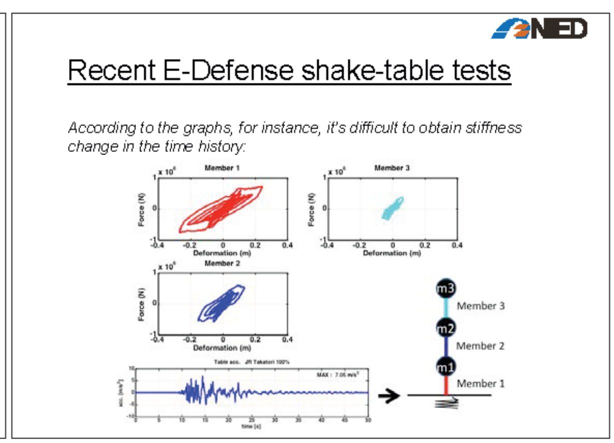

Recent E-Defense shake-table tests
This shows the model of the analysis:
The specimen is simplified as below.
m3
Member 3
m2
Member 2
m1
Member 1


Member 1
Member 3
Member 2
Force (N)
Deformation (m)
Time history and loops of each story:
40%-scaled JR Takatori Station Record
m3
Member 3
m2
Member 2
m1
Member 1


Member 1
Member 3
Member 2
Force (N)
Deformation (m)
Time history and loops of each story:
60%-scaled JR Takatori Station Record
m3
Member 3
m2
Member 2
m1
Member 1


Member 1
Member 3
Member 2
Force (N)
Deformation (m)
Time history and loops of each story:
80%-scaled JR Takatori Station Record
m3
Member 3
m2
Member 2
m1
Member 1


Member 1
Member 3
Member 2
Force (N)
Deformation (m)
Time history and loops of each story:
100%-scaled JR Takatori Station Record
m3
Member 3
m2
Member 2
m1
Member 1

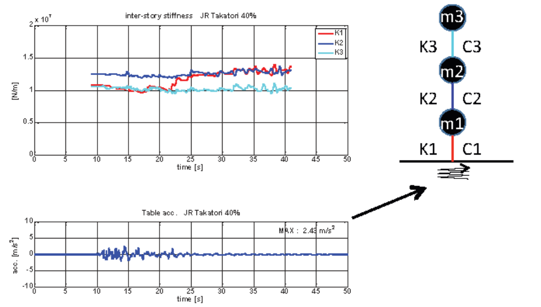

Recent E-Defense shake-table tests
According to the graphs, for instance, it's difficult to obtain stiffness change in the time history.
Member 1
Member 3
Member 2
m3
Member 3
m2
Member 2
m1
Member 1

Recent E-Defense shake-table tests

From now I introduce one of the recent shake-table tests at E-Defense:

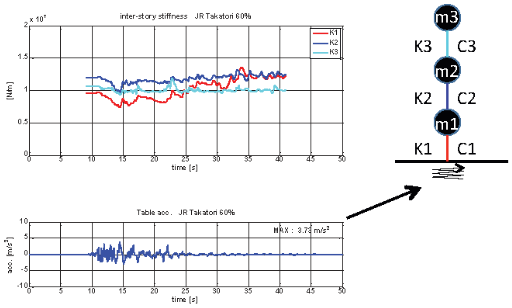
- This is collaboration research ...
- The objective is to observe influences of a future Nankai Trough earthquake on a 1995-Kobe-earthquake damaged structure.
- The specimen was a 3-story, steel-frame building, shaken under one-dimensional input motions.
- To assess its seismic performance, I try to develop a method to quantitatively evaluate its dynamic-characteristics change based on shaking time histories acquired from tests.

Time histories of stiffness of each story:
40%-scaled JR Takatori Station Record

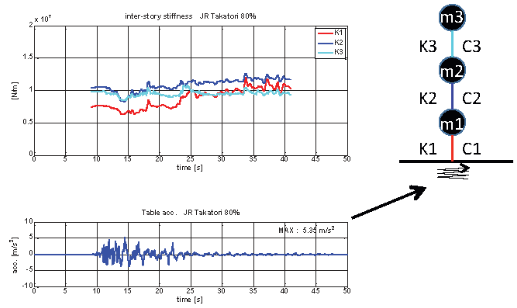


These histories are obtained from the data of accelerations and masses.
Least squares are used.

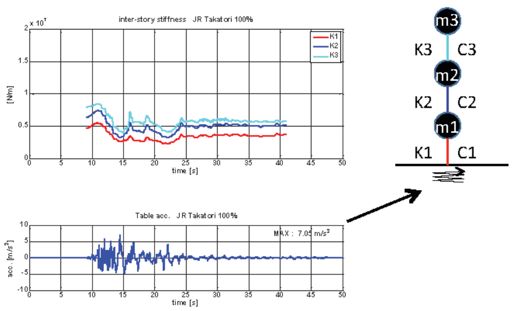
Time histories of stiffness of each story:
60%-scaled JR Takatori Station Record



Time histories of stiffness of each story:
80%-scaled JR Takatori Station Record



Time histories of stiffness of each story:
100%-scaled JR Takatori Station Record

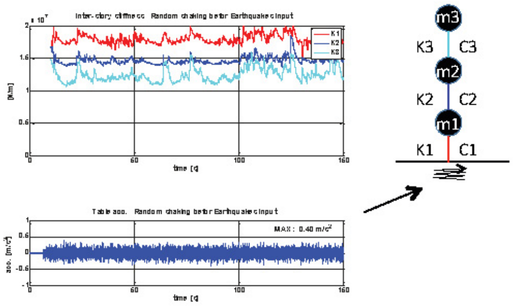


Recent E-Defense shake-table tests

According to these analytical results based on the time histories, it is found that the stiffness of the structure decreases more remarkably in the 100%-record-motion case than in the other three cases.

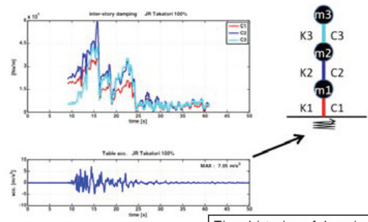
- In this 100%-record-input-motion case, three beams were severely damaged.
- The stiffness of the 1st story is the smallest; in the preparation shaking with small input motions before all shake tests, the stiffness of the 1st story was the largest and decreased with height.
- Since the study is underway, we will see more detailed findings.

Time histories of stiffness of each story:
Random wave shak before earthquakes



Recent E-Defense shake-table tests

This calculation method can employ damping. This is one of the examples:



Time histories of damping of each story:
100%-scaled JR Takatori Station Record

Recent E-Defense shake-table tests

Such data analysis must be good for presentation to clients or stakeholders to easily explain seismic performance as well as for applications to E-Defense shake-table tests.

The scenario ground motions of the Nankai Trough Earthquake were also applied.

This presented research is fundamental because a low-rise structure is focused.

- I expect that very valuable results will be obtained from the Professor Nakashima and major construction company's test that we are going to see today.

Future E-Defense research plan

To mitigate damages due to future earthquakes in Japan, the E-Defense researchers promote studies on RC structures, steel structures, base isolation systems, piping systems, non-structural members and liquefaction phenomena.

We are studying...

- for structures, to identify dynamic characteristics and to develop evaluation technique,
- for geotechnical issues, to examine liquefaction phenomena and to improve their evaluation methods, and
- for base isolation systems, to develop and prove semi-active control technique.

Future research direction

In a next step for U.S. and Japan research communities, possible collaboration can be...

- to improve techniques of analyzing and evaluating testing data...
- to evaluate influences of existing structures on anticipated...
- to apply to electronics and machine technologies,
- to spread earthquake-engineering technology in a low-cost way, and so on.

Future research direction

In a next step for U.S. and Japan research communities...

In addition, it will be essential...

- to establish "simple" procedures to assess seismic performance, and
- to develop methods to estimate "as-is" margin of response of a structure against anticipated ground motions.

Future research direction

In a next step for U.S. and Japan research communities...

In addition, it will be essential...

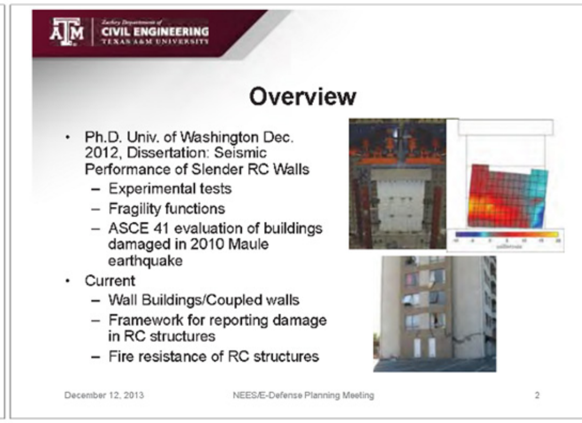
E-Defense now promotes cooperation with...

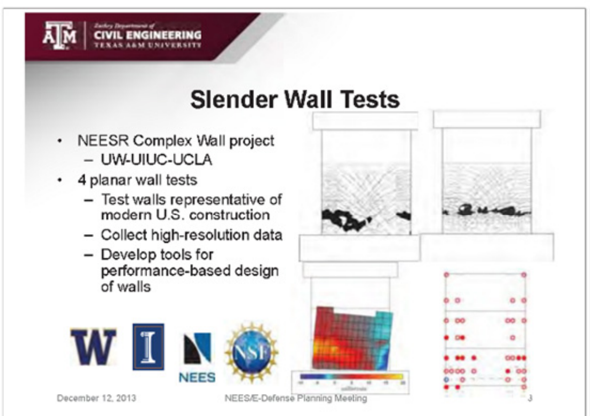
From the viewpoint of establish “resilient societies” to natural disasters including earthquakes, these topics must be valuable for...

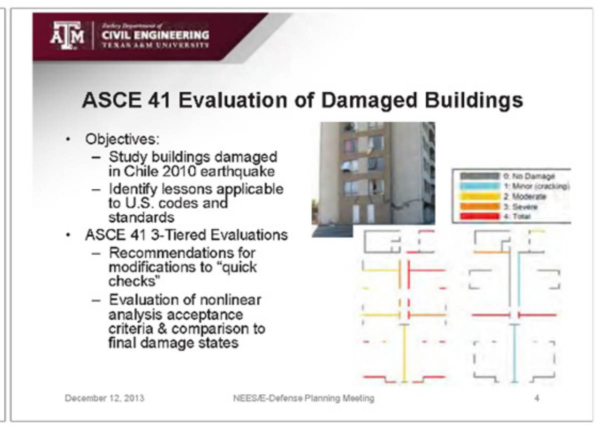
- business continuity plans,
- evacuation plans, and so on.

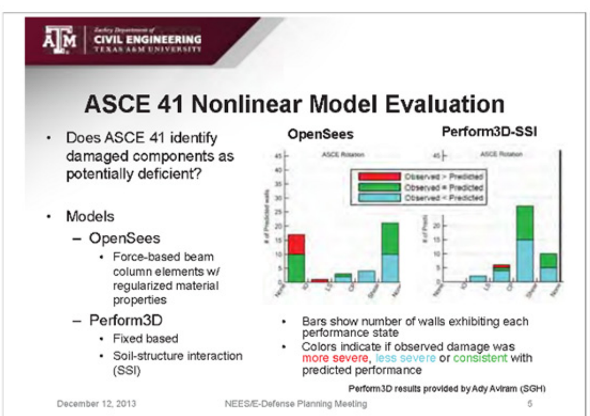
Finally, we pursue creating quantitative evaluation methods by E-Defense testing results and numerical simulation “E-Simulator.”

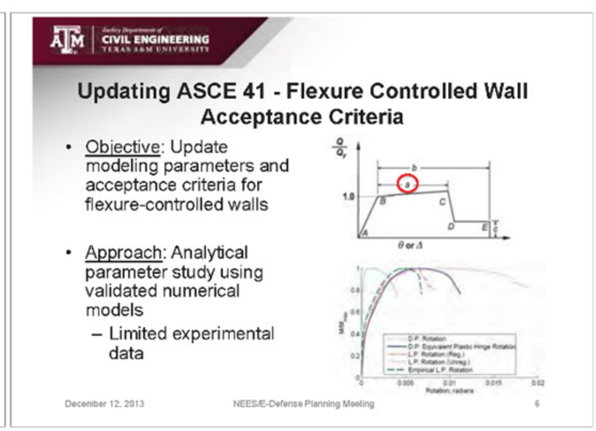
APPENDIX VII: PRESENTED PAPERS IN REINFORCED CONCRETE WORKING GROUP



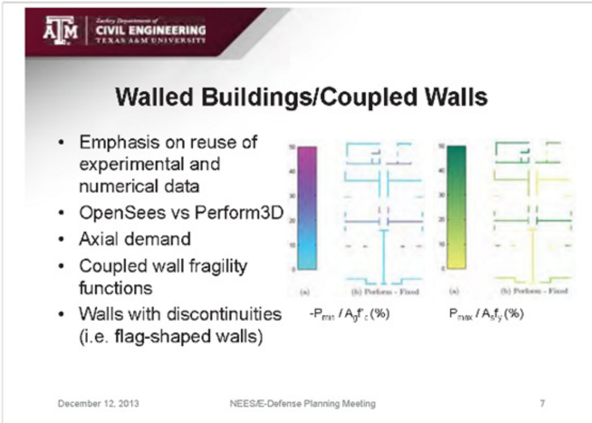


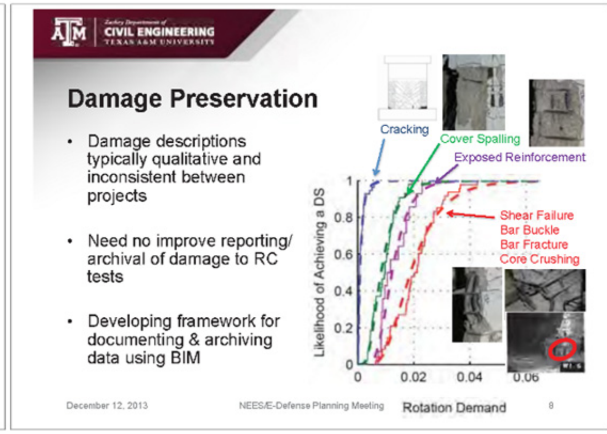


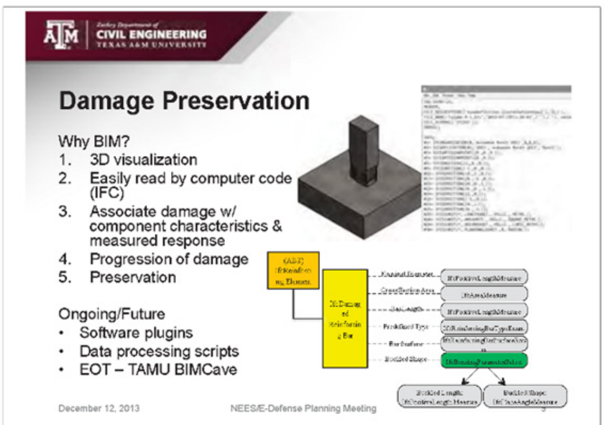


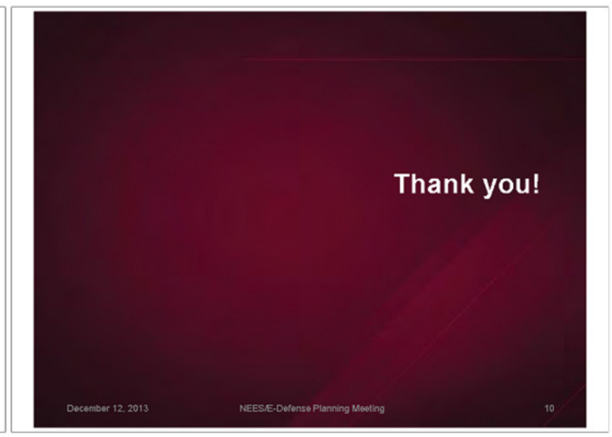


Appendix VII









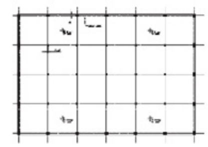
Performance-Based Engineering of Earthquake Resilient Communities

Gregory Deierlein
J.A. Blume Professor of Engineering
Stanford University

NEES – E-Defense Planning Meeting
DPRI December 11-12, 2013

BENCHMARKING BUILDING CODE PERFORMANCE

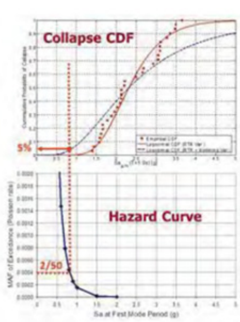
- Office occupancy
- Los Angeles Basin
- Design Code: 2003 IBC / 2002 ACI / ASCE7-02
- Maximum considered EQ demands:
  - S_s = 1.5g; S_1 = 0.9g
  - $S_{a(2\% \text{ in } 50 \text{ yr})}$ = 0.82g
- Design V/W of 0.094g
- Maximum inelastic design drift of 1.9% (2% limit)



perimeter frame system

2

BENCHMARKING BUILDING CODE PERFORMANCE



Calculated Collapse Safety

- 5% Probability of collapse under "Maximum Considered Earthquake"
- MAF_{col} = 1.0 x 10^{-4} collapse/yr

  OR

  0.5% Probability in 50 years

Question: Is this acceptable?

Perhaps, but the immediate practical value is in providing consistency in design requirements among materials, systems, and regions.

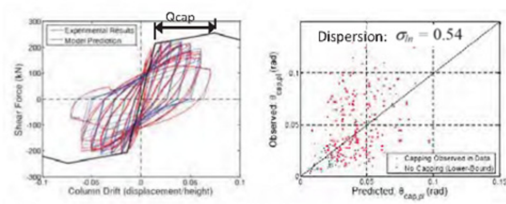
3

Modeling of Structural Components: RC plastic rotation

Example: Calibration of Capping Rotation of RC Beam-Columns

Median: $\theta_p = 0.12(1+0.55a_{sl})(0.16)^{\nu}(0.02+40\rho_{sh})^{0.43}(0.54)^{0.01c_{units}f'_c}(0.66)^{0.1s_n}(2.27)^{10.0\rho}$

Key Design/Detailing Variables:
- r_{sh} – amount of steel stirrups
- n – axial load ratio ($P/Ag\,f'c$)
- a_{sl} – joint bond slip
- s_n – tie spacing

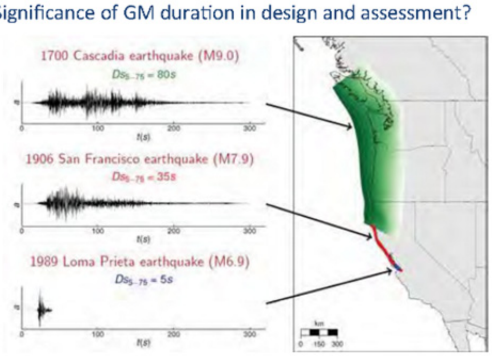


Ref: Haselton et al. (2007); ATC 72-1 (2010)

4

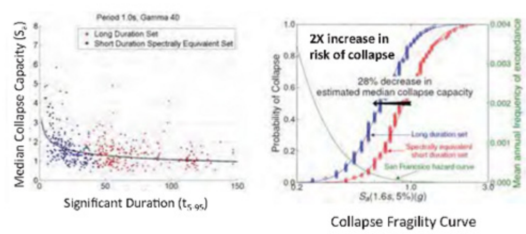
Characterization of Ground Motion Hazard

Significance of GM duration in design and assessment?



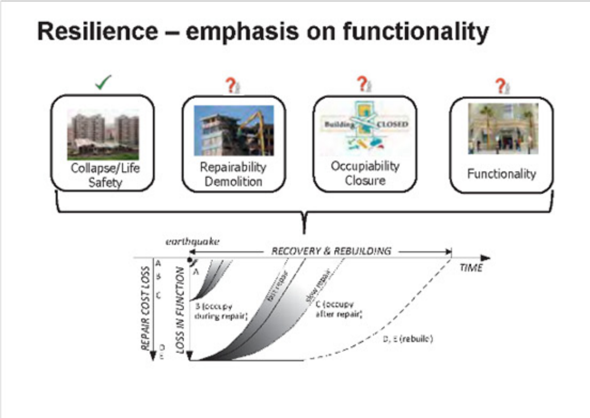
Characterization of Ground Motion Hazard

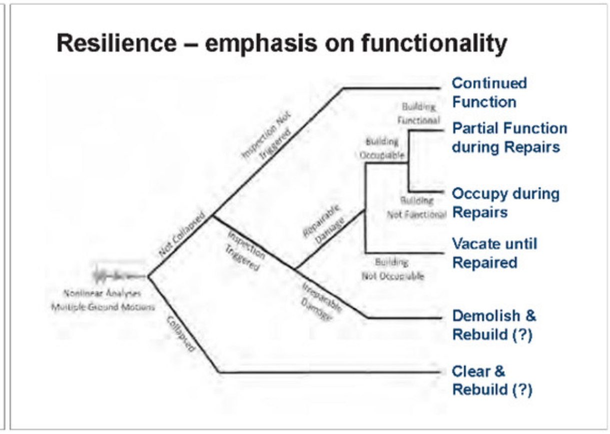
Collapse Capacity of Structure with Moderate Degradation



Duration can have a significant effect, depending on how sensitive the structure is to cyclic degradation.

Appendix VII





Seismic Performance of New Building

Archetype: 42 Story Concrete Shear (2013 residential tower in SF and LA)

NL Dynamic Analyses: LS-DYNA

Performance and Assessment (FEMA P58, REDi):
- Direct damage and repair costs
- Demolition/deconstruction
- Occupancy & Functionality

Structural Enhancements
- damped outrigger
- seismic isolation

Building System Enhancements
- drift resistant façade and partitions
- enhanced elevators and stairs

Almufti, Tipler et al. (2013)

Performance Summary (DBE Level Shaking)

Direct Losses (Repairs)

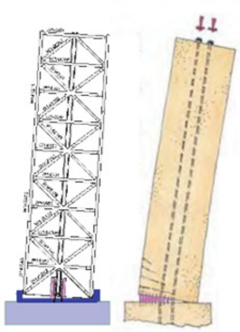
	Standard Design (% building value)	Resilient Design (% building value)
Fixed-Base	15.2%	5.8%
Outrigger	13.4%	3.8%
Base-Isolated	14.4%	4.6%

Repair and Restoration Durations

	Repair Times (Weeks)		Total Time* to Restore Functionality (Weeks)	
	Standard Design	Resilient Design	Standard Design	Resilient Design
Fixed-Base	60	6	84	18
Outrigger	47	3	71	15
Base-Isolated	56	0	80	4 (utilities)

*total time includes ~24 weeks inspection, financing, mobilization, engineering, permits; reduced to ~12 weeks by pre-event planning in resilient design

"rocking/hinging spine systems"

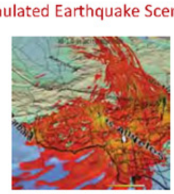


- rocking elastic spine
  - capacity design for story shears and moments
  - distribution of forces
- articulated hinge region
  - strength, stiffness, deformation capacity
- energy dissipation
  - damage control and design with replaceable components
- self-centering ability

11

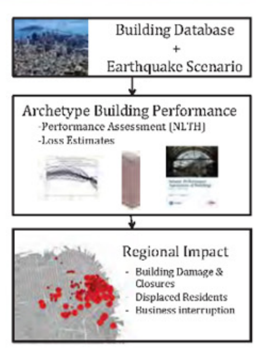
Earthquake Resilient Cities (future)

Simulated Earthquake Scenarios



SCEC M8 earthquake on the southern San Andreas Fault

Utilization of simulated ground motions to assess performance
- long duration motions
- high energy at long periods
- near-fault directivity and pulse effects



Objectives of Experimental Testing (WHY?)

1. understand and quantify behavior
2. calibrate and validate
   - computational analysis models
   - damage and recovery models
3. demonstrate proof of concept for new systems
4. improve design standards and practices

Appendix VII

NEES / E-Defense Workshop
Kyoto, Japan
11th - 13th of December 2013

Reinforced Concrete Task Group
Near to Mid-term
Collaboration ideas related to wall buildings, limit-state investigations, and analytical investigations

Coordinator
Wassim Ghannoum, University of Texas at Austin

Participants
Anna Birely, Texas A&M
Gregory Deierlein, Stanford University
Marc Eberhard, University of Washington, Seattle
Kenneth Elwood, University of British Columbia, Vancouver
Julio Ramirez, Purdue University
Lesley Sneed, Missouri S&T
Andreas Stavridis, University at Buffalo SUNY
John Wallace, University of California Los Angeles

NEES / E-Defense Workshop
Kyoto, Japan
11th - 13th of December 2013

Reinforced Concrete Task Group
Introduction

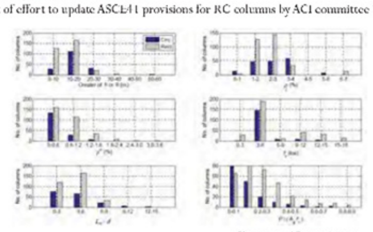
Wassim Ghannoum, University of Texas at Austin

Research Interests

1. RC column limit-states
   1. Databases
   2. ACI 369/ASCE 41: older shear-critical columns limit states
   3. High strength steel
   4. Loading-Rate effects
2. Analysis
   1. RC column analytical model
   2. System level analysis – E-Defense test 2010
3. CFRP repair and retrofit of RC members
4. Digital Image Correlation (DIC) support for research

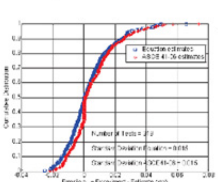
1.1 Database of RC Column Tests

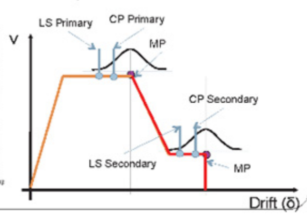
- Builds on PEER database developed by Berry and Eberhard
- Currently contains over 500 tests
- Part of effort to update ASCE41 provisions for RC columns by ACI committee 369



1.2 ACI 369/ASCE 41

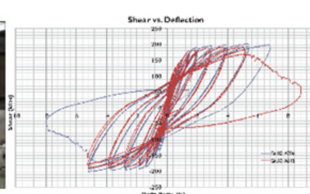
- ACI 369 is tasked with updating concrete provisions of ASCE 41 (seismic evaluation and retrofit of existing buildings)
- New modeling parameters and acceptance criteria for RC members are under way
  - Shear walls (Birely)
  - Columns (Ghannoum, Matamoros)
  - Joints (Lowes, Hasan)
  - Slab/column connection (Kang)
  - Acceptance criteria (Ghannoum, Elwood, Pekelnicky, others)





1.3 High-Strength Steel

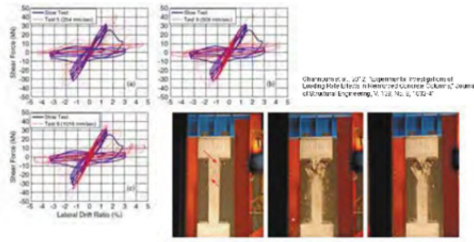
- Investigating behavior of HSS in RC columns; focus on shear
- Recently tested two columns: Grade 60 (415MPa) and Grade 80 (550 MPa)
- Column under high shear stresses
- Axial load ~25% of gross



- Columns showed comparable behavior
- Future tests with GR100 (690 Mpa) , high-strength concrete, and various loading protocols

1.4 Loading-Rate Effects

- Investigating the effects of seismic loading rates on strength, damage, and deformation capacity of RC columns
- Completed project testing flexure shear critical columns at various lateral loading rates
- Strength gains up to 30% observed at high loading rates

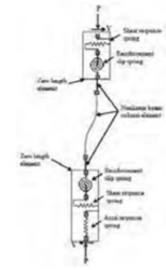


Ghannoum et al., 2012, "Experimental Investigations of Loading Rate Effects in Reinforced Concrete Columns," Journal of Structural Engineering, V. 138, No. 8, 1032-4

- Future tests planned considering various column detailing and loading protocols

2.1 RC Column Analytical Model

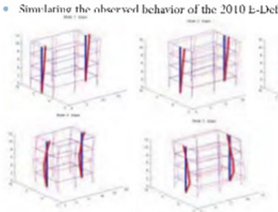
	Leborgne and Ghannoum
Failure types	Shear, flexure-shear
Elements	3 nonlinear elements + zero-length shear springs
Calibration Database	32 columns
Model Description	The shear spring model has the ability during analyses to monitor the deformations between two nodes bracketing the plastic hinge region, as well as forces in the adjacent column element. The model compares the shear force in the column with a limiting shear force and the rotation of the plastic hinge region with a limiting rotation.
Cyclic modeling	The model can simulate the full degrading behavior including in-cycle and cyclic degradation.
Input by user vs. adaptive model	The user can either input fixed values for rotation and shear-force limits or to use the calibrated version of the model that automatically evaluates limits during analysis utilizing the ASCE 41 shear strength equation and a regression-based plastic rotation equation.
OpenSEES Material	PinchingLimitStateMaterial described in Leborgne (2012)



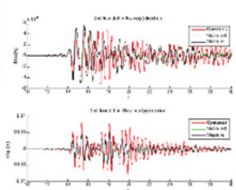
- Expanding calibration to full database

2.2 System Analysis

- Simulating the observed behavior of the 2010 E-Defense test

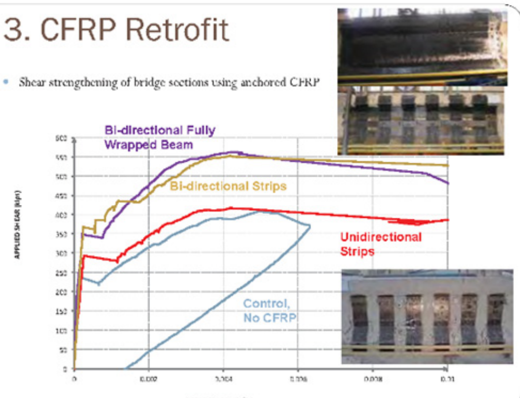


	Natural period (s) - ACI-318-11	
	Model	Exp.
Mode 1	0.46	0.48
Mode 2	0.40	0.30
Mode 3	0.29	
Mode 4	0.14	0.12
Mode 5	0.10	0.07



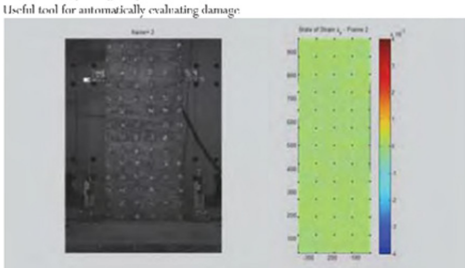
3. CFRP Retrofit

- Shear strengthening of bridge sections using anchored CFRP

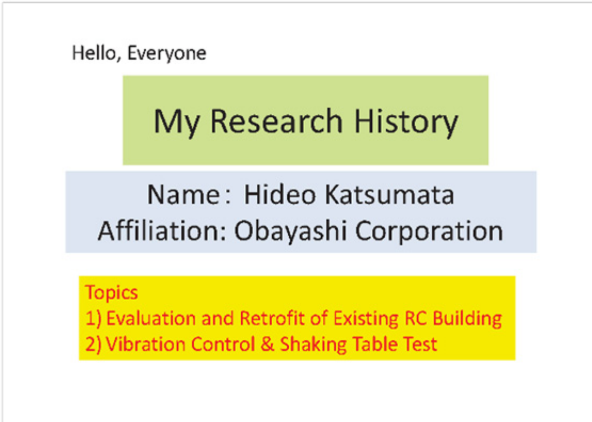


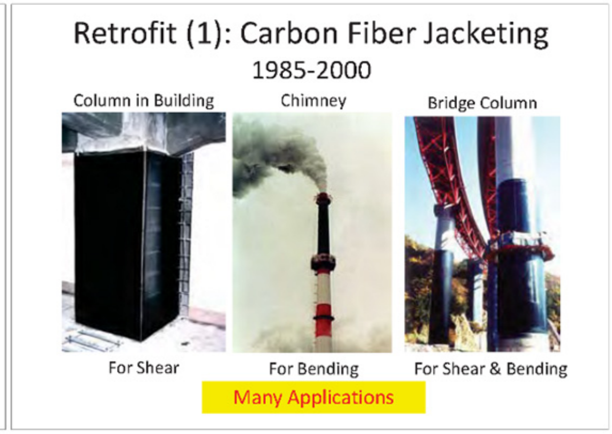
4. DIC Surface Strain Measurements

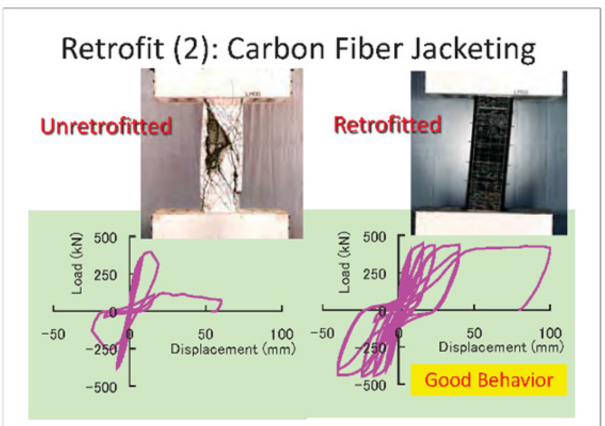
- Surface strain measurements using DIC / resolution ~ 1/20[th] of a pixel
- Needed for improving analytical models
- Useful tool for automatically evaluating damage

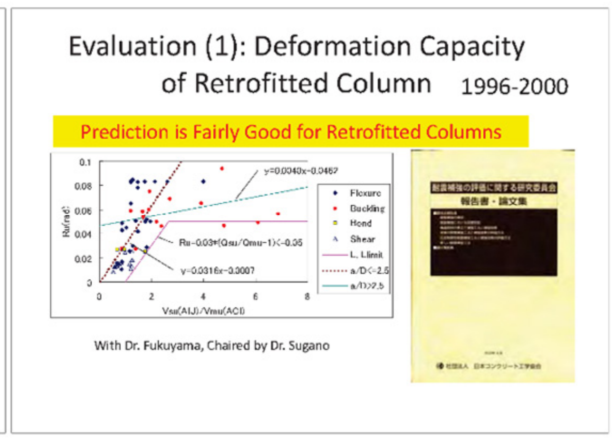


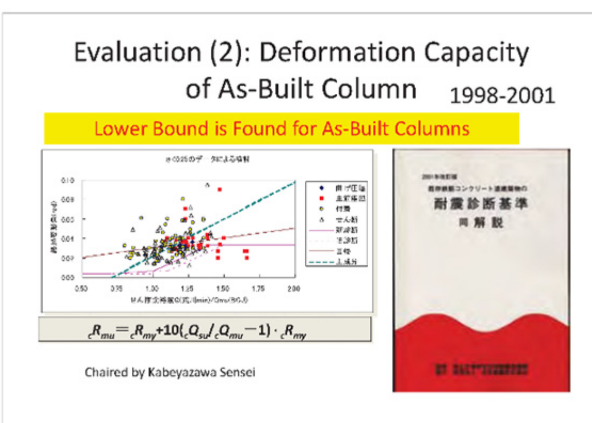
Appendix VII

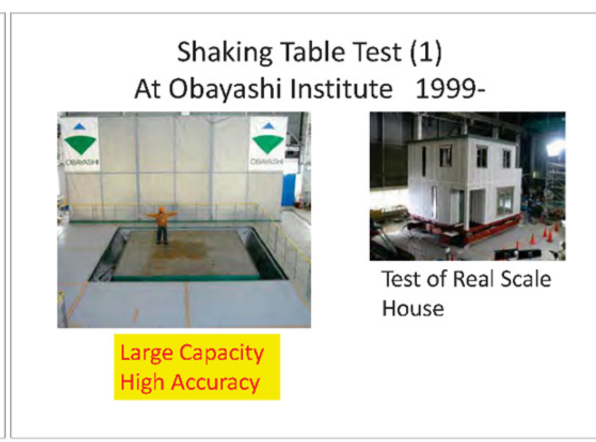


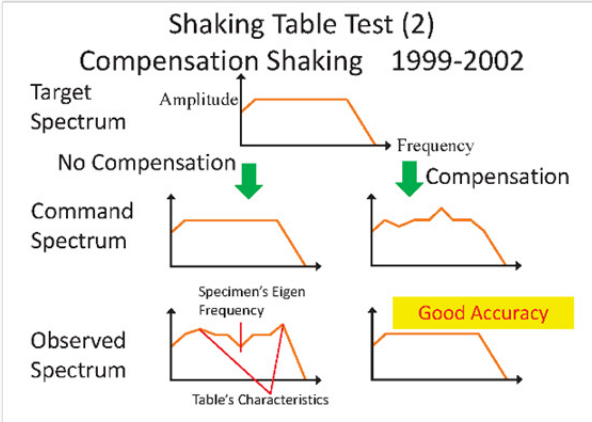


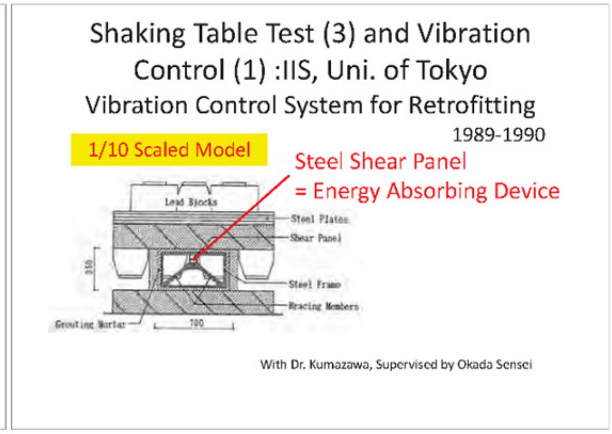


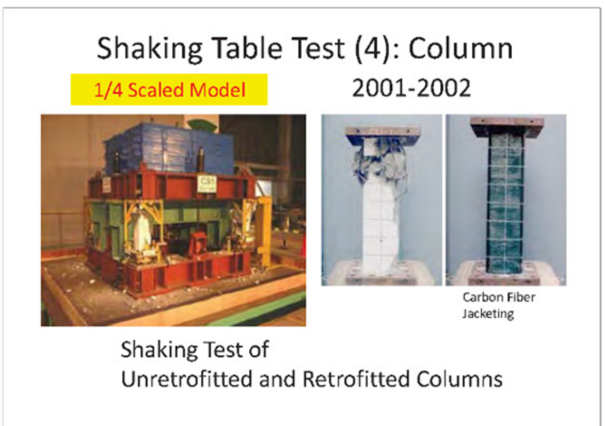




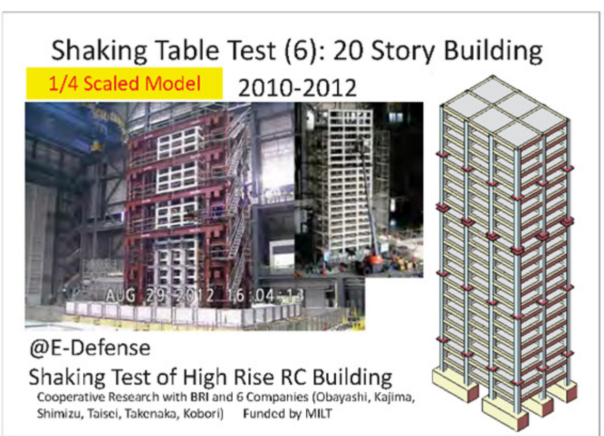


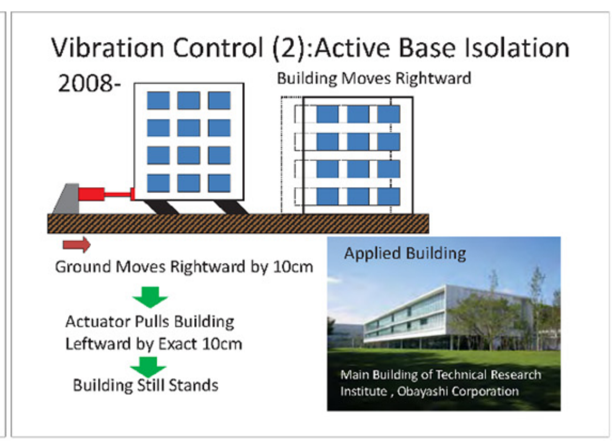

Shaking Table Test (2)
Compensation Shaking 1999-2002
Target Spectrum
Amplitude
Frequency
No Compensation
Compensation
Command Spectrum
Specimen's Eigen Frequency
Good Accuracy
Observed Spectrum
Table's Characteristics

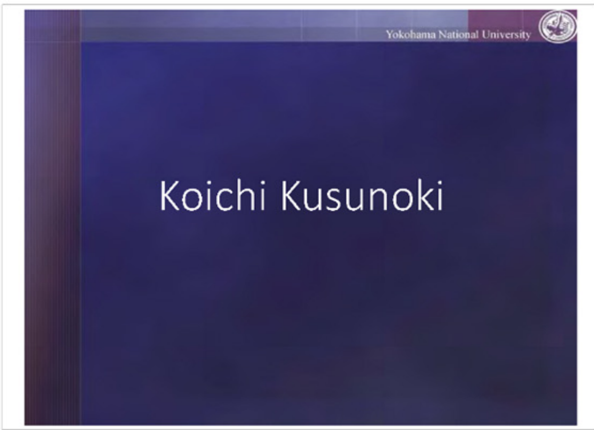

Shaking Table Test (3) and Vibration Control (1) :IIS, Uni. of Tokyo
Vibration Control System for Retrofitting
1989-1990
1/10 Scaled Model
Steel Shear Panel
= Energy Absorbing Device
Lead Blocks
Steel Plates
Shear Panel
Steel Frame
Bracing Members
Grouting Mortar
With Dr. Kumazawa, Supervised by Okada Sensei

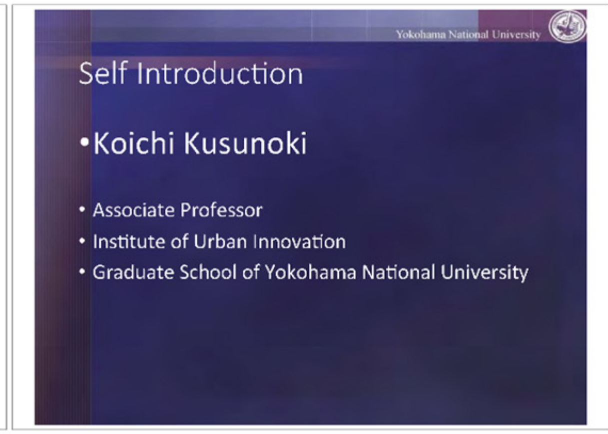

Shaking Table Test (4): Column
1/4 Scaled Model
2001-2002
Carbon Fiber Jacketing
Shaking Test of
Unretrofitted and Retrofitted Columns

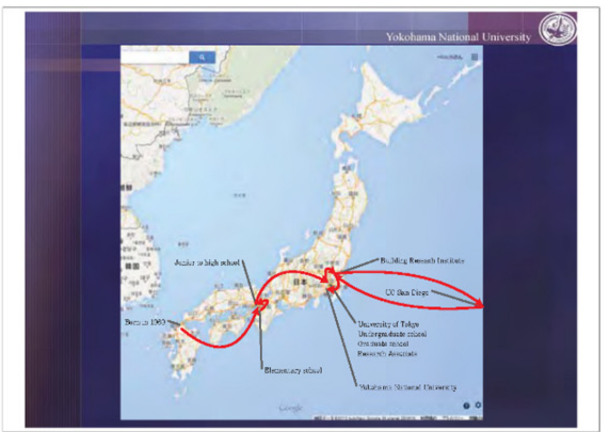

Shaking Table Test (5): 4 Story Building
1/4 Scaled Model
2004-2005
Shaking Test of
As-Built and Repaired Building
Cooperative Research with Kabeyazawa Sensei
Partially Funded by Dai-Dai-Toku Project of MEXT

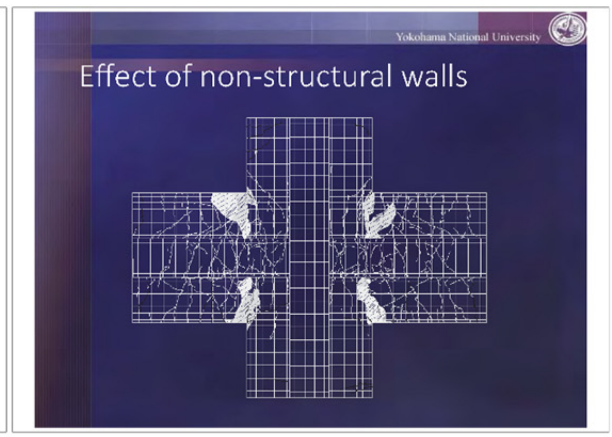

Shaking Table Test (6): 20 Story Building
1/4 Scaled Model
2010-2012
AUG 29 2012 16:04:13
@E-Defense
Shaking Test of High Rise RC Building
Cooperative Research with BRI and 6 Companies (Obayashi, Kajima, Shimizu, Taisei, Takenaka, Kobori) Funded by MILT

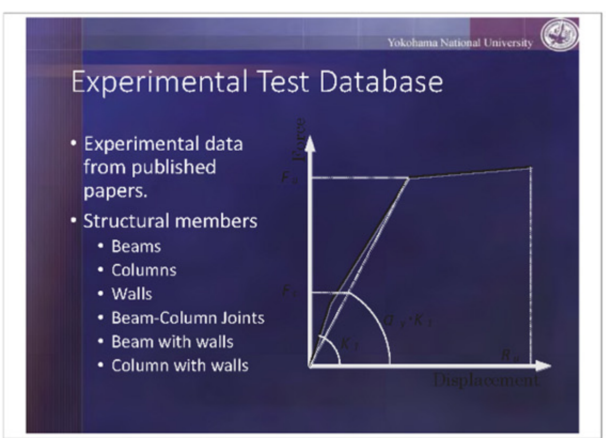

Vibration Control (2):Active Base Isolation
2008-
Building Moves Rightward
Ground Moves Rightward by 10cm
Actuator Pulls Building
Leftward by Exact 10cm
Building Still Stands
Applied Building
Main Building of Technical Research Institute , Obayashi Corporation

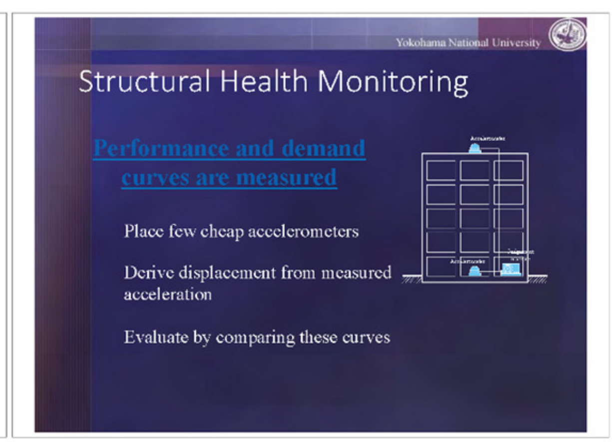

Yokohama National University
Koichi Kusunoki

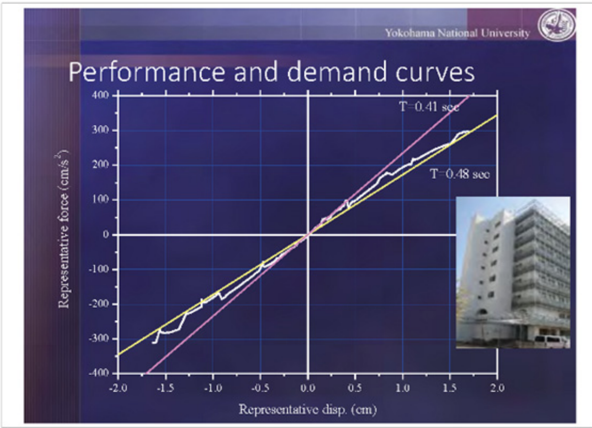

Yokohama National University
Self Introduction
•Koichi Kusunoki
• Associate Professor
• Institute of Urban Innovation
• Graduate School of Yokohama National University

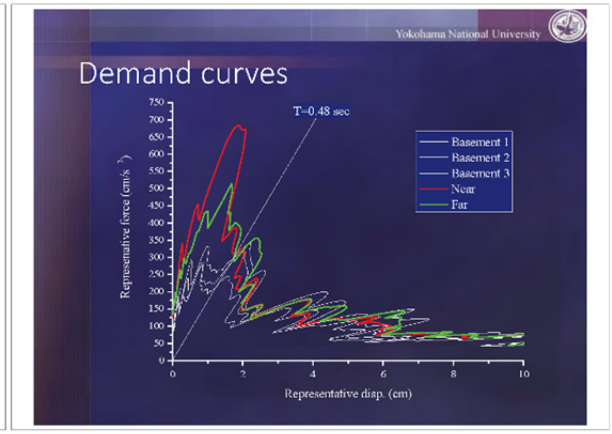

Yokohama National University
Building Research Institute
UC San Diego
University of Tokyo
Elementary school

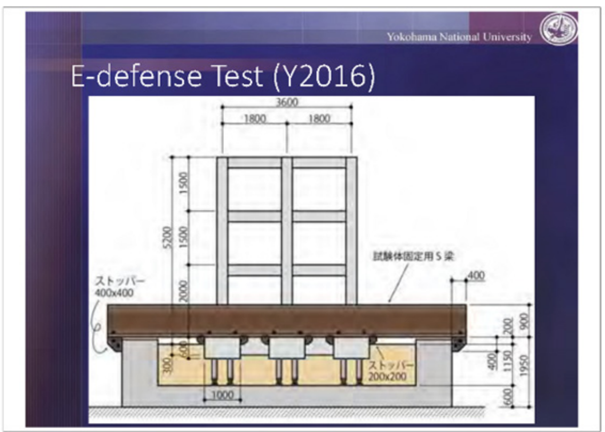

Yokohama National University
Effect of non-structural walls


Yokohama National University
Experimental Test Database
• Experimental data from published papers.
• Structural members
• Beams
• Columns
• Walls
• Beam-Column Joints
• Beam with walls
• Column with walls
Displacement


Yokohama National University
Structural Health Monitoring
Performance and demand curves are measured
Place few cheap accelerometers
Derive displacement from measured acceleration
Evaluate by comparing these curves


Yokohama National University
Performance and demand curves
T=0.41 sec
T=0.48 sec
Representative force (cm/s²)
Representative disp. (cm)
400
300
200
100
0
-100
-200
-300
-400
-2.0
-1.5
-1.0
-0.5
0.0
0.5
1.0
1.5
2.0


Yokohama National University
Demand curves
T=0.48 sec
Basement 1
Basement 2
Basement 3
Near
Far
Representative force (cm/s²)
Representative disp. (cm)
0
2
4
6
8
10


Yokohama National University
E-defense Test (Y2016)
3600
1800
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5200
1500
1500
2000
ストッパー
400x400
試験体固定用S梁
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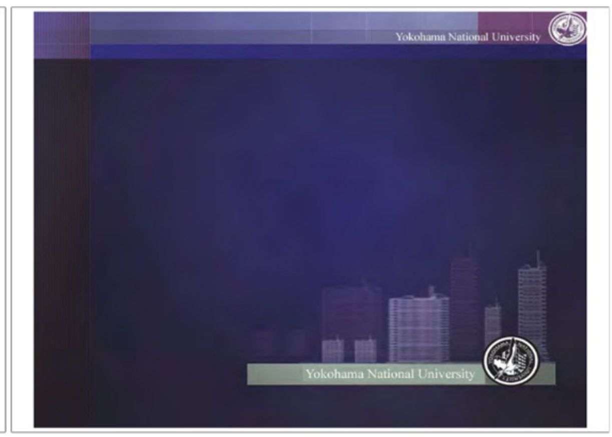
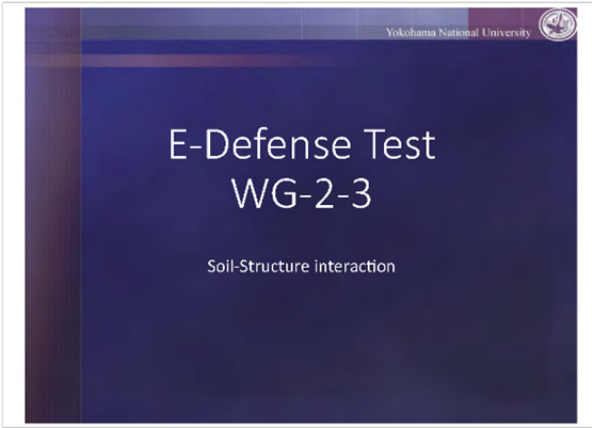
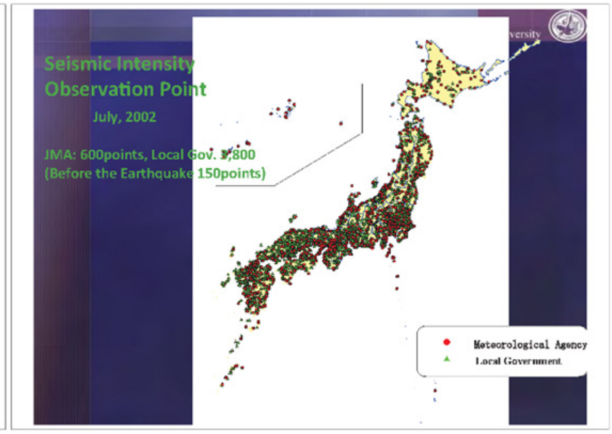
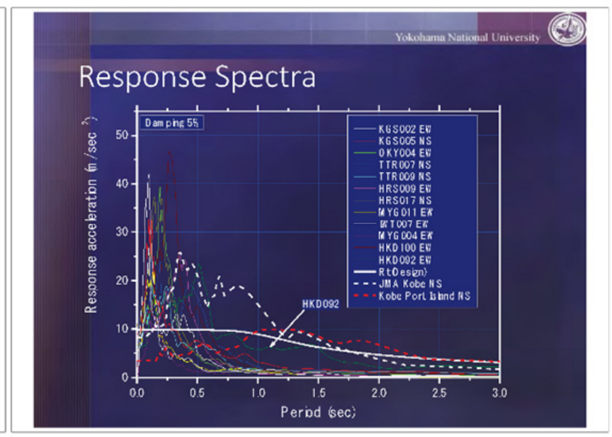
ストッパー
200x200
1000
900
200
400
1150
1950
600

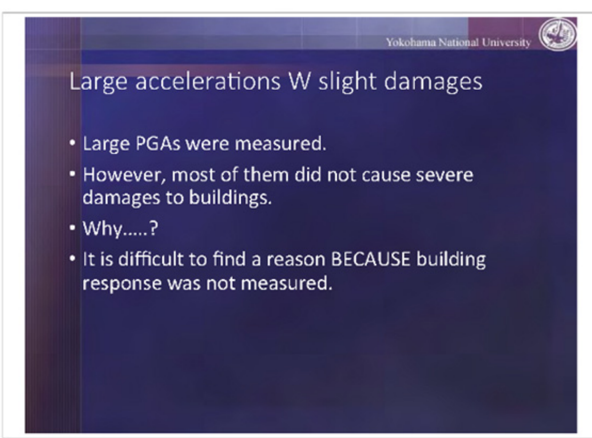

Yokohama National University
Yokohama National University

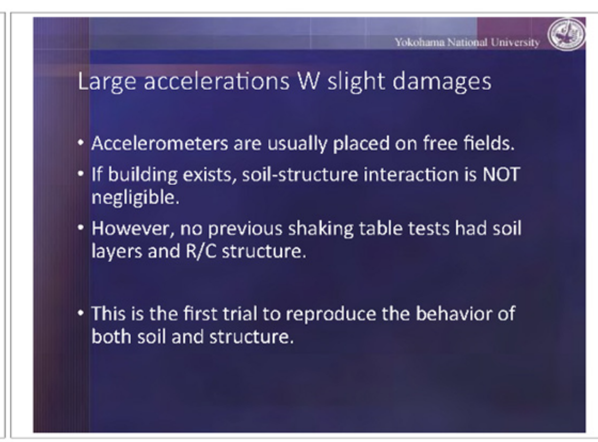
Appendix VII

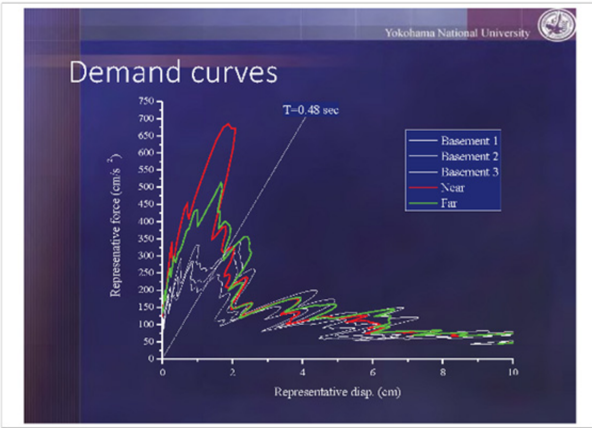


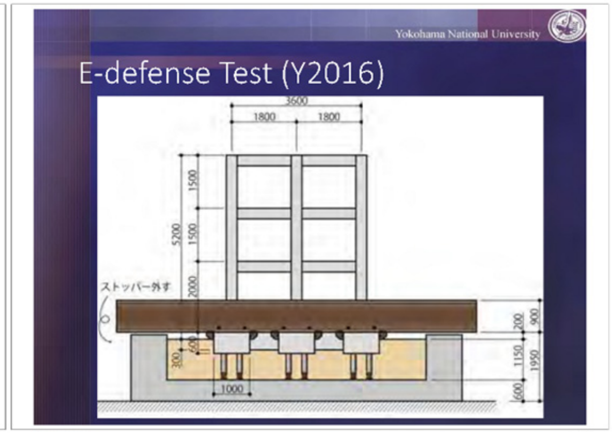









Yokohama National University
Demand curves
T=0.48 sec
Basement 1
Basement 2
Basement 3
Near
Far
Representative force (cm/s²)
Representative disp. (cm)


Yokohama National University
E-defense Test (Y2016)
3600
1800
1800
5200
1500
1500
2000
ストッパー外す
200
900
1150
1950
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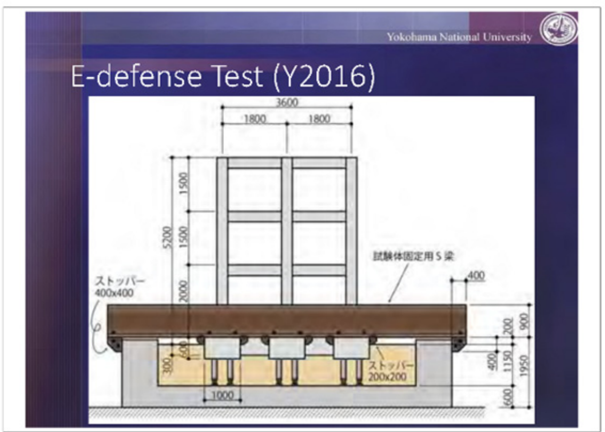
1000


Yokohama National University
E-defense Test (Y2016)
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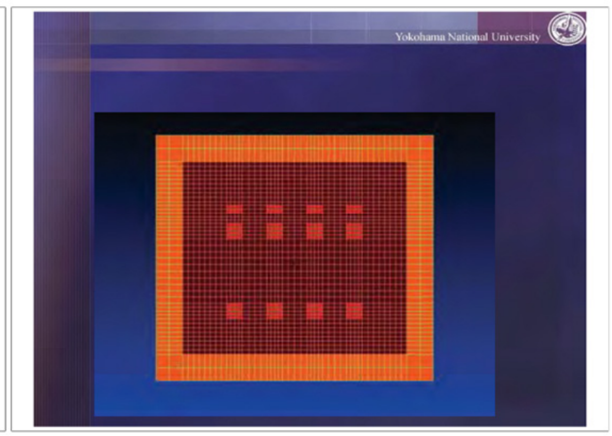
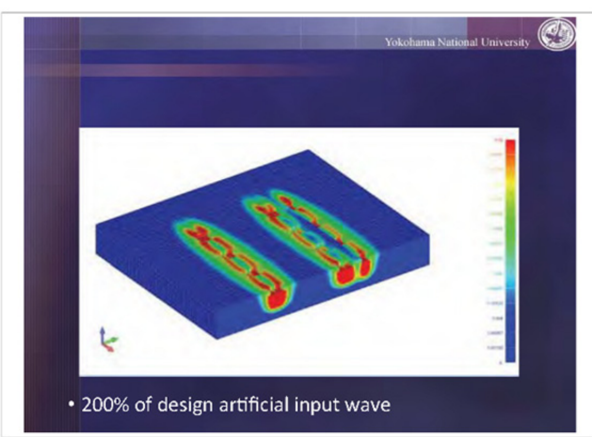
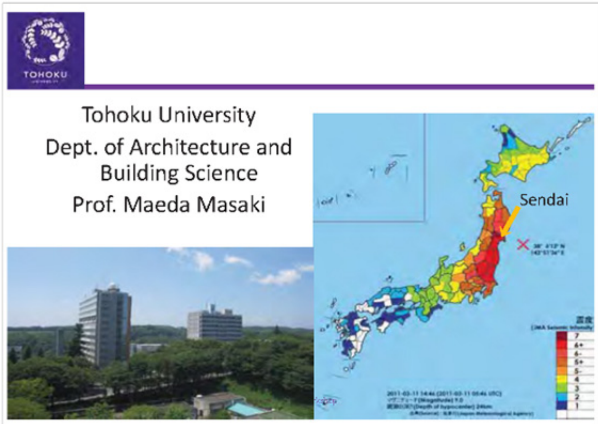
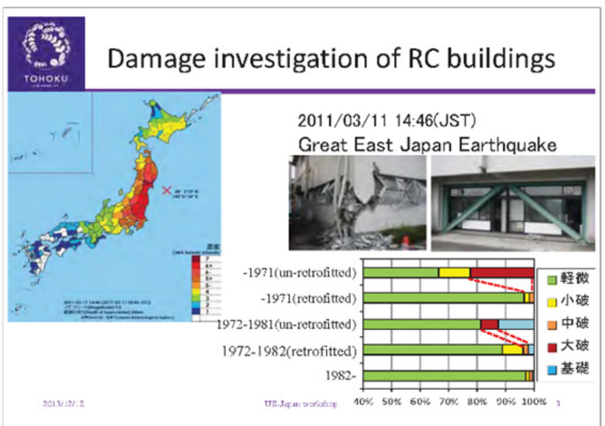
400
ストッパー
200x200
1000

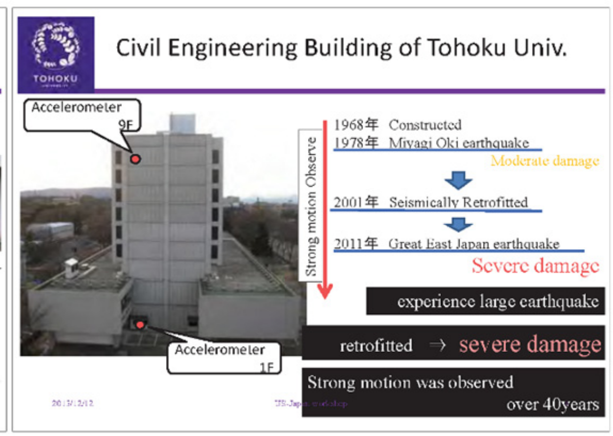

Yokohama National University

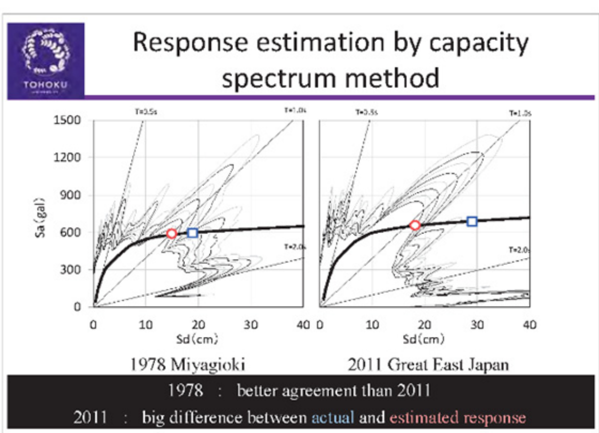

Yokohama National University
• 200% of design artificial input wave

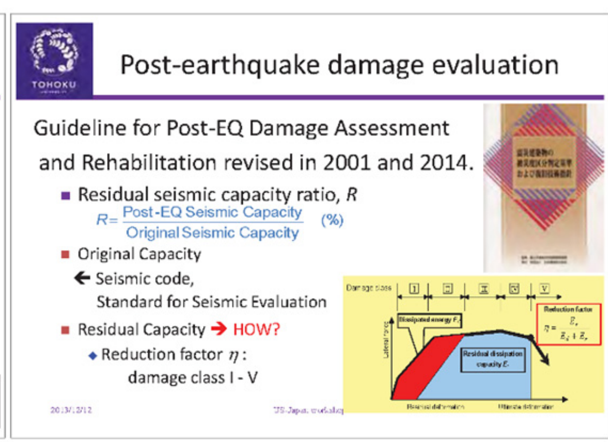

Tohoku University
Dept. of Architecture and Building Science
Prof. Maeda Masaki
Sendai

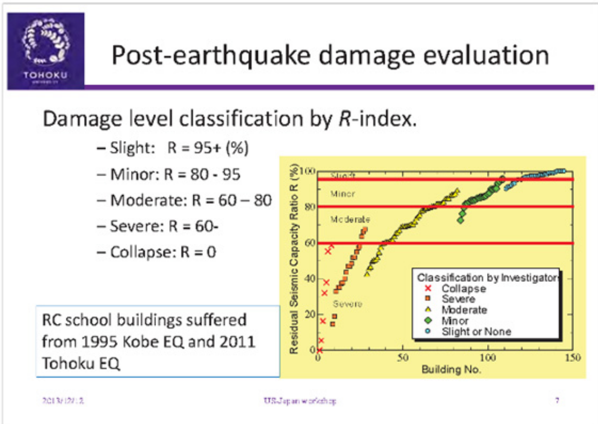

Scope of research interest
Damage investigation and analysis
Post-earthquake damage evaluation
Seismic capacity evaluation

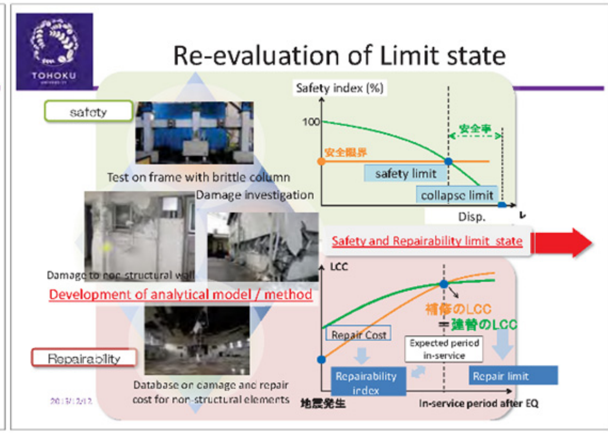

Damage investigation of RC buildings
2011/03/11 14:46(JST)
Great East Japan Earthquake
-1971(un-retrofitted)
-1971(retrofitted)
1972-1981(un-retrofitted)
1972-1982(retrofitted)
1982-
40% 50% 60% 70% 80% 90% 100%
軽微
小破
中破
大破
基礎

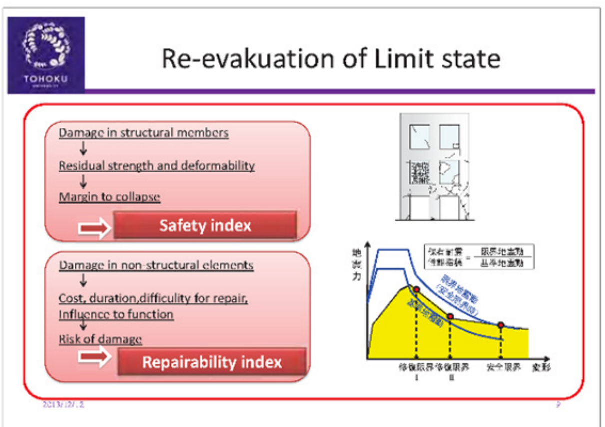

Civil Engineering Building of Tohoku Univ.
Accelerometer 9F
Accelerometer 1F
Strong motion Observe
1968年 Constructed
1978年 Miyagi Oki earthquake
Moderate damage
2001年 Seismically Retrofitted
2011年 Great East Japan earthquake
Severe damage
experience large earthquake
retrofitted → severe damage
Strong motion was observed over 40years


Response estimation by capacity spectrum method
Sa (gal)
Sd (cm)
1978 Miyagioki
2011 Great East Japan
1978 : better agreement than 2011
2011 : big difference between actual and estimated response

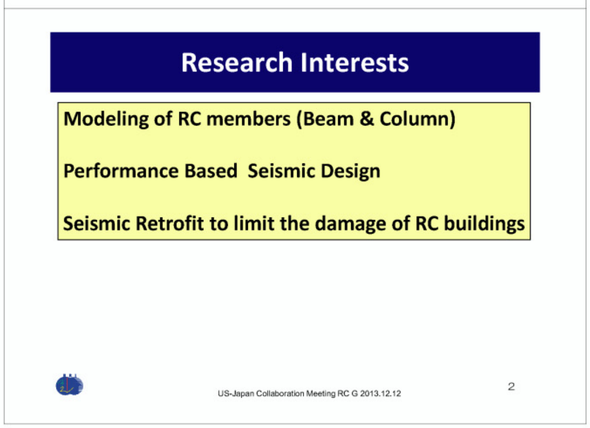

Post-earthquake damage evaluation
Guideline for Post-EQ Damage Assessment and Rehabilitation revised in 2001 and 2014.
Residual seismic capacity ratio, R
R = Post-EQ Seismic Capacity / Original Seismic Capacity (%)
Original Capacity
← Seismic code, Standard for Seismic Evaluation
Residual Capacity → HOW?
Reduction factor η : damage class I - V

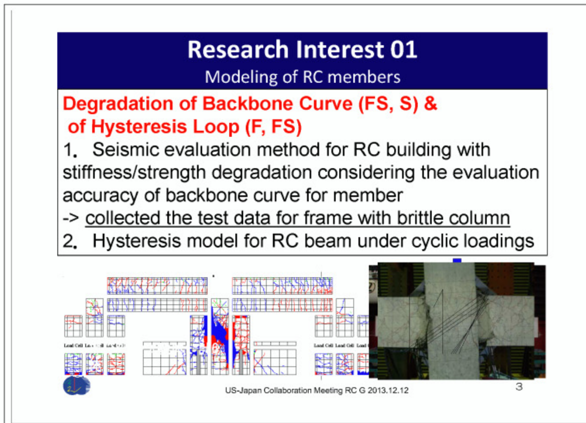

Post-earthquake damage evaluation
Damage level classification by R-index.
– Slight: R = 95+ (%)
– Minor: R = 80 - 95
– Moderate: R = 60 – 80
– Severe: R = 60-
– Collapse: R = 0
RC school buildings suffered from 1995 Kobe EQ and 2011 Tohoku EQ
Residual Seismic Capacity Ratio R (%)
Building No.
Classification by Investigator
Collapse
Severe
Moderate
Minor
Slight or None
TOHOKU

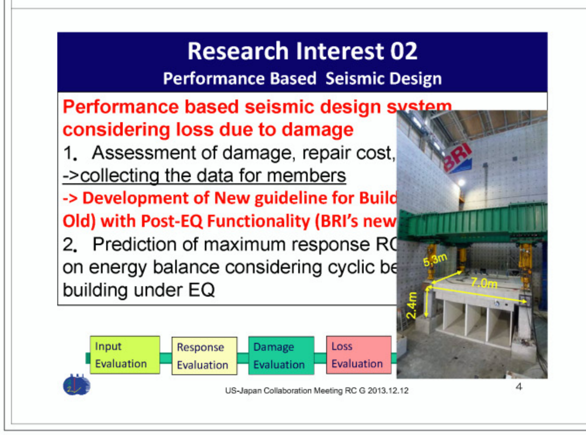

Re-evaluation of Limit state
safety
Test on frame with brittle column
Damage investigation
Safety index (%)
安全限界
safety limit
collapse limit
安全率
Disp.
Safety and Repairability limit state
Damage to non-structural wall
Development of analytical model / method
LCC
補修のLCC
建替のLCC
Repair Cost
Expected period in-service
Repairability
Repairability index
Repair limit
Database on damage and repair cost for non-structural elements
地震発生
In-service period after EQ
TOHOKU

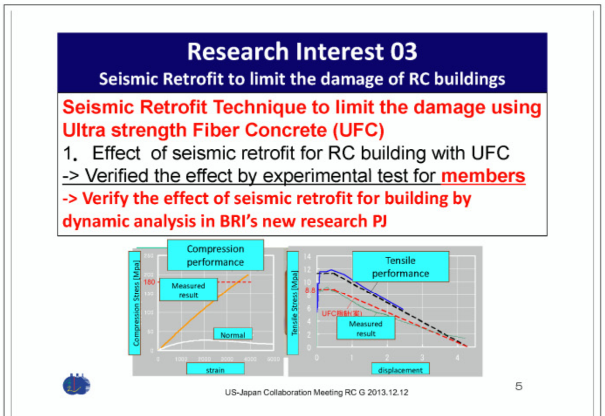

Re-evakuation of Limit state
Damage in structural members
Residual strength and deformability
Margin to collapse
Safety index
Damage in non-structural elements
Cost, duration,difficulty for repair, Influence to function
Risk of damage
Repairability index
TOHOKU

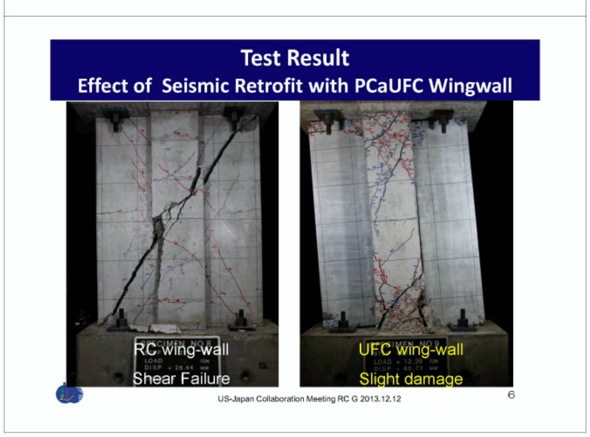
Appendix VII

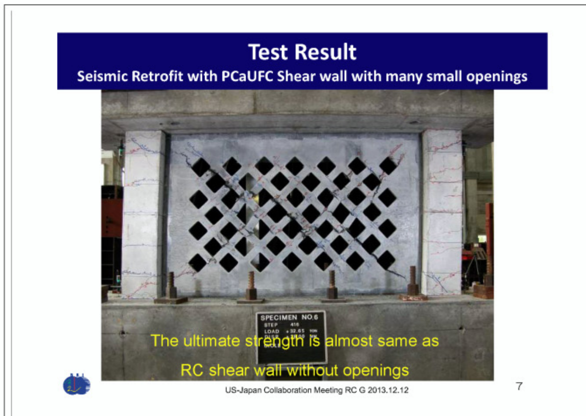












Research Agreement
08.2012-(10 years)

Establishment and operation of database (DB) for reinforced concrete(RC) buildings

Development for performance-based seismic design for RC buildings

Exchange of collaborative research topic

ATC58：Development of Next Generation Performance-Based Seismic Design Procedures for New and Existing Buildings

$$\lambda(dv < DV) = \iiint G(dv \mid dm)\,\mathrm{d}G(dm \mid edp)\,\mathrm{d}G(edp \mid im)\left|\mathrm{d}\lambda(im)\right|$$

Seismic Risk | Loss Analysis | Damage Analysis | Response Analysis | PSHA

Assist. Prof. Tony Yang visited BRI on Aug.14, 2012

International Activity02
(Apr.2013-)

International Council for Research and Innovation in Building and Construction

objectives : stimulate and facilitate international cooperation and information exchange between research institutes and construction sector

W114

Earthquake Engineering and Buildings

Current Main task :

Research Roadmap for Earthquake Engineering

Appendix VII

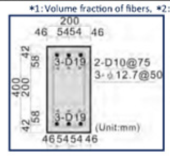
Shear and flexure in prestressed concrete members
Seismic performance of PC buildings
Fire resistance
Low-cycle fatigue
Fiber-reinforced concrete
Confined concrete and HSC
Precast concrete

Minehiro Nishiyama
Professor
Department of Architecture
and Architectural Engineering
Kyoto University

Pre-tensioned beam with fiber-reinforced cocnrete

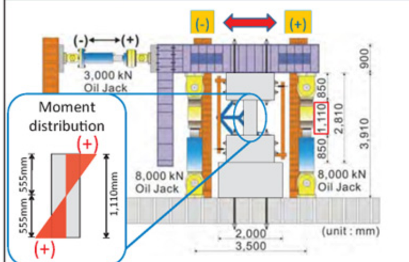
Specimens	V_f*1(%)	P_e (kN)*2	Shear strength Q_{su} (kN)	Flexural strength Q_{fu} (kN)	Shear margin ratio *3
PC3	0.0	433.3*2	512.8	420.3	1.22
SF05	0.5	457.0*2	533.1	426.5	1.25
SF10	1.0	386.1*2	508.8	424.0	1.20

*1: Volume fraction of fibers, *2: Effective prestressing Force, *3: Q_{su}/Q_{fu}



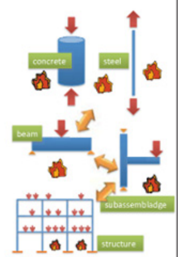
Reinforcements
- Shear Reinforcements – D10 (SD295)
- Tensile Reinforcements – D19 (SD345)
- Prestressing Tendons – 12.7 mm diameter strands (SWPR7BL)

Loading setup



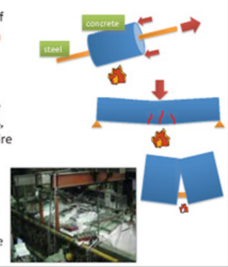
Fire resistance

- Research on fire resistance of
  - materials (concrete and steel): stress-strain relations have been obtained from loading tests at elevated temperatures, and they have been idealized in numerical expressions.
  - members and subassemblages (beam, column and beam-column joints): not many fire resistance tests have been carried out.
  - structures: not enough data have been accumulated because of difficulties in testing, i.e., facilities and testing methods.



Fire resistance

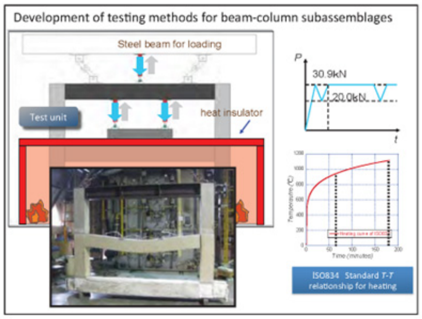
- Research on fire resistance of
  - interfaces (bond between concrete and steel): little information is available.
  - cracks in concrete, which would affect temperature development in members, based on observation in fire tests on RC frames last year.
  - subassemblages and frames: a new testing method has been being developed using a furnace for beams and slabs.



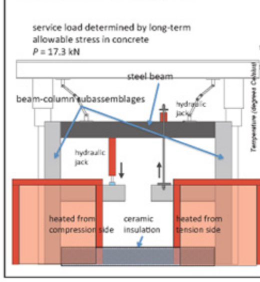
Current focus is on

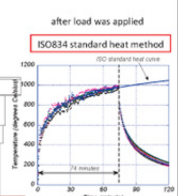
- bond deterioration at elevated temperatures
  - mechanism and idealization
- cracks in concrete
  - relation between crack width and temperature distribution in member
  - fire resistance after an earthquake damages the structure
- testing method on beam-column subassemblages subjected to vertical loading
  - development of testing method

Development of testing methods for beam-column subassemblages

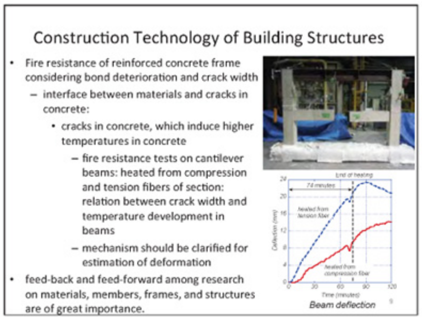


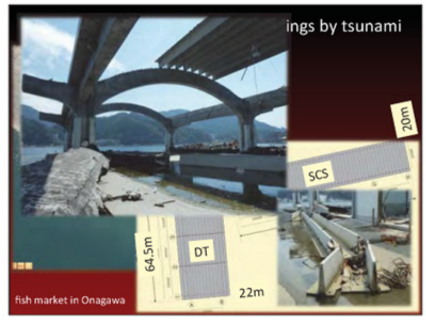
Another testing method

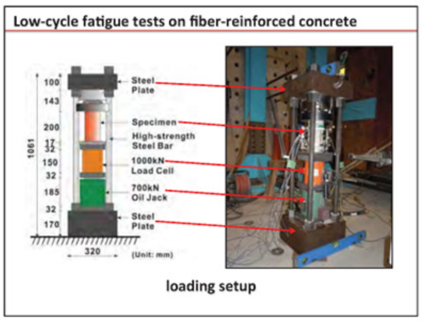


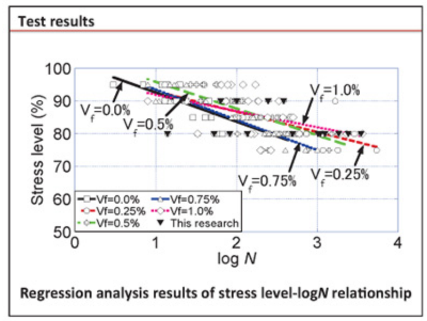


- Heating was ended at 74 minutes just before beam yielded.
- Residual load carrying capacity will be investigated within a few months.


Construction Technology of Building Structures
• Fire resistance of reinforced concrete frame considering bond deterioration and crack width
– interface between materials and cracks in concrete:
• cracks in concrete, which induce higher temperatures in concrete
– fire resistance tests on cantilever beams: heated from compression and tension fibers of section: relation between crack width and temperature development in beams
– mechanism should be clarified for estimation of deformation
• feed-back and feed-forward among research on materials, members, frames, and structures are of great importance.
Beam deflection

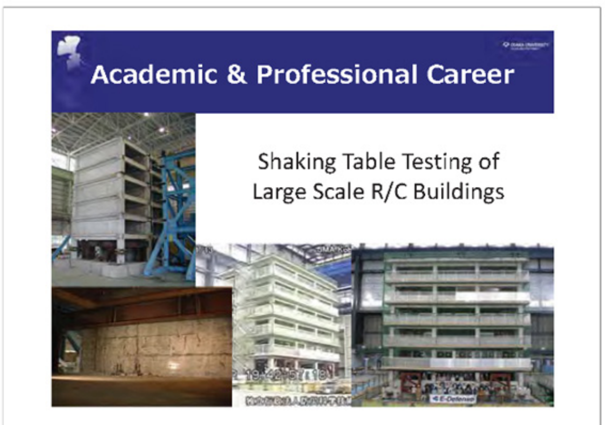

ings by tsunami
20m
SCS
64.5m
DT
22m
fish market in Onagawa

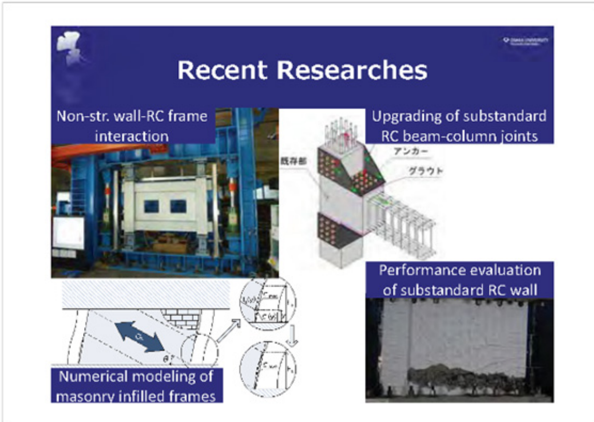

Low-cycle fatigue tests on fiber-reinforced concrete
Steel Plate
Specimen
High-strength Steel Bar
1000kN Load Cell
700kN Oil Jack
Steel Plate
(Unit: mm)
loading setup


Test results
Stress level (%)
log N
Vf=0.0%
Vf=0.5%
Vf=1.0%
Vf=0.75%
Vf=0.25%
This research
Regression analysis results of stress level-logN relationship

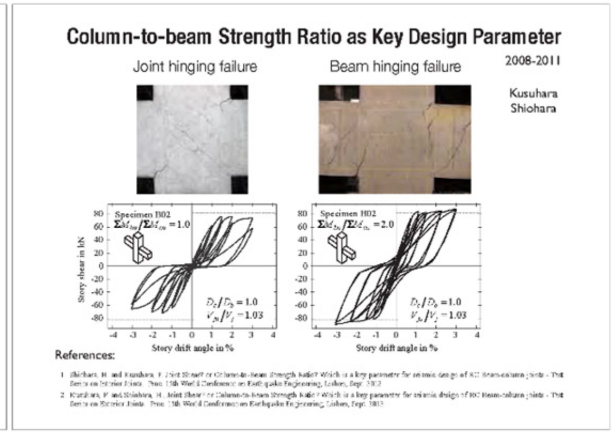
3

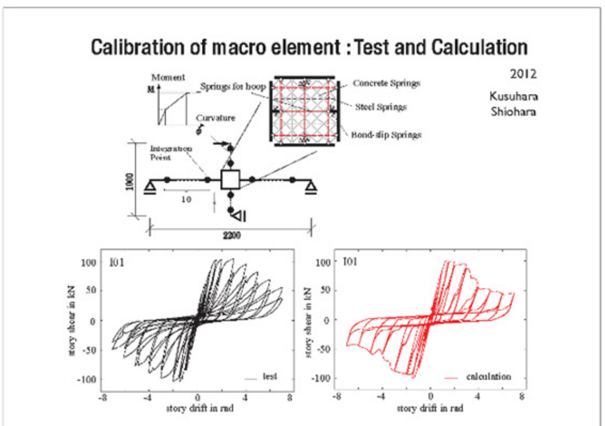
Appendix VII

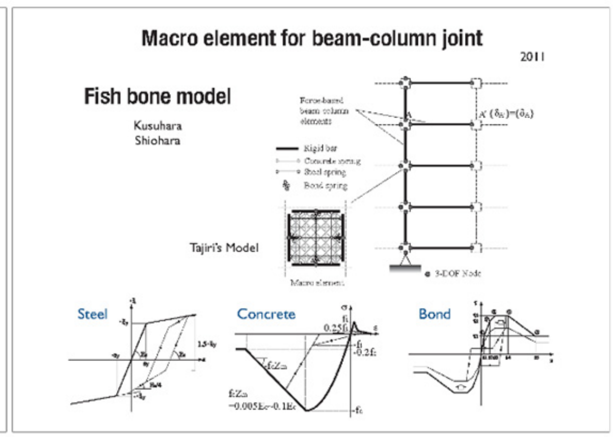


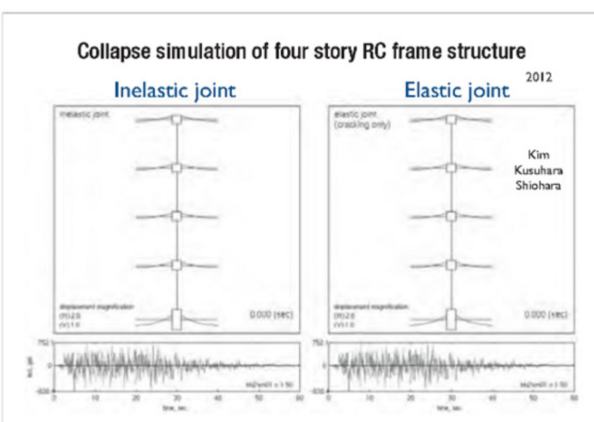

Recent Researches
Non-str. wall-RC frame interaction
Upgrading of substandard RC beam-column joints
既存部
アンカー
グラウト
Performance evaluation of substandard RC wall
Numerical modeling of masonry infilled frames

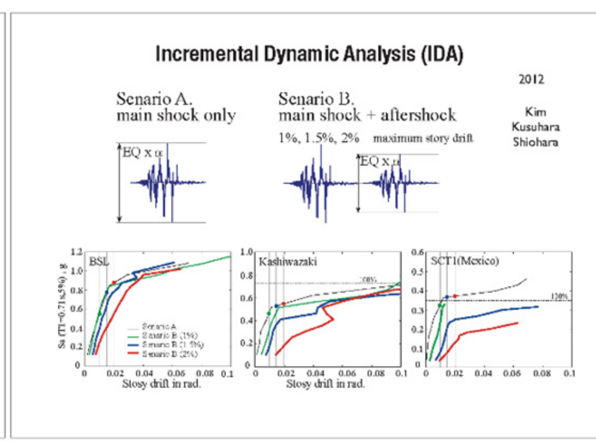

Hitoshi Shiohara
Professor, Dr. of Engineering, FACI
Department of Architectural Engineering
Graduate School of Engineering
The University of Tokyo
7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8656, JAPAN
Research Interests:
1. Modeling of multistory frame structures with poorly designed beam-column joint for collapse simulation
2. Collapse potential evaluation by the combination of main shocks and after shocks
3. Building collapse and bidirectional interaction subject to 3D base excitation
4. Modeling for progressive chain collapse of complicate structural systems
5. Development of redundant connecting system sustaining long term load for existing RC structural renovation
6. Rotational excitation by propagation of surface wave caused by a mega-quake


Column-to-beam Strength Ratio as Key Design Parameter
2008-2011
Joint hinging failure
Beam hinging failure
Kusuhara
Shiohara
Specimen B02
Specimen H02
Story shear in kN
Story drift angle in %
References:


Calibration of macro element : Test and Calculation
2012
Kusuhara
Shiohara
Moment
Springs for hoop
Concrete Springs
Steel Springs
Bond-slip Springs
Curvature
Integration Point
1900
10
2200
I01
story shear in kN
story drift in rad
test
calculation


Macro element for beam-column joint
2011
Fish bone model
Kusuhara
Shiohara
Tajiri's Model
Steel
Concrete
Bond


Collapse simulation of four story RC frame structure
2012
Inelastic joint
Elastic joint
Kim
Kusuhara
Shiohara
0.000 (sec)


Incremental Dynamic Analysis (IDA)
2012
Senario A.
main shock only
Senario B.
main shock + aftershock
1%, 1.5%, 2% maximum story drift
Kim
Kusuhara
Shiohara
EQ x α
BSL
Kashiwazaki
SCT1(Mexico)
Stosy drift in rad.

Thank you

Long Term Collaboration

Seismic Evaluation for Extremely Large Earthquake event

Hitoshi Shiohara

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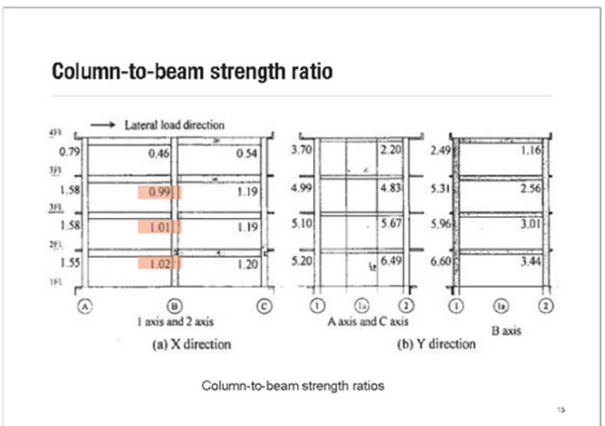
Department of Architectural Engineering
Graduate School of Engineering
The University of Tokyo
7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8656, JAPAN
http://www.rcs.arch.t.u-tokyo.ac.jp/

Research Interests:

1. Modeling of multistory frame structures with poorly designed beam-column joint for collapse simulation
2. Collapsing potential evaluation by the combination of main shocks and after shocks
3. **Building collapse and bidirectional interaction subject to 3D base excitation**
4. **Modeling for progressive collapse of non simplistic structural system**
5. Development of redundant connecting system sustaining long term load for existing RC structural renovation
6. Rotational excitation by propagation of surface wave caused by a mega-quake

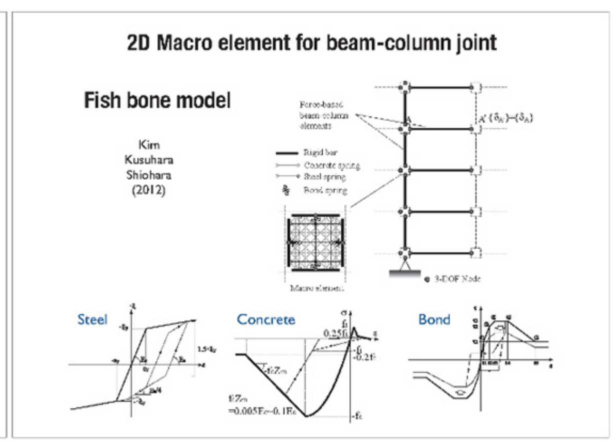

RC Building Collapse
Loss of Life =
No spaces
between floors
13

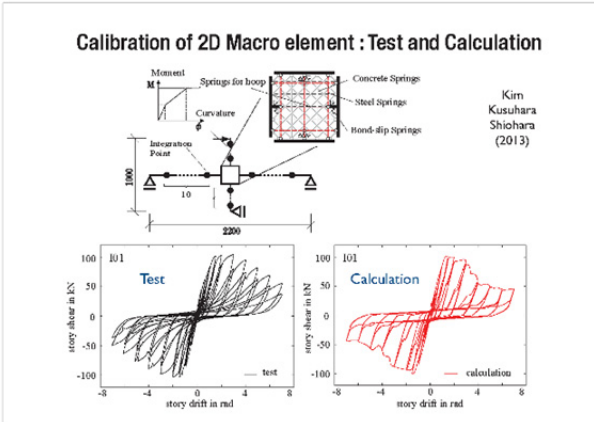

E-Defense test on RC Building in December 2010
E-Defense 3D Shaking Table
Four Storied Wall-Frame
RC Structure
Design conformed to
Japanese & US seismic code
requirements

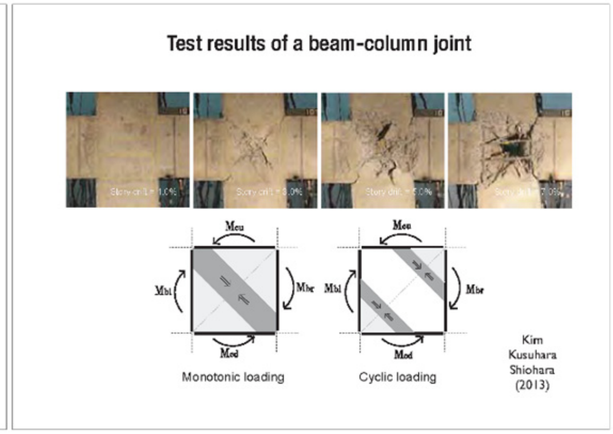

Column-to-beam strength ratio
Lateral load direction
4FL
0.79
0.46
0.54
3FL
1.58
0.99
1.19
2FL
1.58
1.01
1.19
2FL
1.55
1.02
1.20
1FL
3.70
2.20
4.99
4.83
5.10
5.67
5.20
6.49
2.49
1.16
5.31
2.56
5.96
3.01
6.60
3.44
1 axis and 2 axis
(a) X direction
A axis and C axis
(b) Y direction
B axis
Column-to-beam strength ratios
15

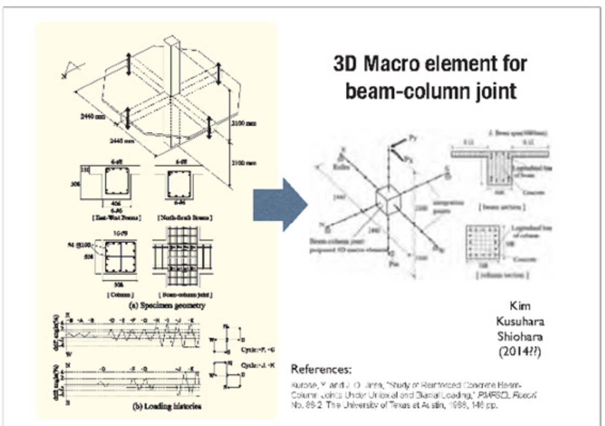

JMA Kobe 100%

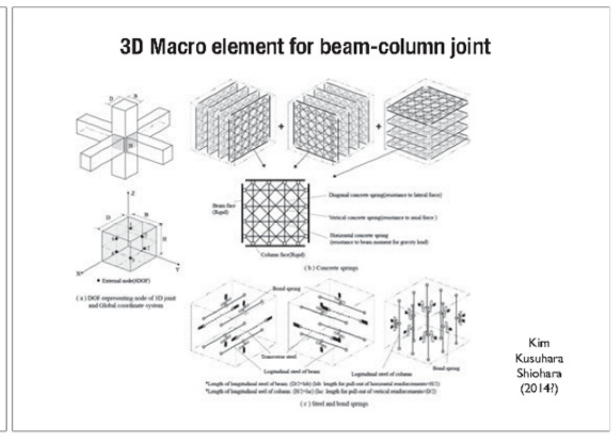

E-Defense
JMA Kobe 100%
NIED

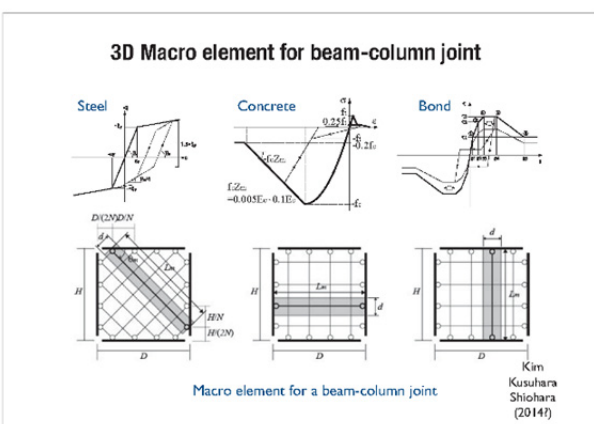

2D Macro element for beam-column joint
Fish bone model
Kim
Kusuhara
Shiohara
(2012)
Steel
Concrete
Bond

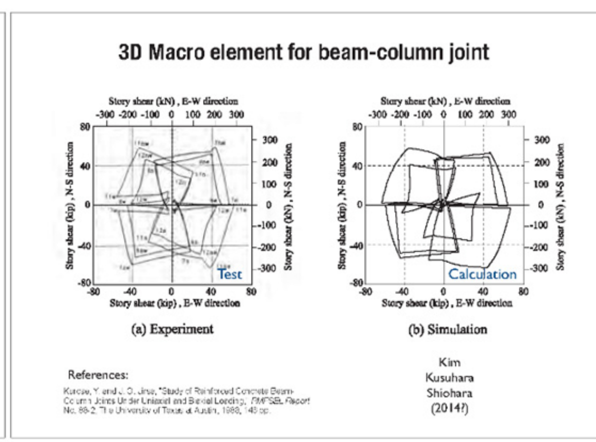

Calibration of 2D Macro element : Test and Calculation
Moment
Springs for hoop
Concrete Springs
Steel Springs
Bond-slip Springs
Curvature
Integration Point
1000
10
2200
Kim
Kusuhara
Shiohara
(2013)
Test
Calculation
story shear in kN
story drift in rad
test
calculation


Test results of a beam-column joint
Monotonic loading
Cyclic loading
Kim
Kusuhara
Shiohara
(2013)


3D Macro element for beam-column joint
(a) Specimen geometry
(b) Loading histories
Kim
Kusuhara
Shiohara
(2014??)
References:
Kurose, Y. and J. O. Jirsa, "Study of Reinforced Concrete Beam-Column Joints Under Uniaxial and Biaxial Loading," PMFSEL Report No. 88-2, The University of Texas at Austin, 1988, 146 pp.

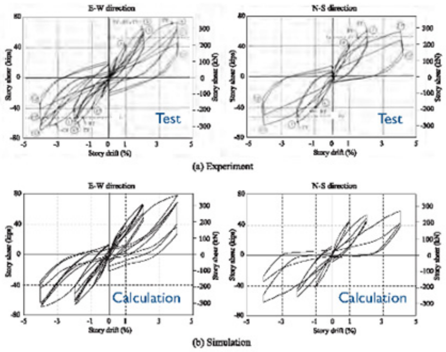

3D Macro element for beam-column joint
Kim
Kusuhara
Shiohara
(2014?)


3D Macro element for beam-column joint
Steel
Concrete
Bond
Macro element for a beam-column joint
Kim
Kusuhara
Shiohara
(2014?)


3D Macro element for beam-column joint
Story shear (kN), E-W direction
Story shear (kip), N-S direction
Story shear (kN), N-S direction
Story shear (kip), E-W direction
Test
Calculation
(a) Experiment
(b) Simulation
References:
Kurose, Y. and J. O. Jirsa, "Study of Reinforced Concrete Beam-Column Joints Under Uniaxial and Biaxial Loading," PMFSEL Report No. 88-2, The University of Texas at Austin, 1988, 146 pp.
Kim
Kusuhara
Shiohara
(2014?)

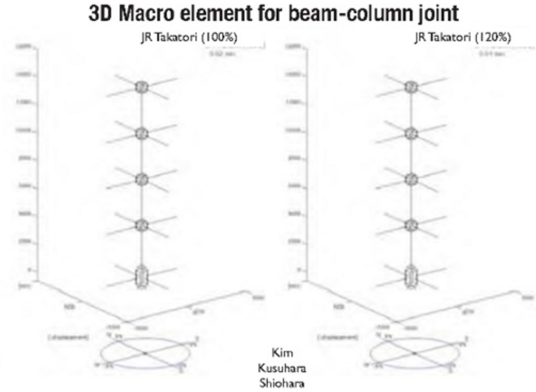
Appendix VII

3D Macro element for beam-column joint



Kim
Kusuhara
Shiohara
(2014?)

3D Macro element for beam-column joint



Kim
Kusuhara
Shiohara

US-Japan Collaboration

(Topic 1)

- Share non-linear modeling for collapse available for the common platform like OpenSees
- Benchmark collapse simulation on US & Japan generic buidlings
- Identify collapse senarios on various structural system including gravity effects
- Design Issue

➡ Common Objective

Technology transfer : transferring knowledge of collapse performance to stake holders

US-Japan Collaboration

(Topic 2)

- Combination of Monitoring & On-time Updating of non-linear structural model (autonomous mechanism incorporated) for more accurate collapse prediction
- Diagnosis based on each building's experience history
- Quick collapse safety assessment utilizing the updated non-linear structural model
- Computer and sensor issue

➡ Common Objectives:

Post-quake decision assistance : Evaluation aftershock collapse vulnerability, for long-term maintainance plan, demolition etc.

US-Japan Collaboration

(Topic 3)

Particularly emphasized

STRUCTURAL SYSTEM but not MEMBER

- Bi-directional cyclic response dependent to 2D loading path
- Various hysteretic behavior due to bi-directional interaction
- Accidental torsion at aftershock
- Unidentified collapse mechanism
- Design Issue

➡ Common Objective :

Identify seismic demand necessary to improve design

MISSOURI UNIVERSITY OF SCIENCE AND TECHNOLOGY — MISSOURI S&T

NEES / E-Defense Workshop

Kyoto, Japan
ecem er 11-13, 2013

Lesley . Sneed, h. ., .
Assistant rofessor of Civil ngineering
Missouri University of Science and Technology Missouri S T

MISSOURI UNIVERSITY OF SCIENCE AND TECHNOLOGY — MISSOURI S&T

Research Interests:

Reinforced and prestressed concrete structural mem ers and systems
Structural models and experimental methods
Innovative methods of repair and strengthening of structures subjected to seismic loading or other extreme hazards
valuation of existing structures
esign codes and construction specifications for structural concrete

MISSOURI UNIVERSITY OF SCIENCE AND TECHNOLOGY — MISSOURI S&T

Repair of Severely Damaged Bridge Columns Under Combined Loading


Severe Damage After Being Subjected to Combined Cyclic Loading


RC Columns in a Typical Curved Bridge

Develop a procedure to repair severely damaged RC bridge columns after severe earthquake damage has occurred
Investigate the structural performance of the repaired columns under combined axial, flexural, shear, and torsional loading conditions

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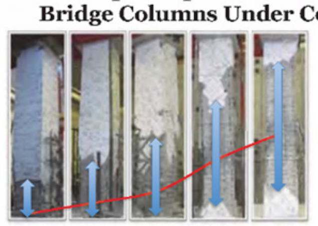
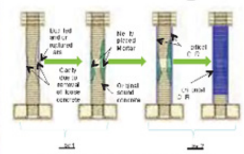
Rapid Repair of Severely Damaged Bridge Columns Under Combined Loading



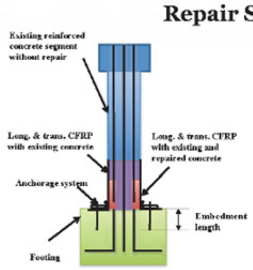
Damage Condition


Rapid Repair Procedure

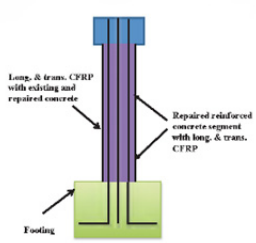

Investigation of Repaired Column Structural Performance

MISSOURI UNIVERSITY OF SCIENCE AND TECHNOLOGY — MISSOURI S&T

Repair Schemes



(a) Flexure Dominant Column Repair



(b) Torsion Dominant Column Repair

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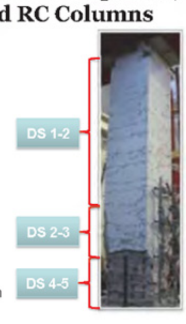
Modeling the Response of Repaired, Severely Damaged RC Columns

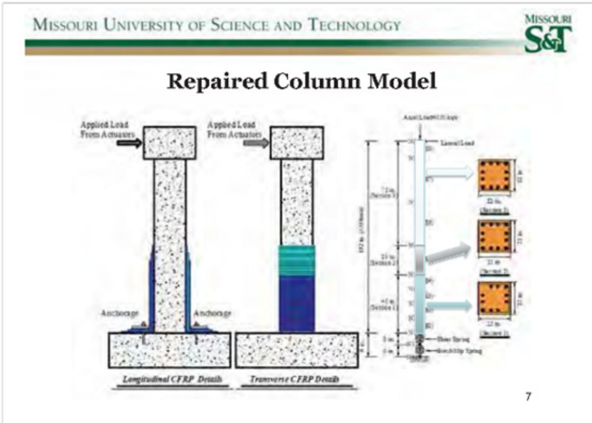
S1 lexural crac s
S2 irst spalling and shear crac s
S3 xtensive crac s and spalling
S4 isi le lateral and longitudinal ars
S5 mminent failure.

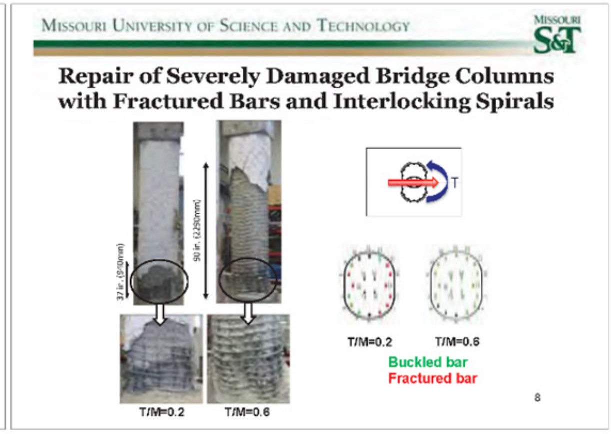
- ✓ The steel properties are modified to account for column softening due to earth ua e damage. S5 0.2 S3 0.5 S2 0.67.
- ✓ C R confined concrete
- ✓ Crac ed concrete in the unrepaired region

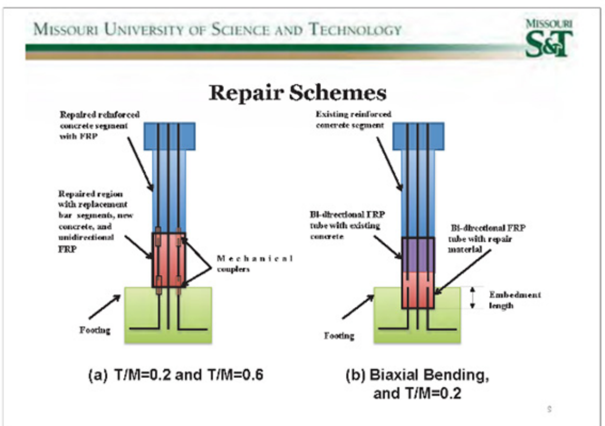


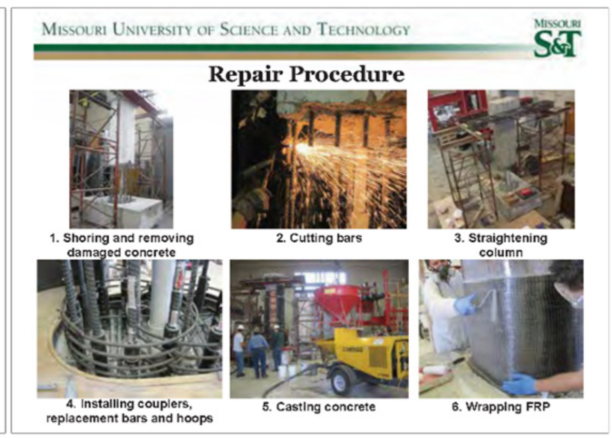
6

Appendix VII









NEES / E-Defense Workshop
Kyoto, Japan
11th - 13th of December 2013

Andreas Stavridis,
University at Buffalo

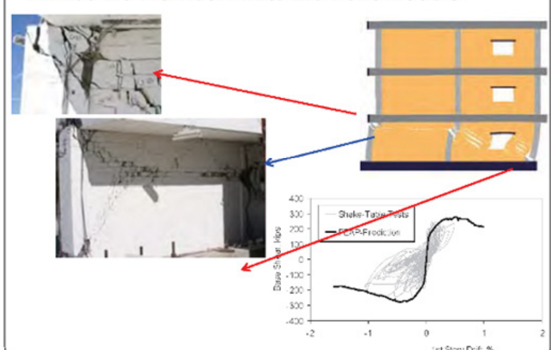
Background: Structural System

1. Concrete structures
   1. Non-ductile infilled frames
   2. Bond-slip and development length of large diameter bars (d_b up to 57 mm)
2. Masonry structures
   1. Reinfroced shear calls
   2. Unreinforced non-structural elements

Background: Simulation Approach

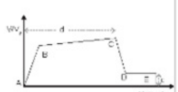
1. Experimental
   1. Quasi-static tests
   2. Shake-table tests
   3. Tests w/ mobile shakers
2. Analytical
   1. Detailed FE element models
   2. Simplified models
   3. Damage quantification

Infilled RC Frames: Finite Element Models



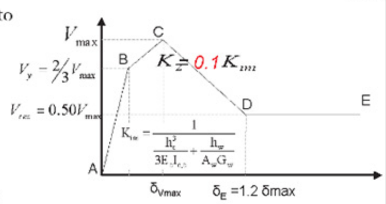
Infilled RC Frames: Simplified Models

Goal: Obtain an ASCE/41-type force-disp. curve with simple calculations.

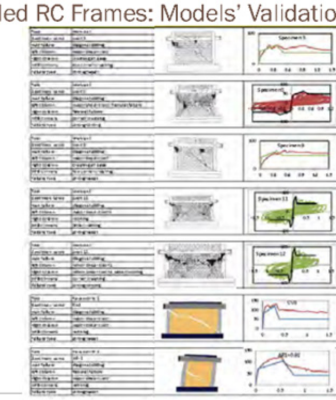


Provides guidelines to estimate:

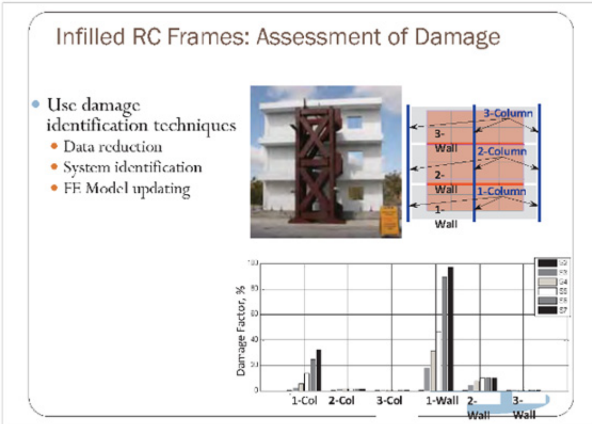
1. Stiffness
2. Max Base Shear
3. 'Yield' Point
4. Residual strength

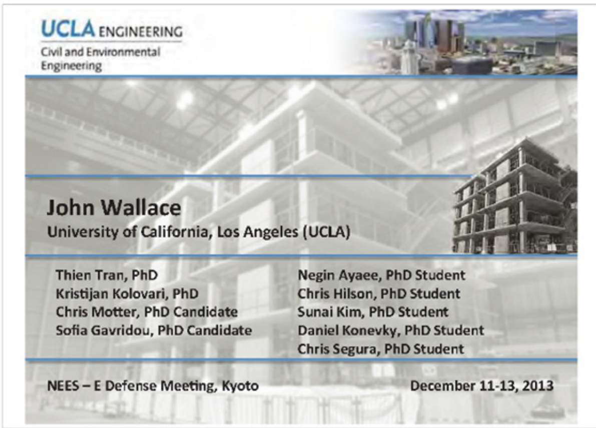


Infilled RC Frames: Models' Validation



Appendix VII

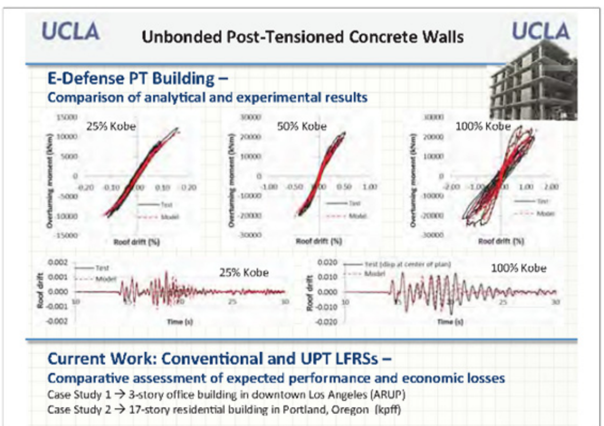


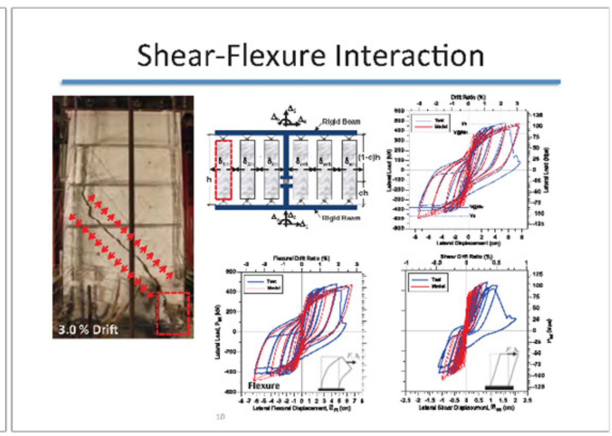


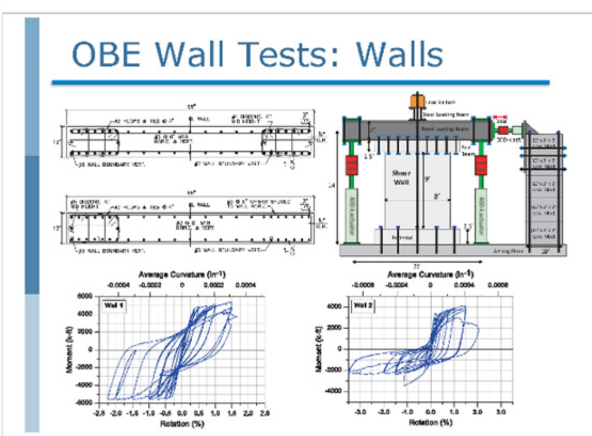
Current Research Interests - Walls

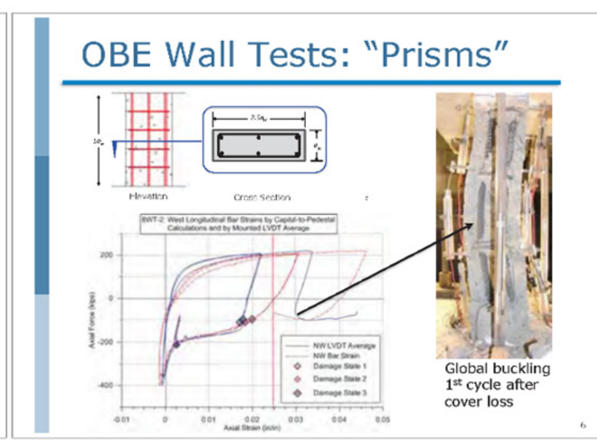
- Testing (Planar, Flanged, Coupled)
  - Detailing (OBE, SBE, Lateral Stability)
  - Load History
  - High-performance (Damage, losses)
  - Databases (Deformation capacities, Reliability)
- Modeling
  - Flexure, flexure-shear interaction, shear, collapse
- System level behavior
  - Testing and modeling
- Walls Workshop
  - US, Japan, NZ, Chile (2014-2016)

UCLA ENGINEERING
Civil and Environmental Engineering



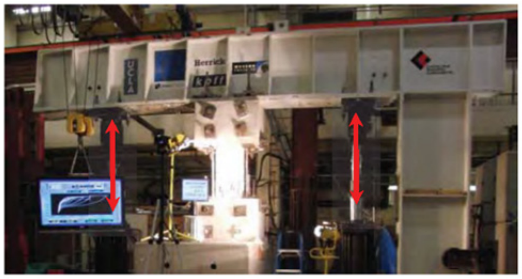






OBE Wall Tests: "Prisms"

- Testing Configuration:



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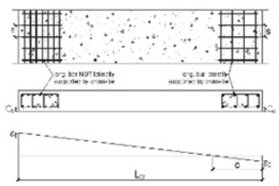
SBE Wall Panel Tests (NEESR)

WP1: Lateral support of longitudinal bars
WP2: Clear cover (C_c)
WP3: Hoop spacing (s)
WP4: Compressive strain (ε_c)

12 Total Tests



ID	Control Variables				Test Variables			Estimated Strain Demands @ 2% Drift	
	f'_c	f_{yt}	$P/A_g f'_c$	$v_u/(f'c)^{1/2}$ [MPa]	C_c	s/d_b	c/L_w		
	Mpa (ksi)	Mpa (ksi)	----	----	mm (in)	----	----	ε_c	ε_t
WP1	35 (5)	414 (60)	0.1	0.25	13 (0.5)	3.2/ 4.0	0.20	0.008	0.032
WP2	35 (5)	414 (60)	0.1	0.25	19 (0.75)	3.2/ 4.0	0.20	0.008	0.032
WP3	35 (5)	414 (60)	0.1	0.25	13 (0.5)	4.8/ 6.0	0.20	0.008	0.032
WP4	35 (5)	414 (60)	0.1	0.25	13 (0.5)	3.2/ 4.0	0.32	0.0128	0.0272

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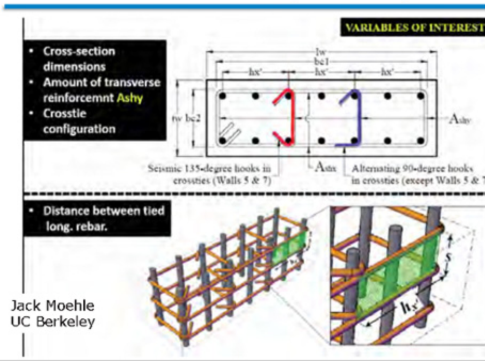
SBE Prism Tests (NEESR)



Jack Moehle
UC Berkeley

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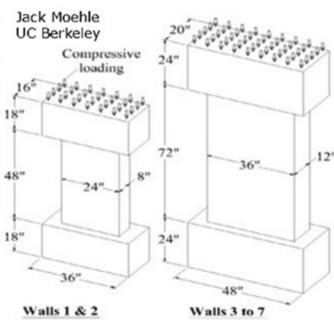
SBE Prism Tests (NEESR)

Jack Moehle
UC Berkeley



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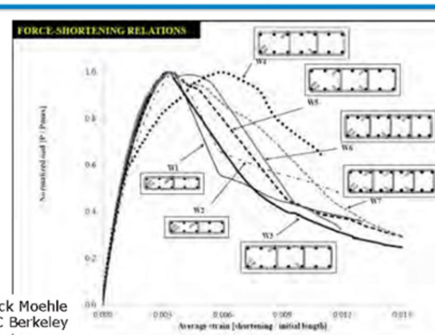
SBE Prism Tests (NEESR)



Jack Moehle
UC Berkeley

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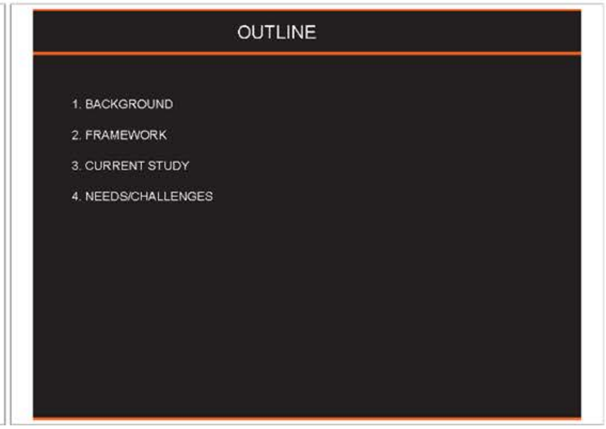
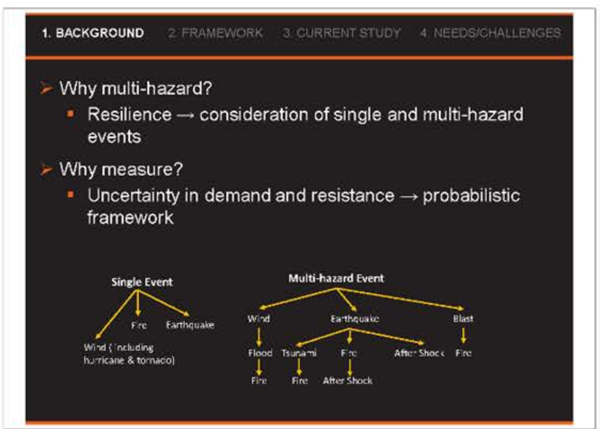
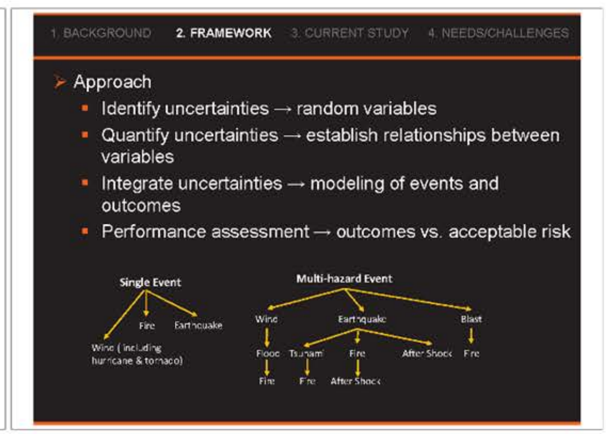
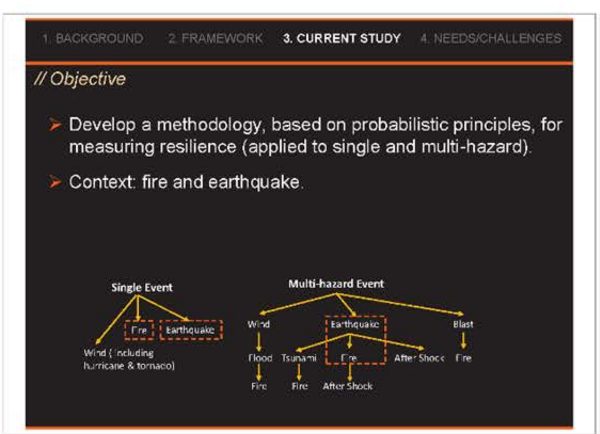
2013 12 13

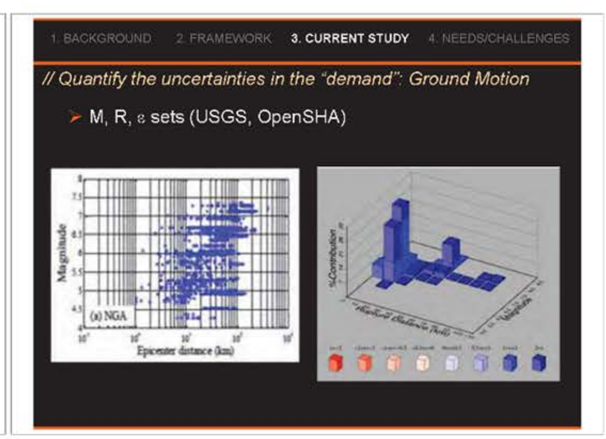
APPENDIX VIII: PRESENTED PAPERS IN STEEL WORKING GROUP



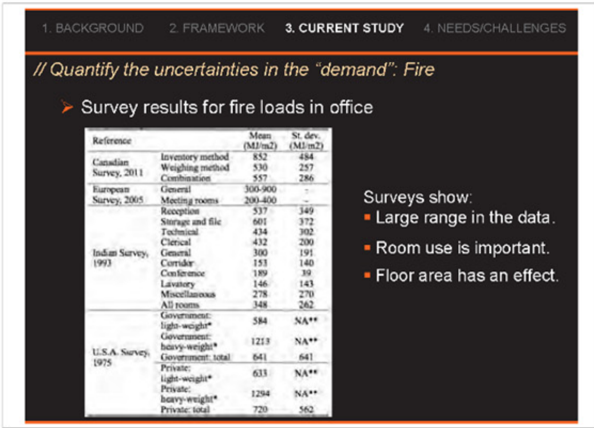




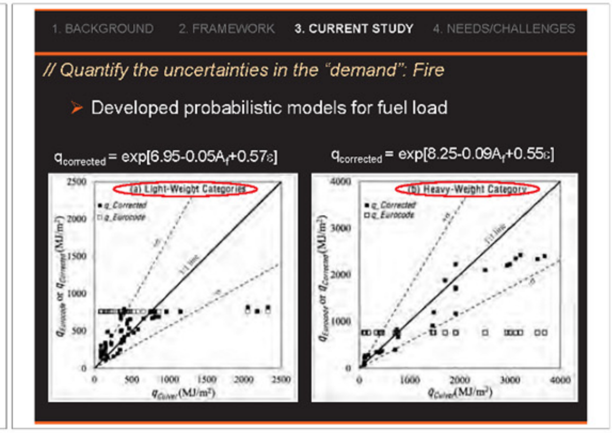


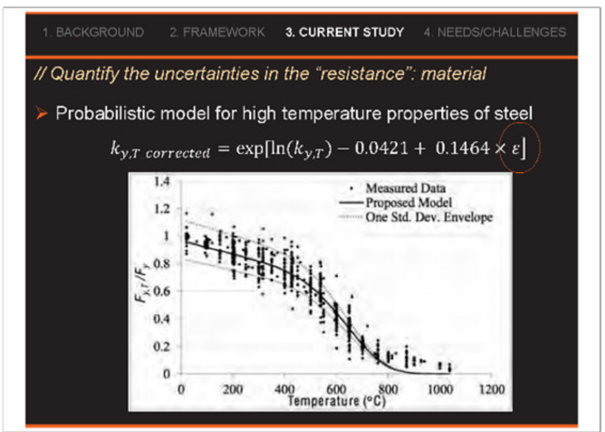


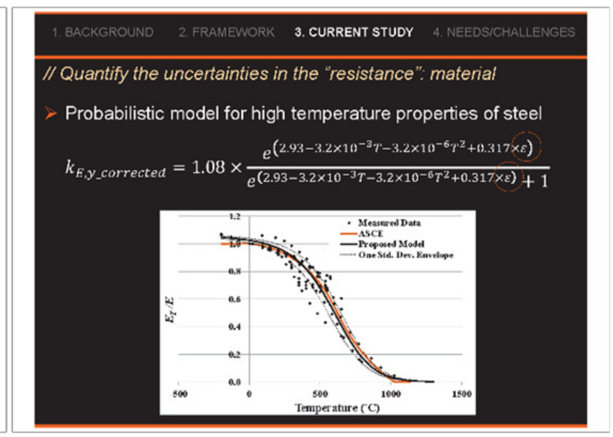
Appendix VIII

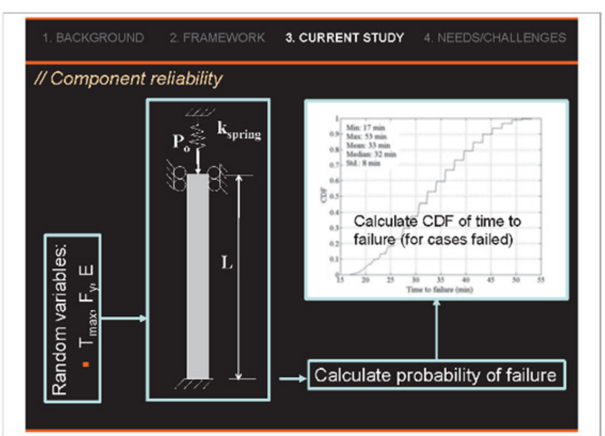


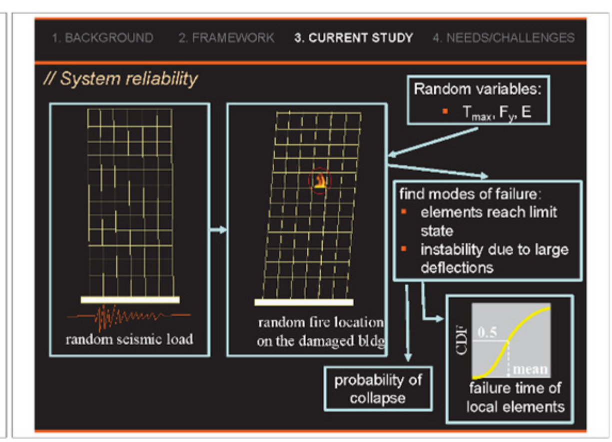
Reference		Mean (MJ/m2)	St. dev. (MJ/m2)
Canadian Survey, 2011	Inventory method	852	484
	Weighing method	530	257
	Combination	557	286
European Survey, 2005	General	300-900	-
	Meeting rooms	200-400	-
Indian Survey, 1993	Reception	537	349
	Storage and file	601	372
	Technical	434	302
	Clerical	432	200
	General	300	191
	Corridor	153	140
	Conference	189	39
	Lavatory	146	143
	Miscellaneous	278	270
	All rooms	348	262
U.S.A. Survey, 1975	Government: light-weight*	584	NA**
	Government: heavy-weight*	1213	NA**
	Government: total	641	641
	Private: light-weight*	633	NA**
	Private: heavy-weight*	1294	NA**
	Private: total	720	562

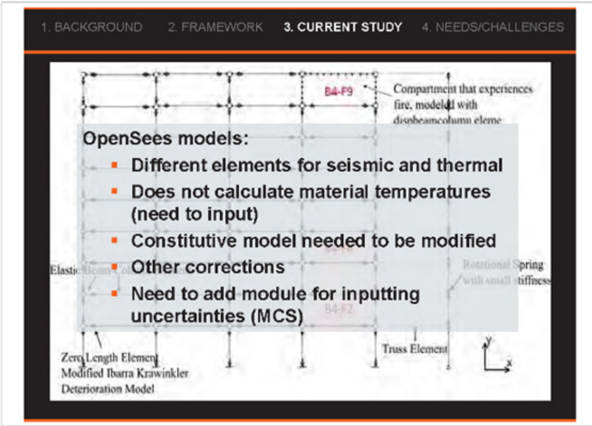


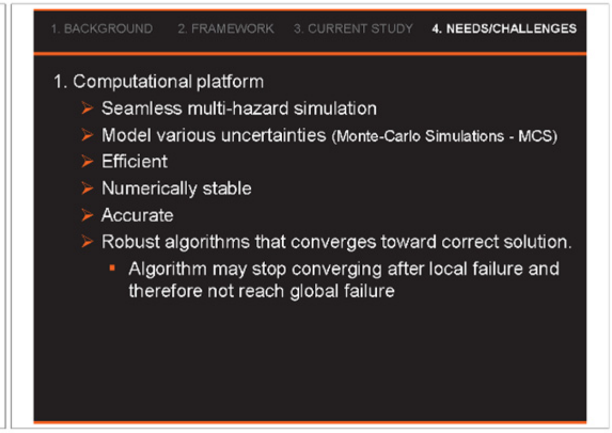


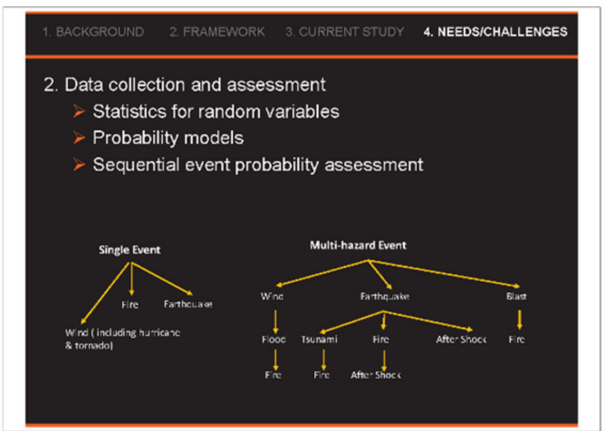


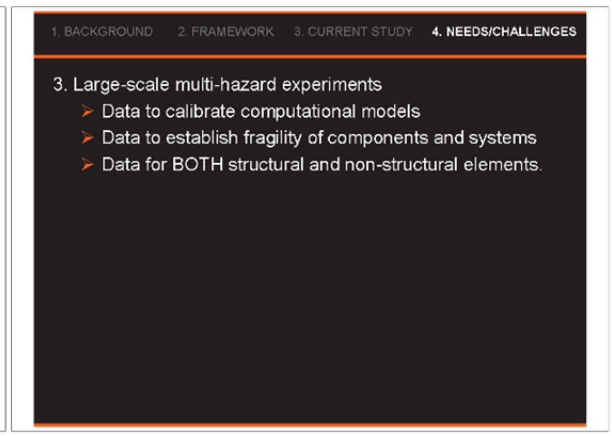




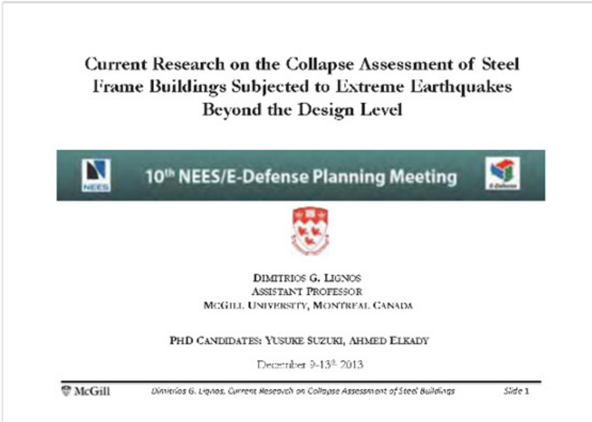

1. BACKGROUND
2. FRAMEWORK
3. CURRENT STUDY
4. NEEDS/CHALLENGES
B4-F9
Compartment that experiences fire, modeled with
OpenSees models:
Different elements for seismic and thermal
Does not calculate material temperatures (need to input)
Constitutive model needed to be modified
Other corrections
Need to add module for inputting uncertainties (MCS)
Zero Length Element
Modified Ibarra Krawinkler Deterioration Model
Truss Element

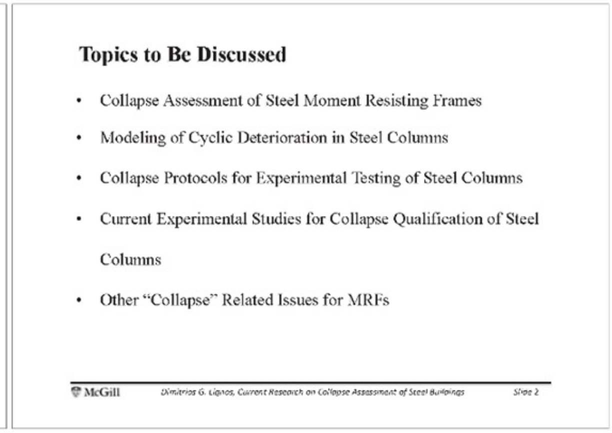

1. BACKGROUND
2. FRAMEWORK
3. CURRENT STUDY
4. NEEDS/CHALLENGES
1. Computational platform
Seamless multi-hazard simulation
Model various uncertainties (Monte-Carlo Simulations - MCS)
Efficient
Numerically stable
Accurate
Robust algorithms that converges toward correct solution.
Algorithm may stop converging after local failure and therefore not reach global failure

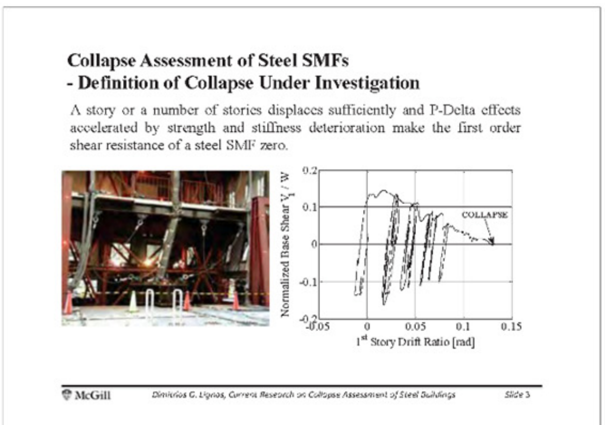

1. BACKGROUND
2. FRAMEWORK
3. CURRENT STUDY
4. NEEDS/CHALLENGES
2. Data collection and assessment
Statistics for random variables
Probability models
Sequential event probability assessment
Single Event
Fire
Earthquake
Wind (including hurricane & tornado)
Multi-hazard Event
Wind
Earthquake
Blast
Flood
Tsunami
Fire
After Shock
Fire
Fire
Fire
After Shock

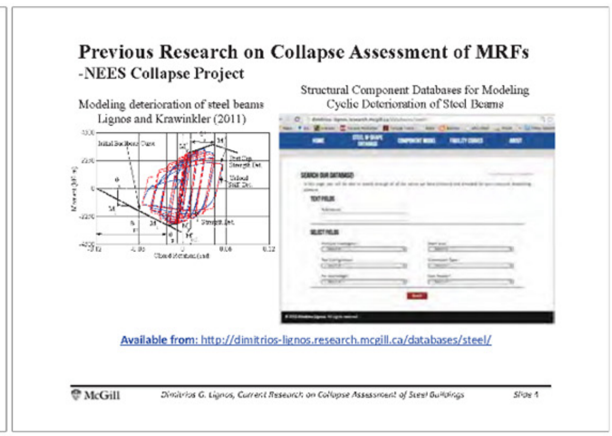

1. BACKGROUND
2. FRAMEWORK
3. CURRENT STUDY
4. NEEDS/CHALLENGES
3. Large-scale multi-hazard experiments
Data to calibrate computational models
Data to establish fragility of components and systems
Data for BOTH structural and non-structural elements.

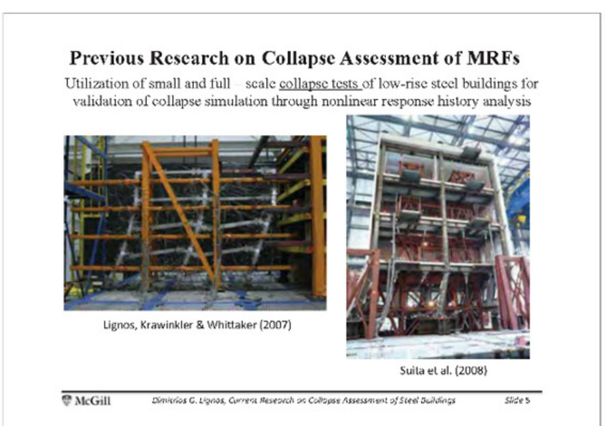
Appendix VIII

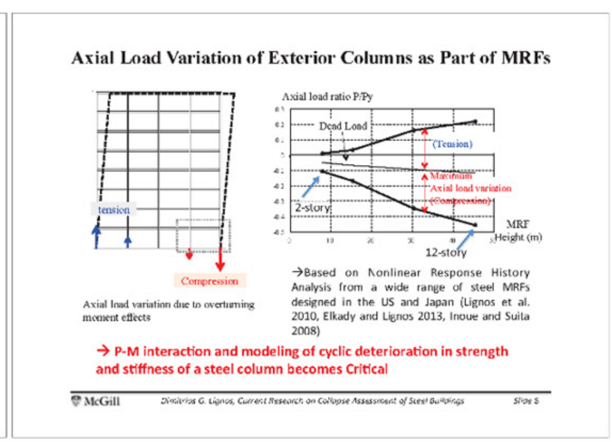


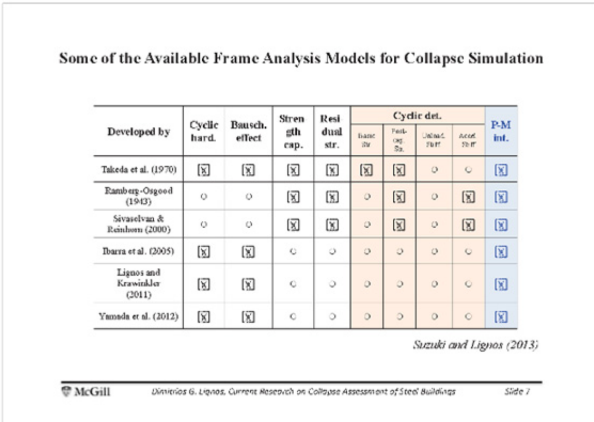




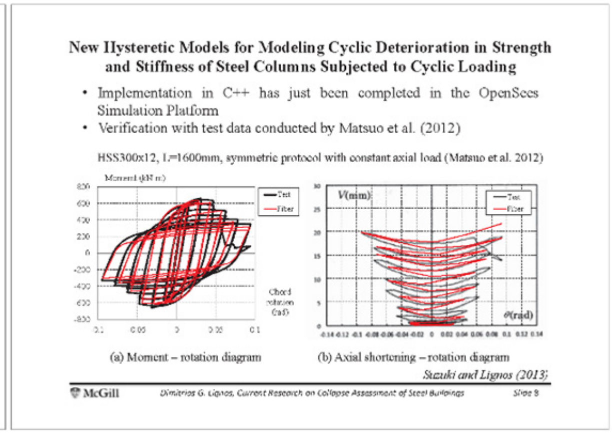


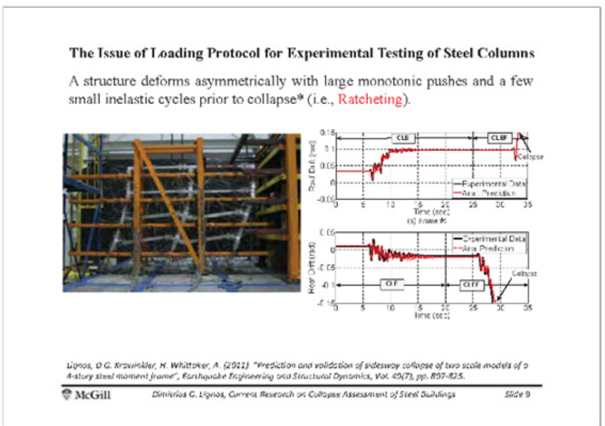


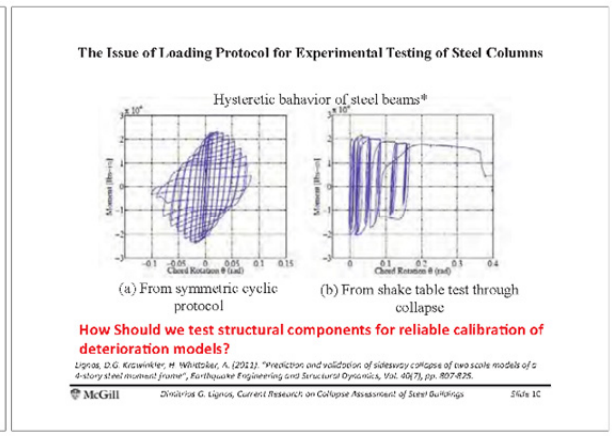


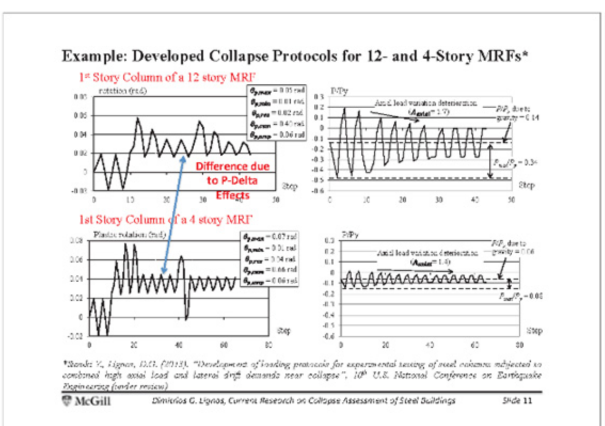


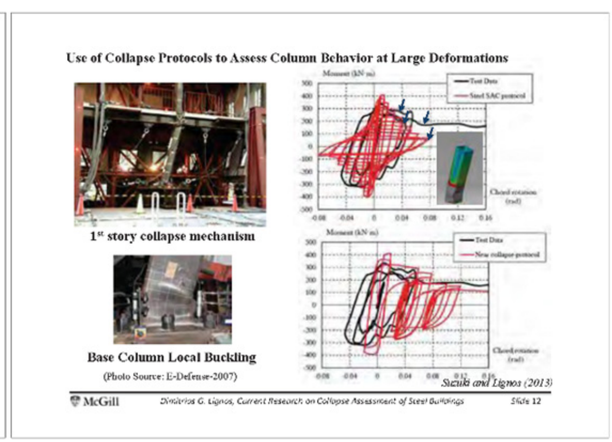
Developed by	Cyclic hard.	Bausch. effect	Strength cap.	Residual str.	Cyclic det.				P-M int.
					Basic Str.	Post-cap. Str.	Unload. Stiff	Accel. Stiff	
Takeda et al. (1970)	[X]	[X]	[X]	[X]	[X]	[X]	○	○	[X]
Ramberg-Osgood (1943)	○	○	[X]	[X]	○	[X]	○	[X]	[X]
Sivaselvan & Reinhorn (2000)	○	○	[X]	[X]	○	[X]	○	[X]	[X]
Ibarra et al. (2005)	[X]	[X]	○	○	○	○	○	○	[X]
Lignos and Krawinkler (2011)	[X]	[X]	○	○	○	○	○	○	[X]
Yamada et al. (2012)	[X]	[X]	○	○	○	○	○	○	[X]



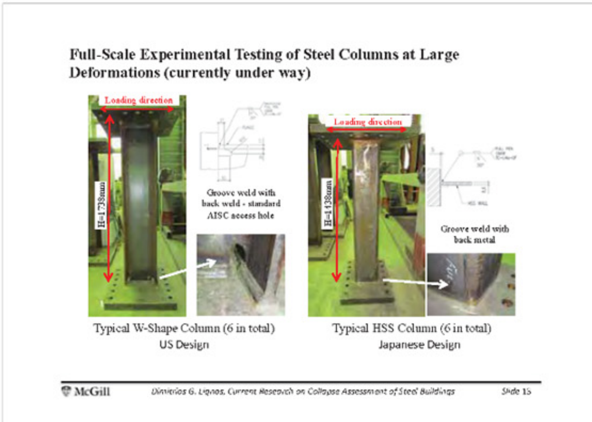


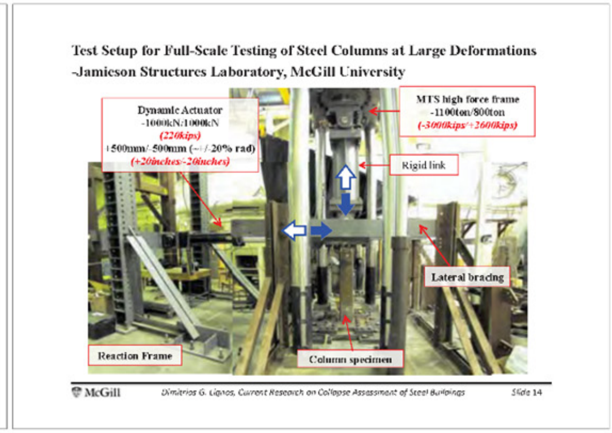


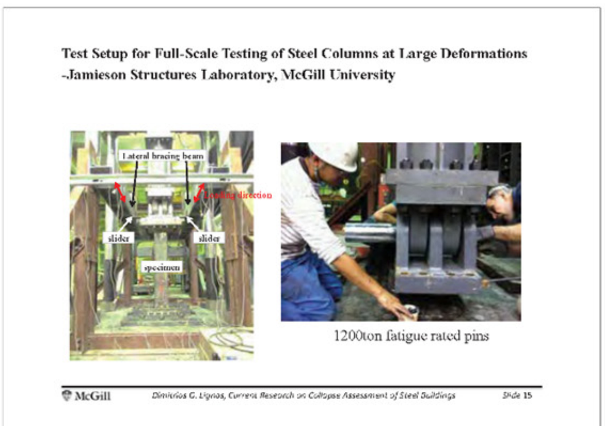


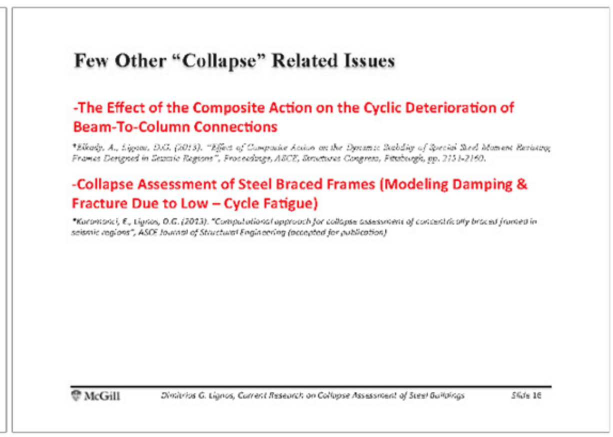


Appendix VIII









Self-Centering Steel Frame Systems

James Ricles, Richard Sause, Ying-Cheng Lin, Choung-Yeol Seo, David Roke, Brent Chancellor, Ebrahim Tahmasebi and Omid Ahmadi
Lehigh University

Judy Liu and Hoseok Chi
Purdue University

Maria Garlock, Erik VanMarcke, Gordana Herning, and Jie Li
Princeton University

NEES/E-Defense Collab. EQ Research Program 10th Planning Meeting
December 11 -13 DPRI, Kyoto University

Introduction: Conventional Earthquake Design Practice in United States

- Design for "Life Safety" (LS) for "Design Basis Earthquake" (DBE) with ~500yr return period (10% in 50 years).
- We expect (but do not explicitly design for):
  - "Immediate Occupancy" (IO) for "Frequently Occurring Earthquake" (FOE) with ~80yr return period.
  - "Collapse Prevention" (CP) for the "Maximum Considered Earthquake" (MCE) with ~2500yr return period.
- Results:
  - Expect modest to serious damage to buildings from earthquake ground motions with short return periods (~100yr to ~500yr).
  - Costs to repair damage or to replace a damaged building can be significant.

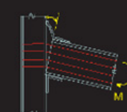
Example: Expected Damage for Conventional Steel Moment Resisting Frame after DBE (~500yr return period)

Reduced beam section steel moment-resisting frame subassembly at 3% rad (0.03 rad) lateral drift

- Damage leads to residual lateral drift.
- Building repair (or replacement) costs can be significant life-cycle costs

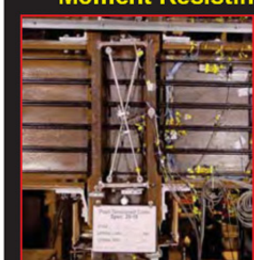
Self Centering (SC) Earthquake-Resistant Structural Systems

Goal: eliminate structural damage for ground motions with return periods up to ~500yr.



- Discrete structural members are post-tensioned (PT) to pre-compress joints.
- Gap opening at joints provides softening of lateral force-drift behavior without damage to members.
- PT forces close joints and permanent lateral drift is avoided (Self Centering).

Early Work on Self-Centering (SC) Steel Moment Resisting Frames (1997-2008)



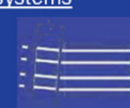
Garlock, Ricles, Sause (2008) Engineering Structures
Garlock, Sause, Ricles (2007) ASCE Journal of Structural Engineering
Rojas, Ricles, Sause (2005) ASCE Journal of Structural Engineering
Garlock, Ricles, Sause (2005) ASCE Journal of Structural Engineering
Ricles, Sause, Peng, Lu (2002) ASCE Journal of Structural Engineering
Ricles, Sause, Garlock, Zhao (2001) ASCE Journal of Structural Engineering
Ricles, Garlock, Sause, Lu (1997) SSRC Annual Meeting Proceedings

Steel SC moment resisting frame (MRF) subassembly at 3% rad drift

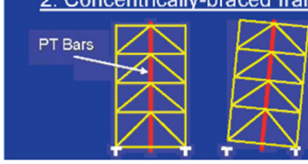
Little damage with potential for Immediate Occupancy (IO) under DBE

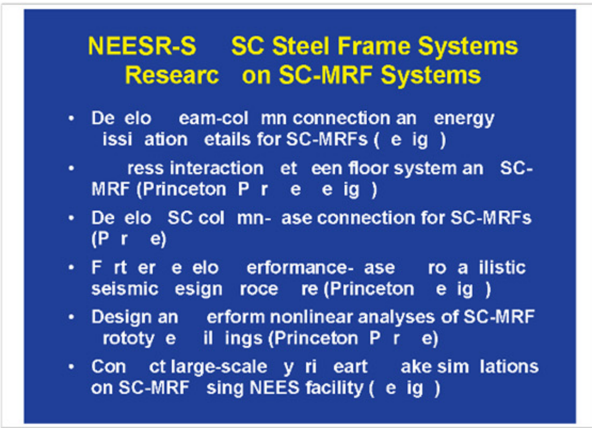
SC Damage-Free Steel Frame Systems Project (NEESR 2004-2010)

1. Moment-resisting frame (SC-MRF) systems

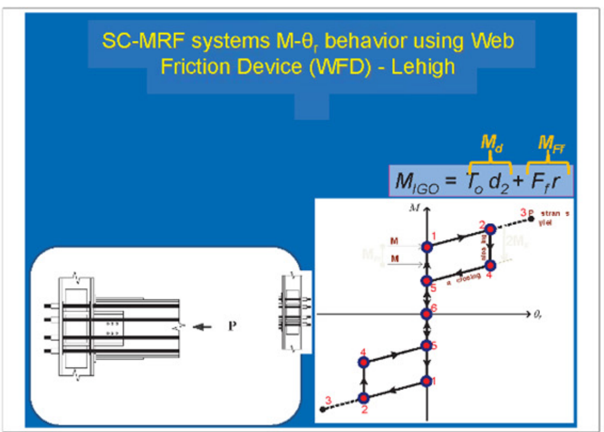


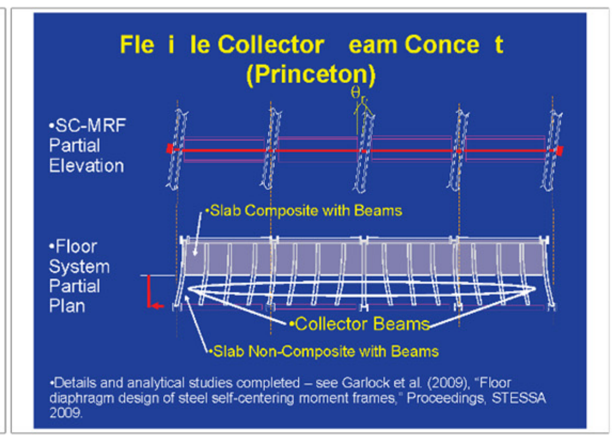
2. Concentrically-braced frame (SC-CBF) systems

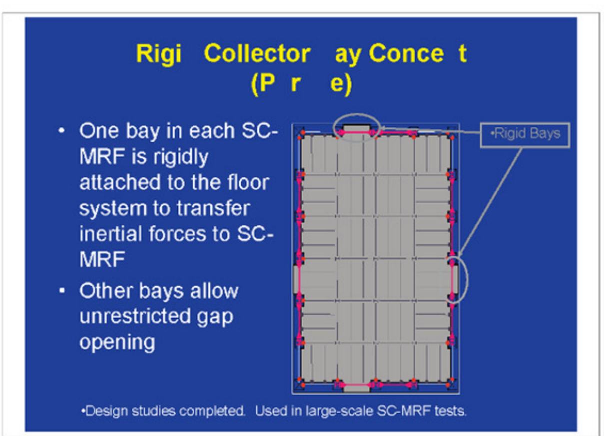


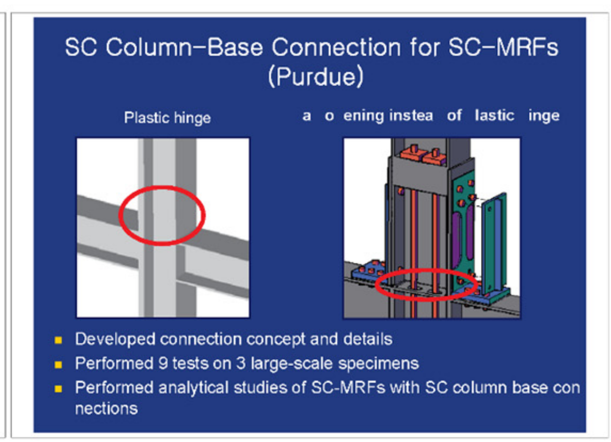

NEESR-S SC Steel Frame Systems
Researc on SC-MRF Systems
De elo eam-col mn connection an energy issi ation etails for SC-MRFs (e ig)
ress interaction et een floor system an SC-MRF (Princeton P r e e ig)
De elo SC col mn- ase connection for SC-MRFs (P r e)
F rt er e elo erformance- ase ro a ilistic seismic esign roce re (Princeton e ig)
Design an erform nonlinear analyses of SC-MRF rototy e il ings (Princeton P r e)
Con ct large-scale y ri eart ake sim lations on SC-MRF sing NEES facility (e ig)

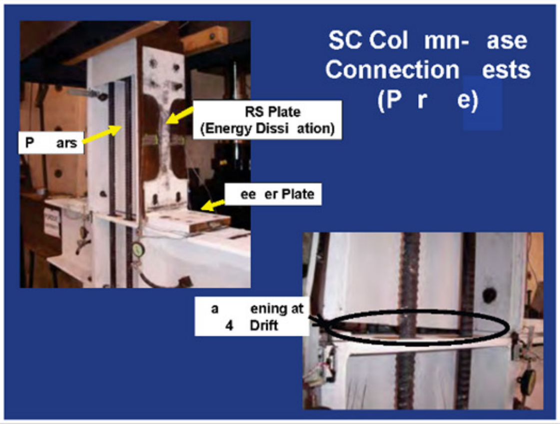

SC Damage-Free Steel Frame Systems
Project SC-MRFs

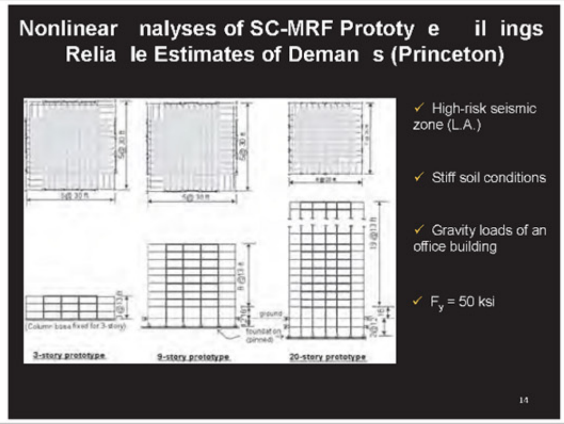

SC-MRF systems M-θr behavior using Web Friction Device (WFD) - Lehigh
M_d
M_{Ff}
$M_{IGO} = T_o d_2 + F_f r$
P

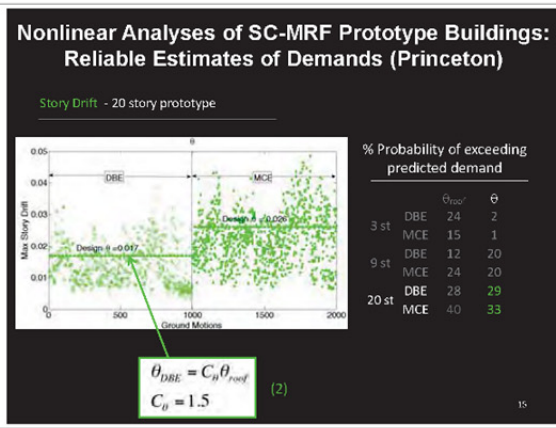

Fle i le Collector eam Conce t
(Princeton)
θr
•SC-MRF Partial Elevation
•Slab Composite with Beams
•Floor System Partial Plan
•Collector Beams
•Slab Non-Composite with Beams
•Details and analytical studies completed – see Garlock et al. (2009), "Floor diaphragm design of steel self-centering moment frames," Proceedings, STESSA 2009.

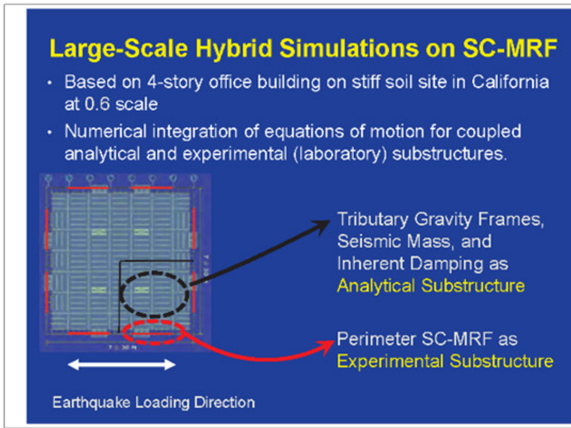

Rigi Collector ay Conce t
(P r e)
One bay in each SC-MRF is rigidly attached to the floor system to transfer inertial forces to SC-MRF
Other bays allow unrestricted gap opening
•Rigid Bays
•Design studies completed. Used in large-scale SC-MRF tests.

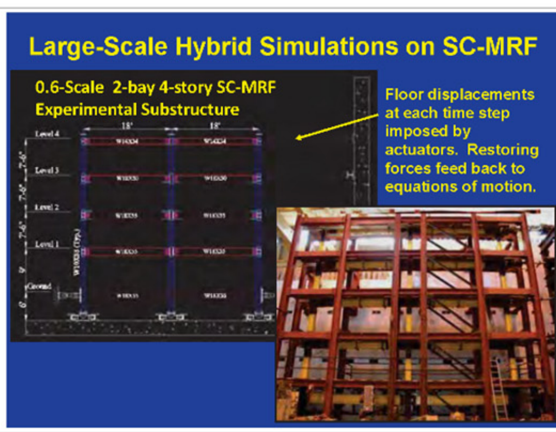

SC Column–Base Connection for SC–MRFs
(Purdue)
Plastic hinge
a o ening instea of lastic inge
Developed connection concept and details
Performed 9 tests on 3 large-scale specimens
Performed analytical studies of SC-MRFs with SC column base con nections

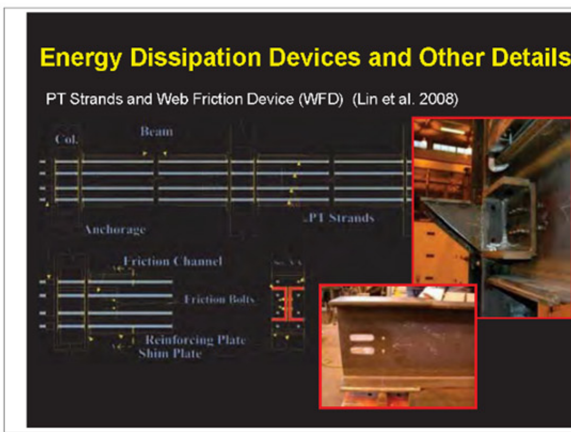

SC Col mn- ase
Connection ests
(P r e)
RS Plate
(Energy Dissi ation)
P ars
ee er Plate
a ening at
4 Drift


Nonlinear nalyses of SC-MRF Prototy e il ings
Relia le Estimates of Deman s (Princeton)
✓ High-risk seismic zone (L.A.)
✓ Stiff soil conditions
✓ Gravity loads of an office building
✓ F_y = 50 ksi
3-story prototype
9-story prototype
20-story prototype
14

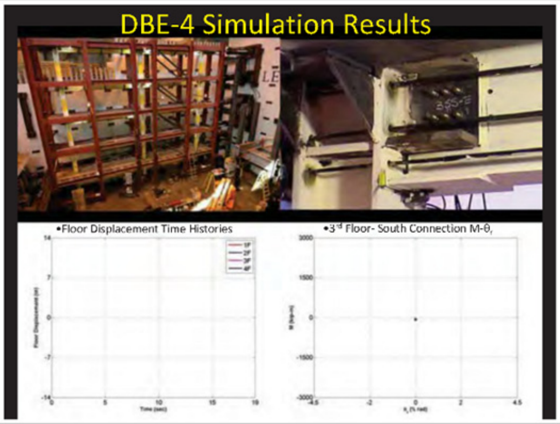

Nonlinear Analyses of SC-MRF Prototype Buildings:
Reliable Estimates of Demands (Princeton)
Story Drift - 20 story prototype
DBE
MCE
Max Story Drift
Ground Motions
% Probability of exceeding predicted demand
θ_{roof} θ
3 st DBE 24 2
MCE 15 1
9 st DBE 12 20
MCE 24 20
20 st DBE 28 29
MCE 40 33
$\theta_{DBE} = C_\theta \theta_{roof}$
$C_\theta = 1.5$
(2)
15

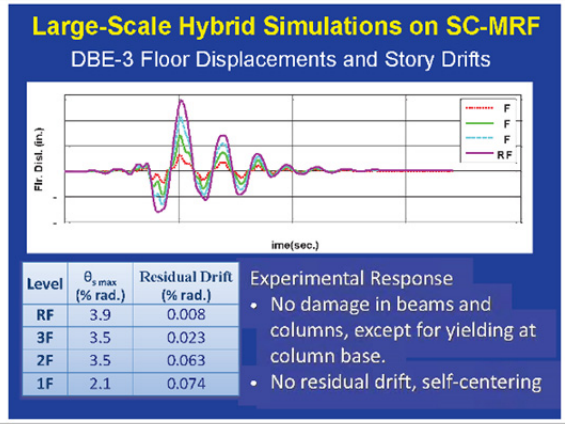

Large-Scale Hybrid Simulations on SC-MRF
• Based on 4-story office building on stiff soil site in California at 0.6 scale
• Numerical integration of equations of motion for coupled analytical and experimental (laboratory) substructures.
Tributary Gravity Frames, Seismic Mass, and Inherent Damping as Analytical Substructure
Perimeter SC-MRF as Experimental Substructure
Earthquake Loading Direction

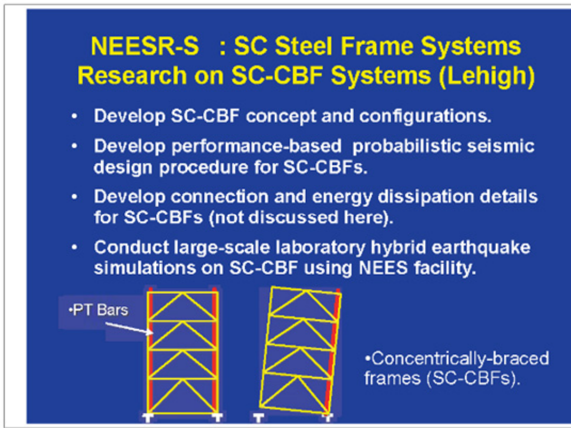

Large-Scale Hybrid Simulations on SC-MRF
0.6-Scale 2-bay 4-story SC-MRF
Experimental Substructure
Floor displacements at each time step imposed by actuators. Restoring forces feed back to equations of motion.

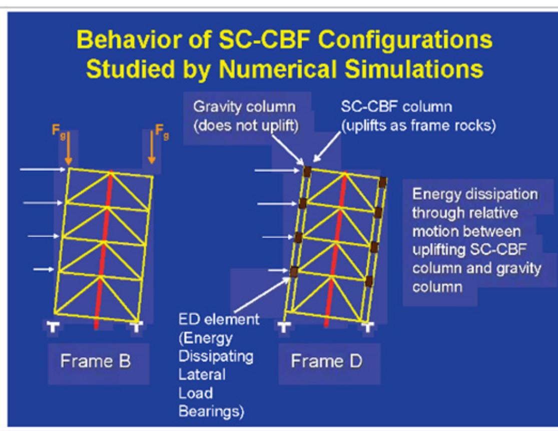

Energy Dissipation Devices and Other Details
PT Strands and Web Friction Device (WFD) (Lin et al. 2008)
Col.
Beam
Anchorage
PT Strands
Friction Channel
Friction Bolts
Reinforcing Plate
Shim Plate

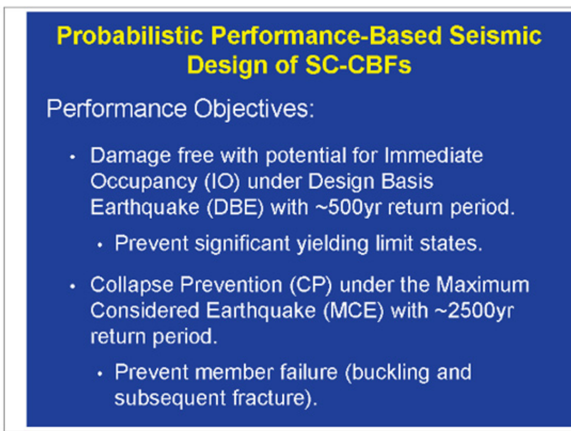
Appendix VIII

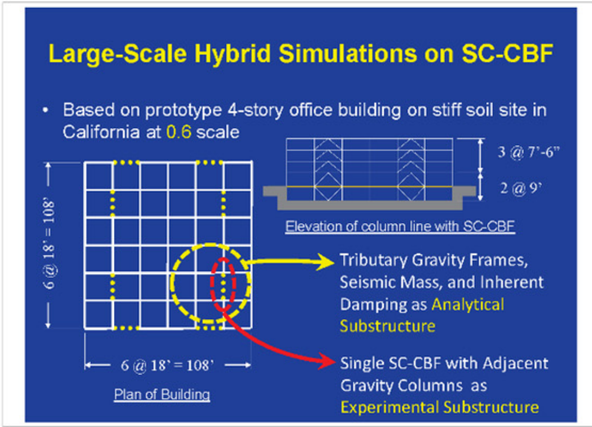


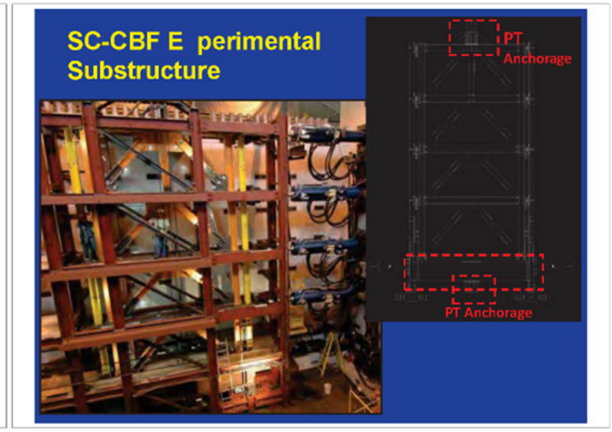




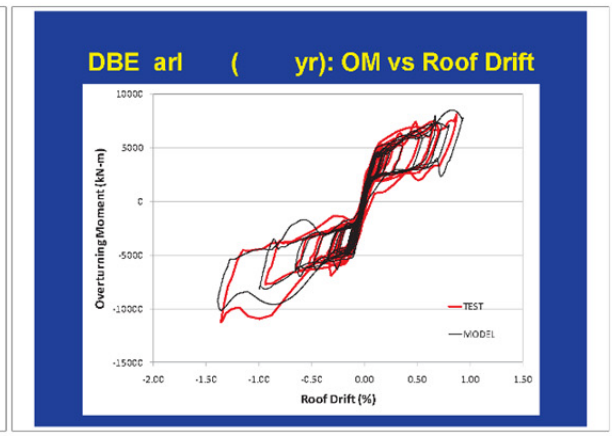





Large-Scale Hybrid Simulations on SC-CBF
• Based on prototype 4-story office building on stiff soil site in California at 0.6 scale
3 @ 7'-6"
2 @ 9'
Elevation of column line with SC-CBF
6 @ 18' = 108'
Tributary Gravity Frames, Seismic Mass, and Inherent Damping as Analytical Substructure
6 @ 18' = 108'
Plan of Building
Single SC-CBF with Adjacent Gravity Columns as Experimental Substructure


SC-CBF E perimental Substructure
PT Anchorage
PT Anchorage

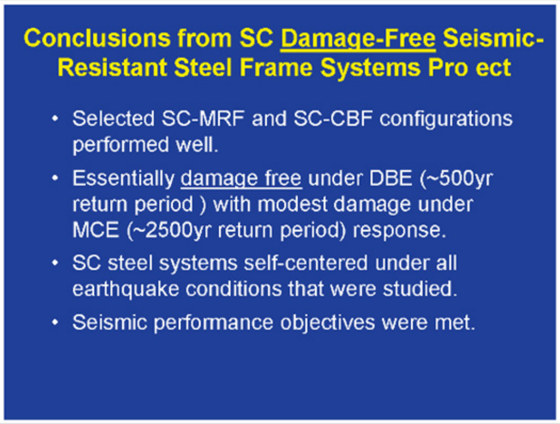

Simulation: DBE arl (yr)
LEHIGH

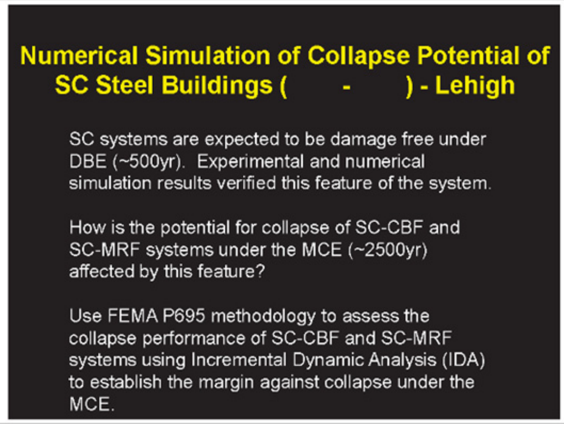

DBE arl (yr): OM vs Roof Drift
Overturning Moment (kN-m)
Roof Drift (%)
TEST
MODEL

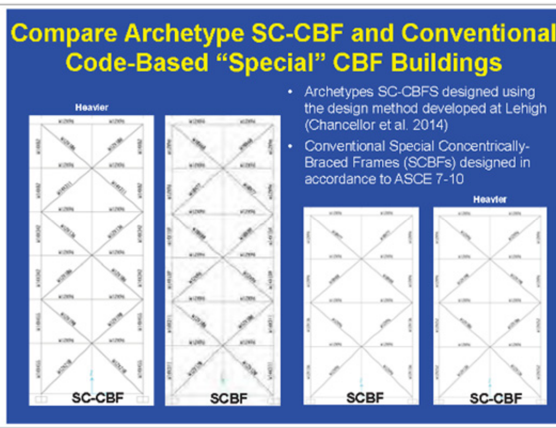

Simulation: e -MCE tak (yr)
LEHIGH

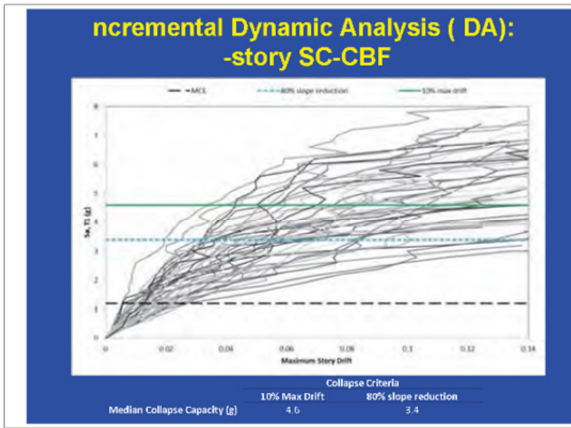

SC-CBF after DBE-Level and MCE-Level Hybrid Simulations
No damage to structural members or connections

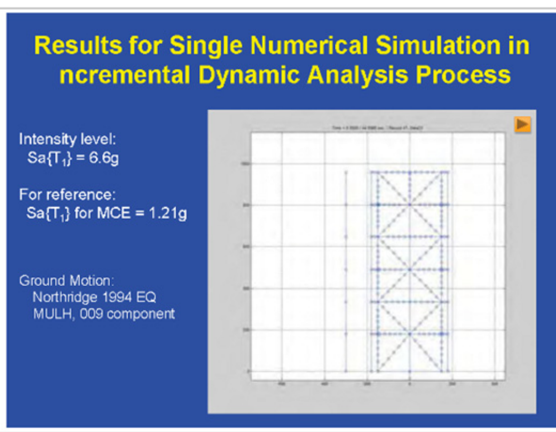
Appendix VIII

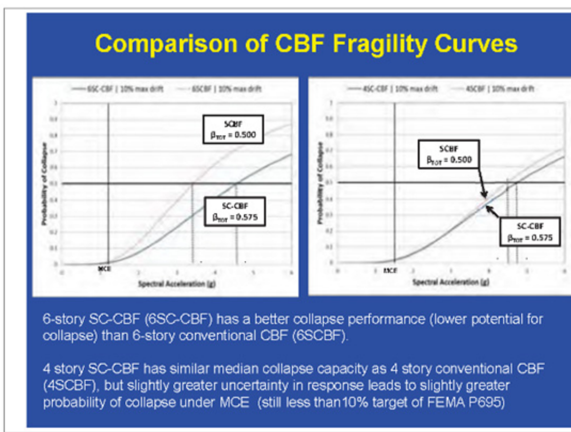


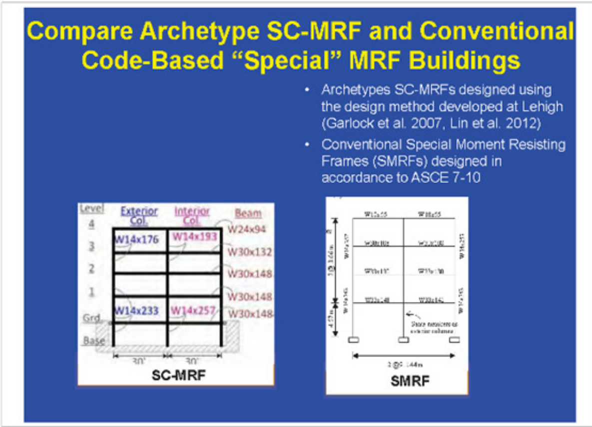


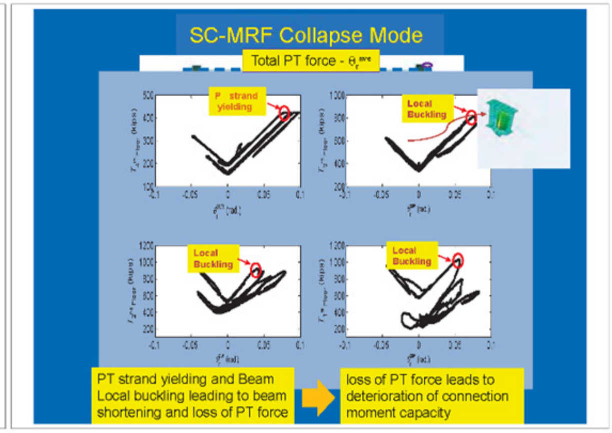


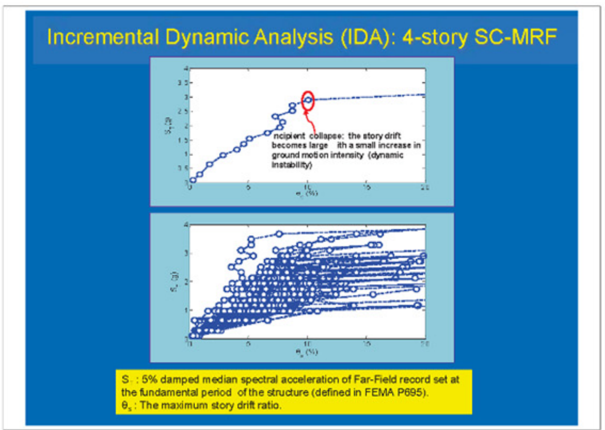


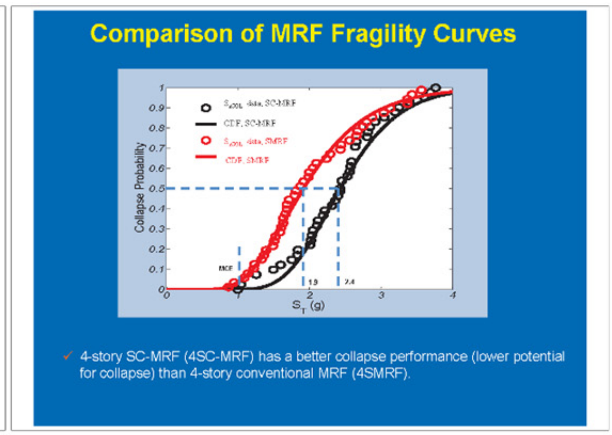












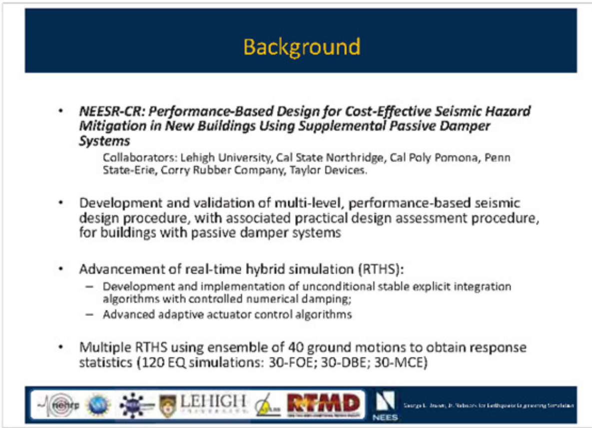
Findings from Simulation of Collapse Potential of SC Steel Buildings

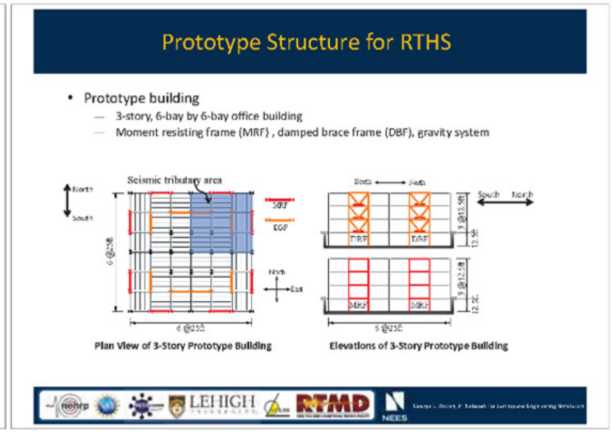
- Study is ongoing, so only preliminary results.
- Collapse performance of SC steel buildings (according to FEMA P695 methodology) appears to be better than that of conventional steel buildings (concentrically-braced frame (CBF) and special moment resisting frame buildings) based on median collapse capacity

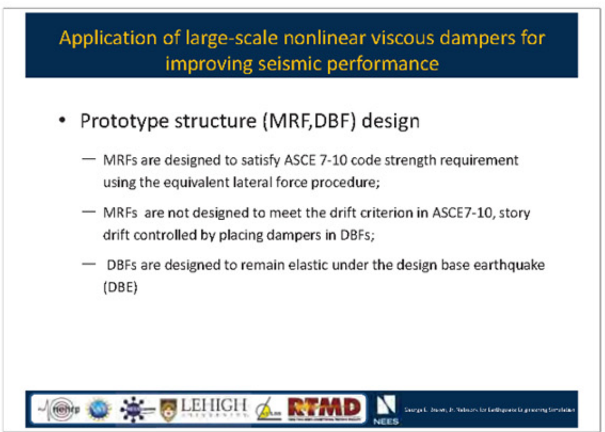
Real-time Hybrid Simulation and Seismic Performance Evaluation of a Large-scale Steel Structure with Nonlinear Viscous Dampers

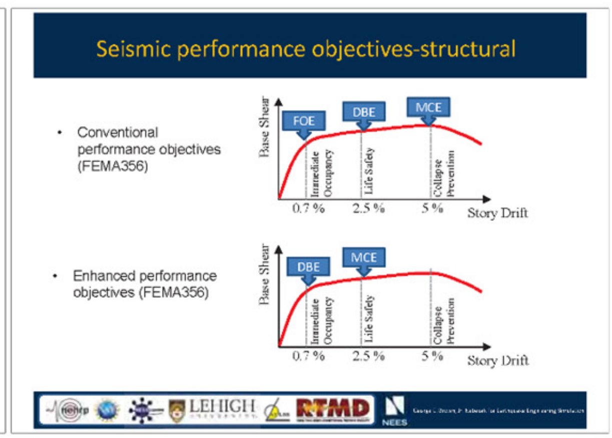
James M. Ricles, Richard Sause
Yunbyeong Chae, Baiping Dong,
Akbar Mahvashmohamamdi, Chinmoy Kolay
Lehigh University

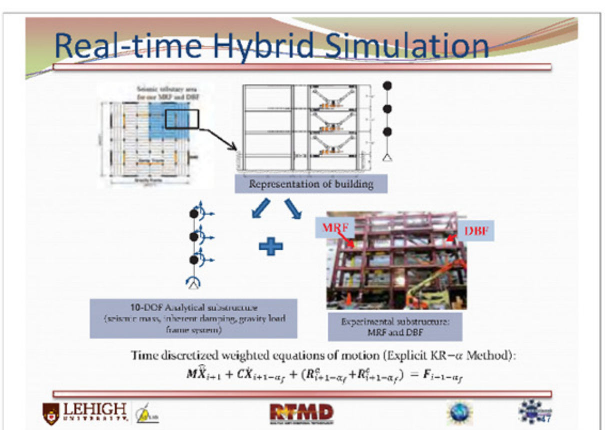
Appendix VIII

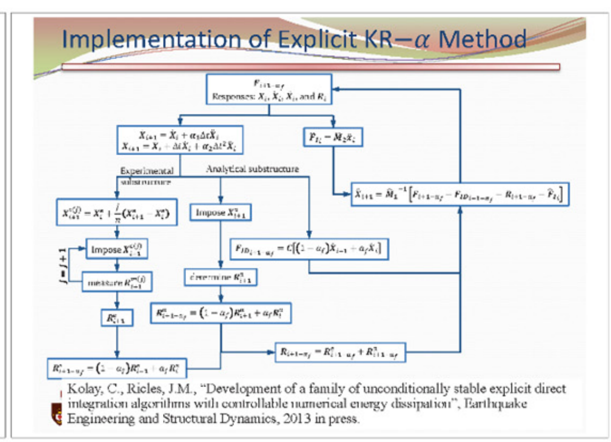


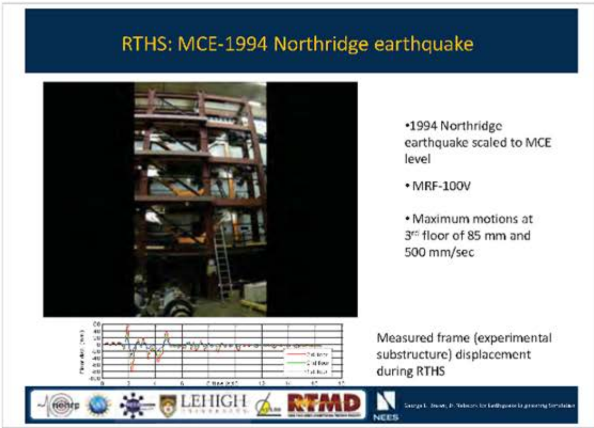


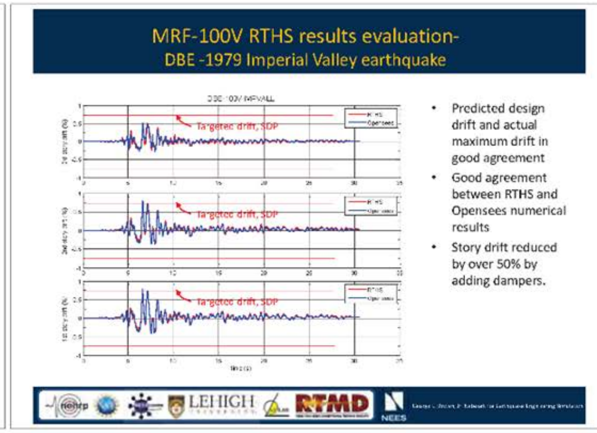


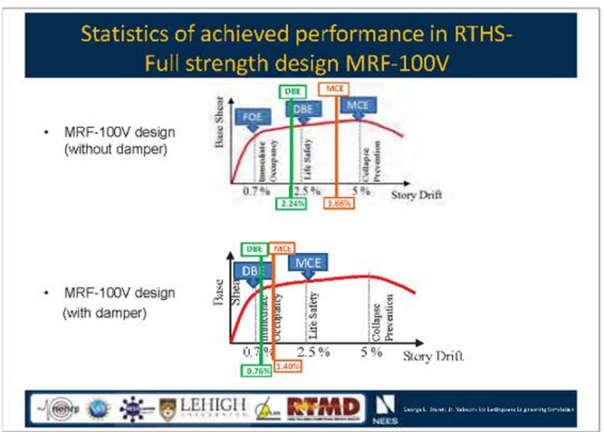


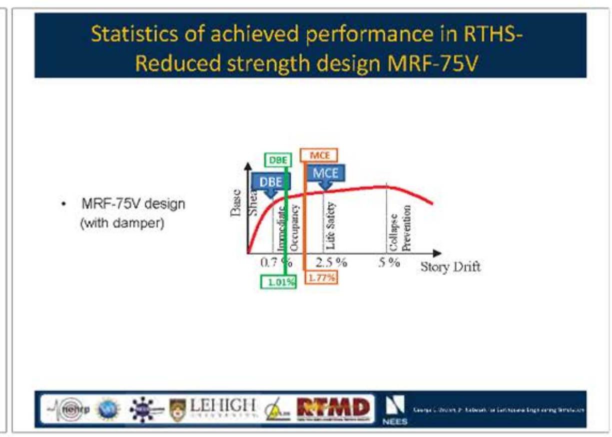


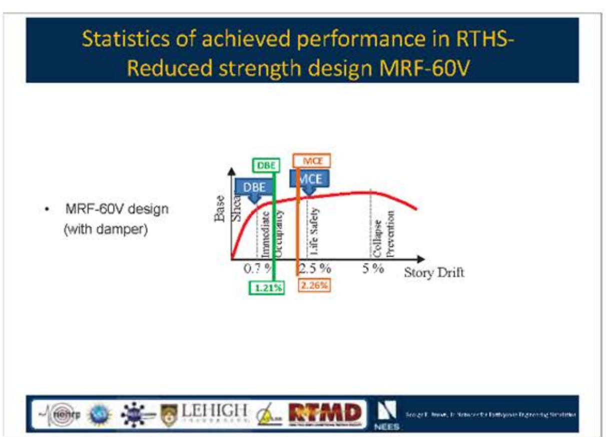



RTHS: MCE-1994 Northridge earthquake
•1994 Northridge earthquake scaled to MCE level
• MRF-100V
• Maximum motions at 3rd floor of 85 mm and 500 mm/sec
Measured frame (experimental substructure) displacement during RTHS
LEHIGH
RTMD
NEES


MRF-100V RTHS results evaluation-
DBE -1979 Imperial Valley earthquake
Targeted drift, SDP
Predicted design drift and actual maximum drift in good agreement
Good agreement between RTHS and Opensees numerical results
Story drift reduced by over 50% by adding dampers.
LEHIGH
RTMD
NEES

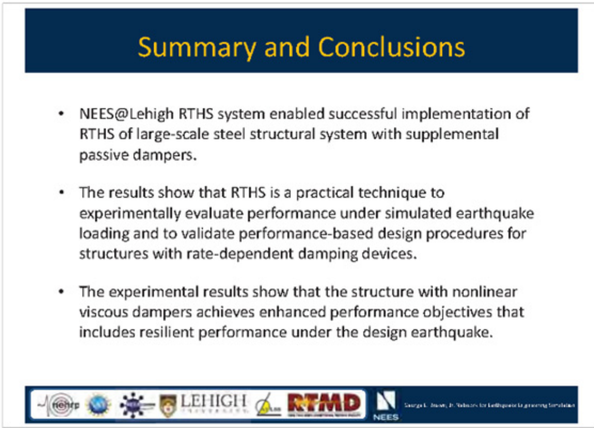

Statistics of achieved performance in RTHS-
Full strength design MRF-100V
MRF-100V design (without damper)
FOE
DBE
MCE
Base Shear
Immediate Occupancy
Life Safety
Collapse Prevention
0.7%
2.5%
5%
Story Drift
2.24%
3.86%
MRF-100V design (with damper)
0.76%
1.40%
LEHIGH
RTMD
NEES

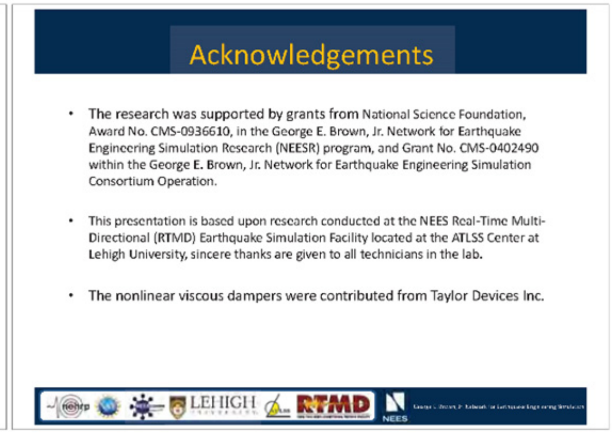

Statistics of achieved performance in RTHS-
Reduced strength design MRF-75V
MRF-75V design (with damper)
DBE
MCE
Base Shear
Immediate Occupancy
Life Safety
Collapse Prevention
0.7%
2.5%
5%
Story Drift
1.01%
1.77%
LEHIGH
RTMD
NEES


Statistics of achieved performance in RTHS-
Reduced strength design MRF-60V
MRF-60V design (with damper)
DBE
MCE
Base Shear
Immediate Occupancy
Life Safety
Collapse Prevention
0.7%
2.5%
5%
Story Drift
1.21%
2.26%
LEHIGH
RTMD
NEES


MCE Level RTHS
1979 Imperial Valley EQ, H-BRA315 Component
Experimental substructure (MRF+DBF)
LEHIGH
RTMD
NEES

Appendix VIII





Deformation Capacity of Beam-Columns

Atsushi SATO
(Nagoya Institute of Technology)

Introduction

【Column Design】
- Strength
- Stability
- Deformation Capacity

【Specifications】
- Plastic Design
  (2010, 1975)
- Limit State Design (LRFD)
  (2010, 1998)

Plastic Design

【Limitations】

[1] Slenderness ratio λ equal or less than 200.

[2] Slenderness ratio and Axial force limitation

i) $N/N_y < 0.15 \quad \lambda \leq 150$

ii) $N/N_y \geq 0.15$

400N Grade $\dfrac{N}{N_y} + \dfrac{\lambda}{120} \leq 1.0$

490N Grade $\dfrac{N}{N_y} + \dfrac{\lambda}{100} \leq 1.0$ → "High Deformability"

Limitation by Ray

$$\frac{N}{N_y} \leq \frac{1 + \frac{M_2}{M_1} - \lambda_o}{1 + \frac{M_2}{M_1} + \lambda_o}$$

N: Axial Force, N_y: Yield Strength, $\lambda = K \cdot (l/i)$, l: Column Length

Limit State Design

【Limitations】

[1] Normalized slenderness ratio λ_c equal or less than 2.0.

[2] Slenderness ratio ${}_f\lambda_c$ and Axial force n_y limitation

$n_y \cdot {}_f\lambda_c^2 \leq 0.25$

[3] Maximum Axial Force and Maximum Slenderness ratio

$n_y = N/N_y \leq 0.75$

$\lambda_b \leq 0.75 {}_p\lambda_b$

[4] Additionaly, Column form plastic hinge.

$-0.5 < M_2/M_1 \leq 1.0 \qquad n_y \cdot \lambda_c^2 \leq 0.10(1 + M_2/M_1)$

$-1.0 \leq M_2/M_1 \leq -0.5 \qquad n_y \cdot \lambda_c^2 \leq 0.05$

"Deformation Capacity $R = 3 \sim 5$ $(= \theta_u/\theta_{pN} - 1)$"

${}_f\lambda_c$: Normalized Slenderness by Buckling Length ($K \cdot l_c$)
λ_c: Normalized Slenderness by Column Length

Maximum Moment in the Column

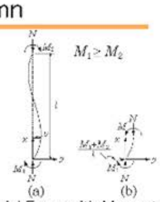
【Equilibrium】

$$EI\frac{d^2v}{dx^2} + Nv - \frac{M_1 + M_2}{l}x + M_1 = 0$$

defromation v

$$v = -\frac{M_1 \cdot \cos\left(\pi\sqrt{\frac{N}{N_E}}\right) + M_2}{EI\frac{\pi^2}{l^2}\frac{N}{N_E}\sin\left(\pi\sqrt{\frac{N}{N_E}}\right)}\sin\left(\frac{\pi}{l}\sqrt{\frac{N}{N_E}}x\right) + \frac{M_1}{EI\frac{\pi^2}{l^2}\frac{N}{N_E}}\cos\left(\frac{\pi}{l}\sqrt{\frac{N}{N_E}}x\right) + \frac{M_1 - M_2}{EI\frac{\pi^2}{l}\frac{N}{N_E}}x - \frac{M_1}{EI\frac{\pi^2}{l^2}\frac{N}{N_E}}$$

$M_1 > M_2$



Axial Force with Moment

where, N_E: Eular Buckling Strength by Column Length (l).

$$N_E = \frac{\pi^2 EI}{l^2}$$

Maximum Moment in the Column

Moment in the Column Member M

$$M = -\frac{M_1 \cdot \cos\left(\pi\sqrt{\frac{N}{N_E}}\right) + M_2}{\sin\left(\pi\sqrt{\frac{N}{N_E}}\right)}\sin\left(\frac{\pi}{l}\sqrt{\frac{N}{N_E}}x\right) + M_1 \cdot \cos\left(\frac{\pi}{l}\sqrt{\frac{N}{N_E}}x\right)$$

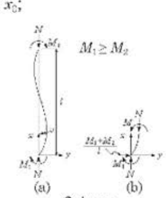
$dM/dx = 0$, Location of Maximum Moment x_0;

$$\tan\left(\frac{\pi}{l}\sqrt{\frac{N}{N_E}}x_0\right) = -\frac{M_1 \cdot \cos\left(\pi\sqrt{\frac{N}{N_E}}\right) + M_2}{M_1 \cdot \sin\left(\pi\sqrt{\frac{N}{N_E}}\right)}$$

Maximum Moment at the End,

$$\frac{M_2}{M_1} \geq -\cos\left(\pi\sqrt{\frac{N}{N_E}}\right)$$

$M_1 \geq M_2$



Column

Maximum Moment at the Column

$$\cos\left(\pi\sqrt{\frac{N}{N_E}}\right) \cong 1 - \frac{\pi^2}{2}\frac{N}{N_E} \cong 1 - 4\frac{N}{N_E} = 1 - 4n_y \cdot \lambda_c^2$$

where,

$$N_E = \frac{\pi^2 EI}{l^2} \qquad \lambda_c = \sqrt{\frac{\sigma_y}{\pi^2 E}}\left(\frac{l}{i}\right) \qquad n_y = \frac{N}{N_y}$$

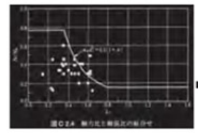
$$\frac{M_2}{M_1} \geq -\cos\left(\pi\sqrt{\frac{N}{N_E}}\right)$$ <Column End>

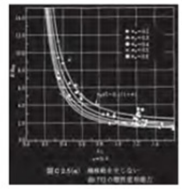
Maximum Moment at the Column End

$$n_y \cdot \lambda_c^2 \leq 0.25\left(1 - \frac{M_2}{M_1}\right)$$

2013.12.12 Steel Group

LSD Limitation





$-0.5 < M_2/M_1 \leq 1.0$

$$n_y \cdot \lambda_c^2 \leq 0.10\left(1 + \frac{M_2}{M_1}\right)$$

→ Full Plastic Moment considering Axial Force M_{pc}.

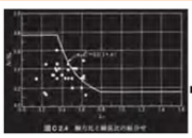
→ Deformation Capacity $R=3 \sim 5(=\theta_u/\theta_{pc}\text{-}1)$

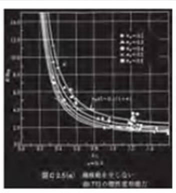
Maximum Moment will be at the Column End

$$n_y \cdot \lambda_c^2 \leq 0.25\left(1 + \frac{M_2}{M_1}\right)$$

2013.12.12 Steel Group

LSD Limitation





$-0.5 < M_2/M_1 \leq 1.0$

$$n_y \cdot \lambda_c^2 \leq 0.10\left(1 + \frac{M_2}{M_1}\right)$$

→ 最大曲げ耐力が軸力を考慮した全塑性モーメント M_{pc} に達する.

→ 塑性変形能力 $R=3 \sim 5(=\theta_u/\theta_{pc}\text{-}1)$ 程度を確保する.

※ Test Result from H section → Lateral Torsional Buckling

部材端に最大曲げモーメントが生じる条件式

$$n_y \cdot \lambda_c^2 \leq 0.25\left(1 + \frac{M_2}{M_1}\right)$$

2013.12.12 Steel Group

Numerical Analysis

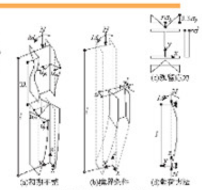
【Local Buckling】

$$u_{x0} = x + \frac{2d_f}{\pi B}\sin\left(\frac{\pi y}{d_f}\right)\left\{\frac{3 \cdot 3\lambda}{4000}\sin\left(\frac{\pi z}{3\lambda}\right) - \frac{3\lambda}{4000}\sin\left(\frac{3\pi z}{3\lambda}\right)\right\}$$

$$u_{y0} = y + \frac{2x}{B}\left\{\frac{3 \cdot 3\lambda}{4000}\sin\left(\frac{\pi z}{3\lambda}\right) - \frac{3\lambda}{4000}\sin\left(\frac{3\pi z}{3\lambda}\right)\right\}$$

$$\lambda = (2bA_f + dA_w)$$

where, b: flange width, d: web height, A_f: flange Area, A_w: web area



解析モデル設定の条件

【Lateral Tortional Buckling】

$$u_{x0} = x + \frac{y}{d_f}\left\{\frac{l}{1000}\sin\left(\frac{\pi z}{l}\right)\right\}$$

$$u_{y0} = y - \frac{x}{d_f}\left\{\frac{l}{1000}\sin\left(\frac{\pi z}{l}\right)\right\}$$

where, $df=H\text{-}t_f$, H: beam height, t_f: flange thickness

2013.12.12 Steel Group

Numerical Analysis

【Boundary】

材端では，材軸の回転とフランジの反りを拘束する.

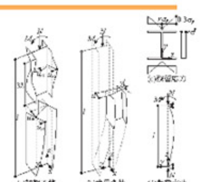
$$u|_{z=0} = u|_{z=l} = \frac{d^2u}{dz^2}\Big|_{z=0} = \frac{d^2u}{dz^2}\Big|_{z=l} = 0$$

$$\gamma|_{z=0} = \gamma_{z=l} = \frac{d\gamma}{dz}\Big|_{z=0} = \frac{d\gamma}{dz}\Big|_{z=l} = 0$$

【Residual Stress】

フランジ端で $0.3\sigma_y$ の圧縮応力度を設定

ウェブは断面内の応力が釣合うように設定



解析モデル設定の条件

【Loading】

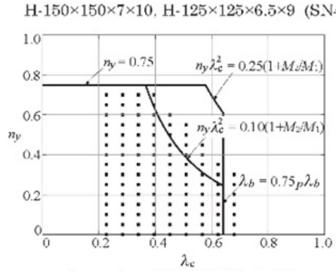
目標の軸力 N を導入した後，軸力を一定に保持した状態で材端の強軸方向に曲げモーメント M を載荷する.

2013.12.12 Steel Group

Parameter

【断面形状】

H-150×150×7×10, H-125×125×6.5×9 (SN400B)



Parameters (H-150×150×7×10)

【Axial Force】

n_y: 0.0 ～ 0.70

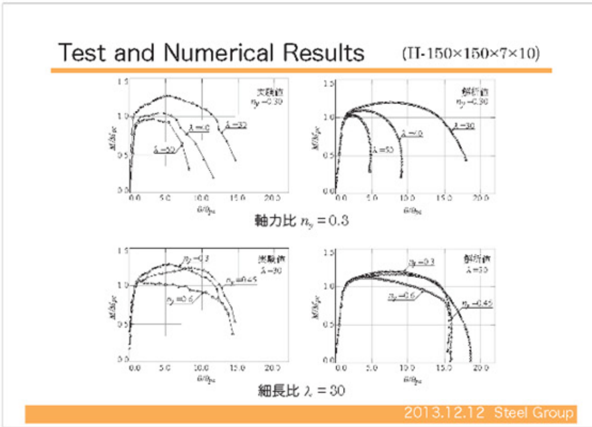
【Slenderness】

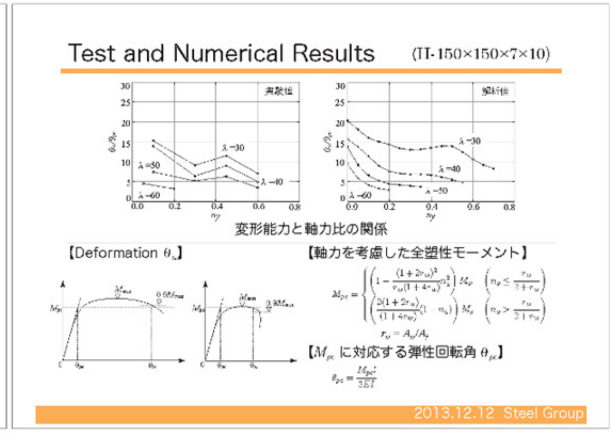
λ: 20 ～ 60 $\quad \lambda_c = \sqrt{\frac{\sigma_y}{\pi^2 E}}\left(\frac{l}{i}\right)$

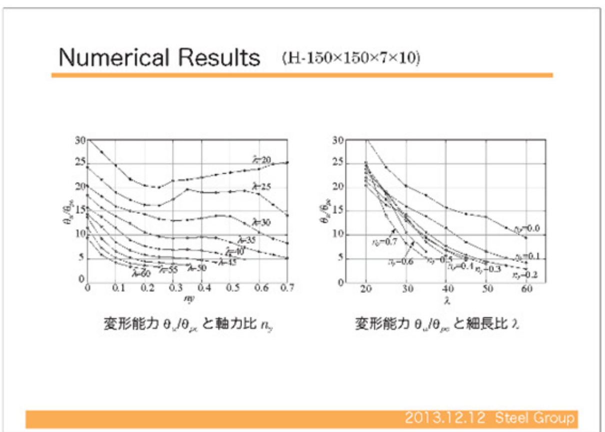
【Cases】

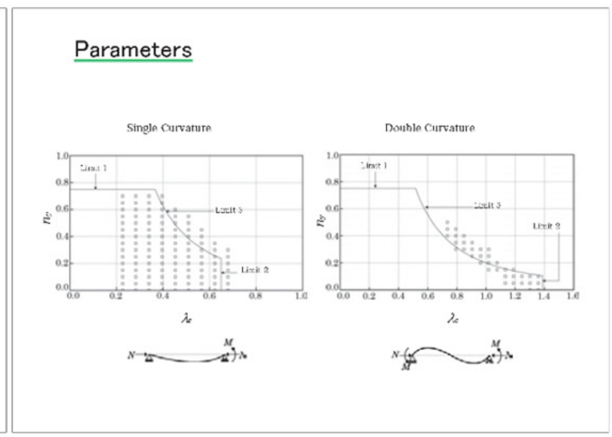
計 110

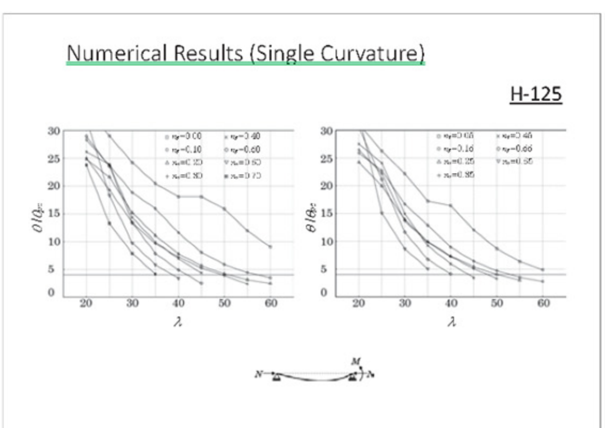
2013.12.12 Steel Group

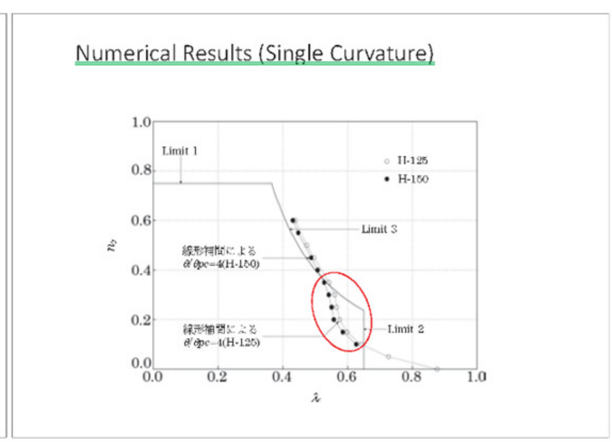

Test and Numerical Results
(H-150×150×7×10)
軸力比 n_y = 0.3
細長比 λ = 30
2013.12.12 Steel Group


Test and Numerical Results
(H-150×150×7×10)
変形能力と軸力比の関係
【Deformation θ_u】
【軸力を考慮した全塑性モーメント】
【M_{pc} に対応する弾性回転角 θ_{pc}】
2013.12.12 Steel Group


Numerical Results
(H-150×150×7×10)
変形能力 θ_u/θ_{pc} と軸力比 n_y
変形能力 θ_u/θ_{pc} と細長比 λ
2013.12.12 Steel Group

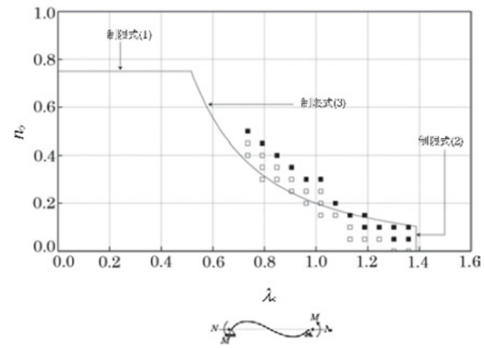

Parameters
Single Curvature
Double Curvature
Limit 1
Limit 2
Limit 3


Numerical Results (Single Curvature)
H-125

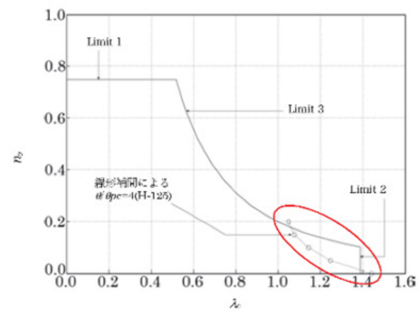

Numerical Results (Single Curvature)
Limit 1
Limit 2
Limit 3
H-125
H-150

Appendix VIII

Numerical Results (Double Curvature)



Numerical Results (Double Curvature)



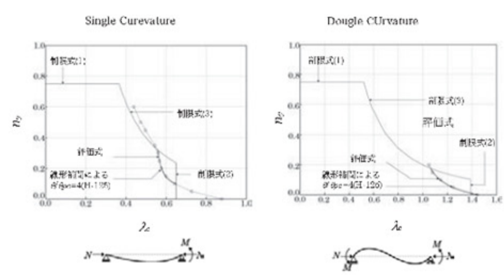
Regression Analysis

$$n_y = \frac{A}{(\lambda_c - B)^2} + C$$

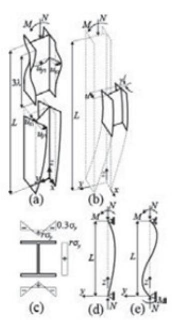
Table 1 Coefficients to specify Lateral Torsional Buckling (H-125)

	A	B	C
Single	0.008	0.453	-0.005
Double	0.025	0.723	-0.047

Results



解析概要



初期不整

横座屈

$$u_{x1} = x + \frac{y}{d_f}\left\{\frac{L}{1000}\sin\left(\frac{\pi z}{L}\right)\right\}$$

$$u_{x2} = y - \frac{x}{d_f}\left\{\frac{L}{1000}\sin\left(\frac{\pi z}{L}\right)\right\}$$

局部座屈

$$u_{x2} = x + \frac{2d_f}{\pi B}\sin\left(\frac{\pi y}{d_f}\right)\left\{\frac{3 \cdot 3\lambda}{4000}\sin\left(\frac{\pi z}{3\lambda}\right) - \frac{3\lambda}{4000}\sin\left(\frac{3\pi z}{3\lambda}\right)\right\}$$

$$u_{y2} = y + \frac{2x}{B}\left\{\frac{3 \cdot 3\lambda}{4000}\sin\left(\frac{\pi z}{3\lambda}\right) - \frac{3\lambda}{4000}\sin\left(\frac{3\pi z}{3\lambda}\right)\right\}$$

$$\lambda = (2bA_f + dA_w)/A$$

境界条件

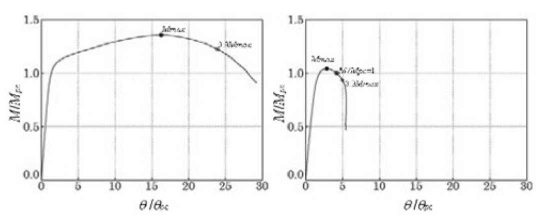
$$u|_{z=0} = u|_{z=L} = \left.\frac{d^2u}{dz^2}\right|_{z=0} = \left.\frac{d^2u}{dz^2}\right|_{z=L} = 0$$

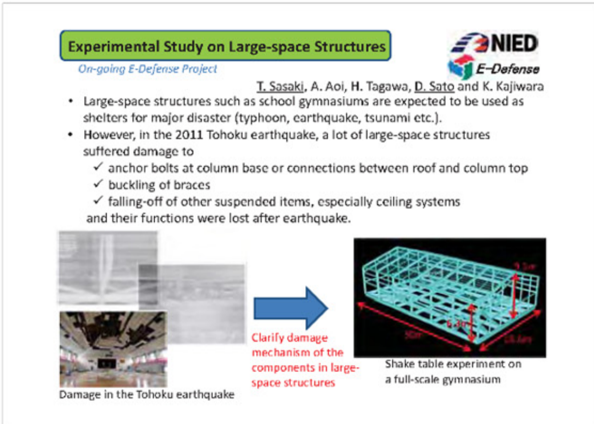
$$\gamma|_{z=0} = \gamma|_{z=L} = \left.\frac{d\gamma}{dz}\right|_{z=0} = \left.\frac{d\gamma}{dz}\right|_{z=L} = 0$$

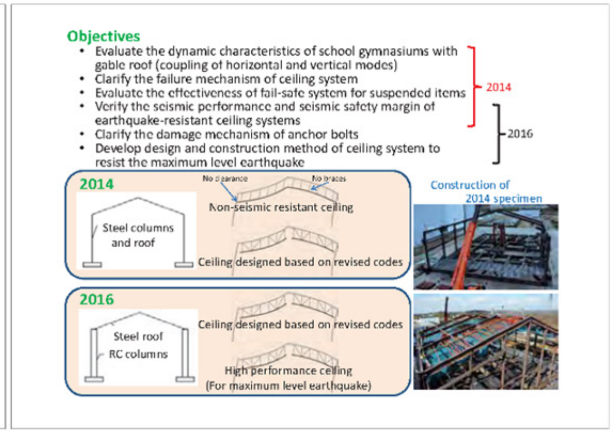
塑性変形能力評価

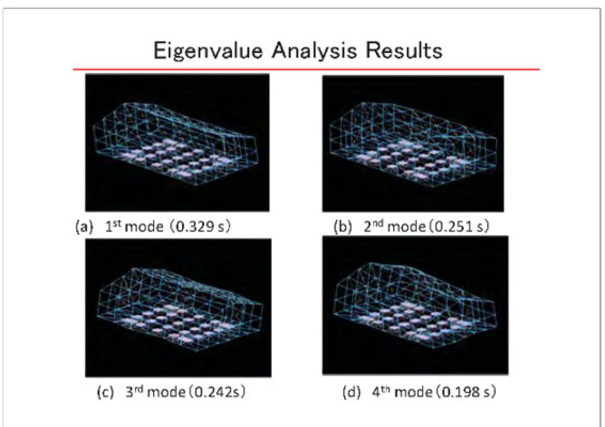
$$M_{pc} = \begin{cases} \left(1 - \frac{(1+2r_w)^2}{(1+4r_w)} n_y^2\right) M_p & \left(n_y \le \frac{r_w}{2+r_w}\right) \\ \left(\frac{2(1+2r_w)}{(1+4r_w)}(1-n_y)\right) M_p & \left(n_y > \frac{r_w}{2+r_w}\right) \end{cases}$$

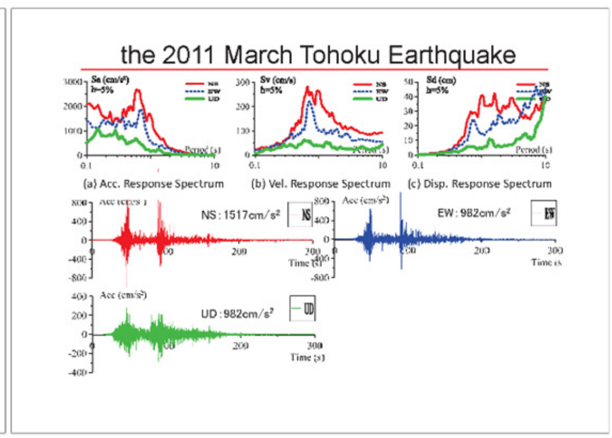
$$\theta_{pc} = \begin{cases} \frac{M_{pc}L}{3EI} & \kappa=0\text{: 片曲げ時} \\ \frac{M_{pc}L}{6EI} & \kappa=1\text{: 逆対称曲げ時} \end{cases}$$

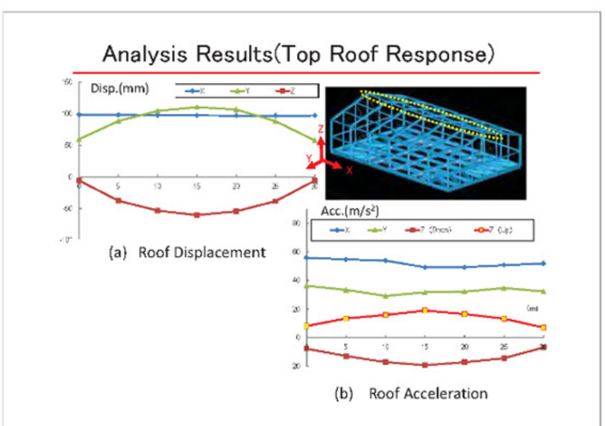



Experimental Study on Large-space Structures
On-going E-Defense Project
NIED
E-Defense
T. Sasaki, A. Aoi, H. Tagawa, D. Sato and K. Kajiwara
• Large-space structures such as school gymnasiums are expected to be used as shelters for major disaster (typhoon, earthquake, tsunami etc.).
• However, in the 2011 Tohoku earthquake, a lot of large-space structures suffered damage to
✓ anchor bolts at column base or connections between roof and column top
✓ buckling of braces
✓ falling-off of other suspended items, especially ceiling systems
and their functions were lost after earthquake.
Clarify damage mechanism of the components in large-space structures
Shake table experiment on a full-scale gymnasium
Damage in the Tohoku earthquake

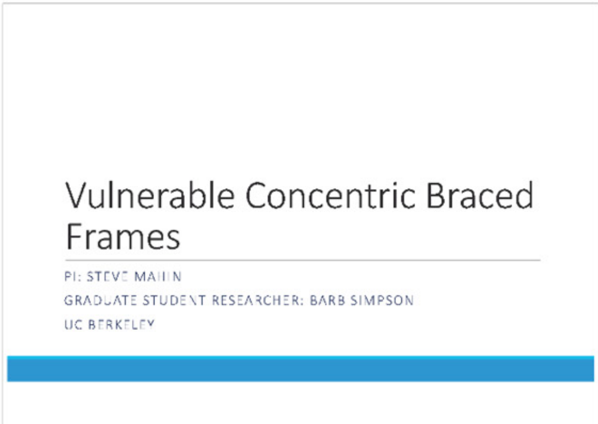

Objectives
• Evaluate the dynamic characteristics of school gymnasiums with gable roof (coupling of horizontal and vertical modes)
• Clarify the failure mechanism of ceiling system
• Evaluate the effectiveness of fail-safe system for suspended items
• Verify the seismic performance and seismic safety margin of earthquake-resistant ceiling systems
• Clarify the damage mechanism of anchor bolts
• Develop design and construction method of ceiling system to resist the maximum level earthquake
2014
2016
2014
No clearance
No braces
Non-seismic resistant ceiling
Steel columns and roof
Ceiling designed based on revised codes
Construction of 2014 specimen
2016
Ceiling designed based on revised codes
Steel roof
RC columns
High performance ceiling
(For maximum level earthquake)

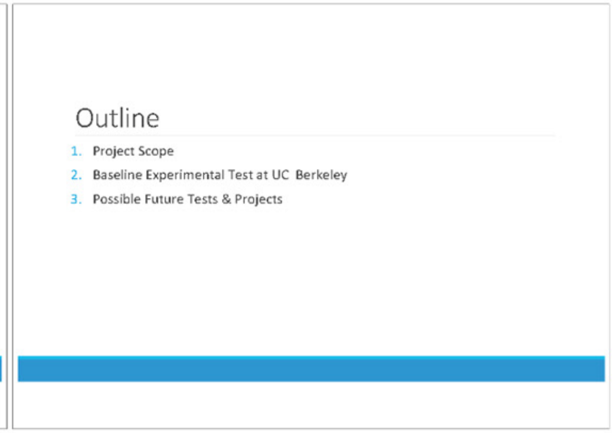

Eigenvalue Analysis Results
(a) 1st mode (0.329 s)
(b) 2nd mode (0.251 s)
(c) 3rd mode (0.242s)
(d) 4th mode (0.198 s)

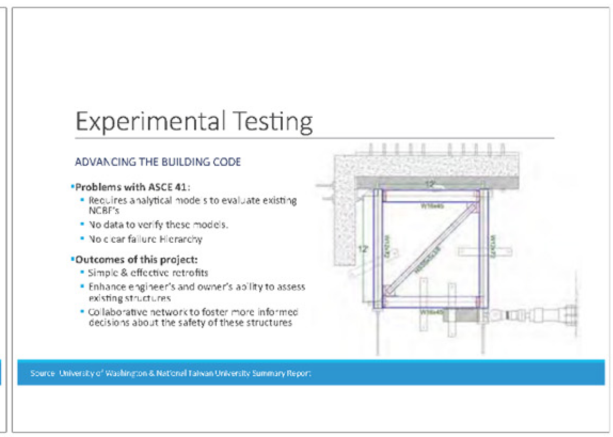

the 2011 March Tohoku Earthquake
Sa (cm/s²)
h=5%
Sv (cm/s)
h=5%
Sd (cm)
h=5%
NS
EW
UD
Period (s)
(a) Acc. Response Spectrum
(b) Vel. Response Spectrum
(c) Disp. Response Spectrum
Acc (cm/s²)
NS : 1517cm/s²
EW : 982cm/s²
UD : 982cm/s²
Time (s)

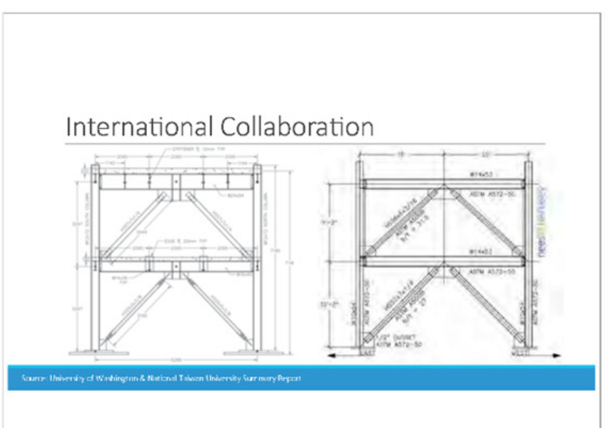

Analysis Results(Top Roof Response)
Disp.(mm)
X
Y
Z
(a) Roof Displacement
Acc.(m/s²)
(b) Roof Acceleration

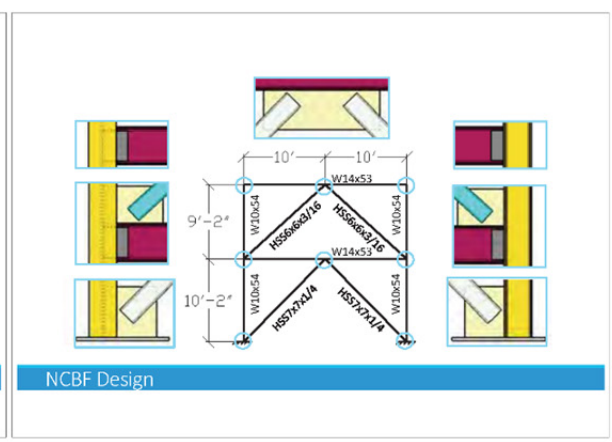
Appendix VIII

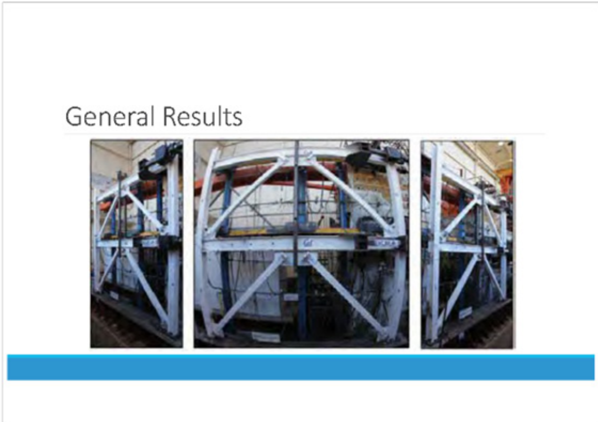


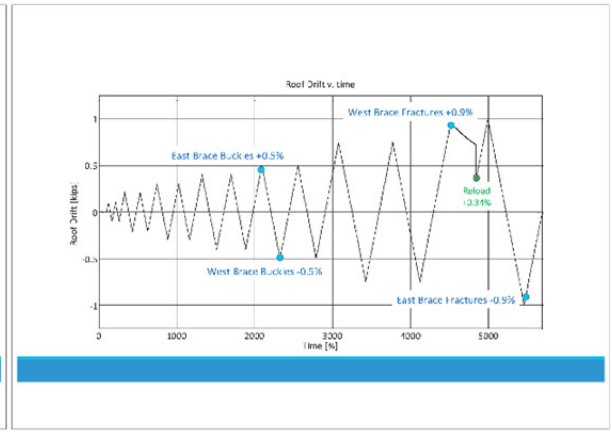


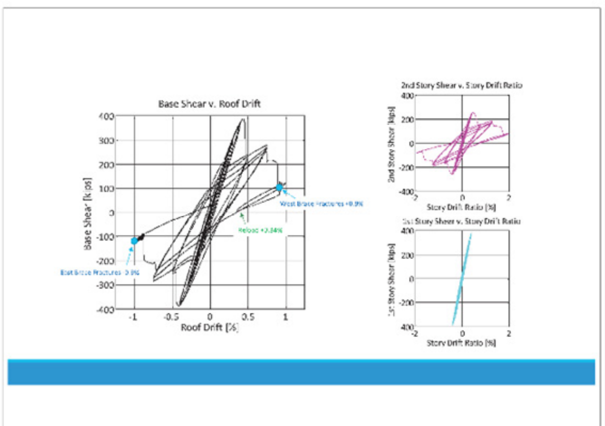


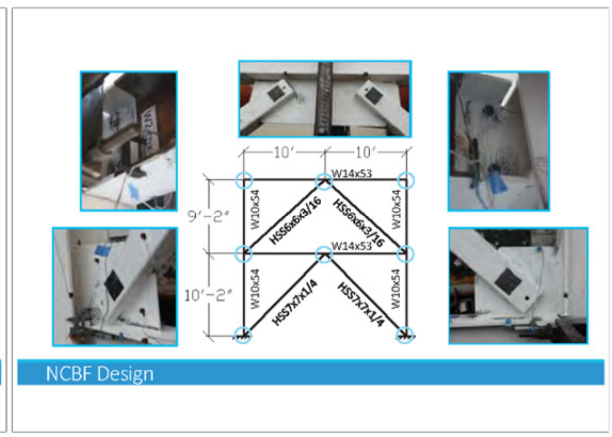


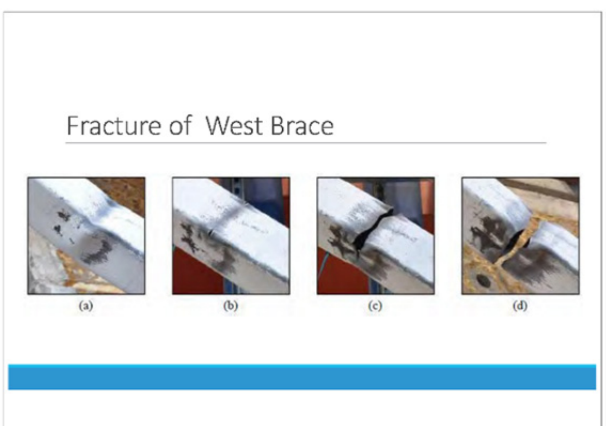


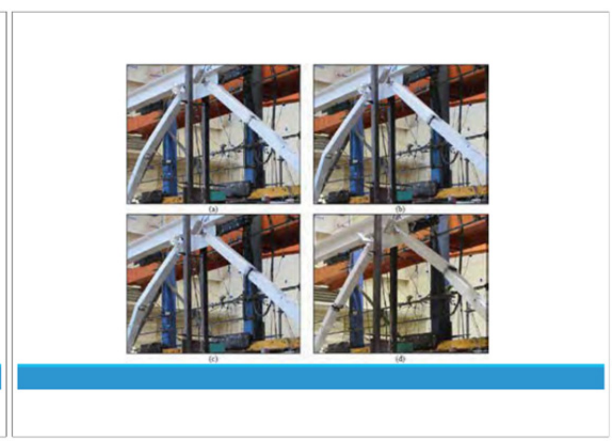

General Results


Roof Drift v. time
West Brace Fractures +0.9%
East Brace Buckles +0.5%
Reload +0.34%
West Brace Buckles -0.5%
East Brace Fractures -0.9%
Roof Drift [kips]
Time [s]

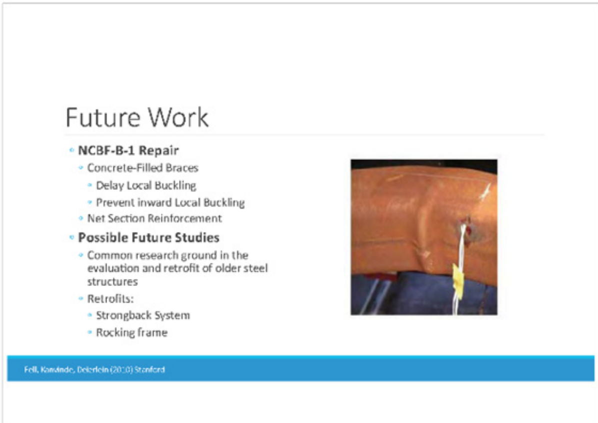

Base Shear v. Roof Drift
Base Shear [kips]
Roof Drift [%]
2nd Story Shear v. Story Drift Ratio
2nd Story Shear [kips]
Story Drift Ratio [%]
1st Story Shear v. Story Drift Ratio
1st Story Shear [kips]
Story Drift Ratio [%]

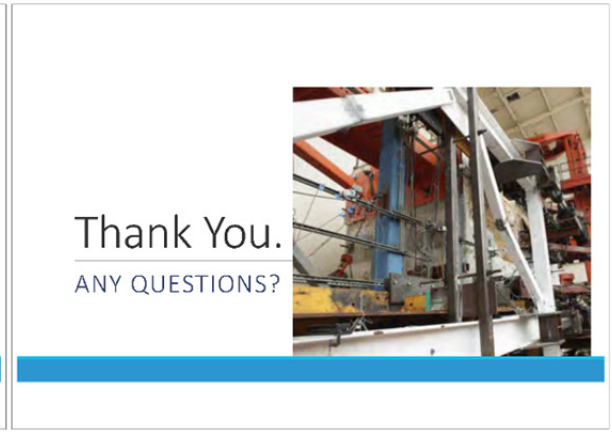

10′
10′
W14x53
9′-2″
10′-2″
W10x54
HSS6x6x3/16
HSS6x6x3/16
W14x53
HSS7x7x1/4
HSS7x7x1/4
W10x54
NCBF Design

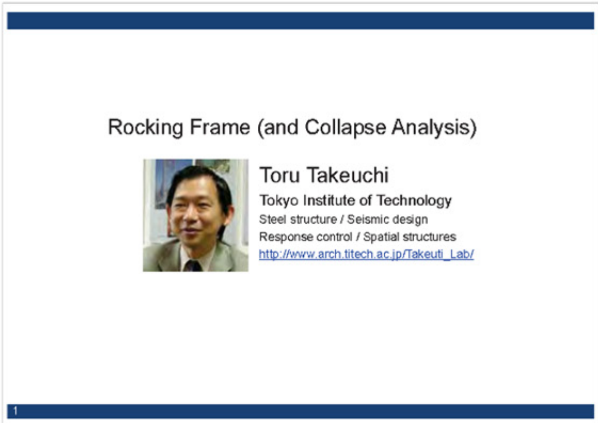

Fracture of West Brace
(a)
(b)
(c)
(d)

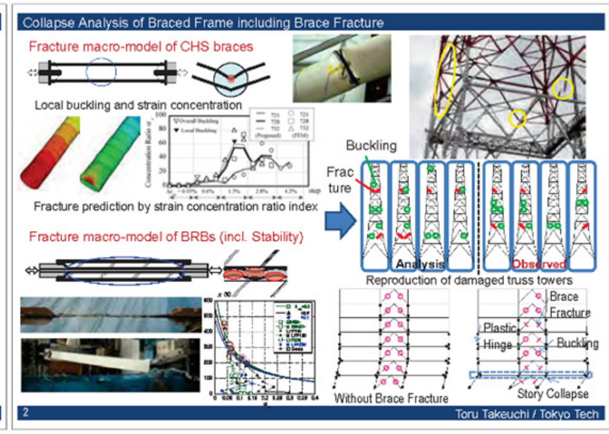


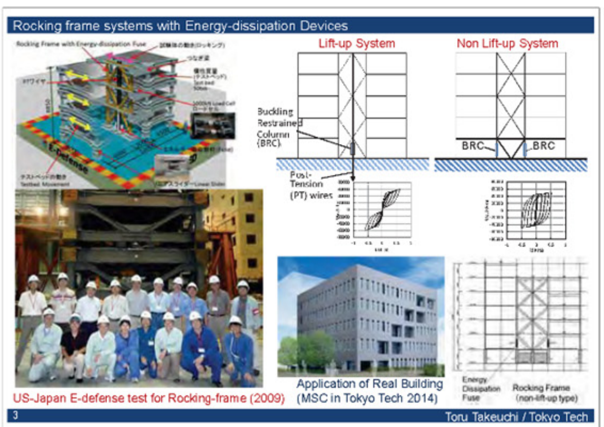
Appendix VIII



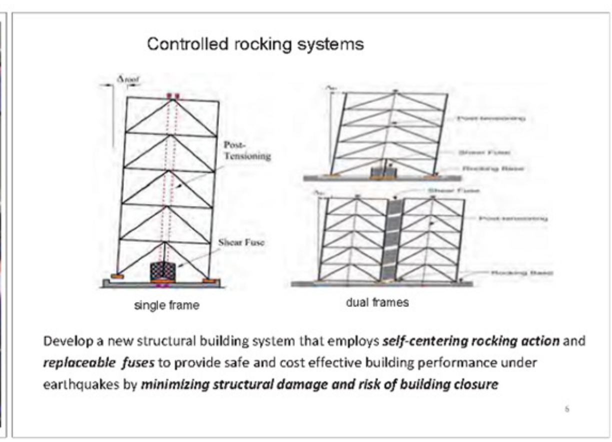



Rocking Frame (and Collapse Analysis)
Toru Takeuchi
Tokyo Institute of Technology
Steel structure / Seismic design
Response control / Spatial structures
http://www.arch.titech.ac.jp/Takeuti_Lab/
1

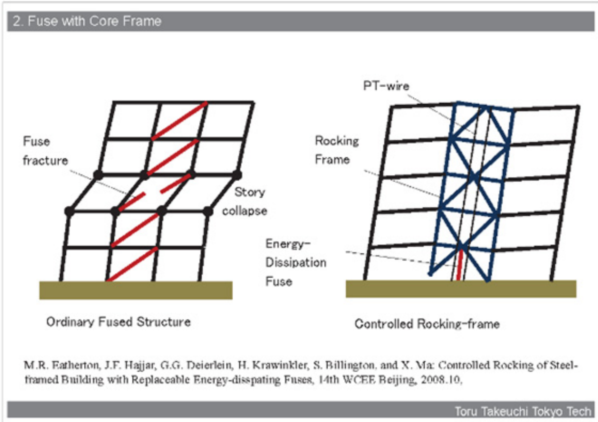

Collapse Analysis of Braced Frame including Brace Fracture
Fracture macro-model of CHS braces
Local buckling and strain concentration
Fracture prediction by strain concentration ratio index
Fracture macro-model of BRBs (incl. Stability)
Buckling
Frac ture
Analysis
Observed
Reproduction of damaged truss towers
Brace Fracture
Plastic Hinge
Buckling
Without Brace Fracture
Story Collapse
2
Toru Takeuchi / Tokyo Tech

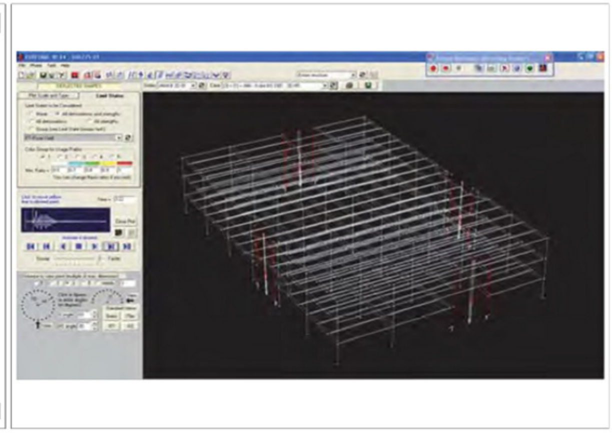

Rocking frame systems with Energy-dissipation Devices
Lift-up System
Non Lift-up System
Buckling Restrained Column (BRC)
BRC
BRC
Post-Tension (PT) wires
US-Japan E-defense test for Rocking-frame (2009)
Application of Real Building (MSC in Tokyo Tech 2014)
Energy Dissipation Fuse
Rocking Frame (non-lift-up type)
3
Toru Takeuchi / Tokyo Tech

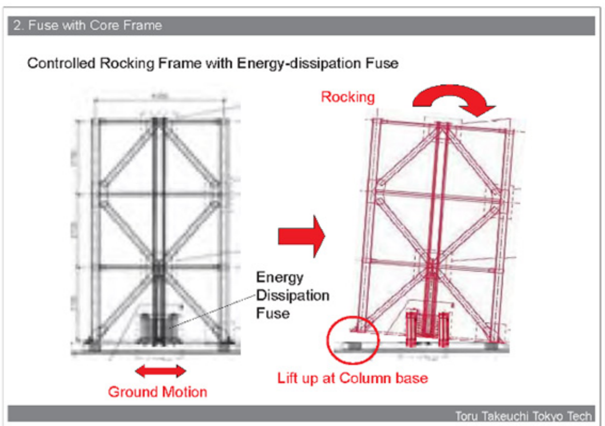

NEES/E-defense Rocking Frame Project Team:
Helmut Krawinkler, Gregory Deierleine, Sarah Billington, Xiang Ma Stanford
Jerome F. Hajjar, Northeastern Univ.; Matthew Eatherton, Virginia Tech
Toru Takeuchi, Kazuhiko Kasai, Shoichi Kishiki, Ryota Matsui, Masaru Oobayashi, Yosuke Yamamoto, Tokyo Institute of Technology
Mitsumasa Midorikawa ,Tetsuhiro Asari, Ryohei Yamazaki, Hokkaido U. Tsuyoshi Hikino, Hyogo Earthquake Engineering Research Center, NIED
David Mar, Tipping – Mar & Assoc.; Greg Luth, GPLA
E-Defense
JISF
NEES
George E. Brown, Jr. Network for Earthquake Engineering Simulation

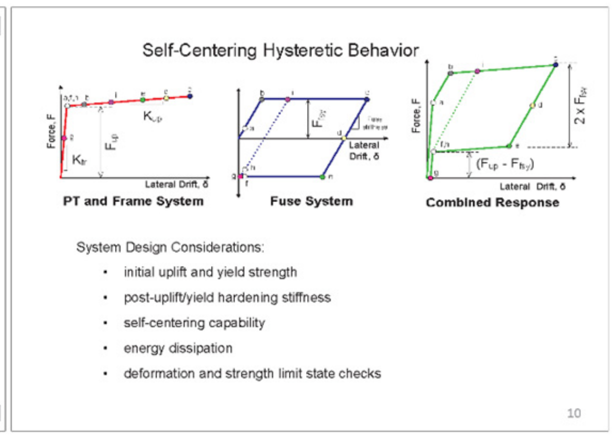

Controlled rocking systems
Post-Tensioning
Shear Fuse
single frame
dual frames
Develop a new structural building system that employs self-centering rocking action and replaceable fuses to provide safe and cost effective building performance under earthquakes by minimizing structural damage and risk of building closure
6

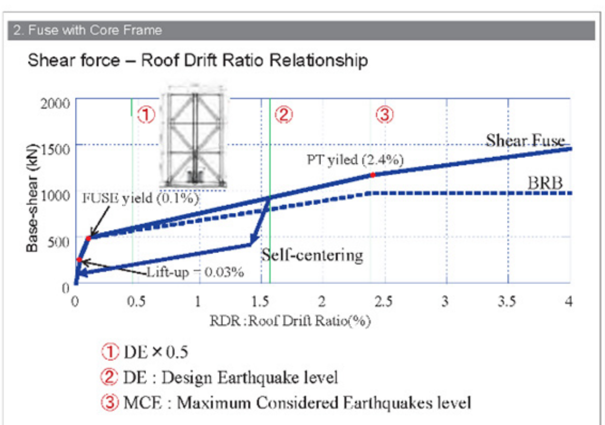
Appendix VIII

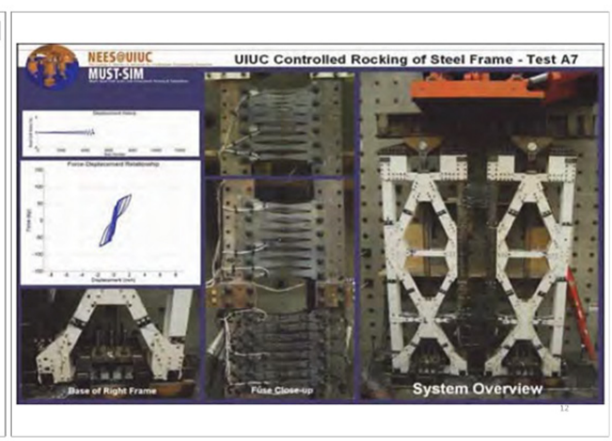


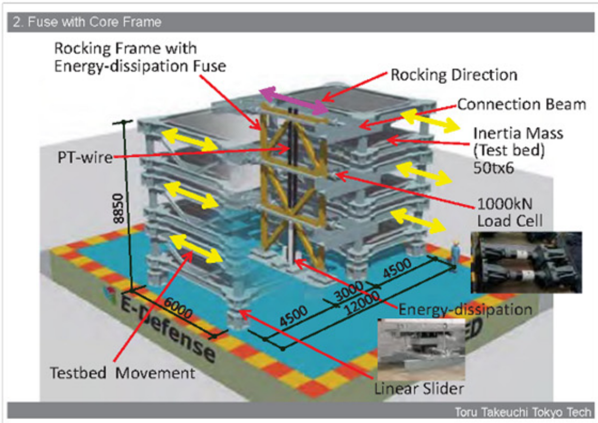


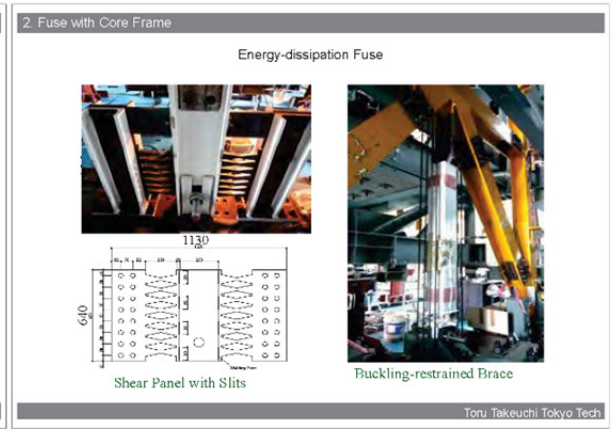


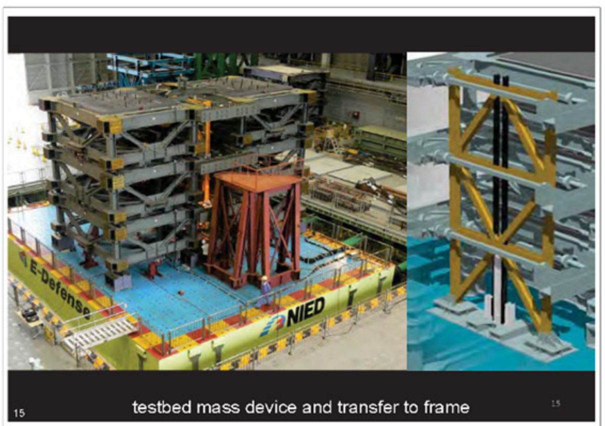


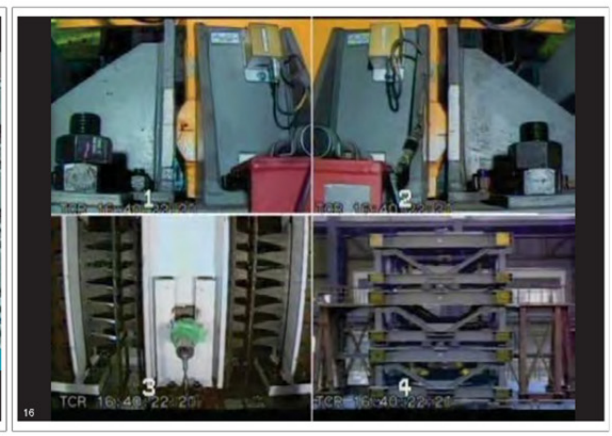


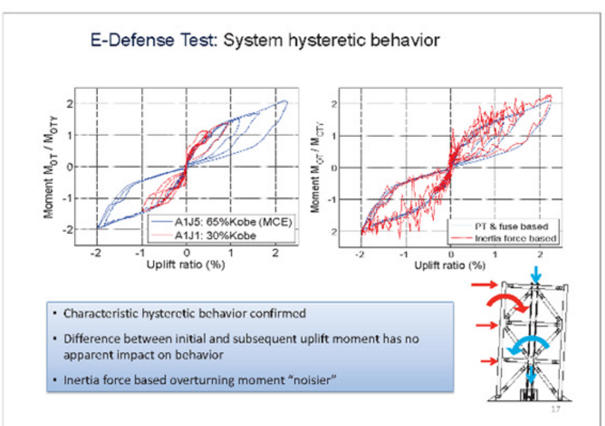












Building Code Standards Development: Self-Centering Rocking Systems

Goal: To develop proposed seismic design requirements for safe and cost-effective implementation of innovative systems that achieve self-centering response through rocking action.

Scope: The study will address seismic design requirements that would ultimately be implemented in the ASCE 7 provisions and associated material specific design specifications (e.g., AISC Seismic Provisions, ACI-318 Chapter 21, etc.).

- Calculation of drifts at DBE and MCE (using S_d and T_{eff} concepts?)
- Calculation of internal forces that accurately reflect the structural dynamics and capacity design requirements.
- Establish clear limit state criteria for onset of damage and collapse safety

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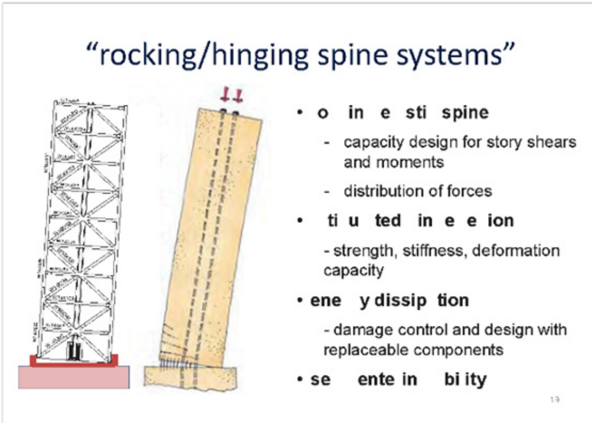
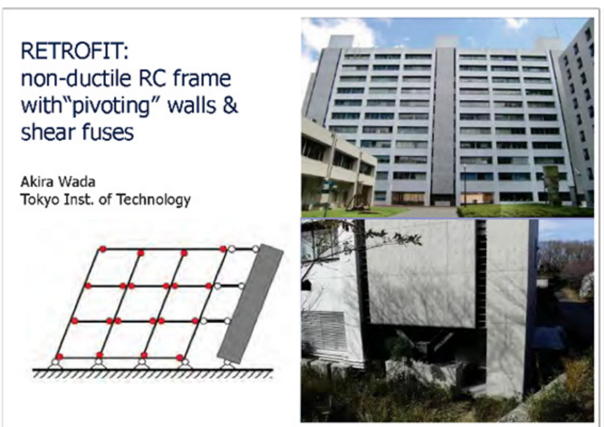
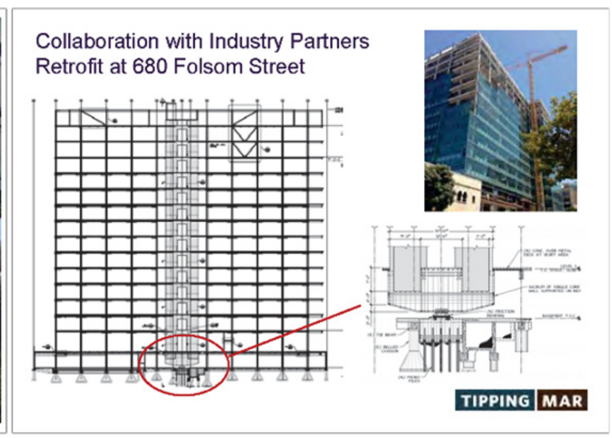
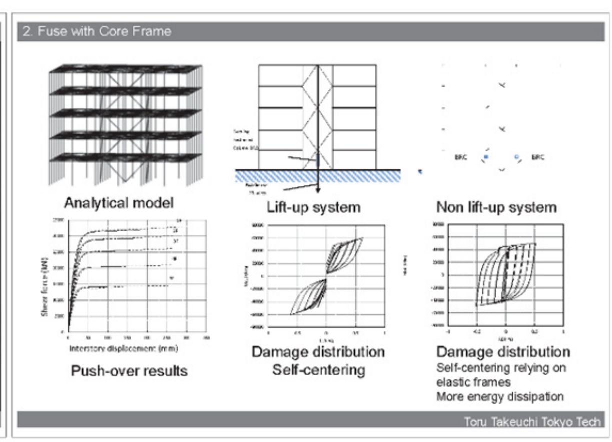
Appendix VIII



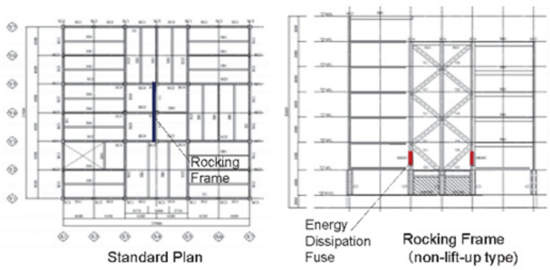






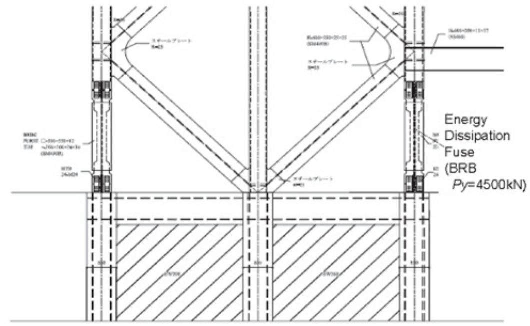
2. Fuse with Core Frame

- Rocking frame (non-lift-up type) is inserted at the center of the building for damage distribution
- Self-centering function is relying on the elastic frames at perimeters



2. Fuse with Core Frame

Rocking Base Detail



Innovation and Design Research

- **Thematic Concept**
  - life cycle design for earthquake effects
  - damage control & design for repair
- **Engineering Design Features**
  - controlled rocking & self-centering
  - energy dissipating replaceable fuses
- **Performance-Based Engineering Framework**
  - quantification of decision variables (losses, downtime)
  - integration of hazard, response, damage, loss
- **Development & Validation**
  - large scale testing and computational simulation
  - design guideline development

Related Paper List

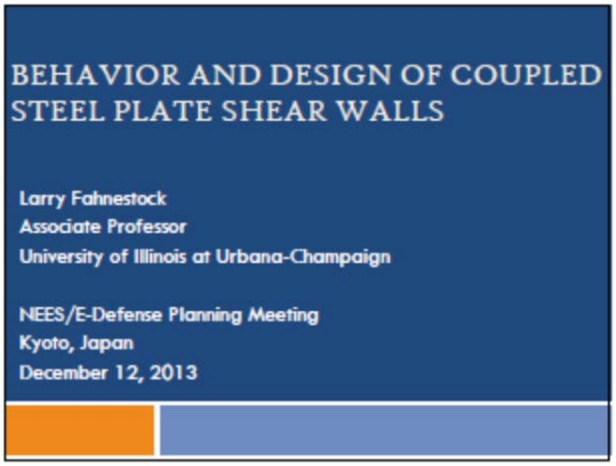
Brace fracture and collapse analysis of braced frames

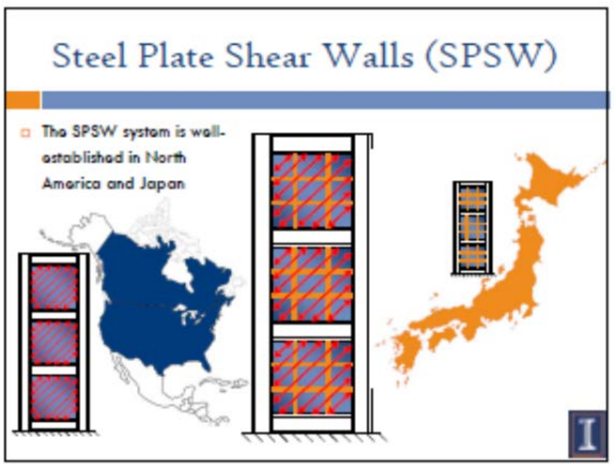
1) T.Takeuchi, M.Ida, S.Yamada, K.Suzuki: Estimation of Cumulative Deformation Capacity of Buckling Restrained Braces, Journal of Structural Engineering, ASCE, Vol.134, No.5, pp.822-831, 2008.5
2) T.Takeuchi, J.F.Hajjar, R,Matusi, K.Nishimoto, I.D.Aiken:Local Buckling Restraint Condition for Core Plates in Buckling Restrained Braces, Journal of Constructional Steel Research, Vol.66, pp.139-149, 2010.2
3) T.Takeuchi, R.Matsui: Cumulative Cyclic Deformation Capacity of Circular Tubular Braces under Local Buckling, Journal of Structural Engineering, ASCE, Vol.137, No.11, pp.1311-1318, 2011.11
4) R. Matsui, T. Takeuchi, Y. Nakamura: Seismic Performance of Tubular Truss Tower Structures Taking Member Fracture into Account, Proceedings of IASS-APCS2012 (Seoul), FF137(CD-ROM), 2012.5
5) R. Matsui, T. Takeuchi: Seismic Performance of Braced Frame Focusing on Brace Fracture, Proceedings of IABSE-IASS2011 (London), p. 248, 2011.9
6) T.Takeuchi, H.Ozaki, R.Matsui, F.Sutcu: Out-of-plane Stability of Buckling -Restrained Braces including Moment Transfer Capacity, Earthquake Engineering & Structural Dynamics, DOI:10.1002/eqe.2376, 2013

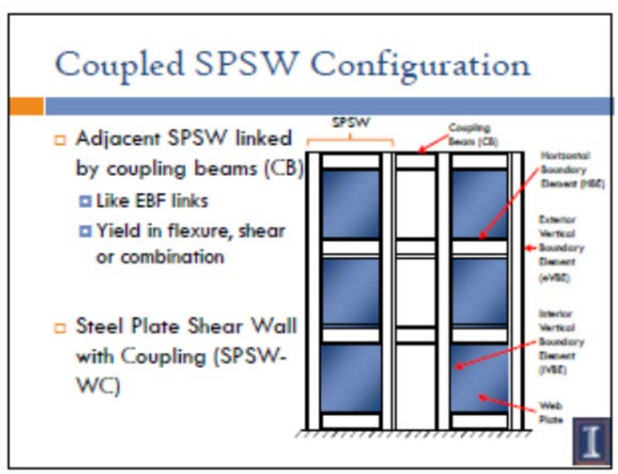
Rocking frame with energy-dissipation devices

6) T.Takeuchi, K.Kasai, M.Midorikawa, Y.Matsuoka: E-Defense Tests on Full-Scale Steel Buildings: Part 4 – Multipurpose Test Bed for Efficient Experiments, Structural Congress 2007(Long Beach), ASCE, 2007.5
7) G.Deierlein, X.Ma, M.Eatherton, J.Hajjar, H.Krawinkler, T.Takeuchi, K.Kasai, M.Midorikawa: Earthquake Resilient Steel Braced Frames with Controlled Rocking and Energy Dissipating Fuses, EUROSTEEL 2011 (Budapest), 2011.8
8) T.Takeuchi, M.Midorikawa, K.Kasai, G.Deierlein, X.Ma, J.F.Hajjar, T.Hikino: Shaking Table Test of Controlled Rocking Frames Using Multipurpose Test Bed, EUROSTEEL 2011 (Budapest), 2011.8

Appendix VIII







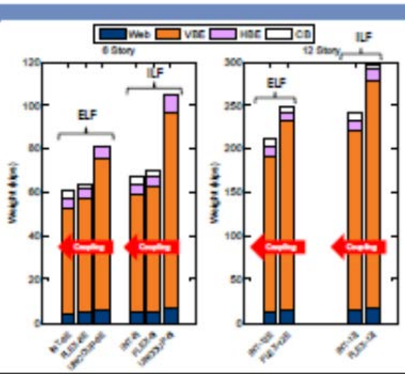
Research Objectives

- Comprehensively characterize behavior and performance of SPSW-WC system
  - Design studies
  - Mechanism analysis
  - Numerical simulations
  - Large-scale testing
- Develop design guidelines that enable adoption of SPSW-WC configuration

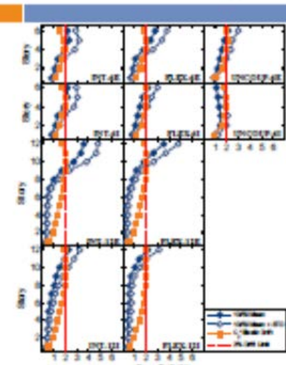
Prototype Designs

- 6-Story
  - Pair of 11 ft wide uncoupled SPSW (UNCOUP)
  - SPSW-WC with flexural yielding CBs (FLEX)
  - SPSW-WC with intermediate yielding CBs (INT)
- 12-Story
  - SPSW-WC with flexural yielding CBs (FLEX)
  - SPSW-WC with intermediate yielding CBs (INT)
  - Uncoupled specimen proved unfeasible
- ELF and ILF lateral force distributions

Prototype Component Weights



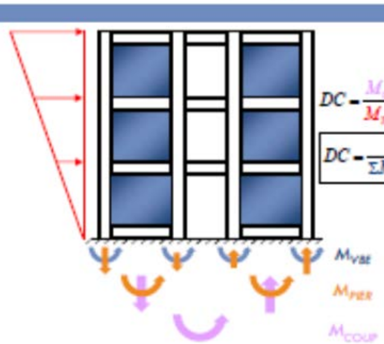
Nonlinear Dynamic Analysis



- Input
  - 3 hazard levels (50/50, 10/50, 2/50)
  - 20 motions at each level
- Observations
  - Maximum response typically occurs at top
  - ILF designs have better performance than ELF
  - More heavily coupled designs have better performance
  - Uncoupled designs perform well but are heavy or infeasible

(Borello & Fahnestock 2013)

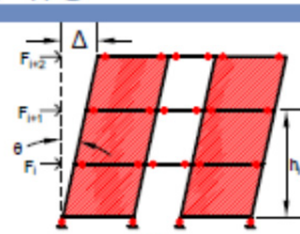
Degree of Coupling



$$DC = \frac{M_{COUP}}{M_{TOTAL}}$$

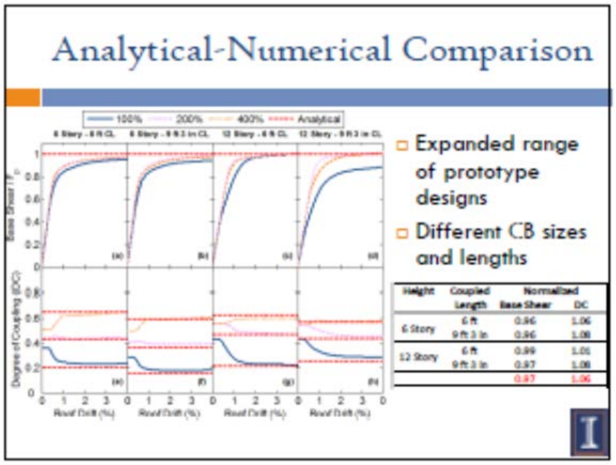
$$DC = \frac{M_{COUP}}{\Sigma M_{VBE} + \Sigma M_{PIER} + M_{COUP}}$$

Plastic Analysis of Multistory SPSW-WC

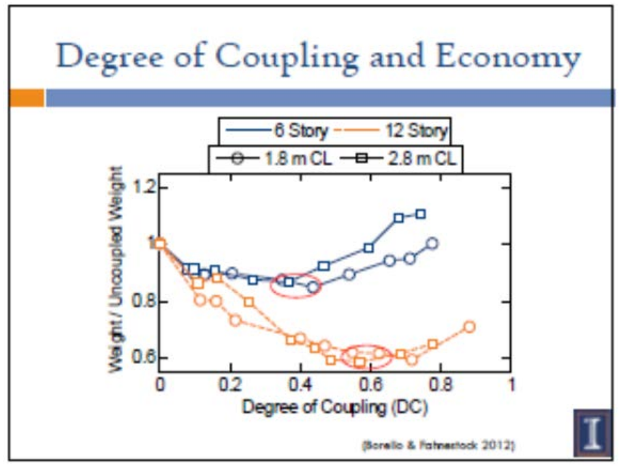


$$DC = \frac{\sum_{i=1}^{n} \frac{2M_{p,CB_i}}{e}(L+e)}{2M_{p,VBE_1} + 2M_{p,VBE_2} + \sum_{i=1}^{n}\left[4M_{p,HBE_i} + 2M_{p,CB_i} + F_y L h_i\left(t_{wi}\sin(2\alpha_i) - t_{wi+1}\sin(2\alpha_{i+1})\right)\right]}$$

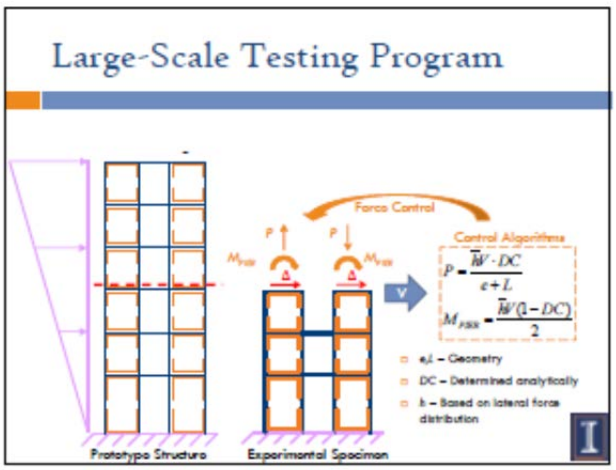
$$\sum_{i=1}^{n} F_i h_i = 2M_{p,VBE_1} + 2M_{p,VBE_2} + \sum_{i=1}^{n}\left[4M_{p,HBE_i} + 2M_{p,CB_i} + F_y L h_i\left(t_{wi}\sin(2\alpha_i) - t_{wi+1}\sin(2\alpha_{i+1})\right)\right]$$



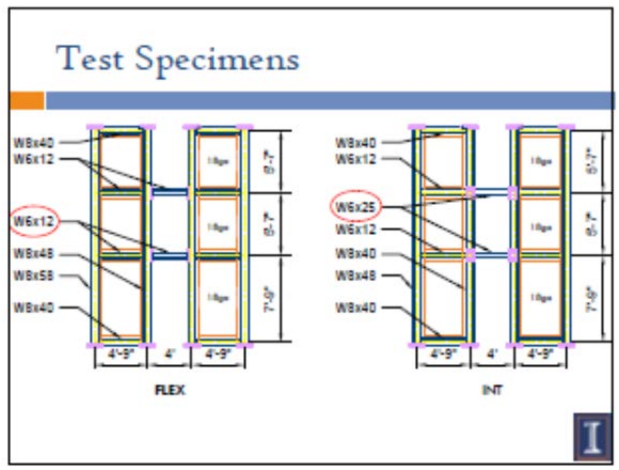
Analytical-Numerical Comparison
100%
200%
400%
Analytical
Base Shear / Vp
Degree of Coupling (DC)
Roof Drift (%)
Expanded range of prototype designs
Different CB sizes and lengths
Height
Coupled Length
Normalized
Base Shear
DC
6 Story
6 ft
0.96
1.06
9 ft 3 in
0.96
1.08
12 Story
6 ft
0.99
1.01
9 ft 3 in
0.97
1.08
0.97
1.06



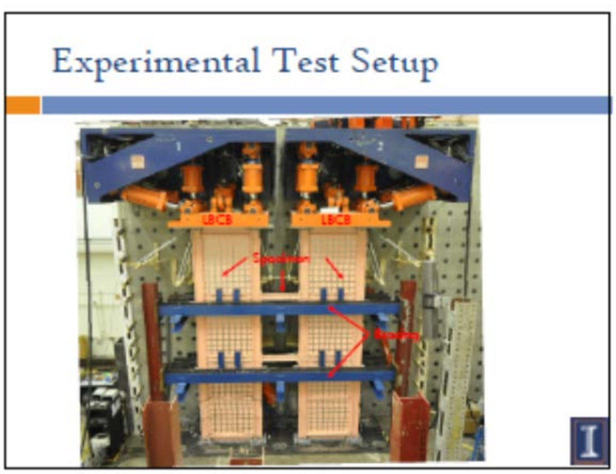
Degree of Coupling and Economy
6 Story
12 Story
1.8 m CL
2.8 m CL
Weight / Uncoupled Weight
Degree of Coupling (DC)
(Borello & Fahnestock 2012)



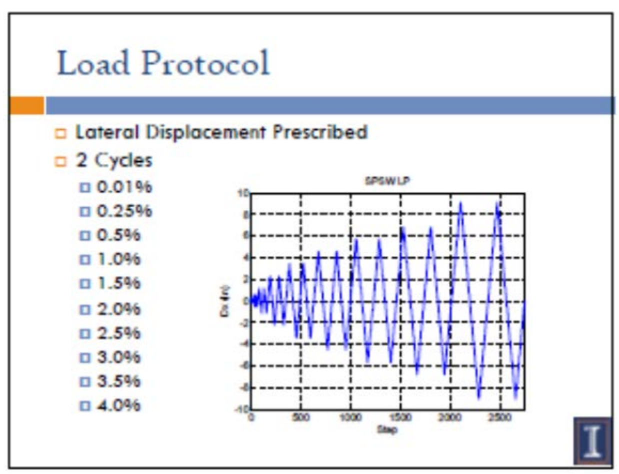
Large-Scale Testing Program
Force Control
Control Algorithms
$P = \frac{\overline{W} \cdot DC}{e+L}$
$M_{FBB} = \frac{\overline{W}(1-DC)}{2}$
e,L – Geometry
DC – Determined analytically
h – Based on lateral force distribution
Prototype Structure
Experimental Specimen



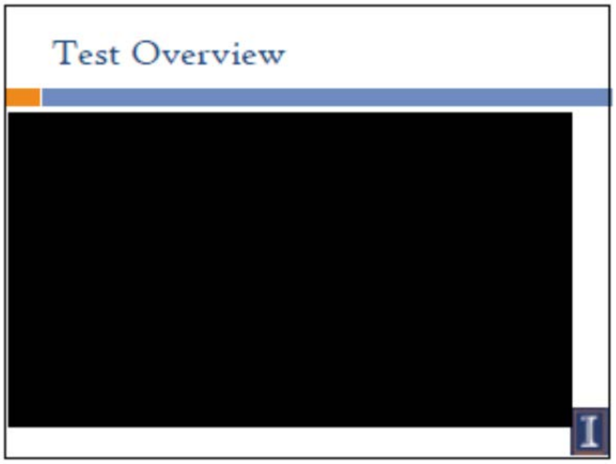
Test Specimens
W8x40
W6x12
W6x12
W8x48
W8x58
W8x40
4'-9"
4'
4'-9"
FLEX
W8x40
W6x12
W6x25
W6x12
W8x40
W8x48
W8x40
INT

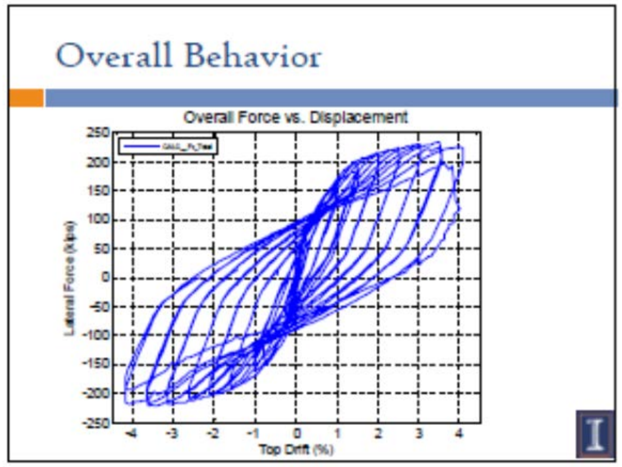


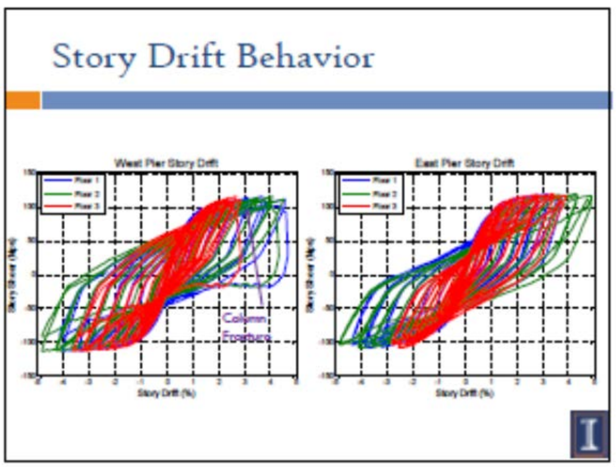
Experimental Test Setup
LBCB
LBCB
Specimen

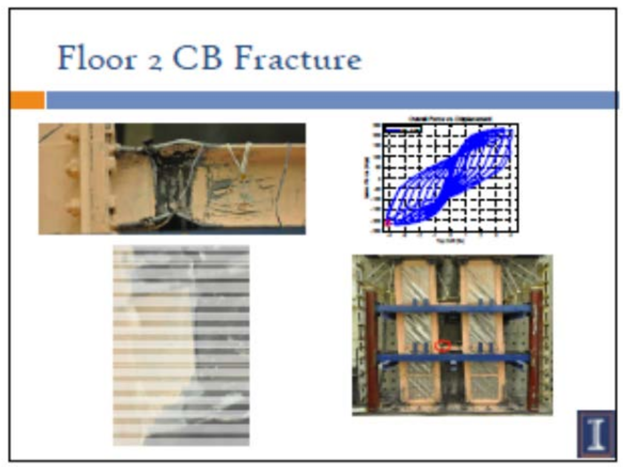


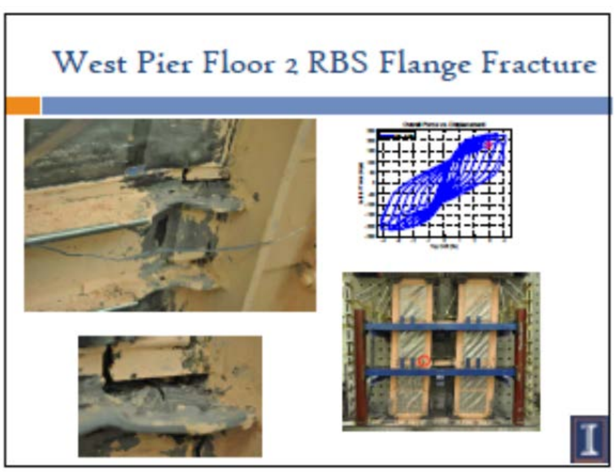
Load Protocol
Lateral Displacement Prescribed
2 Cycles
0.01%
0.25%
0.5%
1.0%
1.5%
2.0%
2.5%
3.0%
3.5%
4.0%
SPSWLP
Step

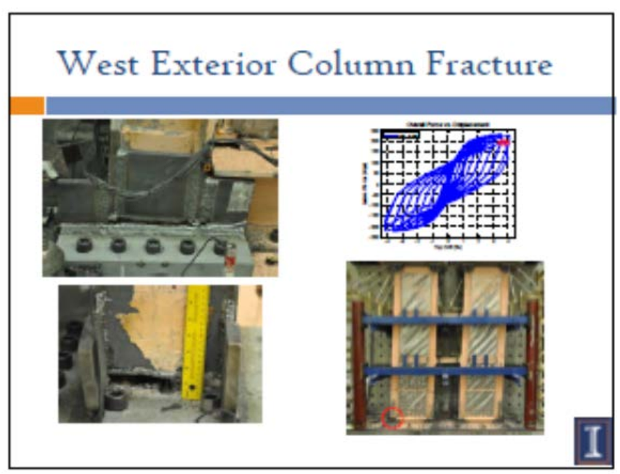

Test Overview


Overall Behavior
Overall Force vs. Displacement
Lateral Force (Kips)
Top Drift (%)

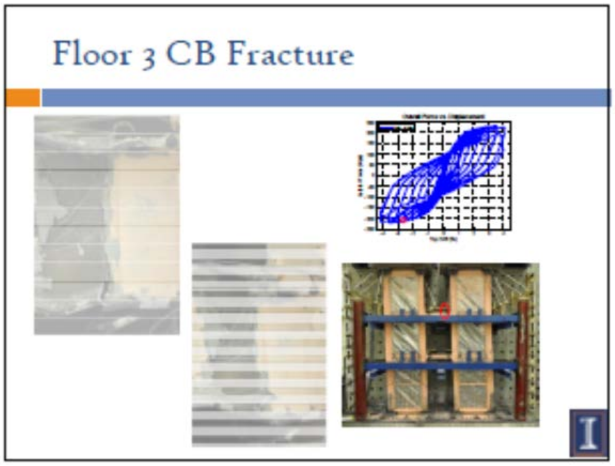

Story Drift Behavior
West Pier Story Drift
East Pier Story Drift
Column Fracture

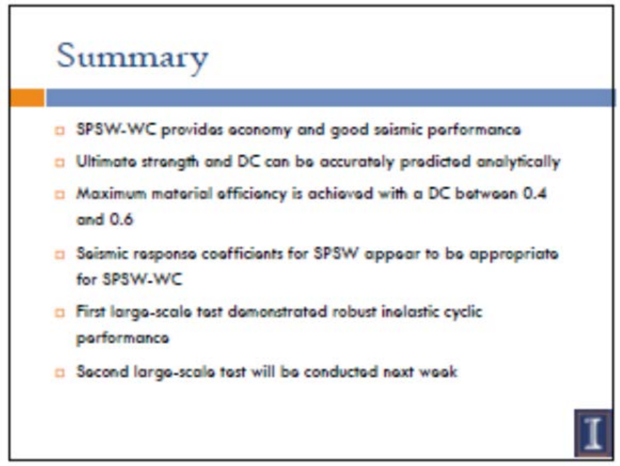

Floor 2 CB Fracture


West Pier Floor 2 RBS Flange Fracture

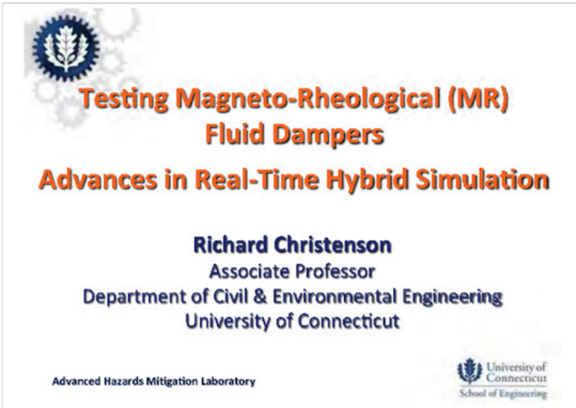

West Exterior Column Fracture

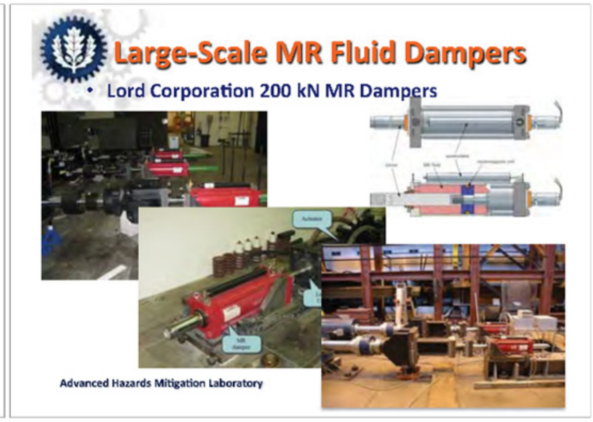
Appendix VIII

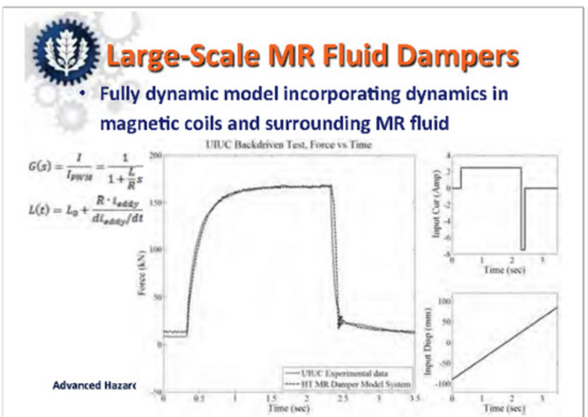


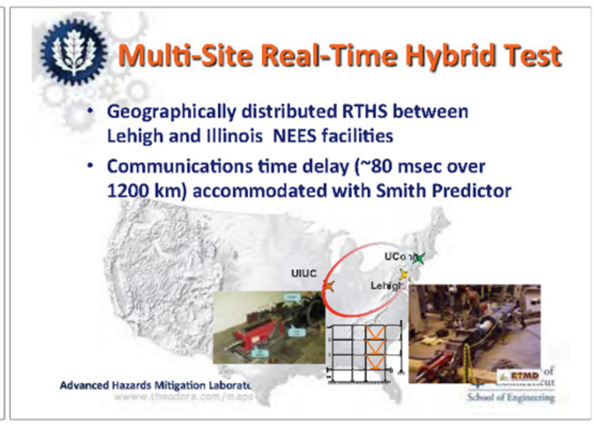


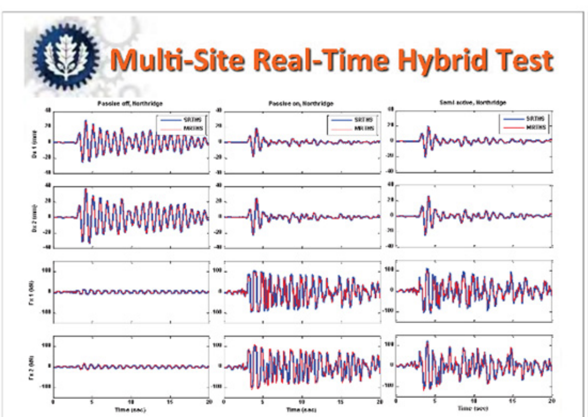
APPENDIX IX: PRESENTED PAPERS IN PROTECTIVE SYSTEMS WORKING GROUP

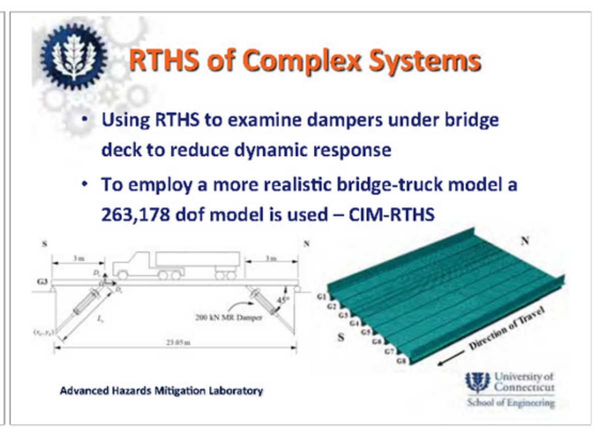




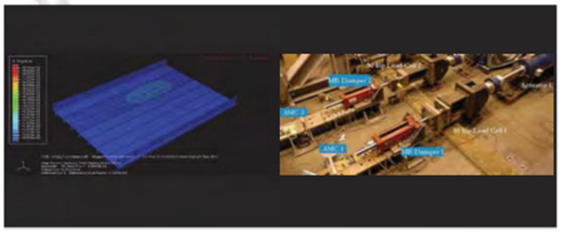








RTHS of Complex Systems



Advanced Hazards Mitigation Laboratory

University of Connecticut
School of Engineering

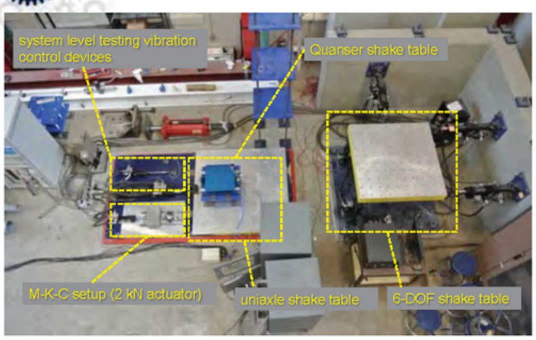
Stability & Performance of RTHS

- Considering systems approach to assess stability and performance of RTHS
- Development and comparison of actuator compensation methods to reduce actuator apparent time delay and tracking

Advanced Hazards Mitigation Laboratory

University of Connecticut
School of Engineering

UCONN RTHS Facility



Advanced Hazards Mitigation Laboratory

University of Connecticut
School of Engineering

International Research Institute of Disaster Science (IRIDeS)

- established in April 2012, in response to the 2011 Great East Japan Earthquake
- to conduct world-leading research on natural disaster science and disaster mitigation.
- contributes to on-going recovery/reconstruction efforts in the affected areas conducting action-oriented research
- pursues effective disaster management to build sustainable and resilient societies.

2011 Great East Japan EQ

- The most powerful known EQ ever to have hit Japan.
- The largest scale long-period/long-duration ground motions are observed.
  - High-rise buildings in Tokyo suffered long-duration shaking.
  - A high-rise building in Osaka, 800 km away from the epicenter, suffered a maximum displacement of 1.4 m at the top.

Long-period ground motions

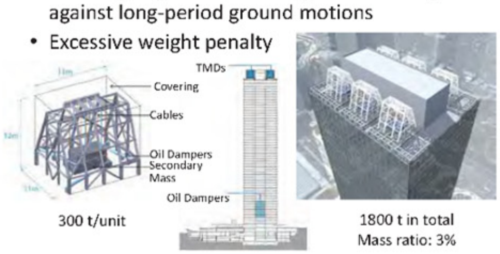
- Long-period ground motions induce large displacements of long-period structures.
- Viscous damping is less effective against low velocity.
- Equivalent damping ratio of hysteretic dampers goes down as the response displacement increases.
- Adding many dampers might result in excessive floor response accelerations when the structure is subjected to short-period ground motions.

Precautionary measures against long-period/long-duration ground motions

- To obtain large control force against low velocity and large displacement, exploit
  - Selective damping provided by tuned mass damper (TMD)
  - Linear rate-independent damping
- Effective in reduction of excessive floor response accelerations induced by high frequency components of ground motions.

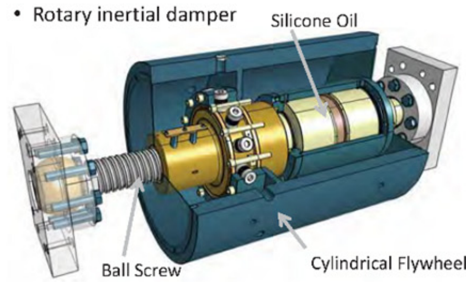
Tuned Mass Damper

- An effective precautionary measure in reducing displacement of high-rise buildings against long-period ground motions
- Excessive weight penalty

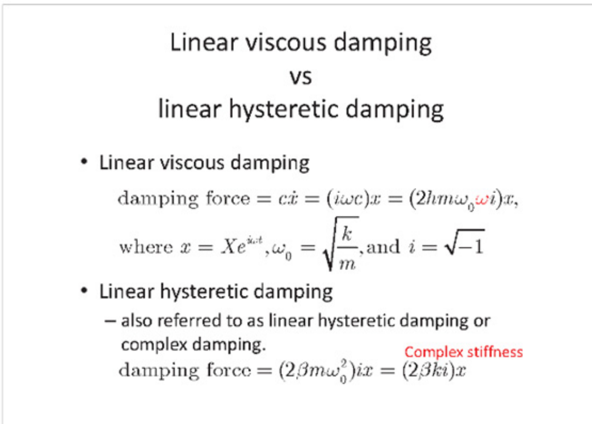


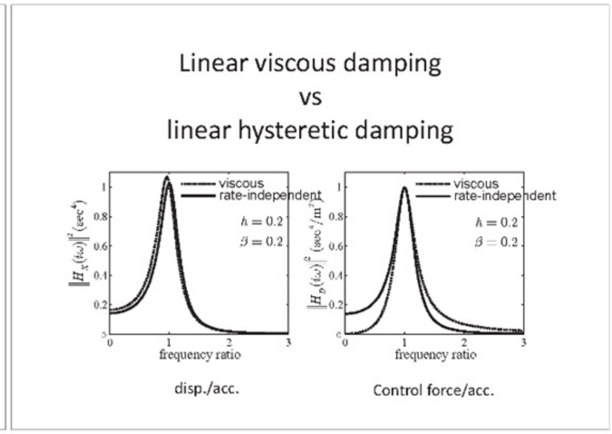
An attractive alternative to classical TMD

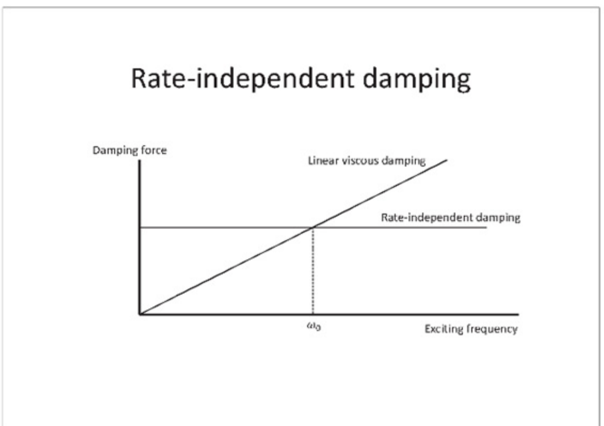
- Rotary inertial damper

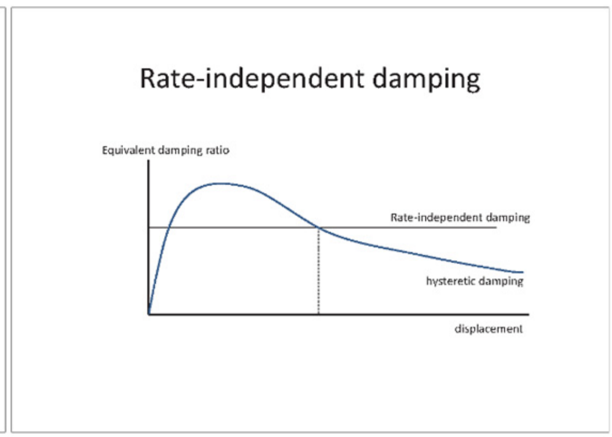


Appendix IX


Linear viscous damping
vs
linear hysteretic damping
• Linear viscous damping
damping force $= c\dot{x} = (i\omega c)x = (2hm\omega_0\omega i)x,$
where $x = Xe^{i\omega t}, \omega_0 = \sqrt{\frac{k}{m}}$, and $i = \sqrt{-1}$
• Linear hysteretic damping
– also referred to as linear hysteretic damping or complex damping.
Complex stiffness
damping force $= (2\beta m\omega_0^2)ix = (2\beta ki)x$


Linear viscous damping
vs
linear hysteretic damping
viscous
rate-independent
$h = 0.2$
$\beta = 0.2$
frequency ratio
viscous
rate-independent
$h = 0.2$
$\beta = 0.2$
frequency ratio
disp./acc.
Control force/acc.


Rate-independent damping
Damping force
Linear viscous damping
Rate-independent damping
ω_0
Exciting frequency


Rate-independent damping
Equivalent damping ratio
Rate-independent damping
hysteretic damping
displacement

NSF CMMI 13-44937 / 13-44622: Oct 2013 – Sept 2016

NEESR Planning: Toward Experimental Verification of Controllable Damping Strategies for Base Isolated Buildings

Advancing Real-Time Hybrid Experiments Calibrated by Full-Scale Physical Tests

Erik A. Johnson (University of Southern California)
Richard E. Christenson (University of Connecticut)

NEES/E-Defense Planning Meeting, 12 December 2013

USC Viterbi School of Engineering | University of Connecticut School of Engineering

Need Tests at Multiple Scales

- Small tests are easier & cheaper & safer
  - But scaling effects can be an issue (*e.g.*, friction, material scales, etc.)
- Large tests are more realistic, therefore more convincing
- Real-world tests are most convincing



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Full-Scale Tests Needed but $$$

- Full-scale test facilities: *e.g.*,
  - UCSD's *Large High-Perf. Outdoor Shake Table*
  - Japan's NIED E-Defense shake table
- E-Defense facility costs:
  + Table occupation (~ $20–40k/day)
  + Table operation (~ $80–120k/day)
  + Specimen construction costs
  + Salaries (research engineers, technicians, safety personnel, etc.)

  4–7 tests per day (*e.g.*, different ground motions or magnitudes, different components, etc.)

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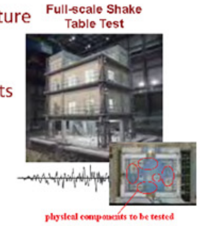
Leverage Full-Scale Experiments with Calibrated Hybrid Tests

- Pseudodynamic (PsD) Substructure Tests and Real-Time Hybrid Simulation (RTHS) can extend scope & impact of full-scale tests
  - Calibrate numerical models with results of full-scale tests

Full-scale Shake Table Test



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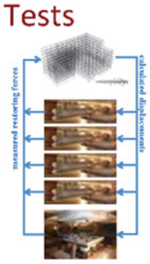
Leverage Full-Scale Experiments with Calibrated Hybrid Tests

- Pseudodynamic (PsD) Substructure Tests and Real-Time Hybrid Simulation (RTHS) can extend scope & impact of full-scale tests
  - Calibrate numerical models with results of full-scale tests
  - Physically test critical components coupled with virtual numerical models of remainder of structure



Real-time Hybrid Simulation

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Why are Controllable Dampers Useful in Base Isolation?

- US Code mandates
  - superstructure remain elastic in large design earthquakes
  - isolation accommodate very large drift
    - significant isolator cost
    - cost of flexible connections
- Need ways to reduce base drift w/o increasing superstructure deformation
  - recent isolator advances (*e.g.*, TFP)



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Appendix IX

Controllably Damped Isolation

- A passive device "knows" nothing more than **local** responses
  - *e.g.*, a passive viscous damper only "knows" the relative velocity across it; the force is **exactly** determined from that velocity
- Controllable dampers can use sensors to measure responses (and, with a good model, estimate other unmeasured responses)
  - allows the damper force to be a function of **global information** of structural response

Analogy: old car brakes vs. anti-lock brakes

Base Isolation Study 2013–15

2011–12 Designed
2012–13 Built

Base Isolation Study 2013–15

2011–12 Designed
2012–13 Built
3 & 8/13 tested
2015 full tests with controllable dampers

Goals:
- Test impulsive and long-period EQs
  - *e.g.*, 2011 Tohoku EQ

Base Isolation Study 2013–15

2011–12 Designed
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2015 full tests with controllable dampers

Goals:
- Test impulsive and long-period EQs
  - *e.g.*, 2011 Tohoku EQ
- Pounding against seismic moat wall

Base Isolation Study 2013–15

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3 & 8/13 tested
2015 full tests with controllable dampers

Goals:
- Test impulsive and long-period EQs
  - *e.g.*, 2011 Tohoku EQ
- Pounding against seismic moat wall
- Test controllable damping performance

Planned Experiments for 2015

- NSF Grant to participate in 2015 tests (among other research tasks)
  - CMMI 13-44937/13-44622 w/co-PI Rich Christenson
  - Oil dampers may be replaced by MR fluid dampers
- Develop numerical models suitable for control design & parameter studies
- Assess variety of command strategies for controllable dampers
- Use E-Defense experiments to calibrate **Real-Time Hybrid Simulations** for testing controllable dampers in base isolated buildings designed to US code

DYNAMIC LOADING EXPERIMENT OF FULL-SCALE OIL DAMPER FOR SEISMIC ISOLATION AGAINST LARGE VELOCITY EXCITAION

Ryota MASEKI *Taisei Corporation*

Outline

1. Introduction for TAISEI Corporation and myself
2. Introduction for dynamic loading experiment of full-scale damper against large velocity excitation
3. Proposal

Introduction for:

TAISEI Corporation
and
myself

Data of TAISEI Corporation and Technology Center :

TAISEI Corporaion
Big general contractor in Japan, founded in 1873.
– Number of workers: 8,087 –

Our technology center, in Yokohama
– Number of researchers: 200 –

Our vibration control team
– Number of members: 4 –

Myself :

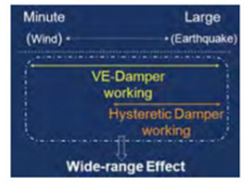
Have been doing developments and applications related to structural control technology including active/ semiactive/passive control for nearly 15 years.

Application of active mass damper to high-rise building to reduce wind induced vibration

Application of semi-active base isolation system to high-rise building to reduce acceleration of upper story

2 stage variable-orifice damper

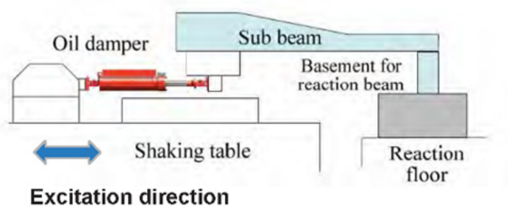
Application of hybrid damper combining a Hysteretic damper and Visco-elastic damper



DYNAMIC LOADING EXPERIMENT OF FULL-SCALE OIL DAMPER FOR SEISMIC ISOLATION AGAINST LARGE VELOCITY EXCITAION

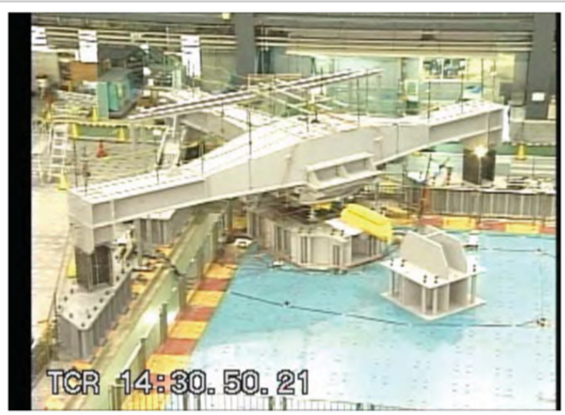
Ryota MASEKI *Taisei Corporation*

Setup of Large velocity excitation test

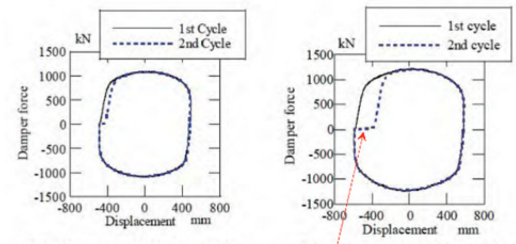


Test cases

Excitation wave	Case	Period (s)	Disp. (mm)	Vel. (m/s)	Number of cycles per excitation
Sinusoidal wave	Osv1	2.5	300	0.75	2
	Osv2		400	1.00	
	Osv3		500	1.25	
	Osv4		600	1.50	



Test results



(a) Case Osv3 (125 cm/s) (b) Case Osv4 (150 cm/s)

Proposal

(1) Development of performance evaluation methods of response control device for long-period earthquake motions and large amplitude earthquake motions

(2) Confirming of limit performance of full-scale devices against long-period earthquake motions and large amplitude earthquake motions

THANK YOU FOR YOUR ATTENTION

PERFORMANCE OF SEISMIC RETROFITTING OF SUPER HIGH-RISE BUILDING BASED ON EARTHQUAKE OBSERVATION RECORDS

Contents

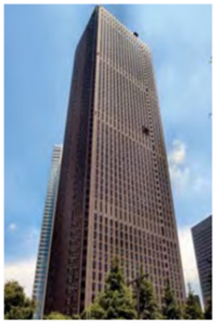
(1) Outline of the seismic retrofitting for high-rise building using deformation-dependent oil damper

(2) Observation results of the 2011 Tohoku Earthquake

(3) Performance verification based on observation records

Appendix IX

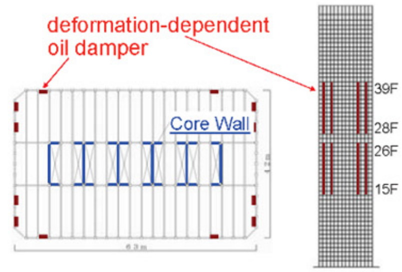
Building applied seismic retrofitting



Location	:	Shinjuku-ward, Tokyo
Main uses	:	Offices
Building area	:	3,666.97 ㎡
Total area	:	183,093.79 ㎡
Number of stories	:	54 stories above ground
Height	:	216m
Structural type	:	Steel structure
Completion date	:	October 1979
First natural period	:	6.5 second (transverse direction) 5.4 second (longitudinal direction)

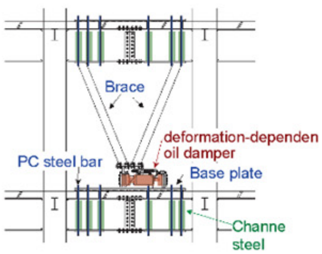
Layout of oil dampers

12 dampers per floor, at 24 floors (15th to 39th floor)
Total 288

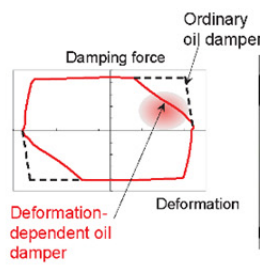


Details of attachment of oil damper

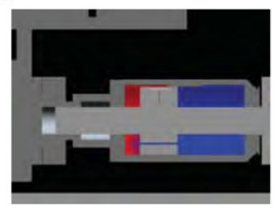
The joint of brace, girder, base plate and slab are performed by press bond with PC steel bar. We don't need weld.



Mechanism of deformation-dependent oil damper



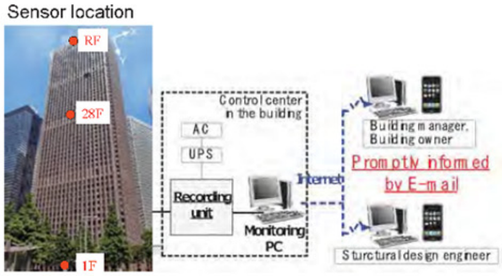
Relationship of damping force and deformation



Mechanism of Deformation-dependent oil damper

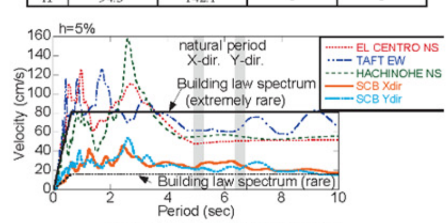
Seismic observation system

Sensor location



Observation Results

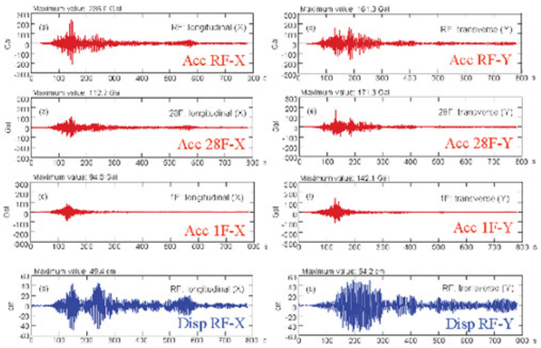
	Maximum acceleration (Gal)		Maximum deformation (cm)	
	Longitudinal (X)	Transverse (Y)	Longitudinal (X)	Transverse (Y)
RF	236.0	161.3	49.4	54.2
28F	112.7	171.3	26.3	33.3
1F	94.3	142.1	-	-



Velocity response spectra (h=5%)

24

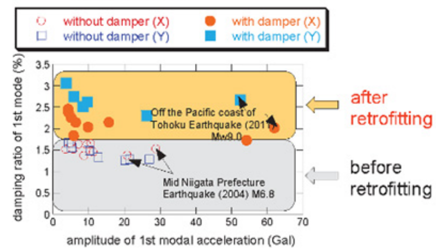
Observed Waves



Additional damping ratio estimated using ARX model

(Longitudinal direction)
Without Damper : 1.5% (average)
With Dampers : 2.1% (average)
0.6% Increased

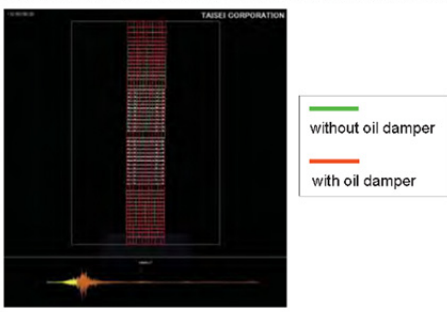
(Transverse direction)
Without Damper : 1.4% (average)
With Dampers : 2.7% (average)
1.3% Increased



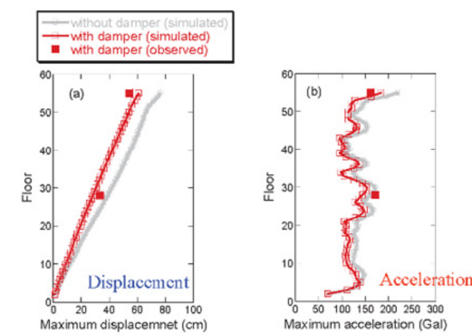
Amplitude of 1st modal acceleration and damping ratio of 1st mode

Simulation results with or without damper

Lumped mass model with 52 stories was used
Mode Superposition method to the 10th mode was used
For under the 3rd mode, damping ratio identified using ARX model was used

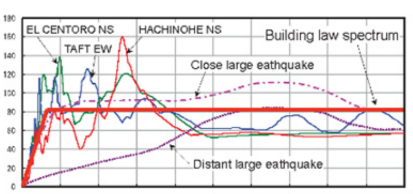


Comparison of Simulated and observed response



Transition of design ground motions in Japan

In 2000, the building standard law was revised.
Before 2000, most of high-rise buildings in Japan were designed considering only "three standard design waves".
According to recent research, long-period ground motions sometimes surpass the building law spectrum in long-period domain.

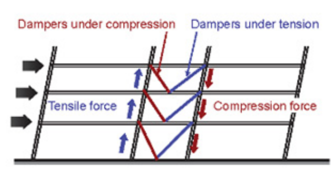


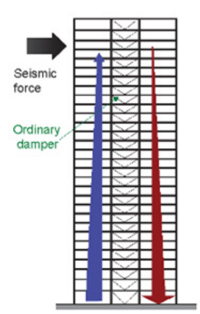
Velocity response spectra of design ground motions(h=5%)

A Problem of retrofitting with ordinary damper

The reaction force of ordinary dampers is large when the frame deformation approaches its maximum value.

If we install ordinary dampers, we have to reinforce surrounding frame such as columns and foundations.

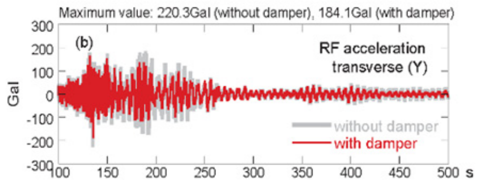




Comparison of acceleration with or without damper

Maximum Accleration (Roof Level in transverse dirction)

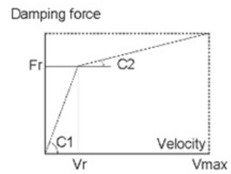
Without Damper : 220.3gal
With Damper : 184.1gal ←20% reduction

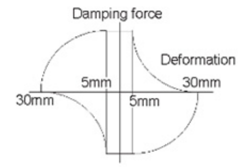


Roof Level Acceleration in Transverse Direction (Analysis)

31

Specification of oil damper



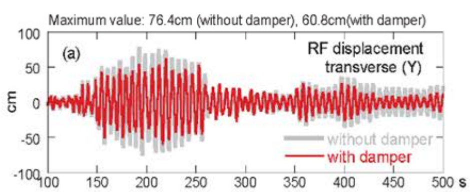


C1	235 kN·sec/cm
C2	3.5 kN·sec/cm
Vr	1.7 cm/sec
Vmax	15 cm/sec
Fr	400 kN
Fmax	446 kN

Comparison of displacement with or without damper

Maximun Displacement (Roof level in transverse dirction)

Without Damper 76.4cm
With Damper 60.8cm ← 20% reduction

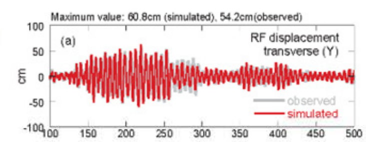


Roof Level Displacement in Transverse Direction (Analysis)

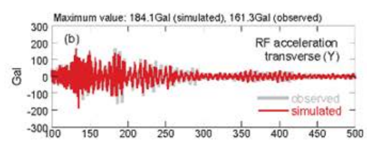
Comparison of simulated and observed response

analytical results were in good agreement with the observed record

Displacement



Acceleration



5. CONCLUSION

We have developed a deformation-dependent oil damper and applied to 54-storey super high-rise building to reduce the vibration induced long-period earthquake ground motion.

The seismic responses were observed in the 2004 Mid Niigata Prefecture Earthquake (without oil damper) and in the 2011 Tohoku Earthquake (with oil damper) and system identification using ARX model and simulation analyses were conducted to estimate the control performance of damper.

It is clarified that the damping ratio was higher and the response lower by 20% as compared to the building without dampers.

The observed responses of the buildings are mostly well simulated.

In conclusion, the performance of the seismic retrofitting of the super high-rise building was confirmed.

Development of Experimental Methods (Hybrid Simulation, Shake Table Testing and Effective Force Method)

Narutoshi Nakata, PhD
Assistant Professor
Department of Civil Engineering
JOHNS HOPKINS UNIVERSITY

Protective Systems
December 11-13, 2013
NEES / E-Defense Meeting

Background in the EFT Method (including only force-feedback control approaches)

Development of Initial Concept

- Mahin and Shing (1985), Thewalt and Mahin (1987): Ideas of force control

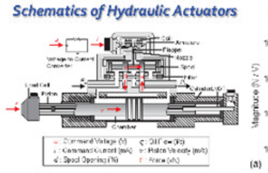
Experimental Implementation of Force Feedback Control

- Dimig, Shield, French et al (1999): EFT of a Linear SDOF with PID and Velocity Feedback Compensation
- Zhao, Shield, French et al (2005): Nonlinear Valve Dynamics for Velocity Feedback Compensation
- Zhao, French, Shield et al (2006): SDOF EFT with Fluid Dampers
- Alleyne and Liu (2000): Lyapunov-based nonlinear controller

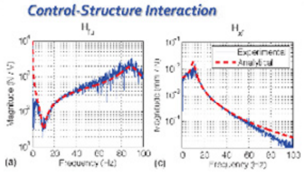
- **Limited to SDOF systems with a single hydraulic actuator**
- **Frequency range is limited to 10 Hz at maximum.**
- **No consideration of robustness in control design**
- **Not expandable to more complex applications**

Dynamic Force Control Using Hydraulic Actuators

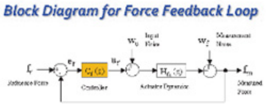
Schematics of Hydraulic Actuators



Control-Structure Interaction



Block Diagram for Force Feedback Loop



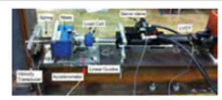
Loop Shaping Control

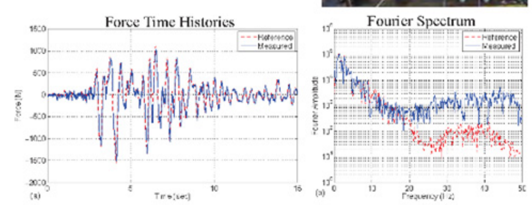
- Robust Control Design
- Compensation for Control-Structure Interaction
- Suppression of Oil-Column Resonance
- Applicable to MIMO systems

Experimental Validation of Dynamic Force Control: (1) SDOF Linear System

Dynamic Force Control Test

- Test Setup: SDOF Linear Mass-Spring Model
- Input: Kobe Earthquake Takatori Record
- Maximum Reference Force: 1500 N



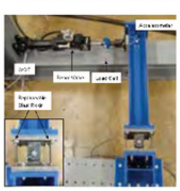


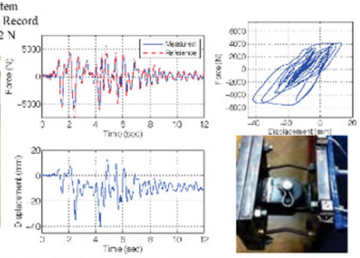
N. Nakata (2013) "Effective Force Testing with a Robust Loop Shaping Controller", *Earthquake Engineering and Structural Dynamics*, 42 (2): 261-275.

Experimental Validation of Dynamic Force Control: (2) SDOF Nonlinear System

Dynamic Force Control Test

- Test Setup: Nonlinear SDOF System
- Input: Kobe Earthquake Takatori Record
- Maximum Reference Force: 7562 N

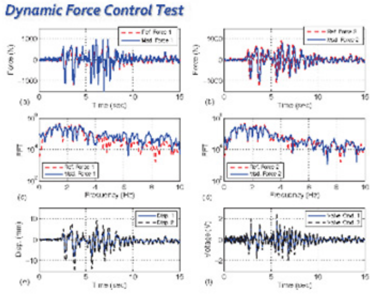


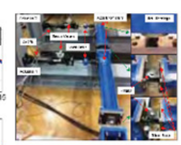


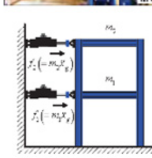
N. Nakata and E. Krug. (2013) "Validation of the Effective Force Test Method with Nonlinear Test Structures", *Journal of Vibration and Control* (DOI: 10.1177/1077546313517585).

Experimental Validation of Dynamic Force Control: (3) MDOF Nonlinear System

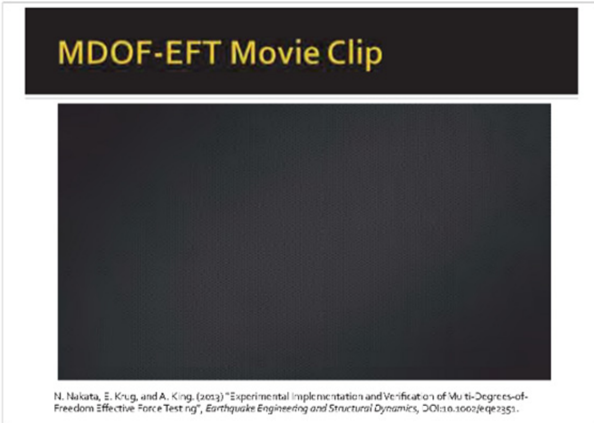
Dynamic Force Control Test





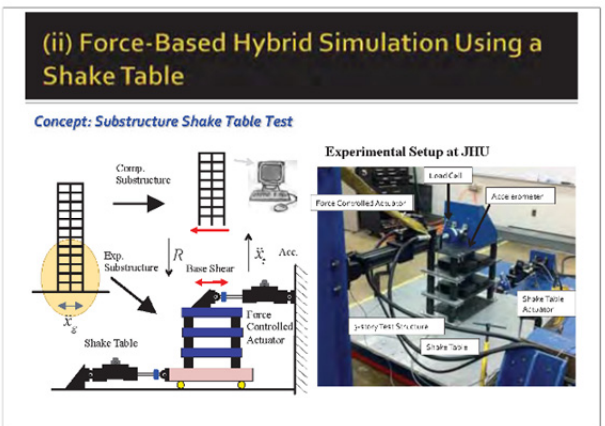


Appendix IX

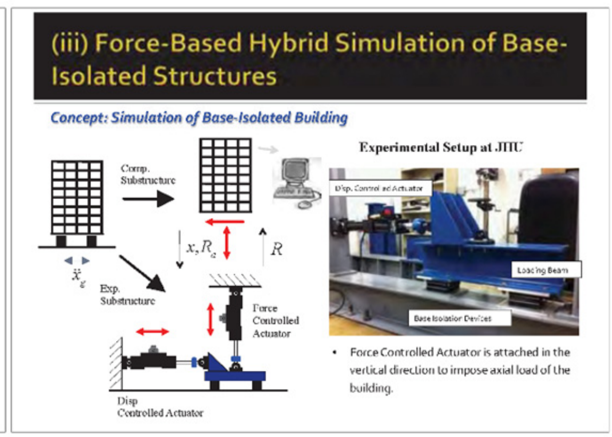


MDOF-EFT Movie Clip
N. Nakata, E. Krug, and A. King. (2013) "Experimental Implementation and Verification of Multi-Degrees-of-Freedom Effective Force Testing", Earthquake Engineering and Structural Dynamics, DOI:10.1002/eqe2351.

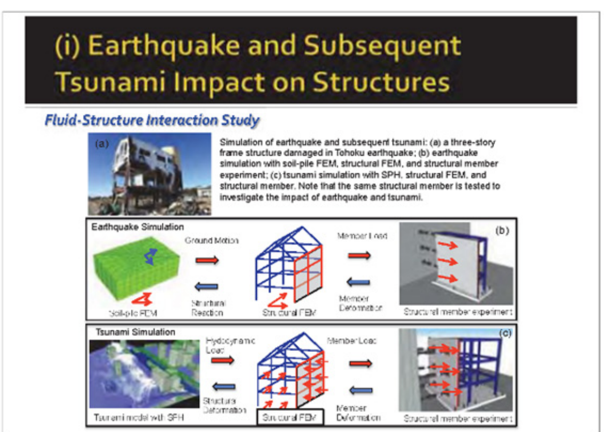
(i) Verification of EFT with Steel Frame Structures
1/4th-Scale Steel Frame
Specifications
Structure: One-Bay One-Story Steel Frame
Configurable Frame: Fixed-Fixed, Fixed-Pin, Pin-Pin
Sections: W6x16 and W4x13
Added Mass: 300kg (4 x 75 kg Steel Plates)
Actuator: Shore Western 911D
Stroke: +-3.0 inch, Load: 5.5 Kip
Servovalve: MTS 252
Objectives
Verify the effectiveness of EFT for performance assessment of steel frame structures
Evaluate the robustness of loop shaping
$f = m\ddot{x}$



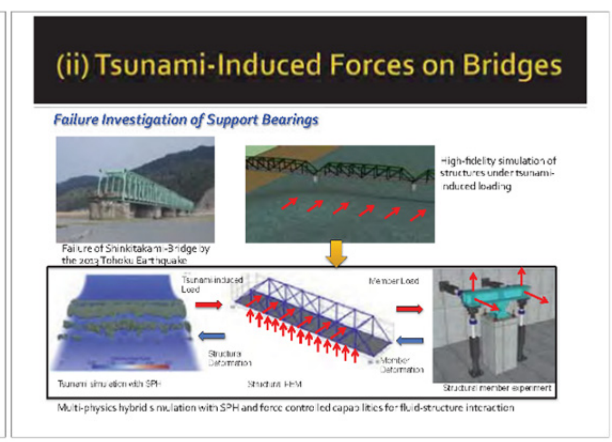
(ii) Force-Based Hybrid Simulation Using a Shake Table
Concept: Substructure Shake Table Test
Comp. Substructure
Exp. Substructure
R
Base Shear
$\ddot{x}_t$
Acc.
$\ddot{x}_g$
Force Controlled Actuator
Shake Table
Experimental Setup at JHU
Load Cell
Force Controlled Actuator
Accelerometer
Shake Table Actuator
3-story Test Structure
Shake Table



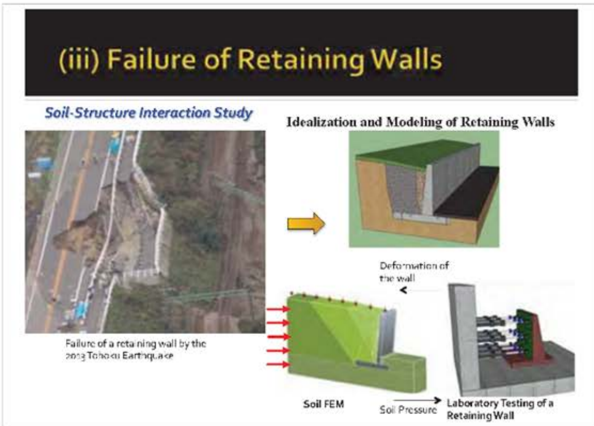
(iii) Force-Based Hybrid Simulation of Base-Isolated Structures
Concept: Simulation of Base-Isolated Building
Comp. Substructure
x, R_z
R
$\ddot{x}_g$
Exp. Substructure
Force Controlled Actuator
Disp Controlled Actuator
Experimental Setup at JHU
Disp. Controlled Actuator
Loading Beam
Base Isolation Devices
Force Controlled Actuator is attached in the vertical direction to impose axial load of the building.

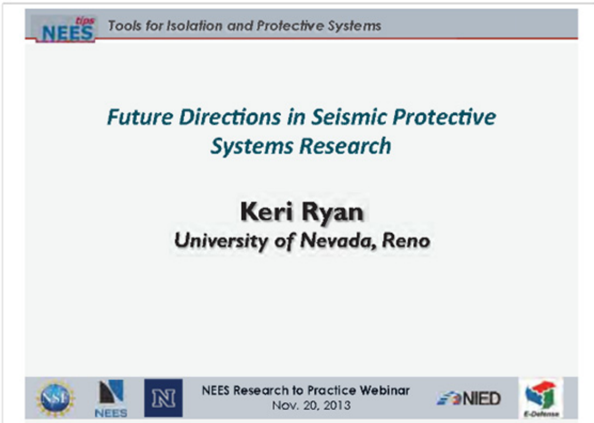


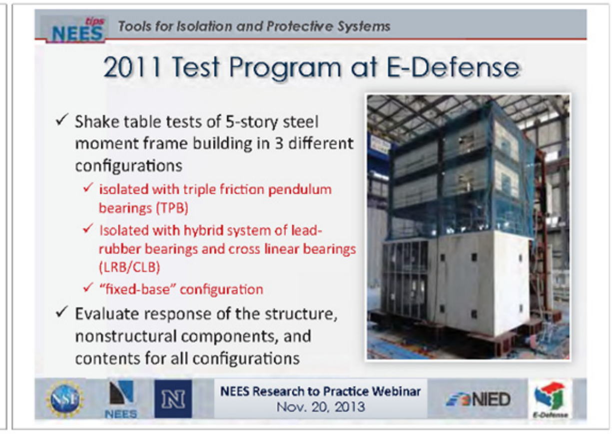
(i) Earthquake and Subsequent Tsunami Impact on Structures
Fluid-Structure Interaction Study
(a)
Simulation of earthquake and subsequent tsunami: (a) a three-story frame structure damaged in Tohoku earthquake; (b) earthquake simulation with soil-pile FEM, structural FEM, and structural member experiment; (c) tsunami simulation with SPH, structural FEM, and structural member. Note that the same structural member is tested to investigate the impact of earthquake and tsunami.
Earthquake Simulation
Ground Motion
Member Load
(b)
Soil-pile FEM
Structural Reaction
Structural FEM
Member Deformation
Structural member experiment
Tsunami Simulation
Hydrodynamic Load
Member Load
(c)
Tsunami model with SPH
Structural Deformation
Structural FEM
Member Deformation
Structural member experiment



(ii) Tsunami-Induced Forces on Bridges
Failure Investigation of Support Bearings
Failure of Shinkitakami-Bridge by the 2011 Tohoku Earthquake
High-fidelity simulation of structures under tsunami-induced loading
Tsunami induced Load
Member Load
Structural Deformation
Member Deformation
Tsunami simulation with SPH
Structural FEM
Structural member experiment
Multi-physics hybrid simulation with SPH and force controlled capabilities for fluid-structure interaction


(iii) Failure of Retaining Walls
Soil-Structure Interaction Study
Idealization and Modeling of Retaining Walls
Failure of a retaining wall by the
Tohoku Earthquake
Deformation of the wall
Soil FEM
Soil Pressure
Laboratory Testing of a Retaining Wall


NEES tips Tools for Isolation and Protective Systems
Future Directions in Seismic Protective Systems Research
Keri Ryan
University of Nevada, Reno
NEES Research to Practice Webinar
Nov. 20, 2013
NIED


NEES tips Tools for Isolation and Protective Systems
2011 Test Program at E-Defense
✓ Shake table tests of 5-story steel moment frame building in 3 different configurations
✓ isolated with triple friction pendulum bearings (TPB)
✓ Isolated with hybrid system of lead-rubber bearings and cross linear bearings (LRB/CLB)
✓ "fixed-base" configuration
✓ Evaluate response of the structure, nonstructural components, and contents for all configurations
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NEES tips Tools for Isolation and Protective Systems
Nonstructural Components and Contents
Ceilings and partitions
Piping
Enclosed contents rooms
4th and 5th floor of building
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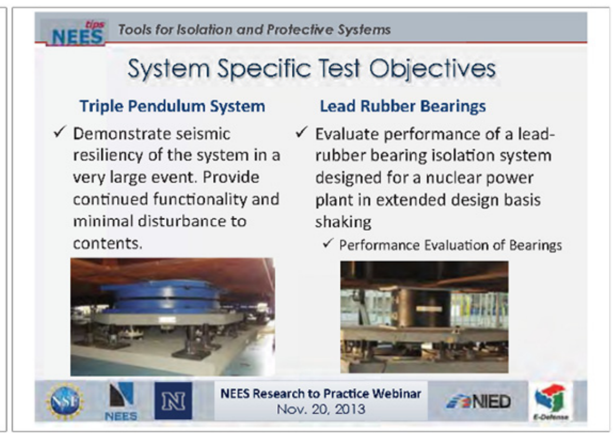
NEES tips Tools for Isolation and Protective Systems
System Specific Test Objectives
Triple Pendulum System
✓ Demonstrate seismic resiliency of the system in a very large event. Provide continued functionality and minimal disturbance to contents.
Lead Rubber Bearings
✓ Evaluate performance of a lead-rubber bearing isolation system designed for a nuclear power plant in extended design basis shaking
✓ Performance Evaluation of Bearings
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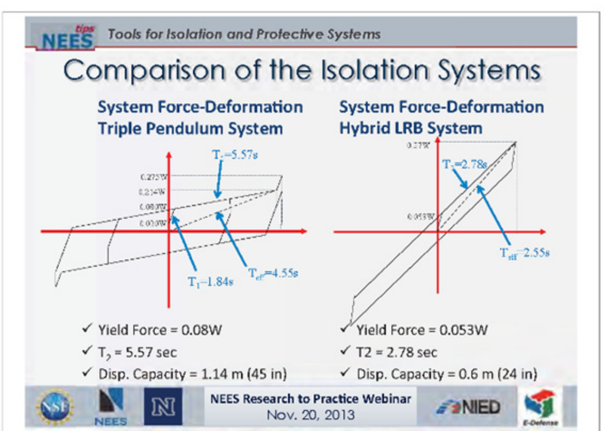
NEES tips Tools for Isolation and Protective Systems
Comparison of the Isolation Systems
System Force-Deformation Triple Pendulum System
System Force-Deformation Hybrid LRB System
T2=5.57s
T1=1.84s
Teff=4.55s
T2=2.78s
Teff=2.55s
✓ Yield Force = 0.08W
✓ T2 = 5.57 sec
✓ Disp. Capacity = 1.14 m (45 in)
✓ Yield Force = 0.053W
✓ T2 = 2.78 sec
✓ Disp. Capacity = 0.6 m (24 in)
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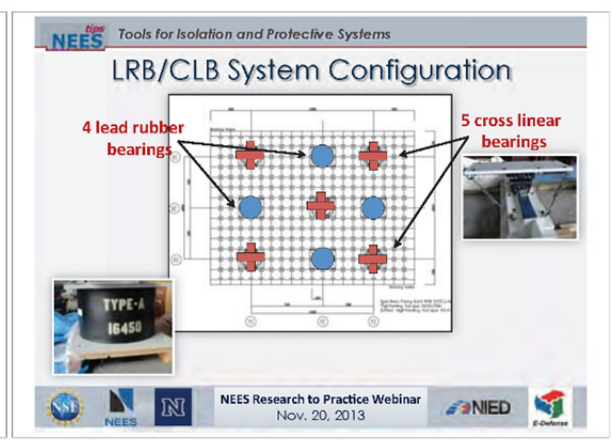
NEES tips Tools for Isolation and Protective Systems
LRB/CLB System Configuration
4 lead rubber bearings
5 cross linear bearings
TYPE-A
16450
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NIED

NEES tips — Tools for Isolation and Protective Systems

Remarks about the Systems

- ✓ Triple pendulum bearings have become the system of choice in the U.S. while elastomeric bearings with dampers are the system of choice in Japan.
- ✓ TPBs can more easily achieve longer period isolation and accommodate large displacement demands but there are some tradeoffs
  - ✓ Larger residual displacements (can they be predicted?)


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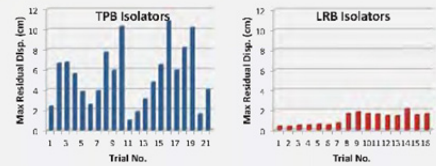
NEES tips — Tools for Isolation and Protective Systems

Summary of Residual Isolator Displacement



TPB System
Peak Residual Disp = 10.8 cm
Average Residual Disp = 5.4 cm

LRB System
Peak Residual Disp = 2.01 cm
Average Residual Disp = 1.2 cm

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NEES tips — Tools for Isolation and Protective Systems

Remarks about the Systems

- ✓ Triple pendulum bearings have become the system of choice in the U.S. while elastomeric bearings with dampers are the system of choice in Japan.
- ✓ TPBs can more easily achieve longer period isolation and accommodate large displacement demands but there are some tradeoffs
  - ✓ Larger residual displacements (can they be predicted?)
  - ✓ Susceptible to horizontal-vertical coupling effects


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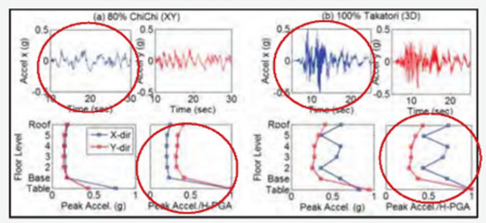
NEES tips — Tools for Isolation and Protective Systems

Floor Acceleration Response in TPB System, XY vs. 3D Motion (Vert. PGA = 0.3g)



- ✓ Evidence of coupling in the higher frequency acceleration histories and higher mode effects in the acceleration profiles

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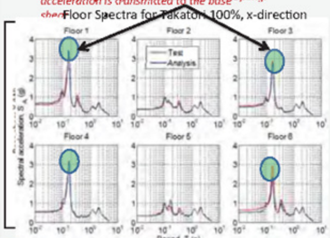
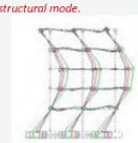
NEES tips — Tools for Isolation and Protective Systems

Horizontal and Vertical Coupling of the Isolation System (Friction Bearings)



The vertical driving frequency was tuned to the frequency of the 2nd structural mode.



2nd Structural Mode
X-direction
T = 0.17 sec

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NEES tips — Tools for Isolation and Protective Systems

Remarks about the Systems

- ✓ The hybrid approach (elastomeric bearings and sliding bearings) is an alternative to achieve longer periods and larger displacement demands, but...
  - ✓ Compliance of the two types of bearings at the base should be carefully considered
  - ✓ Tension is very likely; can it be predicted and accounted for in design?


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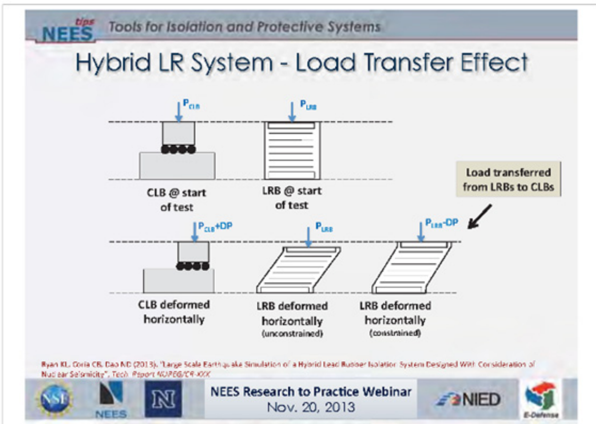
Appendix IX



Tools for Isolation and Protective Systems
Hybrid LR System - Load Transfer Effect
Load transferred from LRBs to CLBs
CLB @ start of test
LRB @ start of test
CLB deformed horizontally
LRB deformed horizontally (unconstrained)
LRB deformed horizontally (constrained)
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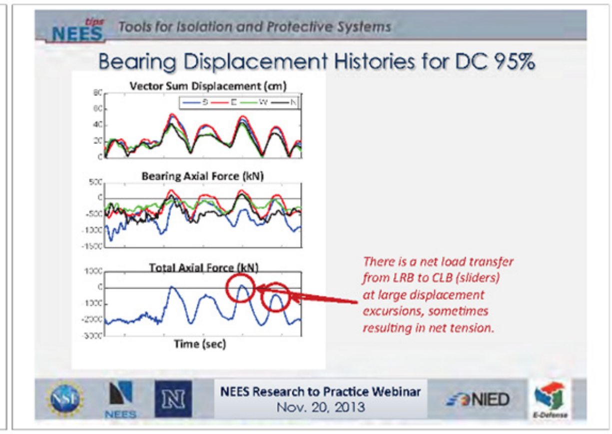

Tools for Isolation and Protective Systems
Bearing Displacement Histories for DC 95%
Vector Sum Displacement (cm)
Bearing Axial Force (kN)
Total Axial Force (kN)
Time (sec)
There is a net load transfer from LRB to CLB (sliders) at large displacement excursions, sometimes resulting in net tension.
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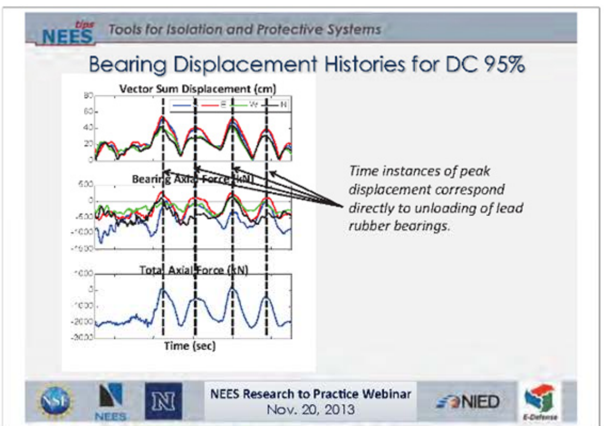

Tools for Isolation and Protective Systems
Bearing Displacement Histories for DC 95%
Vector Sum Displacement (cm)
Bearing Axial Force (kN)
Total Axial Force (kN)
Time (sec)
Time instances of peak displacement correspond directly to unloading of lead rubber bearings.
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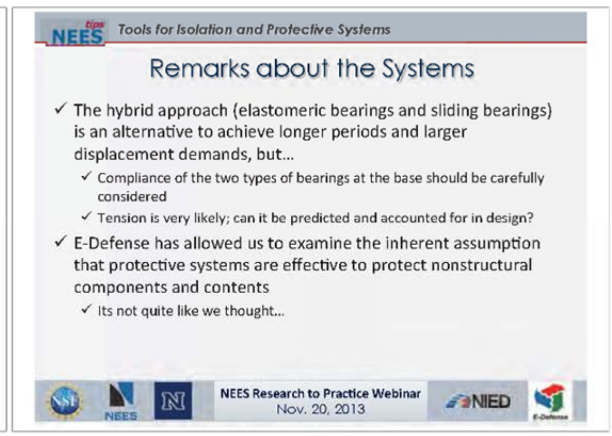

Tools for Isolation and Protective Systems
Remarks about the Systems
✓ The hybrid approach (elastomeric bearings and sliding bearings) is an alternative to achieve longer periods and larger displacement demands, but…
✓ Compliance of the two types of bearings at the base should be carefully considered
✓ Tension is very likely; can it be predicted and accounted for in design?
✓ E-Defense has allowed us to examine the inherent assumption that protective systems are effective to protect nonstructural components and contents
✓ Its not quite like we thought…
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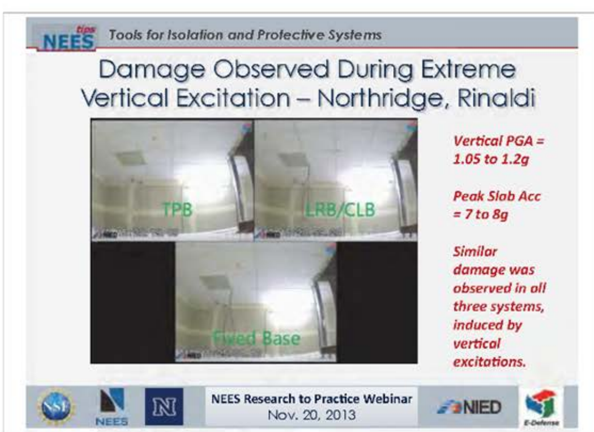

Tools for Isolation and Protective Systems
Damage Observed During Extreme Vertical Excitation – Northridge, Rinaldi
TPB
LRB/CLB
Fixed Base
Vertical PGA = 1.05 to 1.2g
Peak Slab Acc = 7 to 8g
Similar damage was observed in all three systems, induced by vertical excitations.
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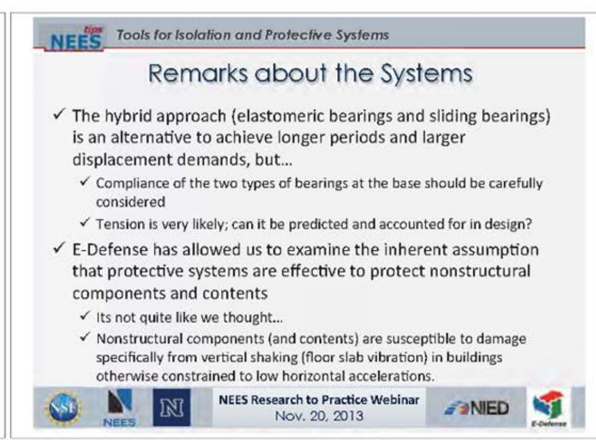

Tools for Isolation and Protective Systems
Remarks about the Systems
✓ The hybrid approach (elastomeric bearings and sliding bearings) is an alternative to achieve longer periods and larger displacement demands, but…
✓ Compliance of the two types of bearings at the base should be carefully considered
✓ Tension is very likely; can it be predicted and accounted for in design?
✓ E-Defense has allowed us to examine the inherent assumption that protective systems are effective to protect nonstructural components and contents
✓ Its not quite like we thought…
✓ Nonstructural components (and contents) are susceptible to damage specifically from vertical shaking (floor slab vibration) in buildings otherwise constrained to low horizontal accelerations.
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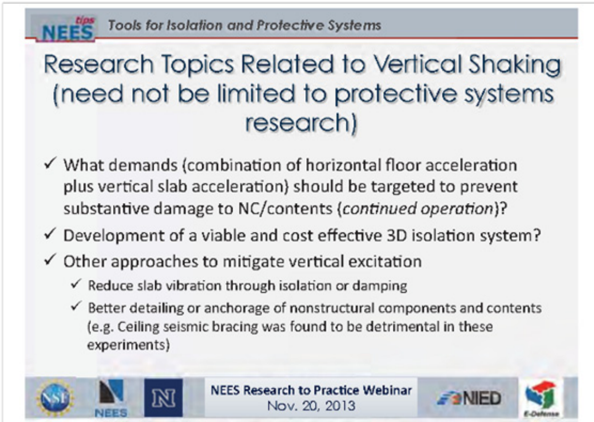
NEES tips
Tools for Isolation and Protective Systems
Research Topics Related to Vertical Shaking (need not be limited to protective systems research)
✓ What demands (combination of horizontal floor acceleration plus vertical slab acceleration) should be targeted to prevent substantive damage to NC/contents (*continued operation*)?
✓ Development of a viable and cost effective 3D isolation system?
✓ Other approaches to mitigate vertical excitation
✓ Reduce slab vibration through isolation or damping
✓ Better detailing or anchorage of nonstructural components and contents (e.g. Ceiling seismic bracing was found to be detrimental in these experiments)
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NEES
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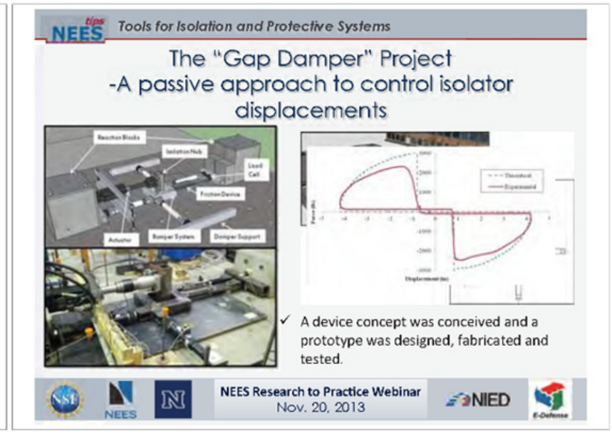
NEES tips
Tools for Isolation and Protective Systems
The "Gap Damper" Project
-A passive approach to control isolator displacements
Reaction Blocks
Isolation Hub
Load Cell
Friction Device
Actuator
Bumper System
Damper Support
✓ A device concept was conceived and a prototype was designed, fabricated and tested.
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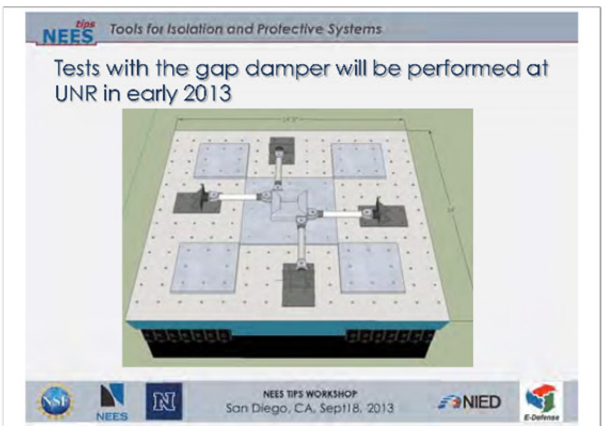
NEES tips
Tools for Isolation and Protective Systems
Tests with the gap damper will be performed at UNR in early 2013
NSF
NEES
NEES TIPS WORKSHOP
San Diego, CA, Sept18, 2013
NIED
E-Defense


NEES tips
Tools for Isolation and Protective Systems
Tests with the gap damper will be performed at UNR in early 2013
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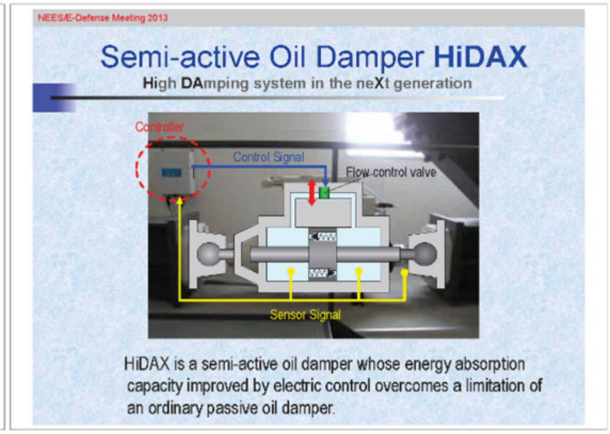
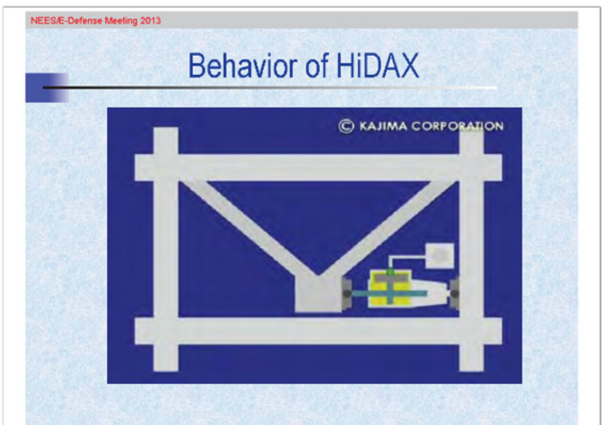
Appendix IX

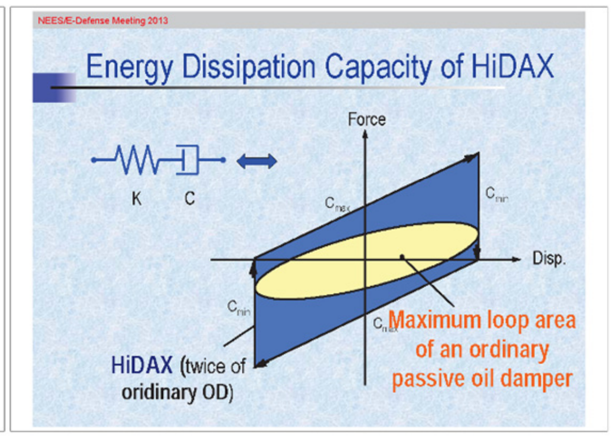
NEES/E-Defense Meeting 2013
2013/12/12
Kan Shimizu



NEES/E-Defense Meeting 2013
Semi-active Oil Damper HiDAX
High DAmping system in the neXt generation
Controller
Control Signal
Flow control valve
Sensor Signal
HiDAX is a semi-active oil damper whose energy absorption capacity improved by electric control overcomes a limitation of an ordinary passive oil damper.

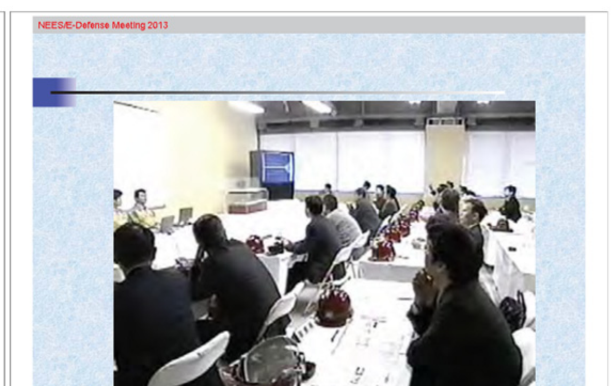


NEES/E-Defense Meeting 2013
Behavior of HiDAX
© KAJIMA CORPORATION

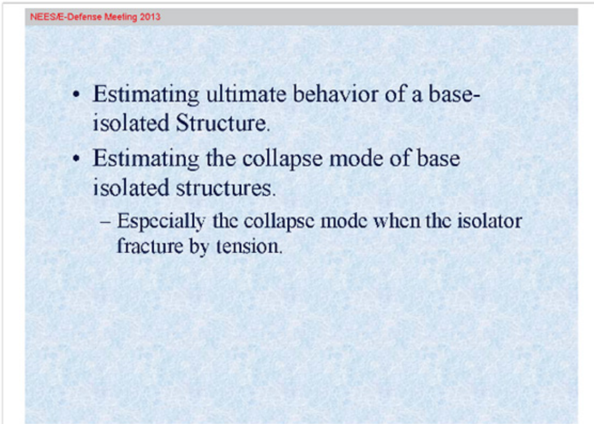


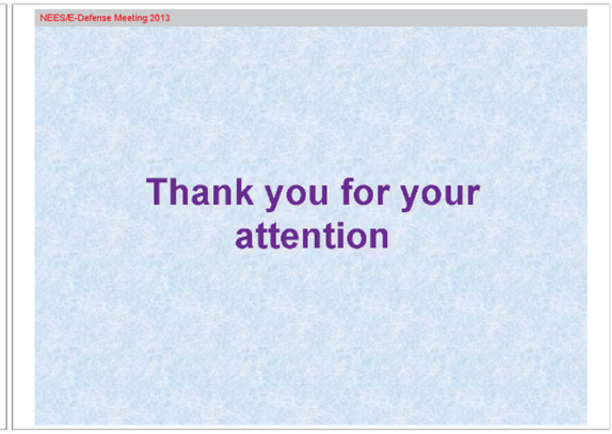
NEES/E-Defense Meeting 2013
Energy Dissipation Capacity of HiDAX
Force
K
C
Disp.
Maximum loop area of an ordinary passive oil damper
HiDAX (twice of oridinary OD)

NEES/E-Defense Meeting 2013
Forced vibration test in actual building with HiDAX

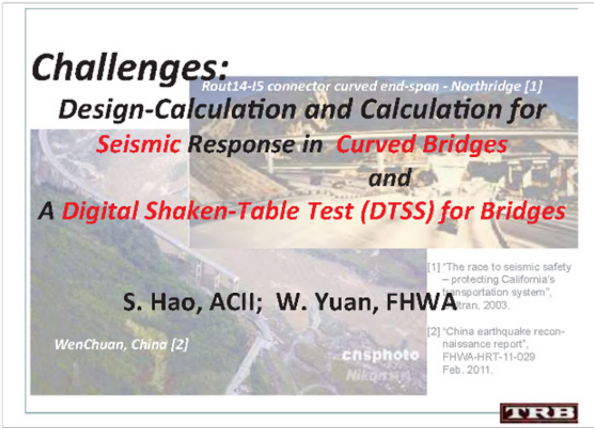


NEES/E-Defense Meeting 2013

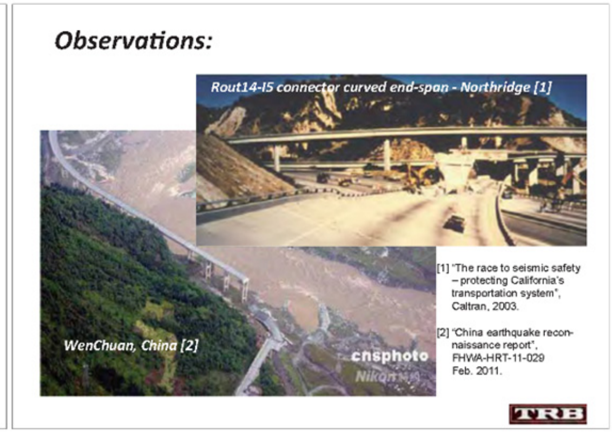

NEES/E-Defense Meeting 2013
• Estimating ultimate behavior of a base-isolated Structure.
• Estimating the collapse mode of base isolated structures.
– Especially the collapse mode when the isolator fracture by tension.


NEES/E-Defense Meeting 2013
Thank you for your attention

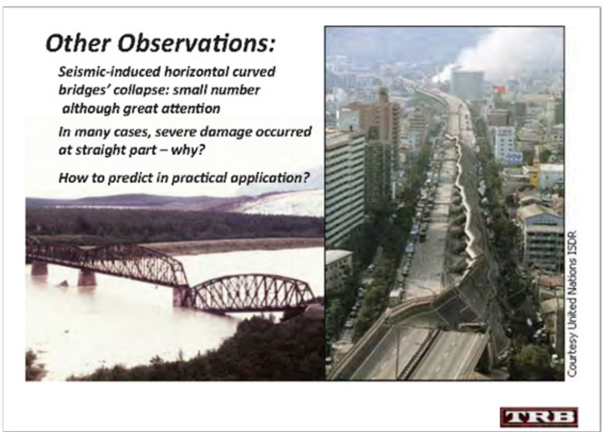
Appendix IX



Challenges:
Rout14-I5 connector curved end-span - Northridge [1]
Design-Calculation and Calculation for
Seismic Response in Curved Bridges
and
A Digital Shaken-Table Test (DTSS) for Bridges
S. Hao, ACII; W. Yuan, FHWA
WenChuan, China [2]
cnsphoto
[2] "China earthquake recon-naissance report", FHWA-HRT-11-029 Feb. 2011.
TRB

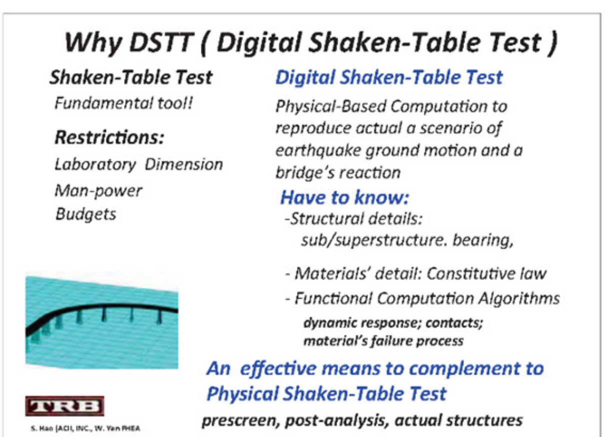


Observations:
Rout14-I5 connector curved end-span - Northridge [1]
WenChuan, China [2]
cnsphoto
[1] "The race to seismic safety – protecting California's transportation system", Caltran, 2003.
[2] "China earthquake recon-naissance report", FHWA-HRT-11-029 Feb. 2011.
TRB

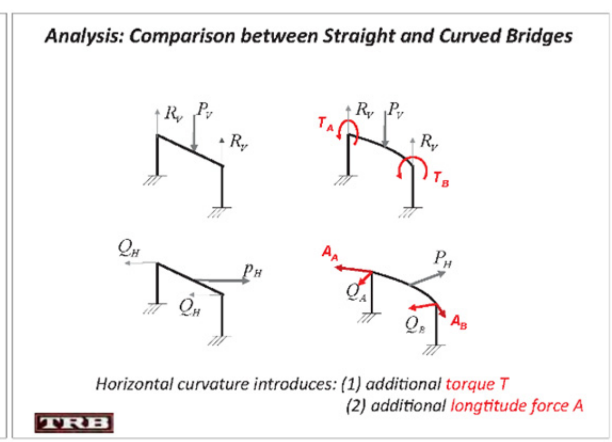


Other Observations:
Seismic-induced horizontal curved bridges' collapse: small number although great attention
In many cases, severe damage occurred at straight part – why?
How to predict in practical application?
Courtesy United Nations ISDR
TRB

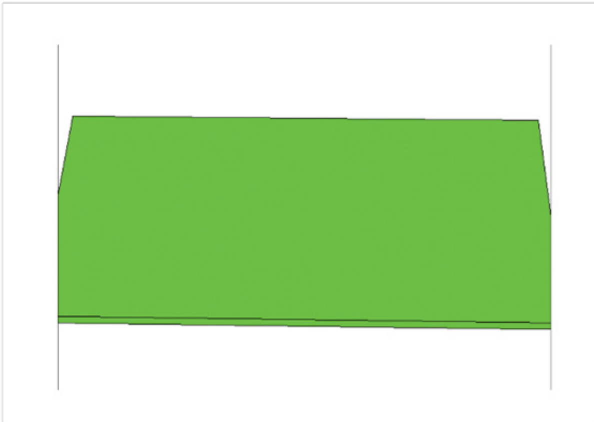
Motivations
-Horizontal curve: an additional structural complex to Bridges
-Two classes of horizontal curvature bridges:
main roads
off-highway: crossing / viaduct
- Regular service conditions:
NCHRP 12-52 TRB report 563
- Irregular service conditions:
seismic – current focus
- Challenges for fast, accurate design/rating calculation,
especially under complicated loads (irregular conditions)
e.g. resonate frequency
bearings lift-up
additional longitude load, torsion
- Methodology in this analysis
theoretical analysis + computation
DSTT: Digital Shaken-Table Test
comparison/verification with experiments/observation
TRB

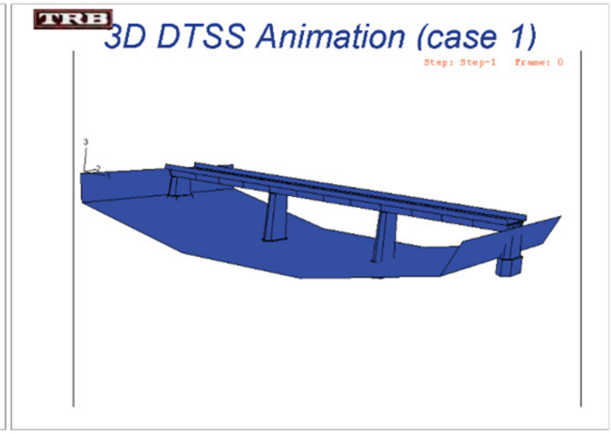


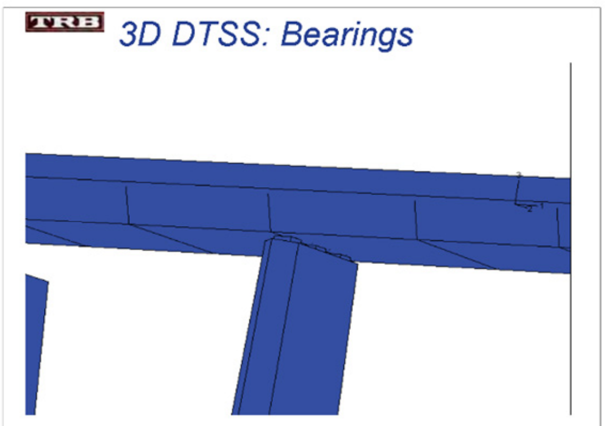
Why DSTT (Digital Shaken-Table Test)
Shaken-Table Test
Fundamental tool!
Restrictions:
Laboratory Dimension
Man-power
Budgets
Digital Shaken-Table Test
Physical-Based Computation to reproduce actual a scenario of earthquake ground motion and a bridge's reaction
Have to know:
-Structural details:
sub/superstructure. bearing,
- Materials' detail: Constitutive law
- Functional Computation Algorithms
dynamic response; contacts;
material's failure process
An effective means to complement to Physical Shaken-Table Test
prescreen, post-analysis, actual structures
TRB
S. Hao (ACII, INC., W. Yen FHEA

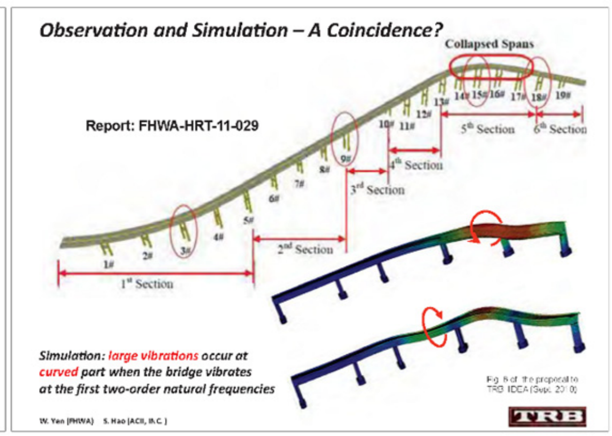


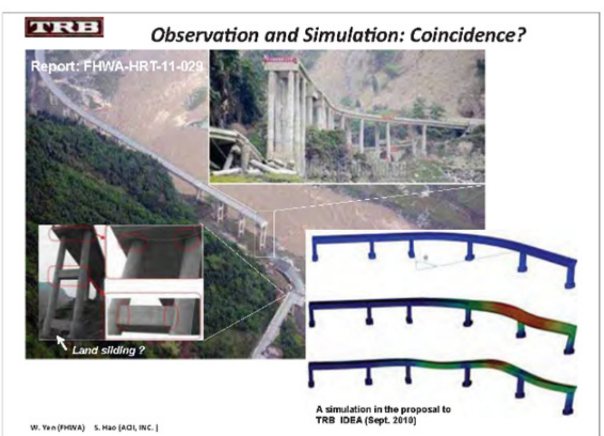
Analysis: Comparison between Straight and Curved Bridges
R_V
P_V
T_A
T_B
Q_H
P_H
A_A
A_B
Q_A
Q_B
Horizontal curvature introduces: (1) additional torque T
(2) additional longtitude force A
TRB

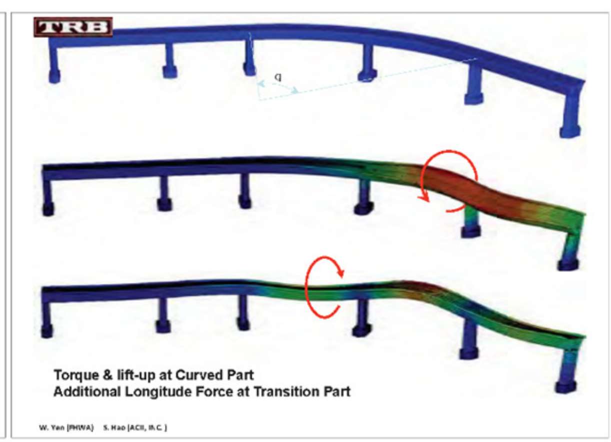



3D DTSS Animation (case 1)
Step: Step-1 Frame: 0


3D DTSS: Bearings


Observation and Simulation – A Coincidence?
Collapsed Spans
Report: FHWA-HRT-11-029
1st Section
2nd Section
3rd Section
4th Section
5th Section
6th Section
Simulation: large vibrations occur at curved part when the bridge vibrates at the first two-order natural frequencies
W. Yen (FHWA) S. Hao (ACII, INC.)


Observation and Simulation: Coincidence?
Report: FHWA-HRT-11-029
Land sliding ?
A simulation in the proposal to TRB IDEA (Sept. 2010)
W. Yen (FHWA) S. Hao (ACII, INC.)


Torque & lift-up at Curved Part
Additional Longitude Force at Transition Part
W. Yen (FHWA) S. Hao (ACII, INC.)

Appendix IX

TRB

Thank You for Your Attention!

Questions?

Refs. [1] Reciprocity in Elasticity (Achenbach, 2003)

Achenbach & Hao, April 14, 2009(17)

Using Base Isolation and Rocking for Earthquake Resilient Design of Structures in Near Fault Regions

Vladimir Calugaru, Yuan Lu, Grigorios Antonellis, and

Marios Panagiotou

Structural Engineering Mechanics and Materials
Department of Civil and Environmental Engineering
University of California, Berkeley

1

Question

In near fault regions, can we economically design the tall buildings and bridges to:

(a) remain operational and

(b) minimize the need for repairs

after large earthquakes (M6.3 to M7.8) ?

2

PART 1

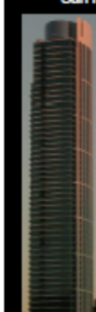
Earthquake Resilient Tall Buildings Using Base Isolation and Rocking Core Walls

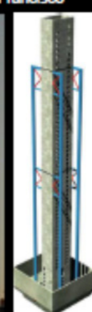
3

Tall RC Wall Buildings in Regions of High Seismicity

RC core walls for earthquake lateral force resistance

One Rincon Hill, 60-stories
San Francisco





Reinforcement
of a core wall

Notes of J.P. Moehle

Construction of Seattle Art Museum, WA, USA
Maffei and Yuen (2007)

4

Damage of Tall Buildings in Recent Earthquakes

2011 M6.3 NZ Earthquake

Out of the 50 tallest (taller than 35 m) buildings (average year of build = 1983) :

- 36 demolished (5 build after 2000)
- 7 fate is undecided
- 7 survived

2011 M6.3 NZ Earthquake

26-story Grand Chancellor Hotel, tallest building in Christchurch, demolished in 2012

Demolition of tall buildings in a densely built environment?

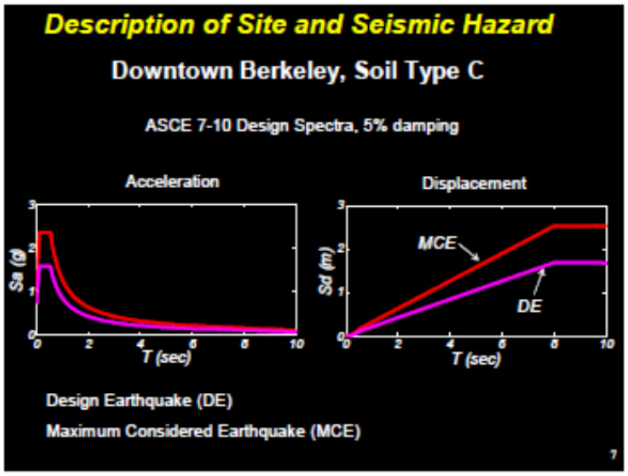
5

Case Study

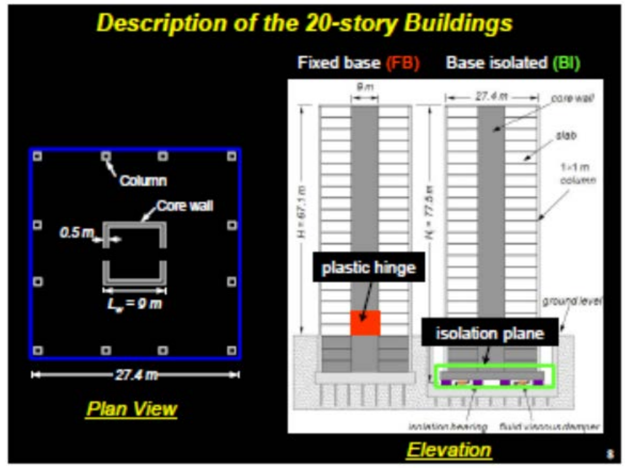
Comparison of seismic response of 20-story base-isolated and conventional fixed-base RC structural wall buildings hypothetically in Downtown Berkeley

6

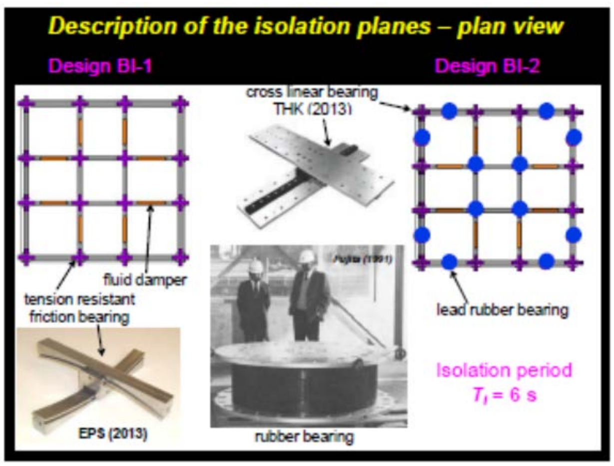
Appendix IX



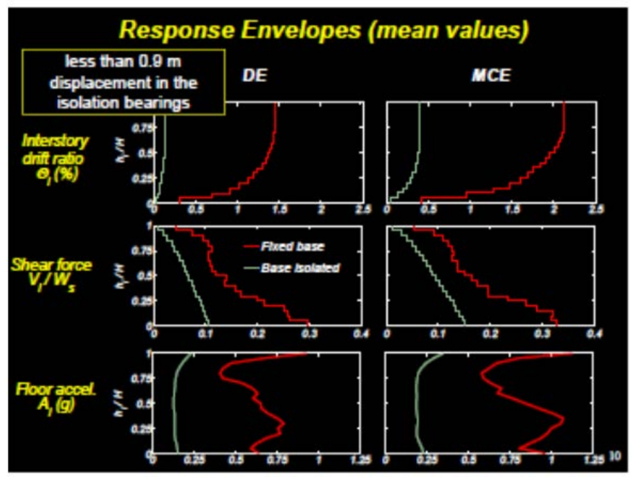
Description of Site and Seismic Hazard
Downtown Berkeley, Soil Type C
ASCE 7-10 Design Spectra, 5% damping
Acceleration
Displacement
Sa (g)
Sd (m)
T (sec)
MCE
DE
Design Earthquake (DE)
Maximum Considered Earthquake (MCE)
7



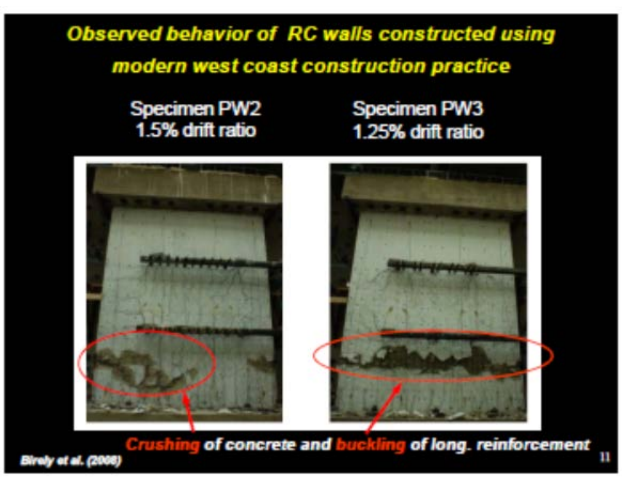
Description of the 20-story Buildings
Fixed base (FB)
Base isolated (BI)
Column
Core wall
0.5 m
L_w = 9 m
27.4 m
Plan View
plastic hinge
isolation plane
Elevation
8



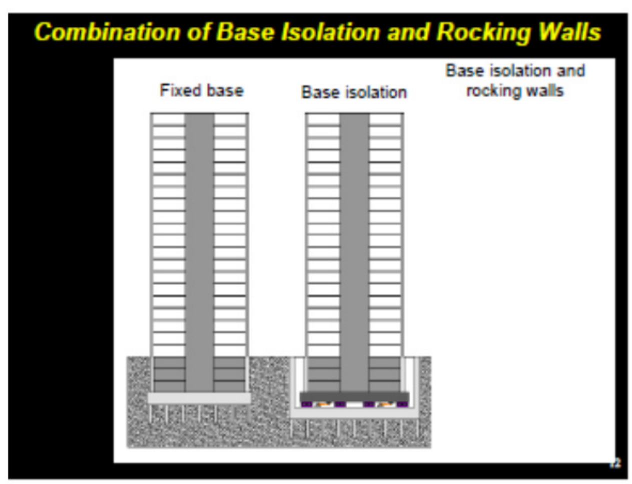
Description of the isolation planes – plan view
Design BI-1
Design BI-2
cross linear bearing
THK (2013)
fluid damper
tension resistant
friction bearing
EPS (2013)
rubber bearing
lead rubber bearing
Isolation period
T_I = 6 s



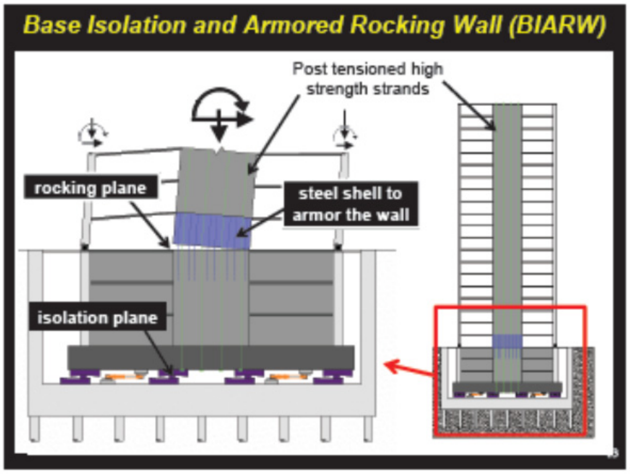
Response Envelopes (mean values)
less than 0.9 m
displacement in the
isolation bearings
DE
MCE
Interstory drift ratio θ_i (%)
Shear force V_i/W_s
Floor accel. A_i (g)
Fixed base
Base isolated
10

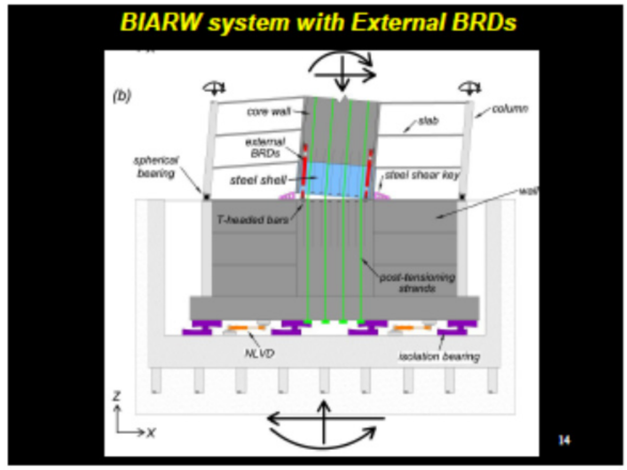


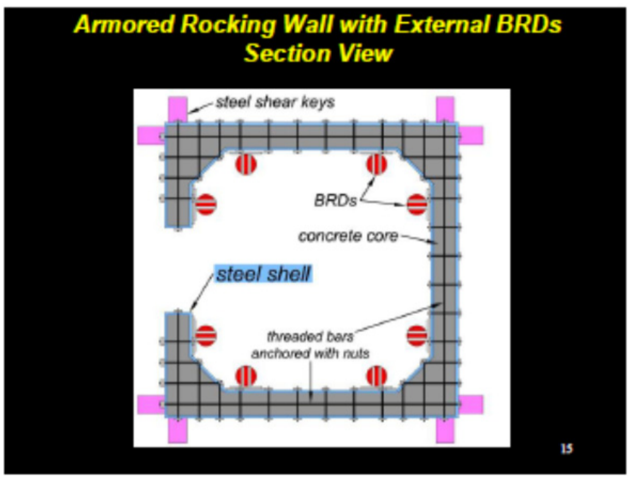
Observed behavior of RC walls constructed using
modern west coast construction practice
Specimen PW2
1.5% drift ratio
Specimen PW3
1.25% drift ratio
Crushing of concrete and buckling of long. reinforcement
Birely et al. (2008)
11



Combination of Base Isolation and Rocking Walls
Fixed base
Base isolation
Base isolation and
rocking walls
12



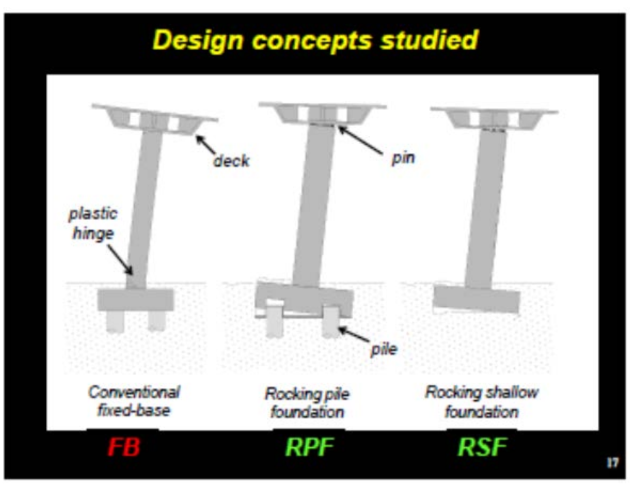




PART 2

Large-scale shake table test of columns supported on rocking shallow foundations

16



Ongoing research project funded by California Department of Transportation (Caltrans)

Experimental part was completed on May 2013

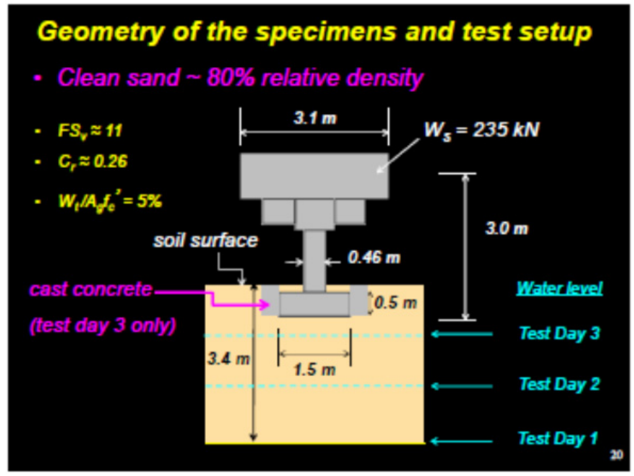
Principal Investigators	Graduate Student Researchers
Marios Panagiotou, UC Berkeley	Grigorios Antonellis, UC Berkeley
Bruce Kutter, UC Davis	Andreas Gavras, UC Davis
Jose Restrepo, UC San Diego	Gabriele Guerrini, UC San Diego
Patrick Fox, UC San Diego	Andrew Sander, UC San Diego
Stephen Mahin, UC Berkeley	

Caltrans

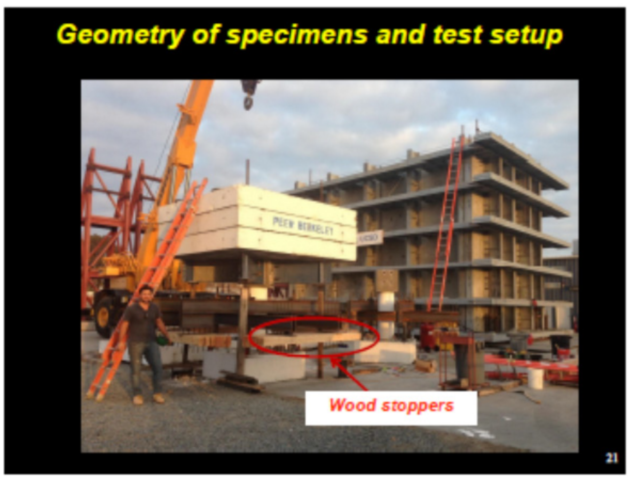
18

Appendix IX

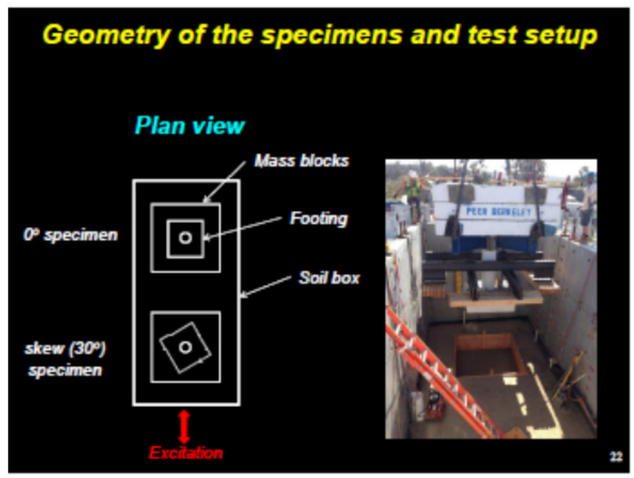
NEES@UCSD large confinement soil box
7.6 m
9.1 m
4.6 m
19



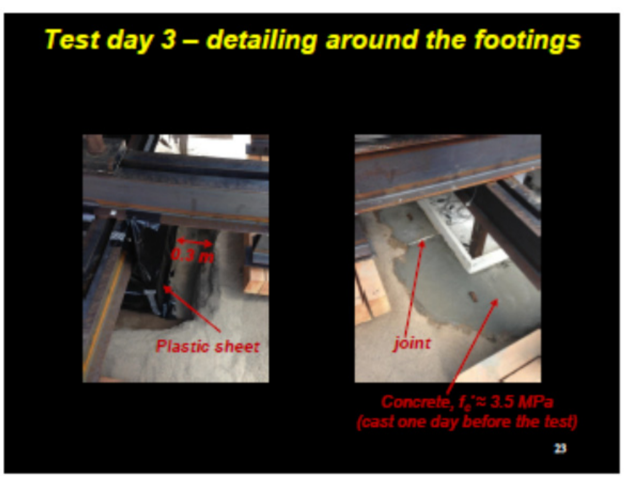
Geometry of the specimens and test setup
• Clean sand ~ 80% relative density
• $FS_v \approx 11$
• $C_r \approx 0.26$
• $W_t/A_g f_c' = 5\%$
3.1 m
W_s = 235 kN
3.0 m
soil surface
0.46 m
cast concrete
(test day 3 only)
0.5 m
Water level
Test Day 3
3.4 m
1.5 m
Test Day 2
Test Day 1
20



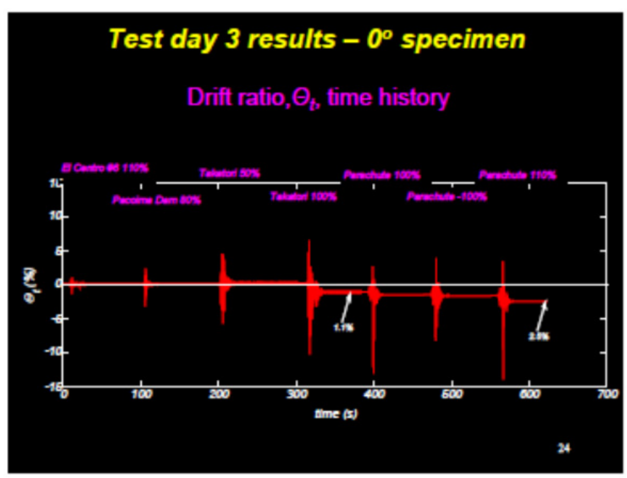
Geometry of specimens and test setup
Wood stoppers
21



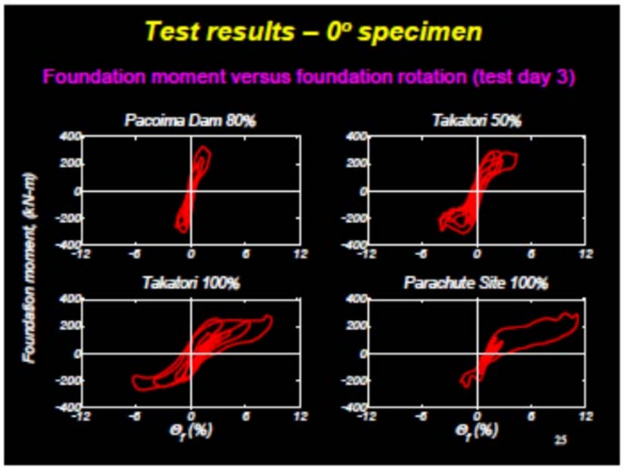
Geometry of the specimens and test setup
Plan view
Mass blocks
Footing
0° specimen
Soil box
skew (30°) specimen
Excitation
22



Test day 3 – detailing around the footings
0.3 m
Plastic sheet
joint
Concrete, $f_c' \approx$ 3.5 MPa
(cast one day before the test)
23



Test day 3 results – 0° specimen
Drift ratio, Θ_t, time history
Θ_t (%)
time (s)
24


Test results – 0° specimen
Foundation moment versus foundation rotation (test day 3)
Pacoima Dam 80%
Takatori 50%
Takatori 100%
Parachute Site 100%
Foundation moment (kN-m)
θ_f (%)
25

APPENDIX X: PRESENTED PAPERS IN GEOTECHNICAL ENGINEERING WORKING GROUP

NEES/E-Defense Collaborative Earthquake Research Program 10th Planning Meeting

Geotechnical Breakout Session

DPRI, Kyoto University

Chairs: Shuji Tamura, Jonathan Stewart
Recorder: Ramin Motamed

Dec 12-13, 2013

Introductions

Affiliation

Primary research interests

Experience with Japan-US collaboration in research?

Agenda

- Introductions. Session overview. Tamura, Stewart
- E Defense Research. Kawamata
- *Ground motions, site response, applications of recordings.*
  - Midorikawa, Rathje, Nakamura, Mikami.
  - Discussion
- *Utilization of field performance data*
  - Sitar, Nakai, Tobita, Kashiwa
  - Discussion
- *Shaking Table Testing and Centrifuge Testing for Soil-Structure Interaction and Related Applications*
  - Gillis, Dashti, Hashash, Fuji, Motamed, Funahara, Frost
  - Discussion

Presentation Goals

- Identify critical research needs.
  - Short term or long term.
  - De-couple needs from research tools
- Are there barriers limiting progress in this area?
- What are the data needs?
- Role of Japan-US collaboration in this area?

- Please adhere to allotted time.
- Please use Q/A following talks for clarifications

Breakout Session Goals

- Identify the most promising areas for future research.
- Can Japan-US collaboration substantively impact advancements in this area?
- What is the role of E-Defense and NEES facilities in meeting research goals?
- Identify barriers (if any) limiting collaborative work and possible solutions

Appendix X

Dynamic interaction between pile foundation and liquefied ground

- Shaking table tests and Effective stress analyses -

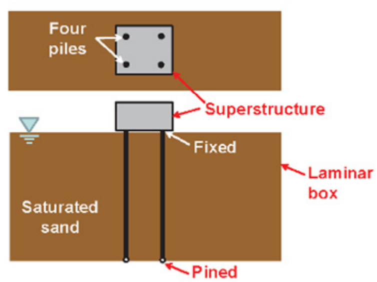
Dec./12/2013

Hideki Funahara

Three tests

Shaking table tests				Numerical simulation
No.	Gravity	Pile type	Main focus	
1	1g	RC pile (Non-linear)	pile damage due to liquefaction	2D
2		Steel pile (Linear)	pile stress and total subgrade reaction	2D & 3D
3	40g	Steel pile (Linear)	components of subgrade reaction	2D

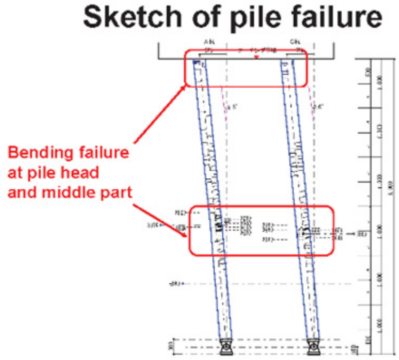
Common conditions



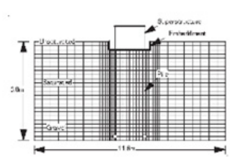
Test No.1 - RC pile failure

(Test No.1: NIED, KAJIMA, TAISEI, TAKENAKA)

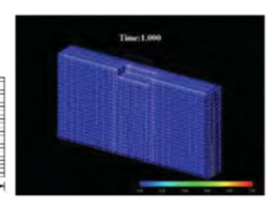
Sketch of pile failure



Numerical simulation of Test No.2 - Steel pile -

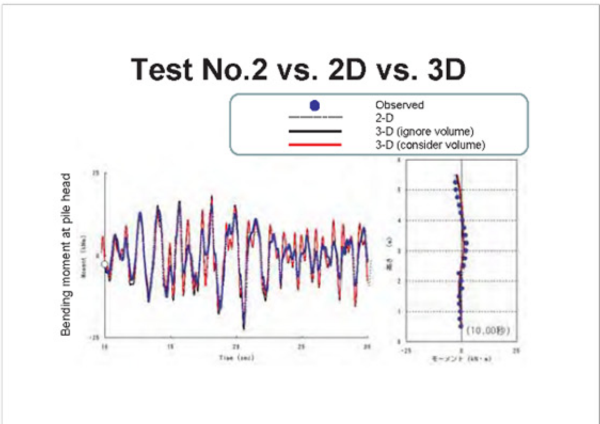


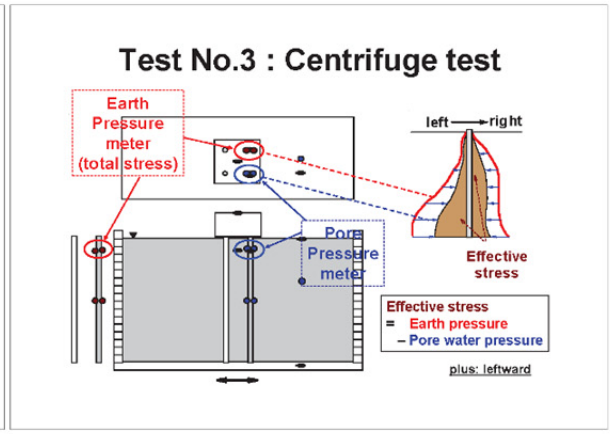
2-D

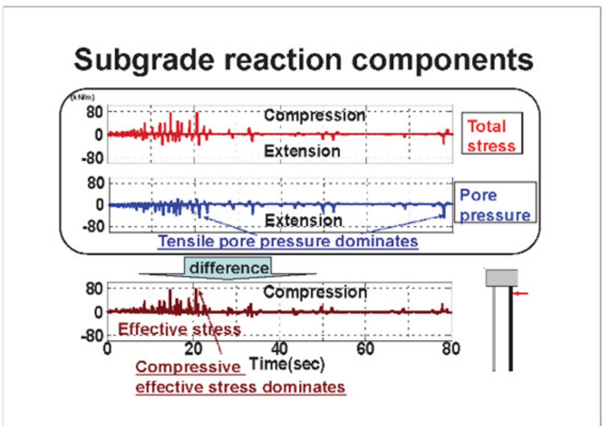


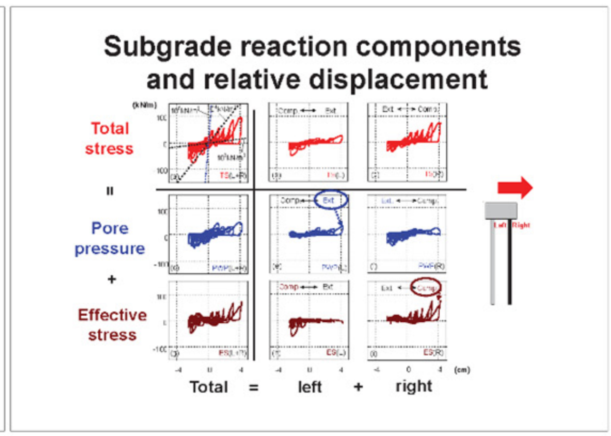
3-D

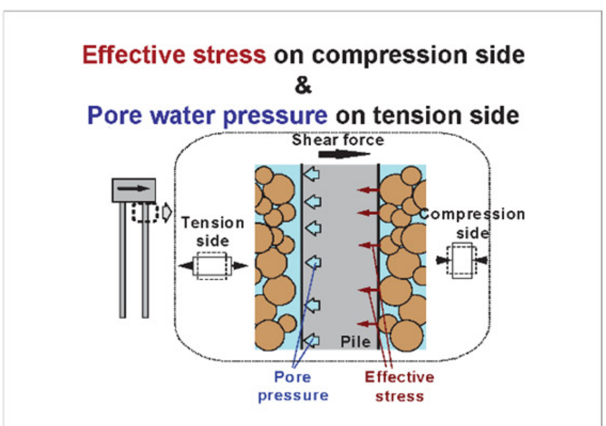
(Test No.2: NIED, TITECH, KAJIMA, TAISEI, TAKENAKA, etc.)

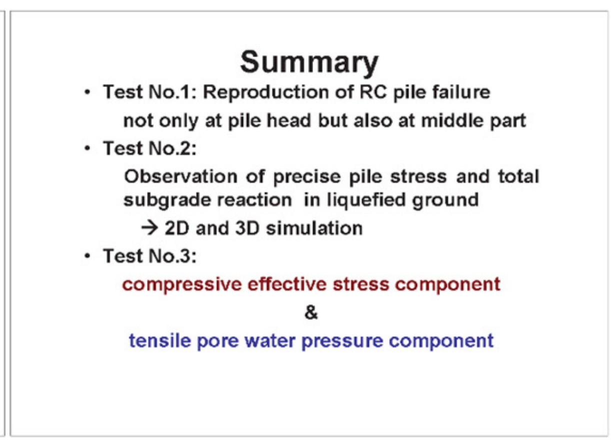

Test No.2 vs. 2D vs. 3D
Observed
2-D
3-D (ignore volume)
3-D (consider volume)
Bending moment at pile head
(10.00秒)


Test No.3 : Centrifuge test
Earth Pressure meter (total stress)
Pore Pressure meter
left
right
Effective stress
Effective stress
= Earth pressure
– Pore water pressure
plus: leftward


Subgrade reaction components
(kN/m)
80
0
-80
Compression
Extension
Total stress
Pore pressure
Tensile pore pressure dominates
difference
Effective stress
0
20
40
60
80
Time(sec)
Compressive effective stress dominates


Subgrade reaction components and relative displacement
Total stress
=
Pore pressure
+
Effective stress
Total
=
left
+
right


Effective stress on compression side
&
Pore water pressure on tension side
Shear force
Tension side
Compression side
Pile
Pore pressure
Effective stress


Summary
• Test No.1: Reproduction of RC pile failure
not only at pile head but also at middle part
• Test No.2:
Observation of precise pile stress and total subgrade reaction in liquefied ground
→ 2D and 3D simulation
• Test No.3:
compressive effective stress component
&
tensile pore water pressure component

Future issues

- Non-linearity of RC pile depending on varying axial force -> E-defense
- Pile behavior in cohesive or intermediate soil
- Liquefaction countermeasure

  (ideally, treated on shear box)

  .so on

Simulation Analysis of damaged structure supported by piles in heavily damaged zone during the 1995 Kobe earthquake

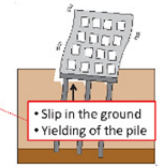
Osaka University Hisatoshi KASHIWA
Takaharu NAKANO
Yuji MIYAMOTO

Motivations for Research

In 1995 Kobe earthquake
Many pile structures were damaged.
(the report by Kinki Branch of AIJ)

- The causes of pile damages have not been analyzed in detail in no liquefaction area yet.
- There are few effective methods to prevent the damage of piles to very large earthquake.

- The seismic behavior of pile structure will be significantly affected by the nonlinear soil-structure interaction.
- It is necessary to investigate the damage factor by the analysis method that can evaluate the nonlinear soil-structure interaction effect.

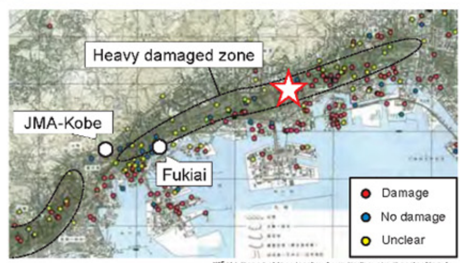


Objectives and Topics

The simulation analysis of damaged structure in Kobe earthquake by 3D-FEM Analysis.

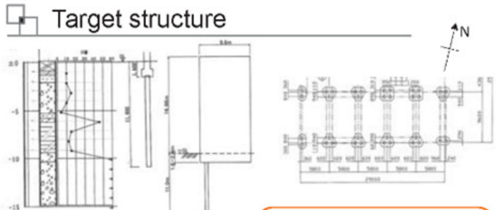
- To clarify the causes of structural damages of piles.
- It is necessary to improve the analysis model. As one of the improvement points, we focus on the parameter of ground property, especially strength of ground.
- The present problem for the evaluation of seismic response of structure during very large earthquake

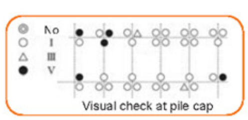
Location of target structure



Target structure is located in the center of the heavy damaged zone.

Target structure

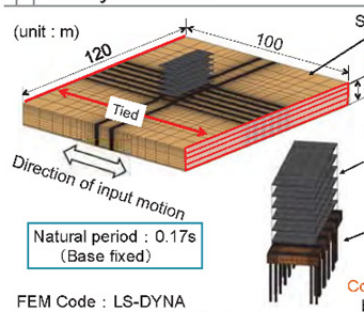




- RC Structure, 6 stories
- Completion : 1994
- Piles : PHC φ600, length 10m
- Footing is embedded in 1.5m
- Sandy ground
- No liquefaction

- Some pile cap damaged (Superstructure : No damage)

Analysis model



Surface layer: Elastic-Plastic (R-O Model)

Superstructure &Footing : Elastic

Piles : Elastic-Plastic and Contact condition between pile-soil

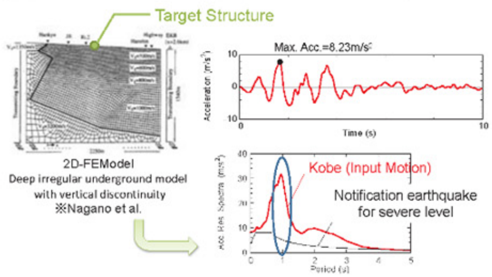
Natural period : 0.17s (Base fixed)

FEM Code : LS-DYNA (Explicit method)

6

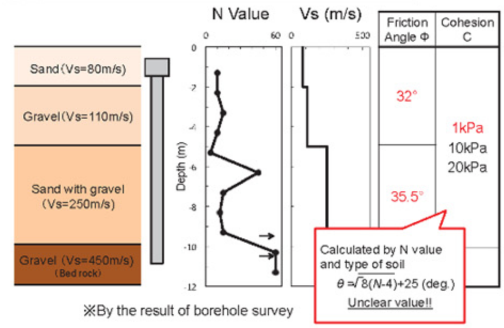
Appendix X

Input ground motion



The input ground motion is far larger than the seismic acceleration of the Notification earthquake for severe level

Properties of surface layer



Cohesion of sandy soil

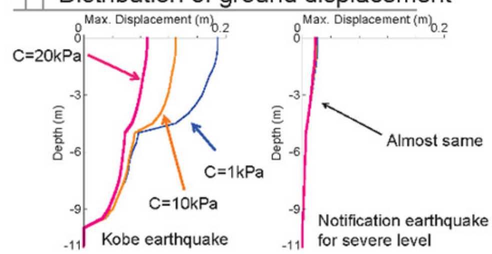
- There are a few report that the sandy soil in natural ground has a little cohesion by the teriaxial compression test with freezing sampling.

Table Triaxial compression test with freezing sampling

	Depth (m)	N Value	Triaxial compression test c (kPa)	Triaxial compression test φ (degree)
A	7.3	21	10.8	41.2
	15.5	36	18.6	39.9
B	5	16.5	18.6	37.9
	14	32.3	40.2	37.1
C	6	24	7.8	33.4
	19	28	27.4	34.7

➢ In this study, three analyses were conducted as parameter for cohesion, c = 1, 10, 20kPa.

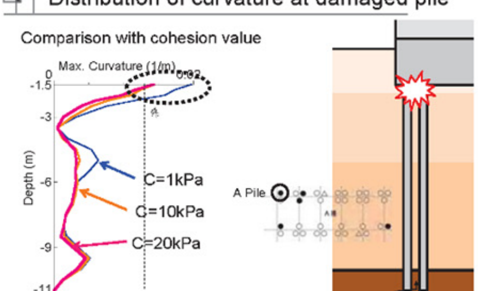
Distribution of ground displacement



➢ In the case of Kobe earthquake, cohesion has significant influence on displacement of ground.
➢ The input ground motion is extremely large.
→ Large ground deformation (Even if no liquefaction)

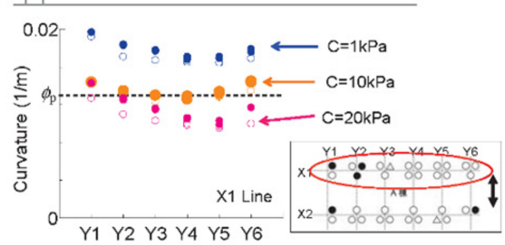
Distribution of curvature at damaged pile

Comparison with cohesion value

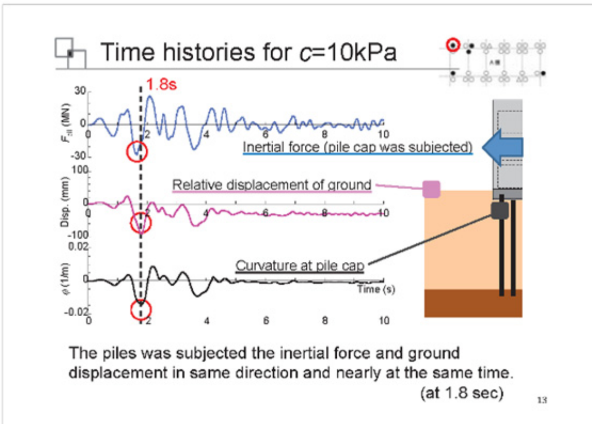


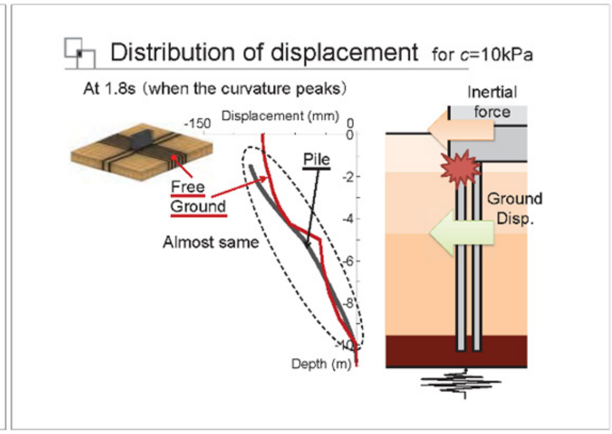
Curvature is concentrated at pile cap, and larger than full plastic value in all cases.

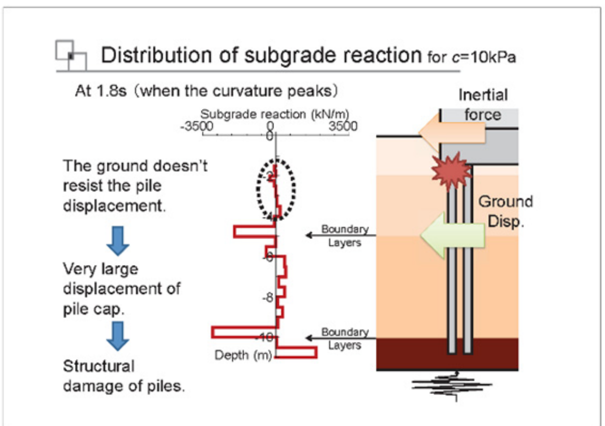
Distribution of maximum curvature

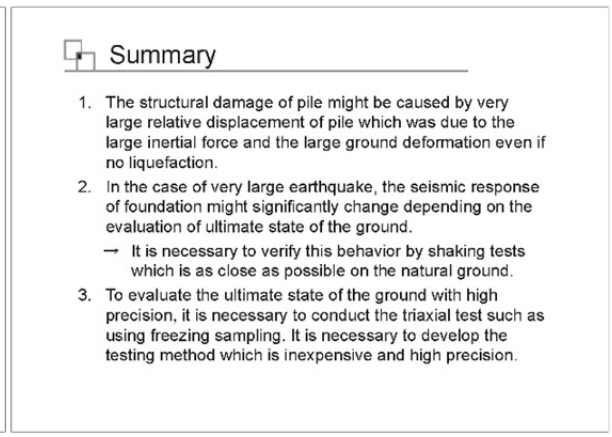


➢ In all cases, curvatures at pile caps in the edge is large and this is correlative with damage situation.
➢ The cohesion of the sand might have significant influence on the seismic response of pile.


Time histories for c=10kPa
1.8s
Inertial force (pile cap was subjected)
Relative displacement of ground
Curvature at pile cap
Time (s)
The piles was subjected the inertial force and ground displacement in same direction and nearly at the same time.
(at 1.8 sec)
13


Distribution of displacement for c=10kPa
At 1.8s (when the curvature peaks)
Displacement (mm)
-150
0
Free Ground
Pile
Almost same
Depth (m)
Inertial force
Ground Disp.


Distribution of subgrade reaction for c=10kPa
At 1.8s (when the curvature peaks)
Subgrade reaction (kN/m)
-3500
0
3500
The ground doesn't resist the pile displacement.
Very large displacement of pile cap.
Structural damage of piles.
Boundary Layers
Boundary Layers
Depth (m)
Inertial force
Ground Disp.


Summary
1. The structural damage of pile might be caused by very large relative displacement of pile which was due to the large inertial force and the large ground deformation even if no liquefaction.
2. In the case of very large earthquake, the seismic response of foundation might significantly change depending on the evaluation of ultimate state of the ground.
→ It is necessary to verify this behavior by shaking tests which is as close as possible on the natural ground.
3. To evaluate the ultimate state of the ground with high precision, it is necessary to conduct the triaxial test such as using freezing sampling. It is necessary to develop the testing method which is inexpensive and high precision.

Appendix X

NEES/E-Defense Collaborative Earthquake Research Program 10th Planning Meeting

GEOTECH & UNDERGROUND STRUCTURES

POSSIBLE FUTURE RESEARCHES USING E-DEFENSE SHAKE TABLE

Yohsuke KAWAMATA

National Research Institute for Earth Science and Disaster Prevention (NIED)

E-Defense

NIED

Keywords on Current Trend

➢ Matured Society ➞ Gradually Declined Society

"Sustainable Development" does not always mean "Continuous Growth"
"Maintenance of the Current Situation".

< Consideration Span >

In this long span of civil engineering, "Accepting the Decline, Preparation for Future Chance of Growth" is also a part of "Sustainable Development".

More Fundamental Research can be a step for future growth

NIED 2

Keywords on Current Trend

➢ Earthquake ➞ Tsunami, Rainstorm, (Tornado)

Improving seismic performance of "single structures"

→ Still important in "developing society"
→ Less impact to "developed society"
means only few chance to get sponsors for E-Defense Test

Possible Composite Disasters damaging large area

- Earthquake followed by Tsunami
  → Give impact from Tsunami or Backwash to buildings along coast on shake table
- Heavy rainstorm before/during/after Earthquake
  → Give rainfall to slope on shake table using special device

3

Keywords on Current Trend

➢ Disaster Prevention ➞ Disaster Mitigation

Disaster Prevention (防災 Bosai):
Prevention = "To keep from happening"
Protect "100%" lives/properties from "design motions" "without" serious consideration on limitation of resource

For instance, Old-fashioned!?

DPRI = Disaster Prevention ~ (established in 1951)
NIED = ~ Disaster Prevention (established in 1963)

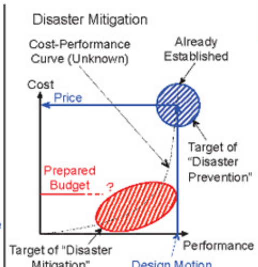
Disaster Mitigation (減災 Gensai):
Mitigation = "To moderate (a quality or condition) in force or intensity"
Protect lives/properties "as much as possible" "with" consideration on limitation of resource

NIED 4

Keywords on Current Trend

Automobile / Computer

Disaster Mitigation



Find **Optimum Solution** with the best cost-performance

NIED 5

Keywords on Current Trend

➢ Hardware ➞ Combination of Hard-, Soft- and Human-wares

Cost High

Our main role

< Hardware : Structure >
More accurate soil investigation, numerical analysis and design
Construction method with higher performance and/or lower cost
Effective performance verification method (including monitoring)

< Software : Plan, Regulation >
Urban planning
Disaster mitigation plan developed by national or local governments
Regulations

Low

< Humanware : Education, Training >
Disaster mitigation education ← E-Defense test movies
Evacuation training program

In the close future, researches on "Hardware" cannot be independent from the other wares!?

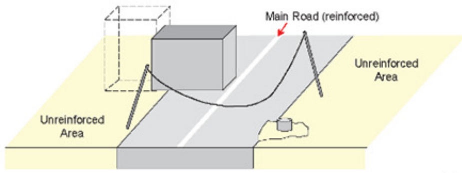
NIED 6

Keywords on Current Trend

An example of "Combination of Hard- and Soft-wares"

- To develop resilient cities, network of main roads needs to be functional even after strong motions.
- For instance, in case that unreinforced land widely spreads around the reinforced road network, can the network be functional?

→ For effective urban planning, it is important to specify the top priority.



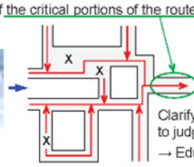
NIED 7

Keywords on Current Trend

An example of "Combination of Hard- and Human-wares"

- In most cases, evacuation plan/training program is developed based on conditions without minor structure damages.
- For instance, if evacuation routes "seem" seriously damaged for evacuating people though they are completely fine as structures, people may "hesitate" using the routes. It may induce fatal jam of evacuation.

→ Special considerations on human behavioral science need to be paid into design of the critical portions of the routes.



Clarify what can be simple index to judge if the route is fine.
→ Educate leaders in societies

NIED 8

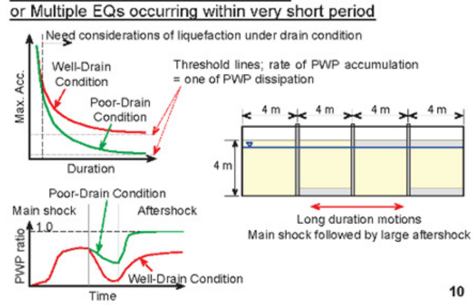
Themes of Future Researches

1. **"More Fundamental Research"**, a step toward further researches
2. **Mitigation against "Newly-remarked Natural Disasters"**, with considerations on other natural disasters than EQ
3. **"Practical Problems" which need to be solved ASAP**, establishing effective "mitigation", not "prevention"
4. **"2 or 3 Dimensional" Seismic Performance**, combining hard-, soft-, and human-wares

NIED 9

Possible Future Researches -1

Liquefaction due to Long Duration EQ
or Multiple EQs occurring within very short period

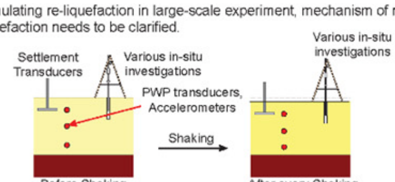


10

Possible Future Researches -1

Evaluation of Re-liquefaction Strength

Simulating re-liquefaction in large-scale experiment, mechanism of re-liquefaction needs to be clarified.

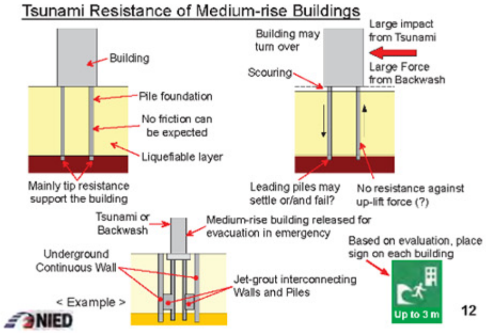


① Start from lower-level motions.
② Repeat inputting the motions until the soil does not liquefy any more.
③ Perform soil investigations after all shakings.
④ Input larger motion. Back to ②

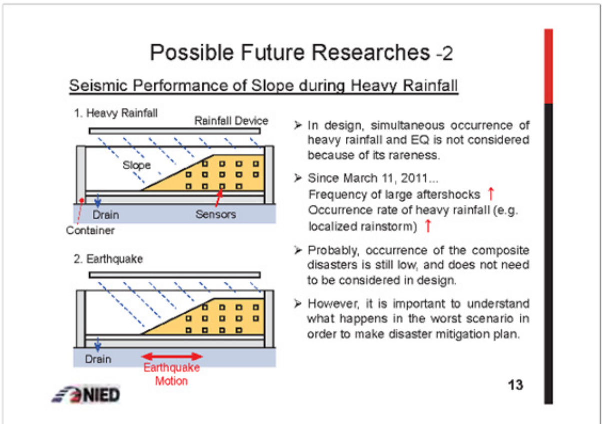
NIED 11

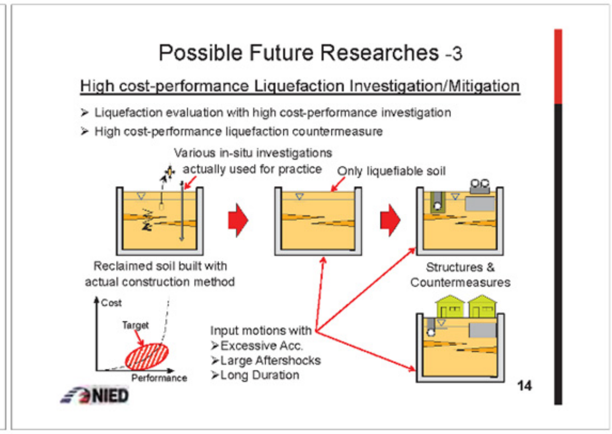
Possible Future Researches -2

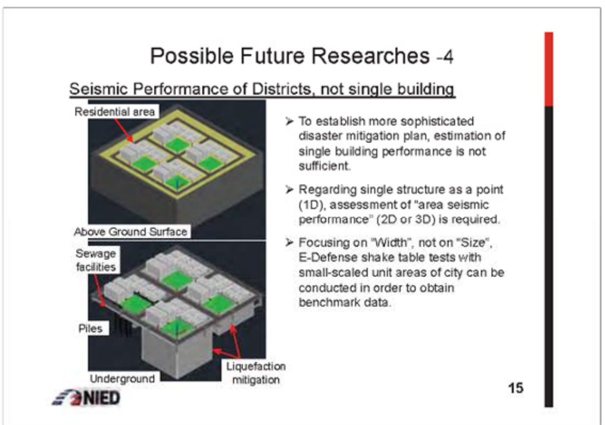
Tsunami Resistance of Medium-rise Buildings

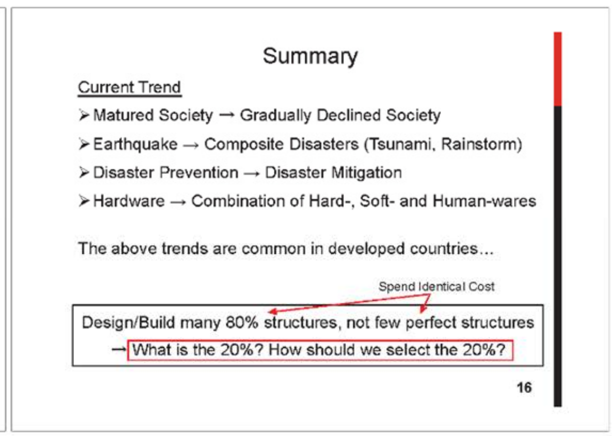


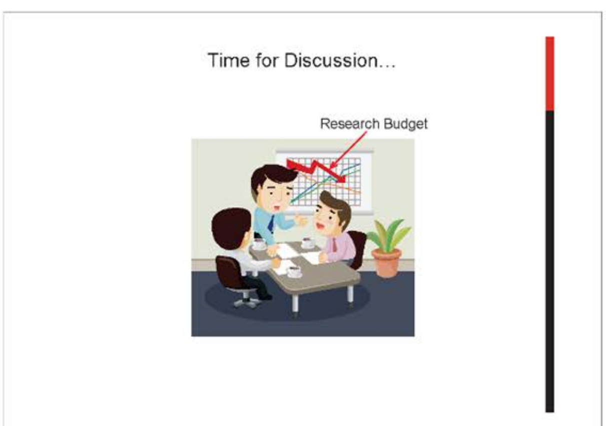
NIED 12

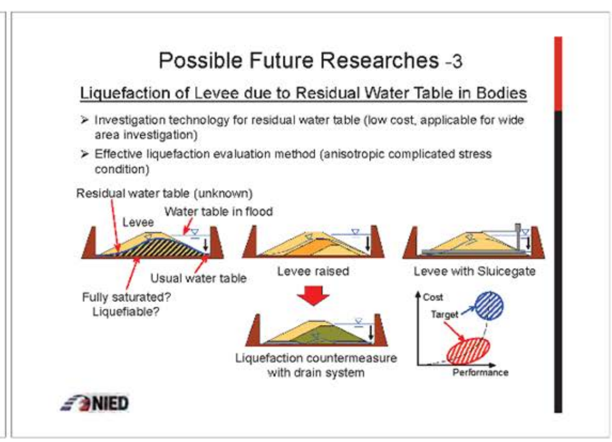

Possible Future Researches -2
Seismic Performance of Slope during Heavy Rainfall
1. Heavy Rainfall
Rainfall Device
Slope
Drain
Sensors
Container
2. Earthquake
Drain
Earthquake Motion
➢ In design, simultaneous occurrence of heavy rainfall and EQ is not considered because of its rareness.
➢ Since March 11, 2011...
Frequency of large aftershocks ↑
Occurrence rate of heavy rainfall (e.g. localized rainstorm) ↑
➢ Probably, occurrence of the composite disasters is still low, and does not need to be considered in design.
➢ However, it is important to understand what happens in the worst scenario in order to make disaster mitigation plan.
NIED
13


Possible Future Researches -3
High cost-performance Liquefaction Investigation/Mitigation
➢ Liquefaction evaluation with high cost-performance investigation
➢ High cost-performance liquefaction countermeasure
Various in-situ investigations actually used for practice
Only liquefiable soil
Reclaimed soil built with actual construction method
Structures & Countermeasures
Cost
Target
Performance
Input motions with
➢Excessive Acc.
➢Large Aftershocks
➢Long Duration
NIED
14

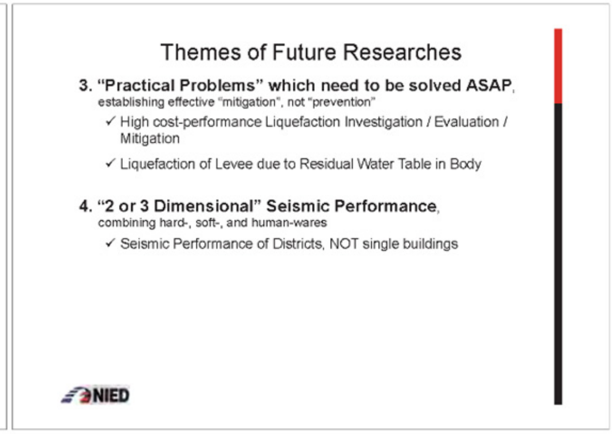

Possible Future Researches -4
Seismic Performance of Districts, not single building
Residential area
Above Ground Surface
Sewage facilities
Piles
Underground
Liquefaction mitigation
➢ To establish more sophisticated disaster mitigation plan, estimation of single building performance is not sufficient.
➢ Regarding single structure as a point (1D), assessment of "area seismic performance" (2D or 3D) is required.
➢ Focusing on "Width", not on "Size", E-Defense shake table tests with small-scaled unit areas of city can be conducted in order to obtain benchmark data.
NIED
15


Summary
Current Trend
➢Matured Society → Gradually Declined Society
➢Earthquake → Composite Disasters (Tsunami, Rainstorm)
➢Disaster Prevention → Disaster Mitigation
➢Hardware → Combination of Hard-, Soft- and Human-wares
The above trends are common in developed countries…
Spend Identical Cost
Design/Build many 80% structures, not few perfect structures
→ What is the 20%? How should we select the 20%?
16


Time for Discussion…
Research Budget


Possible Future Researches -3
Liquefaction of Levee due to Residual Water Table in Bodies
➢ Investigation technology for residual water table (low cost, applicable for wide area investigation)
➢ Effective liquefaction evaluation method (anisotropic complicated stress condition)
Residual water table (unknown)
Water table in flood
Levee
Usual water table
Fully saturated? Liquefiable?
Levee raised
Levee with Sluicegate
Liquefaction countermeasure with drain system
Cost
Target
Performance
NIED


Themes of Future Researches
1. "More Fundamental Research", a step toward further researches
✓ Liquefaction Mechanism against Long Duration EQ
✓ Re-liquefaction Strength
✓ Testing technique (Modification / Newly-develop, construction method, sensors, etc.)
2. Mitigation against "Newly-remarked Natural Disasters", with considerations on other natural disasters than EQ
✓ "Tsunami" Resistance of Medium-rise Buildings
✓ Seismic Performance of Slop during "Heavy Rain"
NIED


Themes of Future Researches
3. "Practical Problems" which need to be solved ASAP, establishing effective "mitigation", not "prevention"
✓ High cost-performance Liquefaction Investigation / Evaluation / Mitigation
✓ Liquefaction of Levee due to Residual Water Table in Body
4. "2 or 3 Dimensional" Seismic Performance, combining hard-, soft-, and human-wares
✓ Seismic Performance of Districts, NOT single buildings
NIED

Appendix X

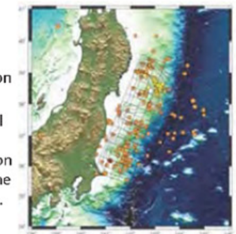
SITE AMPLIFICATION FACTORS DERIVED FROM STRONG MOTION RECORDS OF THE 2011 TOHOKU, JAPAN EARTHQUAKE

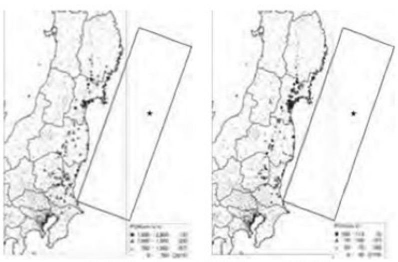
S. Midorikawa
Tokyo Institute of Technology

Tokyo Tech CUEE

The 2011 Tohoku earthquake of Mw9.0 produced many high -intensity strong motion records.

In this presentation, I will talk about site amplification factors on response spectra of the high-intensity records.





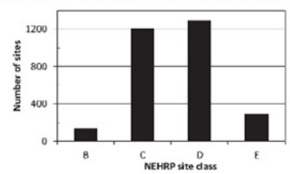
Distribution of PGA and PGV

we have collected and compiled about 3,000 records.
Higher accelerations and velocities are found in areas along the central and southern parts of the fault plane?

Site Classification of Strong Motion Station

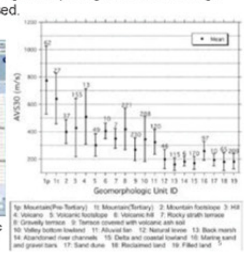
Average shear-wave velocity of ground is evaluated at about 800 sites from PS-logging data and at another about 2100 sites from geomorphologic information.

Then the NEHRP site class for each station is defined.



However, average shear-wave velocity of ground evaluated from geomorphologic information is less reliable, because broad correlation between geomorphologic unit and average shear-wave velocity is used.

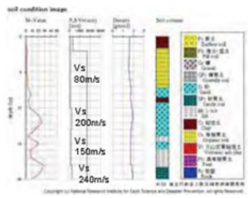
250m-mesh digital geomorphologic Map (Wakamatsu and Matsuoka)



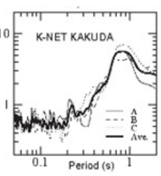
Microtremor Measurements for Site Characterization

we have measured microtremors at about 210 sites in Fukushima, Miyagi and Iwate prefectures where higher intensity data are observed.

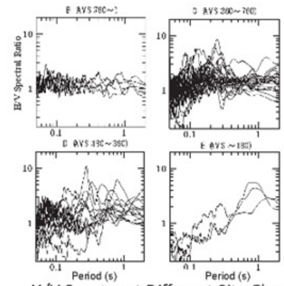
Example of H/V Spectrum of Microtremor



Soil Profile Data



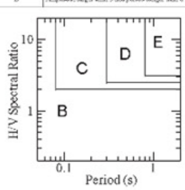
H/V Spectra of Microtremor



H/V Spectra at Different Site Class

At about 50 sites among the sites where microtremors have been measured, the site class is determined from the velocity profile data. Figure show the H/V spectra of microtremors at different site classes.

Site Class	Amplitude and period at peak of H/V spectrum
B	Amplitude smaller than 2 or period shorter than 0.08 sec
C	Amplitude larger than 2 and period of 0.08 to 0.3 sec or Amplitude of 2.0 to 2.5 and period longer than 0.3 sec
D	Amplitude larger than 2 and period of 0.3 to 0.8 sec or Amplitude of 2.5 to 3 and period longer than 0.8 sec
E	Amplitude larger than 3 and period longer than 0.8 sec

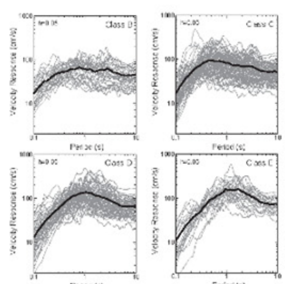


CRITERIA FOR SITE CLASSIFICATION FROM H/V SPECTRUM OF MICROTREMOR

From the observation, the criteria shown in Table 1 are determined for site classification from the H/V spectrum.

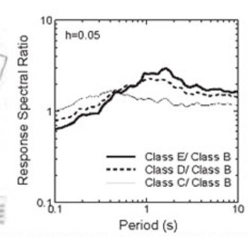
Table shows comparison of the site class from geomorphologic information with that revised from microtremor. At more than 50% of the sites, the site class is reclassified to the different class, suggesting limitations of site classification from geomorphologic information.

		Site classification from geomorphologic information				Total
		B	C	D	E	
Site classification revised from microtremors	B	5	20	3	0	28
	C	2	37	19	6	64
	D	0	14	22	15	51
	E	0	3	9	7	19



The two dimensional horizontal velocity response spectra (h=0.05) are plotted for each site class. In the figure, the average spectrum for each site class is indicated by a thick line. The velocity response spectra are almost constant with period at site class B. The spectral amplitudes become larger at softer site classes. At site class E, the amplitudes tend to be larger at 1 to 2 seconds.

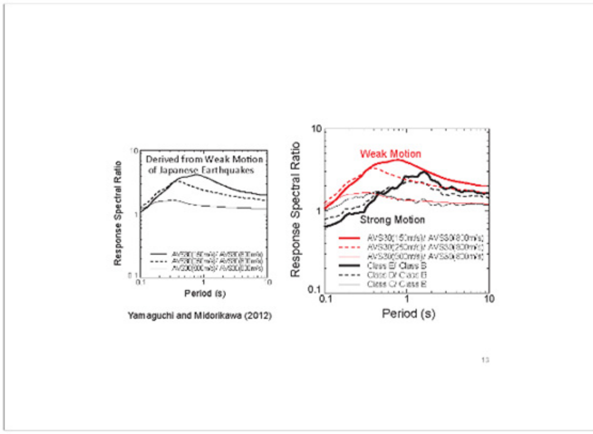
Velocity Response Spectra at Different Site Class



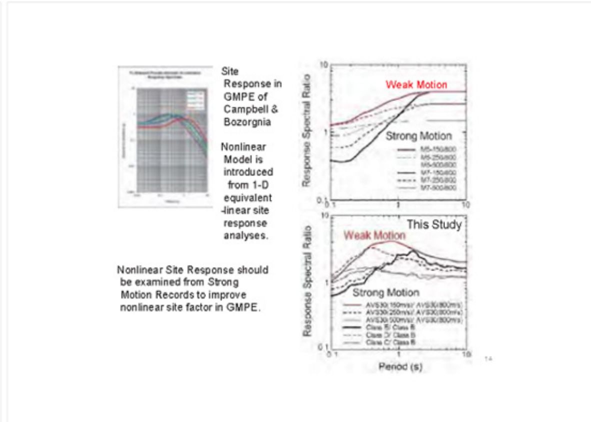
RATIO OF AVERAGE SPECTRA FOR SITE CLASSES C, D AND E WITH RESPECT TO SITE CLASS B

The data used are observed at Fukushima, Miyagi and Iwate prefectures as shown in the left figure, and the distances from the earthquake are similar. The average and standard deviation of the peak horizontal accelerations at site class B are 0.47 g and 0.15 g, respectively. The similar distances and smaller standard deviation suggest that the shaking level inputted to the bedrock at the sites may not have large difference. Therefore, the difference of the average spectra at each site class is considered to be an approximate of site effects.

Appendix X



Derived from Weak Motion of Japanese Earthquakes
Response Spectral Ratio
Period (s)
Yamaguchi and Midorikawa (2012)
Weak Motion
Strong Motion
Class E/ Class B
Class D/ Class B
Class C/ Class B
13



Site Response in GMPE of Campbell & Bozorgnia
Nonlinear Model is introduced from 1-D equivalent -linear site response analyses.
Nonlinear Site Response should be examined from Strong Motion Records to improve nonlinear site factor in GMPE.
Weak Motion
Strong Motion
This Study
Response Spectral Ratio
Period (s)
14

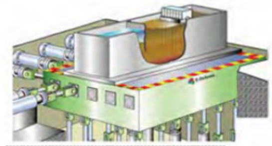
University of Nevada, Reno

Shaking Table Testing Related to Piles and Lateral Spreading

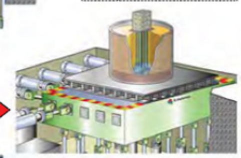
Ramin Motamed, PhD, PE
Department of Civil & Environmental Engineering
University of Nevada, Reno

10th Planning Meeting, NEES/E-Defense Collaborative Earthquake Research Program
Kyoto, December 11-13 2013

Large-Scale Shake Table Experiments at E-Defense (2005-2008)



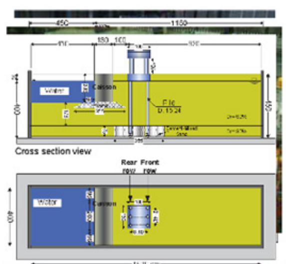
Tests on Lateral Spreading of Liquefied Sand behind a Quay Wall
Large soil container
Height : 5 m
Width : 4 m
Length : 16 m
Weight : 800 tons



Test on Soil-Pile-Structure Interaction
Large cylindrical laminar container
Height : 6.5 m
Diameter : 8 m
Weight : 800 tons

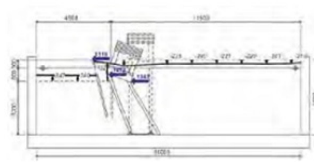
Large-Scale Shake Table Tests at E-Defense

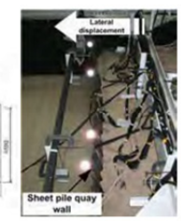
- Two Tests in 2006
- 2×3 pile group in laterally spreading grounds
- Quay wall (sheet pile and caisson)
- Large liquefied soil deformations (1.3m & 2.2m)
- Two dimensional input motion



Observed Damage and Deformations

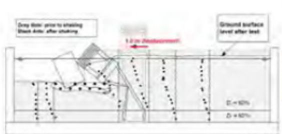
- Test 1

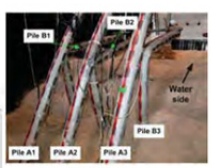




Observed Damage and Deformations

- Test 2

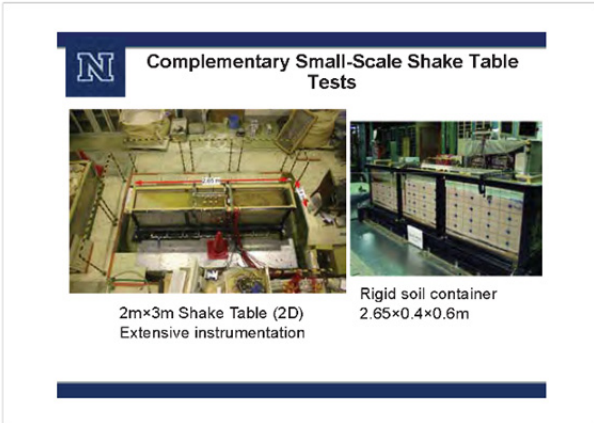


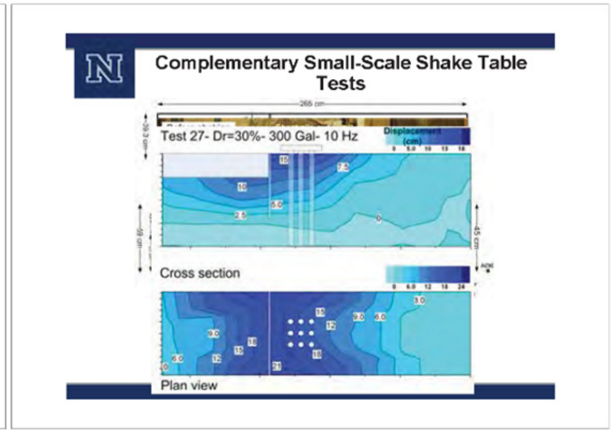


Complementary Small-Scale Shake Table Tests

- About 50 small-scale shake table tests at Univ. of Tokyo
- Overall behavior reproduction, benchmark tests
- Additional mitigation experiments
- Similitude laws (n=10), low confining stress, qualitative in nature
- Extensive parametric study (soil, motion, piles, cap)
- Dense instrumentation
- Successful reproduction of lateral spreading

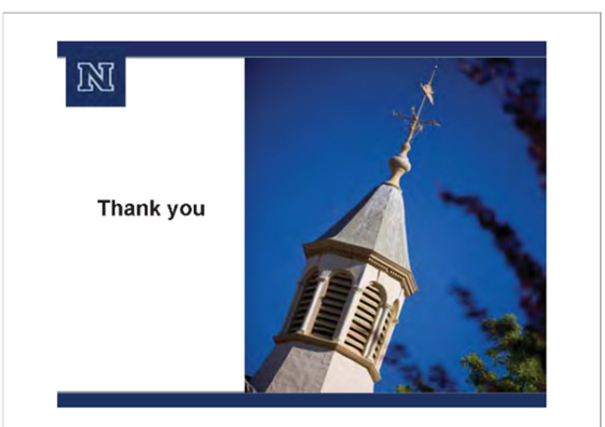
Appendix X

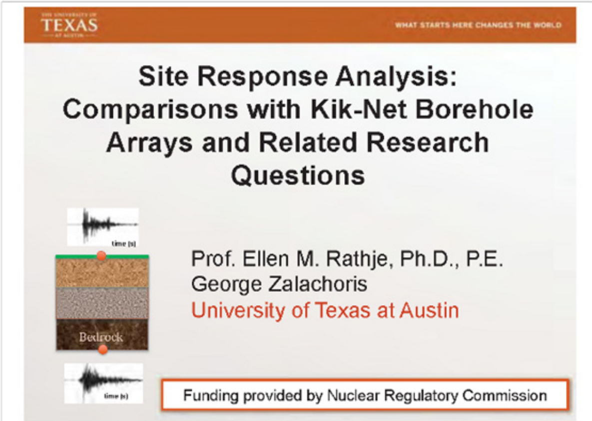

Complementary Small-Scale Shake Table Tests
2m×3m Shake Table (2D)
Extensive instrumentation
Rigid soil container
2.65×0.4×0.6m

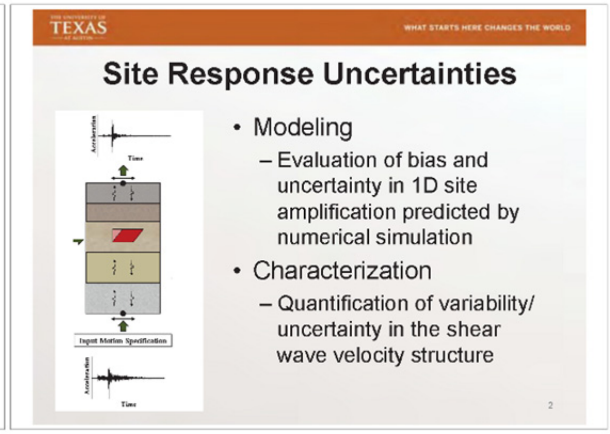

Complementary Small-Scale Shake Table Tests
Test 27- Dr=30%- 300 Gal- 10 Hz
Cross section
Plan view

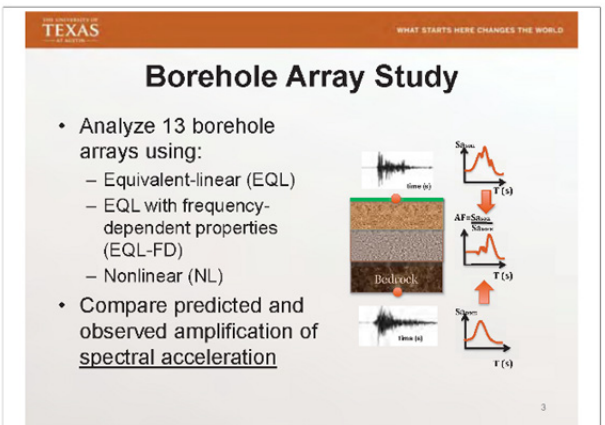

Future Research: Shake Table Facility at UNR
▪ Four shake tables (3 tables 2D and 1 table 6D)
▪ Soil box (rigid and shear)
▪ DAQ and sensors
Tables dimension:
4.3m×4.5m (biaxial)
2.8m×2.8m (6DOF)
NEES@NEVADA

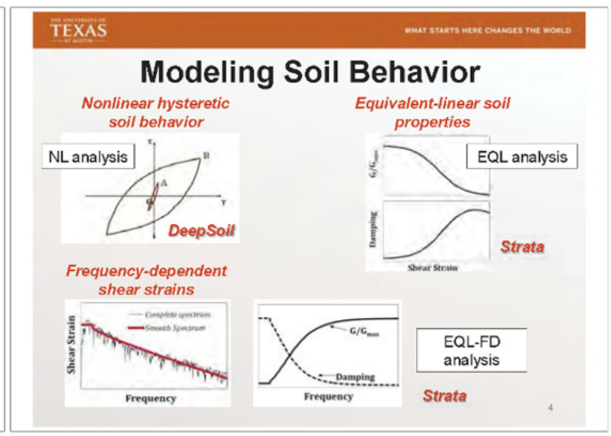

Future Research: Shake Table Facility at UNR
Small acrylic box dimension: 2m × 0.6m × 0.8m
NEES@NEVADA

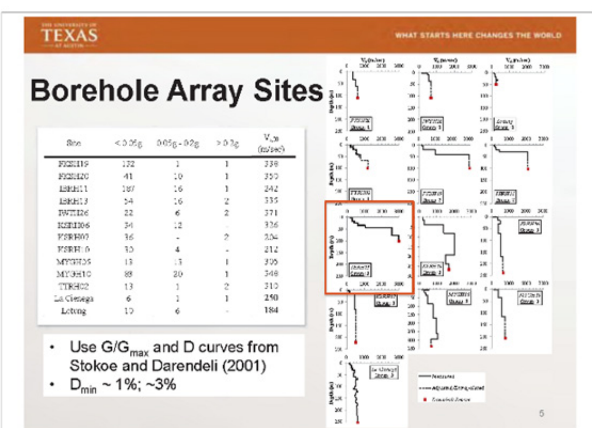

Thank you



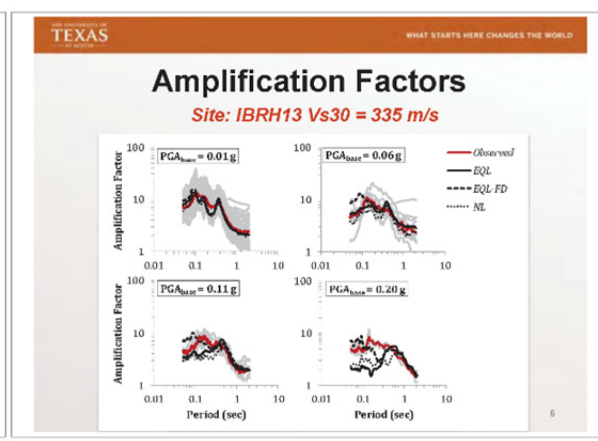




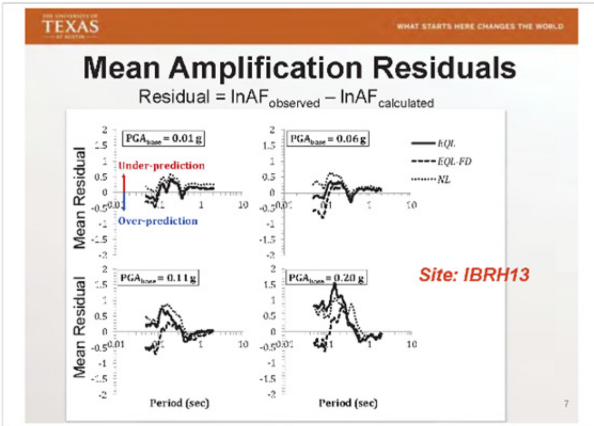


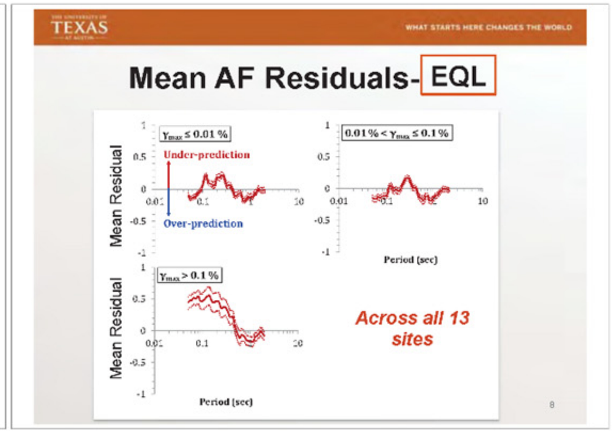


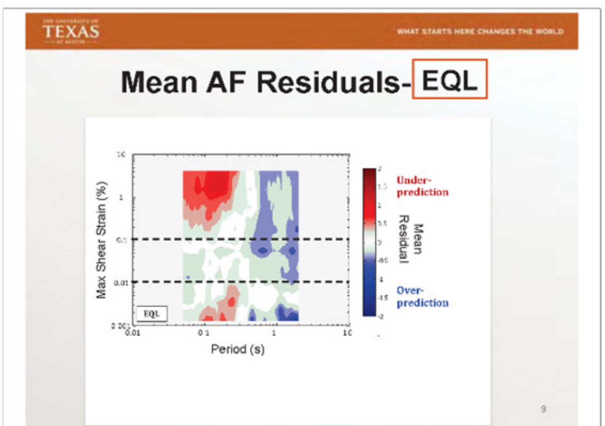
Site	< 0.05g	0.05g - 0.2g	> 0.2g	V_{s30} (m/sec)
FKSH19	132	1	1	338
FKSH20	41	10	1	350
IBRH11	187	16	1	242
IBRH13	54	16	2	335
IWTH26	22	6	2	371
KSRH06	34	12	-	326
KSRH07	36	-	2	204
KSRH10	30	4	-	212
MYGH05	13	13	1	305
MYGH10	88	20	1	348
TTRH02	13	1	2	310
La Cienega	6	1	1	250
Lotung	10	6	-	184

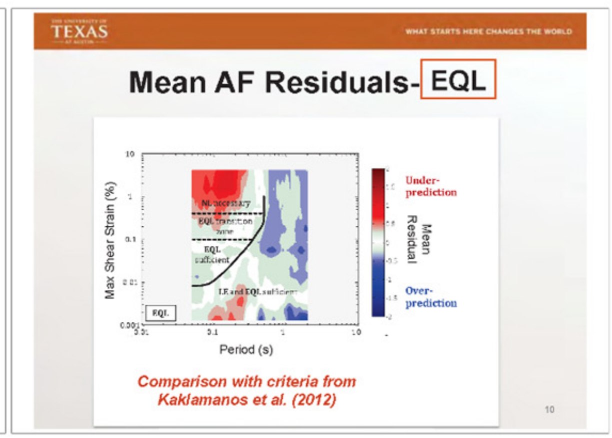


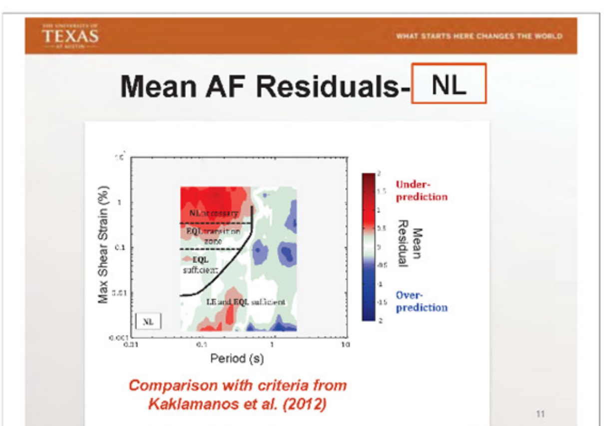
Appendix X

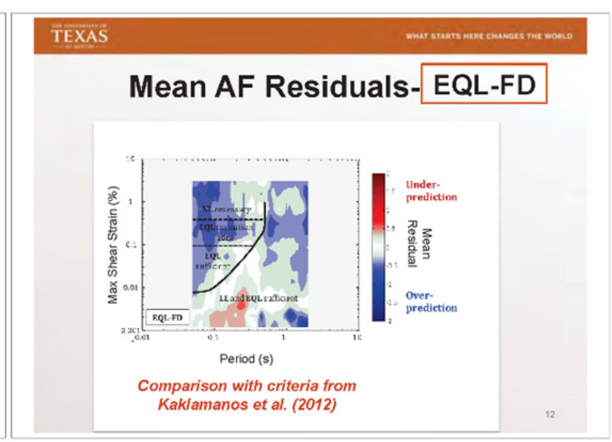

TEXAS
WHAT STARTS HERE CHANGES THE WORLD
Mean Amplification Residuals
Residual = lnAF observed – lnAF calculated
Mean Residual
Under-prediction
Over-prediction
EQL
EQL-FD
NL
Site: IBRH13
Period (sec)
7


TEXAS
WHAT STARTS HERE CHANGES THE WORLD
Mean AF Residuals- EQL
Mean Residual
Under-prediction
Over-prediction
Period (sec)
Across all 13 sites
8


TEXAS
WHAT STARTS HERE CHANGES THE WORLD
Mean AF Residuals- EQL
Max Shear Strain (%)
Period (s)
Under-prediction
Mean Residual
Over-prediction
9


TEXAS
WHAT STARTS HERE CHANGES THE WORLD
Mean AF Residuals- EQL
Max Shear Strain (%)
Period (s)
Under-prediction
Mean Residual
Over-prediction
Comparison with criteria from Kaklamanos et al. (2012)
10


TEXAS
WHAT STARTS HERE CHANGES THE WORLD
Mean AF Residuals- NL
Max Shear Strain (%)
Period (s)
Under-prediction
Mean Residual
Over-prediction
Comparison with criteria from Kaklamanos et al. (2012)
11


TEXAS
WHAT STARTS HERE CHANGES THE WORLD
Mean AF Residuals- EQL-FD
Max Shear Strain (%)
Period (s)
Under-prediction
Mean Residual
Over-prediction
Comparison with criteria from Kaklamanos et al. (2012)
12

Observations

- EQL and NL analyses significantly underpredict motions at γ_{max} > 0.4%
  - Strength correction for G/G_{max} curves will improve results somewhat but will not result in zero bias
- EQL-FD analysis significantly overpredicts motions at γ_{max} > 0.4%
  - Enhancements to this method could improve results

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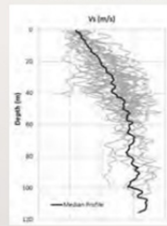
THE UNIVERSITY OF TEXAS AT AUSTIN — WHAT STARTS HERE CHANGES THE WORLD

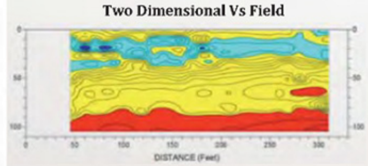
Research Questions

- How does spatial variability influence site amplification?

Measured Vs Data



Two Dimensional Vs Field



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THE UNIVERSITY OF TEXAS AT AUSTIN — WHAT STARTS HERE CHANGES THE WORLD

Research Questions

- How does spatial variability influence site amplification?
  - What shaking table/centrifuge tests can we perform to investigate this issue at large strains?
  - What field data are available to investigate this issue?

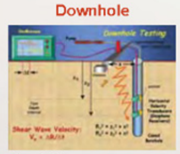
15

THE UNIVERSITY OF TEXAS AT AUSTIN — WHAT STARTS HERE CHANGES THE WORLD

Research Questions

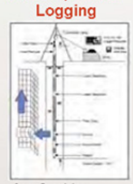
- How well can we characterize spatial variability? Over what scale?

Downhole



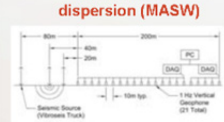
from P. Mayne

PS Suspension Logging



from Geovision

Surface wave dispersion (MASW)



Cox et al (2013)

Appendix X

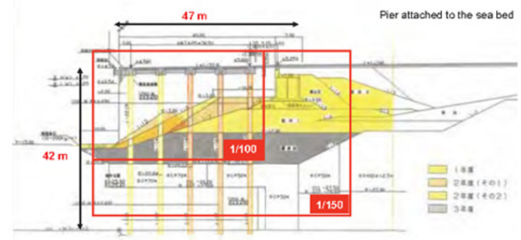
NEES/E-Defense Collaborative Earthquake Research Program 10th Planning Meeting (Rebooting US-Japan Joint Research on Earthquake Engineering)
December 11 to 13, 2013

Next Generation of Physical Model Testing with Generalized Scaling Law - towards LEAP project-

Tetsuo Tobita
DPRI, Kyoto University

DPRI-KU

Is physical modeling possible for large prototype with a sand box: 45W x 30H x 15D (cm)?



There is always some limitations due to the capacity of facility, but,,,

Yes, it is ~~maybe~~ possible!

By exploring possibility of the geotechnical centrifuge modeling with the generalized scaling law

Contents

The generalized scaling law and "New" modelling of models for flat saturated sand deposit

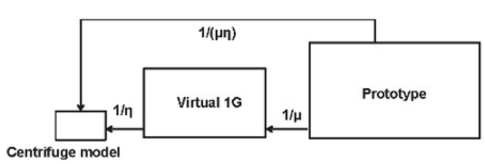
LEAP (Liquefaction Experiment & Analysis Project) (launched in Jan, 2013)

Generalized scaling law

Combination of 2 scaling laws:

(1) 1G model (1/μ) (Iai, *S&F*, 1989)

(2) Centrifuge model (1/η) (Iai et al., *Geotechnique*, 2005)



e.g. 1/100 = 1/5 ☒ 1/20 ☒ 1/1
η=5 μ=20

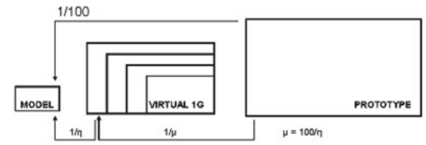
Generalized scaling factors

	(1) Scaling factors for 1g test	(2) Scaling factors for centrifuge test	(3) Generalized scaling factors
Length	μ	η	$\mu\eta$
Density	1	1	1
Time	$\mu^{0.75}$	η	$\mu^{0.75}\eta$
Frequency	$\mu^{-0.75}$	$1/\eta$	$\mu^{-0.75}/\eta$
Acceleration	1	$1/\eta$	$1/\eta$
Velocity	$\mu^{0.75}$	1	$\mu^{0.75}$
Displacement	$\mu^{1.5}$	η	$\mu^{1.5}\eta$
Stress	μ	1	μ
Strain	$\mu^{0.5}$	1	$\mu^{0.5}$
Stiffness	$\mu^{0.5}$	1	$\mu^{0.5}$
Permeability	$\mu^{0.75}$	η	$\mu^{0.75}\eta$
Pore pressure	μ	1	μ
Fluid Pressure	μ	1	μ

Past studies on the generalized scaling law

Pile:	Nishida (2007), Nagaura (2013)
Dry sand:	Noda (2008), Tobita et al. (2011)
Saturated sand:	Tann et al. (2010), Yaoi (2010)
Caisson:	Itoh (2010), Moritani (2011), Takata (2011), Yaoi (2012)

Method: New modelling of models



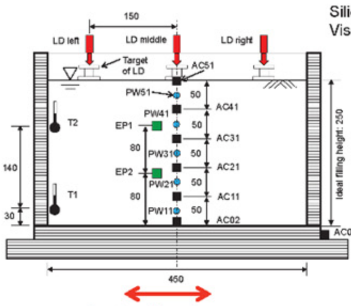
e.g. 1/100 =	1/5	×	1/20	×	1/1
	1/10	×	1/10	×	1/1
	1/50	×	1/2	×	1/1
	1/70	×	1/1.43	×	1/1
	1/η		1/μ		

Centrifugal acc. = η

Tobita et al., IJPMG (2011)

Flat layered saturated sand (Tobita et al., IJPMG, 2011)

Silica sand #7 (D_{50}=0.13 mm)
Viscous fluid (Metolose)



25m deep ground in prototype scale

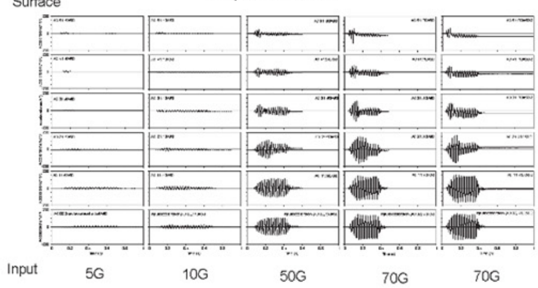
(100G is required for ordinary centrifuge scaling law)

(Even with E-Defense, it is difficult to carry out)

Input motion: sin wave

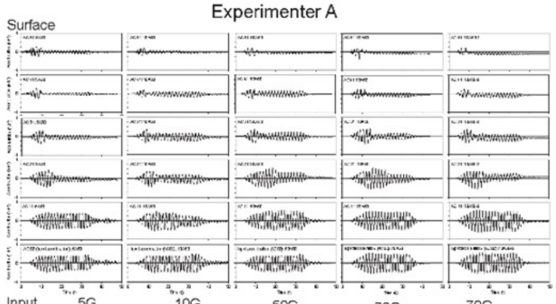
Model scale

Experimenter A

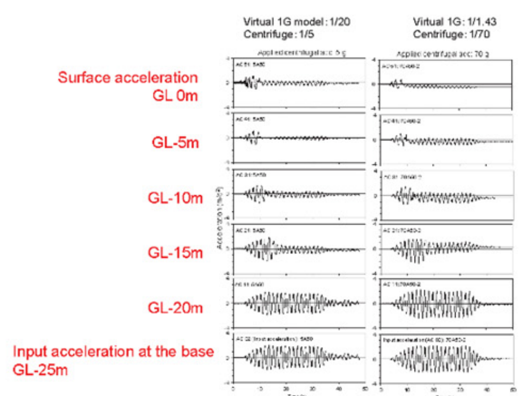


Prototype

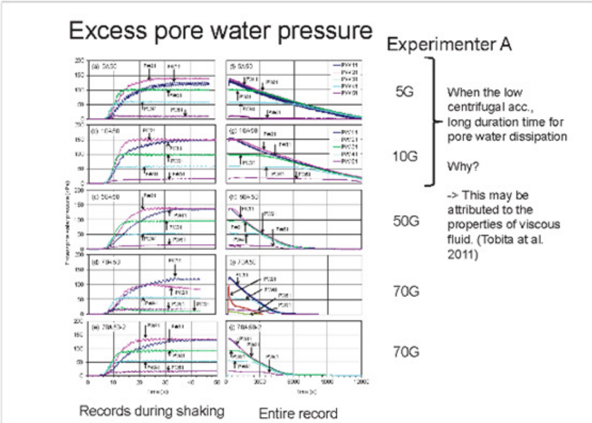
Experimenter A

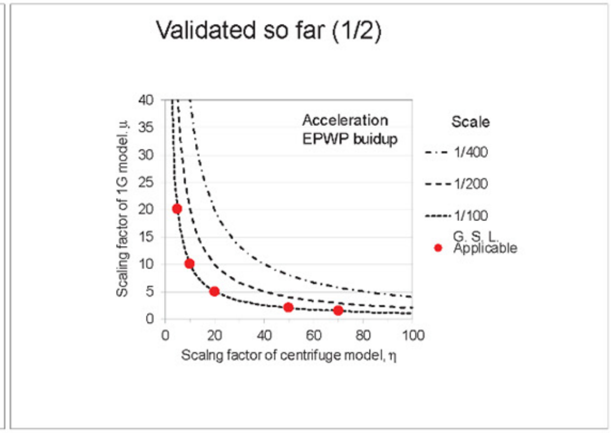


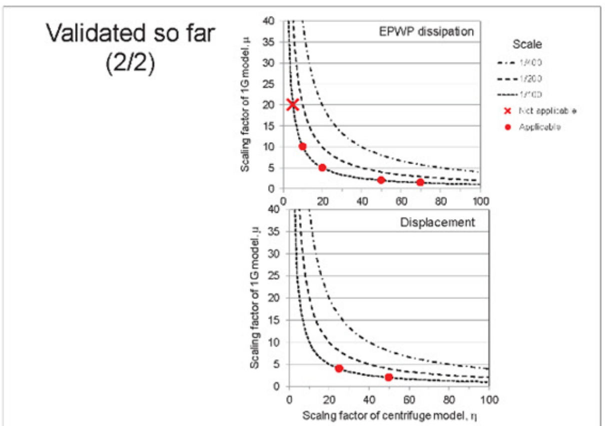
Acceleration of a scale factor of 24 is validated



Appendix X







LEAP (Liquefaction Experiment & Analysis Project) (launched in Jan, 2013)

- Next generation of VELACS project
- International collaboration between centrifuge and numerical modelers from US, Japan and other countries
- Class A prediction of liquefied ground response
- More to come in the Fourth International Conference on Geotechnical Engineering for Disaster mitigation and Rehabilitation (4th GEDMAR) (September 16-18 2014) held in DPRI, Kyoto Univ. in September, 2014
- In 2014, centrifuge model tests with the generalized scaling law

LEAP
Liquefaction Experiment and Analysis Projects

Memorandum:
Discussions on the future plan of the bench mark centrifuge tests and analyses

January 31, 2013 10:00-12:00
Iai's lab. Kyoto University

Attendees:
Susumu Iai
Tetsuo Tobita
Koji Ichii
Bruce Kutter
Majid Manzari
Gopal Madabhushi
Lee Chung Cheng
Chen
Whe-Yi Hung

Planning board:

Susumu Iai
Tetsuo Tobita
Koji Ichii
Mitsu Okamura
Bruce Kutter
Majid Manzari
Gopal Madabhushi

Physical model testing:

DPRI, Kyoto University, Japan
Ehime, Japan
TIT, Japan
University of California, Davis, USA
RPI, USA
University of Cambridge, UK
NCU, National Central Univ., Taiwan
Zhejing University, China (invitation by Bruce)

Numerical analysis:

FLIP ROSE, Japan
FLIP TULIP, Japan
LIQCA, Japan
GeoAsia? (tentative), Japan
GWU, Majid, USA
No.2, USA (invitation by Bruce)
No.3, USA (invitation by Bruce)
Imperial College, U.K. (invitation by Gopal)

Results of class A prediction in Jan, 2013

Centrifugal acc: 50g
Input wave: Sin wave
Frequency: 2 Hz (100 Hz in model scale)
Number of cycles: 20

Model ground
Toyoura sand
Target relative density Dr=40%
Sand is saturated with de-aired water (not viscous fluid)

Properties of Toyoura sand

Specific gravity G_s	2.636
Min. density ρ_{min}	1.638
Max. density ρ_{dmax}	1.329
Max. void ratio: e_{max}	0.983
Min void ratio: e_{min}	0.609

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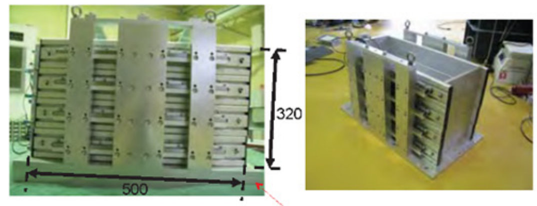
Shear box

Inside dimension: L50cm×D20cm×H32cm



Units in mm

"Flat" or "sloping" base

Membrane (t=0.03mm) is installed.

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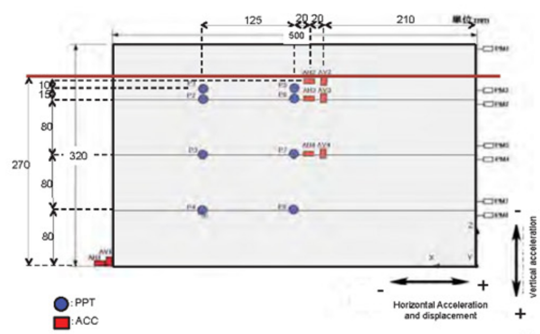
Sensor location: Case 1-1



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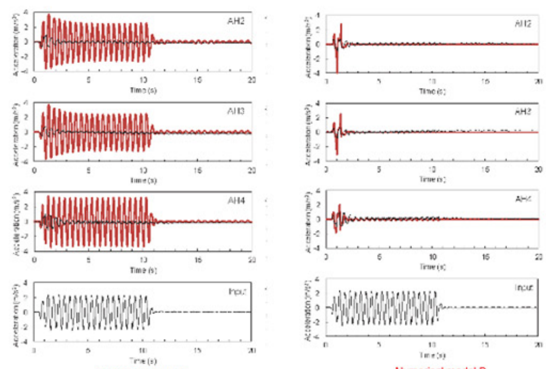
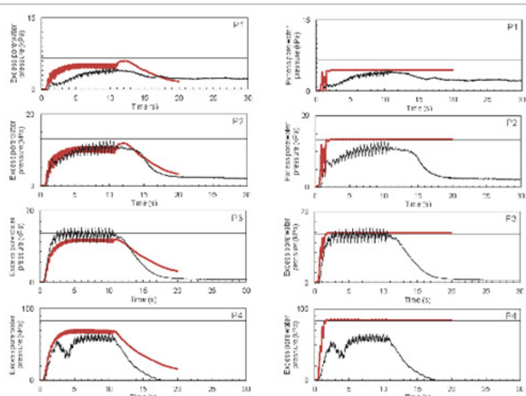
RED: Computed
BLACK: Measured



Numerical model A

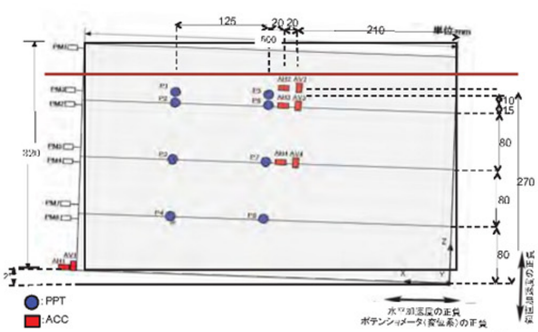
Numerical model B



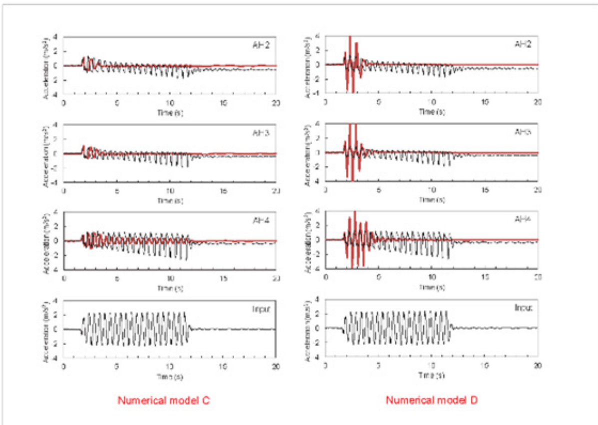
Numerical model A

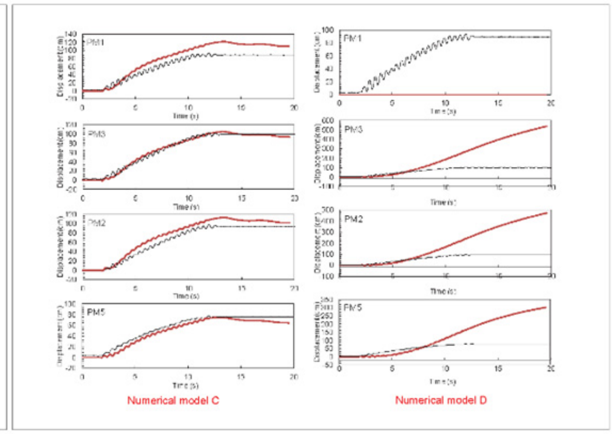
Numerical model B

Sensor location: Case 1-3, and later



Appendix X





Summary

In 2014, under NEESR-Planning Project-LEAP, centrifuge model tests with the generalized scaling law is planned.
(GWU, UCD, RPI, USACE, Div. of safety of dams, URS, TIT, Ehime Univ., Kyoto Univ., Cambridge Univ., and Zhejiang Univ.)

Geotech group is slightly taking the lead.

Issues:
Repeatability of physical testing => "NEW" modelling of models
How to qualitatively evaluate results of Class A (or C) prediction? So far, by impression of professionals.

NEES/E-Defense Collaboration Workshop
2013.12.13

MONITORING OF FOUNDATIONS

Part of
Special Project for Reducing Vulnerability for Urban Mega Earthquake Disasters

Taisei Corporation
SHUNJI FUJII

INTRODUCTION

The damages of foundations and lifelines are not easy to identify after large earthquakes.

The damage of piles during the 1964 Niigata earthquake was found in the re-construction process after 20 Years of the earthquake.

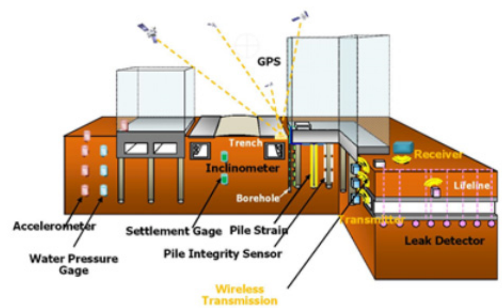
The objective of this study is to develop a health monitoring system to enable real-time assessment of the soil, foundations, and lifelines.

RESEARCH SCHEDULE

	2012	2013	2014	2015	2016
Technology Survey of Sensors	—				
Element Tests	—	—			
System Development		—	—		
Shake Table Test At E-Defence				—	
Completion of Monitoring System					—

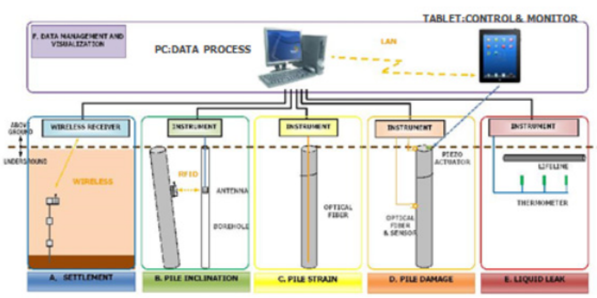
Organization
Taisei Corporation, Kyoto U., Tokyo U., Tokyo Science U., Kobori Research Institute, NIED

CANDIDATES OF INSTRUMENTATION FOR SOILS AND FOUNDATIONS

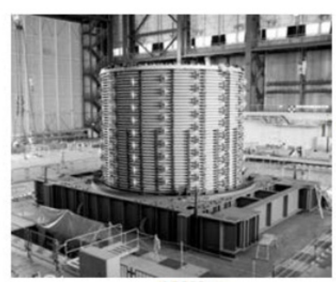


MONITORING SYSTEM

Sensing, Data Transfer, Data Process, Control & Monitor



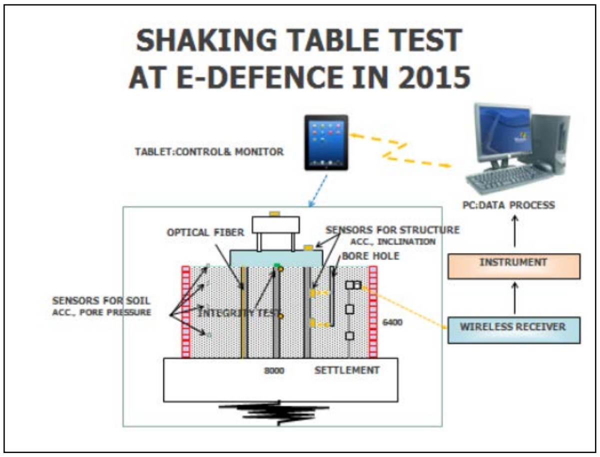
SHAKING TABLE TEST AT E-DEFENCE IN 2015

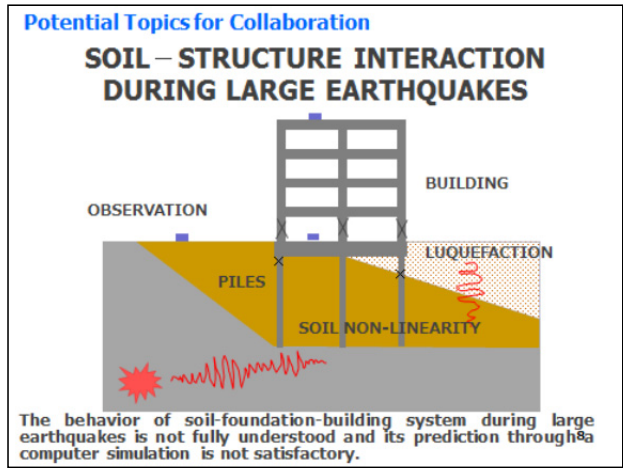


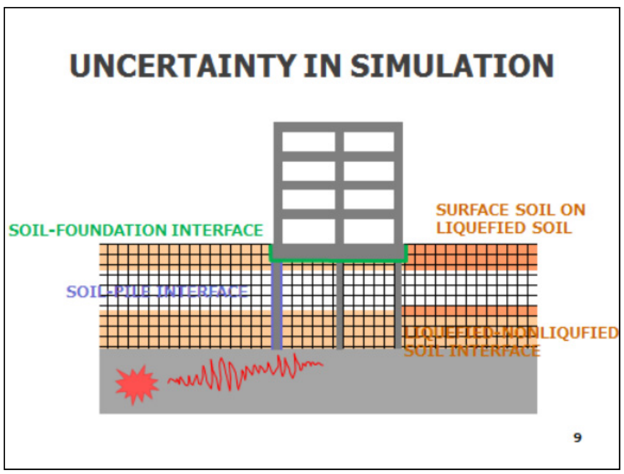
H6400mm

Φ8000mm

Laminar Box at E-Defence







COLLABORATIVE WORK

Develop simulation method for soil-foundation-building system during large earthquakes.

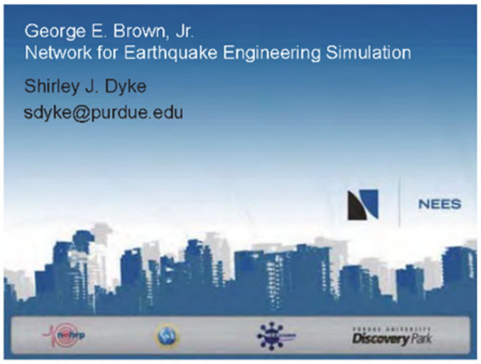
① clarification of the behavior of these interfaces through tests,

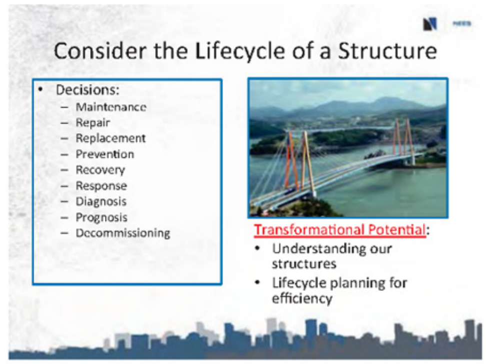
② modeling of the interface behavior and incorporation in simulation programs,

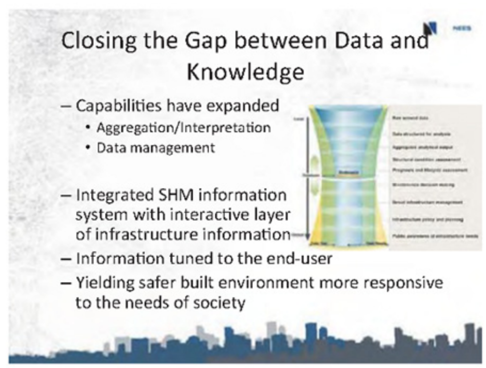
③ verification of the developed simulation technique through the comparison between the simulation and the observation during past earthquakes and with large scale shaking table tests.

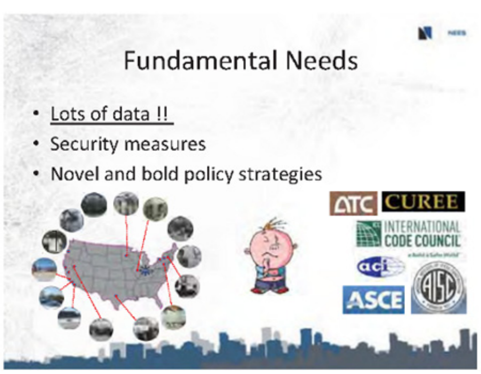
END

APPENDIX XI: PRESENTED PAPERS IN MONITORING WORKING GROUP

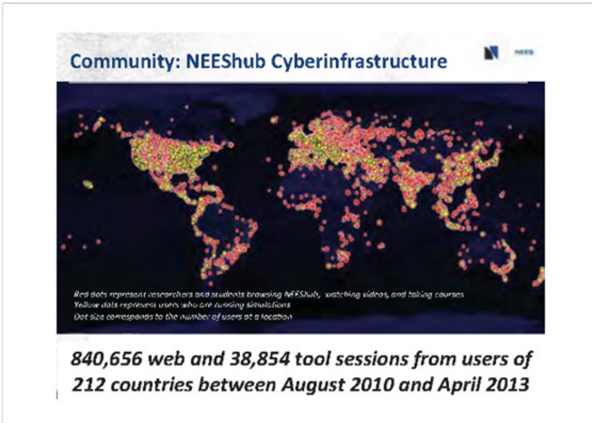


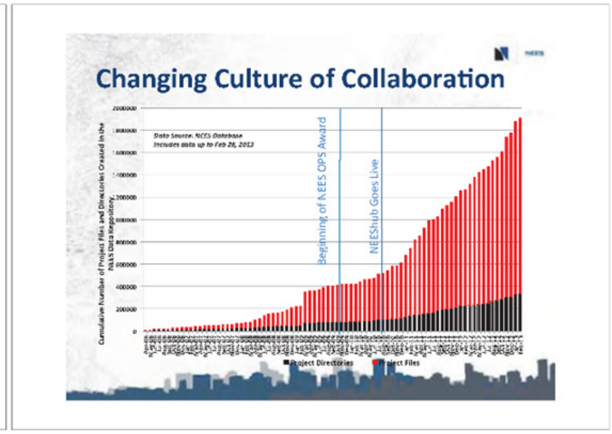


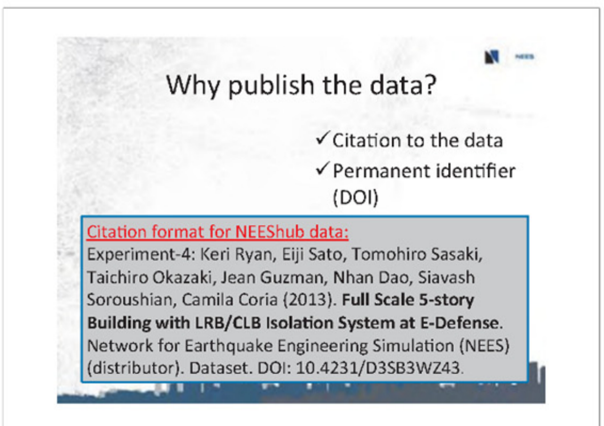


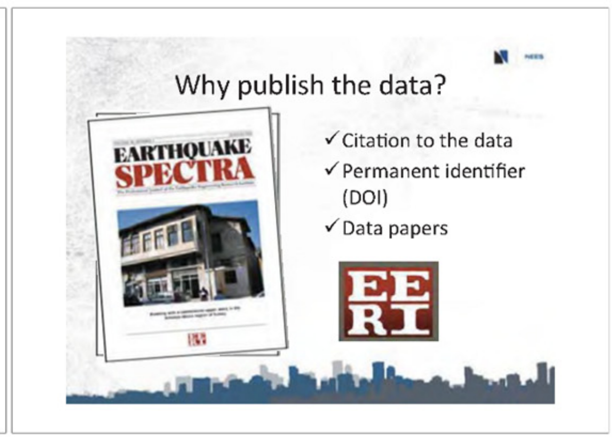


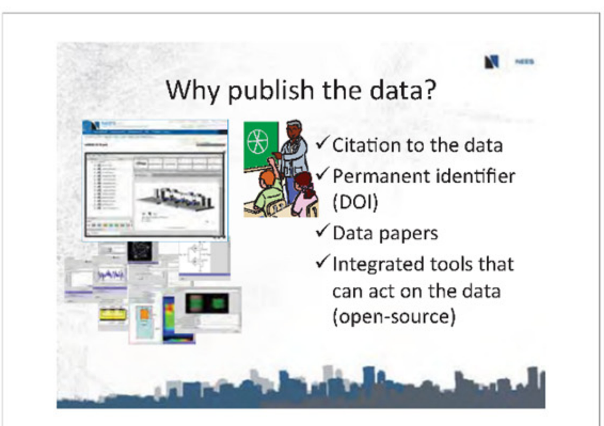
Appendix XI


Community: NEEShub Cyberinfrastructure
Red dots represent researchers and students browsing NEEShub, watching videos, and taking courses
Yellow dots represent users who are running simulations
Dot size corresponds to the number of users at a location
840,656 web and 38,854 tool sessions from users of 212 countries between August 2010 and April 2013


Changing Culture of Collaboration
Data Source: NEES Database
Includes data up to Feb 26, 2013
Beginning of NEES OPS Award
NEEShub Goes Live
Project Directories
Project Files


Why publish the data?
✓Citation to the data
✓Permanent identifier (DOI)
Citation format for NEEShub data:
Experiment-4: Keri Ryan, Eiji Sato, Tomohiro Sasaki, Taichiro Okazaki, Jean Guzman, Nhan Dao, Siavash Soroushian, Camila Coria (2013). Full Scale 5-story Building with LRB/CLB Isolation System at E-Defense. Network for Earthquake Engineering Simulation (NEES) (distributor). Dataset. DOI: 10.4231/D3SB3WZ43.

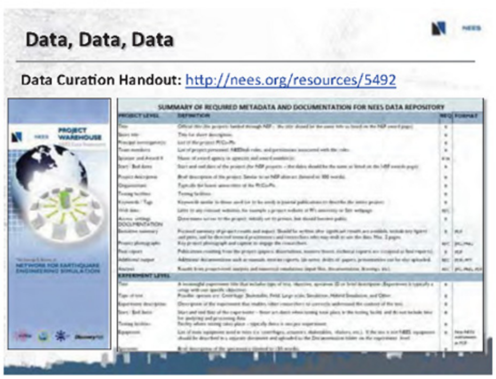

Why publish the data?
EARTHQUAKE SPECTRA
✓Citation to the data
✓Permanent identifier (DOI)
✓Data papers
EERI

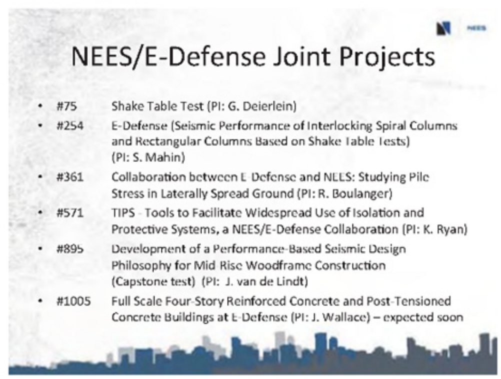

Why publish the data?
✓Citation to the data
✓Permanent identifier (DOI)
✓Data papers
✓Integrated tools that can act on the data (open-source)


Recommendation: Data Interoperability
NEEShub
CYBERINFRA-STRUCTURE


Partnerships and Collaborations
Formal Agreements with International Facilities
• NIED/E-Defense, Japan
• PARI, Japan
• CSRN, Canada
• Tongji University Multi functional Shaking Table Array, China
China-NEES Research Collaboration
• 4 annual workshops and 6 new joint projects started on Disaster Resilience of the Urban Environment
Seismic Engineering Research Infrastructures for European Synergies (SERIES)
• Data Exchanges through the interoperability of databases
• Hybrid Simulation Collaborations


Partnerships and Collaborations
Seismic Eng
Research
Infrastructu
European Sy
(SERIES)
• Data Exchange
interoperability of databases
• Hybrid Simulation
Collaborations
MORE DATA
Celestina
DATA
NEES


Data, Data, Data
Data Curation Handout: http://nees.org/resources/5492
SUMMARY OF REQUIRED METADATA AND DOCUMENTATION FOR NEES DATA REPOSITORY
PROJECT WAREHOUSE


NEES/E-Defense Joint Projects
• #75 Shake Table Test (PI: G. Deierlein)
• #254 E-Defense (Seismic Performance of Interlocking Spiral Columns and Rectangular Columns Based on Shake Table Tests) (PI: S. Mahin)
• #361 Collaboration between E Defense and NEES: Studying Pile Stress in Laterally Spread Ground (PI: R. Boulanger)
• #571 TIPS - Tools to Facilitate Widespread Use of Isolation and Protective Systems, a NEES/E-Defense Collaboration (PI: K. Ryan)
• #895 Development of a Performance-Based Seismic Design Philosophy for Mid Rise Woodframe Construction (Capstone test) (PI: J. van de Lindt)
• #1005 Full Scale Four-Story Reinforced Concrete and Post-Tensioned Concrete Buildings at E-Defense (PI: J. Wallace) – expected soon

Appendix XI

Monitoring Systems for Intelligent Infrastructures: Design, Sensing and Data Analytics

Anne Kiremidjian, Mark Mollineaux, Ram Rajagopal and Konstantinos Balafas
Civil and Environmental Engineering
Stanford University

NEES - E-Defense Workshop 2013
Kyoto, Japan
December 11-13, 2013
Anne Kiremidjian

Acknowledgements

- Ronnie Bajwa (Sensys)
- Jack Baker (Stanford)
- Konstantinos Balafas (Stanford)
- Erdem Coleri (UC Davis)
- Chris Flores (Sensys)
- Haeyoung Noh (CMU)
- Pravin Varaiya (Berkeley)

Supported by NSF/ NEES, Powell Foundation Fellowship

Anne Kiremidjian

Outline

- Introduction
- Current Hardware Development
- Summary of Damage Detection Algorithms
- Response to NEES-E-Defense Questions

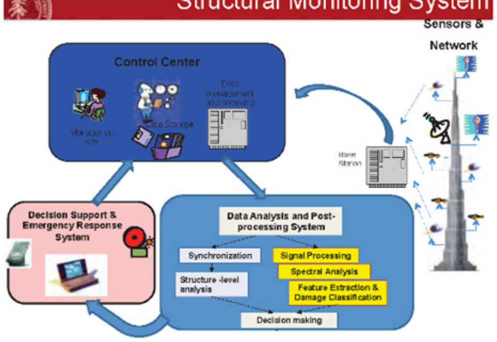
Anne Kiremidjian

Structural Health Monitoring Challenges

- Deployment of monitoring systems in harsh conditions
- Identification of meaningful indicators of damage from data
- Real-time and efficient algorithms for information

Anne Kiremidjian

Structural Monitoring System

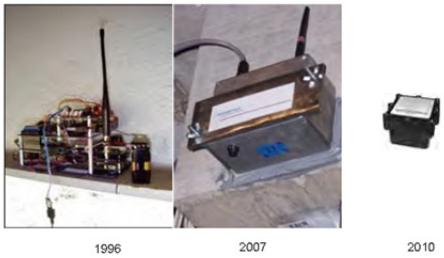


Outline

- Introduction
- Current Hardware Development
- Summary of Damage Detection Algorithms
- Response to NEES-E-Defense Questions

Anne Kiremidjian

Evolution of Wireless Sensing Systems



- MEMS based sensor systems

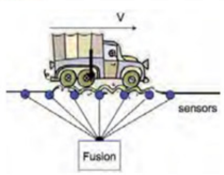
Anne Kiremidjian

Sensor Packaging and Installation

- Protection for harsh environments
- Sensing performance improvement
- Lifetime 10 years

Anne Kiremidjian

Weigh-In-Motion System



- Load cell system
- Requirements: 10 years, 0.5% average error

Anne Kiremidjian

Wireless WIM System

Embedded Load Estimation Algorithm

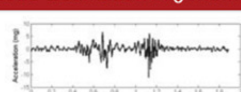
Filter Acceleration

↓

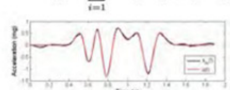
Fit Shape Model

↓

Linear Calibration Peak Displacement vs. Load



$$a_m(t) = \sum_{i=1}^{K} \alpha_i \Psi(t - \mu_i, \sigma_i) + \epsilon(t)$$



$$F_i = \beta_i \frac{\alpha_i}{v^2} \tau(T)$$

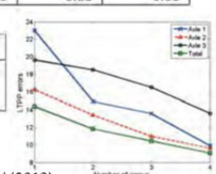
- Each axle displacement is approximated by Gaussian shape, (*fit second derivative of Gaussian)*

Anne Kiremidjian

Performance of Load Estimation

	Temperature compensation		No compensation	
	Mean Error (%)	Std of errors (%)	Mean Error (%)	Std of errors (%)
Axle 1	-0.27	5.25	-0.44	6.66
Axle 2	-0.22	4.75	-0.39	6.27
Axle 3	-0.33	5.81	-0.43	6.63
Total	-0.19	4.09	-0.33	5.61

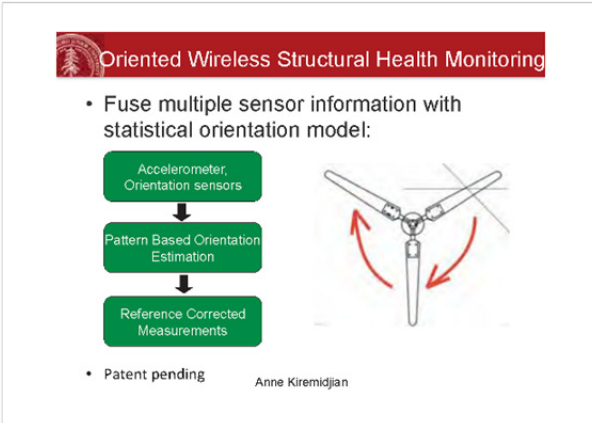
	Wireless WIM error	Conventional WIM error	Maximum allowed error
Axle 1	11.29	18.67	20
Axle 2	10.07	26.49	15
Axle 3	12.44	37.35	15
Total	8.76	23.23	10

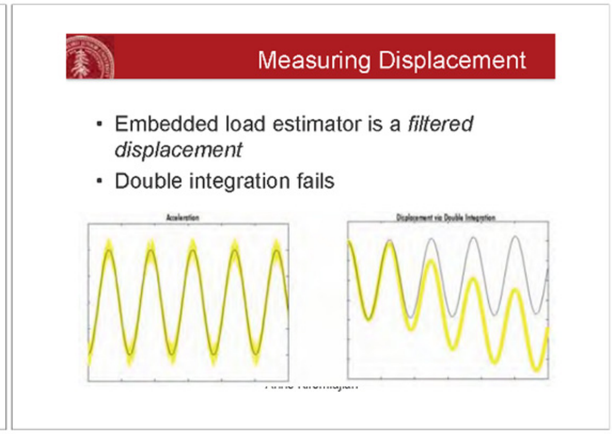


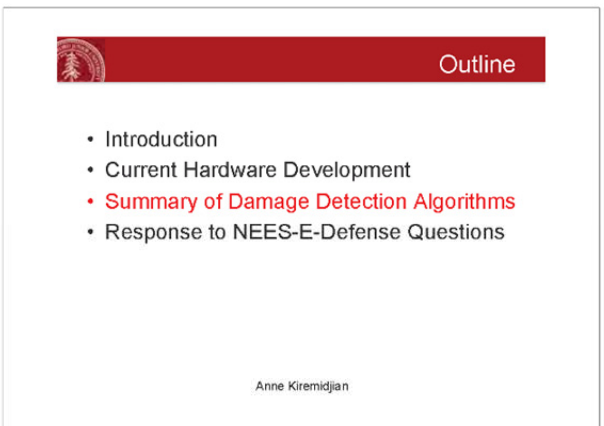
- Rajagopal et al (2011), Bajwa et al (2013)

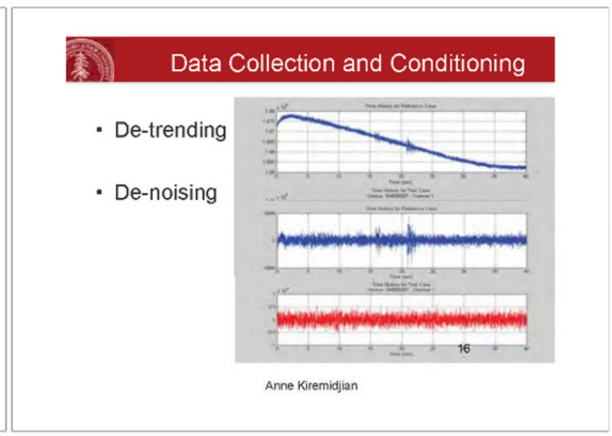
Anne Kiremidjian

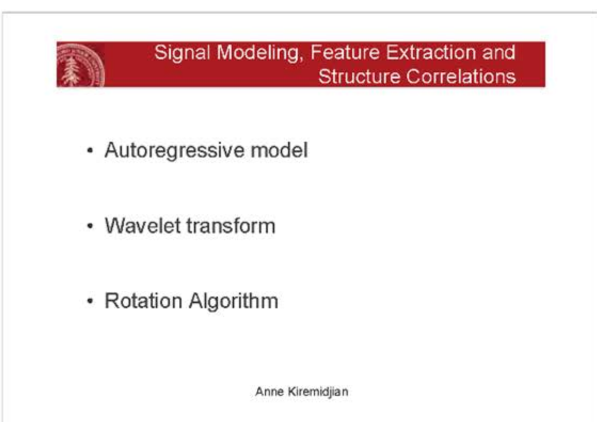
Appendix XI

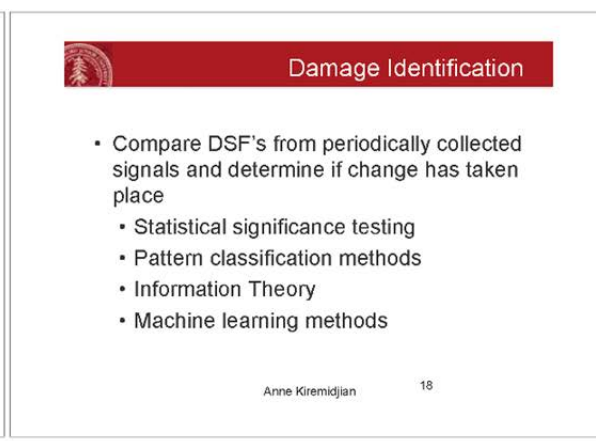

Oriented Wireless Structural Health Monitoring
• Fuse multiple sensor information with statistical orientation model:
Accelerometer, Orientation sensors
Pattern Based Orientation Estimation
Reference Corrected Measurements
• Patent pending
Anne Kiremidjian


Measuring Displacement
• Embedded load estimator is a *filtered displacement*
• Double integration fails

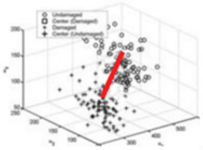

Outline
• Introduction
• Current Hardware Development
• Summary of Damage Detection Algorithms
• Response to NEES-E-Defense Questions
Anne Kiremidjian


Data Collection and Conditioning
• De-trending
• De-noising
16
Anne Kiremidjian


Signal Modeling, Feature Extraction and Structure Correlations
• Autoregressive model
• Wavelet transform
• Rotation Algorithm
Anne Kiremidjian

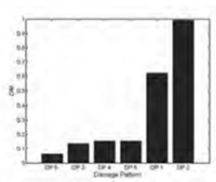

Damage Identification
• Compare DSF's from periodically collected signals and determine if change has taken place
• Statistical significance testing
• Pattern classification methods
• Information Theory
• Machine learning methods
Anne Kiremidjian
18

Mahalanobis Distance as Damage Indicator



Gaussian Mixture

Nair et al., 2005



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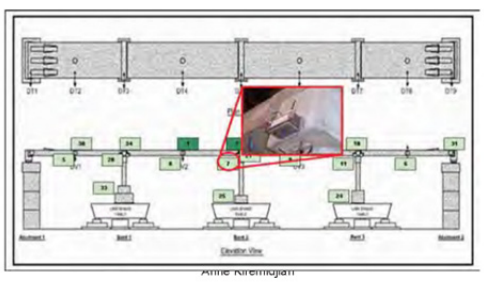
Anne Kiremidjian

Example Applications

- AR – 4-Span Bridge tested at UNR
- Wavelet – 4-Story Steel Frame tested at SUNY Buffalo
- Rotation Algorithm

Anne Kiremidjian

NEES – UNR Project-¼ Scale Bridge Test
AR & Gaussian Mixture Algorithm



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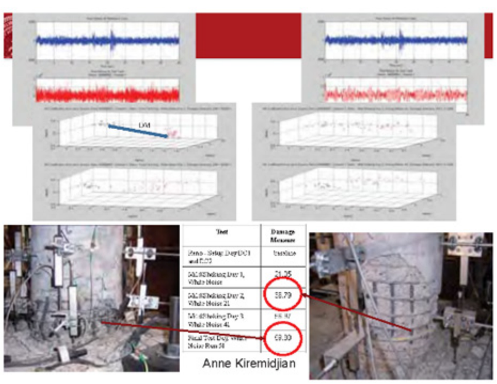

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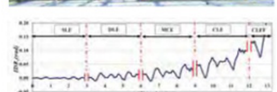
4-Story Steel Frame Test = SUNY, Buffalo
Wavelet Damage Diagnosis

Noh, Lignos & Kiremidjian, 2008

- Use non-stationary signals – e.g. earthquake response motions
- DSF- Feature from wavelet energies of signal
- Correlate DSF to Damage



Story Drift History

4-Story steel moment-resisting frame, NEES facility at SUNY-Buffalo

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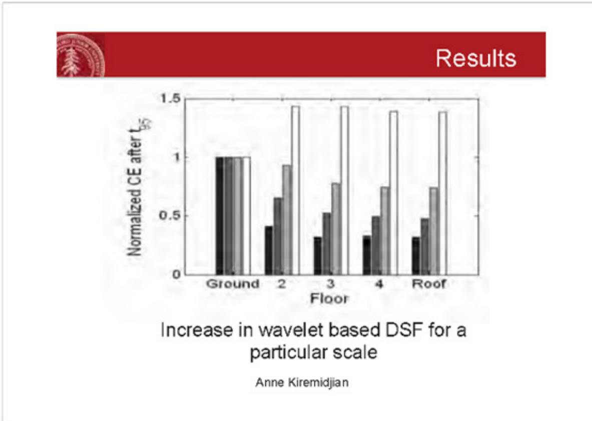
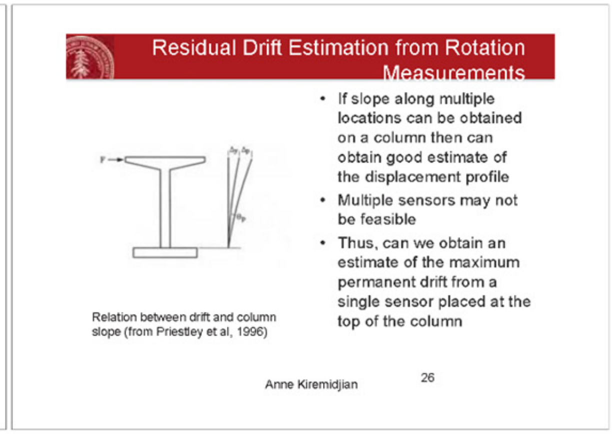
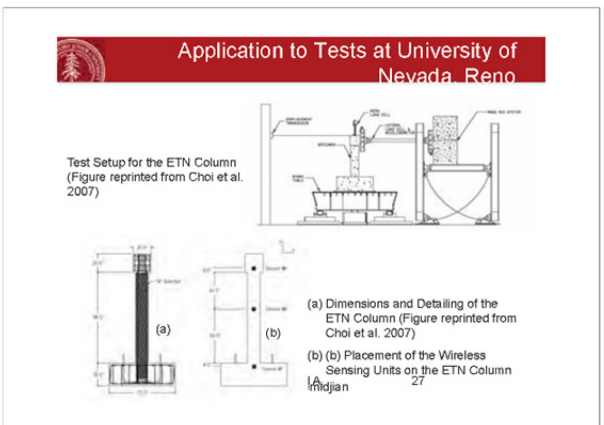
Appendix XI



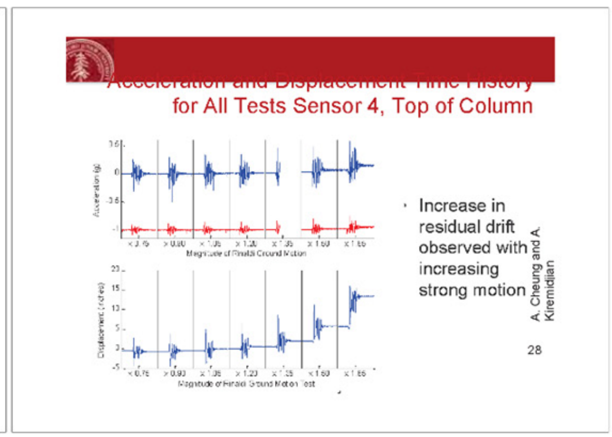
Results
1.5
1
0.5
0
Normalized CE after t_{95}
Ground 2 3 4 Roof
Floor
Increase in wavelet based DSF for a particular scale
Anne Kiremidjian



Residual Drift Estimation from Rotation Measurements
Relation between drift and column slope (from Priestley et al, 1996)
• If slope along multiple locations can be obtained on a column then can obtain good estimate of the displacement profile
• Multiple sensors may not be feasible
• Thus, can we obtain an estimate of the maximum permanent drift from a single sensor placed at the top of the column
Anne Kiremidjian
26



Application to Tests at University of Nevada, Reno
Test Setup for the ETN Column (Figure reprinted from Choi et al. 2007)
(a)
(b)
(a) Dimensions and Detailing of the ETN Column (Figure reprinted from Choi et al. 2007)
(b) (b) Placement of the Wireless Sensing Units on the ETN Column
Midjian
27



Acceleration and Displacement Time History for All Tests Sensor 4, Top of Column
• Increase in residual drift observed with increasing strong motion
A. Cheung and A. Kiremidjian
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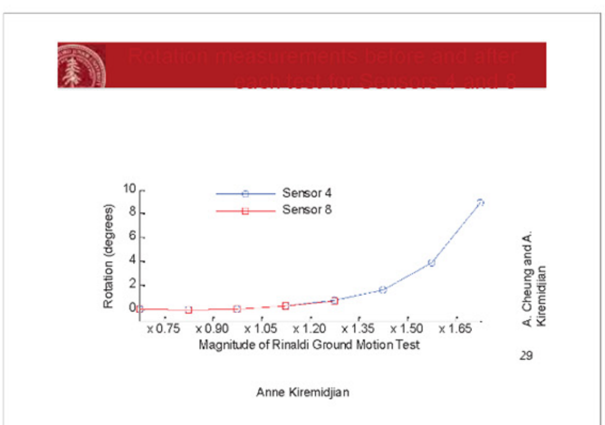
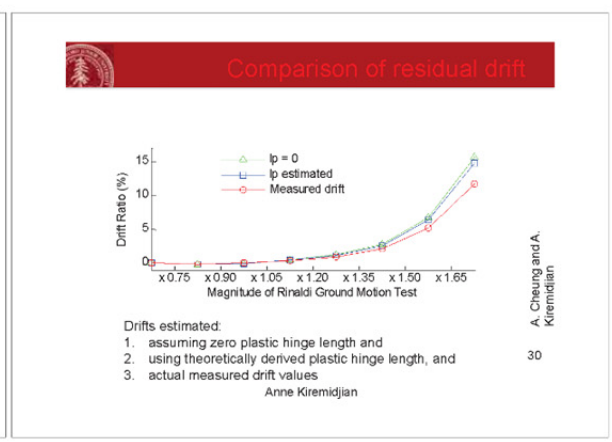


Rotation measurements before and after each test for Sensors 4 and 8
Sensor 4
Sensor 8
Rotation (degrees)
10
8
6
4
2
0
x 0.75 x 0.90 x 1.05 x 1.20 x 1.35 x 1.50 x 1.65
Magnitude of Rinaldi Ground Motion Test
A. Cheung and A. Kiremidjian
29
Anne Kiremidjian



Comparison of residual drift
lp = 0
lp estimated
Measured drift
Drift Ratio (%)
15
10
5
0
x 0.75 x 0.90 x 1.05 x 1.20 x 1.35 x 1.50 x 1.65
Magnitude of Rinaldi Ground Motion Test
Drifts estimated:
1. assuming zero plastic hinge length and
2. using theoretically derived plastic hinge length, and
3. actual measured drift values
Anne Kiremidjian
A. Cheung and A. Kiremidjian
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Outline

- Introduction
- Current Hardware Development
- Summary of Damage Detection Algorithms
- Response to NEES-E-Defense Questions

Anne Kiremidjian

Questions From NEES/E-Defense

- If monitoring systems are tailored to "sense" specific damage modalities in structures, which ones are of greatest importance that should be prioritized?
- How can instrumentation (sensors and sensing systems) be used to illuminate causal relationships between damage and residual capacity of structural systems?
- If there is an opportunity to dedicate a large-scale structural testing program exclusively to structural health monitoring and SHM-driven decision making, what would you propose?

Anne Kiremidjian

Which sensors to prioritize

- Crack sensors –
  - Steel welds
  - Steel members with notches
  - Concrete
- Corrosion sensors
- Direct dynamic displacement sensors

Anne Kiremidjian

Obtain causal relationships between damage and residual capacity

- Systematic testing with gradually increased ground shaking
- Develop relationships between damage measures and observed damage
- Develop analytical models that can be verified by the tests
- Then can develop causal relationships between damage and estimates of residual strength

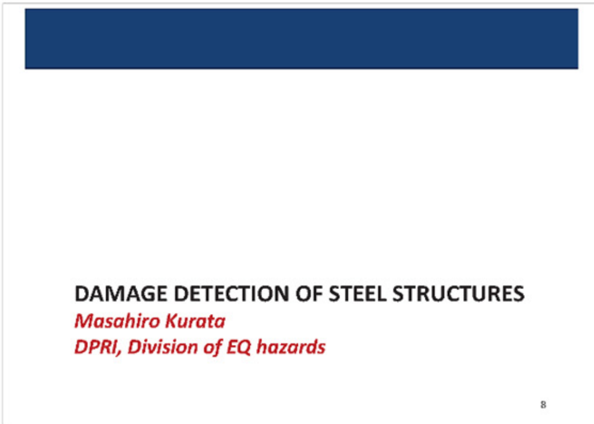
Anne Kiremidjian

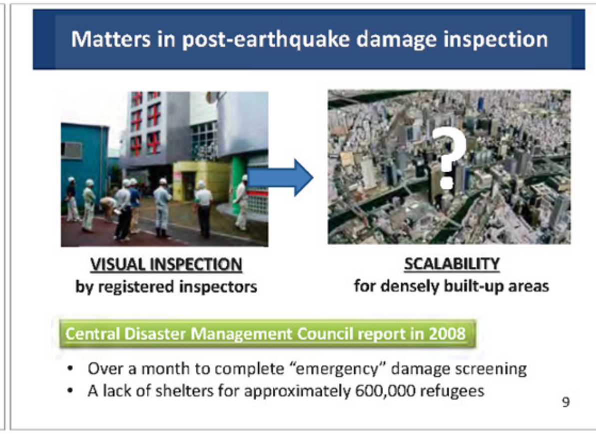
Proposed program for SHM

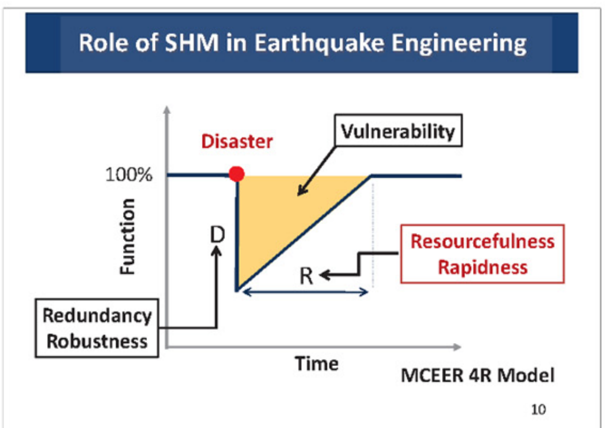
- Develop a test-bed for blind damage prediction based on tests conducted previously
  - Use previous test data to develop and test damage diagnosis and prognosis algorithms
  - Design a new structure and instrument extensively – provide an opportunity for various researchers to participate in the instrumentation
  - Subject to a series of random earthquake motions and obtain damage predictions from various SHM systems
  - Compare predicted and observed damage diagnosis and structural prognosis

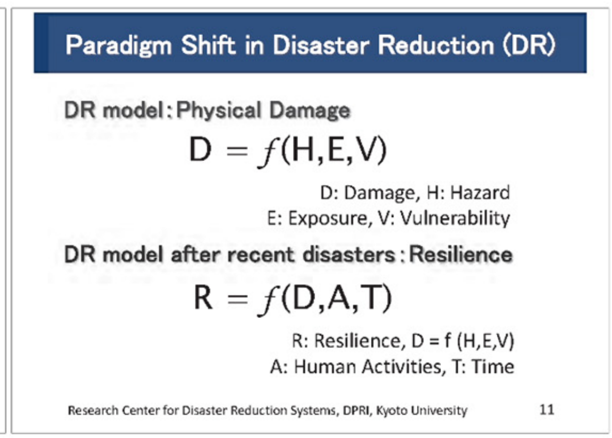
Anne Kiremidjian

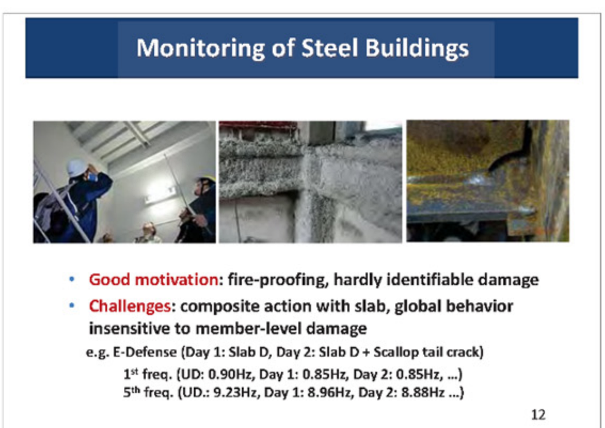
Appendix XI

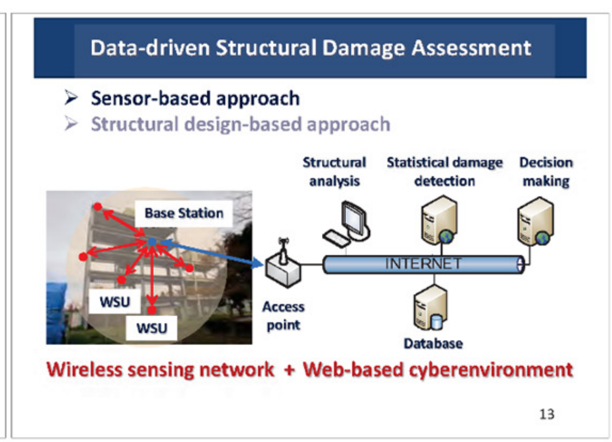

DAMAGE DETECTION OF STEEL STRUCTURES
Masahiro Kurata
DPRI, Division of EQ hazards
8

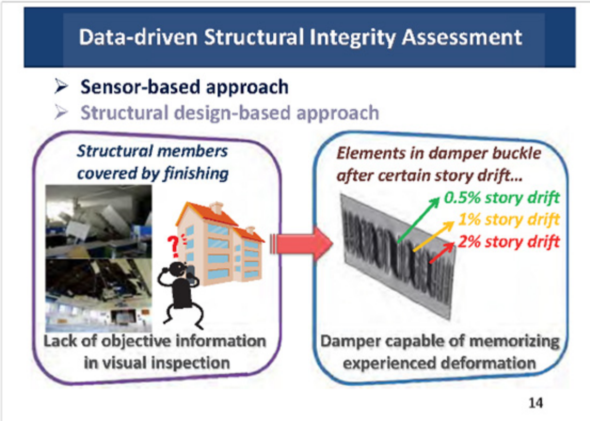

Matters in post-earthquake damage inspection
VISUAL INSPECTION
by registered inspectors
SCALABILITY
for densely built-up areas
Central Disaster Management Council report in 2008
• Over a month to complete "emergency" damage screening
• A lack of shelters for approximately 600,000 refugees
9

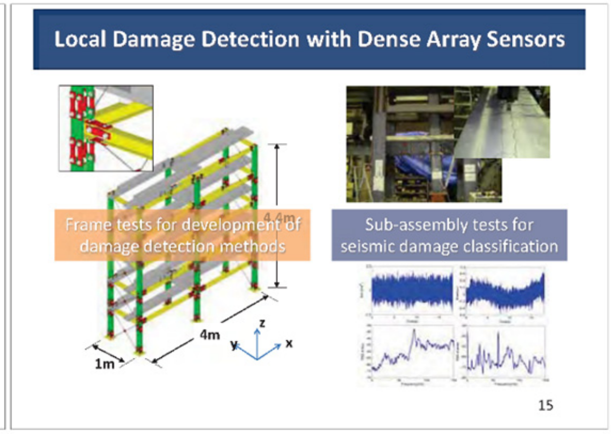

Role of SHM in Earthquake Engineering
Disaster
Vulnerability
100%
Function
D
R
Resourcefulness
Rapidness
Redundancy
Robustness
Time
MCEER 4R Model
10

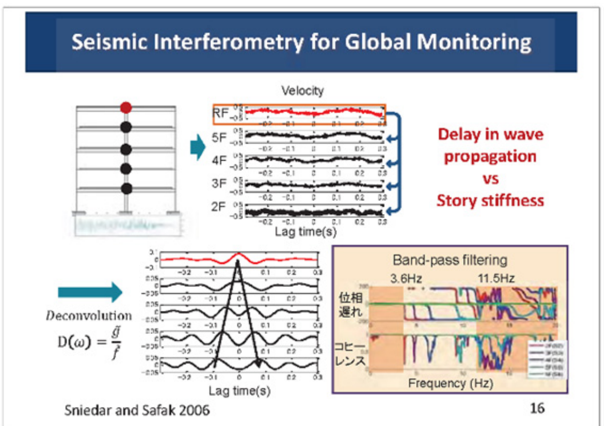

Paradigm Shift in Disaster Reduction (DR)
DR model : Physical Damage
D = f(H,E,V)
D: Damage, H: Hazard
E: Exposure, V: Vulnerability
DR model after recent disasters : Resilience
R = f(D,A,T)
R: Resilience, D = f (H,E,V)
A: Human Activities, T: Time
Research Center for Disaster Reduction Systems, DPRI, Kyoto University
11

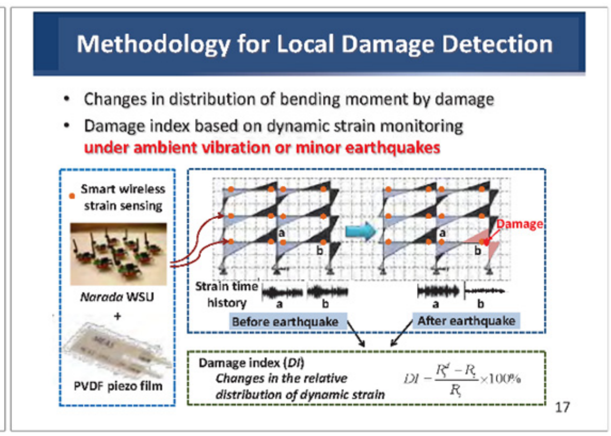

Monitoring of Steel Buildings
• Good motivation: fire-proofing, hardly identifiable damage
• Challenges: composite action with slab, global behavior insensitive to member-level damage
e.g. E-Defense (Day 1: Slab D, Day 2: Slab D + Scallop tail crack)
1st freq. (UD: 0.90Hz, Day 1: 0.85Hz, Day 2: 0.85Hz, ...)
5th freq. (UD.: 9.23Hz, Day 1: 8.96Hz, Day 2: 8.88Hz ...)
12

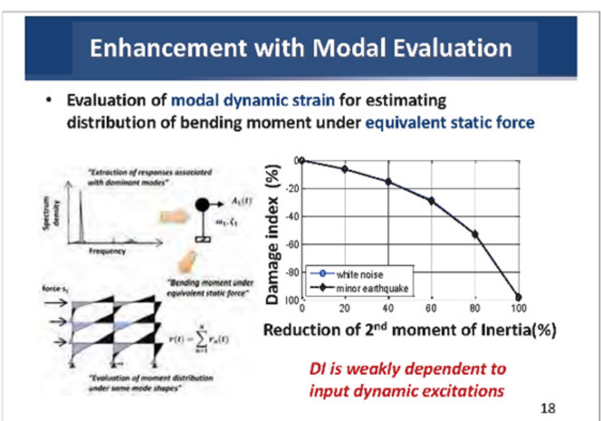

Data-driven Structural Damage Assessment
➢ Sensor-based approach
➢ Structural design-based approach
Structural analysis
Statistical damage detection
Decision making
Base Station
INTERNET
WSU
WSU
Access point
Database
Wireless sensing network + Web-based cyberenvironment
13

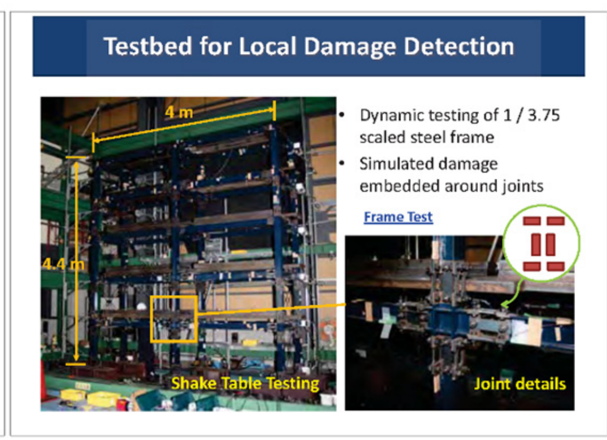

Data-driven Structural Integrity Assessment
Sensor-based approach
Structural design-based approach
Structural members covered by finishing
Lack of objective information in visual inspection
Elements in damper buckle after certain story drift...
0.5% story drift
1% story drift
2% story drift
Damper capable of memorizing experienced deformation
14


Local Damage Detection with Dense Array Sensors
Frame tests for development of damage detection methods
4.4m
4m
1m
Sub-assembly tests for seismic damage classification
15

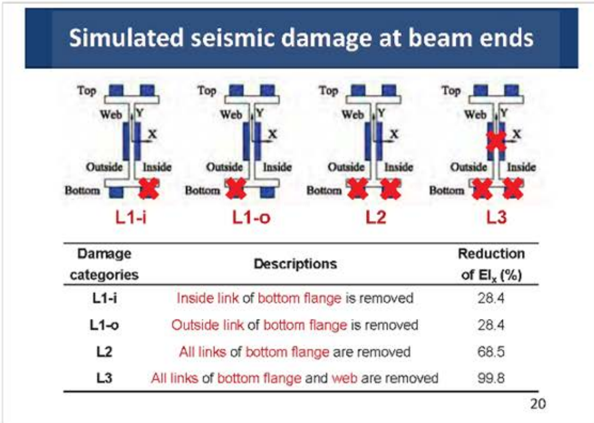

Seismic Interferometry for Global Monitoring
Velocity
RF
5F
4F
3F
2F
Lag time(s)
Delay in wave propagation vs Story stiffness
Deconvolution
D(ω) = ū/f̄
Lag time(s)
Band-pass filtering
3.6Hz
11.5Hz
位相遅れ
コヒーレンス
Frequency (Hz)
Sniedar and Safak 2006
16


Methodology for Local Damage Detection
Changes in distribution of bending moment by damage
Damage index based on dynamic strain monitoring under ambient vibration or minor earthquakes
Smart wireless strain sensing
Narada WSU
+
PVDF piezo film
Damage
Strain time history
Before earthquake
After earthquake
Damage index (DI)
Changes in the relative distribution of dynamic strain
17

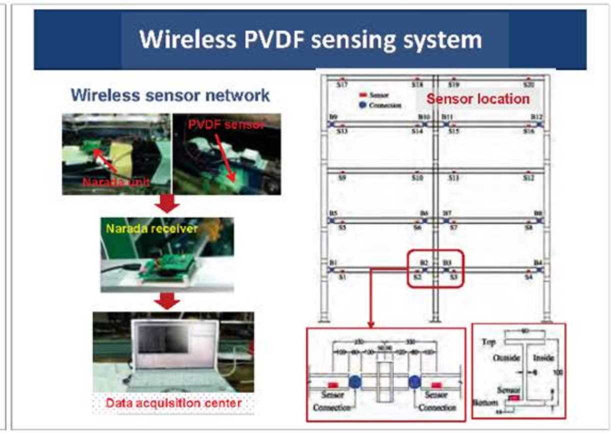

Enhancement with Modal Evaluation
Evaluation of modal dynamic strain for estimating distribution of bending moment under equivalent static force
"Extraction of responses associated with dominant modes"
"Bending moment under equivalent static force"
"Evaluation of moment distribution under same mode shapes"
Damage index (%)
white noise
minor earthquake
Reduction of 2nd moment of Inertia(%)
DI is weakly dependent to input dynamic excitations
18


Testbed for Local Damage Detection
4 m
4.4 m
Dynamic testing of 1 / 3.75 scaled steel frame
Simulated damage embedded around joints
Frame Test
Shake Table Testing
Joint details

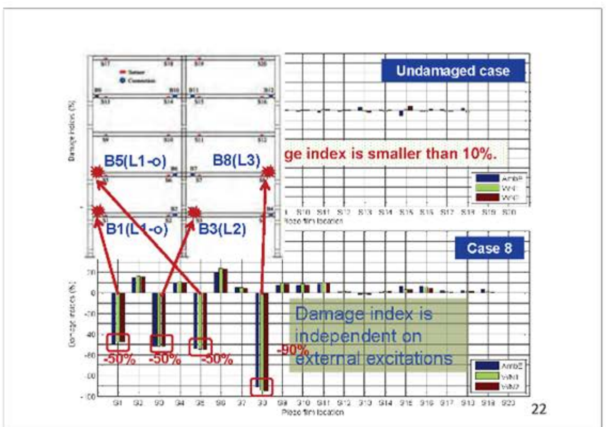
Appendix XI



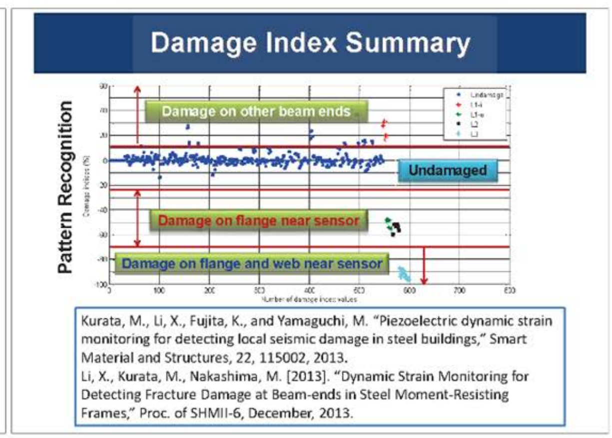
Simulated seismic damage at beam ends
Top
Web
Y
X
Outside
Inside
Bottom
L1-i
L1-o
L2
L3
Damage categories | Descriptions | Reduction of EI_x (%)
L1-i | Inside link of bottom flange is removed | 28.4
L1-o | Outside link of bottom flange is removed | 28.4
L2 | All links of bottom flange are removed | 68.5
L3 | All links of bottom flange and web are removed | 99.8
20



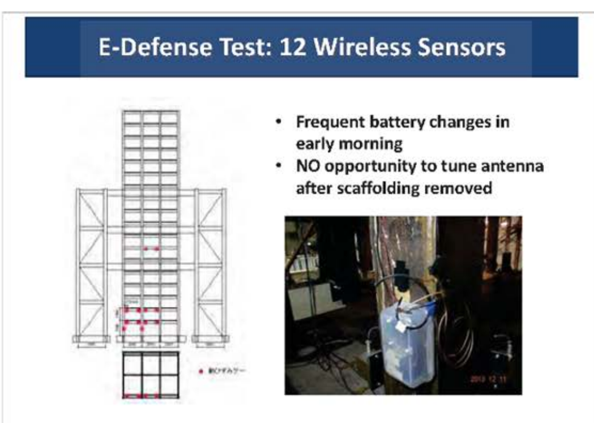
Wireless PVDF sensing system
Wireless sensor network
PVDF sensor
Narada unit
Narada receiver
Data acquisition center
Sensor location
Sensor
Connection
Top
Outside
Inside
Bottom



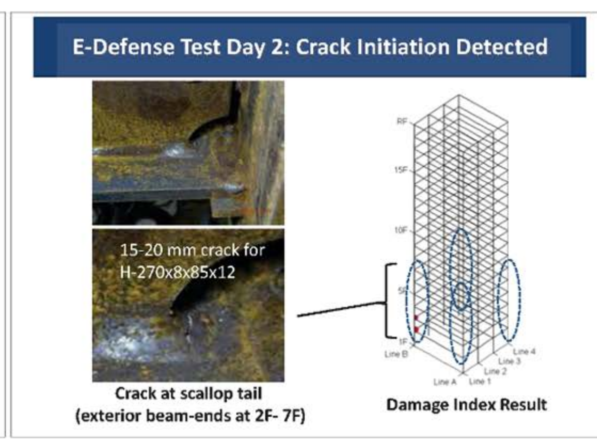
Undamaged case
ge index is smaller than 10%.
B5(L1-o)
B8(L3)
B1(L1-o)
B3(L2)
Case 8
Damage index is independent on external excitations
-50%
-50%
-50%
-90%
22



Damage Index Summary
Pattern Recognition
Damage on other beam ends
Undamaged
Damage on flange near sensor
Damage on flange and web near sensor
Kurata, M., Li, X., Fujita, K., and Yamaguchi, M. "Piezoelectric dynamic strain monitoring for detecting local seismic damage in steel buildings," Smart Material and Structures, 22, 115002, 2013.
Li, X., Kurata, M., Nakashima, M. [2013]. "Dynamic Strain Monitoring for Detecting Fracture Damage at Beam-ends in Steel Moment-Resisting Frames," Proc. of SHMII-6, December, 2013.



E-Defense Test: 12 Wireless Sensors
• Frequent battery changes in early morning
• NO opportunity to tune antenna after scaffolding removed



E-Defense Test Day 2: Crack Initiation Detected
15-20 mm crack for H-270x8x85x12
Crack at scallop tail (exterior beam-ends at 2F- 7F)
Damage Index Result

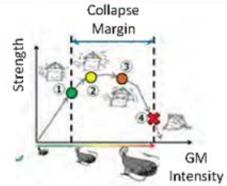
Specific damage modalities in structures

- *Drift-based*:
  - Seismograph, direct-sensing
  - Advancement of simulation techniques for predicting deteriorating behavior, **yet large uncertainties in strong non-linear range** (yielding > local-buckling >> crack or fracture)
  - Interpolation techniques for reducing # of sensors
- RC structures:
  - AE sensors for crack detection
  - Acc. for frequency change
- Steel structures:
  - Strain-based for fracture detection, fracture sound?

No needs for monitoring collapse

26

Causal relationships between damage and residual capacity of structural systems

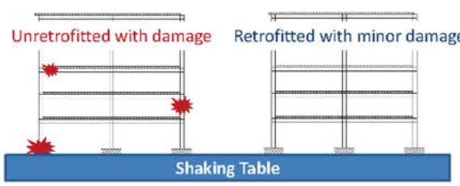


- Allowable damage and demand for monitoring
  - Minor and visually non-identifiable damage need detection
  - Critical and visually-identifiable damage need quantification
- Classification needed with the level of redundancy
  - Several critical damage trigger collapse in bridges but not in buildings

27

Large-scale structural testing program

- Shake table testing of structure-specific earthquake early warning and damage detection
- Blind competition (no tuning for thresholds!) of novel sensing technologies
- Relatively small but two visually identical structures



28

Thank you!

29

- Large dependency on the level of redundancy and ductility of members
  - Need specific approach for each structure type
- Integral-approach:
  - Need accurate information for each damage extent
  - Integrated error
- Direct-approach:
  - Obtain hysteresis loop with acceleration responses
  - Contain large noise yet promising to capture deterioration curve
  - Need real-time monitoring

30

Development of Damage Index

Challenges in Dynamic Strain Monitoring under Small Excitations

A) Variations in sensors

B) Small S/N ratios under ambient vibrations

C) Time-synchronization in multi-floor wireless networks

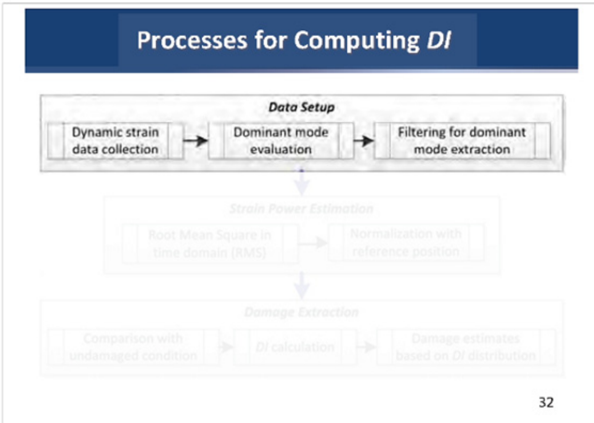
$$DI = \frac{R_i^d - R_i}{R_i} \times 100\%$$

R_i: power of filtered dynamic strain responses

- **Statistical evaluation in time-domain using power of dynamic strain responses**
- **In-network normalization for a comparative study under different input motions**

31

Appendix XI



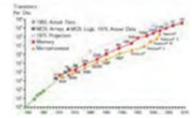
Processes for Computing *DI*
Data Setup
Dynamic strain data collection
Dominant mode evaluation
Filtering for dominant mode extraction
Strain Power Estimation
Root Mean Square in time domain (RMS)
Normalization with reference position
Damage Extraction
Comparison with undamaged condition
DI calculation
Damage estimates based on *DI* distribution
32

Wireless Cyber-Physical System Frameworks for Enhancing Civil Infrastructure Resiliency

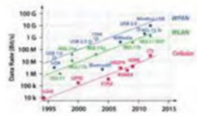
Jerome P. Lynch, Ph.D.
Associate Professor
Department of Civil and Environmental Engineering
Department of Electrical Engineering and Computer Science
University of Michigan

10th NEES/E-Defense Collaborative Earthquake Research Program Meeting
Kyoto, Japan
December 12, 2013

Confluence of Technological Trends

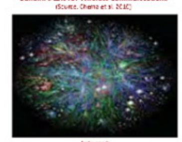


Moore's Law for Processors and Memory
(Source: Intel)



Edholm's Law for Wireless Communications
(Source: Cheng et al. 2010)

Microelectromechanical Systems (MEMS)
(Source: Analog Devices)



Internet
(Source: Wikipedia)

Emergence of Cyber-Physical Systems

- **Cyber-physical systems (CPS):**
  - Coordinated combination of sensing, computing and actuation
  - Integration of embedded computing, wireless communication and low-cost sensing allows the world to be densely sensed and controlled
  - Availability of wireless Internet gives field based sensors/actuators increasing access to computing resources

Early Earthquake Warning Systems

Intelligent Transportation Systems
(Source: University of Michigan)

Emergence of Cyber-Physical Systems

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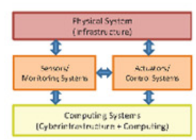
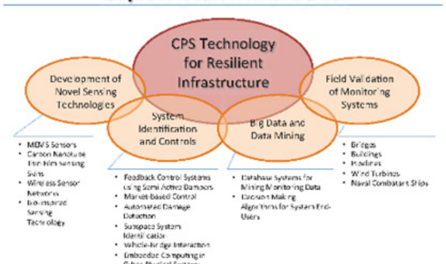


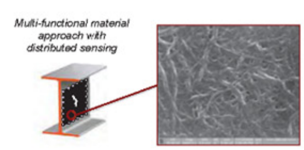
Cyber-physical System (CPS) Framework

My Research Portfolio



Distributed Damage Sensing

- **Distributed sensing based on multifunctional materials:**
  - Materials that whose material properties are modulated to damage
  - Work has explored use of carbon nanotube thin films
  - Distributed sensing functionality provided by impedance tomography



Appendix XI

Distributed Damage Sensing

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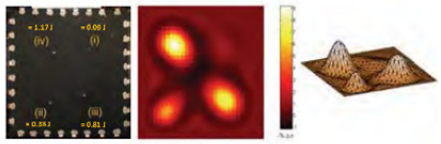
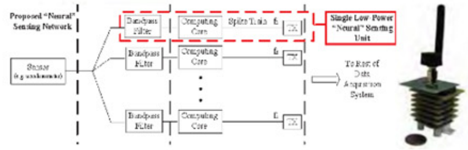


12/12/13 A Wireless Cyber-Physical System Framework for Enhancing the Resiliency of Civil Infrastructure Systems Slide 7

Bio-inspired Sensing Systems

- **Biology unexplored for next-generation sensors:**
  - Nature ripe with sensing, power harvesting, collective intelligence
  - Impressive sensing capabilities with low power levels
- **Bio-inspired compressive sensing based on the cochlea:**
  - Cochlea interprets sound wave through mechanical vibrations of basilar membrane which converts signal into binary spike train



12/12/13 A Wireless Cyber-Physical System Framework for Enhancing the Resiliency of Civil Infrastructure Systems Slide 8

Bio-inspired Sensing Systems

- **Biology unexplored for next-generation sensors:**
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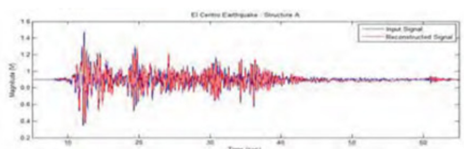
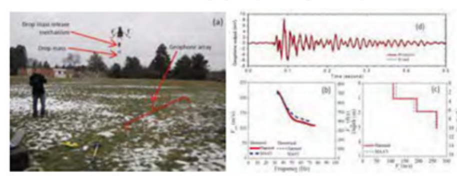


12/12/13 A Wireless Cyber-Physical System Framework for Enhancing the Resiliency of Civil Infrastructure Systems Slide 9

UAV Field Sensing

- **UAV explored for post-event reconnaissance:**
  - Civil infrastructure performance data from extreme events is perishable and needs to be collected as quickly and reliably as possible
  - Site conditions can be dangerous and difficult to reach
  - Quad rotor UAVs are emerging as a promising data acquisition tool



12/12/13 A Wireless Cyber-Physical System Framework for Enhancing the Resiliency of Civil Infrastructure Systems Slide 10

Actuation in the CPS Framework

- **Extensions of the developed wireless CPS framework:**
  - Include actuation and system reconfiguration for system resiliency
  - Feedback control theory upon a CPS framework defined by both static (e.g., infrastructure) and mobile (e.g., societal users) agents:
    - Infrastructure network reconfiguration driven by hybrid system analysis
    - Model predictive control (MPC) approaches

Cascading Failures: Fukushima March/April 2011

Reconfigurable Chilled Water Systems

12/12/13 A Wireless Cyber-Physical System Framework for Enhancing the Resiliency of Civil Infrastructure Systems Slide 11

New Carquinez Bridge

- **New Carquinez Bridge (constructed 2003):**
  - Located in the San Francisco Bay Area (Vallejo, CA)
  - Total bridge length is 1056 m (main span of 728 m)
  - Main deck consists of steel orthotropic box girders
  - Hollow reinforced concrete towers and pre-stressed link beam

New Carquinez Bridge (NCB)

Fault Activity near Vallejo (Source: USGS)

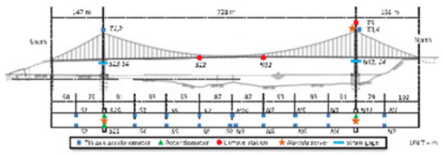
MCE for Vallejo, CA
- San Andreas (M_w=8)
- Hayward (M_w=7.3)
- Franklin (M_w=6.5)

In collaboration with Mr. Patrick Hipley, Caltrans

12/12/13 A Wireless Cyber-Physical System Framework for Enhancing the Resiliency of Civil Infrastructure Systems Slide 12

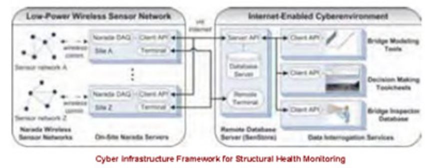
Instrumentation Plan

Sensor Type	Nodes	Channels
Tri-axial accelerometer (girder)	19	57
Tri-axial accelerometer (towers)	4	12
Wind vane, anemometer, temp	3	9
Potentiometer Displacement (girder)	3	3
Strain gages (girder interior)	2	6
TOTAL	**31**	**87**



Data-driven Decision Making

- **Cyberinfrastructure tools offer enormous potential:**
  - Database systems for storage of structure meta- and sensor data
  - Data combined with powerful analytical tools via clients:
    - Physics- and statistics-based information discovery from data
  - Decision-making front-end for infrastructure asset management



Cyber Infrastructure Framework for Structural Health Monitoring

Workshop Question 1

- **If monitoring systems are tailored to "sense" specific damage modalities in structures, which ones are of greatest importance that should be prioritized?**
  - Structural damage modalities:
    - Fatigue/fracture in steel elements
    - Yielding/plastification in steel elements
    - Corrosion in steel elements and steel reinforcement
    - Cracking in reinforced concrete elements
    - Residual deformation of the structure
    - Change in assumed boundary conditions
  - Non-structural damage modalities:
    - Fire-proofing integrity
    - Building utilities (water, lighting, sanitation)

Workshop Question 1

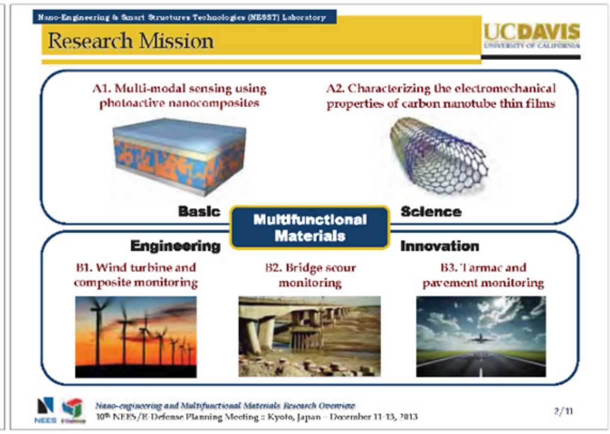
- **How can instrumentation (sensors and sensing systems) be used to illuminate causal relationships between damage and residual capacity of structural systems?**
  - Sensing can be used to track the progression of damage in a structure
  - Progression of mechanism manifestation
  - Models and analytical methods can be embedded to estimate capacity from measures of a structure
  - Damage-specific sensors could then be used to provided richer context for assessing structural capacity

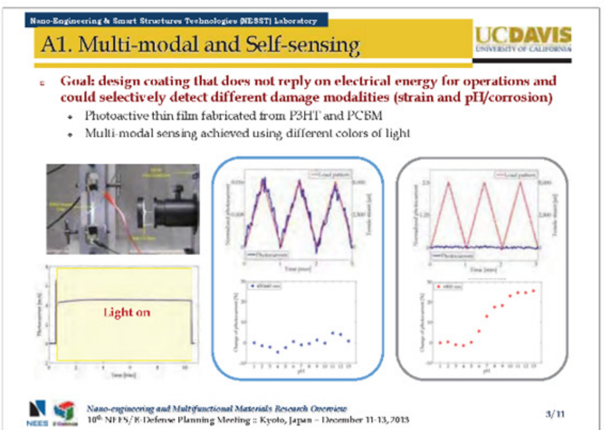
Workshop Question 1

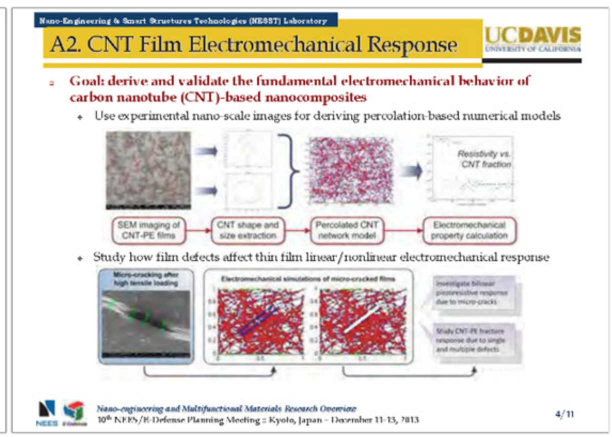
- **If there is an opportunity to dedicate a large-scale structural testing program exclusively to structural health monitoring and SHM-driven decision making, what would you propose?**
  - Pre-event:
    - Structural assessment to quantify inherent system capacity and system boundary conditions
    - System response prediction on varying time-scales (e.g., use of early earthquake monitoring system metrics ahead of shaking)
  - Event:
    - Damage detection based on monitoring at local and global spatial scales
    - Feedback control systems for structural and non-structural
    - Sensor fault and failure detection from seismic damage
  - Post-event:
    - Metrics for building re-occupancy program
    - Interplay of sensed-data analytics and post-event visual inspection

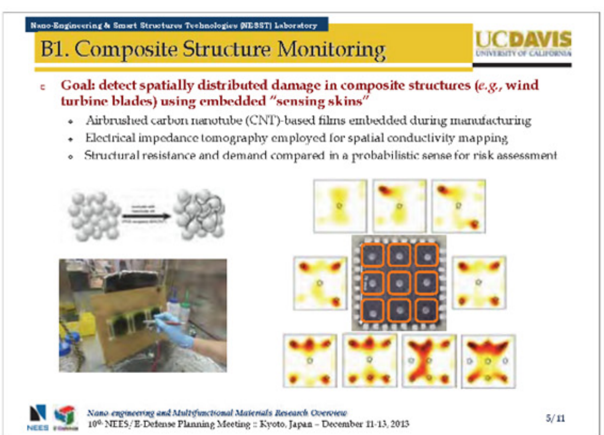
Appendix XI

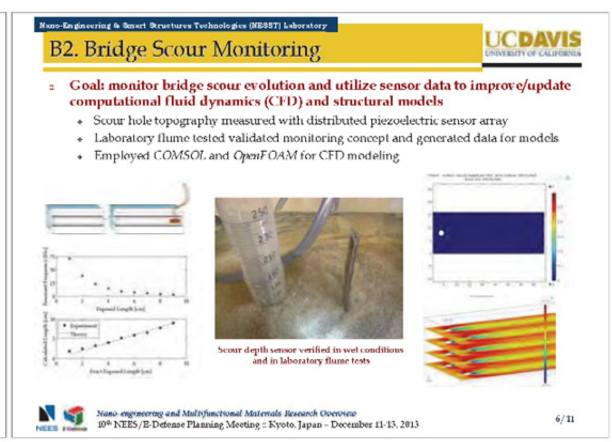

Nano-engineering and Multifunctional Materials Research Overview
UNIVERSITY OF CALIFORNIA, DAVIS
Kenneth J. Loh
Assistant Professor
Department of Civil & Environmental Engineering
Nano-Engineering & Smart Structures Technologies (NESST) Laboratory
University of California, Davis
10th NEES/E-Defense Planning Meeting
Kyoto, Japan
December 12, 2013

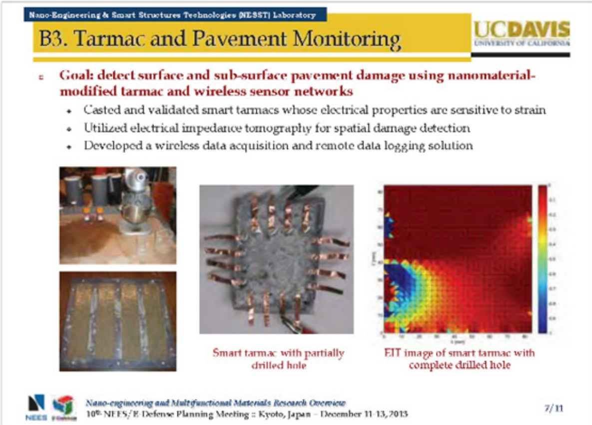

Nano-Engineering & Smart Structures Technologies (NESST) Laboratory
Research Mission
UCDAVIS
UNIVERSITY OF CALIFORNIA
A1. Multi-modal sensing using photoactive nanocomposites
A2. Characterizing the electromechanical properties of carbon nanotube thin films
Basic
Multifunctional Materials
Science
Engineering
Innovation
B1. Wind turbine and composite monitoring
B2. Bridge scour monitoring
B3. Tarmac and pavement monitoring
Nano-engineering and Multifunctional Materials Research Overview
10th NEES/E-Defense Planning Meeting :: Kyoto, Japan – December 11-13, 2013
2/11

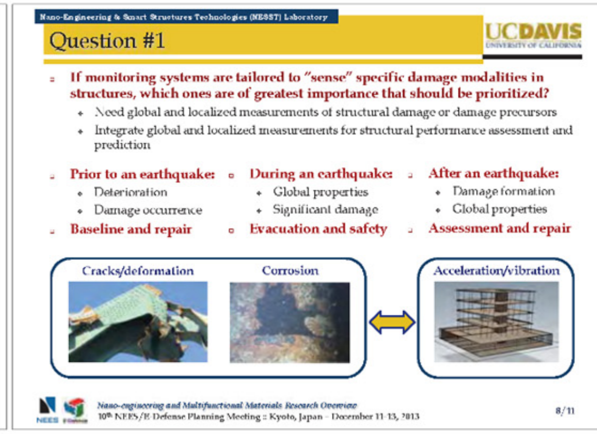

Nano-Engineering & Smart Structures Technologies (NESST) Laboratory
A1. Multi-modal and Self-sensing
UCDAVIS
UNIVERSITY OF CALIFORNIA
Goal: design coating that does not reply on electrical energy for operations and could selectively detect different damage modalities (strain and pH/corrosion)
Photoactive thin film fabricated from P3HT and PCBM
Multi-modal sensing achieved using different colors of light
Light on
Nano-engineering and Multifunctional Materials Research Overview
10th NEES/E-Defense Planning Meeting :: Kyoto, Japan – December 11-13, 2013
3/11

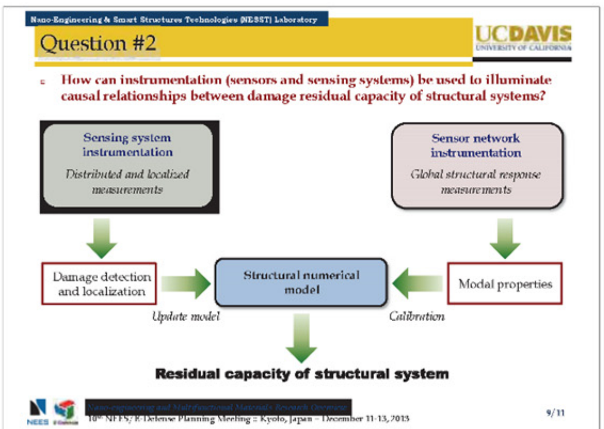

Nano-Engineering & Smart Structures Technologies (NESST) Laboratory
A2. CNT Film Electromechanical Response
UCDAVIS
UNIVERSITY OF CALIFORNIA
Goal: derive and validate the fundamental electromechanical behavior of carbon nanotube (CNT)-based nanocomposites
Use experimental nano-scale images for deriving percolation-based numerical models
Resistivity vs. CNT fraction
SEM imaging of CNT-PE films
CNT shape and size extraction
Percolated CNT network model
Electromechanical property calculation
Study how film defects affect thin film linear/nonlinear electromechanical response
Electromechanical simulations of micro-cracked films
Nano-engineering and Multifunctional Materials Research Overview
10th NEES/E-Defense Planning Meeting :: Kyoto, Japan – December 11-13, 2013
4/11

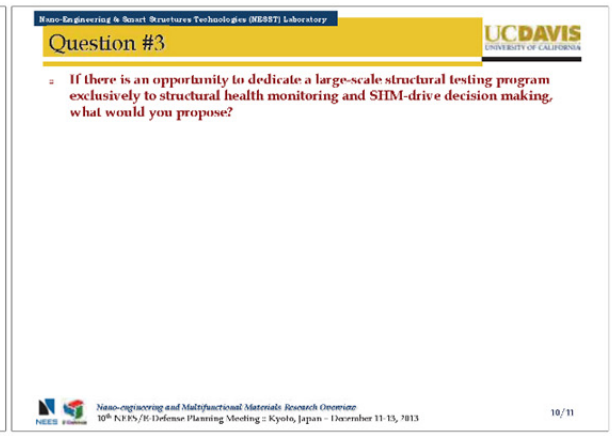

Nano-Engineering & Smart Structures Technologies (NESST) Laboratory
B1. Composite Structure Monitoring
UCDAVIS
UNIVERSITY OF CALIFORNIA
Goal: detect spatially distributed damage in composite structures (e.g., wind turbine blades) using embedded "sensing skins"
Airbrushed carbon nanotube (CNT)-based films embedded during manufacturing
Electrical impedance tomography employed for spatial conductivity mapping
Structural resistance and demand compared in a probabilistic sense for risk assessment
Nano-engineering and Multifunctional Materials Research Overview
10th NEES/E-Defense Planning Meeting :: Kyoto, Japan – December 11-13, 2013
5/11


Nano-Engineering & Smart Structures Technologies (NESST) Laboratory
B2. Bridge Scour Monitoring
UCDAVIS
UNIVERSITY OF CALIFORNIA
Goal: monitor bridge scour evolution and utilize sensor data to improve/update computational fluid dynamics (CFD) and structural models
Scour hole topography measured with distributed piezoelectric sensor array
Laboratory flume tested validated monitoring concept and generated data for models
Employed COMSOL and OpenFOAM for CFD modeling
Scour depth sensor verified in wet conditions and in laboratory flume tests
Nano-engineering and Multifunctional Materials Research Overview
10th NEES/E-Defense Planning Meeting :: Kyoto, Japan – December 11-13, 2013
6/11


Nano-Engineering & Smart Structures Technologies (NESST) Laboratory
B3. Tarmac and Pavement Monitoring
UCDAVIS
UNIVERSITY OF CALIFORNIA
Goal: detect surface and sub-surface pavement damage using nanomaterial-modified tarmac and wireless sensor networks
Casted and validated smart tarmacs whose electrical properties are sensitive to strain
Utilized electrical impedance tomography for spatial damage detection
Developed a wireless data acquisition and remote data logging solution
Smart tarmac with partially drilled hole
EIT image of smart tarmac with complete drilled hole
Nano-engineering and Multifunctional Materials Research Overview
10th NEES/E-Defense Planning Meeting :: Kyoto, Japan – December 11-13, 2013
7/11

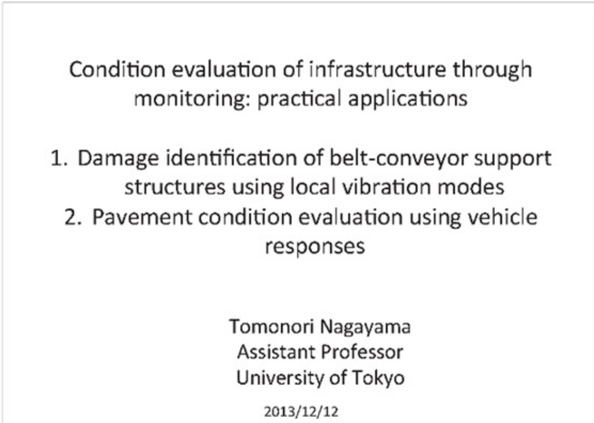

Nano-Engineering & Smart Structures Technologies (NESST) Laboratory
Question #1
UCDAVIS
UNIVERSITY OF CALIFORNIA
If monitoring systems are tailored to "sense" specific damage modalities in structures, which ones are of greatest importance that should be prioritized?
Need global and localized measurements of structural damage or damage precursors
Integrate global and localized measurements for structural performance assessment and prediction
Prior to an earthquake:
Deterioration
Damage occurrence
Baseline and repair
During an earthquake:
Global properties
Significant damage
Evacuation and safety
After an earthquake:
Damage formation
Global properties
Assessment and repair
Cracks/deformation
Corrosion
Acceleration/vibration
Nano-engineering and Multifunctional Materials Research Overview
10th NEES/E-Defense Planning Meeting :: Kyoto, Japan – December 11-13, 2013
8/11

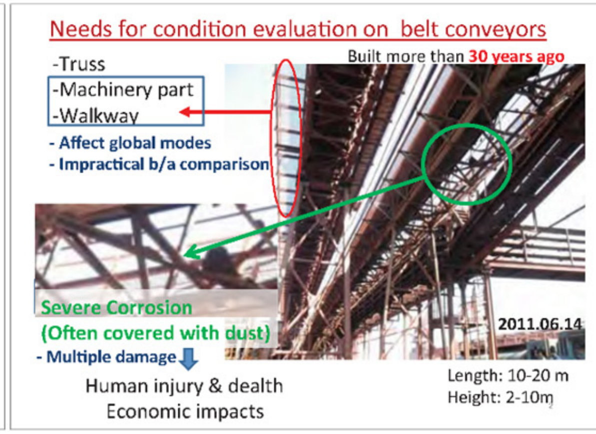

Nano-Engineering & Smart Structures Technologies (NESST) Laboratory
Question #2
UCDAVIS
UNIVERSITY OF CALIFORNIA
How can instrumentation (sensors and sensing systems) be used to illuminate causal relationships between damage residual capacity of structural systems?
Sensing system instrumentation
Distributed and localized measurements
Sensor network instrumentation
Global structural response measurements
Damage detection and localization
Structural numerical model
Modal properties
Update model
Calibration
Residual capacity of structural system
[redacted]
10th NEES/E-Defense Planning Meeting :: Kyoto, Japan – December 11-13, 2013
9/11

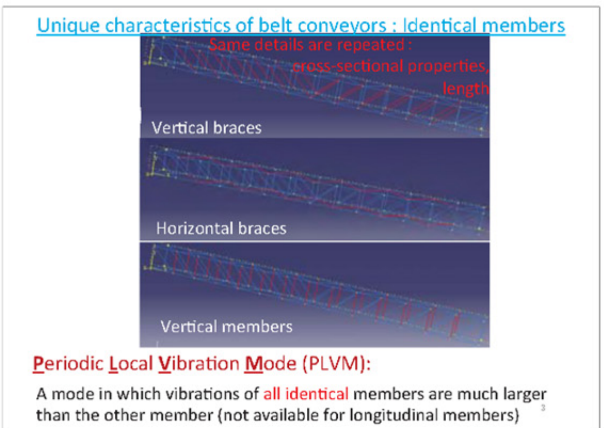

Nano-Engineering & Smart Structures Technologies (NESST) Laboratory
Question #3
UCDAVIS
UNIVERSITY OF CALIFORNIA
If there is an opportunity to dedicate a large-scale structural testing program exclusively to structural health monitoring and SHM-drive decision making, what would you propose?
Nano-engineering and Multifunctional Materials Research Overview
10th NEES/E-Defense Planning Meeting :: Kyoto, Japan – December 11-13, 2013
10/11

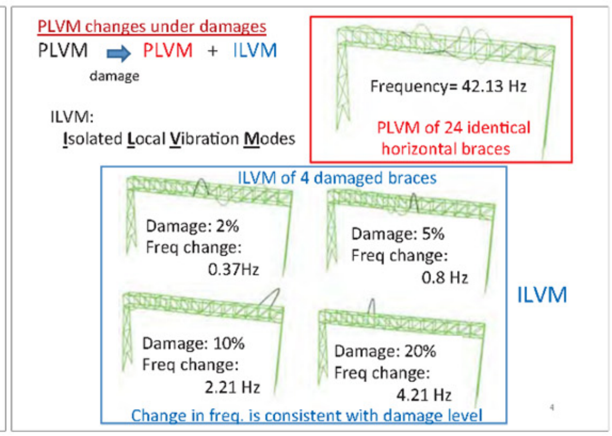

Thank You! Questions?
UNIVERSITY OF CALIFORNIA, DAVIS
Acknowledgements:
This research is supported by the National Science Foundation (NSF), Federal Aviation Administration (FAA), and U.S. Council for International Exchange of Scholars (CIES) Fulbright Scholar Program
FULBRIGHT

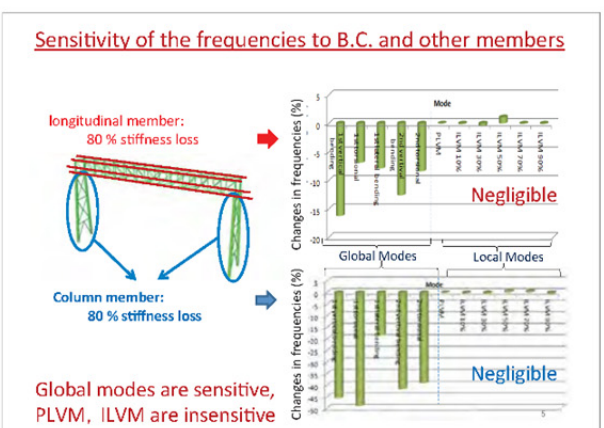
Appendix XI

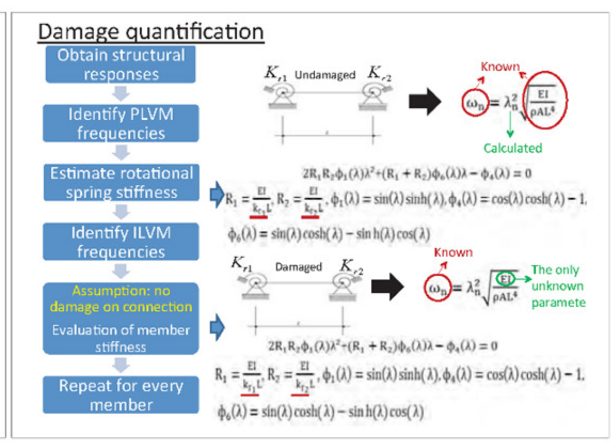

Condition evaluation of infrastructure through monitoring: practical applications
1. Damage identification of belt-conveyor support structures using local vibration modes
2. Pavement condition evaluation using vehicle responses
Tomonori Nagayama
Assistant Professor
University of Tokyo
2013/12/12


Needs for condition evaluation on belt conveyors
Built more than 30 years ago
-Truss
-Machinery part
-Walkway
- Affect global modes
- Impractical b/a comparison
Severe Corrosion
(Often covered with dust)
- Multiple damage
2011.06.14
Human injury & dealth
Economic impacts
Length: 10-20 m
Height: 2-10m


Unique characteristics of belt conveyors : Identical members
Same details are repeated :
cross-sectional properties,
length
Vertical braces
Horizontal braces
Vertical members
Periodic Local Vibration Mode (PLVM):
A mode in which vibrations of all identical members are much larger than the other member (not available for longitudinal members)
3


PLVM changes under damages
PLVM ⇒ PLVM + ILVM
damage
ILVM:
Isolated Local Vibration Modes
Frequency= 42.13 Hz
PLVM of 24 identical horizontal braces
ILVM of 4 damaged braces
Damage: 2%
Freq change:
0.37Hz
Damage: 5%
Freq change:
0.8 Hz
Damage: 10%
Freq change:
2.21 Hz
Damage: 20%
Freq change:
4.21 Hz
ILVM
Change in freq. is consistent with damage level
4

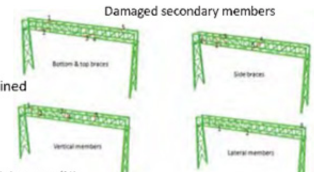

Sensitivity of the frequencies to B.C. and other members
longitudinal member:
80 % stiffness loss
Column member:
80 % stiffness loss
Changes in frequencies (%)
Mode
Negligible
Global Modes
Local Modes
Negligible
Global modes are sensitive,
PLVM, ILVM are insensitive
5


Damage quantification
Obtain structural responses
Identify PLVM frequencies
Estimate rotational spring stiffness
Identify ILVM frequencies
Assumption: no damage on connection
Evaluation of member stiffness
Repeat for every member
Undamaged
Known
Calculated
Damaged
Known
The only unknown paramete

Damage identification on FEM of conveyor truss

- Multiple members are damaged
- Velocity responses are simulated

Change in PLVM and ILVM are examined



Identified damages (%)

Member sets	member 1		member 2		member 3		member 4		member 5	
	Damage	Identified	Damage	Identified	Damage	Identified	Damage	Identified	Damage	Identified
Bottom and top braces	75	74.1	5	4.5	10	10.0	20	19.0	35	35.2
Side braces	90	89.9	5	5.2	65	64.4	25	25.4	25	25.4
Vertical members	85	85.1	5	5.3	55	55.3	15	15.9	30	31.7
Lateral members	5	4.3	15	14.1	40	39.7	-		-	

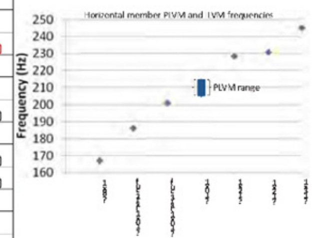
Damage identification using a scale-model

14 members were replaced

Element	Damage
1	φ13×1
2	φ12×1
3	φ11×1
4	φ10×1(1/2 cut)
5	φ12×1
6	φ13×1
7	φ10×1(2/3 cut)
8	φ8×1
9	φ10×1(1/3 cut)
10	φ10×1(1/2 cut)
11	φ9.5×1
12	φ13×1
13	φ8×1
14	φ12×1

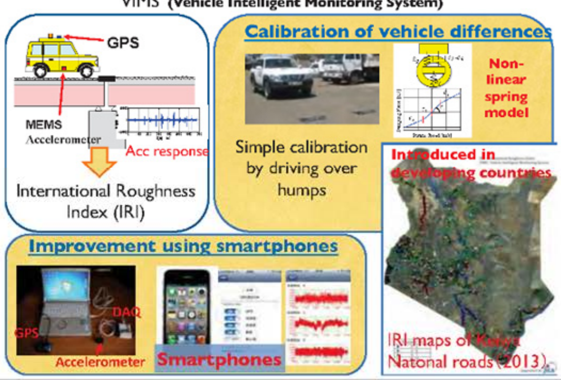
Undamaged members **φ10×1**

- Hammer impact on each member
- LDV measurement



Pavement condition evaluation using vehicle responses

VIMS **(Vehicle Intelligent Monitoring System)**



1. If monitoring systems are tailored to "sense" specific damage modalities in structures, which ones are of greatest importance that should be prioritized?

- From an "importance" perspective, damages which leads to complete collapse. For BC, corrosion on the bottom cords. For bridges, cracks and corrosions on FCMs, scouring around bridge piers.
- Often, this type of failure modes should be addressed not only by sensing, but also by improving the design increasing structural redundancy, in particular for rapidly growing cracks.
- As for post earthquake structural assessment, confirming small vibration level is practical. Examining not the "damage modalities", but "undamage modalities" improve the infrastructure operation by reducing inspection time & cost.

10

2. How can instrumentation (sensors and sensing systems) be used to illuminate causal relationships between damage and residual capacity of structural systems?

- There are structures whose residual capacities can be estimated by evaluating critical members' stiffness. For the BC corrosion example, buckling load is estimated through the stiffness identification.

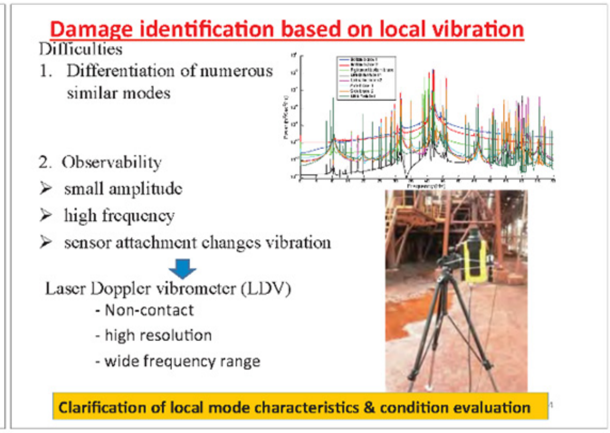
11

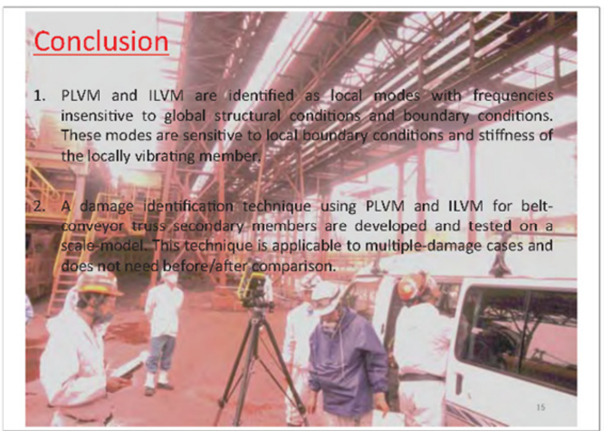
3. If there is an opportunity to dedicate a large-scale structural testing program exclusively to structural health monitoring and SHM-driven decision making, what would you propose?

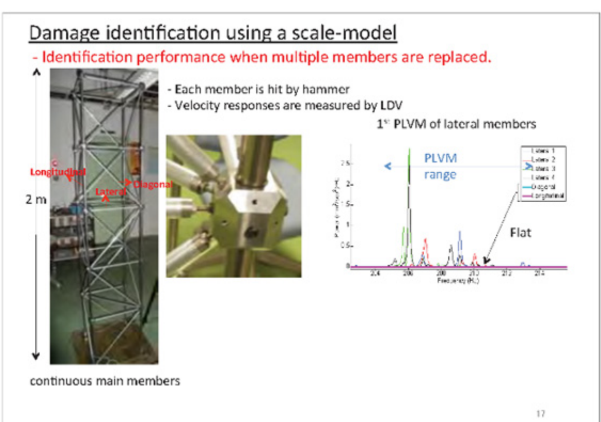
- I would reproduce critical damages in scale models (truss or girder bridges) in a progressive manner and measure local vibrations.
- I would perform thorough investigation to reveal the linear limit under variety of input/response conditions.

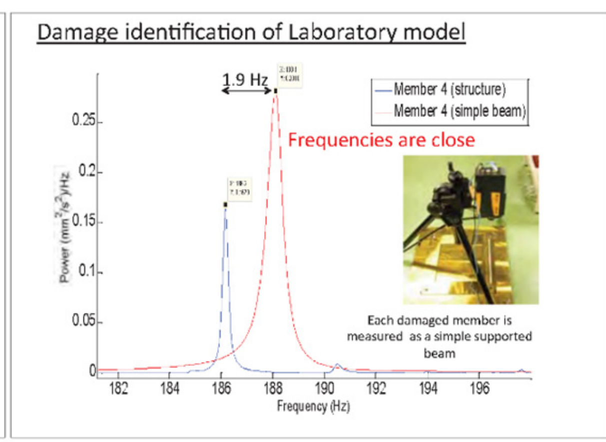
12

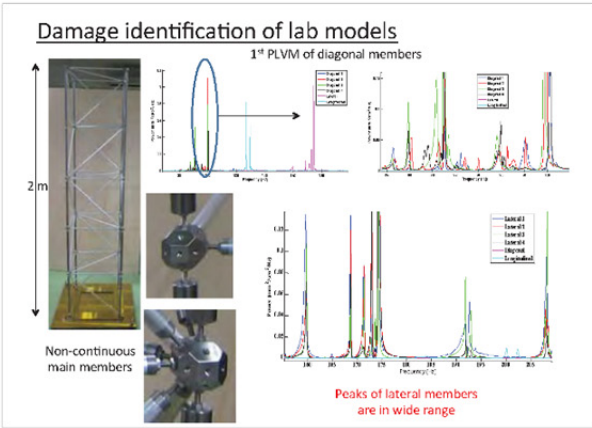
Appendix XI

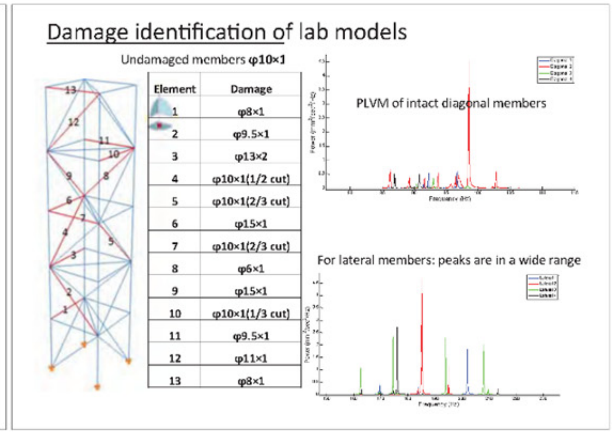

Damage identification based on local vibration
Difficulties
1. Differentiation of numerous similar modes
2. Observability
➢ small amplitude
➢ high frequency
➢ sensor attachment changes vibration
Laser Doppler vibrometer (LDV)
- Non-contact
- high resolution
- wide frequency range
Clarification of local mode characteristics & condition evaluation


Conclusion
1. PLVM and ILVM are identified as local modes with frequencies insensitive to global structural conditions and boundary conditions. These modes are sensitive to local boundary conditions and stiffness of the locally vibrating member.
2. A damage identification technique using PLVM and ILVM for belt-conveyor truss secondary members are developed and tested on a scale-model. This technique is applicable to multiple-damage cases and does not need before/after comparison.
15

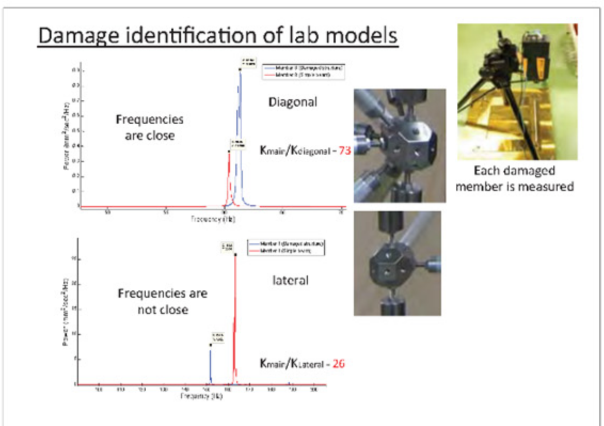

Damage identification using a scale-model
- Identification performance when multiple members are replaced.
- Each member is hit by hammer
- Velocity responses are measured by LDV
1st PLVM of lateral members
PLVM range
Flat
2 m
continuous main members
17

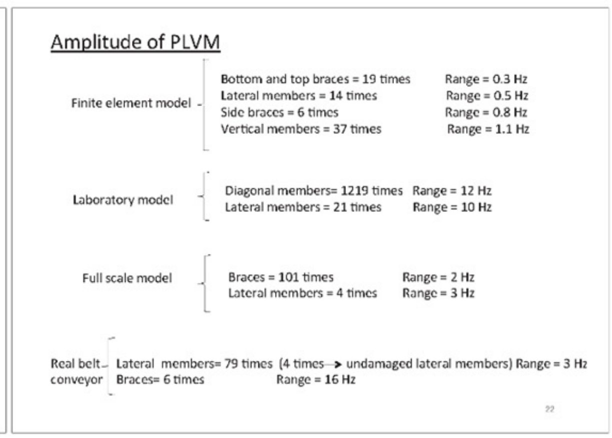

Damage identification of Laboratory model
1.9 Hz
Member 4 (structure)
Member 4 (simple beam)
Frequencies are close
Each damaged member is measured as a simple supported beam
Power (mm²/s²/Hz)
Frequency (Hz)

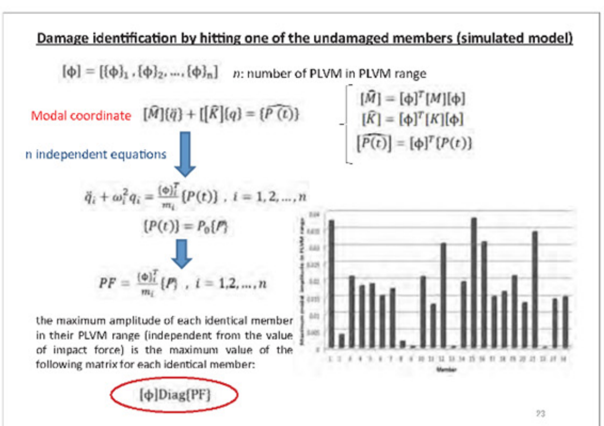


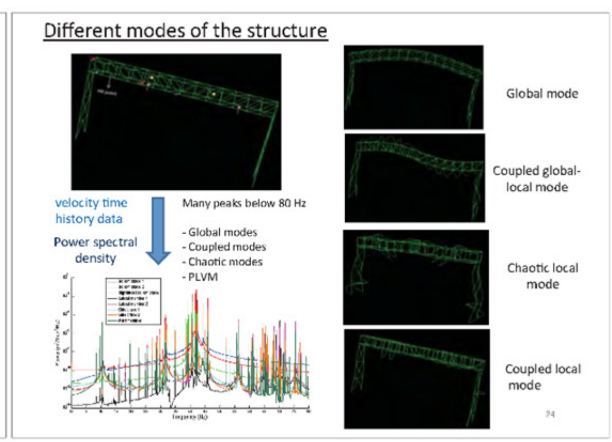


Element	Damage
1	φ8×1
2	φ9.5×1
3	φ13×2
4	φ10×1(1/2 cut)
5	φ10×1(2/3 cut)
6	φ15×1
7	φ10×1(2/3 cut)
8	φ6×1
9	φ15×1
10	φ10×1(1/3 cut)
11	φ9.5×1
12	φ11×1
13	φ8×1

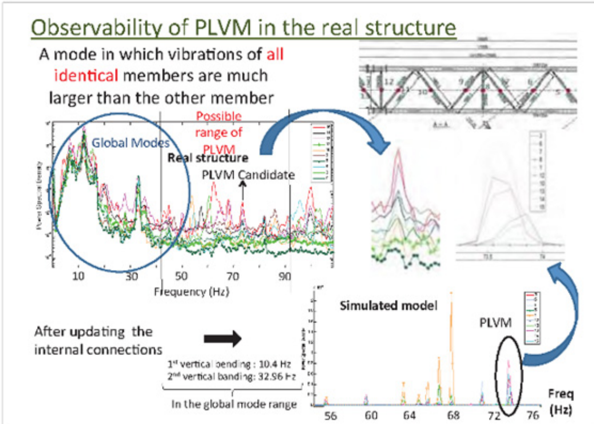


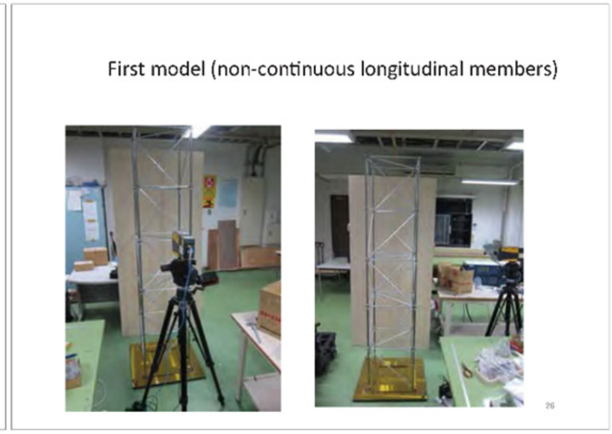


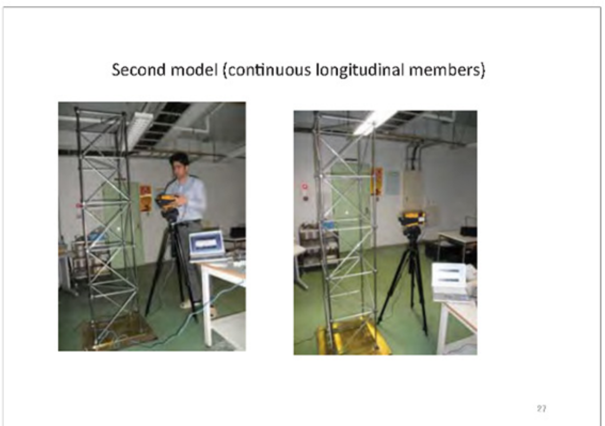




Appendix XI


Observability of PLVM in the real structure
A mode in which vibrations of all identical members are much larger than the other member
Global Modes
Possible range of PLVM
Real structure
PLVM Candidate
10
30
50
70
90
Frequency (Hz)
After updating the internal connections
1st vertical bending : 10.4 Hz
2nd vertical banding: 32.56 Hz
In the global mode range
Simulated model
PLVM
56
60
64
68
72
76
Freq (Hz)


First model (non-continuous longitudinal members)


Second model (continuous longitudinal members)

Direct Sensing of Inter-story Drift Displacements for Buildings

Akira Nishitani
WASEDA University

BACKGROUND

All the buildings in Japan should follow the design philosophy specified by Building Standard Law of Japan.

BACKGROUND (Cont'd)

Seismic design based on the Building Standard Law:

Two stages are considered.

- At S-1: moderate earthquakes (0.1G ground shaking).
- At S-2: strong earthquakes (0.4G ground shaking).

BACKGROUND (Cont'd)

At S-1:

Buildings should :

be designed so as to remain in the elastic range.

All the stories should :

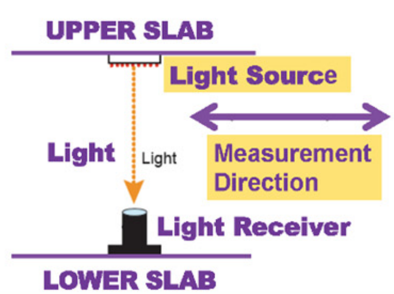
have inter-story drift displacements less than 1/200 of the story height.

BACKGROUND (Cont'd)

The data of those inter-story drift displacements

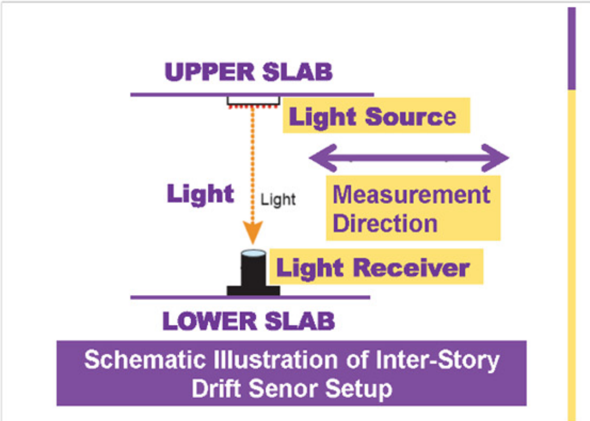
could be a direct index

to judge what the story damages of a building are like during a seismic event.

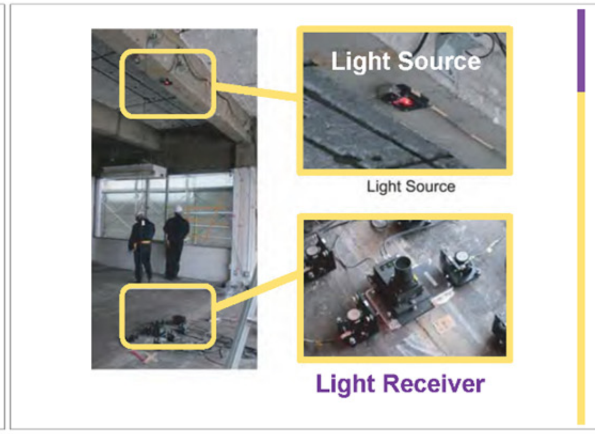


Schematic Illustration of Inter-Story Drift Displacement Senor Setup

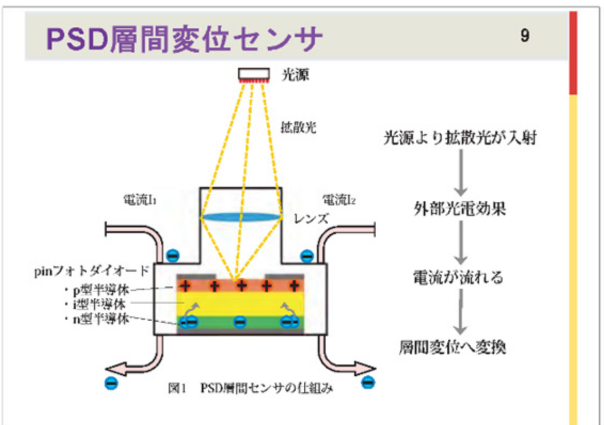
Appendix XI



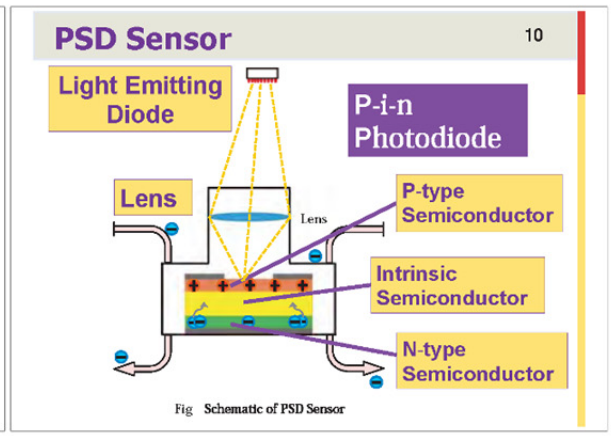
UPPER SLAB
Light Source
Light
Light
Measurement Direction
Light Receiver
LOWER SLAB
Schematic Illustration of Inter-Story Drift Senor Setup



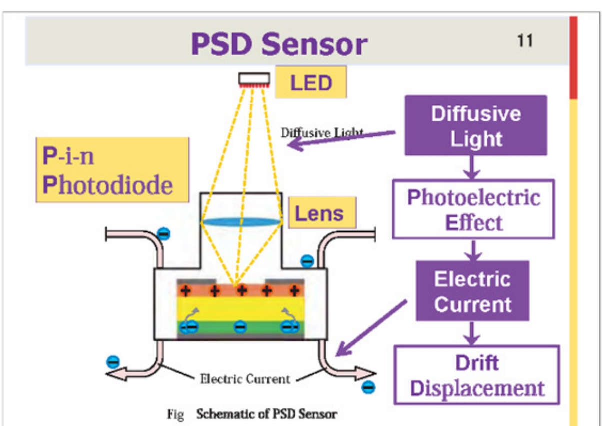
Light Source
Light Source
Light Receiver



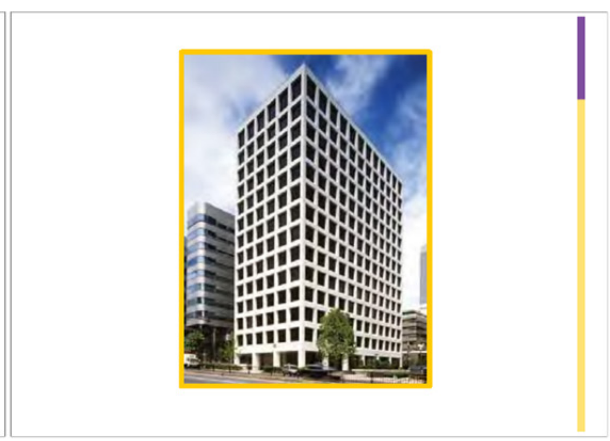
PSD層間変位センサ
9
光源
拡散光
光源より拡散光が入射
外部光電効果
電流が流れる
層間変位へ変換
電流I1
電流I2
レンズ
pinフォトダイオード
・p型半導体
・i型半導体
・n型半導体
図1 PSD層間センサの仕組み



PSD Sensor
10
Light Emitting Diode
P-i-n Photodiode
Lens
Lens
P-type Semiconductor
Intrinsic Semiconductor
N-type Semiconductor
Fig Schematic of PSD Sensor



PSD Sensor
11
LED
Diffusive Light
Diffusive Light
P-i-n Photodiode
Lens
Photoelectric Effect
Electric Current
Drift Displacement
Electric Current
Fig Schematic of PSD Sensor



If monitoring systems are tailored to "sense" specific damage modalities in structures, which ones are of greatest importance that should be prioritized?

As far as building structures are concerned, it is the sensing of inter-story drift displacements.

Those data could tell us directly what the story conditions would be like both during and shortly after the seismic event.

Such information could easily lead to the detection of damaged stories.

Then, we could proceed to the detailed diagnosis.

How can instrumentation (sensors and sensing systems) be used to illuminate causal relationships between damage and residual capacity of structural systems?

Inter-story drift displacement data could be utilized in many ways.

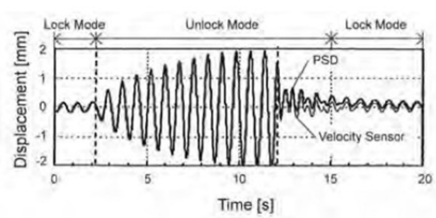
Those data time histories could provide us with the information on residual capacity of structures.

The direct sensing devices could be innovative tools.

If there is an opportunity to dedicate a large-scale structural testing program exclusively to structural health monitoring and SHM-driven decision making, what would you propose?

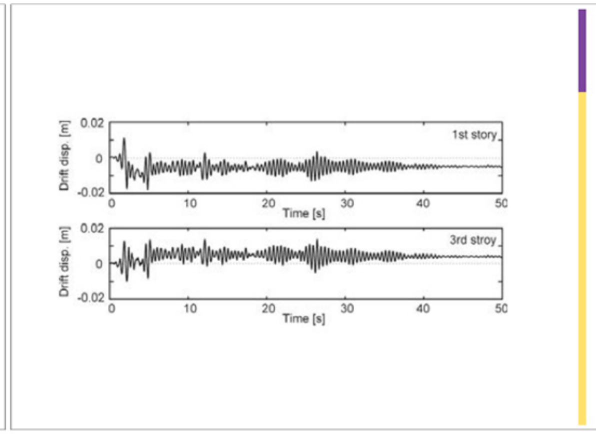
?

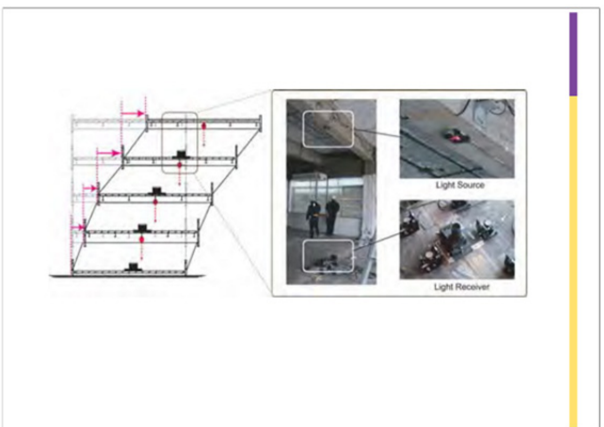
SELF-SEEKING, SELF-CENTERED



Appendix XI

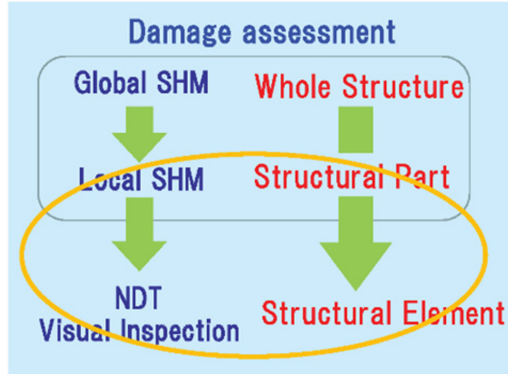

Thanks for your
attention.


Drift disp. [m]
0.02
0
-0.02
1st story
0
10
20
30
40
50
Time [s]
Drift disp. [m]
0.02
0
-0.02
3rd stroy
0
10
20
30
40
50
Time [s]


Light Source
Light Receiver

Structural Health Monitoring for Local Element

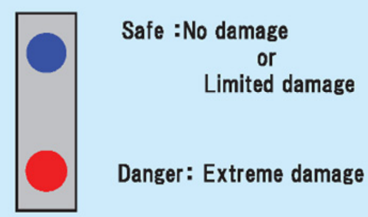
Y. NITTA
Ashikaga Institute of Technology



Interesting

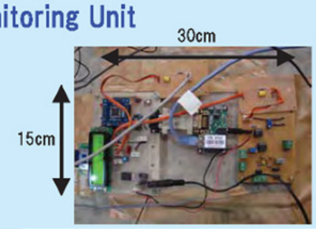
- Simple rapid damage detection system
- Damage detection for local damage
- Real time monitoring with simple calculation (filtering, average etc.)

Rapid Damage Detection



SHM for Beam-Column Connection at E-Defense

Monitoring Unit

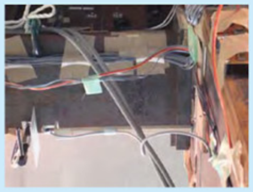


Monitoring Unit	
Sensor board	1
IR Sensor	1
Strain Gage	1
※ Trigger signal is the response of the strain gage.	

Appendix XI

IR Sensor

Measuring gap displacement between column and beam
IR sensor is installed on the column
Reflector Is set on the bottom of the beam flange



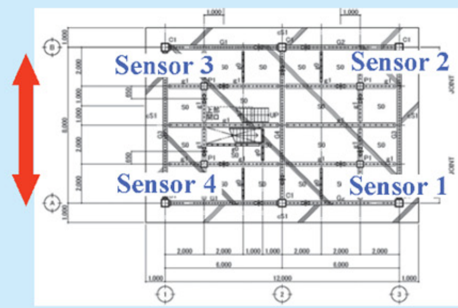
Strain gage

Measuring shear force of beam
Mounted on the bottom of the beam
Location is 1.5m from the beam column connection

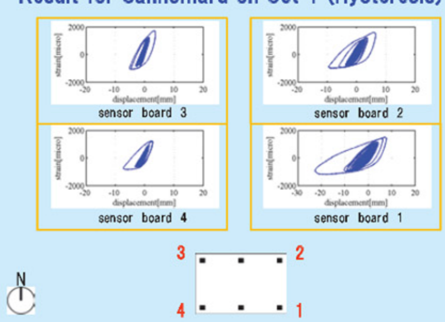
Test Structure

21-stories steel frame building
Welded connections

Sensor location

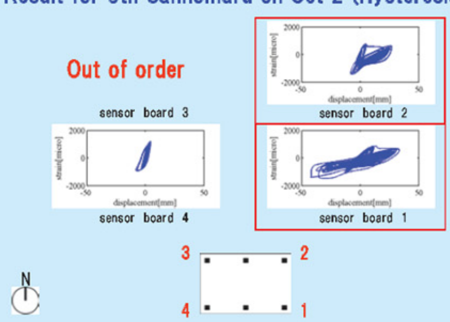


Result for Sannomaru on Oct 1 (Hysteresis)



Result for 5th Sannomaru on Oct 2 (Hysteresis)

Out of order



Result for Sannomaru (Visual inspection)

Fracture on Sensor 1 location

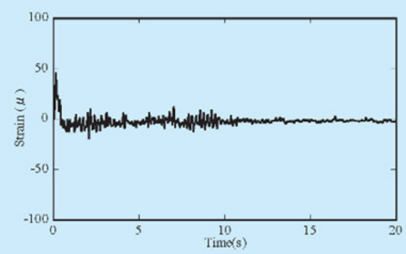
Fracture on Sensor 2 location

Monitoring for Ceiling element

Test Structure of Suspended Ceiling

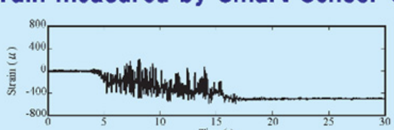
5,000 mm × 5,000 mm

Strain measured by Smart Sensor Unit

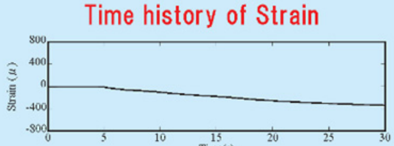


No damage

Strain measured by Smart Sensor Unit



Time history of Strain



Time history of Average

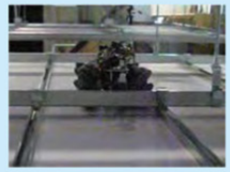
Damage

Summary

- Developing sensor board can detect the damage of local damage on the real-time.
- The proposed system can automatically provide information about the safety of local element.
- The proposed methodology provides the useful information for implementing the detailed SHM.

Not Monitoring
Visual Inspection tool

Inspection tool for inside of ceiling



which ones are greatest importance that should be prioritized?

Real Time

Detect the damage location and only judgment the damages is severe or not.

Cheap sensor and User friendly

Not Real Time

Estimate the residual capacity of the structure.

How can instrumentation be used to illuminate casual relationships between damage and residual capacity of structural systems?

What would you propose?

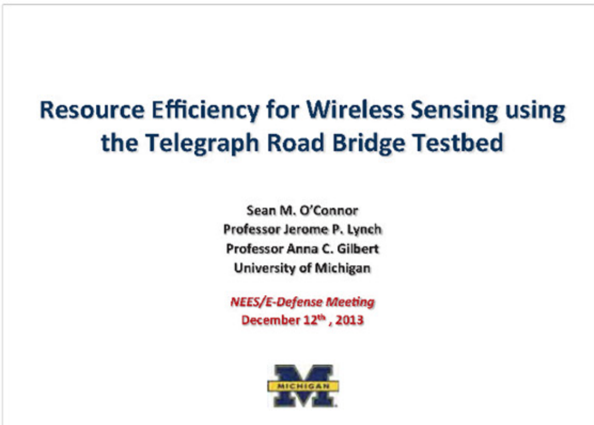
Competition for SHM

Local SHM

Global SHM

Local Monitoring System for RC

Monitoring for Nonstructural element


Resource Efficiency for Wireless Sensing using the Telegraph Road Bridge Testbed
Sean M. O'Connor
Professor Jerome P. Lynch
Professor Anna C. Gilbert
University of Michigan
NEES/E-Defense Meeting
December 12th, 2013
MICHIGAN


Telegraph Road Bridge (TRB)
Constructed 1973 in Monroe, MI
Multi-girder composite steel bridge
Pin & hanger construction
Signs of deterioration
Deck cracking
Corrosion
Abutment failure
Fatigue damage
Link plate and pin assembly
Telegraph Road Bridge
Temporary abutment support
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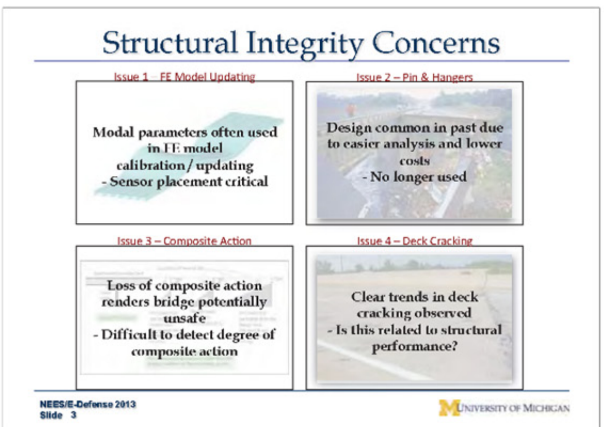
Structural Integrity Concerns
Issue 1 – FE Model Updating
Modal parameters often used in FE model calibration / updating
- Sensor placement critical
Issue 2 – Pin & Hangers
Design common in past due to easier analysis and lower costs
- No longer used
Issue 3 – Composite Action
Loss of composite action renders bridge potentially unsafe
- Difficult to detect degree of composite action
Issue 4 – Deck Cracking
Clear trends in deck cracking observed
- Is this related to structural performance?
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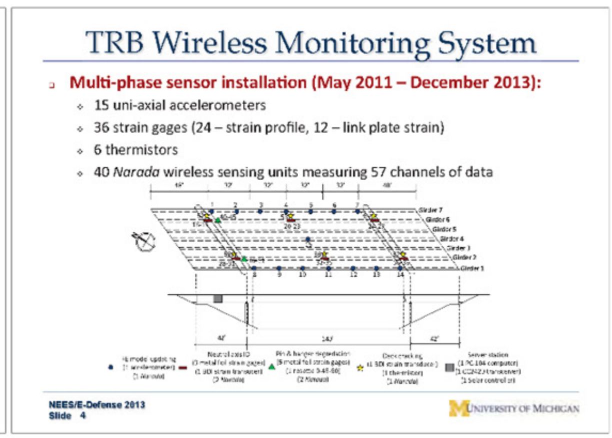
TRB Wireless Monitoring System
Multi-phase sensor installation (May 2011 – December 2013):
15 uni-axial accelerometers
36 strain gages (24 – strain profile, 12 – link plate strain)
6 thermistors
40 Narada wireless sensing units measuring 57 channels of data
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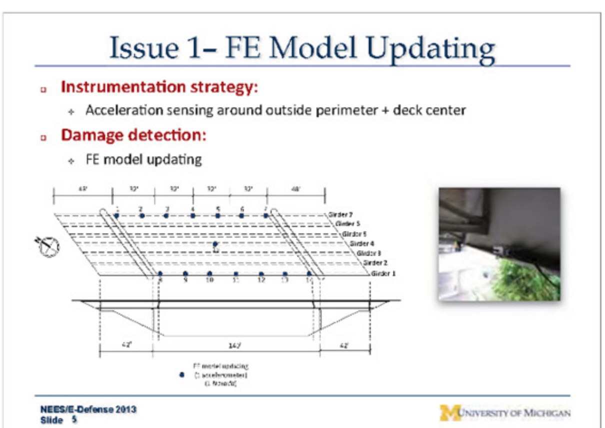
Issue 1– FE Model Updating
Instrumentation strategy:
Acceleration sensing around outside perimeter + deck center
Damage detection:
FE model updating
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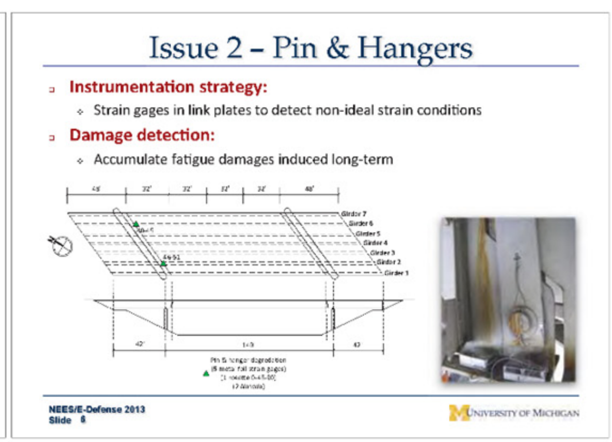
Issue 2 – Pin & Hangers
Instrumentation strategy:
Strain gages in link plates to detect non-ideal strain conditions
Damage detection:
Accumulate fatigue damages induced long-term
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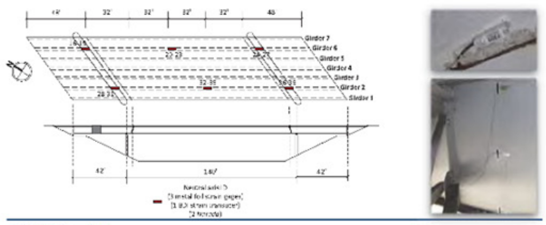
Appendix XI

Issue 3 – Composite Action

- **Instrumentation strategy:**
  - Strain sensing along typical cross sections
- **Damage detection:**
  - Infer degree of composite action by identifying neutral axis location



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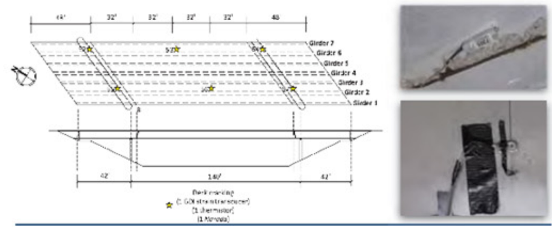
Issue 4 – Deck Cracking

- **Instrumentation strategy:**
  - Monitor strains and temperatures along girders at deck level
- **Damage detection:**
  - Correlate levels of strains, temperatures, and deck crack zones



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Sensing System

- **Communication base station:**
  - Installed May 2011 to south fascia of NB I-275
  - Local receiver base station
  - 3G connection for off-site server communication

MDOT installation cooperation | Solar panel installation | Server base station

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Sensor Modules

- **Watertight enclosure protects from harsh environment**
- **Components enable high quality data acquisition (DAQ)**
  - *Narada* wireless sensor
  - Solar charge circuit
  - Signal conditioning board (anti-aliasing filter + amplification)
  - Sensor (accelerometer, strain gage, thermistor)
  - Sensor specific hardware (Wheatstone bridge, voltage divider)

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Module Installation

Solar panel installation | Sensor modules installed to girder flange

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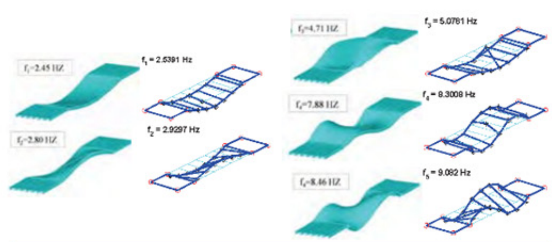
Modal Analysis

- **Automatic extraction of modal parameters:**
  - Frequency Domain Decomposition (FDD) performed at server
  - Modal parameters used for model updating of finite element model



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Strain Gage Installation

- **Strain gages attached at girder section to infer neutral axis:**
  - 3 metal foil strain gages for steel strain
  - 1 BDI strain gage for concrete strain


Metal foil strain gages


BDI strain transducer

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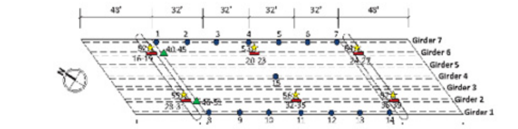
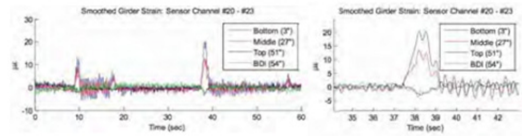
Strain Response Data





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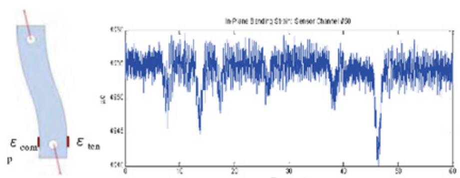
Pin & Hanger Strain

- **Pin-plate locking based on flexural strain response of plate:**
  - Compressive-tensile strain difference (flexural response)
  - Proportional to flexural moment in the hanger plate due to locking
  - Approximately 15 micro-strain



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Challenges of Wireless Sensing

Resource constraints in bridge SHM

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Data Reduction

- **Method 1: Decentralized embedded fatigue life monitoring**
  - Perform fatigue life monitoring on-board the *Narada* wireless sensing unit
  - Converts "data" to "information" – much more useful to bridge managers
  - Transmission only upon request
  - Time (rainflow counting) and spectral (Dirlik) methods
- **Method 2: Compressed Sensing**
  - Directly acquire compressed "measurements" rather than samples
  - Measurements on the order of log(N)

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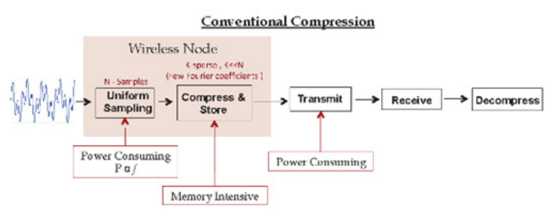
Traditional Paradigm

- **Uniform sampling:**
  - Power consumed at ADC proportional to sampling rate
  - Power consumed at radio during transmission



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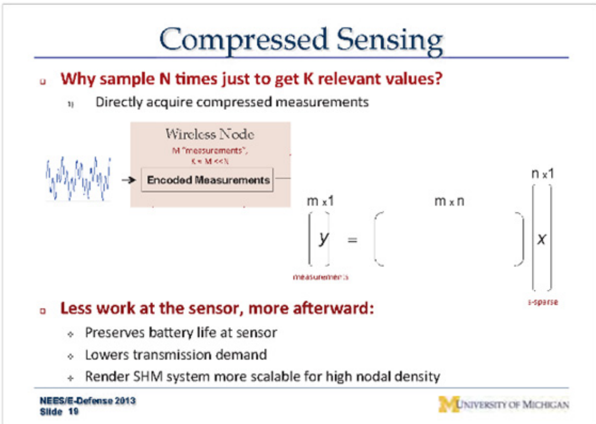
Appendix XI


Compressed Sensing
Why sample N times just to get K relevant values?
Directly acquire compressed measurements
Wireless Node
Encoded Measurements
m x1
m x n
n x1
y
=
x
measurements
s-sparse
Less work at the sensor, more afterward:
Preserves battery life at sensor
Lowers transmission demand
Render SHM system more scalable for high nodal density
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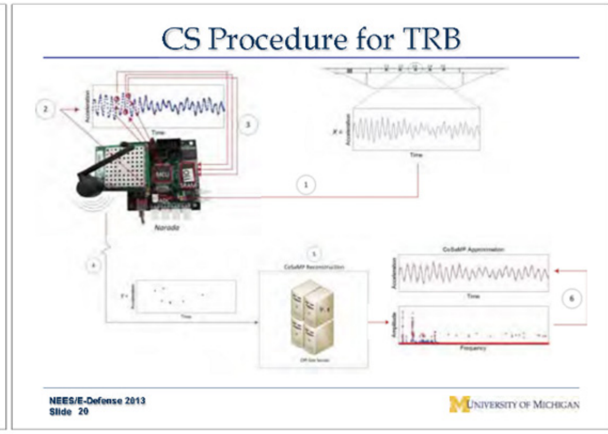
CS Procedure for TRB
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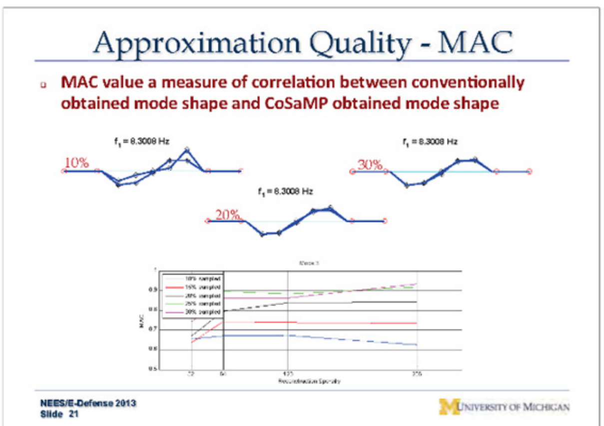
Approximation Quality - MAC
MAC value a measure of correlation between conventionally obtained mode shape and CoSaMP obtained mode shape
10%
20%
30%
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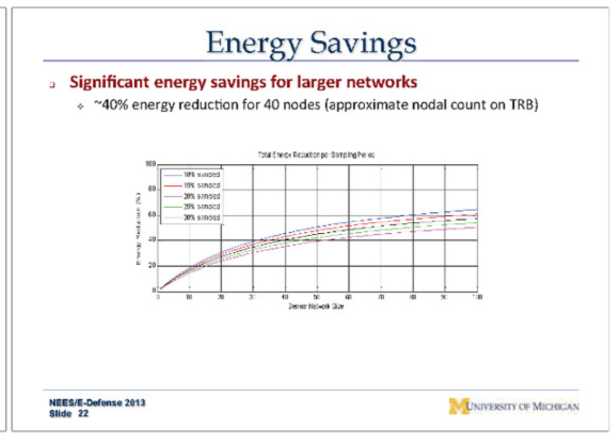
Energy Savings
Significant energy savings for larger networks
~40% energy reduction for 40 nodes (approximate nodal count on TRB)
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Workshop Question #1
Which damage modalities are of greatest importance to sense?
Fatigue
Corrosion
- The result can be sudden failure
Mianus River Bridge (1983)
MDOT specimen
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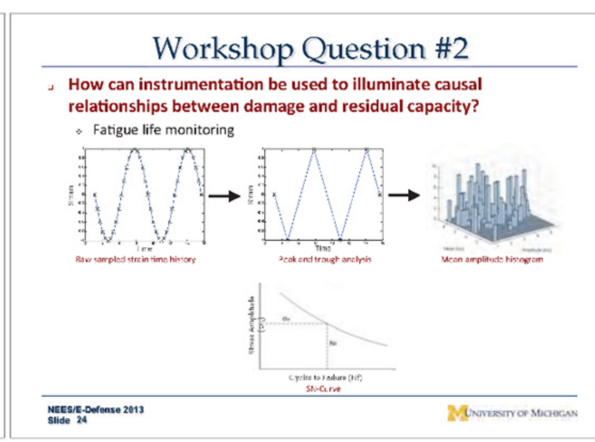
Workshop Question #2
How can instrumentation be used to illuminate causal relationships between damage and residual capacity?
Fatigue life monitoring
Raw sampled strain time history
Peak and trough analysis
Mean amplitude histogram
SN-Curve
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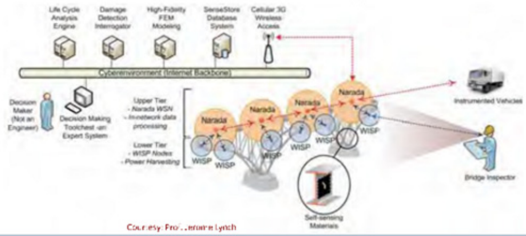
Workshop Question #3

- **Proposed large scale structural testing program for SHM and SHM-driven decision making?**
  - Expand on the current project
  - Increase the sample size for better statistical analyses



Courtesy: Prof. Jerome Lynch

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Thank You!

Acknowledgements:

United States Department of Commerce, National Institute of Standards and Technology (NIST), Technology Innovation Program (TIP) managed under the direction of program manager Dr. Jean-Louis Staudenmann.

Additional support was provided by the Michigan Department of Transportation (MDOT), the California Department of Transportation (Caltrans), the National Science Foundation (NSF), and the Smart Infra-Structure Technology Center (SISTEC).

Additional thanks to the Office of Naval Research (ONR)

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NEES/E-Defense Meeting, December 12, 2013

Outline

- Research Opportunities for SHM
- Post-earthquake Reconnaissance and Field Testing
- Large-scale Laboratory Experiments and Damage Detection
- Meeting Questions

Motivation

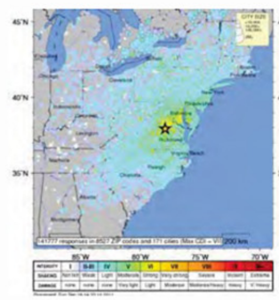
Emerging ability for spatially (and temporally) dense sensing of physical phenomena by embedded networks.

Decision-support
Model Updating
Identification of Spatio-temporal Phenomena
Spatio-temporal Aggregation
Sensing and Local Processing

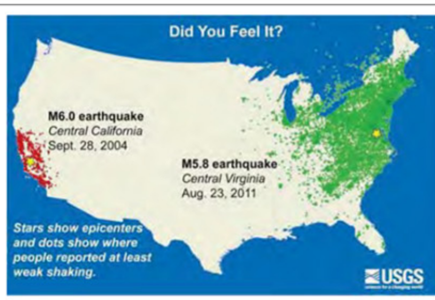
Motivation

23 Aug 2011 M5.8 Mineral, Virginia, EQ

- Was "500-year" event; PGA = 0.27g 20 km from source
- Most felt earthquake in US history – low attenuation, high population density
- Felt from GA to Canada
- Shaking intensity followed regional geologic structure; shaking intensity and damage patterns selective, related to geology/soil conditions
- DC felt strong shaking; EQ felt more like an M6 there

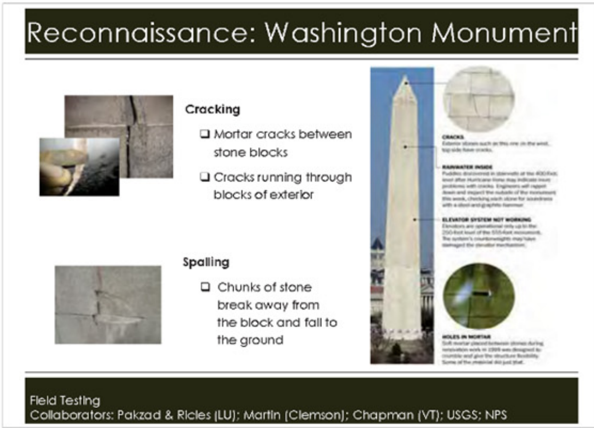


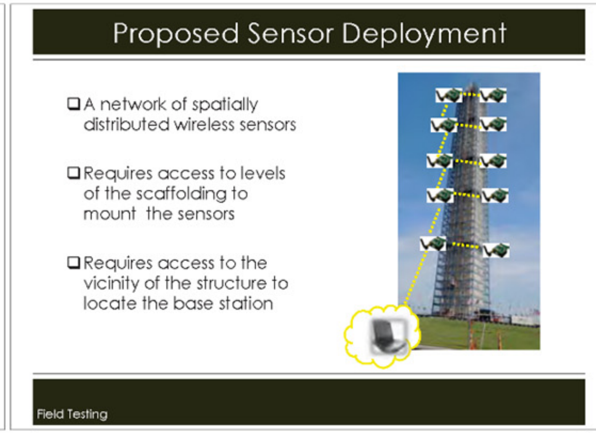
23 Aug 2011 M5.8 Mineral, Virginia, EQ

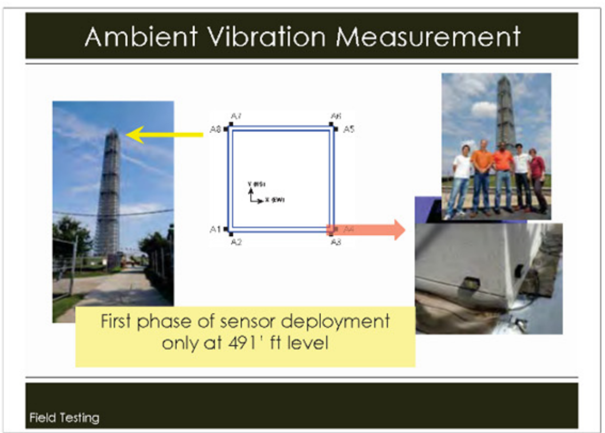


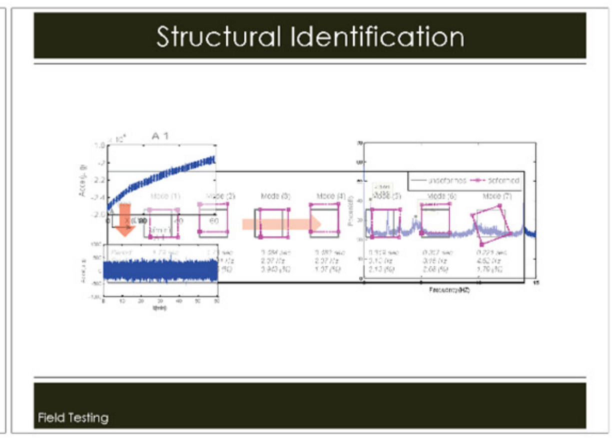
23 Aug 2011 M5.8 Mineral, Virginia, EQ

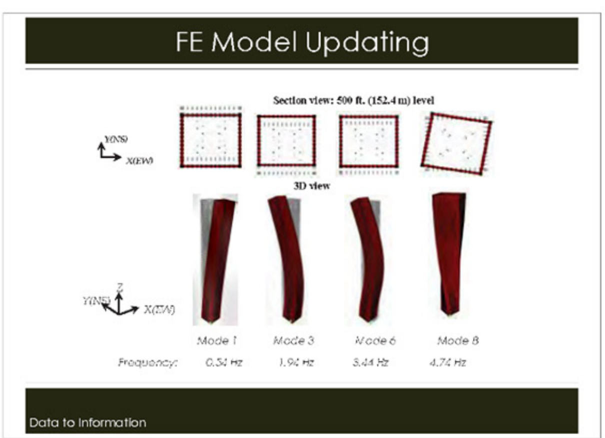
- Magnitude 5.8, Louisa County
- Second-largest Virginia earthquake in history (largest was Mw5.9, Giles County, 1897)
- *Damage to homes, schools and businesses*
- More than 100 sizable aftershocks, up to Mw4.5
- *Epicenter was ~12 miles from North Anna Nuclear Power Station*
- Highlighted underappreciated seismic vulnerability of CEUS
- **Event was poorly recorded**

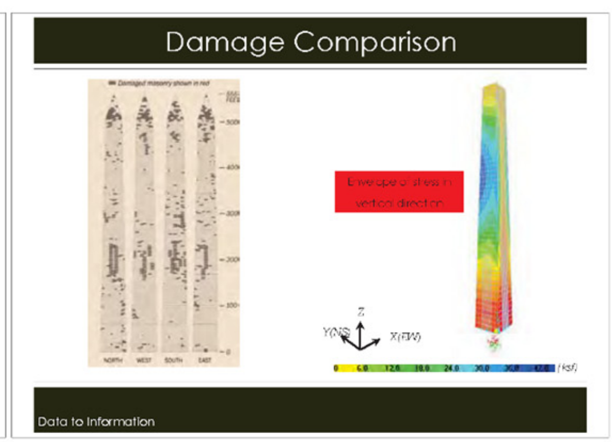

Reconnaissance: Washington Monument
Cracking
❑ Mortar cracks between stone blocks
❑ Cracks running through blocks of exterior
Spalling
❑ Chunks of stone break away from the block and fall to the ground
Field Testing
Collaborators: Pakzad & Ricles (LU); Martin (Clemson); Chapman (VT); USGS; NPS


Proposed Sensor Deployment
❑ A network of spatially distributed wireless sensors
❑ Requires access to levels of the scaffolding to mount the sensors
❑ Requires access to the vicinity of the structure to locate the base station
Field Testing


Ambient Vibration Measurement
First phase of sensor deployment only at 491' ft level
Field Testing


Structural Identification
Field Testing


FE Model Updating
Section view: 500 ft. (152.4 m) level
3D view
Mode 1
Mode 3
Mode 6
Mode 8
Frequency:
0.54 Hz
1.94 Hz
3.44 Hz
4.74 Hz
Data to Information

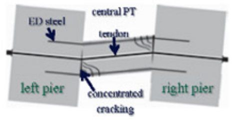

Damage Comparison
Envelope of stress in vertical direction
Data to Information

Appendix XI

Coupled Shear Wall Systems

Conventional diagonally reinforced coupling beams

- Difficult to construct



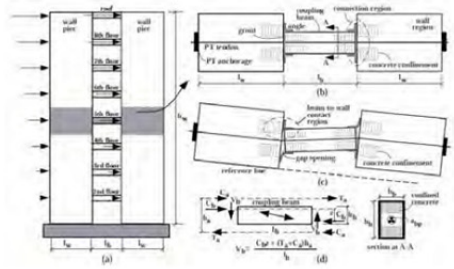
PT unbounded coupling beams

- Eliminate diagonal reinforcement
- Cracking concentrated at beam ends
- Reduced cracking along span

Laboratory Experiment
Collaborators: Kurama (NDU); Mcginnis (UTT); Pakzad, Sause & Ricles (LU)

Coupled Shear Wall Systems

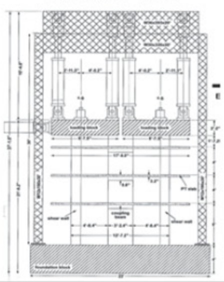
- Shear walls with post-tensioned coupling beams



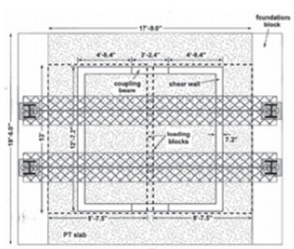
Laboratory Experiment

Test Specimen

Elevation View



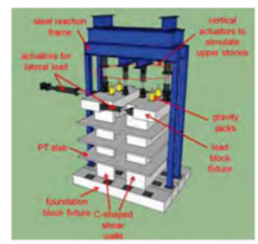
Plan View



Laboratory Experiment

Test Specimen

- 40% scale model of 3 story substructure of the simulated structure
- Quasi-Static lateral cyclic loading until failure



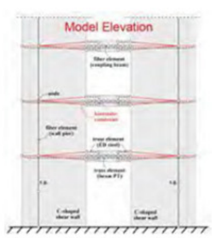
Laboratory Experiment

DRAIN Model

Data from simulation of an 8-story prototype building used to validate the damage detection method

Modeling Assumptions

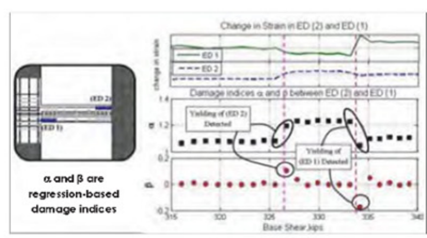
1. Multi-linear idealization of stress-strain curve for all materials
2. Transverse reinforcement not physically modeled (Confided/Unconfined Mander Model adapted)
3. Zero-tension concrete at beam ends
4. Linear-tension concrete in remainder of beam
5. Concrete cover does not lose all strength at ultimate
6. Static monotonic displacement controlled analysis



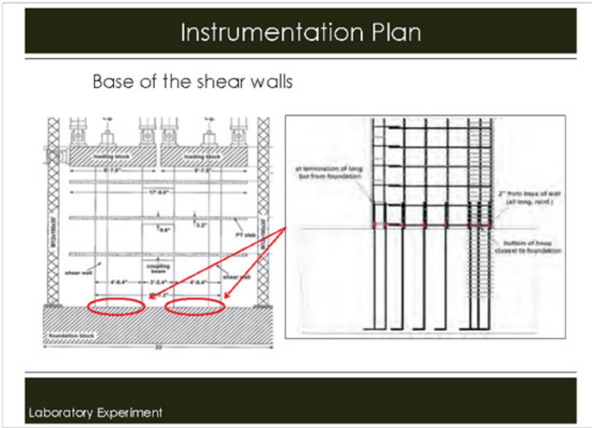
Modeling for Sensor Placement

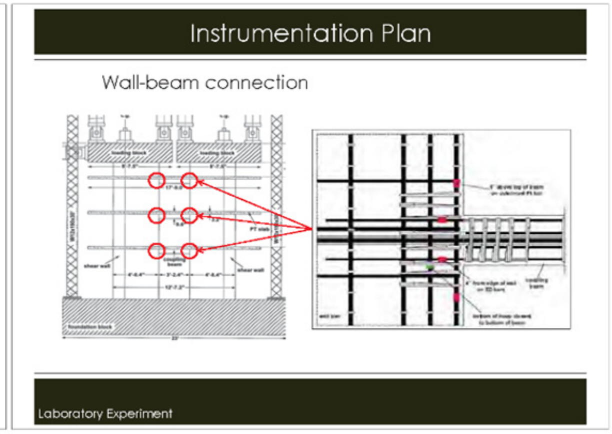
Application of Damage Indices

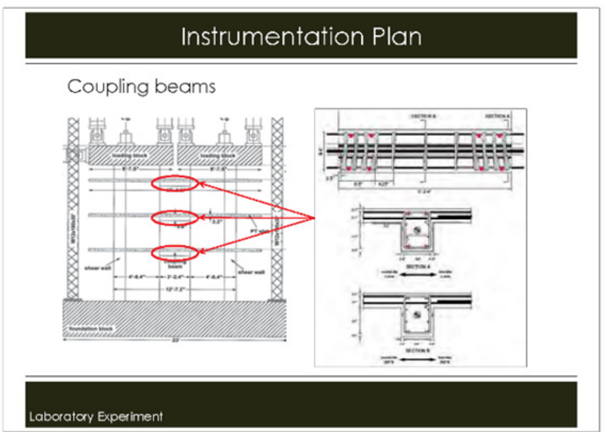
Detection of ED Steel Yielding in Tension

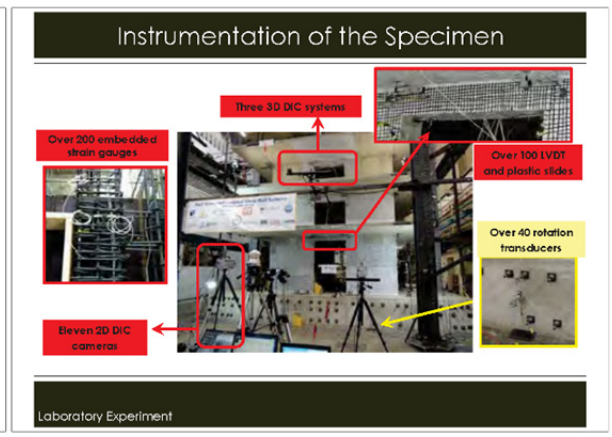


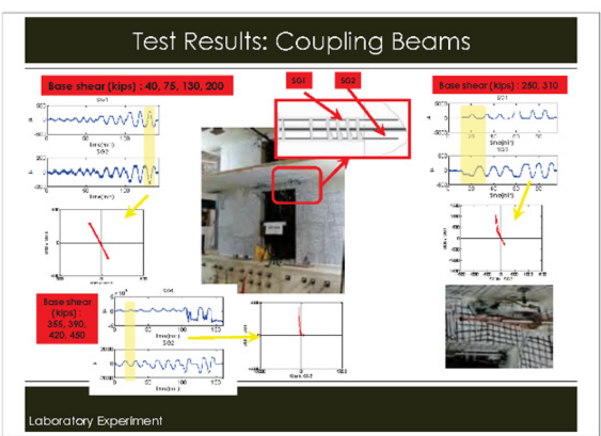
Data Processing & Management

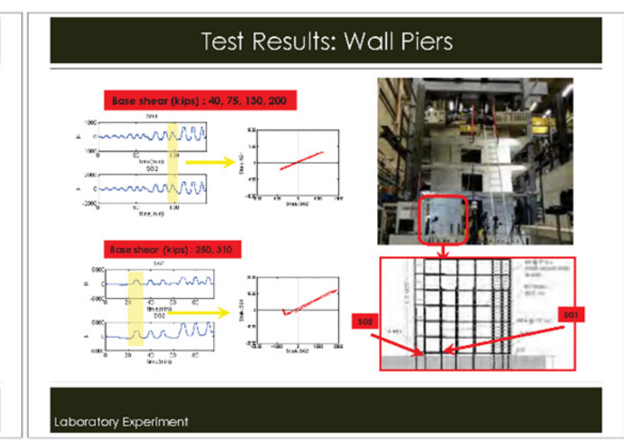

Instrumentation Plan
Base of the shear walls
Laboratory Experiment


Instrumentation Plan
Wall-beam connection
Laboratory Experiment

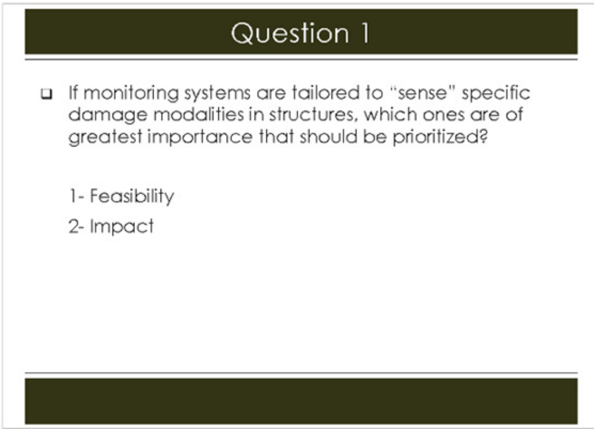

Instrumentation Plan
Coupling beams
Laboratory Experiment

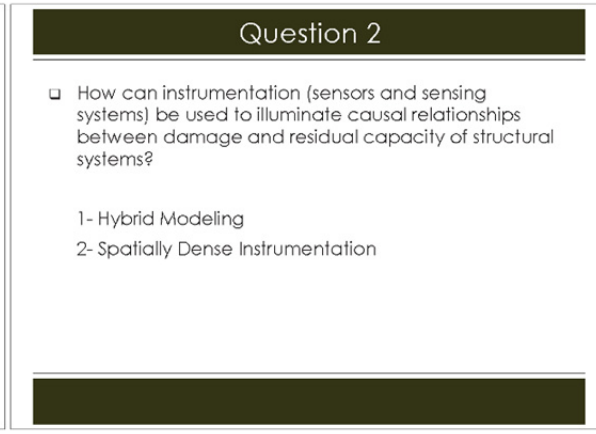

Instrumentation of the Specimen
Three 3D DIC systems
Over 200 embedded strain gauges
Over 100 LVDT and plastic slides
Over 40 rotation transducers
Eleven 2D DIC cameras
Laboratory Experiment

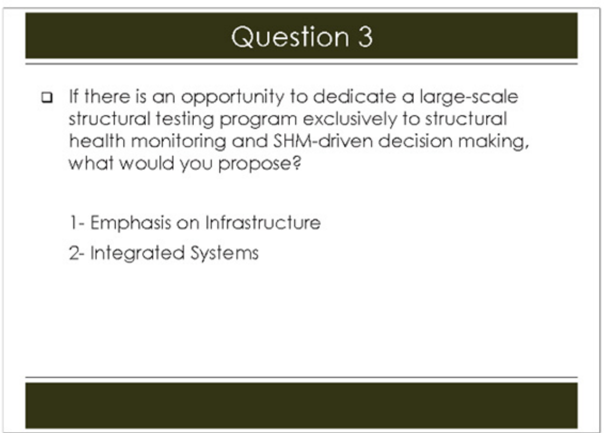

Test Results: Coupling Beams
Base shear (kips) : 40, 75, 130, 200
SG1
SG2
Base shear (kips) : 250, 310
Base shear (kips) : 355, 390, 420, 450
Laboratory Experiment


Test Results: Wall Piers
Base shear (kips) : 40, 75, 130, 200
Base shear (kips) : 250, 310
SG2
SG1
Laboratory Experiment

Appendix XI


Question 1
If monitoring systems are tailored to "sense" specific damage modalities in structures, which ones are of greatest importance that should be prioritized?
1- Feasibility
2- Impact


Question 2
How can instrumentation (sensors and sensing systems) be used to illuminate causal relationships between damage and residual capacity of structural systems?
1- Hybrid Modeling
2- Spatially Dense Instrumentation


Question 3
If there is an opportunity to dedicate a large-scale structural testing program exclusively to structural health monitoring and SHM-driven decision making, what would you propose?
1- Emphasis on Infrastructure
2- Integrated Systems

NEES – E-Defense Monitoring Session

December 11 – 13, 2013

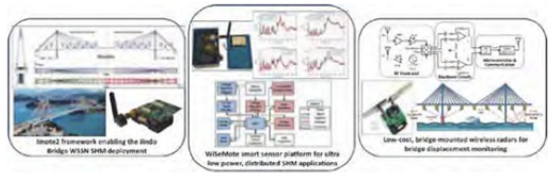
Jennifer A. Rice

Engineering School of Sustainable Infrastructure and Environment
University of Florida

Smart Infrastructure Management Laboratory

UF UNIVERSITY of FLORIDA

Wireless Sensors for SHM



Continuous Monitoring of Unbonded Post-tensioning Tendons

Motivation

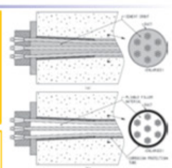
- Incidence of tendon failure in bonded PT bridges.
- Unbonded tendons enables the application of new methods for improved monitoring.

Goal

- To develop an efficient technique for wire breakage detection.
- To assess effectiveness for in-situ applications.

Investigation of Existing Approaches

- Electro-mechanical impedance method
- Acoustic emission technique
- Guided wave ultrasonic testing



Strain Variation in Anchors: A Novel Approach

Key Concepts

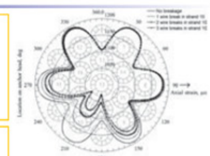
- Large prestressing force results in large strain gradients over the anchors.
- The strain distribution undergoes significant changes due to a wire break.

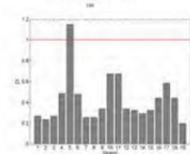
Advantages

- Relative variation of strains among the monitoring points are highly sensitive to wire breaks.
- Low cost sensors and data acquisition.

Damage Model

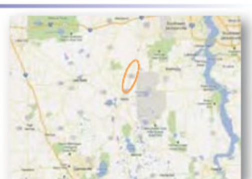
- A robust damage metric is being developed to detect, locate and quantify a breakage event.





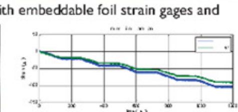
FDOT Long-term Test Pavement

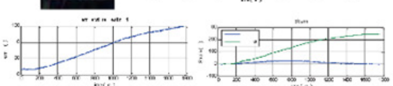
- FDOT concrete test pavement
  - 2.5 miles with 52 test sections
  - Live traffic diverted periodically
- Project challenges
  - Distance between sensors and DAQ cabinets (>100 ft)
  - High channel count
  - Sensor diversity
  - Distributed test pavements
  - Lightening susceptibility
  - Long-term, embedded deployment (10+ years)
  - Limited budget
- Goal
  - Evaluate the feasibility of a hybrid traditional /FOS sensor network for long-term deployment



FBG Sensor Evaluation

- Compare performance of FO gages with embeddable foil strain gages and thermocouples
- Economic feasibility assessment
- Evaluation Phase I
  - Tension
  - Compression
  - Temperature
  - Noise
- Evaluation Phase II
  - Test slab
  - Heavy vehicle simulator (HVS)





Appendix XI

Displacement Sensing for SHM

- Goal: Realize low power, low cost displacement sensing suitable for a range of SHM applications using wireless sensors
- Static displacement
  - Assess bridge deflection in response to known loading
- Low-frequency
  - Many civil structures have very low fundamental vibration frequencies (<1Hz)
- Existing approaches
  - LVDT – requires fixed reference point, not appropriate for practical SHM applications
  - Laser Doppler Vibrometer (LDV) – expensive, bulky, impractical for extended SHM systems
  - GPS – low accuracy/low sampling rate, more recently becoming viable for WSN applications

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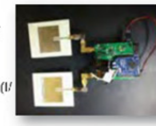
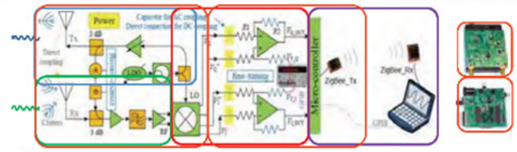
Continuous Wave Radar Sensor

- 2.4 GHz continuous wave radar (5 cm x 5 cm)
- Waveform generated by linear oscillator and transmitted by patch antenna
- Reflected signal is captured by second antenna
- Signals are combined and down-converted to the baseband (I/Q) signals via a quadrature mixer
- Digitized signals are transmitted wirelessly





- Stackable system for configuration and system flexibility

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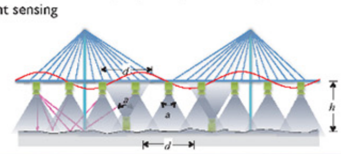
Bridge Monitoring

- Previous applications rely on off-bridge radar placement
- Finite antenna directivity results in an average "area" measurement
- Placing the sensors on the bridge provides discrete point measurements and enables dense deployment
- *Passive Backscattering* utilizes sensors as both transmitters and receivers
- Transmitted signals from one sensor are received by adjacent sensors to create a multi-input multi-output (MIMO) network capable of distributed displacement sensing



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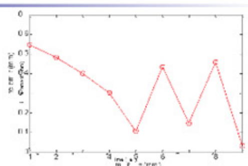
Performance Characterization

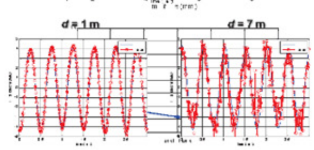
Low Frequency Vibration Performance

- Vertical long stroke shaker
- Sinusoidal motion
  - f : 0.25 – 2 Hz, A: 1 – 9 mm
- Target distance = 50 cm (floor)
- Results
  - RMS error < 0.6 mm with changing amplitude (f = 1.75 Hz)
  - No trend in changing frequency



Target Distance Performance

- Horizontal uniaxial shake table
- Sinusoidal motion
  - f = 2 Hz, A = 4.2 mm
- Target distance: 1 – 8 m (movable vertical partition)
- Results
  - RMS error < 0.3 mm for d < 5 m
  - SNR decreases with increasing d
  - Low SNR makes DC offset calibration impossible above 7m



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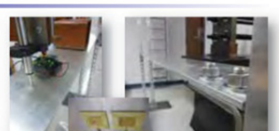
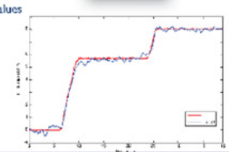
Performance Characterization

Static Deflection Performance

- Simply supported beam (L = 2m)
- Target distance = 50 cm
- Sequential static load application
  - 4.5 kg + 2.25 kg



- Results
  - Good comparison of mean deflection values
  - RMS error < 0.2 mm



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Prioritizing Damage Modalities

- In general (routine monitoring)
  - Known Issues
  - Analyze cost-benefit of a monitoring/maintenance strategy
    - Live cycle cost (LCC) = sum of all costs incurred during the lifetime of a structure

      $LCC = C_{INV} + C_{INSP} + C_{PM} + C_{CM} + C_{U} + C_{F} + C_{SHM}$
    - Maintenance benefit

      $B_{M} = E[LCC_{NM}] - E[LCC_{M}]$
- Post-disaster
  - **Requires probabilistic models describe limit states and failure modes**
  - Maximum displacement/strain/acceleration during event
  - Residual drift/displacement/rotation

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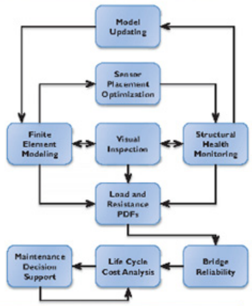
Determining relationship between damage and residual capacity

- Reliability Index: $\beta = \frac{(\mu_R - \mu_L)}{\sqrt{\sigma_R - \sigma_L}}$
  - *R*: resistance of structural elements
  - *L*: loading effects
  - m_R and m_L: mean resistance and mean load effect
  - s_R and s_L: standard deviation of the resistance and load effect
- Probability of failure: $P_f = F(-b)$
- The reliability index is better estimated when the **probabilistic models of both the resistance and the loads can be improved through measured data**



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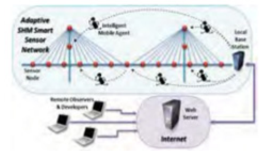
Large-Scale SHM Test Bed

- Spatially dense sensor deployment
- Sensor redundancy
- Examine data quality and system reliability
- Rich baseline data sets
- Fine-tuned models
- Flexible, remotely reprogrammable wireless sensor network for testing embedded algorithms
- Dealing with Big Data



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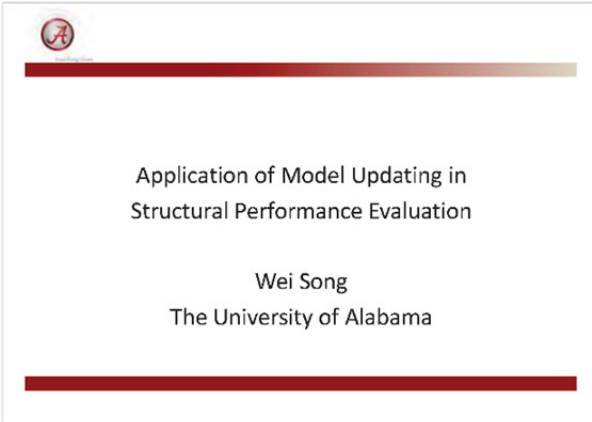
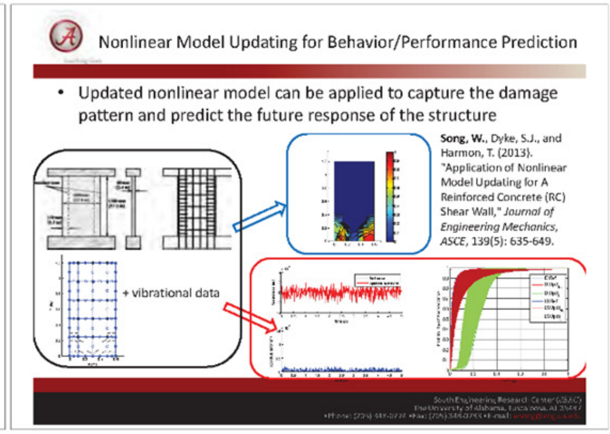
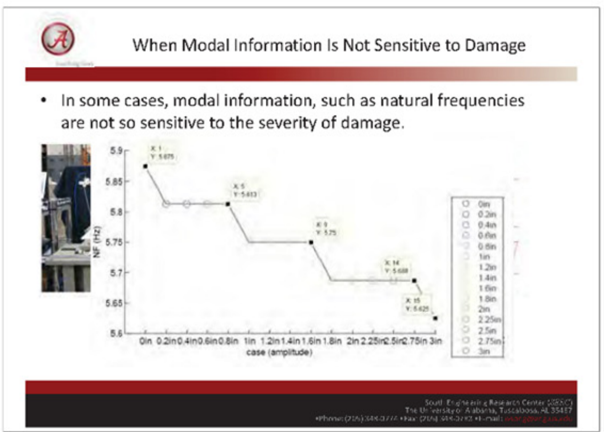
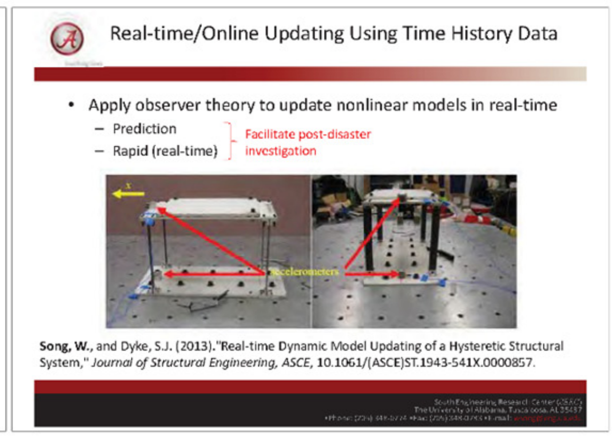
Appendix XI

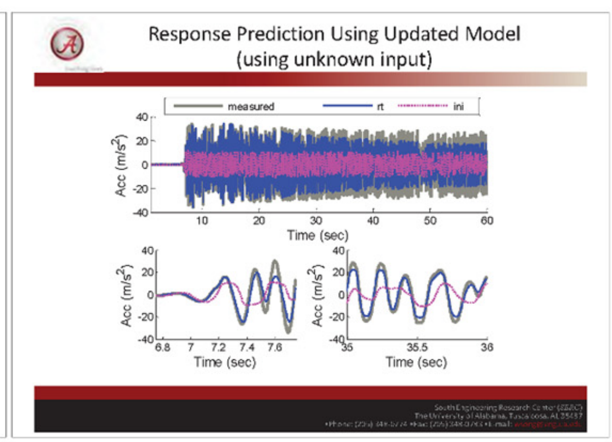

Application of Model Updating in
Structural Performance Evaluation
Wei Song
The University of Alabama


Nonlinear Model Updating for Behavior/Performance Prediction
• Updated nonlinear model can be applied to capture the damage pattern and predict the future response of the structure
+ vibrational data
Song, W., Dyke, S.J., and Harmon, T. (2013). "Application of Nonlinear Model Updating for A Reinforced Concrete (RC) Shear Wall," Journal of Engineering Mechanics, ASCE, 139(5): 635-649.

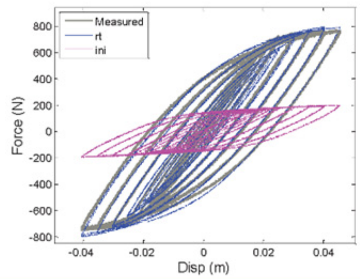

When Modal Information Is Not Sensitive to Damage
• In some cases, modal information, such as natural frequencies are not so sensitive to the severity of damage.
NF (Hz)
case (amplitude)


Real-time/Online Updating Using Time History Data
• Apply observer theory to update nonlinear models in real-time
– Prediction
– Rapid (real-time)
Facilitate post-disaster investigation
Song, W., and Dyke, S.J. (2013)."Real-time Dynamic Model Updating of a Hysteretic Structural System," Journal of Structural Engineering, ASCE, 10.1061/(ASCE)ST.1943-541X.0000857.


Real-time Updating


Response Prediction Using Updated Model
(using unknown input)
measured
rt
ini
Acc (m/s^2)
Time (sec)

Response Prediction Using Updated Model (using unknown input)



South Engineering Research Center (SERC)
The University of Alabama, Tuscaloosa, AL 35487

- If monitoring systems are tailored to "sense" specific damage modalities in structures, which ones are of greatest importance that should be prioritized?

  Corrosion: chloride penetration; Mechanical damage: deformation (direct: displacement, strain; indirect: acceleration, acoustic, image, etc.)
- How can instrumentation (sensors and sensing systems) be used to illuminate causal relationships between damage and residual capacity of structural systems?

  Use sufficient data to construct updated models for behavior/response prediction (matching criterion: modal information, selected response, strain distribution...)
- If there is an opportunity to dedicate a large-scale structural testing program exclusively to structural health monitoring and SHM-driven decision making, what would you propose?

  Examine critical structures/components for model updating study under controllable damage scenarios:

  1) investigate suitable nonlinear model updating techniques for various nonlinear models at different damage stage;
  2) evaluate the updating techniques by comparing updated model to the test data;
  3) apply updated models for decision making, and compare the results;
  4) install multiple sensing system to cross-check/compare the updating results on a benchmark test (for instance, image sensing correlate with strain gage data; acceleration updating correlate with displacement updating).

South Engineering Research Center (SERC)
The University of Alabama, Tuscaloosa, AL 35487

NEES/E-Defense Collaborative Earthquake Research Program

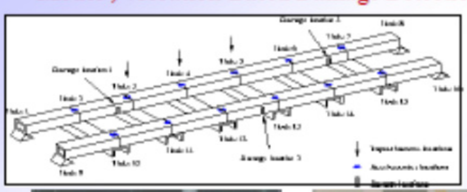
(10th Planning Meeting)

Kincho H. Law
Professor of Civil and Environmental Engineering
(Structural Engineering and Engineering Informatics)
Stanford University
December 11-13, 2013
DPRI, Japan

Model-, Vibration-Based Damage Detection

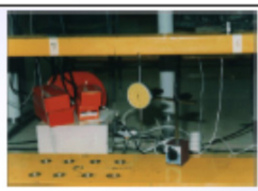
Hoon Sohn 1999

Model-, Vibration-Based Damage Detection



5 m span

0.5 m cross members



Hoon Sohn 1999

Damage Diagnosis Results

Case	Damage Locations	Ritz Vectors H_{max}	Ritz Vectors Rank	Modal Vectors H_{max}	Modal Vectors Rank
1	{2}	{2, 3}	1 (2)	{2, 8, 9}	1 (29)
2	{2}	{2, 3}	1 (12)	{2, 8, 12}	1 (46)
3	{2, 11}	{2, 3}	3 (9)	{2, 3, 8}	13 (41)
4	{2, 11}	{2}	3 (3)	{2, 8, 12}	4 (12)
5	{2, 11}	{2, 11}	1 (1)	{2, 11, 12}	1 (9)
6	{2, 6, 11}	{2, 6, 11}	1 (1)	{2, 6, 11}	1 (1)

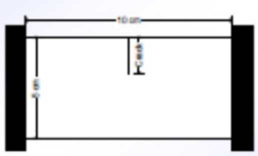
Damage Case 3: Rank: 3(9)
Actual Damage Event: {2, 11}

Rank	Damage Event	Rank	Damage Event	Rank	Damage Event
1	{2, 3}	4	{2, 3, 12}	7	{1, 2, 3}
2	{2, 3, 4}	5	{2}	8	{2, 12}
3	{2, 3, 11}	6	{2, 4}	9	{2, 11}

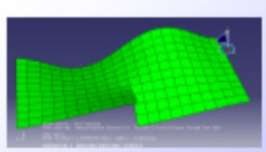
Hoon Sohn 1999

Aluminum Plate with Fatigue Crack

- An aluminum plate component within a ship system:
  - 5 x 10 cm², 5 mm thick aluminum (5083 alloy) plate
  - Finite element model of the plate under ambient excitation employed
  - Synthetic data from the plate with a fatigue crack generated
  - Crack varies from 0.5 to 2 cm in length
- From vibration acceleration time-histories, extract mode shapes:
  - Modal frequencies and shapes used as part of Bayesian damage detection



Aluminum ship component: thin plate with fatigue crack
Crack varied from 0.5 to 2 cm



Primary plate mode in ABAQUS (Mode 3 at 8.4 kHz)
Meshed with 40 by 20 rectangular mesh

Karata, Lynch 2010

Model Updating Results

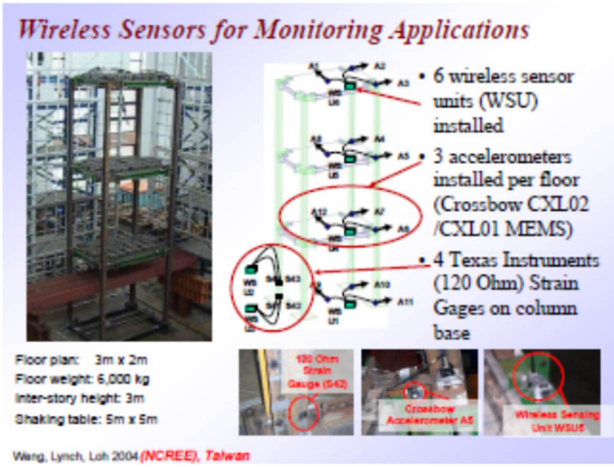
- Model updating detects crack location, depth, and severity:
  - Actual damage state was a crack at 10 cm on top side, 5 cm into the plate
  - Model identified reduced modulus in column 11 to a depth of 5 elements
  - Reduced modulus of elements E_{crack} = 42.1x10⁶ (vs. E_{Al} = 70.0x10⁹)

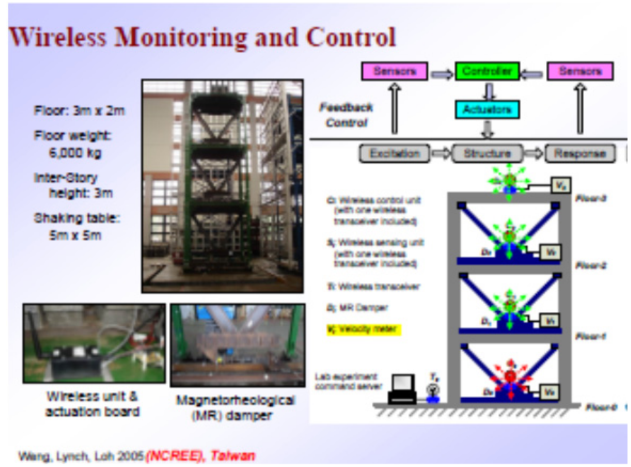
Experimentally derived modal characteristics (obtained from synthetic sensor data)

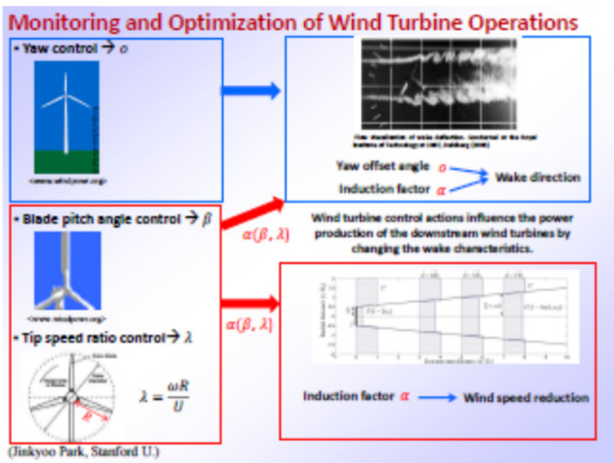
System Identification of Large Scale Continuum Structure Remains Difficult
-- Systematic Archived Data From NEES/E-Defense

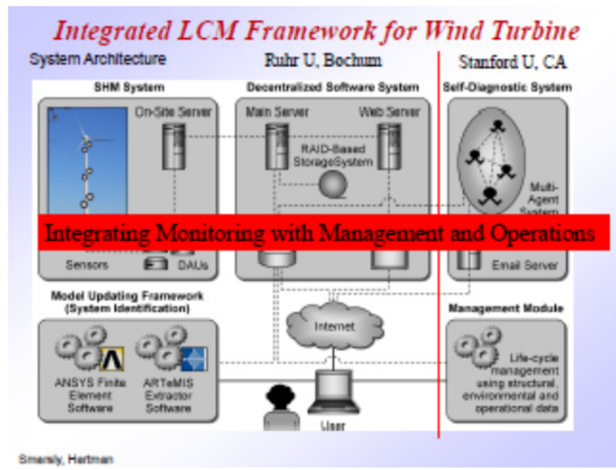
Modal characteristics obtained from the Bayesian updated model of plate

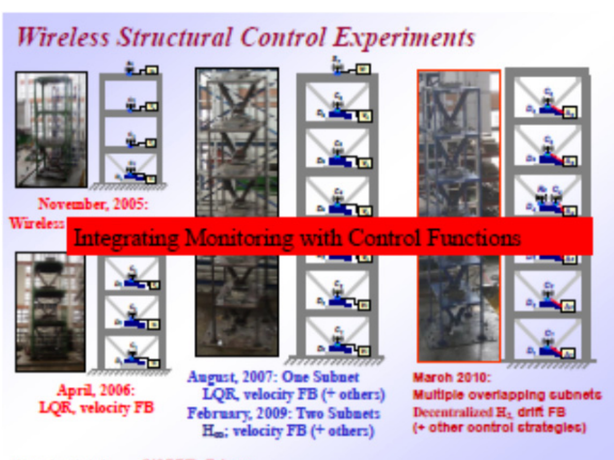
Karata, Lynch 2010

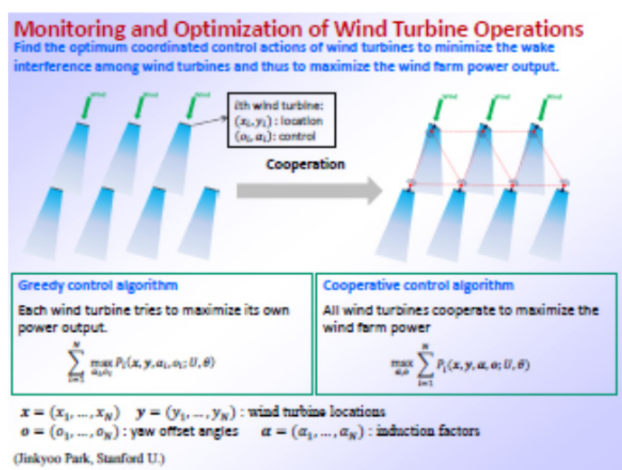

Wireless Sensors for Monitoring Applications
• 6 wireless sensor units (WSU) installed
• 3 accelerometers installed per floor (Crossbow CXL02 /CXL01 MEMS)
• 4 Texas Instruments (120 Ohm) Strain Gages on column base
Floor plan: 3m x 2m
Floor weight: 6,000 kg
Inter-story height: 3m
Shaking table: 5m x 5m
Wang, Lynch, Loh 2004 (NCREE), Taiwan


Wireless Monitoring and Control
Floor: 3m x 2m
Floor weight: 6,000 kg
Inter-Story height: 3m
Shaking table: 5m x 5m
Sensors
Controller
Sensors
Feedback Control
Actuators
Excitation
Structure
Response
Wireless unit & actuation board
Magnetorheological (MR) damper
Wang, Lynch, Loh 2005 (NCREE), Taiwan

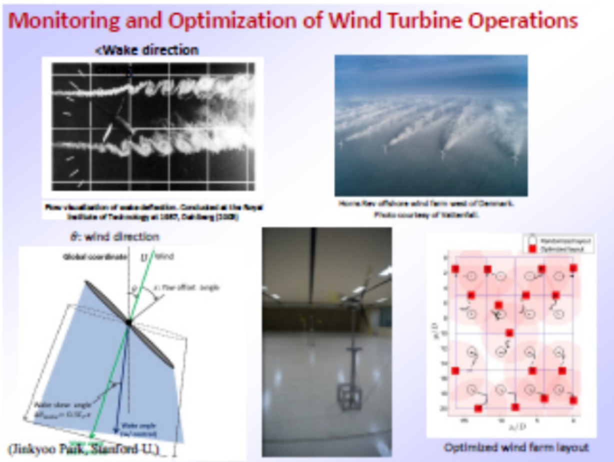

Monitoring and Optimization of Wind Turbine Operations
• Yaw control → o
• Blade pitch angle control → β
• Tip speed ratio control → λ
Yaw offset angle o → Wake direction
Induction factor α
Wind turbine control actions influence the power production of the downstream wind turbines by changing the wake characteristics.
Induction factor α → Wind speed reduction
α(β, λ)
$\lambda = \frac{\omega R}{U}$
(Jinkyoo Park, Stanford U.)


Integrated LCM Framework for Wind Turbine
System Architecture
Ruhr U, Bochum
Stanford U, CA
SHM System
Decentralized Software System
Self-Diagnostic System
On-Site Server
Main Server
Web Server
RAID-Based StorageSystem
Multi-Agent System
Integrating Monitoring with Management and Operations
Sensors
DAUs
Email Server
Model Updating Framework (System Identification)
Management Module
Internet
ANSYS Finite Element Software
ARTeMIS Extractor Software
User
Life-cycle management using structural, environmental and operational data
Smarsly, Hartman

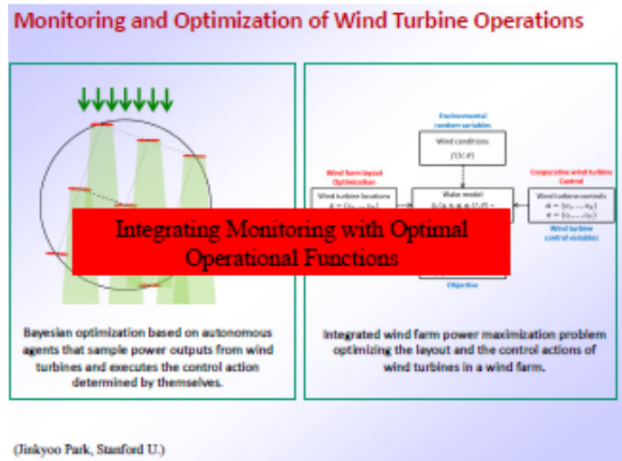

Wireless Structural Control Experiments
November, 2005:
Wireless
Integrating Monitoring with Control Functions
April, 2006:
LQR, velocity FB
August, 2007: One Subnet
LQR, velocity FB (+ others)
February, 2009: Two Subnets
H∞; velocity FB (+ others)
March 2010:
Multiple overlapping subnets
Decentralized H∞ drift FB
(+ other control strategies)
Wang, Lynch, Loh (NCREE), Taiwan


Monitoring and Optimization of Wind Turbine Operations
Find the optimum coordinated control actions of wind turbines to minimize the wake interference among wind turbines and thus to maximize the wind farm power output.
Cooperation
Greedy control algorithm
Each wind turbine tries to maximize its own power output.
Cooperative control algorithm
All wind turbines cooperate to maximize the wind farm power
$x = (x_1, ..., x_N)$ $y = (y_1, ..., y_N)$: wind turbine locations
$o = (o_1, ..., o_N)$: yaw offset angles $\alpha = (\alpha_1, ..., \alpha_N)$: induction factors
(Jinkyoo Park, Stanford U.)

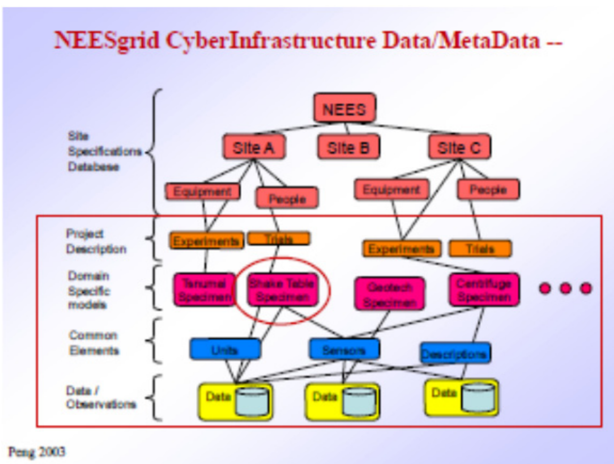
Appendix XI



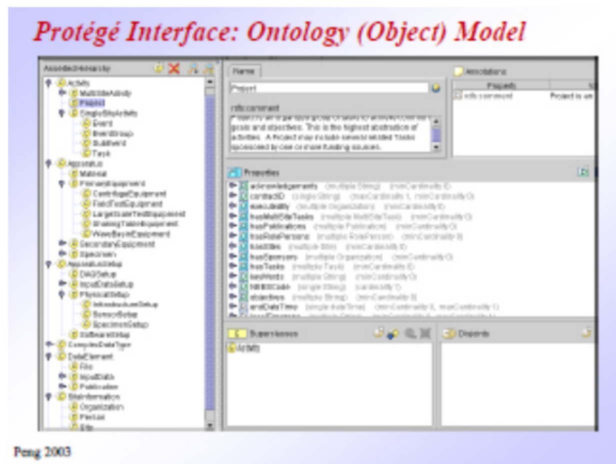
Monitoring and Optimization of Wind Turbine Operations
<Wake direction
θ: wind direction
(Jinkyoo Park, Stanford U.)
Optimized wind farm layout



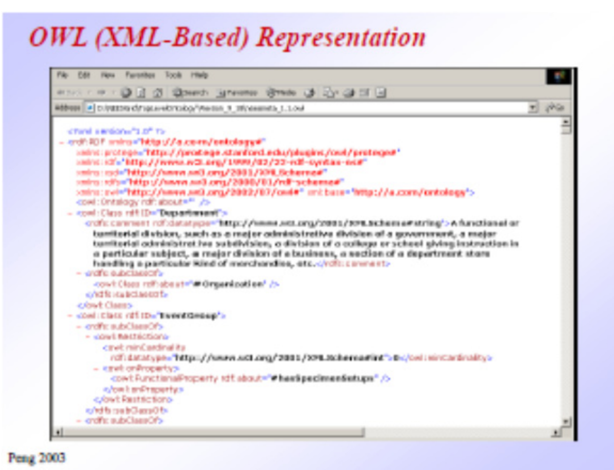
Monitoring and Optimization of Wind Turbine Operations
Integrating Monitoring with Optimal Operational Functions
Bayesian optimization based on autonomous agents that sample power outputs from wind turbines and executes the control action determined by themselves.
Integrated wind farm power maximization problem optimizing the layout and the control actions of wind turbines in a wind farm.
(Jinkyoo Park, Stanford U.)



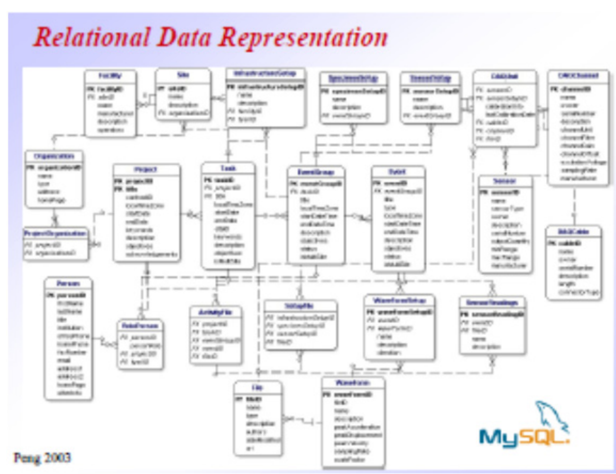
NEESgrid CyberInfrastructure Data/MetaData --
NEES
Site A
Site B
Site C
Site Specifications Database
Equipment
People
Project Description
Experiments
Trials
Domain Specific models
Tsunami Specimen
Shake Table Specimen
Geotech Specimen
Centrifuge Specimen
Common Elements
Units
Sensors
Descriptions
Data / Observations
Data
Peng 2003



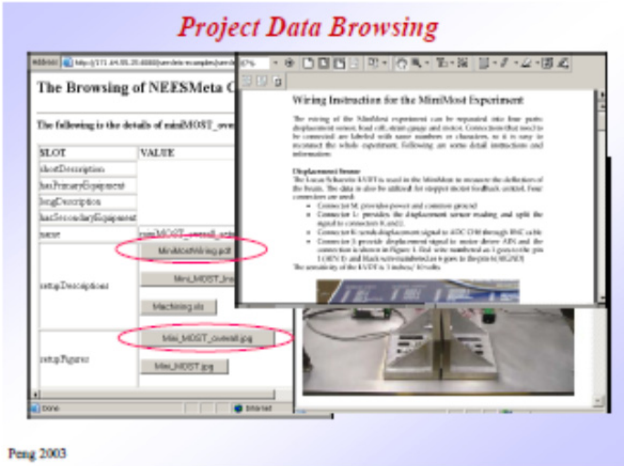
Protégé Interface: Ontology (Object) Model
Peng 2003

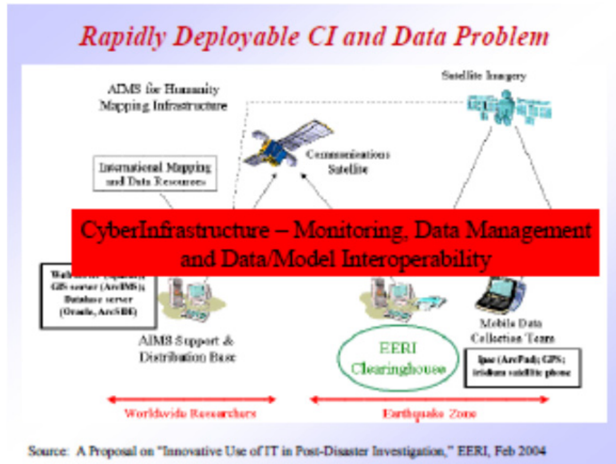


OWL (XML-Based) Representation
Peng 2003



Relational Data Representation
MySQL
Peng 2003


Project Data Browsing
The Browsing of NEESMeta
Wiring Instruction for the MiniMost Experiment
SLOT
VALUE
Peng 2003


Rapidly Deployable CI and Data Problem
AIMS for Humanity
Mapping Infrastructure
Satellite Imagery
International Mapping
and Data Resources
Communications
Satellite
CyberInfrastructure – Monitoring, Data Management
and Data/Model Interoperability
AIMS Support &
Distribution Base
EERI
Clearinghouse
Mobile Data
Collection Team
Worldwide Researchers
Earthquake Zone
Source: A Proposal on "Innovative Use of IT in Post-Disaster Investigation," EERI, Feb 2004

APPENDIX XII: PRESENTED PAPERS IN WORKING GROUP SUMMARY

NEES / E-Defense Workshop
Kyoto, Japan
11th - 13th of December 2013

Reinforced Concrete Group Resolutions
Presented by: Wassim Ghannoum

GOALS for Resilient Cities

1. Collapse prevention and life safety
2. Loss reduction
3. Rapid recovery

Challenges

1. Simulation tools to assess performance
   1. Develop and validate analytical tools
   2. Database sets
   3. Damage limit-states
2. Monitoring and damage evaluation tools
   1. Improve simulation tools
   2. Rapid and post-event assessment tools
3. System-level interactions critical to collapse and losses
4. Improving performance
   1. Assessment and retrofit methodologies
   2. Design criteria
   3. Innovative systems

Resolutions

1. Continued exchange of ideas and data
   - Meetings, visits
   - Workshops on wall systems
   - Workshops on database development
2. Enhanced databases
   - Tools for discovering and sharing
   - Define new limit-states and acceptance criteria
     - Critical damage triggers for repair
   - Extract damage states
   - Improve prediction of limit-states
     - Improve estimates of residual collapse capacity
   - Extract data for advanced simulations

Resolutions

3. System level investigations
   - Loss and functionality
   - Collapse
   - Extreme motions and after-shocks

- Older RC systems focus collapse
- Modern RC systems- focus on benchmarking and minimization of damage
- Innovative RC systems - focus on minimizing damage

Mechanisms for Collaboration

1. Workshops
2. Embedded researchers
3. Team analyses of US and E-defense tests
   1. pre and post tests
   2. Comparison of assessment techniques
4. Companion tests in US for systems tested at E-defense

- Early collaboration in planning phases

Appendix XII

NEES/E-Defense Collaborative Earthquake Research Program 10th Planning Meeting

Advanced Steel Structures

Chairs
Taichiro Okazaki (Hokkaido University)
Gilberto Mosqueda (University of California, San Diego)

Participants

(in alphabetical order)
Del Carpio Ramos, Elkad, Fahnestock, Forgarty, Garlock, Kimura, Kolay, Lignos, Lin, McCormick, Mosqueda, Nishiyama, Okazaki, Ozaki, Ricles, Sasaki, A. Sato, D. Sato, Simpson, Takeuchi

Current Steel Research in Japan

Dimitrios Lignos (McGill University, Canada)
"Current Research on the Collapse Assessment of Steel Buildings Subjected to Extreme Earthquake Loading"

Yoshihiro Kimura (Tohoku University)
"Proposal of new column support system to prevent yielding"

Atsushi Sato (Nagoya Institute of Technology)
"Deformation capacity of beam-columns"

Daiki Sato & Tomohiro Sasaki (NIED)
"Experimental Study on Large-frame structures, an ongoing E-Defense Project"

Toru Takeuchi (Tokyo Institute of Technology)
"Rocking frames"

Current Steel Research in US

Maria Garlock (Princeton University)
"Evaluating resilience within a multi-hazard context"

Larry Fahnestock (Univ. of Illinois at Urbana-Champaign)
"Steel plate shear walls"

Barb Simpson (University of California, Berkeley)
"Vulnerability and retrofit of older braced frames"

Jim Ricles (Lehigh University)
"Self-centering steel frame systems and supplemental passive damper systems"

Breakout Session 1

Theme 1. Collapse assessment of steel structures
Chairs: Yoshihiro Kimura, Jason McCormick
Recorder: Julie Fogarty

Theme 2. Rocking systems
Chairs: Toru Takeuchi, Maria Garlock
Recorder: Kolay Chinmoy

Breakout Session 2

Theme 3. Response control for improved functionality
Chairs: Dimitrios Lignos, Jim Ricles
Recorder: Maikol Del Carpio Ramos

Theme 4. Evaluation and retrofit of older steel structures
Chairs: Atsushi Sato, Larry Fahnestock
Recorder: Barb Simpson

Overarching Research Needs

- Within the meta-theme of 'Resilient Cities'
  - Immediate occupancy and damage free performance under multi-hazard scenarios.
    - Existing structures and new construction
    - Consideration of structural and nonstructural systems
  - Consideration of beyond design basis events
    - Understand and simulate structural behavior from onset of damage to collapse
  - Consideration of multi-hazard loading

Deficient Structures

- Research interests common to US and Japan:
  - Understanding global behavior governed by low ductility limit states
    - Failure hierarchy
    - Soft story
    - Effect of reserve capacity / back-up strength
  - Assessment of current evaluation strategies
  - Establishing database to calibrate / verify numerical models
  - Collapse assessment
  - Testing possible retrofit strategies

Deficient Structures

- Testing possible retrofit strategies
  - Pragmatic / low cost strategies for life safety and collapse prevention
  - Advanced / high performance strategies for immediate occupancy
    - E-Defense shake table
    - Long Term Goal: Demonstration of low-ductility response
    - Interaction between lateral system and gravity-system

Response control for improved functionality

- Research needs for resilient structural systems
  - New response modification systems (material, configurations and devices)
  - Focus on rocking systems
  - Integration of response modification devices with structural and non-structural systems design
  - Consideration of structural and non-structural response
  - Retrofit of deficient structures and non-structural systems

Response control for improved functionality

- Research needs for the next 5 to 10 years
  - Performance based design considering multiple response parameters (drift, velocity, acceleration, residual drift) with acceptable confidence levels
  - Response sensitivity to uncertainty in resistance and demand, development of robust systems
  - Effects of different ground motions characteristics
    - long duration, long period
    - near fault ground motions
  - Cost-benefit studies (life cycle)

Response control for improved functionality

- Research needs for the next 5 to 10 years
  - Effectiveness of response modification systems for low-, mid- and high rise buildings
  - Special structures (large span, open areas)
  - Development of test beds for experimental parametric studies on devices and systems
  - Characterization tests, development, and experimental validation of numerical models of response modification systems and devices

Response control for improved functionality

- Discussion focused on rocking systems
- Application: for existing and new constructions (e.g., spine system, self-centering systems)
- Near term research needs
  - Architectural, serviceability, nonstructural elements
  - Resiliency of gravity system
  - Effects of floor systems (collector systems)
  - collapse resistance
  - Development of effective, practical retrofit solutions that achieve high performance

Response control for improved functionality

- Long term research needs for rocking systems
  - Application to retrofit for non-ductile structures
  - Adaptation of mid and high-rise systems to self-centering, high mode effect
  - Health monitoring

Collapse assessment of steel structures

Research interests common to US and Japan that can be addressed by NEES/E-Defense

1) Immediate opportunities from recent tests at E-Defense
2) Component level behavior
  a. Columns under combined loading, particularly large axial loads
  b. Base plate behavior
3) Dynamic response of steel braced frames through shaking
  a. Consideration of buckling behavior and frame action with post buckling
  b. Effect of brace type (member shape)
  c. Torsional effects as a result of inelastic behavior
4) Irregular structures and torsional behavior
5) High fidelity modeling for collapse simulation

Collapse assessment of steel structures

High Priority Research Opportunities: Near Term

- **Behavior of columns under high axial loads and lateral drift**
  - Experimental and computational work
  - Large-scale testing of columns under high axial loads
- **Embedded base plates/column base connections**
  - Need for more testing on base plate behavior
  - Consideration of realistic column boundary conditions
- **Subassembly Testing**
  - Emphasis on composite action and its effect on cyclic deterioration of beam-to-column connections

Collapse assessment of steel structures

High Priority Research Opportunities: Next 5 to 10 Years

- **Subassembly tests using hybrid simulation**
  - More realistic models to capture deteriorating mechanisms – use of mechanics based models (beyond spring models)
  - Analytical techniques to speed up numerical simulations
  - Critical areas of study include fracture and friction mechanisms
  - Integrate new high fidelity numerical capabilities into hybrid simulation
- **System level experimental testing**
  - Realistic structural configurations
  - Soil – structure interaction
  - Multiple components of loading

Research Effectively Addressed by US-Japan Collaboration

- **Characterize behavior of steel structures under large deformations using NEES Facilities**
  - Carry out hybrid simulation on representative substructures to investigate the interaction between beam and column inelastic behavior
  - Utilize data from large scale column testing (wide flange and box sections) for further development of simulation models
- **System level tests and utilization of E-Defense collapse test data**
  - Evaluation of existing (and new) methodologies for collapse assessment of steel frame buildings
  - Advancement of analytical modeling capabilities to simulate complex deterioration mechanisms
  - System level verification of proposed retrofit and design strategies

Appendix XII

Potential Project 1

Evaluation and Retrofit of Deficient Structures

- **Focus on braced frame systems (parallel to SAC)**
- **Series of component, subassembly, and system testing to collapse of full-scale braced frames**
  - One US design and one with Japanese design
  - Concentric versus eccentric braced frames
  - Brace type (HSS vs. wide-flange braces)
  - Effect of connection detailing on structural response
  - Emphasis on the post buckling behavior
  - Frame action quantification (i.e., reserved capacity)
- **Study torsional behavior with NEES and E-Defense**
  - Tests of irregular structures
  - Torsion induced by asymmetric inelastic behavior

Potential Project 2

Resilient steel rocking systems for extreme events

- **Application to new constructions**
- **Series of component, subassembly, and system testing to Collapse**
  - Verification of response under realistic dynamic loading
  - Validation of concept using 3-D ground motion
  - Architectural, serviceability, nonstructural elements
  - Resiliency of gravity system
  - Effects of floor systems (collector systems)
  - Applications to low- mid- and high-rise structures

Synergistic Collaboration

- **Participation in future planning meetings**
- **Data sharing and archiving**
- **Exchange of students and faculty**
- **Follow in the footsteps of our predecessors….**

Protective Systems Discussion

- **Recommended Efforts to Increase Effective Collaboration**
- **Recommended High Priority Research of Mutual Interest to the US and Japan:**
  - Title, Description, Scientific Importance, Societal Benefit (additional information as needed regarding time frame, priority, and relation to the context of "resilient cities")
- **Opportunities for Payload Projects: (list)**
- **Opportunities and needs for advancing capabilities of numerical simulation: (list)**

Protective Systems Discussion

- **Recommended Efforts to Increase Effective Collaboration**
  - What are past/current examples of effective collaboration?
  - Who are potential collaborators (Japan and US)?
  - What collaboration activities are needed?
  - What needs to be done to increase this collaboration

Protective Systems Discussion

- **Recommended High Priority Research of Mutual Interest to the US and Japan:**
  - What are research topics of interest to group? (priority of projects)
    - Performance of protective systems to strong ground motion
    - Performance and application of protective systems for vertical ground motion
    - Characterization and performance of protective system components
  - Scientific Importance of each topic
  - Societal Benefit of each topic
  - Relation to the context of "resilient cities" of each topic

Protective Systems Discussion

- **Opportunities for Payload Projects:**
  - What are past/current examples of payload projects?
  - What potential payload projects moving forward can meet the priority research needs

Protective Systems Discussion

- **Opportunities and needs for advancing capabilities of numerical simulation:**
  - What are past/current examples of advancing numerical simulation in this collaboration?
  - What are the needs for advancing capabilities of numerical simulation?
  - What are the opportunities for advancing capabilities of numerical simulation?

NEES/E-Defense Collaborative Earthquake Research Program 10th Planning Meeting

Geotechnical Engineering Summary Report

DPRI, Kyoto University

Chairs: Shuji Tamura, Jonathan Stewart
Recorder: Ramin Motamed

Dec 12-13, 2013

Session Agenda

- Introductions & session overview.
- E Defense Research.
- *Ground motions, site response, applications of recordings.*
- *Utilization of field performance data*
- *Shaking Table Testing and Centrifuge Testing for Soil-Structure Interaction and Related Applications*

Research Areas

Societal sustaining systems

1) Multi-hazard risk characterization:
   a) Effects of mainshock/aftershock sequences,
   b) Rain following earthquake,
   c) Tsunami following earthquake.
   d) The issue here is what is the relative impact of the subsequent event (aftershock, rain, tsunami) as a result of the degraded state of the system following the mainshock.

Societal sustaining systems

2) System response in an urban environment
   a) Soil structure interaction. Kinematic effects, energy dissipation, etc.
   b) Seismic earth pressures on subterranean components of foundations from inertial interaction from neighboring buildings,
   c) Are ground motion demands tangibly influenced by the vibrations of adjacent structures?,
   d) Is the damping of an SSI system affected by the presence of close-proximity neighboring structures?

Societal sustaining systems

3) Distributed systems
   a) Flood control systems: Levees, dams, slopes. Including ground failure mechanisms
   b) Lifeline systems. Transportation, pipelines, energy, etc.

Hazard characterization

4) Regional variations in site response
5) Is site response predictable with 1D analysis
6) Vertical-component site response
7) Site parameter estimation from proxies

Hazard characterization

4) Regional variations in site response, including the scaling with the principal site parameter (Vs30) and nonlinearity
   a) Why is nonlinearity different in different regions?
   b) What secondary parameters can improve predictions?

Hazard characterization

5) Is site response predictable from 1D analysis?
   a) Considerations related to geologic complexity and its effects on Vs variability in the region around the site.
   b) Large-strain site response
   c) Soil damping
   d) A challenge in this work is the quality of existing profiles for K-net and Kik-net sites.

Hazard characterization

6) Site response for the vertical component of ground motion.
7) Estimation of Vs30 from proxies for the application of GMPEs in regions without seismic velocity data

Ground failure

8) Next generation liquefaction (NGL):
   a. Development of community liquefaction triggering and effects database
   b. Models for liquefaction triggering and effects derived from this database
   c. Physical model testing to support aspects of the models not constrained by data (e.g., effects of high overburden stress).
9) Prediction of site response for sites that experience liquefaction (e.g., LEAP project).

Ground failure

10)New site characterization techniques

Ground failure

10)New site characterization techniques

a) Understanding surface wave inversion methods
b) Improved cone penetration testing
c) Improved Becker penetration testing

Mitigation

11)Soil improvement. Use field performance data, including recent cases from Japan and NZ where improved ground did not do as well as expected, to guide the design of future physical model tests and related analysis.

12)Mitigation of foundations for existing structures

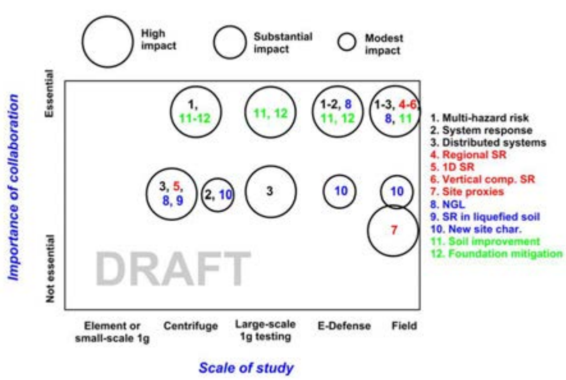
Applications using field performance data

8) Soil-structure interaction. Emphasis on short-period buildings. This emphasis is motivated by observations that such buildings subjected to very strong ground motions (well above design levels) have unexpectedly low damage rates. Our challenge is to understand why. Related issues:

a. Kinematic interaction effects on reducing the ground motions at the base of structures. Piles as mechanism for reducing ground motions.
b. Energy dissipation mechanisms related to SSI,
c. EL vs NL method of analysis.

Big Themes

- Practical tools for reliable prediction of site response
- Liquefaction triggering, effects, and mitigation
- Applications of soil-structure interaction in performance-based engineering



Topic	Japan-US Collaboration Critical?	Critical Role for NEES / E-def?
1. Regional site response	X	
2. Is site response predictable?	X	X
3. Vertical site response	X	X
4. Proxy-based Vs30		
5. Site response with liquefaction	X	X
6. NGL	X	X
7. Soil improvement	X	X
8. Soil-structure interaction	X	X
9. Multi-hazard characterization	X	X
10. Structure-soil-structure interaction	X	X
11. Site characterization	X	X

How do we encourage/strengthen collaboration?

- More clarity on data sharing (both sides)
- Fund research to interpret existing data & perform applicable simulations
- Consortium of US and Japanese testing facilities.
- Student fellowships to support data interpretation & simulation research

10th NEES/E-Defense Collaborative Earthquake Research Program: Monitoring Session Report

Facilitators: Masahiro Kurata & Jerome P. Lynch
Reporter: Kenneth J. Loh

DPRI, Kyoto University, Kyoto, Japan
December 13, 2013

Monitoring Working Group

- **Facilitators:**
  - Masahiro Kurata (Kyoto University)
  - Jerome P. Lynch (University of Michigan)
- **Recorder:**
  - Kenneth J. Loh (UC Davis)
- **Participants:**
  - Shirley Dyke (Purdue University)
  - Tomonori Nagayama (University of Tokyo)
  - Anne Kiremidjian, Stanford University
  - Akira Nishitani (Waseda University)
  - Yoshihiro Nitta (Ashikaga Institute of Tech)
  - Kincho Law (Stanford University)
  - Sean O'Connor (University of Michigan)
  - Shamim Pakzad (Lehigh University)
  - Jennifer Rice (University of Florida)
  - Wei Song (University of Alabama)

Process

- **Pre-workshop Homework:**
  - Distributed working group agenda ahead of the workshop:
    - Question 1: If monitoring systems are tailored to "sense" specific damage modalities in structures, which ones are of greatest importance that should be prioritized?
    - Question 2: How can instrumentation (sensors and sensing systems) be used to illuminate causal relationships between damage and residual system capacity?
    - Question 3: If there is an opportunity to dedicate a large-scale structural testing program exclusively to structural health monitoring and SHM-driven decision making, what would you propose?
- **Workshop Day 1:**
  - Participants presented their research and answers to the three questions
  - Activity 1 focused on post-event decision making aided by monitoring systems
  - Activity 2 focused on estimating residual system capacity based on monitoring data
- **Workshop Day 2:**
  - Refine and Finalize High-Priority Research Topics (3 identified)
  - Describe potential payloads and simulations
  - Plan for trans-Pacific collaboration in the NEES/E-defense joint research program

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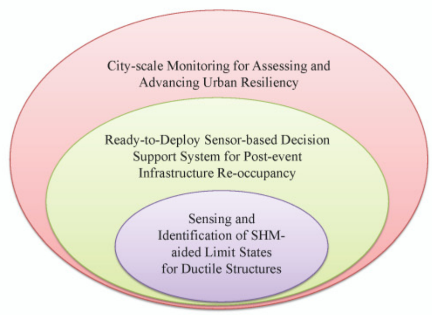
DPRI, Kyoto, Japan – December 11-13, 2013

High Priority Research Areas



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High Priority Research Topic #1

Sensing and Identification of SHM-aided Limit States for Ductile Structures

Summary: A previously missing link between earthquake-resistant design and structural health monitoring (SHM) is a framework that explicitly connects design criteria with the information generated by sensing systems. The grand challenge is to create and sense damage limit states in strong non-linear region after the initiation of strength deterioration with the aid of sensors and sensing systems. The research challenges include the identification of damage limit states with novel SHM technologies and leveraging the NEES/E-Defense data archive of large-scale tests. Design verification tests using densely-instrumented large-scale test beds. Accomplishing this grand challenge will yield opportunities to account for the potential ductility and redundancy in structural systems for post-event safety evaluation and reduce downtime before re-occupation of damaged structures.

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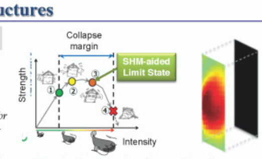
Sensing and Identification of SHM-aided Limit State for Ductile Structures

Description

- Identification of damage limit states in strong nonlinear region of ductile structures:
- *Leverage the NEES/E-Defense data archive of large-scale tests*
- *Create and validate appropriate sensing technologies for damage limit states using densely-instrumented large-scale test beds*
- Experimental test beds to create a data repository well-suited for the identification of damage limit states for ductile structures



Deteriorating behavior of structures with potential ductility

Novel sensors and sensing system

Scientific Importance

- Identification of damage limit states will enable rapid damage assessment
- Damage limit state analysis can be performed within a probabilistic framework
- Novel sensing technologies will enable direct damage quantification of damage limit states
- Assessment of reliability in damage limit states will empower decision-making

Broader Societal Impacts

- Structural-engineer-friendly SHM index
- Incorporation of the potential residual ductility and redundancy in structures during post-event analysis
- Reduced downtime with rapid structural safety assessment
- Greater benefits to infrastructure owners that offset cost of the deployment of SHM systems
- Increase in public confidence in infrastructure safety and post-event decision-making

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High Priority Research Topic #2

Ready-to-Deploy Sensor-based Decision Support System for Post-event Infrastructure Re-occupancy

Summary: Rapid recovery is critical for achieving next-generation resilient communities and for minimizing the adverse socioeconomic impact following a severe earthquake. The grand challenge is to devise new technologies, computational methods, and probabilistic tools for making reliable decisions regarding the immediate re-occupancy and use of infrastructure systems and their intended functionalities. A broad community of stake holders would be engaged to accelerate the transfer of research findings to practice. The research challenges include: developing verified sensing technologies for measuring specific damage modalities (including their initiation and propagation) before, during, and after an earthquake; mining and utilizing existing test data for algorithm and model verification; designing test beds aimed at assessing different structural health monitoring methods applied to different classes of structures; and assessing structural performance, operational capabilities, and rehabilitation priority. The decision support system for re-occupancy and continued operations should incorporate uncertainties while still provide definitive actions that are aligned with the needs and expectations of engineers, owners, facility managers, and stakeholders.

Ready-to-Deploy Sensor-based Decision Support System for Post-event Infrastructure Re-occupancy

Description

- Devise reliable decision support framework for the re-occupancy and continued operations of damaged but structurally sound infrastructure
- Utilize existing test data and new tests to create a probabilistic framework that generates definitive actions for re-occupancy, use, and repair
- Explicit coupling between quantitative SHM data and qualitative visual inspection for improved re-occupancy decisions

Re-occupying building after earthquake

Scientific Importance

- Design and optimize sensors and algorithms for characterizing damage initiation and propagation
- Create test beds for assessing SHM technologies and methods when applied to different classes of structures or construction methods
- Implement validated models for prediction of structural response to different excitations
- Develop probabilistic decision-making framework that integrates structural resistance and demand

Broader Societal Impacts

- Significantly enhance the resiliency of large urban environments following major earthquakes
- Reduce socioeconomic impact of major events
- Improve psychological well-being
- Enhance functionality and operations of disaster-impacted regions
- Dedicate shelter and recovery resources to areas of greatest need
- Prioritize repairs and rehabilitation efforts

High Priority Research Topic #3

City-scale Monitoring for Assessing and Advancing Urban Resiliency

Summary: To take on the scientific and technological challenges associated with creating truly resilient cities, existing experimental programs should be expanded to include a focus on city-scale response (physical and social) to natural hazard events. Monitoring technologies, in conjunction with advance simulation tools, can be used to provide a more comprehensive view of how infrastructure systems and human populations respond to earthquakes. Incorporation of emerging information sources, such as crowd-sourcing, remote sensing, and social media, will enhance regional-scale responses. In the context of future NEES/E-defense research collaborations, specific focus should be paid on the development of monitoring technologies that can learn and track the physical weaknesses and vulnerabilities that may exist at points of connection of infrastructure systems. Experimental programs should also be devoted to the testing aimed at understanding how component performance impacts the performance of the infrastructure system or network of which that component is a part. Simulation tools can be used to further advance how decision makers can rapidly utilize monitoring data to assess system fragilities and to allocate resources immediately after the event in the ensuing days and weeks.

City-scale Monitoring for Assessing and Advancing Urban Resiliency

Description

- Diffusion of monitoring technologies, emerging data sources, and simulation tools to assess infrastructure performance and societal response
- Experimental programs to understand how component performance impacts the performance of global systems/networks
- Simulation tools created and calibrated to aid decision makers to assess system fragilities and to allocate resources post-event on varying time-scales

Interconnected Infrastructure Systems

Scientific Importance

- With fundamental knowledge in the infrastructure system interdependency lacking, experimental testing and computer simulation will:
  - *Advance sensing methods and data aggregation systems for monitor points of system connection*
  - *Create simulation tools to model the mechanisms of cascading failures in infrastructure systems*
  - *Optimize data-driven decision-support systems for allocation of emergency response at the regional-scale*

Broader Societal Impacts

- Identify pre-event weaknesses in city-scale systems for hardening to ensure global system performance and to eliminate cascading failures
- Rapidly assess health of urban physical infrastructure post-event:
  - *Allocate emergency response resources*
  - *Enhance the operations of first responders*
- Minimize time to full regional and global economic recovery of region and social impact

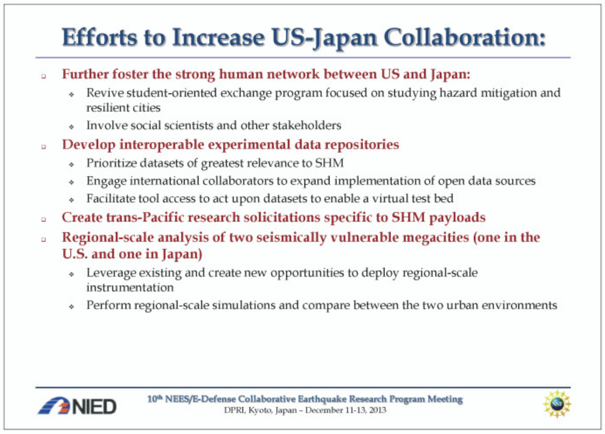
Experimental Program

- **Opportunities for Payload Projects:**
  - Creation of large-scale testing program that are open to the broader research community for the purposes of identifying damage limit states:
    - Test specimens designed to illuminate specific damage mechanisms at local and global length scales
    - Open access to the research community to validate novel sensor technologies
    - Intelligent sensors for real-time agent software migration of embedded damage detection algorithms
    - Create datasets for blind assessment of damage detection algorithms (in addition to the research, consider supplemental student competition possibilities)
    - Assess the reliability and durability of sensors and sensing systems
  - Engage the diverse stakeholder community:
    - Involve visual inspectors to evaluate tested specimens to identify optimal ways of combining SHM data with visual inspections for re-occupancy decisions
    - Quantify the benefits of SHM systems for cost-benefit analyses

Simulation Tools

- **Opportunities for Advancing Capabilities of Numerical Simulation:**
  - Use testbed data to enhance the simulation of regional responses to earthquakes, especially the performance of physical infrastructure under ground motion
    - Reduce the uncertainty inherent in numerical models of structures, especially structures responding in their nonlinear response regime, through advance online or real-time model-updating techniques
    - Agent-based simulation of societal response to earthquakes over varying time-scales

Appendix XII



APPENDIX XIII: SUMMARY OF STUDENT ACTIVITIES PROGRAM

AS PART OF THE TENTH PLANNING MEETING OF NEES/E-DEFENSE COLLABORATIVE RESEARCH ON EARTHQUAKE ENGINEERING

Introduction

In parallel to the tenth planning meeting, a "student activities program" was organized and implemented. It is for the first time that such explicit student collaboration was organized in the NEES/E-Defense collaborative research. Eight students from the United States, one student from Canada, and ten students from Japan gathered and exercised intensive exchange, both technical and social. The students' travel to and stay in Japan was supported jointly by the NSF and DPRI, Kyoto University. A summary of the student activities program is shown below.

Local Organizing Committee (DPRI, Kyoto University):

Chair,	Ryosuke Nishi
Vice-Chair,	Mayako Yamaguchi
Member,	Liusheng He, Xiaohua Li, Lei Zhang, Kaede Minegishi, Takuma Togo, Hiroyuki Inamasu, Miho Sato, and Akiko Suzuki

Program Agenda

December 10, 2013	Social gathering over dinner at Fushimi (organized by Miho Sato)
December 13, 2013	Student discussion (organized by Mayako Yamaguchi and Ryosuke Nishi)
	Social gathering over dinner at Fushimi (organized by Akiko Suzuki)
December 14, 2013	Exploration of Kyoto (organized by Hiroyuki Inamasu)

List of Participants

First Name	Last Name	Affiliation	Title
From Japan			
Liusheng	He	DPRI, Kyoto Univ.	Doctoral Student
Hiroyuki	Inamasu	DPRI, Kyoto Univ.	Undergraduate Student
Xiaohua	Li	DPRI, Kyoto Univ.	Doctoral Student
Kaede	Minegishi	DPRI, Kyoto Univ.	Master Course Student
Ryousuke	Nishi	DPRI, Kyoto Univ.	Master Course Student
Miho	Sato	DPRI, Kyoto Univ.	Undergraduate Student
Akiko	Suzuki	DPRI, Kyoto Univ.	Undergraduate Student
Takuma	Togo	DPRI, Kyoto Univ.	Master Course Student
Mayako	Yamaguchi	DPRI, Kyoto Univ.	Master Course Student
Lei	Zhang	DPRI, Kyoto Univ.	Doctoral Student

From the United States

Kolay	Chinmoy	Lehigh University	Doctoral Student
Maikol	Del Carpio Ramos	State University of New York at Buffalo	Doctoral Student
Julie	Fogarty	University of Michigan	Graduate Student
Kenneth	Gillis	University of Colorado, Boulder	Doctoral Student
Dorian	Krausz	Univ. of California, Los Angeles	Graduate Student
Jinhan	Kwon	University of Texas at Austin	Doctoral Student
Sean	O'Connor	University of Michigan	Graduate Student
Barb	Simpson	UC Berkeley	Graduate Student
From Canada			
Ahmed	Elkady	McGill University	Doctoral Student

Summary of Student Discussion Session

Facilitator: Tracy Becker
Recorder: Sean O'Connor

The focus of the student group discussion was to share a general overview of the workshop as well as future ideas for large scale testing and applications of test data. In addition, several challenges associated with U.S.-Japan collaboration were discussed.

In response to the workshop in general, the majority of the group especially appreciated the breakout sessions. Most of the students were excited to be involved in discussions directly relevant to their research fields and current knowledge base. The workshop was an excellent opportunity for the students to interact with highly regarded professionals from their respective fields. Graduate students often feel that their research focus is very narrow and the session presentations and discussions provided a broader look at research opportunities. The student group also offered ideas on ways to improve the workshop. The student group expressed interest in a presentation topics and discussion agenda prior to the workshop, in order to better prepare and contribute to session discussions. Also, the addition of U.S. and Japan practicing engineers would have introduced a valuable perspective to session discussions.

A majority of the discussion dealt with ideas and challenges for large scale testing. The geotechnical student group expressed interest in soil-structure interaction testing at E-Defense for vertical ground motion. In particular, collaboration among geotechnical engineers and protective systems engineers could address important concerns in high rise buildings and base isolation systems when vertical ground motion occurs. In addition, multi-hazard analysis, particularly the sequence of aftershock events following a major earthquake, are well suited for E-Defense tests, as the shake table can provide many shaking events in a much shorter time period than field testing of actual events. The geotechnical students also saw a lot of value in testing for liquefaction mitigation techniques at E-Defense, particularly for residential housing and developing easily adoptable standards or methods for new construction. The structures groups expressed interest in E-Defense for several test scenarios, ranging from collapse testing using W-shape columns to near collapse response assessment of base isolated systems. The testing of braced frame structures provided an enthusiastic discussion among the students as design philosophy tends to differ not only among U.S.-Japan counterparts but also among U.S. counterparts. Using E-Defense to perform dynamic testing of vulnerable braced frame structures rather than the quasi-static testing available to some was mentioned. Also mentioned was hybrid testing of high rise buildings to determine relationships among component level and system level failure in braced frame structures. As the workshop had a major emphasis on resilience, several structural engineers emphasized the use of large scale testing to develop damage free buildings. Among the monitoring group, discussions on the use of large scale testing resulted in a desire to have more control in the design of structures being used to evaluate sensors and monitoring techniques. Particularly, test specimens and loading scenarios tailored towards specific damage modes would assists the structural monitoring group in developing sensors, models and algorithms for structural health monitoring. The monitoring group sees E-Defense as a great opportunity to conduct SHM prioritized testing to identify damage limit states, meticulously characterizing the large gap between safe and collapse states to fully utilize the residual capacity of ductile structures for re-occupancy following a major event. The group also mentioned a desire to perform shake table testing for non-structural health monitoring and also for developing cost-effective monitoring systems. The monitoring group also discussed the opening up SHM relevant data sets for blind-testing to accelerate the development of SHM models and algorithms and make use of existing test data.

A discussion on U.S.-Japan collaboration raised many interesting challenges including differences in language, lab environment, design culture and standards, facilities, and data. In order for U.S.-Japan collaborations to be successful, the group expressed the obvious need for sharing. In particular, open access to test data as well as facilities would expedite advancements in each field of study. Opening up the design of test specimens to the entire engineering community was suggested as way to get the most value out of each test preformed. Laboratory access was an interesting topic among U.S. and Japan students. The U.S. students generally expressed limited access to lab equipment, governed by daytime working hours of lab technicians, while Japanese students have much more freedom with test scheduling. Aside from this issue, the large time difference between U.S. and Japan poses challenges to joint hybrid testing. Differences in design culture and standards led to questions on how to design experiments that are relevant to both U.S. and Japan to optimize the data being generated by large scale testing. The student group conceded that this is a difficult problem to solve although several suggestions were made, such as designing structures easily adaptable to both U.S. and Japan standards (*e.g.,* interchangeable connections, removable braces, etc.).

Appendix XIII

Group Photo after Student Discussion Session

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