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
Disclaimer

The opinions, findings, and conclusions or recommendations expressed in this publication are those of the author(s) and do not necessarily reflect the views of the study sponsor(s) or the Pacific Earthquake Engineering Research Center.
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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.
## Preface

### Joint Technical Coordinating Committee

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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.
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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
Summary and Resolutions

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.
Summary and Resolutions

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.
# APPENDIX I: LIST OF PARTICIPANTS

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<tr>
<td>Andreas Stavridis</td>
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<tr>
<td>Jonathan Stewart</td>
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<tr>
<td>John Wallace</td>
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<td><a href="mailto:gpwl1@psu.edu">gpwl1@psu.edu</a></td>
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<td>Gordon Warn</td>
<td>Penn State University</td>
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<tr>
<td>Shunji Fujii</td>
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<tr>
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<tr>
<td>Hideki Funahara</td>
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<td>Hiroki Hamaguchi</td>
<td>Research &amp; Development Institute, Takenaka</td>
<td><a href="mailto:hamaguchi.hiroki@takenaka.co.jp">hamaguchi.hiroki@takenaka.co.jp</a></td>
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<tr>
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<tr>
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<tr>
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<td>Nippon Steel &amp; Sumitomo Metal</td>
<td><a href="mailto:kanno.kx4.ryoichi@jp.nssmc.com">kanno.kx4.ryoichi@jp.nssmc.com</a></td>
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<tr>
<td>Hisatoshi Kashiwa</td>
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<td><a href="mailto:katsumata.hideo@obayashi.co.jp">katsumata.hideo@obayashi.co.jp</a></td>
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<tr>
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<td><a href="mailto:kawamata@bosai.go.jp">kawamata@bosai.go.jp</a></td>
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<tr>
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# APPENDIX II: PROGRAM AND SCHEDULE

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<tr>
<th>Time</th>
<th>Title</th>
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<tr>
<td><strong>DAY1</strong></td>
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<tr>
<td>9:00 – 9:20</td>
<td>Registration</td>
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<tr>
<td>9:30 – 9:45</td>
<td>Opening@Kihada Hall</td>
<td>Japanese Host President of NIED Director of DPRI Program Director of NSF President of NEES</td>
<td>Nakashima &amp; Mahin</td>
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<tr>
<td></td>
<td>Greeting from Japan</td>
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<td></td>
<td>Greeting from U.S.</td>
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<td>Nakashima &amp; Mahin</td>
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<tr>
<td>9:45 – 10:15</td>
<td>A history of U.S./Japan collaboration on EE</td>
<td>Nakashima</td>
<td>Ramirez &amp; Kajiwara</td>
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<tr>
<td></td>
<td>An overview of current U.S./Japan collaboration (NEES/E-Defense)</td>
<td>Mahin</td>
<td>Ramirez &amp; Kajiwara</td>
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<tr>
<td>10:15 – 11:00</td>
<td>Recent activities of E-Defense</td>
<td>Kajiwara</td>
<td>Nakashima &amp; Mahin</td>
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<tr>
<td>11:00 – 11:30</td>
<td>Identification of workshop themes – Resilient City</td>
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<td>Nakashima &amp; Mahin</td>
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<td></td>
<td>Session grouping</td>
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<td>Nakashima &amp; Mahin</td>
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<tr>
<td>11:30 – 12:00</td>
<td>Lunch (Box lunch provided)</td>
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<tr>
<td>12:00 – 16:30</td>
<td>Tour to E-Defense – Collapse test of a high-rise steel building</td>
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<td>(Briefing in limousines)</td>
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<td></td>
<td>A rapid summary of E-Defense test (videos)</td>
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<td>17:30 – 19:30</td>
<td>Banquet at DPRI @Restaurant</td>
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<td>Kihada</td>
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<td><strong>DAY2</strong></td>
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<td>9:30 – 10:00</td>
<td>Instructions to session discussion@Wood Hall</td>
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<td>Pauschke</td>
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<td>10:00 – 12:00</td>
<td>Concurrent session: RC structures@Wood Hall</td>
<td>Presentations</td>
<td>Kusunoki &amp; Ghannoum</td>
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<td>Concurrent session: Steel structures@Seminar Room 1</td>
<td>Presentations</td>
<td>Okazaki &amp; Mosqueda</td>
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<tr>
<td></td>
<td>Concurrent session: Protective systems@Seminar Room 2</td>
<td>Presentations</td>
<td>Ikago &amp; Christensen</td>
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<tr>
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<td>Concurrent session: Geotech and underground structures@Seminar Room 4</td>
<td>Presentations</td>
<td>Tamura &amp; Stewart</td>
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<td>Concurrent session: Monitoring@Seminar Room 5</td>
<td>Presentations</td>
<td>Kurata &amp; Lynch</td>
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<tr>
<td>12:00 – 13:00</td>
<td>Lunch (Kyoto Univ. Cafeteria)</td>
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<td>Discussion</td>
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<td>Kusunoki &amp; Ghannoum</td>
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<td>Tamura &amp; Stewart</td>
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<td>Kurata &amp; Lynch</td>
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**DAY 3**

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<tr>
<td>9:30 – 12:00</td>
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<td>Group report preparation</td>
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<td>Ghannoum &amp; Kusunoki</td>
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<td>Concurrent session: Steel structures@Seminar Room 1</td>
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<td>Group report preparation</td>
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<td>Group report preparation</td>
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<td>Christensen &amp; Ikago</td>
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<td>Concurrent session: Geotech and underground structures@Seminar Room 4</td>
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<td>Group report preparation</td>
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<td>Stewart &amp; Tamura</td>
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<td>Group report preparation</td>
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<td>Lynch &amp; Kurata</td>
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<td>12:00 – 13:00</td>
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<td>13:00 – 15:00</td>
<td>Session reports:</td>
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<td>(1) RC</td>
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<td>(4) Geotech &amp; underground structures</td>
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<td>Stewart</td>
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<td>(5) Monitoring</td>
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<td>Lynch</td>
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<td>15:00 – 15:20</td>
<td>Break</td>
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<td>15:20 – 15:50</td>
<td>Resolution</td>
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<td>Mahin &amp; Nakashima</td>
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<td>15:50 – 16:00</td>
<td>Closure</td>
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<td>Ramirez &amp; Kajiwara</td>
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<td>Mahin &amp; Nakashima</td>
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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.

Figure 1 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
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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.

Figure 2 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 function 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.

Table 1  Fluid Consumption Before and After Upgrade

<table>
<thead>
<tr>
<th>Motion's Name</th>
<th>Fluid Consumption (kL)</th>
<th>Acc. Capacity (kL)</th>
<th>Bypass Pattern</th>
<th>Fluid Consumption (kL)</th>
<th>Acc. Capacity (kL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sendai</td>
<td>23.2</td>
<td>No Bypass</td>
<td></td>
<td>23.2</td>
<td></td>
</tr>
<tr>
<td>Iwanuma</td>
<td>31.7</td>
<td>Pattern 1</td>
<td></td>
<td>23.3</td>
<td></td>
</tr>
<tr>
<td>Sannomaru</td>
<td>42.5</td>
<td>Pattern 2</td>
<td></td>
<td>23.6</td>
<td></td>
</tr>
<tr>
<td>Furukawa</td>
<td>49.1</td>
<td>Pattern 2V</td>
<td></td>
<td>21.7</td>
<td></td>
</tr>
<tr>
<td>JR Takatori</td>
<td>14.5</td>
<td>No Bypass</td>
<td></td>
<td>14.5</td>
<td></td>
</tr>
</tbody>
</table>

Table 2  Decrease of maximum acceleration due to payload

<table>
<thead>
<tr>
<th>Payload (tonf)</th>
<th>Horizontal direction</th>
<th>Vertical direction</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Number of unloaded actuators</td>
<td>Number of unloaded actuators</td>
</tr>
<tr>
<td></td>
<td>0 1 2 3 4 5 6 7</td>
<td>0 1 2 3 4 5 6 7</td>
</tr>
<tr>
<td>0</td>
<td>1.7 1.4 1.0 0.7</td>
<td>2.3 1.9 1.6 1.5</td>
</tr>
<tr>
<td>600</td>
<td>1.2 1.0 0.7 0.5</td>
<td>1.7 1.4 1.2 1.1</td>
</tr>
<tr>
<td>1200</td>
<td>0.9 0.9 0.5 0.4</td>
<td>1.5 1.2 1.0 0.8</td>
</tr>
</tbody>
</table>
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), Yasuhiro 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
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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
Steel Working Group

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
Appendix IV

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.

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

(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.
Appendix IV

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).

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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 publicly. 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.
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**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 CO2 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
- 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
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?
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):
Appendix IV

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.

Scale of study
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.
Appendix IV

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 stakeholders 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

City-scale Monitoring for Assessing and Advancing Urban Resiliency

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
Appendix IV

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 TECHNICAL 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

NSF Update
NEESE-Defense Collaborative Earthquake Research Program
10th Planning Meeting
Kyoto University
December 11-13, 2013
Joy Pauschke, Ph.D., P.E.,
Co-Director of NSF-NEESE
George E. Brown, Jr. National Science Foundation
Collaborative Research Program on Earthquake Engineering and Seismic Hazards

State of NEES (Summary)
• 2003-2004 NEES MREFC Construction
• 2005-2014 NEES Operations and Research
• 2015-2019 Currently in (re)planning phase
  – Continued commitment to supporting natural hazards research, including earthquake engineering research
  – Continued commitment to supporting U.S. earthquake engineering research community collaboration with Japanese and C-Defense
    researchers and stakeholders for possible collaboration
  – Future trends include research partners for multi-hazard mitigation
    – Including earthquake engineering for sustainable infrastructures

Science Across Virtual Institutes (SAVI)
• SAVI is a mechanism for teams of NSF-funded investigators to network with partners abroad, leverage resources to advance shared research interests, and engage students in international collaboration.
• Provides supplemental resources to realize collaborative synergy, not intended as primary source of research funding.

SAVI: The Details
• SAVI supports U.S. side of collaboration
  • International partners seek new funding from their national sources, if needed
  • How to apply?
    • Supplement to existing NSF award
    • Stand-alone proposal (EAGER, others in NEES program)
    • Part of larger proposal
  • Funding: typically $30k-400k/yr for 2-5 yrs
• Eligible costs may include
  • Research team meetings
  • Research workshop
  • Team training and co-mentoring
  • International Research experiences for students

For more on SAVI
• For more information, including what's been funded to date,
  – See SAVI website:
    http://www.nsf.gov/SAVI
  – Talk to your NSF Program Officer

National Science Foundation
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
(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
“Ume-san” & “Joe-san” friendship and mutual-trust over many years (with much Sake) was the source of US-Japan collaboration.

Hajime Umemura
Univ. of Tokyo

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


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

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

15 m
15 m
21.5 m
Appendix VI

Recollection of Test of Full-Scale Six Story Steel Braced Frames at BRI

1 m actuator installed
1 m high resolution digital disp. transducer
steel tube brace
measuring at 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

Highways
Buildings

1995 Kobe

Construction of Large-Scale Experimental Facilities for Earthquake Engineering Research

E-Defense Ready in April, 2005
NEES Ready in October, 2004

Planning Meetings

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

MEXT-NEES, August 3, 2005
MEXT-NSF, Sept 13, 2005
A History of Planning Meetings

<table>
<thead>
<tr>
<th>Planning Meetings</th>
<th>First</th>
<th>April 6 to 8, 2004 at Kobe</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Second</td>
<td>July 12 to 13, 2004 at Washington DC</td>
</tr>
<tr>
<td></td>
<td>Third</td>
<td>January 17, 2005 at E-Defense</td>
</tr>
<tr>
<td></td>
<td>Fourth</td>
<td>August 2 to 3, 2005 at E-Defense</td>
</tr>
<tr>
<td></td>
<td>Fifth</td>
<td>September 27 to 29, 2006 at E-Defense</td>
</tr>
<tr>
<td></td>
<td>Sixth</td>
<td>September 28 to 30, 2007 at E-Defense</td>
</tr>
<tr>
<td></td>
<td>Seventh</td>
<td>September 18 to 19, 2009 at E-Defense</td>
</tr>
<tr>
<td></td>
<td>Eighth</td>
<td>September 17 and 18, 2010 at E-Defense</td>
</tr>
<tr>
<td></td>
<td>Ninth</td>
<td>August 26 and 27, 2011 at E-Defense</td>
</tr>
</tbody>
</table>
Appendix VI

Overviews on NEES/E-Defense Collaboration on Earthquake Engineering

Stephen Mahin

Overview on NEES/E-Defense Collaboration on Earthquake Engineering Research

Stephen Mahin
Director
Pacific Earthquake Engineering Research Center


Annual Research Planning Meetings
Proceedings
- White papers
- Plenary papers on past and possible future research
- Breakout session reports
- Resolutions
- Participant lists
- Agenda
- Planning Reports
- Detailed information on specimen designs

Concurrent Construction of Large-Scale Experimental Facilities for Earthquake Engineering Research in the US and Japan

10 Year Anniversary Approaching!

NEES Ready in October, 2004
E-Defense Ready in April, 2005

Phase I NEES/E-Defense Collaboration Major Themes

Steel Structures
Bridges

NEES/E-Defense Phase I: Bridge Program

E-Defense

Institute of Civil Engineering

Full-scale tests involving US and Japanese researchers

NEESR: Controlled Rocking Frame System

Lead by Greg Deierlein of Stanford Univ.

- Large-Scale Validations
- Real grounding for interactions
- FT, P&ID, and rocking details
- Proof of Concept
- Capacity and ductility
design criteria
- Performance Assessment
- Nonlinear computer simulations
- Life-cycle benefit cost analysis

Develop a new structural building system that employs self-containing rocking action and replaceable fuses to provide safe and cost-effective earthquake resistance.

*Key Concept – design for repair*

Phase 1: Steel Buildings

E-Defense Steel Collapse

Value-Added Structures (replacement details)

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. Electrical energy facilities
5. Simulation
6. Health monitoring
Appendix VI

Phase 2 – 2010-2014
Focus on Achieving Seismic Resilience of Communities
Six Thrust Areas
1. High Performance (RC) Structures
2. Seismic Generation, Isolation, and Control
3. Underground Structures
4. Advanced Steel Buildings
5. Simulation
6. Health monitoring

Phase 2 – High Performance Buildings + Isolation and Control
December 2010 - August 2013

Conventional and self-centering RC frame buildings

“New” unseen damage isolation

NEEStips project (Keri Ryan, UNR)

Triax Acceleration Test System

LNE with Line of Steelers: Steel Bar Members

NEEStips project (Keri Ryan, UNR)

Rapid tests:
- Nonstructural: Ceiling, partitions, cladding, fire sprinklers
- Staged office, hospital, and lab scenario

Collaboration key to advancement in Earthquake Engineering:
NEESE/SE Defence Planning Meetings

Many participants from Japan and the UK

Underground Structures and Geotechnical

T-Engineering Shaking Table Tests

E-Engineering Shaking Table 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 ensure safety against major structural failures and loss of life, not to limit damage or maintain functions

Geotechnical purpose: To ensure extreme events, 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.”

Engineered Effective in Reducing Loss of Life

Nonstructural Elements Also Pose Life Safety Concerns

Structures Should Not Be Considered Individually: Disaster vs Catastrophe

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

Non-Structural Damage - Sendai

Disasters → Catastrophes

Potential Loss of Work Caused by Natural Disasters

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

Potential Loss of Work Caused by Natural Disasters: Earthquake Only

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.

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

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.

Collapse Margin
Resistance
Deformation
Collapse

A delicate balance between safety and cost

(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.

Earthquake Response
Structural damage
Damage to lifelines
Damage to piles
Liquidation sensor

Engineering Research Need Associated with Resiliency

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
(1) Prediction of earthquake damage to metropolitan regions

Response
(III) Advancement of capacity for urban disaster responses

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

Research Objectives

Objectives of Research:
1. Quantification of collapse margin of urban buildings
2. Monitoring and condition assessment of buildings
3. Structural damage
4. Interactive SSI system
5. Monitoring and response evaluation of SSI
6. Seisso-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

<table>
<thead>
<tr>
<th>Year</th>
<th>2017</th>
<th>2018</th>
<th>2019</th>
<th>2021</th>
<th>2025</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Earthquake</td>
<td>Foundation</td>
<td>Design</td>
<td>Evaluation</td>
<td>Simulation</td>
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<tr>
<td>2.</td>
<td>Earthquake</td>
<td>Preparation</td>
<td>Design</td>
<td>Evaluation</td>
<td>Simulation</td>
</tr>
<tr>
<td>3.</td>
<td>Foundation Testing</td>
<td>Preparation</td>
<td>Design</td>
<td>Evaluation</td>
<td>Simulation</td>
</tr>
<tr>
<td>4.</td>
<td>Foundation Testing</td>
<td>Preparation</td>
<td>Design</td>
<td>Evaluation</td>
<td>Simulation</td>
</tr>
<tr>
<td>5.</td>
<td>Earthquake</td>
<td>Foundation</td>
<td>Design</td>
<td>Evaluation</td>
<td>Simulation</td>
</tr>
</tbody>
</table>

Research Team

Oversight Committee
- Presidents: M. Nakashima, Ph.D.
- O. Ogi, Professor, NED
- K. Kojima, President, NED
- K. Kojima, Vice-President
- Kobe Institute
  - M. Koizumi, Secretary

Research Team

<table>
<thead>
<tr>
<th>Team</th>
<th>Members</th>
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</thead>
<tbody>
<tr>
<td>1.</td>
<td>Steel collapse</td>
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<tr>
<td>2.</td>
<td>RC collapse</td>
</tr>
<tr>
<td>3.</td>
<td>Monitoring superstructure</td>
</tr>
<tr>
<td>4.</td>
<td>Monitoring soil-foundation</td>
</tr>
<tr>
<td>5.</td>
<td>Monitoring NBI system</td>
</tr>
</tbody>
</table>

### 1. Collapse Margin of Steel High-Rise Buildings

**Background:**
Higher performance has been considered in the design and construction of high-rises 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

**Planned shaking table test Kobe**

### 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 excitation**

### 3. 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**

**Damage Assessment System**
Appendix VI

4.2 Monitoring – Soil and Foundation

Background:
Prompt condition assessment for soils, foundations, and underground facilities 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.

4.3 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.

4.4 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.

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
- Beam Fracture
- Column Failure
- PD-Effect

Damage Levels:
- Input: [medium] [large] [extreme]
- Damage: 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)

Monitoring and Condition Assessment
(Planned on December 2013)

- Level 1 System: 28 servo-type accelerometers, 200Hz Sampling
- Level 2 System: 152 MEMS sensors (912 components), 500Hz Sampling

Synthesized Ground Motion Selected for Test

- Considered – Three simultaneous ruptures of "Nankai Trough" Huge Event, with location at Nagoya Areas

Synthesized Ground Motion

- Maximum Level: 180 cm/s
- Medium Level: 10 cm/s

Synthesized Acceleration History

- Amplification of Original History:
  - Average (110 cm/s) baseline
  - Large (180 cm/s) 1.64 times
  - Very Large I (220 cm/s) 2 times
  - Very Large II (250 cm/s) 2.27 times
  - Very Large III (300 cm/s) 2.73 times
  - Very Large IV (340 cm/s) 3.1 times (at the table capacity)
- Contracted to $1/\sqrt{3}$ with respect to time domain
### Appendix VI

<table>
<thead>
<tr>
<th>定義</th>
<th>印象値</th>
<th>落下速度</th>
<th>落下実測</th>
</tr>
</thead>
<tbody>
<tr>
<td>12/9</td>
<td>10%</td>
<td>50cm/s</td>
<td>35cm/s</td>
</tr>
<tr>
<td>12/10</td>
<td>10%</td>
<td>70cm/s</td>
<td>45cm/s</td>
</tr>
<tr>
<td>12/11</td>
<td>10%</td>
<td>90cm/s</td>
<td>60cm/s</td>
</tr>
</tbody>
</table>

* 印象値算出モデルでの入力値を想定レベル
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 19th NIED/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, Kawamoto, 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 follows:

- 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.

Anticipated Nankai Trough earthquakes (after the 2011 Great Disaster)

After the disaster, a working group of the Central Disaster Management Council revisited 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 8.1.

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.
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.

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.

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 on safety assessment of base isolators against long-period, long-duration earthquakes.
- 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 quantification of margin of high-rise-structure failure.

<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.

MEXT and NIED installed additional facilities for E-Defense upgrade 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 the table possible to simulate 2011 earthquake recordings and future scenarios.

<table>
<thead>
<tr>
<th>Scenario (kN)</th>
<th>Maximum acceleration ($g = 9.81m/s^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Horizontal direction ($x, y$)</td>
</tr>
<tr>
<td></td>
<td>Number of inactive actuators</td>
</tr>
<tr>
<td>0</td>
<td>1.7</td>
</tr>
<tr>
<td>600</td>
<td>1.2</td>
</tr>
<tr>
<td>1,200</td>
<td>0.9</td>
</tr>
</tbody>
</table>

A unit of number in the table is gravitational acceleration, $1G = 9.81m/s^2$. 
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.

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.

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.
Appendix VI

Recent E-Defense shake-table tests

This shows the model of the analysis:

![Diagram of specimen](image)

The specimen is simplified as below:

![Graphs showing deformation and force](image)

Time history and loops of each story:
- 40% scaled JR Takata Station Record
- 60% scaled JR Takata Station Record
- 80% scaled JR Takata Station Record

According to the graphs, for instance, it's difficult to obtain stiffness change in the time history.
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.

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

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.
Appendix VI

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 tests 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

NEES/E-Defense Planning Meeting
Introduction to U.S. Researcher Anna Birey
Anna Birey
Assistant Professor
Texas A&M University

Overview
- Experimental tests
- Fragility functions
- ASCE 41 evaluation of buildings damaged in 2010 Maule earthquake
- Current
  - Wall, buildings/Coupled walls
  - Framework for reporting damage in RC structures
  - Fire resistance of RC structures

Slender Wall Tests
- NEESR Complex Wall project
  - UW-UIC-UCLA
- 4-planar wall tests
  - Test walls representative of modern U.S. construction
  - Collect high-resolution data
  - Develop tools for performance-based design of walls

ASCE 41 Evaluation of Damaged Buildings
- Objectives:
  - Study buildings damaged in Chile 2010 earthquake
  - Identify lessons applicable to U.S. codes and standards
- ASCE 41 3-Tiered Evaluations
  - Recommendations for modifications to "quick checks"
  - Evaluation of nonlinear analysis acceptance criteria & comparison to final damage states

ASCE 41 Nonlinear Model Evaluation
- Does ASCE 41 identify damaged components as potentially deficient?
- Models
  - OpenSees
    - Force-based beam column elements w/ realistic material properties
  - Perform3D
    - Fixed based
    - Soil-structure interaction (SSI)
- Summary: number of walls exhibiting each performance state:
  - Colors indicate if observed damage was more severe, less severe or constant w/ predicted performance
  - Results: results provided by Tony Antunes (CIVIL)

Updating ASCE 41 - Flexure Controlled Wall Acceptance Criteria
- Objective: Update modeling parameters and acceptance criteria for flexure-controlled walls
- Approach:
  - Analytical parameter study using validated numerical models
  - Limited experimental data
### Appendix VII

#### Walled Buildings/Coupled Walls
- Emphasis on reuse of experimental and numerical data
- OpenSees vs Perform3D
- Axial demand
- Coupled wall fragility functions
- Walls with discontinuities (i.e. tag-shaped walls)

#### Damage Preservation
- Damage descriptions typically qualitative and inconsistent between projects
- Need to improve reporting/archival of damage to RC tests
- Developing framework for documenting & archiving data using BIM

---

#### Damage Preservation

**Why BIM?**
1. 3D visualization
2. Easily read by computer code (IFC)
3. Associate damage w/ component characteristics & measured response
4. Progression of damage
5. Preservation

**Ongoing/Future**
- Software plugins
- Data processing scripts
- EOT = TAMU BIM Cave
**Performance-Based Engineering of Earthquake Resilient Communities**

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

NEES – E-Defense Planning Meeting  
DPR October 12-12, 2013

**Benchmarking Building Code Performance**

- Office occupancy  
- Los Angeles Basin  
- Design Code: 2003 IBC / 2002 ACI / ASCE7-02  
- Maximum considered (E) demand:  
  - $S_s = 1.5g$  
  - $S_s = 0.9g$  
  - $S_{E,ED,5yr}$ = 0.82g  
- Design V/W of 0.094  
- Maximum inelastic design drift of 1.9% (2% limit)

**Characterization of Ground Motion Hazard**

- Significance of GM duration in design and assessment?

**Collapse Capacity of Structure with Moderate Degradation**

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

**BENCHMARKING BUILDING CODE PERFORMANCE**

Calculated Collapse Safety

- 5% Probability of collapse under “Maximum Considered Earthquake”
- MAT = 1.0 x 10^4 collapse/yr
- OR
- 0.5% Probability in 50 years

**Modeling of Structural Components: RC plastic rotation**

Example: Calibration of Capping Rotation of RC Beam-Columns

Median: $\theta_c = 0.12(1 + 0.55\alpha_e)(0.16(0.02 + 40\alpha_e)^{0.6}(0.54)^{(0.05)})(2.27)^{0.5(\alpha_e)}$

Key Design/Detailing Variables:

- $c_m$ – amount of steel stirrups
- $c_n$ – axial load ratio (N/4f’c)
- $\alpha_e$ – joint bond slip
- $b_e$ – bond length

[Ref: [ACI 318-14]]
Appendix VII

Resilience – emphasis on functionality

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, RED): Direct damage and repair costs
- Demolition/deconstruction
- Occupancy & Functionality

Structural Enhancements:
- Damped outrigger
- Seismic isolated

Building System Enhancements:
- Drift resistant façade and partitions
- Enhanced elevators and stairs

Performance Summary (DBE Level Shaking)

<table>
<thead>
<tr>
<th>Direct Losses (Repairs)</th>
<th>Standard Design (vs. building value)</th>
<th>Resilient Design (vs. building value)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fixed-Base</td>
<td>15.2%</td>
<td>5.8%</td>
</tr>
<tr>
<td>Outrigger</td>
<td>13.4%</td>
<td>3.8%</td>
</tr>
<tr>
<td>Base-Isolated</td>
<td>14.4%</td>
<td>4.6%</td>
</tr>
</tbody>
</table>

Repair and Restoration Durations

<table>
<thead>
<tr>
<th>Repair Times (Weeks)</th>
<th>Total Time* to Restore Functionality (Weeks)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard Design</td>
<td>Resilient Design Standard Design Resilient Design</td>
</tr>
<tr>
<td>Fixed-Base</td>
<td>60</td>
</tr>
<tr>
<td>Outrigger</td>
<td>47</td>
</tr>
<tr>
<td>Base-Isolated</td>
<td>59</td>
</tr>
</tbody>
</table>

*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

Earthquake Resilient Cities (future)

Simulated Earthquake Scenarios

- SCAL 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

Archetype Building Performance
- Performance assessment
- Geotechnical inputs
- Displaced residues
- Regional interaction

Building Database

Regional Impact
- Building damage &
- Displaced displaced residents
- Resilience assessment

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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:
Wasim Ghanim, University of Texas at Austin

Participants:
Anita Arbird, Texas A&M
Gregory Crouse, Boston University
Marc Delrobert, University of Michigan, Ann Arbor
Kenneth Eldredge, University of British Columbia, Vancouver
John Ramstake, Brookhaven National Laboratory
Andrew Starfield, Ohio State University
John Wallace, University of Colorado Boulder

Research Interests
1. RC column limit-states
   1. Databases
2. ACI 369/ASCE 41: seismic and critical columns limit states
3. High strength steel
4. Loading rate effects
5. Analysis
   1. RC column analytical models
2. System level analysis - E Defense test 2010
3. CFFT repair and retrofit of RC members
4. Digital Image Correlation (DIC) support for research

1.1 Database of RC Column Tests
- Developed an interactive database developed by Berry and Herland
- Currently contains over 500 tests
- Part of effort to replace ACI 318 for RC columns by ACI committee 318

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
- New shear walls (shear)
- Columns (sharpen, Matsumoto)
- Joints (Korea, Korea)
- Slab-column interaction (Sang)
- Acceptance criteria (sharpen, Ishiwak, Akihiko, others)

1.3 High-Strength Steel
- Investigating behavior of HSS in RC columns: focus on shear
- Currently testing two columns, Grade 80 (690 MPa) and Grade 100 (900 MPa)
- Behavior under high shear stresses
- Axial load < 25% of gross

- Columns showed comparable behavior
- Future tests with Grade 100 (690 MPa), high strength concrete, and various loading protocols

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1.4 Loading-Rate Effects

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

- Future tests planned considering various column detailing and loading protocols

2.1 RC Column Analytical Model

- Expanding calibration to full database

2.2 System Analysis

- See figure 3: observed behavior of the 2009 earthquake

<table>
<thead>
<tr>
<th>Material type</th>
<th>M10.5</th>
<th>M12.2</th>
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</thead>
<tbody>
<tr>
<td>Model</td>
<td>Exp</td>
<td>Exp</td>
</tr>
<tr>
<td>M10.5</td>
<td>0.40</td>
<td>0.40</td>
</tr>
<tr>
<td>M12.2</td>
<td>0.50</td>
<td>0.52</td>
</tr>
<tr>
<td>M12.4</td>
<td>0.60</td>
<td>0.62</td>
</tr>
<tr>
<td>M12.5</td>
<td>0.60</td>
<td>0.67</td>
</tr>
</tbody>
</table>

3. CFRP Retrofit

- See Figure 4: strengthening of bridge sections using anchored CFRP

4. DIC Surface Strain Measurements

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

My Research History

Name: Hideo Katsumata
Affiliation: Obayashi Corporation

Topics:
1) Evaluation and Retrofit of Existing RC Building
2) Vibration Control & Shaking Table Test

Retrofit (1): Carbon Fiber Jacketing
1985-2000

- Column in Building
- Chimney
- Bridge Column

Many Applications

Retrofit (2): Carbon Fiber Jacketing

Unretrofitted

Retrofitted

Load (kN)

Displacement (mm)

Good Behavior

Evaluation (1): Deformation Capacity of Retrofitted Column
1996-2000

Prediction is Fairly Good for Retrofitted Columns

Evaluation (2): Deformation Capacity of As-Built Column
1998-2001

Lower Bound is Found for As-Built Columns

Chaired by Kebayazawa Sensei

Shaking Table Test (1)
At Obayashi Institute
1999-

Test of Real Scale House

Large Capacity
High Accuracy
Appendix VII

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

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

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 Kabayama Senori
- Partially Funded by Dei-Osato Project of MEXT

Shaking Table Test (6): 20 Story Building
1/4 Scaled Model 2010-2012
- @E-Defense
- Shaking Test of High Rise RC Building
- Cooperative Research with IIT and 6 Companies (Ohashi, Kajima, Shimizu, Taisei, Takenaka, Kobon)
- Funded by MEXT

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

Self Introduction

- Koichi Kusunoki
  - Associate Professor
  - Institute of Urban Innovation
  - Graduate School of Yokohama National University

Effect of non-structural walls

Experimental Test Database

- Experimental data from published papers.
- Structural members
  - Beams
  - Columns
  - Walls
  - Beam-Column Joints
  - Beam with walls
  - Column with walls

Structural Health Monitoring

- Performance and demand curves are measured
  - Place few cheap accelerometers
  - Derive displacement from measured acceleration
  - Evaluate by comparing these curves
Appendix VII

E-Defense Test
WG-2-3

Soil-Structure interaction

Response Spectra

Large accelerations W slight damages

- Large PGAs were measured.
- However, most of them did not cause severe damages to buildings.
- Why.....?
- It is difficult to find a reason BECAUSE building response was not measured.

Large accelerations W slight damages

- Accelerometers are usually placed on free fields.
- If building exists, soil-structure interaction is NOT negligible.
- However, no previous shaking table tests had soil layers and R/C structure.
- This is the first trial to reproduce the behavior of both soil and structure.
Appendix VII

Demand curves

E-defense Test (Y2016)

E-defense Test (Y2016)

200% of design artificial input wave
Appendix VII

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

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

Damage investigation of RC buildings

Civil Engineering Building of Tohoku Univ.

Response estimation by capacity spectrum method

Post-earthquake damage evaluation

Guideline for Post-EQ Damage Assessment and Rehabilitation revised in 2001 and 2014.
- Residual seismic capacity ratio, $R$
  - Post-EQ Seismic Capacity (%)
  - Original Capacity
  - Seismic code, Standard for Seismic Evaluation
- Residual Capacity $\rightarrow$ HOW?
- Reduction factor $\eta$
  - damage class I - V

1978 Miyagi-ki
2011 Great East Japan
1978 : better agreement than 2011
2011 : big difference between actual and estimated response

Severe damage
Experience large earthquake
Retrofitted $\rightarrow$ severe damage
Strong motion was observed over 40 years
Appendix VII

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.

Re-evaluation of Limit state

Safety index

Repairability index

Damage in structural members
- Residual strength and deformability
- Indications to collapse

Damage in non-structural elements
- Cost, duration, difficulty for repair, influence on function

Safety index

Repairability index
Appendix VII

Self-Introduction

Building Research Institute
Structural Research Group
Senior Research Engineer
Tomohisa MUKAI

Research Interests

Modeling of RC members (Beam & Column)
Performance Based Seismic Design
Seismic Retrofit to limit the damage of RC buildings

Research Interest 01
Modeling of RC members
Degradation of Backbone Curve (FS, S) &
of Hysteresis Loop (F, FS)
1. Seismic evaluation method for RC building with
   stiffness/strength degradation considering the evaluation
   accuracy of backbone curve for member
   -> collected the test data for frame with brittle column
2. Hysteresis model for RC beam under cyclic loadings

Research Interest 02
Performance Based Seismic Design
Performance based seismic design system
considering loss due to damage
1. Assessment of damage, repair costs,
   -> collecting the data for members
   -> Development of New guideline for Building Old with Post-EQ Functionality (BRJ's new
   2. Prediction of maximum response RC
   on energy balance considering cyclic behavior
   building under EQ

Research Interest 03
Seismic Retrofit to limit the damage of RC buildings
Seismic Retrofit Technique to limit the damage using
Ultra strength Fiber Concrete (UFC)
1. Effect of seismic retrofit for RC building with UFC
   -> Verified the effect by experimental test for members
   -> Verify the effect of seismic retrofit for building by
dynamic analysis in BRJ’s new research PI

Test Result
Seismic Retrofit with PCAUFC Shear wall with many small openings

The ultimate response is almost same
RC shear wall with small openings

Test Result
Effect of Seismic Retrofit with PCAUFC Wingwall

RC wing wall
Shear Failure

UFC wing wall
Sign damage

International Activity 01

USC Campus
CE Laboratory 1
CE Laboratory 2

Prof. Kenneth Elnash
ACI Fall Convention (2011)
Asst. Prof. Tony Yang
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

International Activity02
(Apr.2013-)

W114
Earthquake Engineering and Buildings
Current Main task:
Research Roadmap for Earthquake Engineering

Exchange of collaborative research topic

\[ \Delta(hv < DF) = \sum G(hv) \text{d}h v \sum \text{d}e p \sum \text{d}e p \sum \text{d}e p \]
Appendix VII

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

Pre-tensioned beam with fiber-reinforced concrete

<table>
<thead>
<tr>
<th>Specimen</th>
<th>$f_{y}/[N/mm^2]$</th>
<th>$f_c/[N/mm^2]$</th>
<th>Shear strength (N/mm²)</th>
<th>Resistance strength (N/mm²)</th>
<th>Shear strain rate [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>PC8</td>
<td>60</td>
<td>413</td>
<td>533.8</td>
<td>600.8</td>
<td>1.23</td>
</tr>
<tr>
<td>PS9</td>
<td>6.5</td>
<td>413</td>
<td>553.1</td>
<td>630.6</td>
<td>1.25</td>
</tr>
<tr>
<td>P10</td>
<td>1.0</td>
<td>380</td>
<td>508.8</td>
<td>604.0</td>
<td>1.20</td>
</tr>
</tbody>
</table>

- V: Volume fraction of fibers
- N: Effective prestressing force
- Q: $Q/V_0$

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.

- Subassemblies and frames: a new testing method has been developed using a furnace for beams and columns.

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.

- Subassemblies and frames: a new testing method has been developed using a furnace for beams and columns.

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 subassemblies subjected to vertical loading
  - Development of testing method

Development of testing methods for beam-column subassemblies

Another testing method

- After load was applied
  - Bond deterioration determined by long-term shear strength in concrete
  - Bond deterioration
  - Bond deterioration capacity will be investigated within a few months.
Appendix VII

Construction Technology of Building Structures

- Fire resistance of reinforced concrete frame considering bond deterioration and crack width
  - Interplay between materials and cracks in concrete
  - Cracks in concrete, which induce higher temperatures in concrete
  - Fire resistance tests on concrete beams: heated from compressive and tensile fibers of concrete
  - Tests show crack width and temperature development in beams
  - Rectification should be clarified for estimation of deformation
- Feed back and feed-forward among research on materials, members, frames, and structures are of great importance.

Low-cycle fatigue tests on fiber-reinforced concrete

Test results

Regression analysis results of stress level-logN relationship
Appendix VII

Self-Introduction

Yasushi SANADA
Associate Professor
OSAKA University

Academic & Professional Career

-2001 PhD in the Univ. of Tokyo
  *Performance evaluation of R/C buildings

2001-2006 Research Assoc. (Assist. Prof.)
  in the Univ. of Tokyo

2006-2012 Assoc. Prof. Toyohashi Univ. of Tech.

2012-present Assoc. Prof. Osaka University

Academic & Professional Career

Shaking Table Testing of
Large Scale R/C Buildings

Academic & Professional Career

-2001 PhD in the Univ. of Tokyo
  *Performance evaluation of R/C buildings

2001-2006 Research Assoc. (Assist. Prof.)
  in the Univ. of Tokyo
  *Post-earthquake field investigations

2006-2012 Assoc. Prof. Toyohashi Univ. of Tech.

2012-present Assoc. Prof. Osaka University

Academic & Professional Career

Career of Post-EQ Field Investigation

2003 Barn, Iran EQ
2004 Niigata, Japan EQ
2005 Kashmir, Pakistan EQ
2006 Central Java, Indonesia EQ
2007 South Sumatra, Indonesia
2008 West Java, Indonesia EQ
2009 West Sumatra, Indonesia
2011 Christchurch, New Zealand
2011 Tohoku, Japan EQ
2013 Bohol, Philippines EQ

Academic & Professional Career

-2001 PhD in the Univ. of Tokyo
  *Performance evaluation of R/C buildings

2001-2006 Research Assoc. (Assist. Prof.)
  in the Univ. of Tokyo
  *Post-earthquake field investigations

2006-2012 Assoc. Prof. Toyohashi Univ. of Tech.
  *Performance evaluation of masonry buildings

2012-present Assoc. Prof. Osaka University
Recent Researches

- Non-str. wall-RC frame interaction
- Upgrading of substandard RC beam-columns
- Performance evaluation of substandard RC wall
- Numerical modeling of masonry infilled frames
Appendix VII

Hitoshi Shiohara

Research Interests:
1. Modeling of multi-storey frame structures with poorly designed beam-column joint for collapse simulation
2. Collapse potential evaluation by the combination of main shocks and aftershocks
3. Evaluating collapse and bidirectional interaction subject to 3D base excitation
4. Modeling for progressive chain collapse of complex structural systems
5. Development of redundent connecting system sustaining long term load for existing RC structural renovation
6. Rotational excitation by propagation of surface wave caused by a megaquake

Calibration of macro element: Test and Calculation

Macro element for beam-column joint

Collapse simulation of four story RC frame structure

Incremental Dynamic Analysis (IDA)

References:

2012

Kazushiro Shiohara

Kazushiro Shiohara
Appendix VII

Thank you

Long Term Collaboration
Seismic Evaluation for Extremely Large Earthquake event

Hitoshi Shiohara
Professor, Dr. of Engineering, FACI
Department of Architecture and Engineering
Graduate School of Engineering
The University of Tokyo
hshiohara@arch.t.u-tokyo.ac.jp

Research Interests:
1. Modeling of multi-story frame structures with poorly designed lower-column joints 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 PC structural innovation
6. Progressive collapse by propagation of surface wave caused by a mega quake
Appendix VII

**RC Building Collapse**

Loss of Life = No spaces between floors

**E-Defense test on RC Building in December 2010**

E-Defense 3D Shaking Table
Four-Storey Wall Frame
RC Structure
Design conformed to Japanese & US seismic code requirements

**Column-to-beam strength ratio**

<table>
<thead>
<tr>
<th>Lateral load direction</th>
<th>1.00</th>
<th>0.70</th>
<th>0.50</th>
<th>0.30</th>
<th>0.10</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
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<tr>
<td>0.30</td>
<td>0.99</td>
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<td>0.99</td>
<td>0.99</td>
<td>0.99</td>
<td>0.99</td>
</tr>
</tbody>
</table>

Column-to-beam strength ratios

**2D Macro element for beam-column joint**

Fish bone model

Kim Kachiha Shakes (2012)

Steel
Concrete
Bond
Appendix VII

Calibration of 2D Macro element: Test and Calculation

Test results of a beam-column joint

3D Macro element for beam-column joint

References:
Kim Koschny. (2014)
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 buildings
- Identify collapse scenarios on various structural systems including gravity effects
- Design Issue

Common Objective
Technology transfer: transferring knowledge of collapse performance to stakeholders

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 Objective:
Post-earthquake decision assistance: evaluation aftershock collapse vulnerability for long-term maintenance 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
Appendix VII

NEES / E-Defense Workshop
Kyoto, Japan
econ er 11-13, 2013

Lesley Sneed, h., Assistant Professor of Civil Engineering
Missouri University of Science and Technology
Missouri S T

Research Interests:
- Reinforced and prestressed concrete structural members and systems
- Structural models and experimental methods
- Innovative methods to repair and strengthen existing structures
- Evaluation of existing structures, codes and construction specifications for structural concrete

Repair of Severely Damaged Bridge Columns Under Combined Loading
- 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

Rapid Repair of Severely Damaged Bridge Columns Under Combined Loading
- Rapid Repair Procedure
- Investigation of Repaired Column Structural Performance

Repair Schemes
- (a) Flexure Dominant Column Repair
- (b) Torsion Dominant Column Repair

Modeling the Response of Repaired, Severely Damaged RC Columns
- The steel properties are modified to account for column softening due to earthquake damage
- The confining concrete
- Cracked concrete in the unrepaired region
Appendix VII

Background: Structural System

1. Concrete structures
2. Non-ductile infilled frames
3. Bond-slip and development length of large-diameter bars (d_b up to 57 mm)
4. Masonry structures
5. Reinforced shear walls
6. 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-displacement curve with simple calculations.

Provides guidelines to estimate:
1. Stiffness
   \[ V_s = \frac{2}{\sqrt{3}} \sqrt{E} \]
2. Max Base Shear
   \[ V_{base} = 0.5 \sqrt{E} \]
3. "Yield" Point
4. Residual strength

\[ \delta_{y} = 1.2 \delta_{max} \]
Appendix VII

Infilled RC Frames: Assessment of Damage

- Use damage identification techniques
- Data reduction
- System identification
- Model updating
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)
Appendix VII

OBE Wall Tests: "Prisms"

- Testing Configuration:

SBE Wall Panel Tests (NEESR)

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

12 Total Tests

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<tr>
<th>ID</th>
<th>εc</th>
<th>Cc</th>
<th>A/Ac</th>
<th>εc (Deg)</th>
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<td>0.30</td>
<td>12</td>
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SBE Prism Tests (NEESR)

- Cross-section dimensions
- Amount of transverse reinforcement fully
- Geometric configuration
- Distance between tied long, other:

SBE Prism Tests (NEESR)

- Force-straining relations

Jack Moehle
UC Berkeley
APPENDIX VIII: PRESENTED PAPERS IN STEEL WORKING GROUP

NEES/E-Defense 10th planning meeting – December 10-13, 2013

Evaluating resilience in a multi-hazard context

Marc E. Moreya Gariock
Negar Esham Khorasani
Princeton University

Paolo Gandolfi
University of Illinois at Urbana Champaign

OUTLINE

1. BACKGROUND
2. FRAMEWORK
3. CURRENT STUDY
4. NEEDS/CHALLENGES

1. BACKGROUND
2. FRAMEWORK
3. CURRENT STUDY
4. NEEDS/CHALLENGES

Why multi-hazard?
- Resilience — consideration of single and multi-hazard events

Why measure?
- Uncertainty in demand and resistance — probabilistic framework

Approach
- Identify uncertainties — random variables
- Quantify uncertainties — establish relationships between variables
- Integrate uncertainties — modeling of events and outcomes
- Performance assessment — outcomes vs. acceptable risk

Objective
- Develop a methodology, based on probabilistic principles, for measuring resilience (applied to single and multi-hazard).
- Context: fire and earthquake.

// Quantify the uncertainties in the "demand": Ground Motion
- M, R, a sets (USGS, OpenSHA)
Appendix VIII

// Quantify the uncertainties in the “demand”: Fire

- Survey results for fire loads in office

  Surveys show:
  - Large range in the data.
  - Room use is important.
  - Floor area has an effect.

// Quantify the uncertainties in the “demand”: Fire

- Developed probabilistic models for fuel load

  \[ q_{corrected} = \exp(0.95 - 0.05A + 0.57) \]

// Quantify the uncertainties in the “resistance”: material

- Probabilistic model for high temperature properties of steel

  \[ k_{T_{corrected}} = \exp[\ln(k_{T}) - 0.0421 + 0.1464 \times d] \]

// Quantify the uncertainties in the “resistance”: material

- Probabilistic model for high temperature properties of steel

  \[ k_{T'_{corrected}} = 1.08 \times \frac{e^{(2.09 - 3.2 \times 10^{-7}T + 3.2 \times 10^{-14}T^2 + 0.3176x)}}{e^{(2.85 - 3.2 \times 10^{-7}T + 3.2 \times 10^{-14}T^2 + 0.3176x)} + 1} \]

// Component reliability

- Calculate CDF of time to failure (for cases failed)

  Random variables: \( T, F, E \)

  Calculate probability of failure

// System reliability

- Random fire location on the damaged billet

  Failure time of local elements

  Probability of collapse

  Failure modes of failure:
  - Elements reach limit state
  - Instability due to large deflections

  Random variables: \( T, F, E \)
Appendix VIII

1. Computational platform
- Seamless multi-hazard simulation
- Model various uncertainties (Monte-Carlo Simulations - MCS)
- Efficient
- Numerically stable
- Accurate
- Robust algorithms that converge to correct solution.
  - Algorithm may stop converging after local failure and therefore not reach global failure

2. Data collection and assessment
- Statistics for random variables
- Probability models
- Sequential event probability assessment

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.
Current Research on the Collapse Assessment of Steel Frame Buildings Subjected to Extreme Earthquakes Beyond the Design Level

Topics to Be Discussed
- Collapse Assessment of Steel Moment Resisting Frames
- Modeling of Cyclic Deterioration in Steel Columns
- Collapse Protocols for Experimental Testing of Steel Columns
- Current Experimental Studies for Collapse Qualification of Steel Columns
- Other “Collapse” Related Issues for MRFs

Collapse Assessment of Steel SMFs - Definition of Collapse Under Investigation
A story or a number of stories displaces sufficiently and P-Delta effects actuated by strength and stiffness deterioration make the first order shear resistance of a steel SMF zero.

Previous Research on Collapse Assessment of MRFs
NEES Collapse Project
Structural Component Database for Modeling Cyclic Deterioration of Steel Bases

Previous Research on Collapse Assessment of MRFs
Utilization of small and full scale collapse tests of low-rise steel buildings for validation of collapse simulation through nonlinear response history analysis

Axial Load Variation of Exterior Columns as Part of MRFs
- Based on nonlinear response history analysis from a wide range of steel MRFs designed in the US and Japan (Ligges et al. 2010, Elshafi and Ligges 2010, Imura and Suzuki 2007)
- P-M interaction and modeling of cyclic deterioration in strength and stiffness of a steel column becomes critical
Appendix VIII

Some of the Available Frame Analysis Models for Collapse Simulation

<table>
<thead>
<tr>
<th>Developed by</th>
<th>Cycle</th>
<th>Base</th>
<th>Stem</th>
<th>Load</th>
<th>Dead</th>
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<td>Boc et al. (2005)</td>
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<tr>
<td>Cao et al. (2011)</td>
<td>Yes</td>
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</table>

Szelke and Lignos (2015)

New Hysteretic Models for Modeling Cyclic Deterioration in Strength and Stiffness of Steel Columns Subjected to Cyclic Loading

- Implementation in C++ has just been completed (Simulation Platform)
- Verification with test data conducted by Miniau et al. (2012)

The Issue of Loading Protocol for Experimental Testing of Steel Columns

A structure deforms asymmetrically with large monotonic pushes and a few small inelastic cycles prior to collapse* (i.e., ratcheting).

The Issue of Loading Protocol for Experimental Testing of Steel Columns

Hysteretic behavior of steel beams*

(a) From symmetric-cyclic protocol

(b) From shake table test through collapse

How should we test structural components for reliable calibration of deterioration models?

Example: Developed Collapse Protocols for 12- and 4-Story MRFs*

1st Story Columns of a 12-story MRF

2nd Story Columns of a 4-story MRF

Use of Collapse Protocols to Assess Column Behavior at Large Deformations

Base Column Local Building

1st story collapse mechanism
Appendix VIII

Full-Scale Experimental Testing of Steel Columns at Large Deformations (currently under way)

Typical W-Shape Column (6 in total)
US Design

Typical HPS Column (6 in total)
Japanese Design

Test Setup for Full-Scale Testing of Steel Columns at Large Deformations
-Jamieson Structures Laboratory, McGill University

1200ton fatigue rated pins

Few Other “Collapse” Related Issues

-The Effect of the Composite Action on the Cyclic Deterioration of Beam-To-Column Connections


-Collapse Assessment of Steel Braced Frames (Modeling Damping & Fracture Due to Low-Cycle Fatigue)


Thank you for your Attention!
Appendix VIII

Self-Centering Steel Frame Systems

James Ricles, Richard Sause, Ying-Cheng Lin, Choung-Yeol Seo, David Roxie, Brent Chancellor, Ebrahim Tahmassebi and Omid Ahmadi
Lehigh University
Judy Liu and Hoseok Chi
Purdue University
Maria Garlock, Erik VanMarcke, Gordana Herning, and Jie Li
Princeton 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 ~90yr return period.
  - “Collapse Prevention” (CP) for the “Maximum Considered Earthquake” (MCE) with ~3000yr 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)

- 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)

Ricles, Sause, Garlock, Zhao (2001) ASCE Journal of Structural Engineering
Ricles, Garlock, Sause, Lu. (1997) SSRC Annual Meeting Proceedings

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

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

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

Steel SC moment resisting frame (MRF) subassembly at 3% rad drift.
Little damage with potential for Immediate Occupancy (IO) under DBE.
Appendix VIII

NEESR-S SC Steel Frame Systems Research on SC-MRF Systems

- De elo eam-col mn connection an energy dissipation details for SC-MRFs
- Rees interaction et een floor system an SC-MRF (Princeton P r e e l g)
- De elo SC col mn-ase connection for SC-MRFs (P r e e)
- F r te e elo erformance-ase ro e liastic seismic esign roce (Princeton e l g)
- Design an erformance nonlinear analyses of SC-MRF rotary e ilings (Princeton P r e e)
- Conct large-scale y ti earake simlations on SC-MRF sing NEEs facility (e l g)

SC-MRF systems M-8 behavior using Web Friction Device (WFD) - Lehigh

\[ M_{\text{fric}} = T \cdot \Delta_0 + F \cdot \Delta \]

Fle l e Collector eam Conect (Princeton)

- SC-MRF Partial Elevation
- Floor System Partial Plan
- Slab Composite with Beams
- Collector Beams
- Slab Non-Composite with Beams

- Details and analytical studies completed – see Garlock et al. (2009), “Floor deck design of steel self-centering moment frames,” Proceedings, STESSA 2009

Rigj Collector ay Conect (Princeton)

- 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

- Design studies completed Used in large-scale SC-MRF tests

SC Column-Base Connection for SC-MRFs (Purdue)

- Developed connection concept and details
- Performed 5 tests on 3 large-scale specimens
- Performed analytical studies of SC-MRFs with SC column base connections
Appendix VIII

- **DBE-4 Simulation Results**
- **Large-Scale Hybrid Simulations on SC-MRF**
  - DBE-3 Floor Displacements and Story Drifts
  - Experimental Response
    - No damage in beams and columns, except for yielding at column base.
    - No residual drift, self-centering

- **SC Damage-Free Steel Frame Systems**
  - Project: SC-CBFs

- **NEESR-S: SC Steel Frame Systems**
  - Research on SC-CBF Systems (Lehigh)
    - Develop SC-CBF concept and configurations.
    - Develop performance-based probabilistic seismic design procedure for SC-CBFs.
    - Develop connection and energy dissipation details for SC-CBFs (not discussed here).
    - Conduct large-scale laboratory hybrid earthquake simulations on SC-CBF using NEES facility.

- **Behavior of SC-CBF Configurations Studied by Numerical Simulations**
  - Gravity column (does not uplift)
  - SC-CBF column (uplifts as frame rocks)
  - Energy dissipation through relative motion between uplifting SC-CBF column and gravity column

- **Probabilistic Performance-Based Seismic Design of SC-CBFs**
  - Performance Objectives:
    - Damage free with potential for Immediate Occupancy (IO) under Design Basis Earthquake (DBE) with ~500yr return period.
    - Prevent significant yielding limit states.
    - Collapse Prevention (CP) under the Maximum Considered Earthquake (MCE) with ~2500yr return period.
    - Prevent member failure (buckling and subsequent fracture).
Appendix VIII

Large-Scale Hybrid Simulations on SC-CBF
- Based on prototype 4-story office building on stiff soil site in California at 0.8 scale
  - Tributary Gravity Frames, Seismic Mass, and inherent Damping as analytical Substructure
  - Single SC-CBF with Adjacent Gravity Columns as Experimental Substructure

SC-CBF Experimental Substructure

Simulation: DBE arl (yr)

Simulation: e -MCE tak (yr)

DBE arl (yr): OM vs Roof Drift

SC-CBF after DBE-Level and MCE-Level Hybrid Simulations

No damage to structural members or connections
Appendix VIII

Conclusions from SC **Damage-Free** Seismic-Resistant Steel Frame Systems Project
- Selected SC-MRF and SC-CBF configurations performed well.
- Essentially **damage free** under DBE (~500yr return period) with modest damage under MCE (~2500yr return period) response.
- SC steel systems self-centered under all earthquake conditions that were studied.
- Seismic performance objectives were met.

**Numerical Simulation of Collapse Potential of SC Steel Buildings** (SCBF, MRF) - Lehigh
SC systems are expected to be damage free under DBE (~500yr). Experimental and numerical simulation results verified this feature of the system.

How is the potential for collapse of SC-CBF and SC-MRF systems under the MCE (~2500yr) affected by this feature?

Use FEMA P695 methodology to assess the collapse performance of SC-CBF and SC-MRF systems using Incremental Dynamic Analysis (IDA) to establish the margin against collapse under the MCE.

**Compare Archetype SC-CBF and Conventional Code-Based “Special” CBF Buildings**
- Archetypes SC-CBFs designed using the design method developed at Lehigh (Chang et al. 2014)
- Conventional Special Concentrically-Based Frames (SCBFs) designed in accordance to ASCE 7-10

**Incremental Dynamic Analysis (IDA): 5-story SC-CBF**
- Median Collapse Capacity (k)
  - 10% Med: 8.1
  - 50% Med: 8.4
  - 90% Med: 8.1

**Results for Single Numerical Simulation in Incremental Dynamic Analysis Process**
- Intensity level: SSEF3 = 6.6g
- For reference: SSEF5 for MCE = 1.21g
- Ground Motion: Northridge 1994 EQ MULH, 002 component

**Comparison of CBF Fragility Curves**
- 6-story SC-CBF (SSCBF) has a better collapse performance (lower potential for collapse) than 6-story conventional CBF (SCBF)
- 4-story SC-CBF has similar median collapse capacity as 4-story conventional CBF (SCBF), but slightly greater uncertainty in response leads to slightly greater probability of collapse under MCE (still less than 10% target of FEMA P695)
Appendix VIII

Compare Archetype SC-MRF and Conventional Code-Based “Special” MRF Buildings

- Archetypes SC-MRFs designed using the design method developed at Lehigh (Garaco et al., 2007; Lin et al., 2012)
- Conventional Special Moment Resisting Frames (SMRFs) designed in accordance to ASCE 7-10

Incremental Dynamic Analysis (IDA): 4-story SC-MRF

- 4-story SC-MRF has a better collapse performance (lower potential for collapse) than 4-story conventional MRF (CFMRF)

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 (SMRF)) 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
Yunbyong Chae, Baoping Dong,
Akbar Mahvashmohamamdi, Chinmoy Kolay
Lehigh University

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Appendix VIII

Background

- **NEERI-ER: Performance-Based Design for Cost-Effective Seismic Hazard Mitigation in New Buildings Using Supplemental Passive Damper Systems**
  Collaborators: Lehigh University, Cal State Northridge, Cal Poly Pomona, Penn State-Erie, Curry Rubber Company, Taylor Devices.

- Development and validation of multi-level, performance-based seismic design procedure, with associated practical design assessment procedure, for buildings with passive damper systems

- Advancement of real-time hybrid simulation (RTHS):
  - Development and implementation of unconditional stable explicit integration algorithms with controlled numerical damping,
  - Advanced adaptive actuator control algorithms

- Multiple RTHS using ensemble of 40 ground motions to obtain response statistics (120 EQ simulations: 30-10E, 30-DBE, 30-MCE)

Prototype Structure for RTHS

- Prototype building
  - 3 stories, 2-bay by 6-bay office building
  - Moment resisting frame (MRF), braced frame (DBF), gravity system

Application of large-scale nonlinear viscous dampers for improving seismic performance

- Prototype structure (MRF, DBF) design
  - MRFs are designed to satisfy ASCE 7-10 code strength requirement using the equivalent lateral force procedure,
  - MRFs are not designed to meet the drift criteria in ASCE 7-10, story drift controlled by placing dampers in DBFs,
  - DBFs are designed to remain elastic under the design base earthquake (DBE)

Seismic performance objectives-structural

- Conventional performance objectives (FEMA 356)

- Enhanced performance objectives (FEMA 356)

Real-time Hybrid Simulation

Implementation of Explicit KR—α Method

\[
\begin{align*}
K_{r,s}\vec{u}_s(t) + C_{r,s}\vec{u}_s(t) + R_{r,s}\vec{u}_s(t) &= F_{r,s}\quad \text{(MRF)} \\
K_{b,s}\vec{u}_b(t) + C_{b,s}\vec{u}_b(t) + R_{b,s}\vec{u}_b(t) &= F_{b,s}\quad \text{(DBF)}
\end{align*}
\]

Appendix VIII

Summary and Conclusions

- NEES@Lehigh RTHS system enabled successful implementation of RTHS of large-scale steel structural system with supplemental passive dampers.
- The results show that RTHS is a practical technique to experimentally evaluate performance under simulated earthquake loading and to validate performance-based design procedures for structures with rate-dependent damping devices.
- The experimental results show that the structure with nonlinear viscous dampers achieves enhanced performance objectives that includes resilient performance under the design earthquake.

Acknowledgements

- The research was supported by grants from National Science Foundation, Award No. CMS-0836646, in the George E. Brown, Jr. Network for Earthquake Engineering Simulation (NEES) program, and Grant No. CMS-0402490 within the George E. Brown, Jr. Network for Earthquake Engineering Simulation Consortium Operation.
- This presentation is based upon research conducted at the NEES Real-Time Multi-Directional (RTMD) Earthquake Simulation Facility located at the ARLSSI Center at Lehigh University, sincere thanks are given to all technicians in the lab.
- The nonlinear viscous dampers were contributed from Taylor Devices Inc.

Thank you!
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 $\lambda$, equal or less than 200.
2. Slenderness ratio and Axial force limitation
   a) $N/N_y \leq 0.15$, $\lambda \leq 150$
   b) $N/N_y > 0.15$
      6KN Grade $N/N_y + \frac{\lambda}{150} \leq 1.0$
      8KN Grade $N/N_y + \frac{\lambda}{100} \leq 1.0$

   Limitation by Ray

"High Deformability"

AX: Axial Force, $N$: Yield Strength, $\lambda$: Slenderness

Limit State Design
[Limitations]
1. Normalized slenderness ratio $\lambda$, equal or less than 200
2. Slenderness ratio $\lambda$, and Axial force $N$, limitation
   $n_\lambda = 0.25$
3. Maximum Axial Force and Maximum Slenderness ratio
   $n_\lambda = 0.75$
4. Additional, Column form plastic hinge
   $-0.5 \leq M/M_s \leq 1.0$
   $n_\lambda, \lambda \leq 0.75$ (1 + M/M_s) $\frac{M_s}{N_s} \leq 0.5$
   $n_\lambda, \lambda \leq 0.05$

Maximum Moment in the Column
[Equilibrium]

Maximum Moment in the Column

Moment in the Column Member $M$

Maximum Moment at the End,

$M = \frac{M_1}{\lambda} N_s \left[ \pi \sqrt{N_s} \right]$

where, $N_s$: Euler Buckling Strength by Column Length$
$
Appendix VIII

**Regression Analysis**

\[ R_p = \frac{A}{(\lambda_e - B)^3} + C \]

**Table 1** Coefficients to specify Lateral Torsional Buckling (11-125)

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<th>A</th>
<th>B</th>
<th>C</th>
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<td>Single</td>
<td>1.000</td>
<td>0.450</td>
<td>-0.440</td>
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<tr>
<td>Double</td>
<td>0.850</td>
<td>0.700</td>
<td>-0.540</td>
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**Results**
Appendix VIII

Experimental Study on Large-space Structures

- Clarity damage mechanism of the components in large-space structures
- 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 systems for suspended items
- Verify the structural performance and seismic safety margin of earthquake-resistant ceiling systems
- Clarify the damage mechanisms of anchor bolts
- Develop design and construction method of ceiling system to resist the maximum level earthquake

Construction of ceiling system based on revised codes

2014

Steel roof and RC columns
Non-asbestos resistant ceiling
Ceilings designed based on revised codes

2015

High performance ceiling
(Resilient against fire and earthquakes)

Eigenvalue Analysis Results

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

the 2011 March Tohoku Earthquake

Analysis Results (Top Roof Response)

(a) Roof Displacement
(b) Roof Acceleration
Appendix VIII

Vulnerable Concentric Braced Frames

PH: STEVE MAEIN
GRADUATE STUDENT RESEARCHER: BARB SIMPSON
UC BERKELEY

Outline
1. Project Scope
2. Baseline Experimental Test at UC Berkeley
3. Possible Future Tests & Projects

Project Scope

GROUNDHABILITIES OF OLDER BRACED FRAMES:
- Load paths (loads:
  - Vertical
  - Horizontal
  - In-plane & out-of-plane)
- Prior to 2002:
  - Very few seismic regulations
  - Braced frames prone to a variety of failures:
    - Service provisions
    - Load path failures
  - International Collaboration:
    - University of Washington
    - National Taiwan University

Experimental Testing

ADVANCING THE BUILDING CODE
- Improves the building code to improve existing NCBFs
- Verifies the seismic capacity
- Enhances the seismic performance
- Outcomes of this project:
  - Simple & efficient formulas
  - Enhance engineers and owners' ability to assess existing structures
  - Collaborative network to foster more informed decision making about the safety of these structures

International Collaboration

NCBF Design
Appendix VIII

General Results

Fracture of West Brace

NCBF Design
Future Work

- NCSF-8:1 Repair
  - Concrete-filled braces
  - Delay Local Buckling
  - Prevent Inward Local Buckling
  - Hot Section Reinforcement
- Possible Future Studies
  - Common research ground in the evaluation and retrofit of older steel structures
  - Retrofit:
    - Stiffened System
    - Racking Frame

Thank You.
ANY QUESTIONS?
Appendix VIII

Rocking Frame (and Collapse Analysis)

Toru Takeuchi
Tokyo Institute of Technology
Vibration control / Structural design
http://www.knm.titech.ac.jp/takeuchi lab/

Collapse Analysis of Rocking Frames Including Brace Fracture
Fracture macro-model of CHS braces
Fracture macro-model of BRBs (incl. Slippage)
Reproduction of damaged floor system

NRF5/8-defense Rocking Frame Project Team:

Helmut Kwokstricker, Gregory Decklewine, Sarah Billington, Xiang Ma
George E. Brown, Jr. Network for Earthquake Engineering Simulation

Controlled rocking systems

Develop a new structural building system that employs self-centering rocking action and replaceable braces to provide safe and cost-effective building performance under earthquakes by minimizing structural damage and risk of building collapse.
E-Defense Test: System hysteretic behavior

- Characteristic hysteretic behavior confirmed
- Difference between initial and subsequent uplift moment has no apparent impact on behavior
- Inertia force based overturning moment "noiser"

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., ASCE Seismic Provisions, ACI-318 Chapter 21, etc.).

- Calculation of drifts at DBE and MCE (using $S_d$ and $T_p$ 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
Appendix VIII

“rocking/hinging spine systems”
- Capacity design for story shears and moments
- Distribution of forces
- Tied spine
  - Strength, stiffness, deformation capacity
- Energy dissipation
  - Damage control and design with replaceable components
- Seismicity

RETROFIT:
non-ductile RC frame with “pivoting” walls & shear fuses

Akira Wada
Tokyo Inst. of Technology

Collaboration with Industry Partners
"Early Adopters" of System Innovations

Ind City

Collaboration with Industry Partners
Retrofit at 680 Folsom Street

2. Fuse with Core Frame
Tokyo Tech Element Strategy Center

2. Fuse with Core Frame

Analytical model
Lift-up system
Non-lift-up system
Push-over results
Damage distribution
Self-centering
Damage distribution
Self-centering relying on elastic frames
More energy dissipation

Tipping Mar

Tokyo Tech
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
Appendix VIII

BEHAVIOR AND DESIGN OF COUPLED STEEL PLATE SHEAR WALLS

Larry Fahnestock
Associate Professor
University of Illinois at Urbana-Champaign

NEES/E-Defense Planning Meeting
Kyoto, Japan
December 12, 2013

Research Team

ILUINOIS

University of Washington

Steel Plate Shear Walls (SPSW)

- The SPSW system is well-established in North America and Japan

Stiffened and Unstiffened SPSW

Coupled SPSW Motivation

- Incorporating coupling in SPSW expands the potential applications
- MKA, Seattle Federal Courthouses
- The coupled SPSW configuration can provide additional benefits:
  - Architectural flexibility
  - Structural efficiency
  - Energy dissipation
  - Limited prior research
- Zhao & Ateshian, 2004
- Lü et al., 2012

Coupled SPSW Configuration

- Adjacent SPSW linked by coupling beams (CB)
- Like EBF links
- Yield in flexure, shear, or combination
- Steel Plate Shear Wall with Coupling (SPSW-WC)
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
  - ELF designs have better performance than ILF
  - More heavily coupled designs have better performance
  - Uncoupled designs perform well but are heavy and infeasible

(Benito & Pelavicchio 2012)

Degree of Coupling

Plastic Analysis of Multistory SPSW-WC

\[ DC = \frac{M_{\text{_MIN}}}{M_{\text{BAY}}} \]

\[ DC = 2M_{\text{MIN}} + 2M_{\text{MAX}} + M_{\text{COUP}} + \frac{F_A}{2M_{\text{MIN}} + 2M_{\text{MAX}} + M_{\text{COUP}}} \]
Appendix VIII

Analytical-Numerical Comparison

Degree of Coupling and Economy

Large-Scale Testing Program

Test Specimens

Experimental Test Setup

Load Protocol
Summary

- SPSW-WC provides economy and good seismic performance
- Ultimate strength and DC can be accurately predicted analytically
- Maximum material efficiency is achieved with a DC between 0.4 and 0.6
- Seismic response coefficients for SPSW appear to be appropriate for SPSW-WC
- First large-scale test demonstrated robust inelastic cyclic performance
- Second large-scale test will be conducted next week
APPENDIX IX: PRESENTED PAPERS IN PROTECTIVE SYSTEMS WORKING GROUP

Testing Magneto-Rheological (MR) Fluid Dampers
Advances in Real-Time Hybrid Simulation

Richard Christenson
Associate Professor
Department of Civil & Environmental Engineering
University of Connecticut

Large-Scale MR Fluid Dampers
Lord Corporation 200 kN MR Dampers

Multi-Site Real-Time Hybrid Test
- Fully dynamic model incorporating dynamics in magnetic coils and surrounding MR fluid
- Geographically distributed RTHS between Lehigh and Illinois NEES facilities
- Communications time delay (~80 msec over 1200 km) accommodated with Smith Predictor

RTHS of Complex Systems
- Using RTHS to examine dampers under bridge deck to reduce dynamic response
- To employ a more realistic bridge-truck model a 263,178 dof model is used – CIM-RTHS
Appendix IX

**RTHS of Complex Systems**

**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

**UCONN RTHS Facility**
Appendix IX

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

1800 t in total
Mass ratio: 3%

An attractive alternative to classical TMD

- Rotary inertial damper
- Silicone Oil

- Ball Screw
- Cylindrical Flywheel
Appendix IX

Linear viscous damping

vs

Linear viscous damping

damping force \( \dot{x} = i\omega_0 x = (2i\beta \omega_0 \omega_0) x \)

where \( x = X e^{i\omega t}, \omega_0 = \sqrt{\frac{k}{m}} \), and \( i = \sqrt{-1} \)

Linear hysteretic damping

also referred to as linear hysteretic damping or complex damping.

Complex stiffness

damping force \( (2i\beta m \omega_0^2) \dot{x} = (2i\beta \omega_0) x \)

Rate-independent damping

Rate-independent damping
Appendix IX

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

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

Full-Scale Tests Needed but $$$

- Full-scale test facilities: e.g.,
  - UCSD’s Large High-Hpf. Outdoor Shake Table
  - Japan’s NEED E-Defense shake table
- E-Defense facility costs:
  - 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.)

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

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)
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
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
2012–13 Built
3 & 8/13 tested
2015 full tests with controllable dampers

Goals:
- Test impulsive and long-period EQs
  - e.g., 2013 Tohoku EQ
- Pounding against seismic moat wall

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
- 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 13-44937/13-44822 w/ co-PI Nick Christenson
  - Old 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
Appendix IX

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

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 Corporation
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
Appendix IX

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 EXCITATION

Ryota MASEKI  Taisei Corporation

Setup of Large velocity excitation test

Test cases

<table>
<thead>
<tr>
<th>Excitation wave</th>
<th>Case</th>
<th>Period (s)</th>
<th>Disp. (mm)</th>
<th>Vel. (m/s)</th>
<th>Number of cycles per excitation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sinusoidal wave</td>
<td>Ow1</td>
<td>2.5</td>
<td>300</td>
<td>0.75</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Ow2</td>
<td></td>
<td>400</td>
<td>1.00</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ow3</td>
<td></td>
<td>500</td>
<td>1.25</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ow4</td>
<td></td>
<td>600</td>
<td>1.50</td>
<td></td>
</tr>
</tbody>
</table>
Appendix IX

Test results

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

Delay of damper force

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

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

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

**Building applied seismic retrofitting**

- **Location**: Shinjuku-ward, Tokyo
- **Main uses**: Office
- **Building area**: 3,666.97 m²
- **Total area**: 183,083.79 m²
- **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, girders, base plate and slab are performed by press bond with PC steel bar. We don't need weld.

**Mechanism of deformation-dependent oil damper**

- **Damping force**: Ordinary oil damper
- **Deformation**: Deformation-dependent oil damper

- Relationship of damping force and deformation
- Mechanism of Deformation-dependent oil damper

**Seismic observation system**

- **Sensor location**: 39F, 29F, 17th

**Observation Results**

<table>
<thead>
<tr>
<th>Maximum acceleration (gal)</th>
<th>Maximum deformation (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Longitudinal (X)</td>
<td>Transverse (Y)</td>
</tr>
<tr>
<td>49</td>
<td>123.0</td>
</tr>
<tr>
<td>28F</td>
<td>112.7</td>
</tr>
<tr>
<td>17F</td>
<td>94.3</td>
</tr>
</tbody>
</table>

![Velocity response spectra (h=5%)](image-url)
Appendix IX

**Observed Waves**

**Additional damping ratio estimated using ARX model**

*(Longitudinal direction)*
- Without Damper: 1.5% (average)
- With Damper: 2.1% (average)

0.6% increased

*(Transverse direction)*
- Without Damper: 1.4% (average)
- With Damper: 2.7% (average)

1.3% increased

Amplitude of 1st model 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.

**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.
Appendix IX

Comparison of acceleration with or without damper

Maximum Acceleration (Roof Level in transverse direction)

<table>
<thead>
<tr>
<th></th>
<th>Without Damper</th>
<th>With Damper</th>
</tr>
</thead>
<tbody>
<tr>
<td>GA</td>
<td>220.3 gal</td>
<td>184.1 gal</td>
</tr>
<tr>
<td>% Reduction</td>
<td>19%</td>
<td>36%</td>
</tr>
</tbody>
</table>

Roof Level Acceleration in Transverse Direction (Analysis)

Comparison of displacement with or without damper

Maximum Displacement (Roof level in transverse direction)

<table>
<thead>
<tr>
<th></th>
<th>Without Damper</th>
<th>With Damper</th>
</tr>
</thead>
<tbody>
<tr>
<td>ECm</td>
<td>76.4 cm</td>
<td>60.8 cm</td>
</tr>
<tr>
<td>% Reduction</td>
<td>20%</td>
<td>20%</td>
</tr>
</tbody>
</table>

Roof Level Displacement in Transverse Direction (Analysis)

Specification of oil damper

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>333 kN/m²/s</td>
</tr>
<tr>
<td>C2</td>
<td>3.5 kN/m²</td>
</tr>
<tr>
<td>%</td>
<td>1.3%</td>
</tr>
<tr>
<td>vmax</td>
<td>15 m/s</td>
</tr>
<tr>
<td>Fmax</td>
<td>300 kN</td>
</tr>
</tbody>
</table>

Comparison of simulated and observed response

Analytical results were in good agreement with the observed record

Comparison of acceleration with or without damper

5. CONCLUSION

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

The seismic responses were observed in the 2004 Mid-Nihata Prefecture Earthquake (without oil damper) and in the 2011 Tohoku Earthquake (with oil damper) and system identification using APOX 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.
Appendix IX

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 12-13, 2013
NEES / E-Defense Meeting

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

Development of Initial Concept

Experimental Implementation of Force Feedback Control
- Diming, Shiel, French et al. (1995): EFT of a Linear SDOF with PID and Velocity Feedback Compensation
- Zhao, Shiel, French et al. (2006): Nonlinear Valve Dynamics for Velocity Feedback Compensation
- Zhao, French, Shiel et al. (2006): SDOF EFT with Fluid Dampers
- Allgowe and Liu (2000): Laplace-based nonlinear controller

- Limited to SDOF systems with a single hydraulic actuator
- Frequency range is limited to ±1 Hz at maximum.
- No consideration of robustness in control design
- Not expandable to more complex applications

Dynamic Force Control Using Hydraulic Actuators

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

Dynamic Force Control Test
- Test Setup: SDOF Linear MDOF System
- Input: Kobe Earthquake Ground Motion
- Maximum Reference Force: 1500 N

Damping Time Histories
- Force Time Histories
- Force Spectrum


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

Dynamic Force Control Test
- Test Setup: SDOF Nonlinear System
- Input: Kobe Earthquake Ground Motion
- Maximum Reference Force: 1500 N


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

Dynamic Force Control Test
- Test Setup: MDOF Nonlinear System
- Input: Kobe Earthquake Ground Motion
- Maximum Reference Force: 1500 N

Appendix IX

(i) Verification of EFT with Steel Frame Structures

**Specifications**
- Structure: One-Story One-Story Steel Frame
- Configurable Frame: Fixed-Flex, Fixed-Pin, Pin-Pin
- Sections: W16×14 and W14×14
- Added Mass: 300 kg (4 x 75 kg steel plates)
- Actuator: Three-Stage 150 kN
- Stroke: ±1.5 inches, Load: 9.5 kips
- Servo-hydraulic MTS 200

**Objectives**
- Verify the effectiveness of EFT for performance assessment of steel frame structures
- Evaluate the robustness of keep-shaking

(ii) Force-Based Hybrid Simulation Using a Shake Table

**Concept:** Substructure Shake Table Test

(iii) Force-Based Hybrid Simulation of Base-Isoleted Structures

**Concept:** Simulation of Base-Isoleted Building

(iv) Earthquake and Subsequent Tsunami Impact on Structures

**Fluid-Structure Interaction Study**

(v) Tsunami-Induced Forces on Bridges

**Failure Investigation of Support Bearings**
(iii) Failure of Retaining Walls

Appendix IX
Appendix IX

Future Directions in Seismic Protective Systems Research

Keri Ryan
University of Nevada, Reno

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

Nonstructural Components and Contents

Ceilings and partitions
Piping
Enclosed contents rooms
4th and 5th floor of building

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

Comparison of the Isolation Systems

System-Deformation Comparison

- Triple Pendulum System
  - Yield Force = 0.088W
  - 1.8 s
  - Displacement Capacity = 1.14 m (45 in)

- Hybrid LRB System
  - Yield Force = 0.053W
  - 2.8 s
  - Displacement Capacity = 0.6 m (24 in)

LRB/CLB System Configuration

4 lead rubber bearings
5 cross linear bearings
Appendix IX

Remarks about the Systems

- Tripple 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

Summary of Residual Isolator Displacement

- TPS System
  - Peak Residual Disp = 10.8 cm
  - Average Residual Disp = 5.4 cm
- LRB System
  - Peak Residual Disp = 3.61 cm
  - Average Residual Disp = 1.2 cm

Floor Acceleration Response in TBP 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

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

- 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?
Appendix IX

Hybrid LR System - Load Transfer Effect

CLB @ start of test
URB @ start of test

Load transferred from URB to CLB

CLB deformed horizontally
URB deformed horizontally
URB deformed vertically

There is a net load transfer from URB to CLB (either) at large displacement excursions, sometimes resulting in net torsion.

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.

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 assumptions that protective systems are effective to protect nonstructural components and contents...

Its not quite like we thought...

Damage Observed During Extreme Vertical Excitation – Northridge, Rinaldi

Vertical PGA = 1.85 to 2.0g
Peak Stab Acc = 7 to 8g

Similar damage was observed in all three systems, induced by vertical excitations.

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 decking (floor slab vibration) in buildings otherwise constrained to low horizontal accelerations.
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. Ceilings; seismic bracing was found to be detrimental in these experiments)

Tests with the gap damper will be performed at UNR in early 2013

The “Gap Damper” Project
- A passive approach to control isolator displacements

A device concept was conceived and a prototype was designed, fabricated and tested.
- Estimating ultimate behavior of a base-isolated structure.
- Estimating the collapse mode of base isolated structures:
  - Especially the collapse mode when the isolator fractures by tension.

Thank you for your attention.
Appendix IX

Challenges:
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
Wenzhou, China (2)

Observations:
Route 14-15 connector curved end-spans - Northridge (1)

Other Observations:
Seismic-induced horizontal curved bridges’ collapse: small number although great attention
In many cases, severe damage occurred at straight part — why?

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

Why DTSS (Digital Shaken-Table Test)
Shaken-Table Test
Fundamental tool

Restrictions:
Laboratory Dimension
Manpower
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
- Materials' detail: Constitutive law
- Functional Computation Algorithms
dynamic response; contact; material’s failure process

An effective means to complement to Physical Shaken-Table Test prescreen, post-analysis, actual structures

Analysis: Comparison between Straight and Curved Bridges

Horizontal curvature introduces:
(1) additional torque $T$
(2) additional longitude force $A$

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Appendix IX

Thank You for Your Attention!

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

Vladimir Calugaru, Yuan Lu, Grigoris Antonellis, and Marios Panagiotou

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

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)?

PART 1
Earthquake Resilient Tall Buildings Using Base Isolation and Rocking Core Walls

Tall RC Wall Buildings in Regions of High Seismicity

RC core walls for earthquake lateral force resistance

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 = 1963):
- 36 demolished (5 built after 2000)
- 7 fate is undecided
- 7 survived

Case Study

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

Base Isolation and Armored Rocking Wall (BIARW)

BIARW system with External BRDs

PART 2
Large-scale shake table test of columns supported on rocking shallow foundations

Design concepts studied

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

Experimental part was completed on May 2013

Principal Investigators
Marios Panagiotou, UC Berkeley
Bruce Kutter, UC Davis
Jose Restrepo, UC San Diego
Patrick Fox, UC San Diego
Stephen Mahin, UC Berkeley

Graduate Student Researchers
Grigorios Antonellis, UC Berkeley
Andreas Gavras, UC Davis
Gabriele Guerrini, UC San Diego
Andrew Sander, UC San Diego
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

Chair: Shoji Tamura, Jonathan Stewart
Recorder: Ramzi 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.
  - Vidorikawa, Rathi, Nakamura, Mikami.
  - Discussion
- Utilization of field performance data
  - Sitar, Nakai, Tobita, Kashina
  - Discussion
- Shaking Table Testing and Centrifuge Testing for Soil-Structure Interaction and Related Applications
  - Gillis, Dashi, Heshsh, Fujii, 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

<table>
<thead>
<tr>
<th>No</th>
<th>Gravity</th>
<th>Pile type</th>
<th>Main focus</th>
<th>Numerical simulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1g</td>
<td>RC pile (Non-linear)</td>
<td>pile damage due to liquefaction</td>
<td>2D</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>Steel pile (Linear)</td>
<td>pile stress and total subgrade reaction</td>
<td>2D &amp; 3D</td>
</tr>
<tr>
<td>3</td>
<td>40g</td>
<td>Steel pile (Linear)</td>
<td>components of subgrade reaction</td>
<td>2D</td>
</tr>
</tbody>
</table>

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 -

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

Test No.2 vs. 2D vs. 3D

Test No.3: Centrifuge test

Effective stress on compression side & Pore water pressure on tension side

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
Motivations for Research

In 1995 Kobe earthquake
- Many pile structures were damaged.
- 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.
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

- By the result of borehole survey
- Calculated by N value and type of soil
- \( d = \frac{V_s}{4} \times 1.25 \) (deg.)
- Undrained value

Cohesion of sandy soil

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

<table>
<thead>
<tr>
<th>Depth (m)</th>
<th>N Value</th>
<th>Triaxial compression test</th>
<th>( c ) (kPa)</th>
<th>( \phi ) (degree)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>7.3</td>
<td>21</td>
<td>10.8</td>
<td>41.2</td>
</tr>
<tr>
<td></td>
<td>15.5</td>
<td>36</td>
<td>18.6</td>
<td>39.9</td>
</tr>
<tr>
<td></td>
<td>14</td>
<td>32.3</td>
<td>18.6</td>
<td>37.9</td>
</tr>
<tr>
<td>B</td>
<td>5.5</td>
<td>24</td>
<td>18.6</td>
<td>37.1</td>
</tr>
<tr>
<td></td>
<td>19</td>
<td>28</td>
<td>7.8</td>
<td>33.4</td>
</tr>
<tr>
<td>C</td>
<td>6</td>
<td>24</td>
<td>27.4</td>
<td>34.7</td>
</tr>
</tbody>
</table>

- In this study, three analyses were conducted as parameters for cohesion, \( c = 1, 10, 20 \) kPa.

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

- 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 are large and this is correlated with damage situation.
- The cohesion of the sand might have significant influence on the seismic response of pile.
Appendix X

**Time histories for $c=10\text{kPa}$**

The piles were subjected to the inertial force and ground displacement in the same direction and nearly at the same time (at 1.8 sec).

**Distribution of displacement for $c=10\text{kPa}$**

At 1.8 sec (when the curvature peaks), the displacement was as follows:
- Free Ground: Almost same
- Pile: Depth (mm)
- Ground Disp: Depth (m)

**Distribution of subgrade reaction for $c=10\text{kPa}$**

At 1.8 sec (when the curvature peaks), the subgrade reaction was as follows:
- Subgrade reaction (kN/m)
- Inertial force
- Ground Disp
- Depth (m)

**Summary**

1. The structural damage of piles might be caused by very large relative displacement of piles which was due to the large inertial force and the large ground deformation even if no liquefaction.
2. In the case of very large earthquakes, 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 to 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

Keywords on Current Trend

- Matured Society → Gradually Declined Society
  - "Sustainable Development" does not always mean "Continuous Growth" or "Maintenance of the Current Situation);
  - Consideration Span
    - Company Management: depends on length of term of CEO
    - Politics (Ideal): as long as possible
    - Politics (Real): depends on private benefits of politicians
    - Building Design: depends on the life cycle of the building
    - Civil Engineering: no end as long as society exists
  - In the 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.

- Earthquake → Tsunami, Rainstorm, (Tornado)
  - Improving seismic performance of 'single structures'
  - Still important in "developing society" for E-Defense Test
  - Possible Composite Disasters damaging large area
    - Earthquake followed by Tsunami
    - Heavy rainstorm before/during/after Earthquake
  - Heavy rainstorm before/during/after Earthquake
    - Give rainfall to slope on shake table using special device

- Disaster Prevention → Disaster Mitigation
  - Disaster Prevention: To keep from happening
  - Mitigation = "To moderate (a quality or condition) in force or intensity" or "Protect lives and properties from "design motions." Without" serious consideration on limitation of resource (For instance, Old-fashioned?)
  - NIED = Disaster Prevention (established in 1951)
  - NIED = Disaster Prevention (established in 1953)

- Hardware → Combination of Hard-, Soft- and Human-ware
  - More accurate soil investigation, numerical analysis and design
  - Construction method with higher performance and lower cost
  - Effective performance verification method (including monitoring)
  - Software: Plan, Regulation
  - Urban planning
  - Disaster mitigation plan developed by national or local governments, Regulations

- Our main role

In the close future, researches on "Hardware" cannot be independent from the other wares?
Appendix X

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, considering hard, soft, and human-structures

Possible Future Researches -1

Evaluation of Re-liquefaction Strength
Simulating re-liquefaction in large-scale experiment, mechanism of re-liquefaction needs to be clarified

Possible Future Researches -2

Tsunami Resistance of Medium-rise Buildings
Understanding of tsunami wave behavior is needed for designing tsunami-resistant buildings.
Appendix X

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 Slab during "Heavy Rain"

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-waves
   - Seismic Performance of Districts, NOT single buildings
Appendix X

SITE AMPLIFICATION FACTORS DERIVED FROM STRONG MOTION RECORDS OF THE 2011 TOHOKU, JAPAN EARTHQUAKE

S. Midorikawa
Tokyo Institute of Technology

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.

Site Classification of Strong Motion Station
Average shear-wave velocity of ground is evaluated at about 800 sites from PB-logging data and another about 2,100 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.

Microtremor Measurements for Site Characterization
Appendix X

![Diagram showing response spectra and site response analysis.](Image)

The nonlinear site response should be examined from strong motion records to improve nonlinear site factor in GMPE.
Appendix X

Shaking Table Testing Related to Piles and Lateral Spreading

Ramin Motamed, PhD, P.Eng
Department of Civil & Environmental Engineering
University of Nevada, Reno

10th Pan-Canadian Conference on Earthquake Engineering
June 28-30, 2010

Large-Scale Shake Table Experiments at E-Defense (2005-2008)

- Tests on Lateral Spreading of Liquefied Sand behind a clay wall
- Large soil container
  - Height: 3 m
  - Width: 4 m
  - Weight: 800 tons

Test on Soil-Pile Structure Interaction
- Large cylindrical terminal container
  - Height: 6.3 m
  - Diameter: 5 m
  - Weight: 300 tons

Large-Scale Shake Table Tests at E-Defense

- Two Tests in 2006
- 2x3 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

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
2.85×0.4×0.8m

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:
4.2m×4.5m (braze)
2.8m×2.8m (6DOF)

Thank you
Site Response Analysis: Comparisons with Kik-Net Borehole Arrays and Related Research Questions

Prof. Ellen M. Rathje, Ph.D., P.E.
George Zelachoris
University of Texas at Austin

Funding provided by Nuclear Regulatory Commission

Site Response Uncertainties

• Modeling
  – Evaluation of bias and uncertainty in site amplification predicted by numerical simulation
• Characterization
  – Quantification of variability/uncertainty in the shear wave velocity structure

Borehole Array Study

• Analyze 13 borehole arrays using:
  – Equivalent-linear (EQL)
  – EQL with frequency-dependent properties (EQL-FD)
  – Nonlinear (NL)
• Compare predicted and observed amplification of spectral acceleration

Modeling Soil Behavior

Nonlinear hysteretic soil behavior
Equivalent-linear soil properties

DeepSoil
Frequency-dependent shear strains
EQL-FD analysis
Strata

Borehole Array Sites

• Use GIGmax and D curves from Stikle and Darendeli (2001)
• $Q_{max} = 1\% \sim 3\%$

Amplification Factors

Site: IBRH13 Vs30 = 335 m/s
Appendix X

Observations
- EQL and NL analyses significantly underpredict motions at $\frac{\xi}{v}_{\text{max}} > 0.4\%$
  - Strength correction for $\frac{G}{G_{\text{max}}}$ curves will improve results somewhat but will not result in zero bias
- EQL-FD analysis significantly overpredicts motions at $\frac{\xi}{v}_{\text{max}} > 0.4\%$
  - Enhancements to this method could improve results

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?

- How well can we characterize spatial variability? Over what scale?
Is physical modeling possible for large prototype with a sand box: 48W x 30H x 150 (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 (lai, S&F, 1989)
2. Centrifuge model (1/η) (lai et al., Geotechnique, 2005)

Example:

\[ \eta = 5 \]
\[ \mu = 20 \]

<table>
<thead>
<tr>
<th>Generalized scaling factors</th>
<th>(1) Scaling factors for test</th>
<th>(2) Scaling factors for centrifuge test</th>
<th>(3) Generalized scaling factors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>μ</td>
<td>η</td>
<td>μ</td>
</tr>
<tr>
<td>Density</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Time</td>
<td>μ^(-0.25)</td>
<td>η</td>
<td>μ^(-0.25)η</td>
</tr>
<tr>
<td>Frequency</td>
<td>1</td>
<td>1/η</td>
<td>1/η^(-0.25)</td>
</tr>
<tr>
<td>Acceleration</td>
<td>1</td>
<td>1/η</td>
<td>1/η^(-0.25)</td>
</tr>
<tr>
<td>Velocity</td>
<td>μ^(-0.25)</td>
<td>1</td>
<td>μ^(-0.25)</td>
</tr>
<tr>
<td>Displacement</td>
<td>μ^(-0.25)</td>
<td>η</td>
<td>μ^(-0.25)η</td>
</tr>
<tr>
<td>Stress</td>
<td>μ</td>
<td>1</td>
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</tr>
<tr>
<td>Stress</td>
<td>μ</td>
<td>1</td>
<td>μ</td>
</tr>
<tr>
<td>Stiffness</td>
<td>μ^(-0.25)</td>
<td>η</td>
<td>μ^(-0.25)η</td>
</tr>
<tr>
<td>Permeability</td>
<td>μ^(-0.25)</td>
<td>η</td>
<td>μ^(-0.25)η</td>
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<tr>
<td>Pore pressure</td>
<td>μ</td>
<td>1</td>
<td>μ</td>
</tr>
<tr>
<td>Fluid Pressure</td>
<td>μ</td>
<td>1</td>
<td>μ</td>
</tr>
</tbody>
</table>
Past studies on the generalized scaling law

Dry sand: Node (2008), Tobita et al. (2011)
Saturated sand: Tanig et al. (2010), Yosi (2010)

Method: New modelling of models

\[
\begin{array}{cccc}
1/100 & 1/20 & 1/1 \\
1/10 & 1/10 & 1/1 \\
1/50 & 1/2 & 1/1 \\
1/70 & 1/1.43 & 1/1 \\
1/η & 1/η & 1/η \\
\end{array}
\]

Centrifugal acc. = η

Tobita et al., UP isolation (2011)

Flat layered saturated sand (Tobita et al., UP isolation, 2011)
Silica sand #7 (Dp=0.13 mm)
Viscous fluid (Metolose)

25m deep ground in prototype scale
(1000 is required for ordinary centrifuge scaling law)
(Even with E-Defense, it is difficult to carry out)

Model scale
Experimenter A

Prototype
Experimenter A

Surface acceleration
GL 0m
GL-6m
GL-10m
GL-15m
GL-25m

Input acceleration at the base
GL-25m

Accelerations of a scale factor of 24 is validated
Appendix X

**Excess pore water pressure**

**Experiment A**

When the test centrifugal acceleration is too high, it may not be possible to achieve the desired pore water pressure. This may be attributed to the properties of various soils. (Toda et al. 2011)

**Validated so far (1/2)**

Accelerator EPWP buildup

Scale

- 1/400
- 1/1000
- 1/100
- Scale L

- Applicable

**Validated so far (2/2)**

Displacement

Scaling factor of centrifuge model, \( \beta \)

LEAP (Liquefaction Experiment & Analysis Project) (launched in Jan, 2013)

- Next generation of VELAC 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 GEDMHR) (September 15-18, 2014) to be held in DPPRI, Kyoto Univ., in September, 2014
- In 2014, centrifuge model tests with the generalized scaling law

**Planning board:**

- Susumu Iai
- Tetsumi Toshita
- Koji Ichihara
- Minoru Okamura
- Bruce Kutter
- Majid Morzari
- Gopal Madabhushi
- Lee Chung Cheng
- Wine-Yi Hung

**Physical model testing:**

- DPPRI, Kyoto University, Japan
- Ehime, Japan
- IIT, Japan
- University of California, Davis, USA
- RPI, USA
- University of Cambridge, UK
- NSU, National Central Univ., Taiwan
- Zhejiang University, China (invitation by Bruce)

**Numerical analysis:**

- PFLP, ROSE, Japan
- PFLP, TULIP, Japan
- LDQA, Japan
- Geohaz, (tentative), Japan
- GWU, Majid, USA
- No. 2, USA (invited by Bruce)
- No. 3, USA (invited by Bruce)
- Imperial College, U.K., (invitation by Gopal)
Appendix X

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 p_{min}: 1.695
Max. density p_{max}: 1.329
Max. void ratio e_{max}: 0.983
Min. void ratio e_{min}: 0.698

Shear box
Inside dimensions: L150cm x W150cm x H50cm

Sensor location: Case 1-1

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.
(GMU, 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.
INTRODUCTION
The damages of foundations and lifelines are not easy to identify after large earthquakes.

The damage of piles during the 1960 Niigata earthquake was found in the reconstruction 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

<table>
<thead>
<tr>
<th>Year</th>
<th>2012</th>
<th>2013</th>
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<th>2016</th>
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<td>Technology Survey of Sensors</td>
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<td>Element Tests</td>
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<td>System Development</td>
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<td>Shake Table Test At E-Defence</td>
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<tr>
<td>Completion of Monitoring System</td>
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Organization
Taisei Corporation, Kyoto U., Tokyo U., Tokyo Science U., Kobori Research Institute, NIED

MONITORING SYSTEM
Sensing, Data Transfer, Data Process, Control & Monitor

SHAKING TABLE TEST AT E-DEFENCE IN 2015

Laminar Box at E-Defence
Appendix X

SHAKING TABLE TEST AT E-DEFENCE IN 2015

Potential Topics for Collaboration
SOIL – STRUCTURE INTERACTION DURING LARGE EARTHQUAKES

The behavior of soil-foundation-building system during large earthquakes is not fully understood and its prediction through computer simulation is not satisfactory.

UNCERTAINTY IN SIMULATION

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

Data “Stuff”
- Need:
  - Effective lifecycle management and monitoring will require access to more data and information
  - Acquire, transfer, convert, the data into forms that are accessible
- Impediments:
  - Volume of data
  - Language barriers
  - Technologies need to work together
  - Privacy, proprietary and cybersecurity risks
  - Quality and trustworthiness of the data
  - Education, awareness gaps

Closing the Gap between Data and Knowledge
- Capabilities have expanded
  - Aggregation/Interpretation
  - Data management
- Integrated SHM information system with interactive layer of infrastructure information
- Information tuned to the end-user
- Yielding safer built environment more responsive to the needs of society

Fundamental Needs
- Lots of data
- Security measures
- Novel and bold policy strategies

Data “Available”
- NEES – Project Warehouse
- SERIES – Portal
- E-defense (ASEBI)
- Etc.
Appendix XI

Community: NEEShub Cyberinfrastructure

840,656 web and 38,854 tool sessions from users of 212 countries between August 2010 and April 2013

Changing Culture of Collaboration

Why publish the data?

- Citation to the data
- Permanent Identifier (DOI)

Citation format for NEEShub data:

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
Appendix XI

Partnerships and Collaborations

• Korea-Australia Joint Research Institute
• Korea-Lithuania Joint Research Institute
• Korea-Italy Joint Research Institute
• Korea-Japan Joint Research Institute
• Korea-Taiwan Joint Research Institute

China-NEES/Defense Collaborations

• Earthquake Engineering Research Center (ERCoC) - China
• China Earthquake Engineering Research Center (CEECC)
• China Earthquake Engineering Research Center (CEERCC)

SEER Program

• Seismic Engineering Research Team (SEER)
• Seismic Engineering Research Team (SEER2)

CELESTINA

• Celestina Data
• Celestina Data

Data, Data, Data

Data Curation Handout: [http://nees.org/resources/5493](http://nees.org/resources/5493)

NEES/Defense Joint Projects

- #775: Shake Table Test (PI: G. Desotero)
- #254: Earth Defense - Seismic Performance of Interlocking Spiral Columns and Rectangular Columns Based on Shake Table Tests (PI: G. Mahon)
- #901: Collaboration between Earth Defense and NEES: Studying (PI: R. Bozorgnia)
- #894: Development of a Performance-Based Seismic Design Philosophy for Mid-Rise Woodframe Construction (Capstone Team) (PI: L. van de Lindt)
- #1005: Full Scale Four-Story Reinforced Concrete and Post Tensioned Concrete Buildings at Earth Defense (PI: J. Waller) - expected soon
Appendix XI

Monitoring Systems for Intelligent Infrastructures: Design, Sensing and Data Analytics
Anne Kiremidjian, Mark Molineaux, 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 Celen (UC Davis)
• Chris Flores (Sensys)
• Hyeyoung 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
Appendix XI

Evolution of Wireless Sensing Systems

• MEMS based sensor systems

Sensor Packaging and Installation

• Protection for harsh environments
• Sensing performance improvement
• Lifetime 10 years

Weigh-in-Motion System

• Load cell system
• Requirements: 10 years, 0.5% average error

Embedded Load Estimation Algorithm

• Each axle displacement is approximated by Gaussian shape, (fit second derivative of Gaussian)

Performance of Load Estimation

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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

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

Data Collection and Conditioning

- De-trending
- De-noising

Signal Modeling, Feature Extraction and Structure Correlations

- Autoregressive model
- Wavelet transform
- Rotation Algorithm

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
Appendix XI

Mahalanobis Distance as Damage Indicator

Example Applications

- AR – 4-Span Bridge tested at UNR
- Wavelet – 4-Story Steel Frame tested at SUNY Buffalo
- Rotation Algorithm

NEES – UNR Project-½ Scale Bridge Test
AR & Gaussian Mixture Algorithm

4-Story Steel Frame Test = SUNY, Buffalo
Wavelet Damage Diagnosis
Non-Stationary signals—e.g., earthquake response motions
DSF Feature from wavelet energies of signal
Correlate DSF to Damage

4-Story steel moment-resisting frame, NEES facility at SUNY-Buffalo
Anne Kremer-Jan
Appendix XI

Outline

- Introduction
- Current Hardware Development
- Summary of Damage Detection Algorithms
- Response to NEES/E-Defense Questions

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?

Which sensors to prioritize

- Crack sensors –
  - Steel welds
  - Steel members with notches
  - Concrete
- Corrosion sensors
- Direct dynamic displacement sensors

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

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
Appendix XI

DAMAGE DETECTION OF STEEL STRUCTURES
Masahiro Kurata
DPRI, Division of EQ hazards

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

Role of SHM in Earthquake Engineering

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

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. (U.D.: 0.99Hz, Day 1: 8.85Hz, Day 2: 0.85Hz, ...)
5th freq. (U.D.: 9.23Hz, Day 1: 8.96Hz, Day 2: 8.88Hz, ...)

Data-driven Structural Damage Assessment

Sensor-based approach
Structural design-based approach

Wireless sensing network + Web-based cyberenvironment
Appendix XI

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...
- Damper capable of memorizing experienced deformation

Local Damage Detection with Dense Array Sensors

- Frame tests for developing novel damage detection methods
- Sub-assembly tests for seismic damage classification

Seismic Interferometry for Global Monitoring

- Velocity
- Delay in wave propagation vs Story stiffness

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

Enhancement with Modal Evaluation

- Evaluation of modal dynamic strain for estimating distribution of bending moment under equivalent static force

Testbed for Local Damage Detection

- Dynamic testing of 1/3.75 scaled steel frame
- Simulated damage embedded around joints

DI is weakly dependent to input dynamic excitations
Appendix XI

Simulated seismic damage at beam ends

<table>
<thead>
<tr>
<th>Damage categories</th>
<th>Descriptions</th>
<th>Reduction of $E_R$ (%)</th>
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<tbody>
<tr>
<td>L1-1</td>
<td>Inside link of bottom flange is removed</td>
<td>28.4</td>
</tr>
<tr>
<td>L1-0</td>
<td>Outside link of bottom flange is removed</td>
<td>28.4</td>
</tr>
<tr>
<td>L2</td>
<td>All links of bottom flange are removed</td>
<td>62.5</td>
</tr>
<tr>
<td>L3</td>
<td>All links of bottom flange and web are removed</td>
<td>99.0</td>
</tr>
</tbody>
</table>

Wireless PVDF sensing system

Damage Index Summary


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

Crack at scallop tail (exterior beam-ends at 2F-7F)

Damage Index Result
Appendix XI

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)
  - Interpretation 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?

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

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

Thank you!

Development of Damage Index

- 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

\[ DI = \frac{R_u - R_d}{R_u} \times 100\% \]

- Statistical evaluation in time-domain using power of dynamic strain responses
- In-network normalization for a comparative study under different input motions
Appendix XI

![Diagram of Processes for Computing DI](image-url)
Wireless Cyber-Physical System Frameworks for Enhancing Civil Infrastructure Resiliency

Jerome P. Lynch, Ph.D.
Associate Professor
Department of Civil and Environmental Engineering
University of Michigan

10th U.S.-Japan Defensio Cybersecurity Symposium, 2013

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

My Research Portfolio

- **Central theme:** Resilience of Civil Infrastructure
- **Focus:** CPS technology for resilient infrastructure
- **Key Areas:**
  - Sensor Technologies
  - Data Fusion and Data Mining
  - Structural Response and Monitoring
  - Failures and Data Sensing

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

Confluence of Technological Trends

Emergence of Cyber-Physical Systems

- **Cyber-physical systems (CPS):**
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CPS Technology for Resilient Infrastructure

- **Central theme:** Resilience of Civil Infrastructure
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  - Data Fusion and Data Mining
  - Structural Response and Monitoring
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Appendix XI

**Distributed Damage Sensing**
- Distributed sensing based on multifunctional materials:
  - Materials whose material properties are modulated to damage
  - Work has explored use of carbon nanotube thin films
  - Distributed sensing functionality provided by impedance tomography

**Bio-inspired Sensing Systems**
- Biology unexplored for next-generation sensors:
  - Nature ripe with sensing, power harvesting, collective intelligence
  - Impossibly 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

**Bio-inspired Sensing Systems**
- Biology unexplored for next-generation sensors:
  - Nature ripe with sensing, power harvesting, collective intelligence
  - Impossibly 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

**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
  - Quadcopter UAVs are emerging as a promising data acquisition tool

**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) agents
  - Infrastructure network reconfiguration driven by hybrid system analysis
  - Mixed predictive control (MPC) approaches

**New Carquinez Bridge**
- New Carquinez Bridge (constructed 2003):
  - Located in the San Francisco Bay Area (Vallejo, CA)
  - Total bridge length is 1065 m (main span of 130 m)
  - Main deck consists of steel pretensioned box girders
  - Hollow reinforced concrete towers and pre-stressed link beams
Appendix XI

Instrumentation Plan

<table>
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<tr>
<th>Modality</th>
<th>Value</th>
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<td>Structural damage modalities</td>
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<tr>
<td>Fatigue/fracture</td>
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<tr>
<td>Fatigue/fracture in steel elements</td>
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<tr>
<td>Corrosion in steel elements and steel reinforcement</td>
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<tr>
<td>Cracking in reinforced concrete elements</td>
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<td>Residual deflection of the structure</td>
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<tr>
<td>Change in assumed boundary conditions</td>
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<tr>
<td>Non structural damage modalities</td>
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<tr>
<td>Fire-proofing integrity</td>
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</tr>
<tr>
<td>Building utilities (sealer, lighting, sanitation)</td>
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</tbody>
</table>

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 context-based information discovery from data
    - Decision-making front end for infrastructure asset management

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
    - Corrosion in steel elements and steel reinforcement
    - Cracking in reinforced concrete elements
    - Residual deflection of the structure
    - Change in assumed boundary conditions
  - Nonstructural damage modalities:
    - Fire-proofing integrity
    - Building utilities (sealer, 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 provide 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 systems capacity and system boundary conditions
  - Post-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 sensoric damage
  - Post-event:
    - Metrics for building re-occupancy programs
    - Interplay of semi-transparent analytics and post-event visual inspection

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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 & Structural Properties Laboratory
University of California, Davis

12th NDIPT-Defense Planning Meeting
Kyoto, Japan
December 12, 2012

Research Mission

A1. Multi-modal and Self-sensing

- Goal: design coating that does not rely on electrical energy for operation and could selectively detect different damage modalities (strain and pH/corrosion)
- Photothermal thin film fabricated from P3HT and PCBM
- Multi-modal sensing achieved using different colors of light

A2. CNT Film Electromechanical Response

- Goal: derive and validate the fundamental electromechanical behavior of carbon nanotube (CNT)-based nanocomposites
- Use experimental nano-scale images for deriving real-world numerical models

B1. Composite Structure Monitoring

- Goal: detect spatially distributed damage in composite structures (e.g., wind turbine blades) using embedded "sensing skins"
- Superelastic carbon nanotube (CNT) based film embedded during manufacturing
- Electrical impedance tomography employed for spatial conductivity mapping
- Structural resistance and damage compared in a probabilistic sense for risk assessment

B2. Bridge Scour Monitoring

- Goal: smooth bridge sensor evolution and utilize sensor data to improve/validate computational fluid dynamics (CFD) and structural models
- Scour hole topography assessed with distributed piezoelectric sensor array
- Laboratory (test) validated monitoring concept with generated digital models
- Employed COMSOL and OpenFOAM for CFD modeling

Nano-engineering and Structural Properties Laboratory

UC DAVIS

3/19

Nano-engineering and Multifunctional Materials Research Overview

UNIVERSITY OF CALIFORNIA, DAVIS

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Nano-engineering and Structural Properties Laboratory

UC DAVIS

3/19
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?
  - Need global and localized measurements of structural damage or damage precursors
  - Integrate global and localized assessments for structural performance assessment and predictions

- Prior to an earthquake
  - Deformation
  - Global properties
  - Damage occurrence
  - Vibrational damage

- After an earthquake
  - Fracture and safety
  - Global properties
  - Assessment and repair

Question #2

- How can instrumentation (sensors and sensing systems) be used to illuminate causal relationships between damage residual capacity of structural systems?

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?

Thank You! Questions?

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

- Truss
  - Machinery part
  - Walkway

- Affect global modes
- Impractical b/a comparison

Severe Corrosion
(Often covered with dust)
- Multiple damage
- Human injury & death
- Economic impacts

2011.06.14
Length: 30-20 m
Height: 2:10m

Unique characteristics of belt conveyors: identical members
(A mode in which vibrations of all identical members are much larger than the other member (not available for longitudinal members)

Periodic Local Vibration Mode (PLVM):

PLVM changes under damages
PLVM = PLVM + ILVM
damage

ILVM: Isolated Local Vibration Modes

ILVM of 24 identical horizontal braces

Frequency: 4.13 Hz
PLVM of 4 damaged braces

Damage: 2%
Freq change: 0.37 Hz
Damage: 5%
Freq change: 0.8 Hz
Damage: 10%
Freq change: 2.21 Hz
Damage: 20%
Freq change: 4.21 Hz
Change in freq. is consistent with damage level

Sensitivity of the frequencies to B.C. and other members

Global modes are sensitive, PLVM, ILVM are insensitive

Damage quantification

Obtain structural responses
Identify PLVM frequencies
Estimate rotational spring stiffness
Identify ILVM frequencies
Analyze for damage on connections
Evaluation of member stiffness
Repeat for every member

Known

The only unknown parameter
Appendix XI

Damage identification on FEM of conveyor truss

- Multiple members are damaged
- Velocity responses are simulated
- Change in PLVM and ILVM are examined

<table>
<thead>
<tr>
<th>Member sets</th>
<th>Damage geol.</th>
<th>Damage geol.</th>
<th>Damage identified</th>
<th>Damage identified</th>
<th>Damage identified</th>
<th>Damage identified</th>
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<tr>
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<tr>
<td>Side braces</td>
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<td>89.9</td>
<td>5</td>
<td>5.2</td>
<td>63</td>
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<tr>
<td>Vertical members</td>
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<td>85.1</td>
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<td>5.3</td>
<td>55</td>
<td>55.3</td>
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<tr>
<td>Lateral members</td>
<td>5</td>
<td>4.3</td>
<td>5</td>
<td>4.3</td>
<td>14</td>
<td>14.1</td>
</tr>
</tbody>
</table>

Damage identification using a scale-model

- 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 lead 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.

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.

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.

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**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 dynamics and boundary conditions. These modes are sensitive to local bending stiffness and disharmony of the locally vibrating member.
2. A damage identification technique using PLVM and ILVM for both composite and regular members is developed and tested on a scale model. This technique is applicable to multiple damage cases and structural failure after comparison.

**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

**Damage identification of Laboratory model**

- Frequencies are close
- Each damaged member is measured as a simple supported beam
- Initial 19 Hz
Appendix XI

Damage identification of lab models

1st PUMV of diagonal members

Peaks of lateral members are in scale range

Non-continuous main members

Damage identification of lab models

Undamaged members of PUMVs

PLVM of intact diagonal members

For lateral members: peaks are in a wide range

Amplitude of PUMVs

Finite element model
- Bottom and top braces = 17 times
- Lateral members = 14 times
- Side braces = 6 times
- Vertical members = 37 times

Range = 0.3 Hz
Range = 0.5 Hz
Range = 0.8 Hz
Range = 1.1 Hz

Laboratory model
- Diagonal members = 129 times
- Lateral members = 21 times
- Vertical members = 37 times

Range = 12 Hz
Range = 10 Hz
Range = 3 Hz

Full scale model
- Braces = 30 times
- Lateral members = 4 times

Range = 2 Hz
Range = 3 Hz

Real bridge: Lateral members = 79 times
- Undamaged lateral members

Range = 3 Hz

Different modes of the structure

Global mode
Coupled global-local mode
Chaotic local mode
Coupled local mode

Modal coordinate

\[ \mathbf{\dot{\mathbf{x}}} = \mathbf{M}^{-1} \mathbf{K} \mathbf{\ddot{\mathbf{x}}} + \mathbf{M}^{-1} \mathbf{Q} \mathbf{\dot{\mathbf{x}}} \]

\[ \mathbf{P} = \begin{bmatrix} P_1 & \cdots & P_m \end{bmatrix} \]

\[ \mathbf{P} = \mathbf{M}^{-1} \mathbf{K} \mathbf{\dot{\mathbf{x}}} + \mathbf{M}^{-1} \mathbf{Q} \mathbf{\ddot{\mathbf{x}}} \]

\[ \mathbf{M}^{-1} \mathbf{K} \mathbf{\ddot{\mathbf{x}}} + \mathbf{M}^{-1} \mathbf{Q} \mathbf{\dot{\mathbf{x}}} = \mathbf{P} \]

The maximum amplitude of each identified member in their PUMV range (independent of the value of input force) is the maximum value of the following matrix for each identified member:

\[ \mathbf{P} = \mathbf{M}^{-1} \mathbf{K} \mathbf{\dot{\mathbf{x}}} + \mathbf{M}^{-1} \mathbf{Q} \mathbf{\ddot{\mathbf{x}}} \]

\[ \mathbf{P} = \begin{bmatrix} P_1 & \cdots & P_m \end{bmatrix} \]

\[ \mathbf{P} = \mathbf{M}^{-1} \mathbf{K} \mathbf{\dot{\mathbf{x}}} + \mathbf{M}^{-1} \mathbf{Q} \mathbf{\ddot{\mathbf{x}}} \]

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\[ \mathbf{M}^{-1} \mathbf{K} \mathbf{\ddot{\mathbf{x}}} + \mathbf{M}^{-1} \mathbf{Q} \mathbf{\dot{\mathbf{x}}} = \mathbf{P} \]

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\[ \mathbf{P} = \mathbf{M}^{-1} \mathbf{K} \mathbf{\dot{\mathbf{x}}} + \mathbf{M}^{-1} \mathbf{Q} \mathbf{\ddot{\mathbf{x}}} \]
Appendix XI

Observability of PLVM in the real structure

A mode in which vibrations of all identical members are much larger than the other members

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.
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
Thanks for your attention.
Appendix XI

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

Safe: No damage or Limited damage

Danger: Extreme damage

SHM for Beam-Column Connection at E-Defense

Monitoring Unit

<table>
<thead>
<tr>
<th>Monitoring Unit</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensor board</td>
<td>1</td>
</tr>
<tr>
<td>LV Sensor</td>
<td>1</td>
</tr>
<tr>
<td>Strain Gage</td>
<td>1</td>
</tr>
</tbody>
</table>

**Note:** 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

N 1
3 2
4 1
Appendix XI

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
Inspector 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
Appendix XI

Resource Efficiency for Wireless Sensing using the Telegraph Road Bridge Testbed

Sean M. O’Connor
Professor Jerome P. Lynch
Professor Anja C. Gilbert
University of Michigan

MEES/Defense Meeting
December 12th, 2013

Structural Integrity Concerns

- Modal parameter often used in 11 model calibration/updating
  - Sensor placement critical

- Loss of composite action readers bridge potentially unstable
  - Difficult to detect degree of composite action

- Clear trends in deck cracking observed
  - Is this related to structural performance?

TRB Wireless Monitoring System

- Multi-phase sensor installation (May 2011 – December 2013):
  - 35 uni-axial accelerometers
  - 36 strain gages (24 strain profile, 12 – link plate strain)
  - 6 thermistors
  - 40 Nanodeal wireless sensing units measuring 57 channels of data

Issue 1 – FE Model Updating

- Instrumentation strategy:
  - Acceleration sensing around outside perimeter + deck center

- Damage detection:
  - FE model updating

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
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

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

Sensing System

- Communication base station:
  - Installed May 2011 in south fascia of NB I-75
  - Local receiver base station
  - RS-232 connection for off-site server communication

Sensor Modules

- Watertight enclosure protects from harsh environment
- Components enable high quality data acquisition (DAQ)
  - Remote wireless sensor
  - Solar charge circuit
  - Signal conditioning board (anti-aliasing filter + amplification)
  - Sensor (accelerometer, strain gauge, thermistor)
  - Sensor specific hardware (Wheatstone bridge, voltage divider)

Module Installation

- Automatic extraction of modal parameters:
  - Frequency Domain Decomposition (FDD) performed at server
  - Modal parameters used for model updating of finite element model
Appendix XI

Strain Gage Installation
- Strain gages attached at girdle section to infer neutral axis:
  - 3 metal foil strain gages for steel strain
  - 1 BDI strain gage for concrete strain

Strain Response Data

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 microstrains

Challenges of Wireless Sensing

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 (rainfall counting) and spectral (DFT) methods

- Method 2: Compressed Sensing
  - Directly acquire compressed "measurements" rather than samples
  - Measurements on the order of log(N)

Traditional Paradigm
- Uniform sampling:
  - Power consumed at ADC proportional to sampling rate
  - Power consumed at radio during transmission

Conventional Compression
- Wireless Node
- Uniform Sampling
- Compress & Store
- Transfer
- Receive
- Decompress
- Power Consuming
- Money/Inkwell
Appendix XI

**Compressed Sensing**
- Why sample N times just to get K relevant values?
  - Directly acquire compressed measurements

- Less work at the sensor, more afterward:
  - Preserves battery life at sensor
  - Lowers transmission demand
  - Render SNM system more scalable for high nodal density

**Approximation Quality - MAC**
- MAC value a measure of correlation between conventionally obtained mode shape and CoSaMP obtained mode shape

**Energy Savings**
- Significant energy savings for larger networks
  - ~40% energy reduction for 40 nodes (approximate nodal count on TRB)

**Workshop Question #1**
- Which damage modalities are of greatest importance to sense?
  - Fatigue
  - Corrosion
    - The result can be sudden failure

**Workshop Question #2**
- How can instrumentation be used to illuminate causal relationships between damage and residual capacity?
  - Fatigue life monitoring

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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

Thank You!

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Additional thanks to the Office of Naval Research (ONR)
Appendix XI

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

23 Aug 2011 M5.8 Mineral, Virginia, EQ

- Was “100-year” event: PGA ~ 0.7g
- 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/salt conditions
- DC felt strong shaking; EQ felt more like an M6 there

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
Appendix XI

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

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

Ambient Vibration Measurement

Note: First phase of sensor deployment only at 491 ft level

Structural Identification

FE Model Updating

Data to Information

Damage Comparison

Data to Information
Appendix XI

Coupled Shear Wall Systems

- Conventional diagonally reinforced coupling beams
  - Difficult to construct

- PT unbonded coupling beams
  - Eliminate diagonal reinforcement
  - Crack concentrated at beam ends
  - Reduced cracking along span

Test Specimen

- 40% scale model of 3-story substructure of the simulated structure
- Quasi-Static lateral cyclic loading until failure

DRAIN Model

Data from simulation of an 8-story prototype building used to validate the damage detection method

Modeling Assumptions
1. Multi-linear degradation of stress-strain curve for all materials
2. Tensile reinforcement not physically modeled (Columns/Unreinforced Members displayed)
3. Zero-tension concrete at boom ends
4. Linear tension concrete in remainder of boom
5. Concrete cover does not lose all strength at collapse
6. Monitor monochromatic displacement controlled analysis

Application of Damage Indices

Detection of ED Steel Yielding in Tension

Modeling for Sensor Placement

Data Processing & Management
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
Appendix XI

NEES – E-Defense Monitoring Session
December 11 – 13, 2013

Jennifer A. Rice
Engineering School of Sustainable Infrastructures and Environment
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 pre-stressing 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 (>150 ft)
- High channel count
- Sensor diversity
- Distributed test pavements
- Lightning 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 F0 gage 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 (< 1 Hz)
- Existing approaches
  - EVDT -- requires fixed reference point, not appropriate for practical SHM applications
  - Laser Doppler Velocimeter (LDV) -- expensive, bulky, impractical for extended SHM systems
  - GPS -- low accuracy/low sampling rate, more recently becoming viable for WSN applications

Continuous Wave Radar Sensor
- 3.4 GHz continuous wave radar (3 cm x 3 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) signal via a quadrature mixer
- Optimized signals are transmitted wirelessly
- Scalable system for configuration and system flexibility

Bridge Monitoring
- Previous applications rely on off-bridge radar placement
- Finite antennas directly 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

Performance Characterization
- Low frequency vibration performance:
  - Vertical and horizontal
  - Baseline motion
  - Target distance = 30 cm (far)
  - Results
    - RMS error < 3% with shifting ambiguity
    - Reduced data rate (32 kHz)

Target Distance Performance
- Horizontal circular walkable
- Statistical motion
- Target distance = 1.5 m (24 kHz)
- Results
  - RMS error < 4% with shifting ambiguity
  - Lower SHM volume, lower data rate (10 kHz)

Prioritizing Damage Modalities
- In general (routine monitoring)
  - Known issues
  - Analyze cost-benefit of a monitoring/maintenance strategy
  - $LCC = C_{OPE} + C_{MNT} + C_{MNT}^d + C_{RPR} + C_{OPE}^d$
  - Maintenance benefits
  - Post-disaster
    - Requires probabilistic models describing damage 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: $\Phi \left( \frac{R_i - \mu_i}{\sigma_i} \right)$
- $R$: resistance of structural elements
- $L$: loading effects
- $\mu_i$ and $\sigma_i$: mean resistance and mean load effect
- $\Phi$: standard deviation of the resistance and load effect
- Probability of failure: $P_f = \Phi(i)$
- The reliability index is better estimated when the probabilistic models of both the resistance and the loads can be improved through measured data

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
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.


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.

Real-time/Online Updating Using Time History Data

- Apply observer theory to update nonlinear models in real-time:
  - Prediction
  - Rapid (real-time) investigation


Real-time Updating

Response Prediction Using Updated Model (using unknown input)
Appendix XI

- If monitoring systems are tailored to "sense" specific damage modalities in structures, which ones are of greatest importance that should be prioritized?
- Correlation: chloride penetration, mechanical damage, deformation (e.g., displacement, strains), pavement: 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, etc.
- If there is an opportunity to duplicate a large-scale structural testing program exclusively to structural health monitoring and SHM-driven decision making, what would you propose?
  - Examine critical structural components for model updating study under controllable damage scenarios:
    1. Investigate suitable nonlinear model updating techniques for various nonlinear models at different damage stages;
    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 systems to cross-check/compare the updating results on a benchmark test (for instance, image sensing correlate with strain data; acceleration updating correlate with displacement updating).
Appendix XI

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

Damage Diagnosis Results

Aluminum Plate with Fatigue Crack

Model Updating Results

System Identification of Large Scale Continuum Structure Remains Difficult
— Systematic Archived Data From NEES/E-Defense
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 Holmen Unnesen

GOALS for Resilient Cities
1. Collapse prevention and life safety
2. Loss reduction
3. Rapid recovery

Challenges
1. Simulation tools to assess performance
2. Develop and validate analytical tools
3. Database sets
4. Damage limit-states
5. Monitoring and damage evaluation tools
   1. Improve simulation tools
   2. Rapid and post-event assessment tools
5. System-level interactions critical to collapse and losses
6. 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
     • Extract 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
   • Pre- and post-tests
   • Comparison of assessment techniques
4. Companion tests in US for systems tested at E-defense
   • Early collaboration in planning phases
Appendix XII

Superplastisizer for RC ideas

40 more years of collaboration
Kampai!
# 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

## 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"
- **Daiji Sato & Tomohiro Sasaki (NED)**
  - "Experimental Study on Large-frame structures, an ongoing E-Defense Project"
- **Tora 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:** Tora 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
## Appendix XII

### 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

- 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
### 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

- 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?
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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

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

4) Regional variations in site response, including the scaling with the principal site parameter ($V_s30$) and nonlinearity
   a) Why is nonlinearity different in different regions?
   b) What secondary parameters can improve predictions?

5) Is site response predictable from 1D analysis?
   a) Considerations related to geologic complexity and its effects on $V_s$ 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.

6) Site response for the vertical component of ground motion.
7) Estimation of $V_s30$ 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
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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

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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 Karata & Jerome P. Lynch
Reporter: Kenneth J. Loh

DPERI, Kyoto University, Kyoto, Japan
December 13, 2013

Monitoring Working Group
- Facilitators:
  - Masahiro Karata (Kyoto University)
  - Jerome P. Lynch (University of Michigan)
- Recorder:
  - Kenneth J. Loh (UC Davis)
- Participants:
  - Shilady Dyke (Purdue University)
  - Tomonori Nagayama (University of Tokyo)
  - Janos Kempenaer (Stanford University)
  - Akira Nishihara (Osaka University)
  - Yoshifumi Nada (Ashiya Institute of Tech)
  - Koichi Kato (Stanford University)
  - Scott O'Connor (University of Michigan)
  - Shamin Falakz (Lehigh University)
  - Jennifer Rice (University of Florida)
  - Wei Song (University of Alabama)

Process
- Pre-workshop Homework:
  - Develop working group agendas ahead of the workshop
  - Question 1: How can monitoring systems be integrated into "smart" systems and sensor networks in buildings, which are a future goal? What are opportunities for collaboration? What are the implications for future research?
  - Question 2: How can we best utilize sensor-based systems to directly inform decision making? What are the challenges and opportunities for sensor-based systems in the future?
  - Question 3: What are the implications for future research?
  - Question 4: How can sensors be integrated into "smart" systems and sensor networks in buildings, which are a future goal? What are opportunities for collaboration? What are the implications for future research?
  - Question 5: What are the implications for future research?
- Workshop Day 1:
  - Participants present their research and answers to these questions
  - Activity 1: Focus on post-event decision making and monitoring systems
  - Activity 2: Focus on monitoring structural steel system capacity based on monitoring data
- Workshop Day 2:
  - Retire and finalize high-priority research topics (3 identified)
  - Describe potential payloads and simulations
  - Plan for trans-Pacific collaboration in the NEES/E-Defense post-earthquake research program

High Priority Research Areas

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 sensors. The grand challenge is to create and sensor system that is able to identify damage limit states in structures that are weakened by earthquakes. The research challenges include the identification of damage limit states with novel SHM technologies. Leveraging the NEES/E-Defense data archive of large-scale tests, the feasibility of using sensor on a large-scale test bed. The research will yield opportunities to quantify the potential for ductility and redundancy in structural systems, and the implications for post-event safety evaluation and re-occupation of damaged structures.

Scientific Importance:
- Identification of damage limit states in structures is the next frontier of structural health monitoring
- Sensing technologies need to be developed and validated in large-scale test beds
- The development of a framework that can be used to identify damage limit states
- The development of a framework that can be used to identify damage limit states
- The development of a framework that can be used to identify damage limit states

Description:
- Identification of damage limit states in strong, nonlinear regions
- New sensors and sensors and sensing systems
- New sensors and sensors and sensing systems
- New sensors and sensors and sensing systems

Broader Societal Impacts:
- Structural, wind-driven damage on buildings
- Improvements in the safety and reliability of structural systems
- New sensors and sensors and sensing systems
- New sensors and sensors and sensing systems
- New sensors and sensors and sensing systems

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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 local community of stakeholders would be engaged to accelerate the transfer of research findings to practice. The research challenges include: developing verified sensing technologies for measuring specific damage reduction (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 providing definitive actions that are aligned with the needs and expectations of engineers, owners, facility managers, and stakeholders.

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 hazards. Monitoring technologies, in conjunction with advanced 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 sciences, such as crowdsourcing, remote sensing, and social media, will enhance regional-scale responses. In the context of future NISEE’s defense collaborations, specific focus should be paid on the development of monitoring technologies that can sense and track the physical weaknesses and vulnerabilities that may exist at points of connection of infrastructure systems. Experimental programs should also be directed 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 fragility and to allocate resources immediately after the event in the ensuing days and weeks.

Experimental Program

- Opportunities for PayLoad Projects
  - Creation of large-scale testing programs that are open to the broader research community for the purposes of identifying damage-resistant structures
  - 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 databases for blind assessment of damage detection algorithms in addition to the research toward experimental student COMPETe Program
  - Assess the reliability and durability of sensors and sensing systems
  - Engage the diverse stakeholder community
  - Foster visual inspections to evaluate test specimens to identify optimal ways of combining SHM data with visual inspection for re-occupancy decisions
  - Increase the benefits of SHM systems for cost-benefit analyses

Simulation Tools

- Opportunities for Advancing Capabilities of Numerical Simulations
  - Use testbed data to enhance the simulation of regional responses to earthquakes, especially the performance of physical infrastructure under ground motion
  - Reduce the hierarchical structure of numerical models of structures, especially structures responding to their respective response regime through advance online or real-time model updating techniques
  - Agent-based simulation of societal response to earthquakes over varying timescales

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 social response
- Experimental programs to understand how component performance impacts the performance of global systems
- Simulation tools to model and calibrate urban and socioeconomic interactions to model system fragility and allocate resources post-event for varying timescales

Scientific Importance:
- With fundamental knowledge in the infrastructure system improvisatory lack, experimental testing and computer simulation will advance methods of real-time and virtual simulation tools to model the performance of infrastructure systems
- Optimal data-driven decision support systems for allocation of emergency response resources of the region

Broader Societal Impacts:
- Identify per-event weaknesses toesty to robust systems for handling to ensure global system performance and to eliminate cascading failures
- Rapidly assess built of urban physical infrastructure post-event
- Filter emergency response resources
- Minimize losses to vital regional and global economic recovery of region and social impact

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

Description:
- Device-reliable decision support framework for the re-occupancy and continued operations of damaged but structurally sound infrastructure
- Utilize existing test data and new tools to create a probabilistic framework that generates information about re-occupancy, use, and repairs
- Explore coupling between quantitative SHM data and qualitative visual inspection for improved re-occupancy decisions

Scientific Importance:
- Design and optimize sensor algorithms for characterizing damage initiation and propagation
- Create hands-off monitoring strategies to assess infrastructures structures or construction methods
- Implement validated models for prediction of structural response to different scenarios
- Develop probabilistic decision-making frameworks that incorporate event-related uncertainties and demands

Broader Societal Impacts:
- Significantly enhances the resiliency of large urban environments following major earthquakes
- Reduces economic impact of major events
- Improves psychological well-being
- Enhances functionality and operations of disaster-impacted regions
- Enhances disaster and recovery resources to areas of greatest need
- Protects economies and infrastructure efforts
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Efforts to Increase US-Japan Collaboration:

1. Further foster the strong human network between US and Japan:
   - Revise student-oriented exchange program focused on studying hazard mitigation and resilient cities
   - Involve social scientists and other stakeholders

2. Develop interoperable experimental data repositories:
   - Provide datasets of greatest relevance to SHM
   - Engage international collaborations to expand implementation of open data sources
   - Facilitate real access to act upon datasets to enable a virtual test bed

3. Create trans-Pacific research collaborations specific to SHM payoffs:
   - Regional-scale analysis of two seismically vulnerable megalopolises (one in the US and one in Japan)
     - Leverage existing and create new opportunities to deploy regional-scale instrumentation
     - Perform regional-scale simulations and compare between the two urban environments

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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

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<th>First Name</th>
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<td>From Japan</td>
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<td>Lei</td>
<td>Zhang</td>
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<td>Doctoral Student</td>
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From the United States
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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.).
Group Photo after Student Discussion Session
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**PEER 2014/06**  
December 2013.

**PEER 2014/05**  
*Seismic Velocity Site Characterization of Thirty-One Chilean Seismometer Stations by Spectral Analysis of Surface Wave Dispersion.*  
Robert Kayen, Brad D. Carkin, Skye Corbet, Camilo Pinilla, Allan Ng, Edward Gorbis, and Christine Truong. April 2014.

**PEER 2014/04**  
*Effect of Vertical Acceleration on Shear Strength of Reinforced Concrete Columns.*  

**PEER 2014/03**  
*Retest of Thirty-Year-Old Neoprene Isolation Bearings.*  

**PEER 2014/02**  
*Theoretical Development of Hybrid Simulation Applied to Plate Structures.*  

**PEER 2014/01**  
*Performance-Based Seismic Assessment of Skewed Bridges.*  

**PEER 2013/26**  
December 2013.

**PEER 2013/25**  
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