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On the Use of Digital Twins for Structural Health and Performance Monitoring and Rapid Post-Event Assessment

2020 PEER Annual Meeting

The Future of Performance-Based Natural Hazards Engineering

January 16-17, 2020, Berkeley, California

Ertugrul Taciroglu
Professor, University of California, Los Angeles

Hamed Ebrahimian
Assistant Professor, University of Reno, Nevada

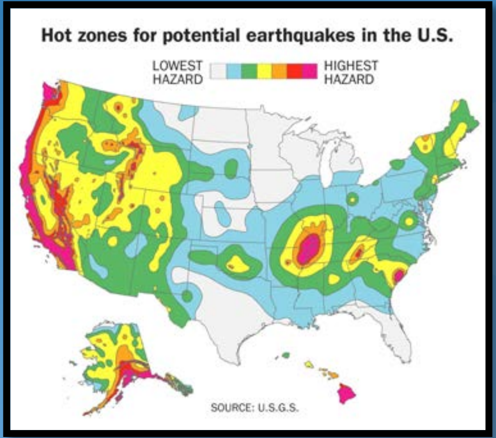
S. Farid Ghahari
Project Scientist, University of California, Los Angeles

Outline

- Why is SHM needed?
- Current Practice
- The Ideal Solution (IMHO)
- Digital Twins + Bayesian Model Updating
  - Validation: Samoa Channel Bridge
  - Verification: The Golden Gate Bridge
  - Application examples:
    - Post-Earthquake Assessment: San Roque Canyon Bridge
    - Operational Monitoring: The San Roque Canyon Bridge

Structures Need Doctors!

- Gradual damage is inevitable
  - Aging
  - Permanent and cyclic loading
  - Environmental effects (temperature, humidity, etc.)
  - Minor earthquakes
- Older structures
  - Recently understood vulnerabilities
  - Configurational or utilization changes
- Severe events can/will also happen
  - Natural (Earthquakes, Fires, Hurricanes)
  - Anthropogenic



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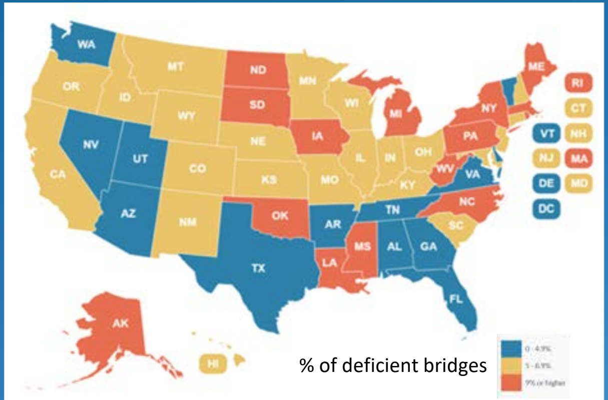
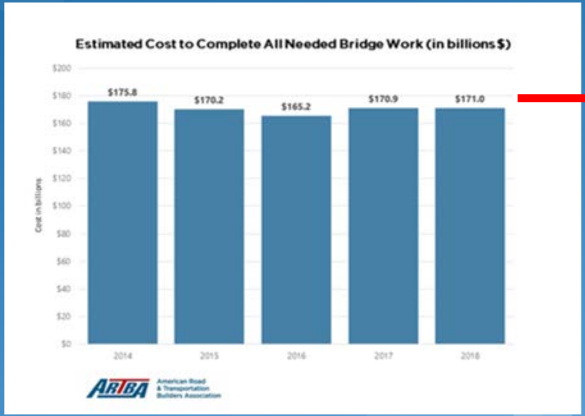
Our Bridges Are Old

"There are more than 56000 structurally deficient bridges in US",
American Road and Transportation Builders Association



Estimated cost to complete all needed bridge works (billion $)



Resources must be carefully managed!

SHM: yesterday option, current need, future necessity

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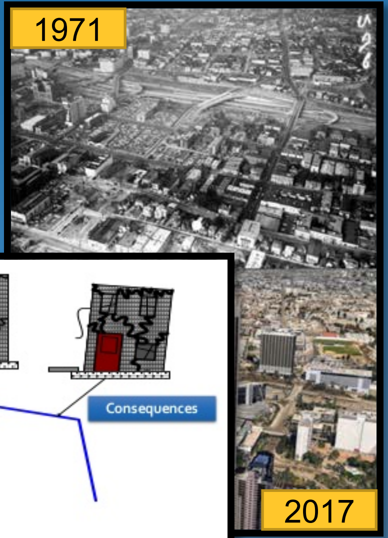
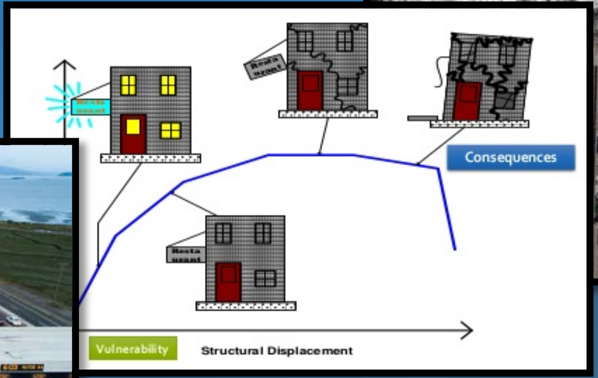
Today Challenges

- Inventories of complex structures and infrastructure are exponentially growing
- Design philosophy has changed from the life safety to business continuity
- Indirect costs are becoming higher and higher!





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Current Practice: Periodic Inspection

- Visual inspection
  - Time-consuming and expensive
  - Periodic (discontinuous)
  - Service interruptions
  - Subjective and prone to human errors

Visual inspections are costly and time-consuming and thus, must be prioritized after a major event.

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Current Practice: Periodic Inspection

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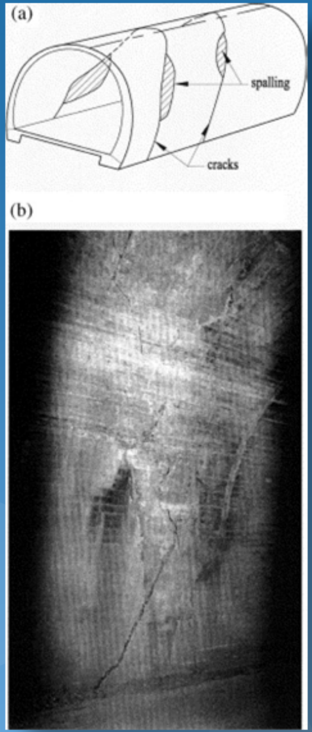
  - Service interruptions
  - Subjective and prone to human errors
- The system-level source and consequence of visible damage are hard to realize. Invisible damages include:
  - Loss of pretension forces
  - Fatigue
  - Foundations
  - Cascading effect

Damage may manifest in inaccessible locations (box girders, pile foundations, etc.).



Tunnel damage observed during the 1999 Chi-Chi Taiwan Earthquake (Wang et al., 2001).

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- Life-cycle/operational damage types include
  - Concrete damage, corrosion
  - Deterioration of bearings, scouring
  - Collisions, fire, etc.

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Instances that were perceived to be OK!

After an Event

In case of an emergency we need to answer the following questions:

1. Do we need to stop operation?
2. If so, when will it be safe to restart?
3. Where do we send the first responders?
4. Can we quickly assess structural damage?
   - *Is there damage in the system?* ← *detection*
   - *What are the damaged components?* ← *localization*
   - *How significant is the damage?* ← *quantification*

JR East evacuation during the 2011 Tohoku Eq.

- Health assessment must be carried out quickly to minimize unnecessary downtime
  - Bridges are under operational traffic while aftershocks are coming
- Decision must be made based on quantitative results
  - Wrong decisions can result in disasters
- There is no time to do tests
  - Number of assets in affected regions are large and resources are typically limited
- Number of assets to be inspected is typically very large
  - The proposed method must be scalable
- Logistics may become chaotic in the aftermath of a major event
  - The health assessment process must be automated

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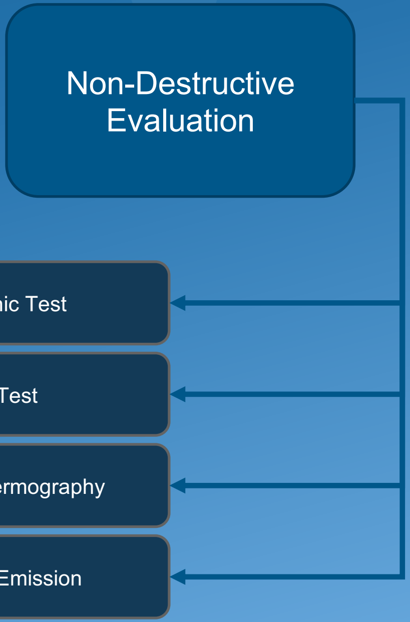
Sensor-Based SHM Solutions

- Expensive
- Not applicable at every location
- Not applicable continuously
- Cause Performance interruptions
- Typically no system-level insight



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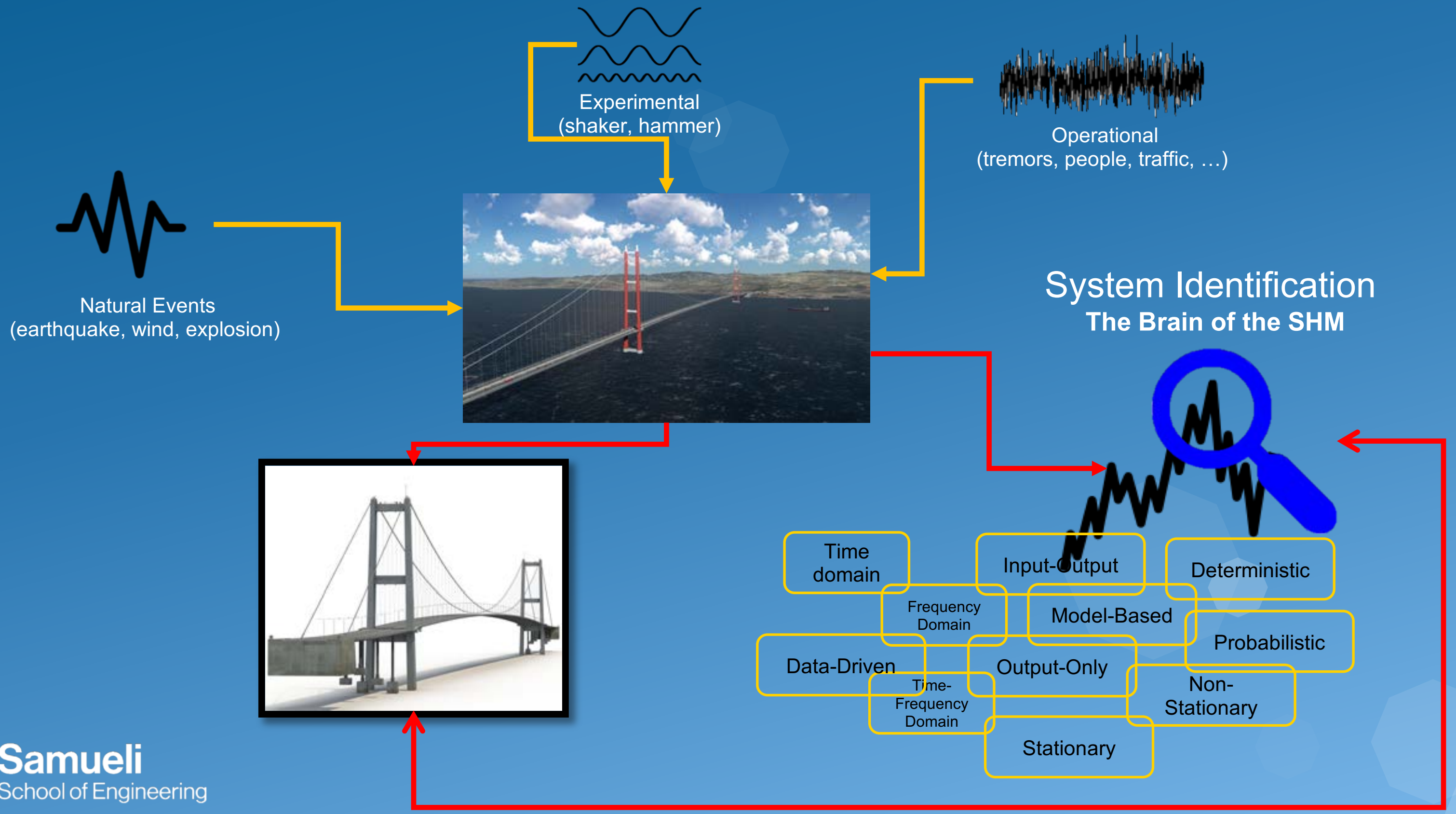
Vibration-Based SHM Solutions



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Existing SHM Solutions

Sensing Technology — Interpretation Algorithm

Non-Destructive Evaluation

- Expensive
- Not applicable at every location
- Not applicable continuously
- Cause Performance interruptions
- Typically no system-level insight

Methods:
- Ultrasonic Test
- Tap Test
- Infrared Thermography
- Acoustic Emission

Vibration-Based Structural Health Monitoring

Data Mining

- Training data dependent
- Non-predictive
- Large and unquantified uncertainty
- No system-level insight
- Dense sensor installation

Operational Modal Analysis

- Insensitive Modal properties
- Linear response assumption
- White noise input assumption
- Classical damping

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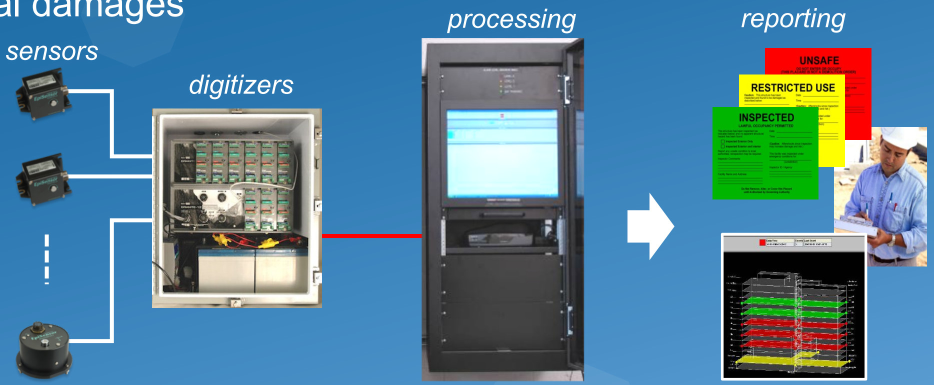
A Robust SHM & Rapid PEA Framework

- It should work for rapid post-event (e.g., earthquake) damage assessment as well as long-term health/performance monitoring
- It must be able to identify hidden and local damages
- It must be
  - ✓ practical
  - ✓ low cost
  - ✓ quantitative
  - ✓ reliable/accurate
  - ✓ automated
  - ✓ scalable
  - ✓ fast



- It should minimize operation/service interruptions
- It should help identify preventative maintenance
- It should be self-improving
- It should take advantage of technology advancements over time

Dubai (UAE) Rapid PEA Command Center

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SHM Solutions

Sensing Technology — Interpretation Algorithm

Non-Destructive Evaluation

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Ultrasonic Test

Tap Test

Infrared Thermography

Acoustic Emission

Vibration-Based Structural Health Monitoring

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Operational Modal Analysis

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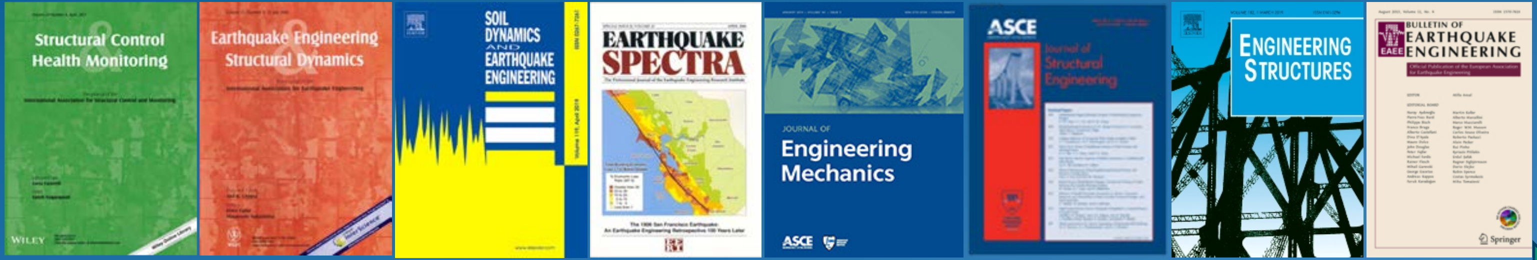
Digital Twin

- Physics-based model
- Nonlinear behavior
- Arbitrary input excitations
- Uncertainty quantification
- Remaining life estimation
- Case-specific
- System level insight
- Hidden damage identification

A Decade of Study



2006 → 2019

Parameter identification of framed structures using an improved finite element model-updating method—Part I: formulation and verification
Eunjong Yu, Ertugrul Taciroglu, John W. Wallace

Modal System Identification and Finite Element Model Updating of a 15-Story Building Using Earthquake and Ambient Vibration Data

On Forced Vibration Testing for Quantifying Damage in Building Structures

Performance of equilibrium-based system identification algorithms with incomplete state data

Ambient and Forced Vibration Testing of a Reinforced Concrete Building before and after Its Seismic Retrofitting

Parametric Identification of Nondegrading Hysteresis in a Laterally and Torsionally Coupled Building Using an Unscented Kalman Filter

Story-by-story estimation of the stiffness parameters of laterally-torsionally coupled buildings using forced or ambient vibration data: I. Formulation and verification
Roshanak Omrani, Ralph E. Hudson, Ertugrul Taciroglu

Blind identification of soil–structure systems

Response-only modal identification of structures using limited sensors
F. Abazarsa, S. F. Ghahari, F. Nateghi, E. Taciroglu

Blind Modal Identification of Non-Classically Damped Systems from Free or Ambient Vibration Records

Response-only modal identification of structures using strong motion data
S. F. Ghahari, F. Abazarsa, M. A. Ghannad, E. Taciroglu

Blind modal identification of structures from spatially sparse seismic response signals
S. F. Ghahari, F. Abazarsa, M. A. Ghannad, M. Çelebi, E. Taciroglu

Extended Blind Modal Identification Technique for Nonstationary Excitations and Its Verification and Validation

Blind identification of the Millikan Library from earthquake data considering soil–structure interaction
S. F. Ghahari, F. Abazarsa, O. Avci, M. Çelebi, E. Taciroglu

Blind modal identification of non-classically damped structures under non-stationary excitations
S. F. Ghahari, F. Abazarsa, E. Taciroglu

Bayesian identification of soil-foundation stiffness of building structures
Nima Shirzad-Ghaleroudkhani, Mojtaba Mahsuli, S. Farid Ghahari, Ertugrul Taciroglu

Probabilistic blind identification of site effects from ground surface signals

Blind identification of site effects and bedrock motion from surface response signals

Estimation of the Soil-Structure Model Parameters for the Millikan Library Building Using a Sequential Bayesian Finite Element Model Updating Technique
Hamed Ebrahimian, S. Farid Ghahari, Domniki Asimaki, Ertugrul Taciroglu

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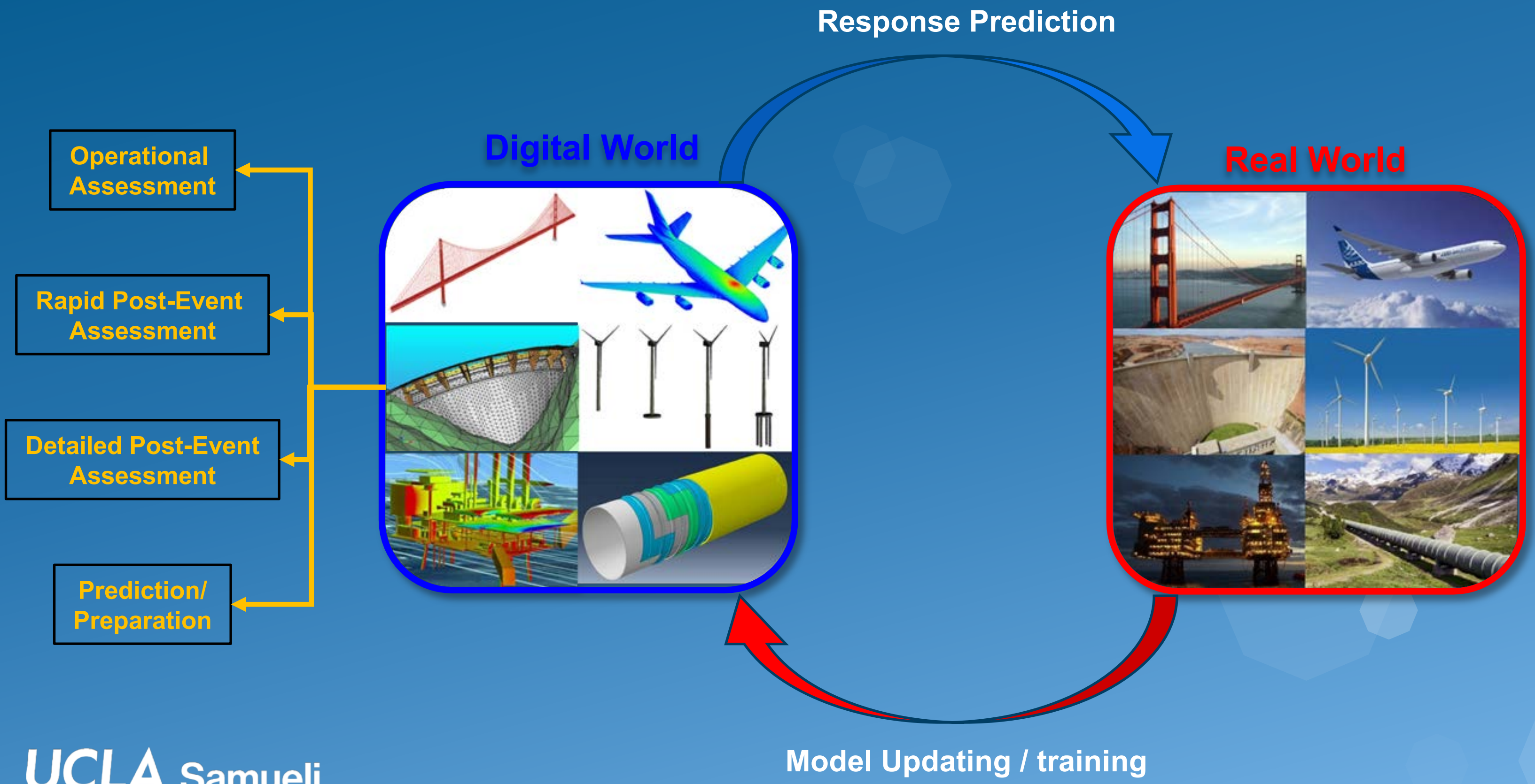
Our Solution: SHM Rapid PEA using Digital Twins



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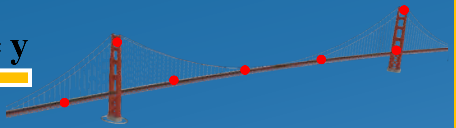
Some Theory

Nonlinear FE Model

Measurement

$$\mathbf{Y} = \mathbf{y}$$



$$\hat{\mathbf{Y}} = \mathbf{f}(\boldsymbol{\Psi})$$

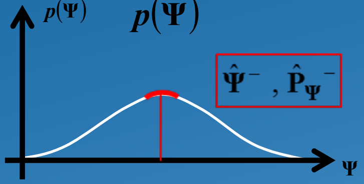
Simulation Error Model

$$\mathbf{Y} - \hat{\mathbf{Y}}(\boldsymbol{\Psi}) \sim N(0, \mathbf{R})$$

Regardless of the type of excitation (operational, event)

Prior Information

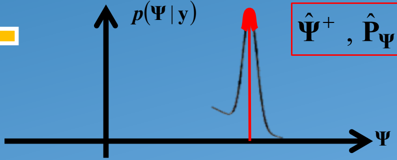
$$p(\boldsymbol{\Psi})$$



$$\hat{\boldsymbol{\Psi}}^{-}, \hat{\mathbf{P}}_{\boldsymbol{\Psi}}^{-}$$

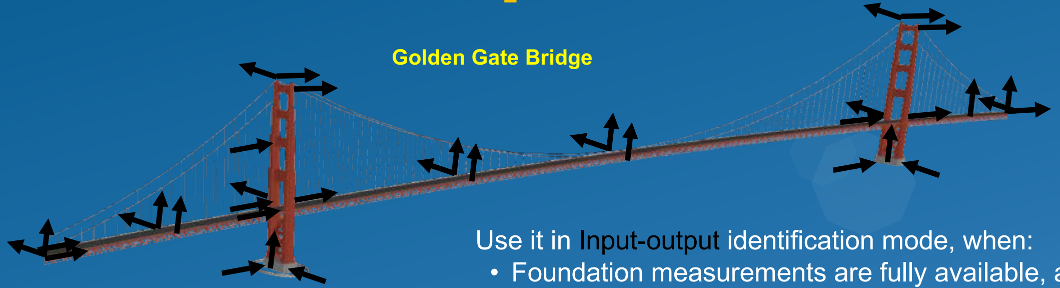
Bayesian Updating

$$p(\boldsymbol{\Psi} \mid \mathbf{y}) = \frac{p(\mathbf{y} \mid \boldsymbol{\Psi})\, p(\boldsymbol{\Psi})}{p(\mathbf{y})}$$



$$\hat{\boldsymbol{\Psi}}^{+}, \hat{\mathbf{P}}_{\boldsymbol{\Psi}}^{+}$$

Method's Capabilities



Use it in Input-output identification mode, when:
- Foundation measurements are fully available, and
- SSI is negligible, or
- Only the superstructure is of interest

Use it in output-only identification mode, when:
- No input motion is available
- Kinematic and inertial interactions are of interest

Use it in partial input-output identification, when:
- Not all foundation motions are measured, and
- SSI is negligible, or
- only the superstructure is of interest

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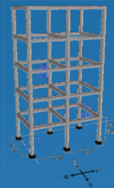
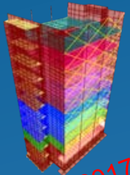
Progress Toward Real-Life Applications

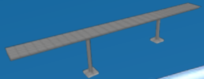


2014
Nonlinear model updating using input-output data

2015
Joint input and nonlinear system ID

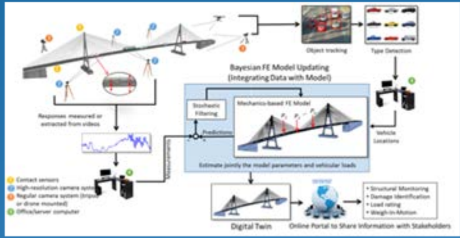


2016
Parallelization
Scalability



2017
Real-world, large-scale applications

2018
Heterogeneous sensors
Information fusion



Problem scale & complexity
Real-world applications
Technology development

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Some of Our Past & Ongoing Projects

Caltrans: Comparative Study of Model Predictions and Data from Caltrans/CSMIP Bridge Instrumentation Program: A Case study on the Eureka-Samoa Channel Bridge

CGS: Identification of Soil-Foundation-Structure Interaction Effects using Recorded Strong Motion Response Data from Instrumented Buildings

CGS: Identification of Spatial Variability in Bridge Foundation Input Motions

Caltrans: Development of Accurate Damping Models for Nonlinear Time History Analysis

CGS: Identification of Earthquake Input Excitations for CSMIP-Instrumented Buildings

UCLA ITS: Digital Twins for Bridge Health Monitoring & Management

SCEC: Output-Only Bayesian Nonlinear Site Characterization using Geotechnical Downhole Array Data

FHWA: Digital Twins for Bridge Management through the Integrating of Computer Vision and Finite Element Models, Phase I

CGS: Characterization of Nonlinear Dynamic Soil Properties from Geotechnical Downhole Array Data

FHWA: Digital Twins for Bridge Management through the Integrating of Computer Vision and Finite Element Models, Phase II

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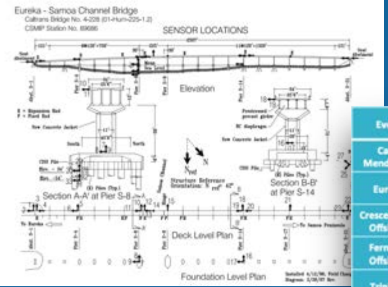
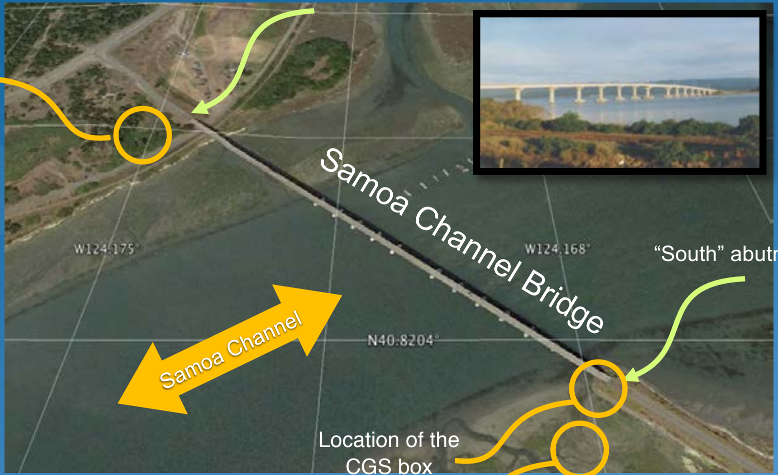
Samoa Bridge



Earthquake Data

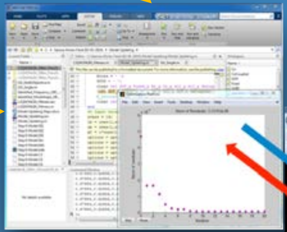
Event	Date	Magnitude	Source Location		Ep. Dist.(km)	PGA (g)*	PSA (g)**	Data Availability
			Lat.(N)	Long.(W)				
Cape Mendocino	03/16/00	5.6 Mw	40.39	125.24	102.5	0.006	0.020	Yes
Eureka	06/17/02	5.3 ML	40.83	124.61	36.9	0.053	0.108	No
Crescent City Offshore	06/14/05	7.2 ML	41.33	125.87	153.4	0.009	0.031	Yes
Ferndale Offshore	02/26/07	5.4 ML	40.642	124.87	62.5	0.011	0.022	Yes
Trinidad	06/24/07	5.1 ML	41.13	124.81	63.9	0.028	0.072	Yes
Willow Creek	04/29/08	5.4 Mw	40.84	123.50	56.5	0.017	0.032	Yes
Trinidad	08/16/08	4.6 Mw	41.18	124.20	40.2	0.018	0.057	Yes
Ferndale Area	01/09/10	6.5 Mw	40.65	124.76	53.9	0.150	0.370	Yes

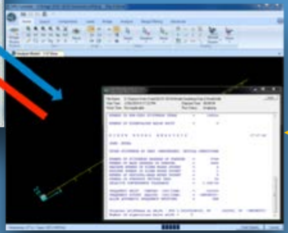


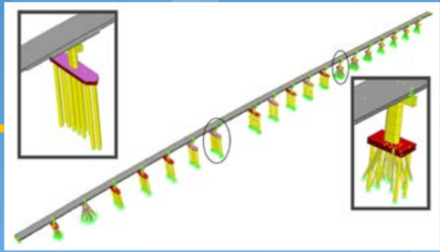
BMID

Ambient Data

Classic







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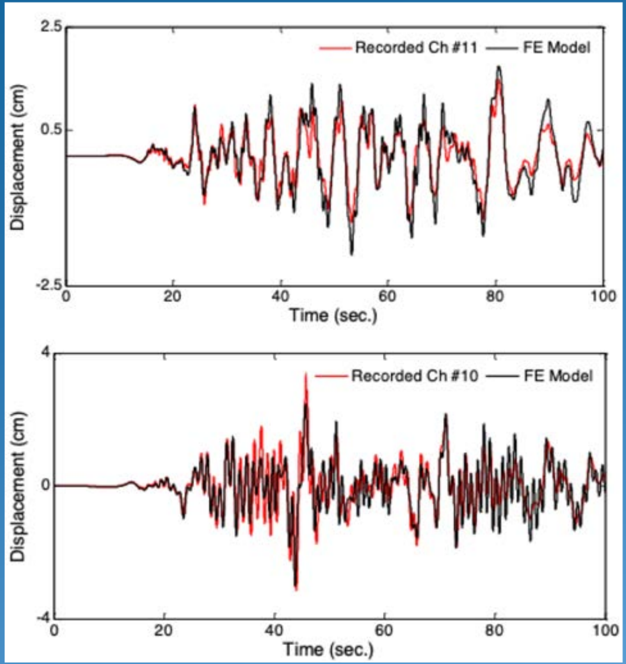
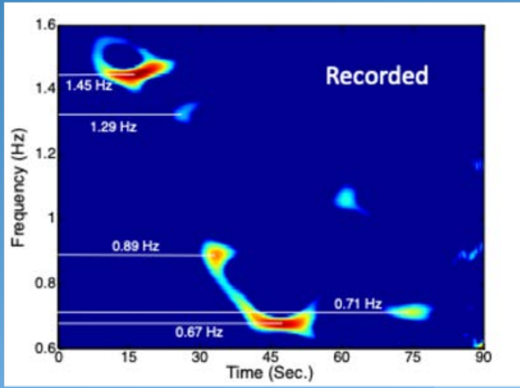
Response Prediction

An earthquake occurred right after completing the project!





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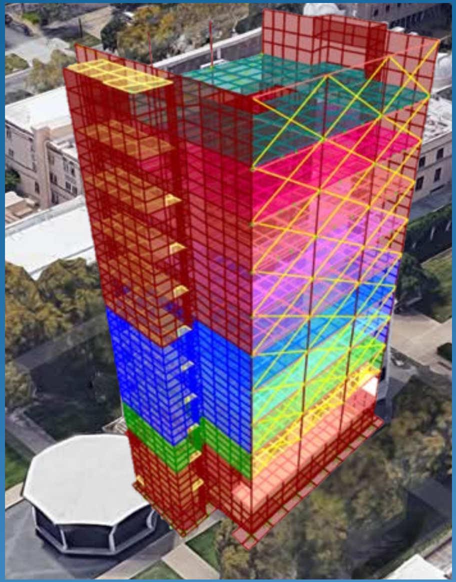
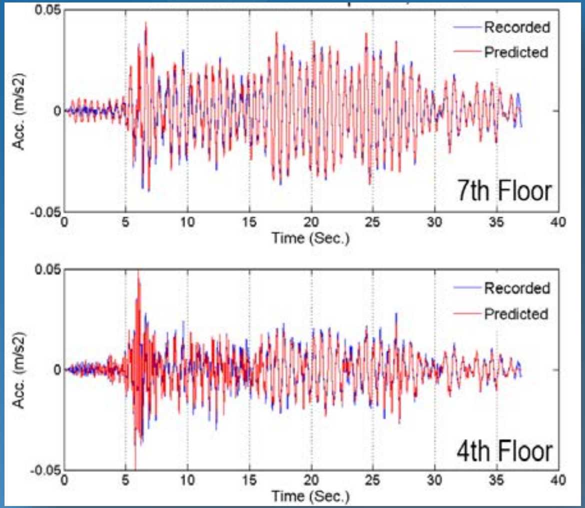
CSMIP Buildings



Blind Prediction



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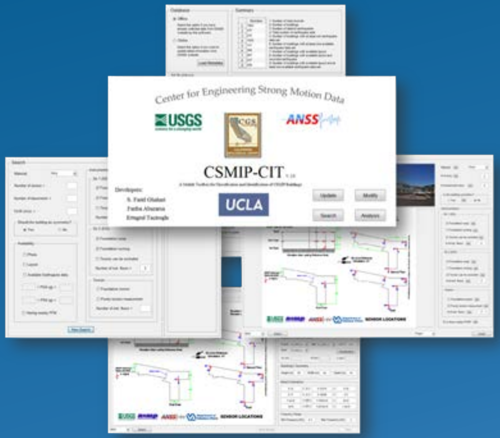
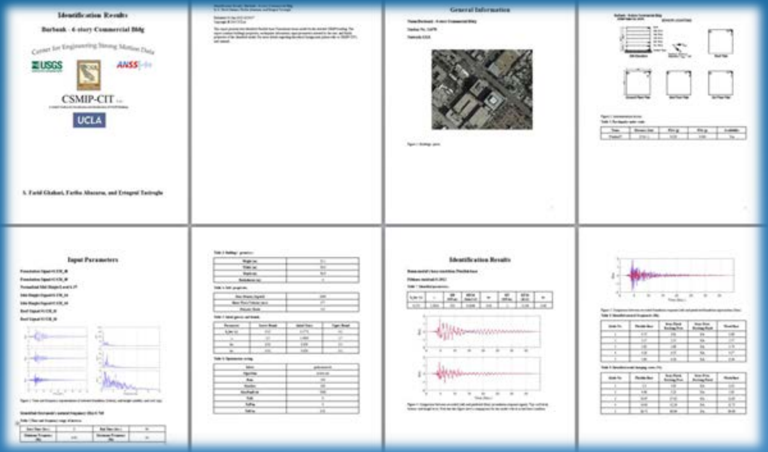
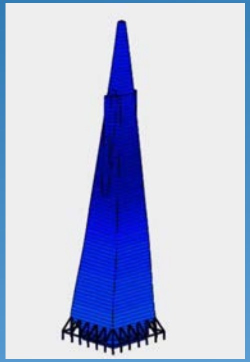
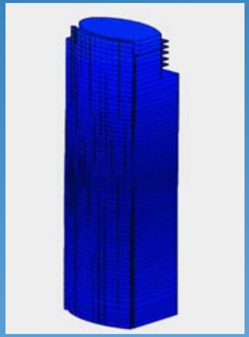
CSMIP Buildings



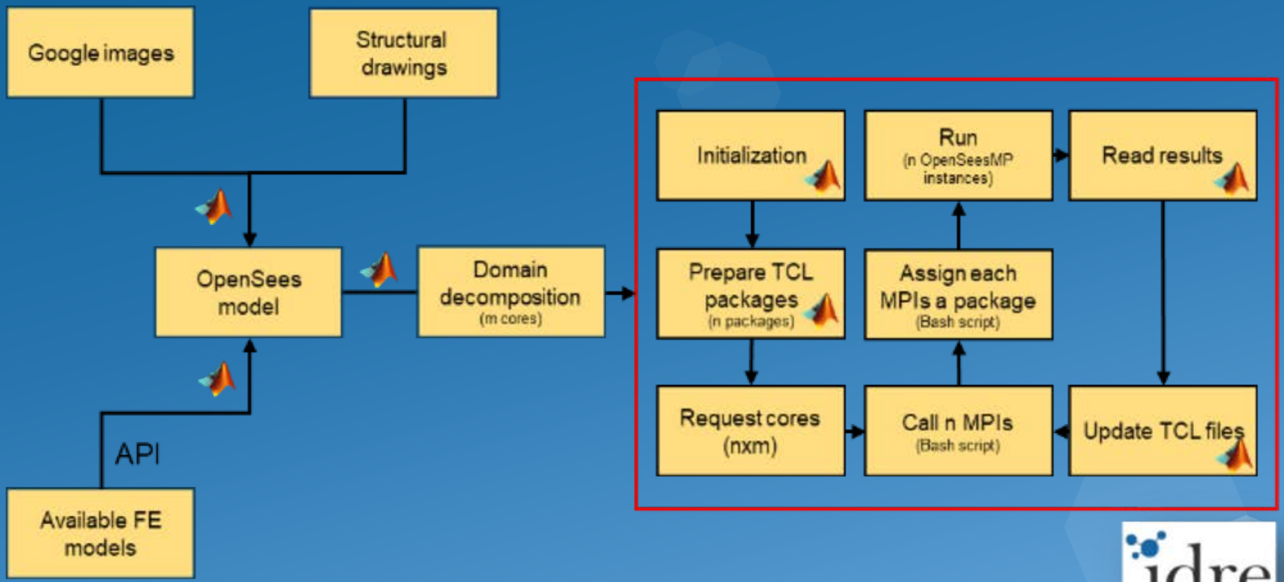






Tutorial available at YouTube (https://www.youtube.com/watch?v=yMUpOmnP4yU)

Workflow To Solve Any Problem Size



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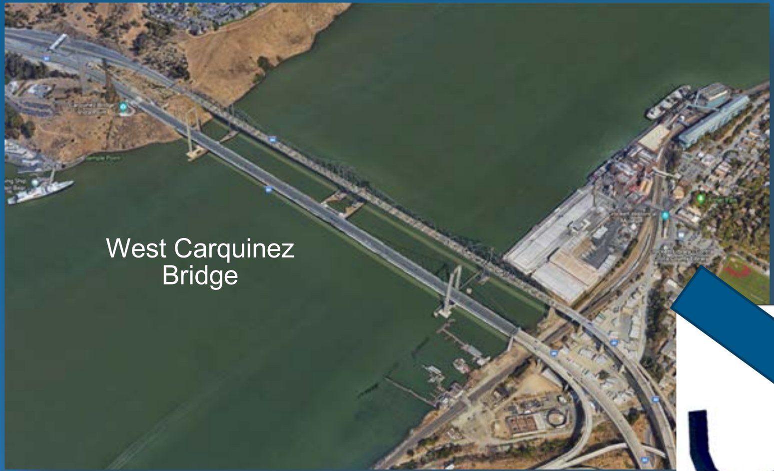
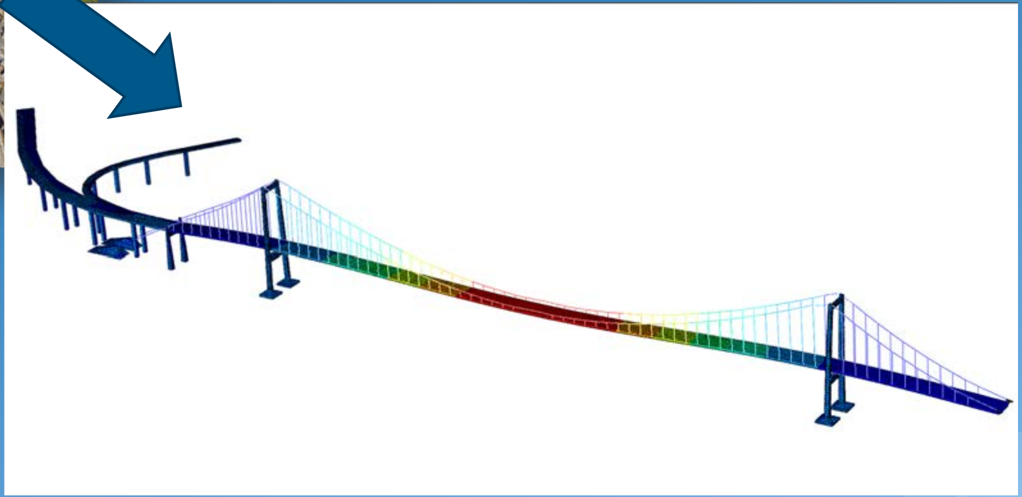
Modeling Capabilities





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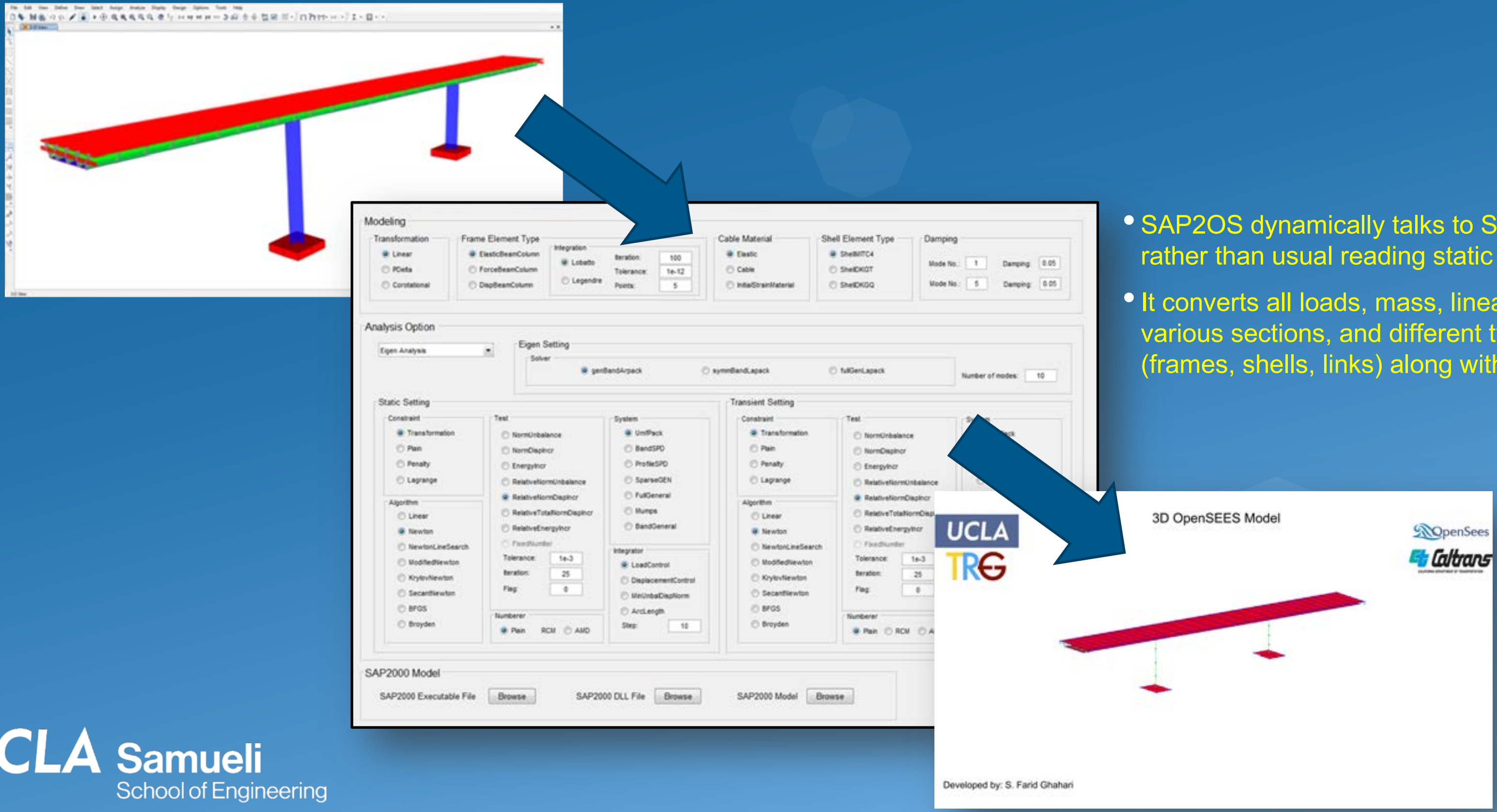
Modeling Tools



- SAP2OS dynamically talks to SAP through API rather than usual reading static text file;
- It converts all loads, mass, linear materials, various sections, and different types of elements (frames, shells, links) along with the geometry

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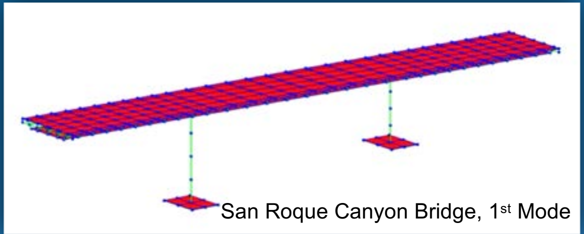
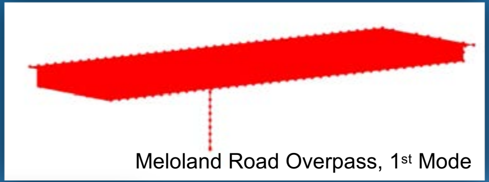
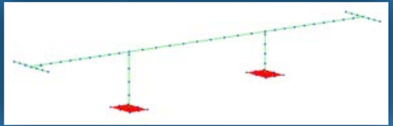
SAP2OS Converter Tool



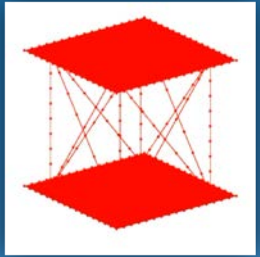
San Roque Canyon Bridge, 1st Mode



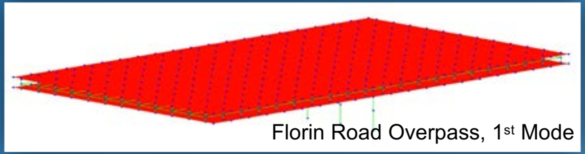
Meloland Road Overpass, 1st Mode



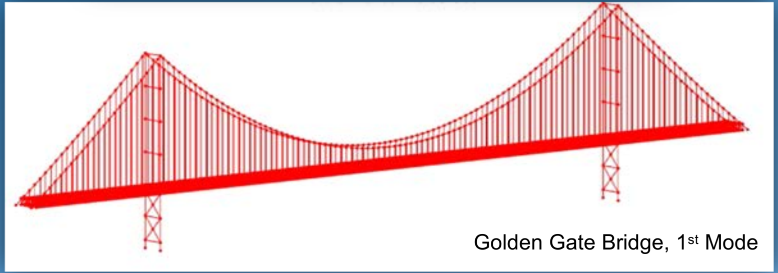
San Roque Canyon Bridge (Stick model), 1st Mode



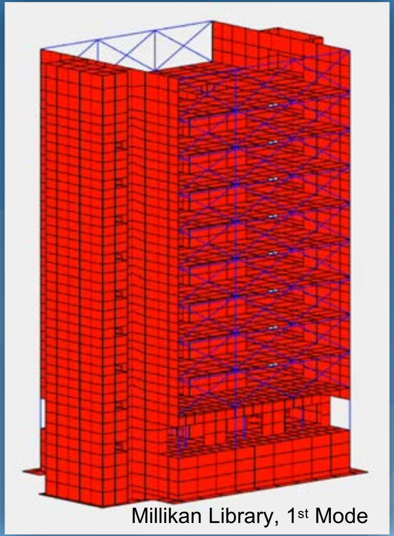
Garner Valley Structure, 1st Mode



Florin Road Overpass, 1st Mode



Golden Gate Bridge, 1st Mode



Millikan Library, 1st Mode

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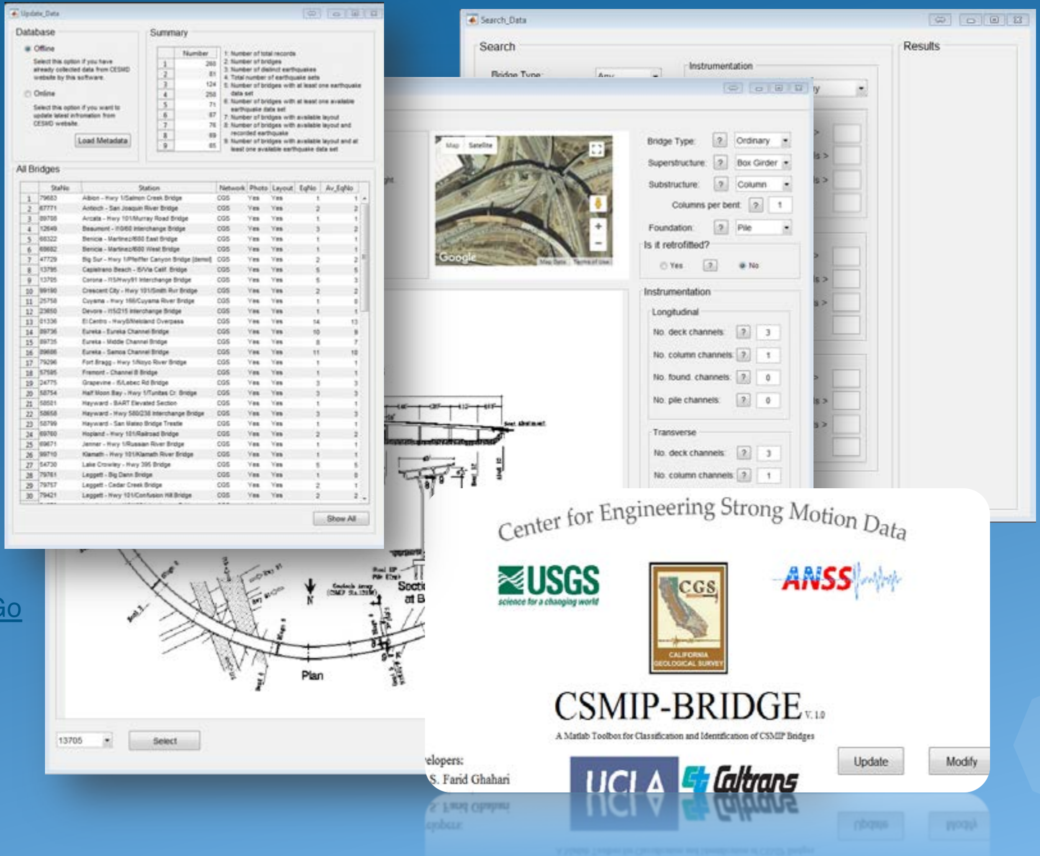
CSMIP-BRIDGE v1.0

- Automatically connects to CESMD (http://strongmotioncenter.org/)
- Retrieves all bridge data
- Determines number of various data sets (instrumented bridges, earthquake data sets per bridge, …)
- Reads all available information of each bridge
- User is able to add additional information
- Search module helps to classify bridges based on their specifications



https://youtu.be/GX69tdeEmGo

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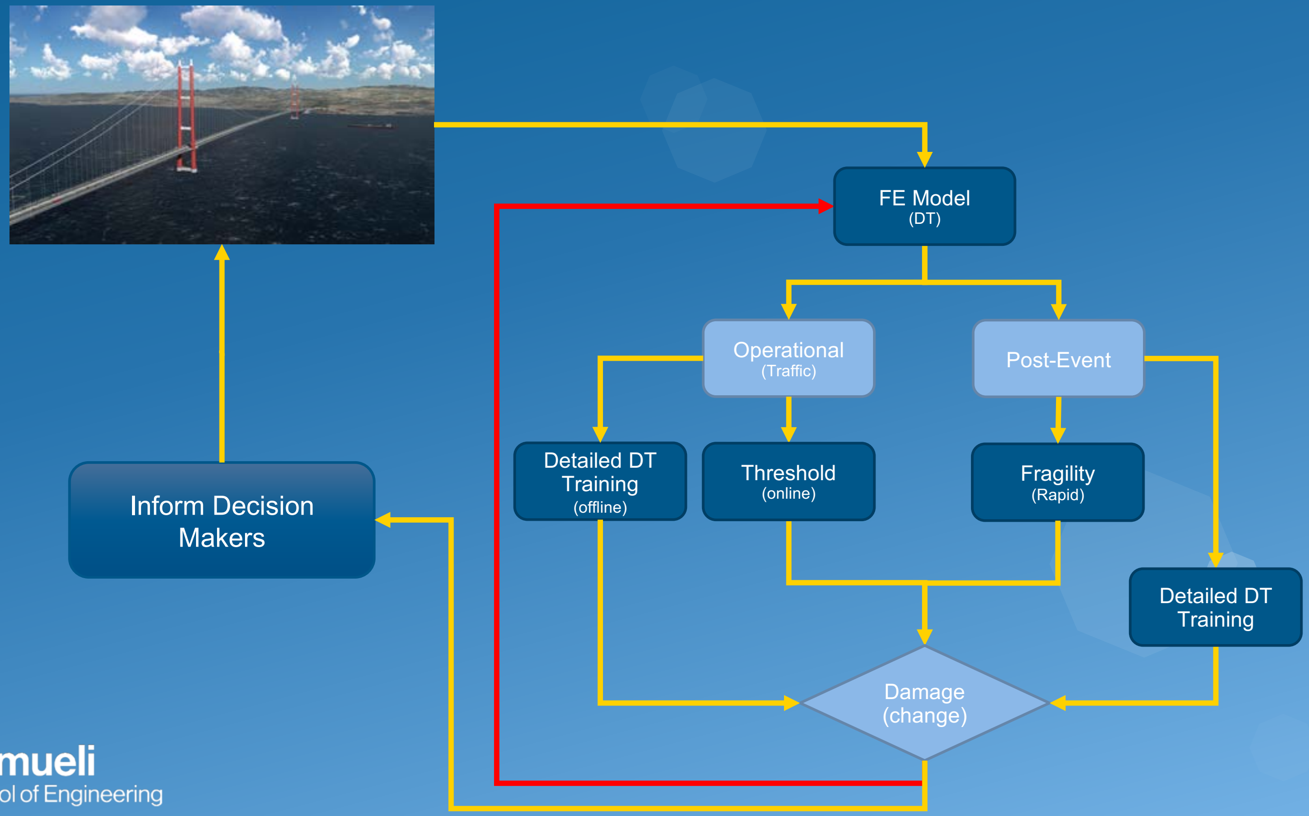
Our SPHM Workflow



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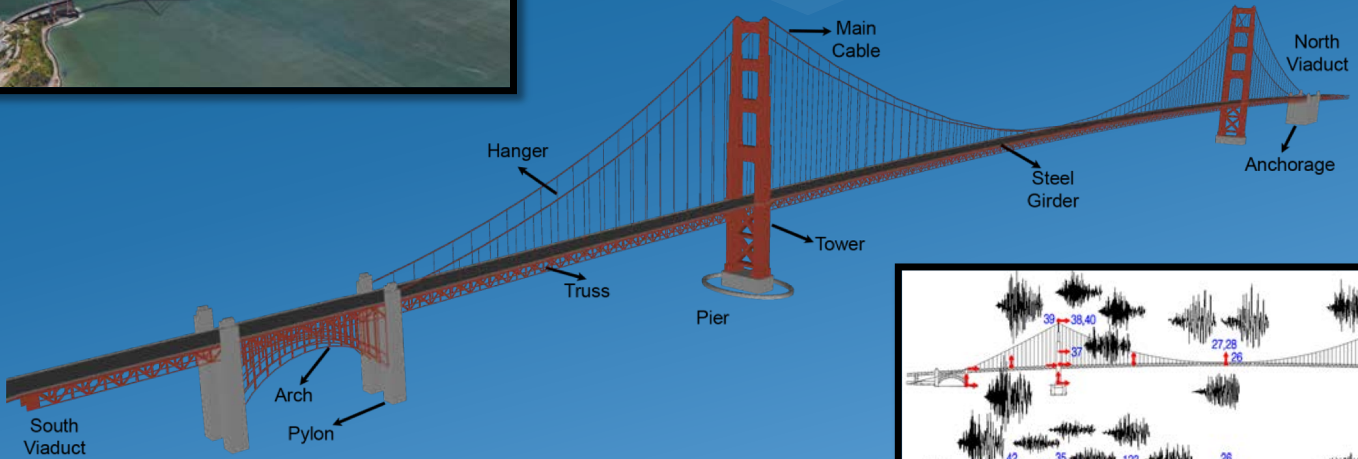
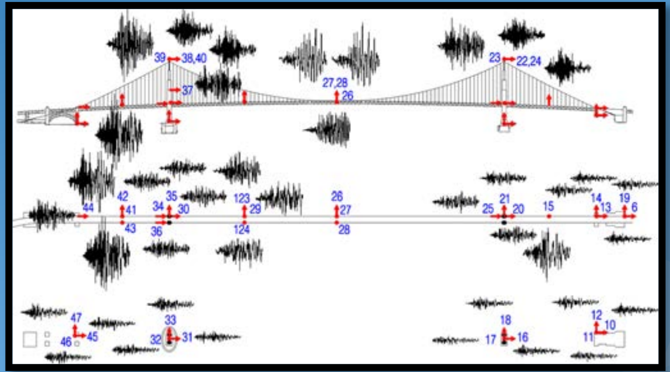
Detailed Post-Earthquake Assessment

Golden Gate Bridge, 2014 South Napa Earthquake





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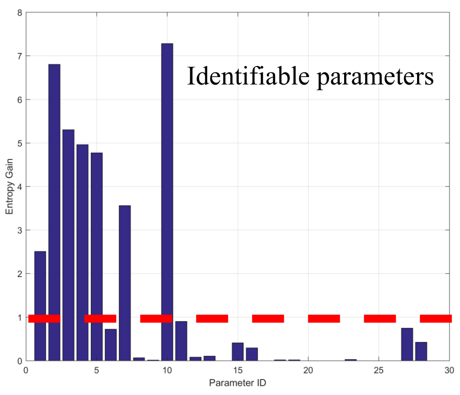
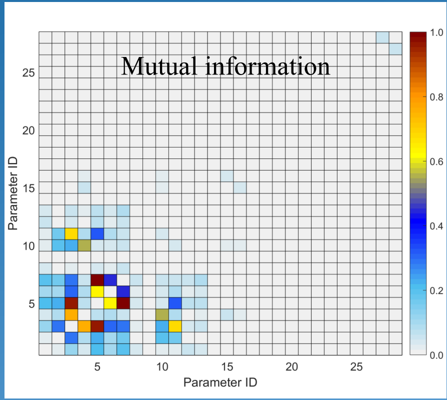
Identifiability

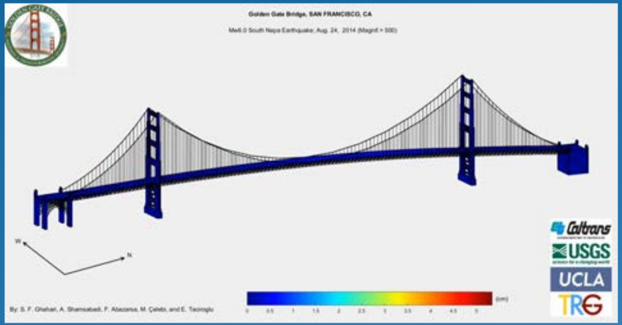
- We need to know how much information will be available through the posted channels
- We initially considered 66 unknown parameters.
- By removing certain parameters, we ended up with 28 unknown parameters.

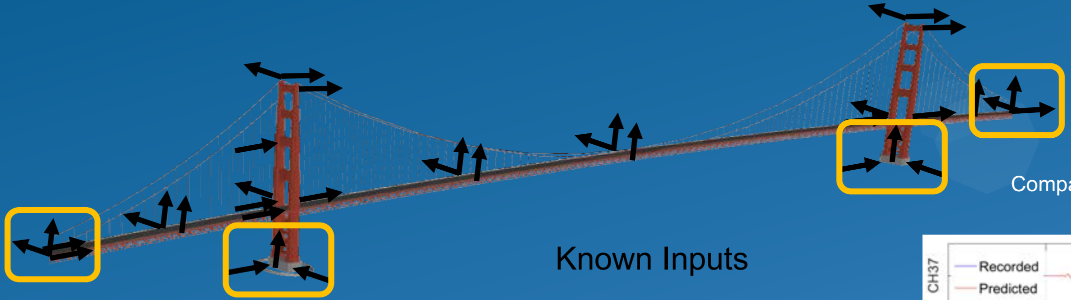




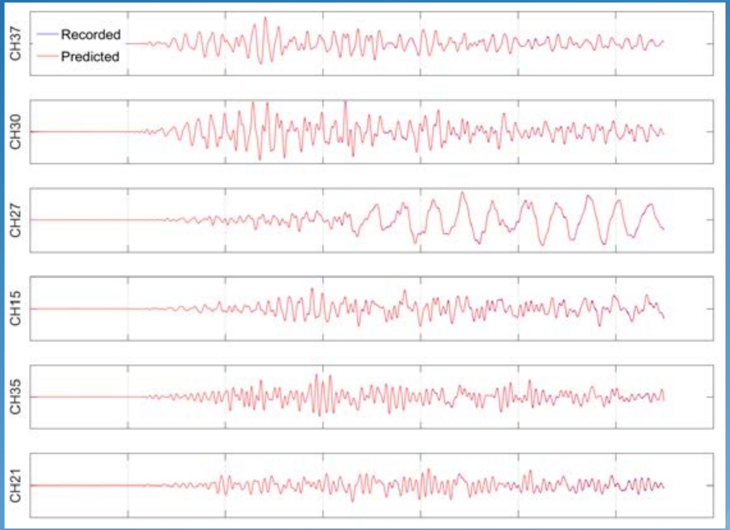
Final selection	No.	Element	Type
●	1	Bottom Bracing	Elastic Modules
●	2	Cable	Elastic Modules
●	3	Chord	Elastic Modules
●	4	Deck	Elastic Modules
●	5	Diagonal Bar	Elastic Modules
	6	Floor Beam	Elastic Modules
●	7	Hanger	Elastic Modules
	8	Kneebrace	Elastic Modules
	9	Top Bracing	Elastic Modules
●	10	Tower	Elastic Modules
	11	Track Girder	Elastic Modules
	12	Transverse Strut	Elastic Modules
	13	Vertical Rod	Elastic Modules
	14	Vertical Bar	Elastic Modules
	15	South Tower-South Side Span	Spring Stiffness, M2
	16	North Tower-North Side Span	Spring Stiffness, M2
	17	South Abutment	Spring Stiffness, P
	18	South Abutment	Spring Stiffness, V2
	19	South Abutment	Spring Stiffness, V3
	20	South Abutment	Spring Stiffness, T
	21	South Abutment	Spring Stiffness, M2
	22	North Abutment	Spring Stiffness, P
	23	North Abutment	Spring Stiffness, V2
	24	North Abutment	Spring Stiffness, V3
	25	North Abutment	Spring Stiffness, T
	26	North Abutment	Spring Stiffness, M2
●	27	Damping	Alpha
●	28	Damping	beta

IO Verification (Synthetic Data)





Comparison between recorded (simulated) and predicted responses at selected channels



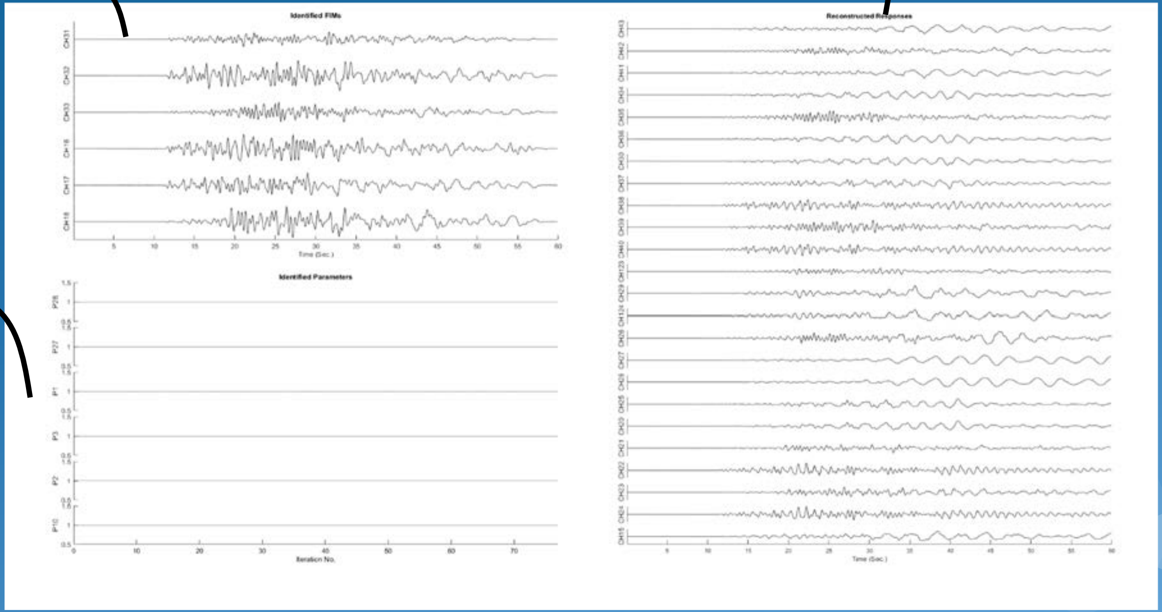
Parameter	Initial Error (%)	Final Error (%)
Tower's E	50	0.03
Cable's E	50	0.04
Chord's E	50	0.23
Bottom Bracing's E	50	1.59
Mass-Prop. Damping	50	2.38
Stiffness-Prop. Damping	50	13.76

OO Verification (Synthetic Data)

Recorded vs. predicted responses

Exact vs. estimated FIMs

Exact. identified parameters



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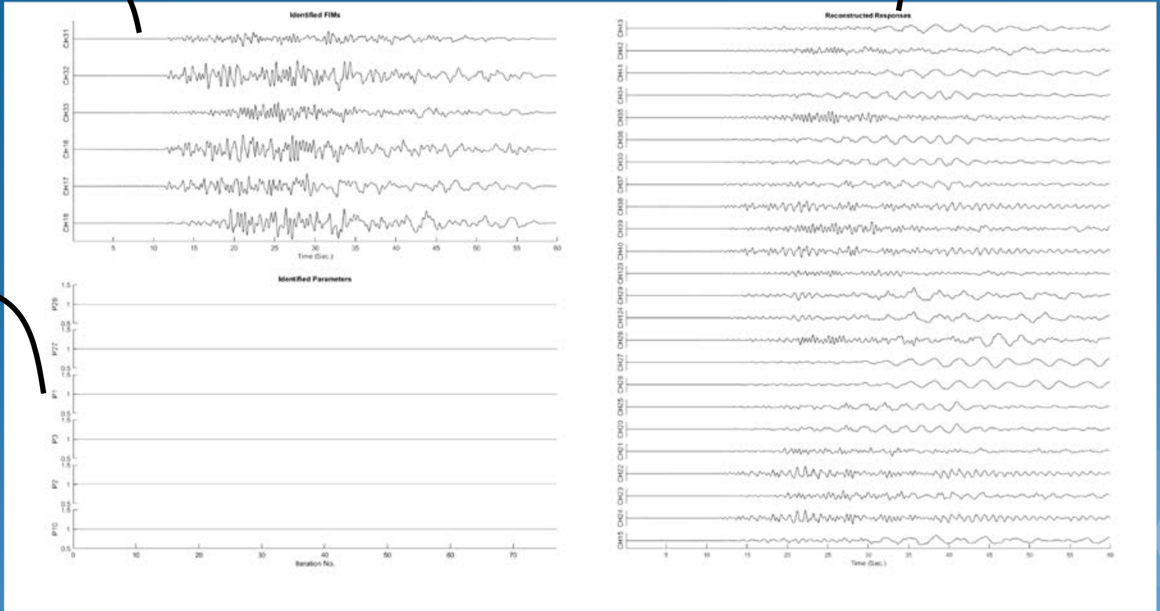
OO Validation (Real Data)

Recorded vs. predicted responses

Exact vs. estimated FIMs

Exact. identified parameters



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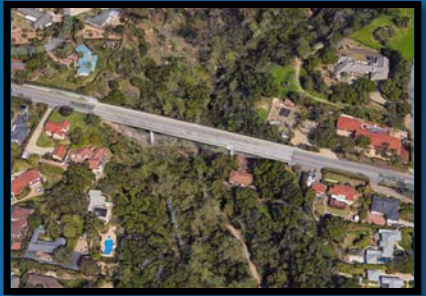
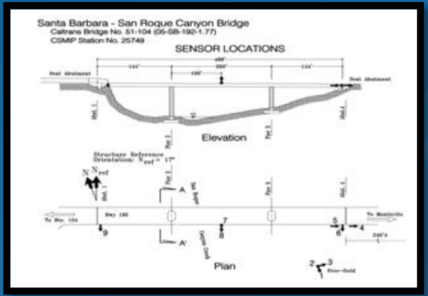
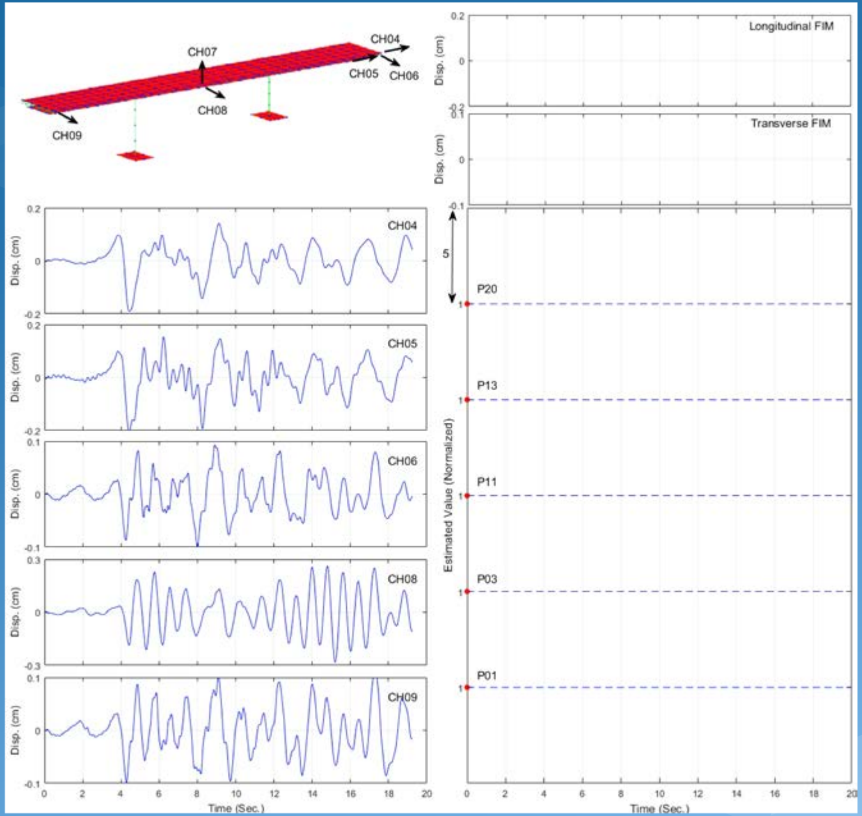
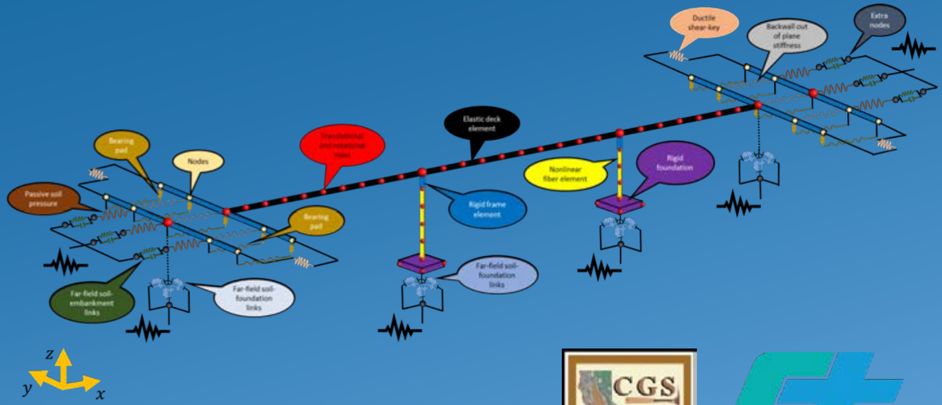
Ordinary Bridges: A validation study (SRC)









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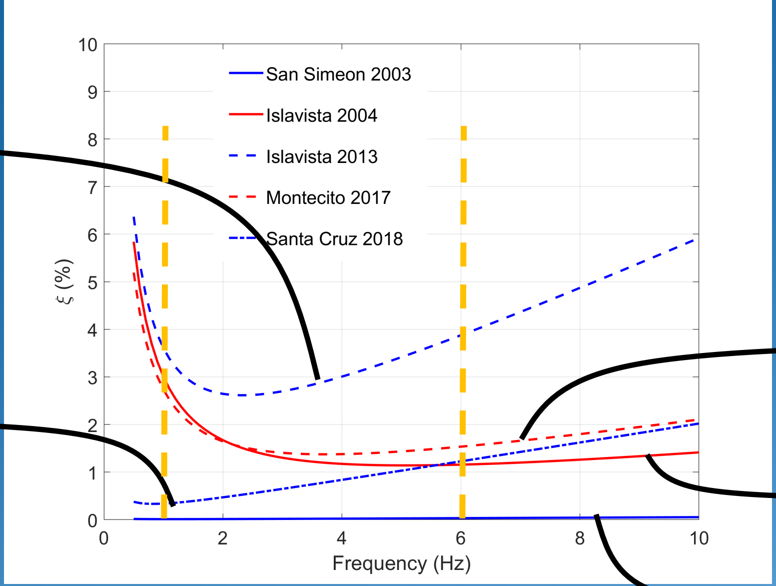
CGS CALIFORNIA GEOLOGICAL SURVEY

Caltrans

By-Product: Rayleigh Damping

ML=4.8
Depth=8 Km
R=18.0 Km
PGA=0.041 g
PSA=0.152 g

Mw=5.3
Depth=9.9 Km
R=68.0 Km
PGA=0.016 g
PSA=0.058 g



Larger level of excitation and higher frequency content wake up diffuse damping resources in the structure.
Contrary to the MRO, the role of boundaries in energy dissipation is small (at least in these limited low-intensity earthquakes). So the larger the intensity level is, the higher Rayleigh damping is observed.

ML=3.4
Depth=14.2 Km
R=9.5 Km
PGA=0.022 g
PSA=0.046 g

ML=4.4
Depth=4.4 Km
R=27.2 Km
PGA=0.016 g
PSA=0.047 g

Mw=6.5
Depth=4.7 Km
R=187.0 Km
PGA=0.015 g
PSA=0.045 g

High-frequency content of the low-amplitude far earthquakes is filtered out. The bridge moves quasi-statically!

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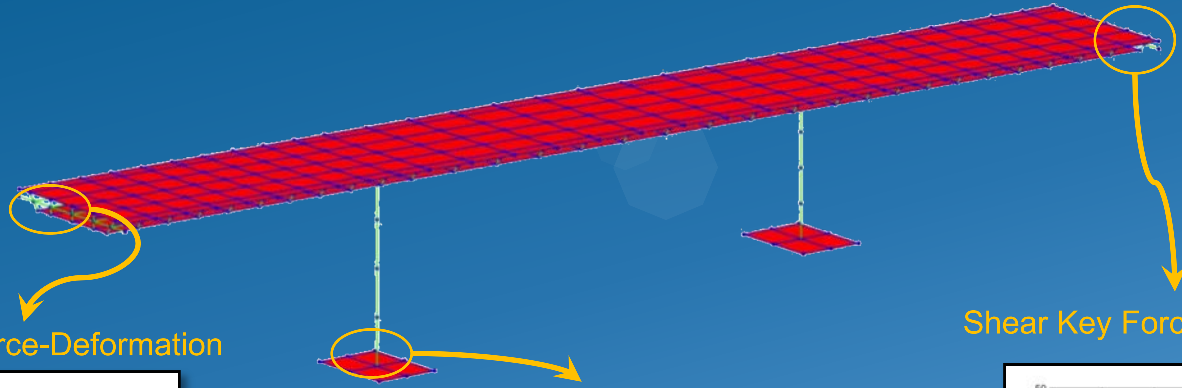
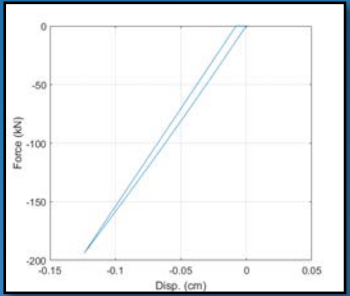
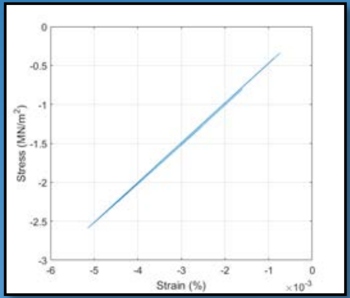
Virtual Sensors!



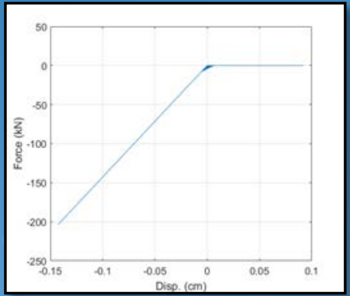
Passive Soil Force-Deformation



Concrete Fiber Material Response



Shear Key Force-Deformation



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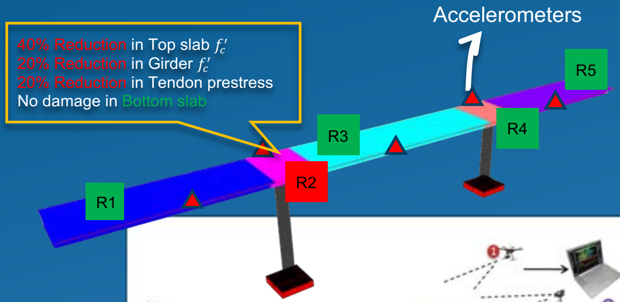
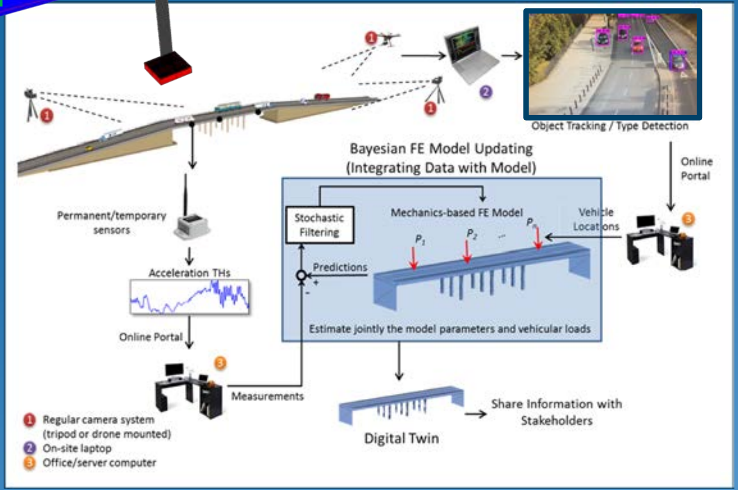
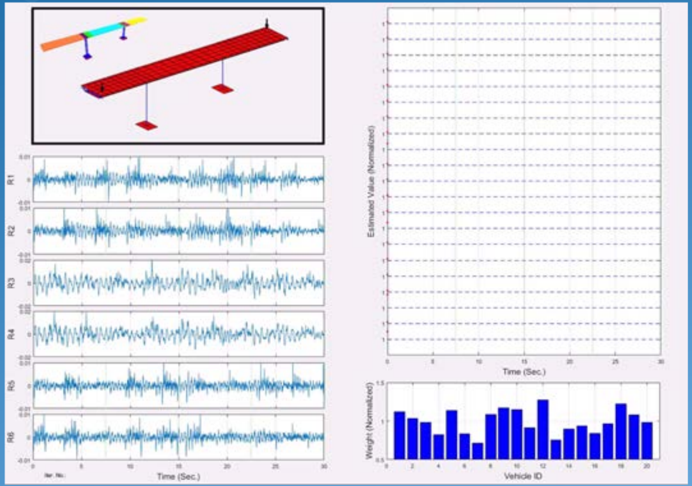
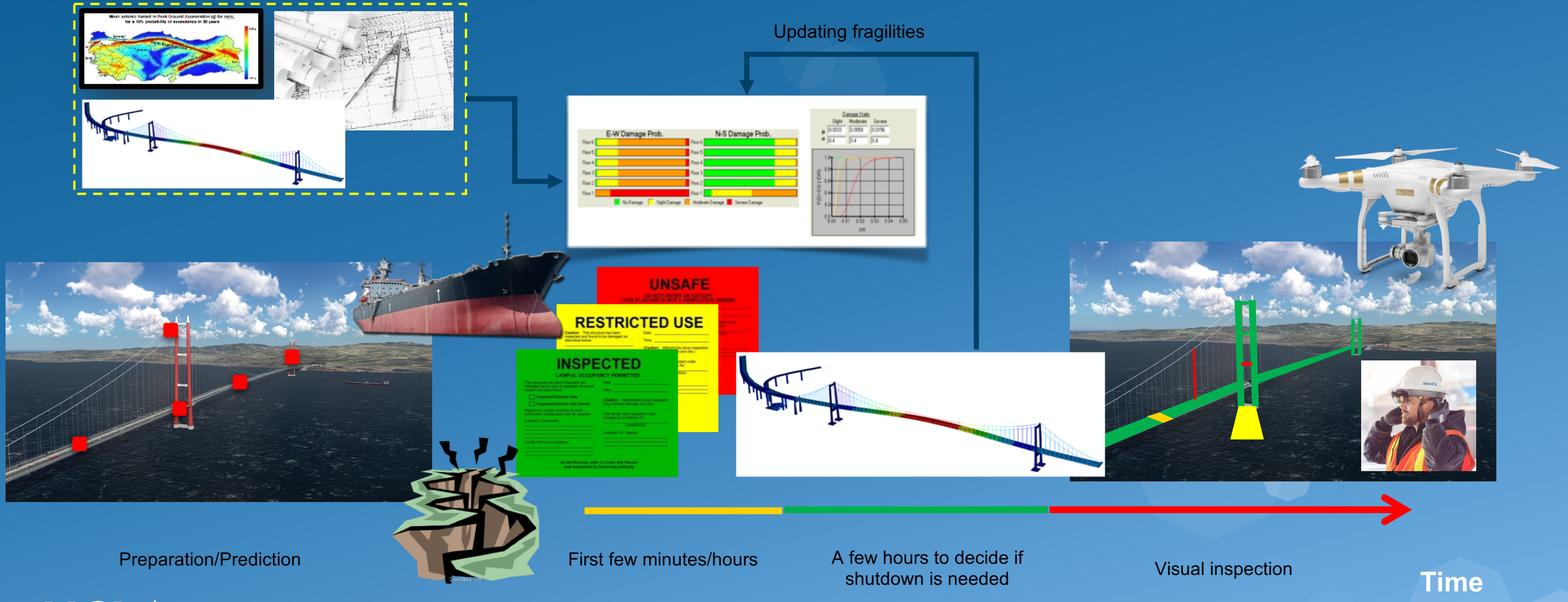
Operational Condition Assessment







Rapid Post-Event Assessment



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