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

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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
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
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!
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.
Current Practice: Periodic Inspection

- Visual inspection
  - Time-consuming and expensive
  - Periodic (discontinuous)
  - 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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  - Collisions, fire, etc.
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

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.
Sensor-Based SHM Solutions

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

Non-Destructive Evaluation

- Ultrasonic Test
- Tap Test
- Infrared Thermography
- Acoustic Emission
Vibration-Based SHM Solutions

Experimental (shaker, hammer)

Natural Events (earthquake, wind, explosion)

Operational (tremors, people, traffic, …)

System Identification
The Brain of the SHM

Time domain
Frequency Domain
Time-Frequency Domain
Input-Output
Output-Only
Model-Based
Data-Driven
Deterministic
Probabilistic
Non-Stationary
Stationary

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Existing SHM Solutions

Non-Destructive Evaluation

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

Vibration-Based Structural Health Monitoring

- Data Mining
- Operational Modal Analysis

Sensing Technology
Interpretation Algorithm

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

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

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

Non-Destructive Evaluation
- Ultrasonic Test
- Tap Test
- Infrared Thermography
- Acoustic Emission

Vibration-Based Structural Health Monitoring
- Data Mining
- Operational Modal Analysis
- Digital Twin

- Training data dependent
- Non-predictive
- Large and unquantified uncertainty
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- Dense sensor installation
- Insensitive Modal properties
- Linear response assumption
- White noise input assumption
- Classical damping
- Physics-based model
- Nonlinear behavior
- Arbitrary input excitations
- Uncertainty quantification
- Remaining life estimation
- Case-specific
- System level insight
- Hidden damage identification

- Expensive
- Not applicable at every location
- Not applicable continuously
- Performance interruption
- No system-level insight
A Decade of Study

2006-2019

Parametric identification of framed structures using an improved finite element model updating method—Part I: formulation and verification

Enhance, Liang-Qing, and Peter Wolter

Modal System Identification and Finite Element Model Updating of a 19-Story Building Using Earthquake and Ambient Vibration Data

Liu Guolei and Guangyu Sun

On Forced Vibration Testing for Quantifying Damage in Building Structures

T. T. T. Tsang and S. Y. Choy

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

E. A. T. C. Little, Y. T. Tsang, and P. R. J. D. Telegraph

Blind identification of soil–structure systems

T. T. T. Tsang and S. Y. Choy

Response-only modal identification of structures using limited sensors

A. V. Badria, S. Y. Choy, and T. T. T. Tsang

Response-only modal identification of structures using strong motion data

A. V. Badria, S. Y. Choy, and T. T. T. Tsang

Blind modal identification of structures from spatially sparse seismic response signals

A. V. Badria, S. Y. Choy, and T. T. T. Tsang

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

A. V. Badria, S. Y. Choy, and T. T. T. Tsang

Blind modal identification of non-classically damped structures under non-stationary excitations

A. V. Badria, S. Y. Choy, and T. T. T. Tsang

Bayesian identification of soil-foundation stiffness of building structures

N. E. M. Hoque, M. M. Chowdhury, and S. Y. Choy

Probabilistic Model Identification of Site Effects from Surface Response Signals

N. E. M. Hoque, M. M. Chowdhury, and S. Y. Choy

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

N. E. M. Hoque, M. M. Chowdhury, and S. Y. Choy

Estimation of the Substructure Model Parameters for the Millennium Library Building Using a Sequential Bayesian Finite Element Model Updating Technique

E. K. Bekiroglu, S. Y. Choy, and Y. Z. Chang

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Our Solution: SHM Rapid PEA using Digital Twins

- Operational Assessment
- Rapid Post-Event Assessment
- Detailed Post-Event Assessment
- Prediction/Preparation

Digital World

Response Prediction

Real World

Model Updating / training
Some Theory

Nonlinear FE Model

Prior Information

Simulation Error Model

Bayesian Updating

Regardless of the type of excitation (operational, event)

\[ \hat{Y} = f(\Psi) \]

\[ Y - \hat{Y}(\Psi) \sim N(0, R) \]
Method’s Capabilities

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

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

**Vincent Thomas Bridge**
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
Progress Toward Real-Life Applications

- Parallelization
- Scalability
- Nonlinear model updating using input-output data
- Real-world, large-scale applications
- Joint input and nonlinear system ID
- Heterogeneous sensors
- Information fusion

2014
- Nonlinear model updating using input-output data

2015
- Parallelization
- Scalability
- Joint input and nonlinear system ID

2016
- Real-world, large-scale applications

2017
- Heterogeneous sensors
- Information fusion

2018
- 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
Samoa Bridge

Earthquake Data

<table>
<thead>
<tr>
<th>Event</th>
<th>Date</th>
<th>Magnitude</th>
<th>Source Location</th>
<th>Sp. Dist. (km)</th>
<th>PGA (g)</th>
<th>PGV (cm/s)</th>
<th>Data Availability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Large Monarchic</td>
<td>09/04/01</td>
<td>5.8 Mw</td>
<td>40.39</td>
<td>125.24</td>
<td>0.006</td>
<td>0.002</td>
<td>Yes</td>
</tr>
<tr>
<td>Turmoil</td>
<td>08/27/02</td>
<td>5.3 Ml</td>
<td>40.39</td>
<td>120.61</td>
<td>0.035</td>
<td>0.128</td>
<td>No</td>
</tr>
<tr>
<td>Crescent City</td>
<td>06/04/05</td>
<td>7.2 Ml</td>
<td>41.39</td>
<td>125.87</td>
<td>0.059</td>
<td>0.015</td>
<td>Yes</td>
</tr>
<tr>
<td>Offshore</td>
<td>02/25/20</td>
<td>5.1 Ml</td>
<td>40.862</td>
<td>124.87</td>
<td>0.011</td>
<td>0.022</td>
<td>Yes</td>
</tr>
<tr>
<td>Trinidad</td>
<td>08/04/07</td>
<td>5.1 Ml</td>
<td>41.18</td>
<td>124.80</td>
<td>0.028</td>
<td>0.072</td>
<td>Yes</td>
</tr>
<tr>
<td>Willow Creek</td>
<td>06/06/08</td>
<td>5.4 Mw</td>
<td>40.64</td>
<td>123.50</td>
<td>0.017</td>
<td>0.092</td>
<td>Yes</td>
</tr>
<tr>
<td>Trinidad</td>
<td>08/14/08</td>
<td>6.8 Mw</td>
<td>41.18</td>
<td>124.20</td>
<td>0.018</td>
<td>0.075</td>
<td>Yes</td>
</tr>
<tr>
<td>Radial Area</td>
<td>01/09/13</td>
<td>6.5 Mw</td>
<td>40.65</td>
<td>126.76</td>
<td>0.150</td>
<td>0.370</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Ambient Data

BMD

Classic

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“North” abutment

“South” abutment

Location of the CGS box

Geotechnical array

Samoa Channel Bridge

Samoa Channel

3.1143844

N40.82044
Response Prediction

An earthquake occurred right after completing the project!
CSMIP Buildings

Blind Prediction

7th Floor

4th Floor
Workflow To Solve Any Problem Size

- Google images
- Structural drawings
- OpenSees model
- Domain decomposition (n cores)
- Available FE models
- Initialization
- Run (in OpenSeesMP instances)
- Read results
- Prepare TCL packages (n packages)
- Assign each MPIs a package (Bash script)
- Request cores (nxm)
- Call n MPIs (Bash script)
- Update TCL files
Modeling Capabilities

West Carquinez Bridge
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.
SAP2OS Converter Tool

San Roque Canyon Bridge, 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

Meloland Road Overpass, 1st Mode

Millikan Library, 1st Mode
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
Our SPHM Workflow

Inform Decision Makers

FE Model (DT)

Operational (Traffic)

Post-Event

Detailed DT Training (offline)

Threshold (online)

Fragility (Rapid)

Damage (change)

Detailed DT Training
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.

### Identifiable parameters

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

### Mutual information

Final selection

- 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.
IO Verification (Synthetic Data)

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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Initial Error (%)</th>
<th>Final Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tower’s E</td>
<td>50</td>
<td>0.03</td>
</tr>
<tr>
<td>Cable’s E</td>
<td>50</td>
<td>0.04</td>
</tr>
<tr>
<td>Chord’s E</td>
<td>50</td>
<td>0.23</td>
</tr>
<tr>
<td>Bottom Bracing’s E</td>
<td>50</td>
<td>1.59</td>
</tr>
<tr>
<td>Mass-Prop. Damping</td>
<td>50</td>
<td>2.38</td>
</tr>
<tr>
<td>Stiffness-Prop. Damping</td>
<td>50</td>
<td>13.76</td>
</tr>
</tbody>
</table>
OO Verification (Synthetic Data)

Recorded vs. predicted responses

Exact vs. estimated FIMs

Exact identified parameters
OO Validation (Real Data)

Exact vs. estimated FIMs

Recorded vs. predicted responses

Exact identified parameters
Ordinary Bridges: A validation study (SRC)
By-Product: Rayleigh Damping

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.

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

Passive Soil Force-Deformation

Concrete Fiber Material Response

Shear Key Force-Deformation
Operational Condition Assessment

- 40% Reduction in Top slab $f'\text{c}$
- 20% Reduction in Girder $f'\text{c}$
- 20% Reduction in Tendon prestress
- No damage in Bottom slab

Accelerometers

Bayesian FE Model Updating
(Integrating Data with Model)

Digital Twin

Share Information with Stakeholders
Rapid Post-Event Assessment

First few minutes/hours

A few hours to decide if shutdown is needed

Visual inspection

Preparation/Prediction

Updating fragilities
thank you