THE PIVOTAL ROLE OF INSTRUMENTATION IN ACHIEVING A SUSTAINABLE INFRASTRUCTURE
A Structural Engineer’s Perspective

2022 UCI CEE Affiliates Meeting
May 18, 2022

Farzad Naeim, PhD, SE, Esq, NAE
Adjunct Professor, University of California, Irvine
What is the problem?

- Achieving a sustainable infrastructure in USA is an important and noble objective.
- Most, if not all, of the efforts so far though are concentrated on analysis and design techniques and methodologies.
- But how would you ever know if you have achieved a sustainable building or not?
  - Not days, weeks or months after a disaster, but immediately?
What is the solution?

1. Use existing instrumentation
2. Instrument more structures
3. Move from instrumentation to health monitoring
4. Realize what Talhan Biro calls “Black Box for Structures"
Talhan Biro’s Concept of Building Black Boxes

Flight’s memory stored in ‘Black boxes’

Commercial aircraft are required to carry two data recorders. One records all radio transmissions and sounds in the cockpit and the other monitors parameters of the flight such as airspeed and altitude – all vital in reconstructing an accident.

BLACK BOX

High-temperature insulation

Stainless steel shell

Circuit boards

Data storage: Older analog units use magnetic tape and newer ones use computer chips. Underwater locator beacon transmits a ‘ping’ once a second.

S2HM in a box: blackbox for structures

S2HM = Structural Seismic Health Monitoring

Factual data + Proven methods

After an event + Continuously


SOURCE: National Transportation Safety Board

May 18, 2022
UCI CEE Affiliates Meeting
Cars + Accidents

Performance Target: Life Safety
Design: Nonlinear Analysis with performance target
Testing: Full scale Prototype testing
Risk: Unrepairable Car
Solution/Timeline: Replacement, days
Funding source: Insurance (+ Owner)
Societal & Economic Impact: a few people, $k

Risk: Same performance target/aspiration, but vastly different Societal & Economic Impact

Structures + Earthquakes

Performance Target: Life Safety
Design: Linear Analysis with performance aspirations
Testing: Generalized component testing
Risk: Unusable Building and/or Infrastructure
Solution/Timeline: Costly Repair/Replacement, years
Funding source: Owner (+ some $s from insurance)
Societal & Economic Impact: thousands of people, $B
Cars + Accidents

Performance Target: Life Safety
Design: Nonlinear Analysis with performance target
Testing: Full scale Prototype testing
Risk: Unrepairable Car
Solution/Timeline: Replacement, days
Funding source: Insurance (+ Owner)
Societal & Economic Impact: a few people, $k

Different Design Approach (MRI vs Xray): Majority of Building Designs are based on linear-analyses, not driven by specific performance targets

Structures + Earthquakes

Performance Target: Life Safety
Design: Linear Analysis with performance aspirations
Testing: Generalized component testing
Risk: Unusable Building and/or Infrastructure
Solution/Timeline: Costly Repair/Replacement, years
Funding source: Owner (+ some $s from insurance)
Societal & Economic Impact: thousands of people, $B

May 18, 2022
UCI CEE Affiliates Meeting
Structural integrity and sustainability are not the same!

Severe nonstructural damage at the International Airport in Santiago as a result of the 2010 Maule, Chile earthquake.

(Miranda, Kazantzi and Vamvatsikos, 2018)
Structural integrity and sustainability are not the same!

Severe nonstructural damage of the commercial building as a result of the 2011 Christchurch, New Zealand earthquake.
Many of these buildings maybe life-safe but are unlikely to be functional or repairable in a short time after a major earthquake.
Europe Implementation of S2HM

Q-NAVI Installations in Japan

California Strong Motion Instrumentation Program (CSMIP) contains data for 300+ extensively instrumented buildings.

All buildings are connected to a central server via Internet.

The data is automatically processed and sent to the server immediately following any triggering earthquake.

This data is available at [https://www.cesmd.org](https://www.cesmd.org)

Individual owners can enter into an agreement with CSMIP to monitor their instrumented buildings and publish the data on the CSMIP server.

USGS has a number of even more extensively instrumented buildings.
San Francisco - 62-story Residential Bldg
(CSMIP Station No. 58389)
(NSMP Station No. 8389)

Elevation A-A' (N/S)  Elevation B-B' (E/W)

Level 1 (P4) Plan

Level 5 (Lobby) Plan

SENDER LOCATIONS

12" concrete wall

3" seismic joint

6" seismic joint

Adjacent 7-story podium structure

12" mat foundation

Structure Reference Orientation: $N_{ref} = 315^\circ$

32" concrete shear walls

Outrigger concrete columns (28" x 76")

Level 1 (P4) Plan

Level 5 (Lobby) Plan

Adjacent podium structure

Tower projection

Tower projection

$N_{ref}$


Installed: 5/18/2012

Courtesy of John Hooper
Please note that for reliable real-time structural health monitoring and performance evaluations a substantially larger number of channels may be necessary (Naeim 2011).

- The sensors shall be connected by dedicated cabling to one or more central recorders, interconnected for common time and triggering.
- At least three uniaxial horizontal accelerometers on each chosen floor.
EXAMPLES OF UTILITY
Use of Fragility Functions

Response Parameter

Fragility Functions

Animation courtesy of Prof. Eduardo Miranda

\[ \text{IDR} = \frac{\Delta}{H} \]
Example of a structural fragility function

INCREASING STORY DRIFT RATIO

DM₁  DM₂  DM₃  DM₄

First Visible Damage  Wide cracks  Punching failure  Loss of vertical carrying capacity

Illustration courtesy of Prof. Eduardo Miranda
Example of a structural fragility function

- **First Visible Damage**
- **Wide cracks**
- **Punching failure**
- **Loss of vertical carrying capacity**

Illustration courtesy of Prof. Eduardo Miranda
Example of a nonstructural fragility function

INCREASING STORY DRIFT RATIO

DM₁  DM₂  DM₃

Light cracking  Damage to panels  Damage to panels and frames

Illustration courtesy of Prof. Eduardo Miranda
Example of a nonstructural fragility function

<table>
<thead>
<tr>
<th>Specimen Name</th>
<th>$D_{S1}$</th>
<th>$D_{S2}$</th>
<th>$D_{S3}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S1$</td>
<td>0.0013</td>
<td>0.0025</td>
<td>0.0056</td>
</tr>
<tr>
<td>$S2$</td>
<td>0.0013</td>
<td>0.0026</td>
<td>0.0068</td>
</tr>
<tr>
<td>$S3$</td>
<td>0.0013</td>
<td>0.0026</td>
<td>0.0070</td>
</tr>
<tr>
<td>$S4$</td>
<td>0.0013</td>
<td>0.0026</td>
<td>0.0075</td>
</tr>
<tr>
<td>$S5$</td>
<td>0.0013</td>
<td>0.0037</td>
<td>0.0079</td>
</tr>
<tr>
<td>$S6$</td>
<td>0.0014</td>
<td>0.0042</td>
<td>0.0081</td>
</tr>
<tr>
<td>$S7$</td>
<td>0.0017</td>
<td>0.0042</td>
<td>0.0094</td>
</tr>
<tr>
<td>$S8$</td>
<td>0.0017</td>
<td>0.0046</td>
<td>0.0102</td>
</tr>
<tr>
<td>$S9$</td>
<td>0.0019</td>
<td>0.0052</td>
<td>0.0113</td>
</tr>
<tr>
<td>$S10$</td>
<td>0.0020</td>
<td>0.0052</td>
<td>0.0115</td>
</tr>
<tr>
<td>$S11$</td>
<td>0.0021</td>
<td>0.0052</td>
<td>0.0115</td>
</tr>
<tr>
<td>$S12$</td>
<td>0.0021</td>
<td>0.0052</td>
<td>0.0188</td>
</tr>
</tbody>
</table>

Illustration courtesy of Prof. Eduardo Miranda
Example #1: Sylmar County Hospital

1994 Northridge Earthquake
Example #1: Sylmar County Hospital

- No significant structural damage but...
Example #1: Sylmar County Hospital

- Floor-by-floor structural system status:

Using HAZUS-MH Fragility Functions

No Damage to Slight Damage
Example #1: Sylmar County Hospital

- Floor-by-floor nonstructural system status:

  Using HAZUS-MH Fragility Functions

![Diagram showing floor-by-floor damage probabilities with E-W and N-S damage probabilities.

Moderate to Severe Damage]
Example #1: Sylmar County Hospital

• Suspended ceilings on the first floor:

Using FEMA P-58 Fragility Functions

Photo from Naeim, F. (1997)
Example #1: Sylmar County Hospital

- Unanchored file cabinets on the 6th floor:

  Using FEMA P-58 Fragility Functions

  Photo from Naeim, F. (1997)
## Example #2: Universal City Hotel

- **1994 Northridge Earthquake**
- **Deterministic floor-by-floor structural system status**

![Floor Damage Table]

Status: **Immediate Occupancy**
Example #2: Universal City Hotel

- Probabilistic floor-by-floor structural system status

Using HAZUS-MH Fragility Functions

Status: **No Damage to Slight Damage**; damage more likely in the N-S direction.
Example #2: Universal City Hotel

- Probabilistic floor-by-floor nonstructural system status

Using HAZUS-MH Fragility Functions

Status: No Damage to Severe damage; damage more severe in the N-S direction and in upper floors
Example #2: Universal City Hotel

- Suspended Ceiling at Penthouse

Using FEMA P-58 Fragility Functions

Status: Major damage

Photo from Naeim, F. (1997)
EXAMPLES OF S2HM IMPLEMENTATION IN CALIFORNIA?

None!

Despite some incentives provided by cities like San Francisco
• We need an attitude and a cultural change
• The relatively low cost of instrumentation and S2HM and the huge post-earthquake advantages it provides must be made clear to the public.
• Attractive incentives should be thought of and provided to those who implement S2HM.
• Changing the culture may not be easy but it is absolutely necessary if we want to achieve a sustainable infrastructure.
Thank you!