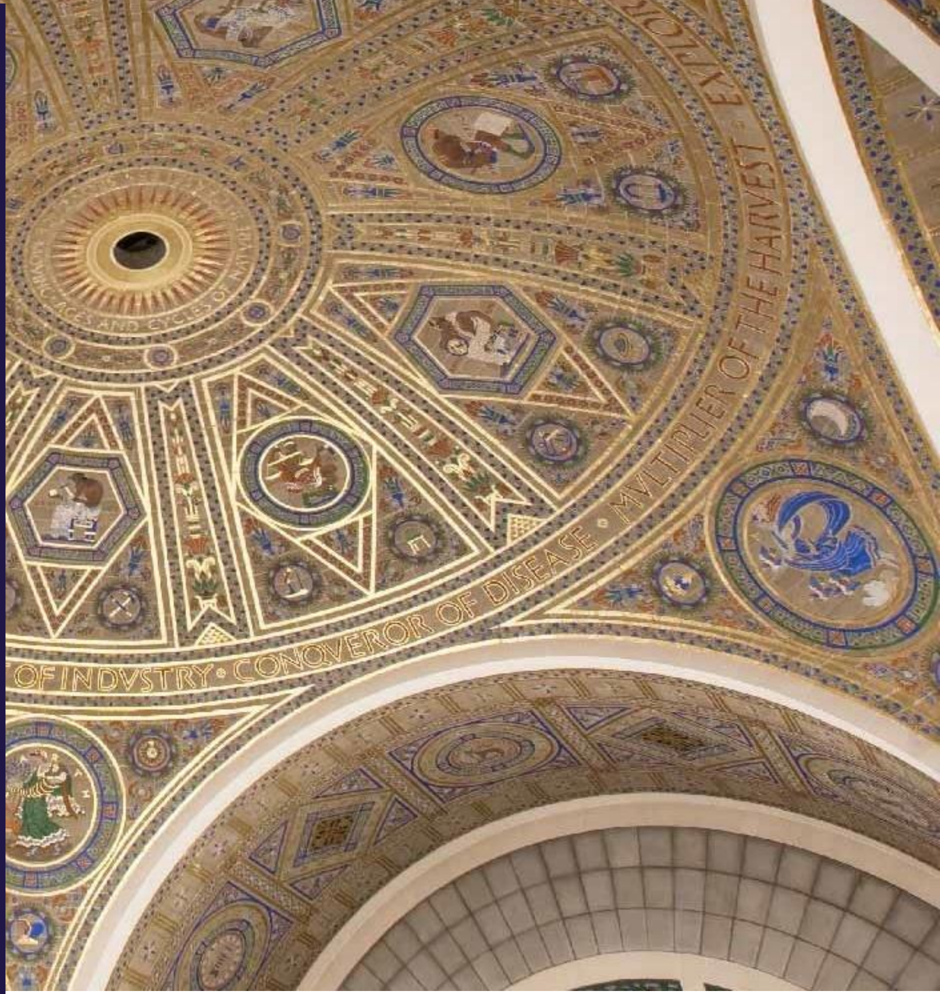
NATIONAL ACADEMIES Sciences Engineering Medicine

TRB TRANSPORTATION RESEARCH BOARD

TRB Webinar: Improving Seismic Bridge Design After the Northridge Earthquake

October 30, 2024

12:00 – 1:30 PM



PDH Certification Information

1.5 Professional Development Hours (PDH) – see follow-up email

You must attend the entire webinar.

Questions? Contact Andie Pitchford at TRBwebinar@nas.edu

The Transportation Research Board has met the standards and requirements of the Registered Continuing Education Program. Credit earned on completion of this program will be reported to RCEP at RCEP.net. A certificate of completion will be issued to each participant. As such, it does not include content that may be deemed or construed to be an approval or endorsement by the RCEP.

ENGINEERING RCEP REGISTERED CONTINUING EDUCATION PROGRAM

Purpose Statement

This webinar will reflect on this event’s lasting legacy, discuss advancements in innovative seismic design, and explore the lessons learned for future seismic resilience of bridge structures.

Learning Objectives

At the end of this webinar, you will be able to:

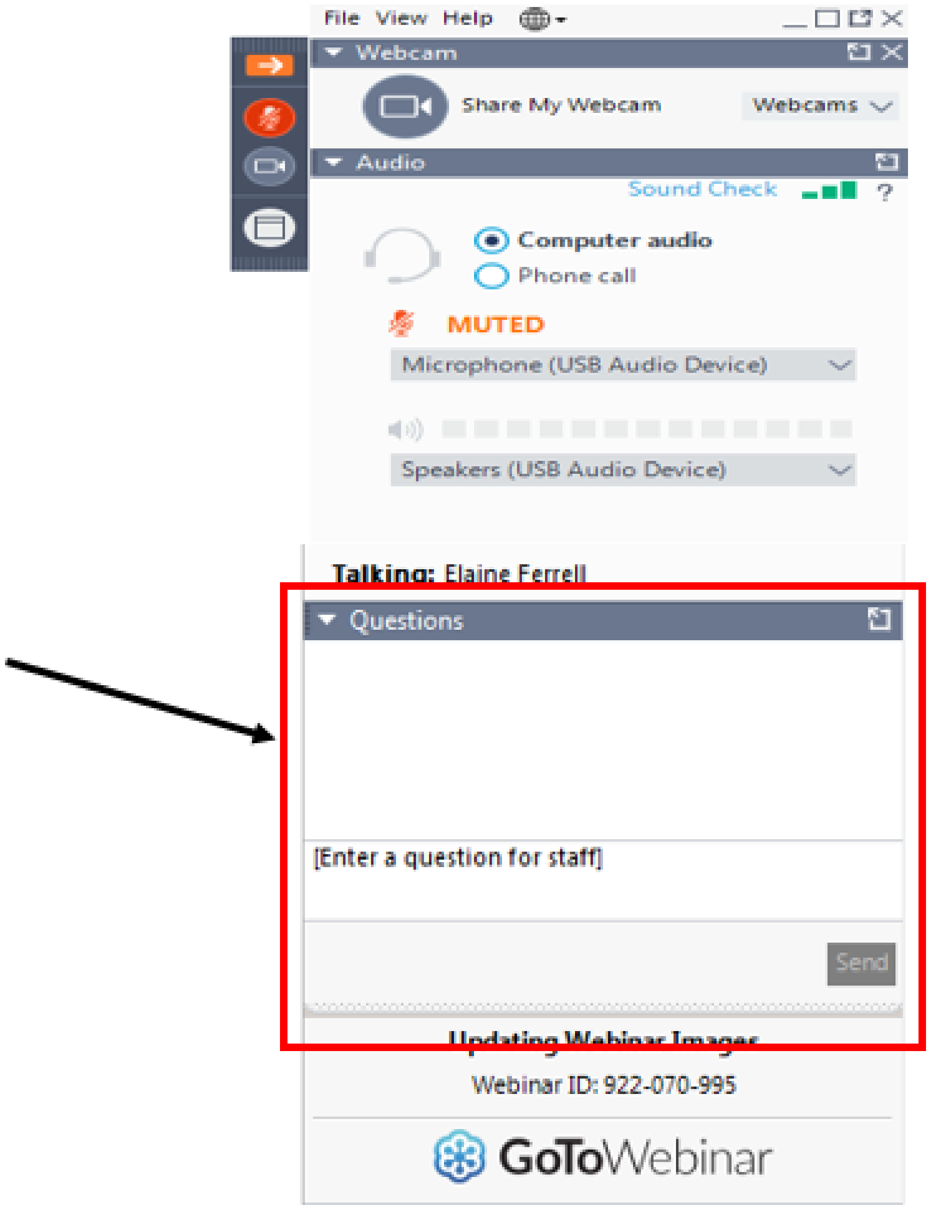
(1) Articulate the effects of the Northridge earthquake on the industry moving forward

(2) Apply new seismic bridge design concepts to improve resiliency

(3) Balance mass and stiffness in bridge structure seismic design

Questions and Answers

- Please type your questions into your webinar control panel
- We will read your questions out loud, and answer as many as time allows



Today's presenters

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Dr. Kyle Rollins

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Northridge Earthquake and California Bridges, a Historical Perspective

Mark Mahan
Ph.D., PE

Office of Earthquake Engineering, Analysis & Research
California Department of Transportation

Objectives: California Experience

- Focus: 1994 Northridge Earthquake
- History: Influence of three major California earthquakes.
  - 1971 San Fernando EQ.
  - 1989 Loma Prieta EQ.
  - 1994 Northridge EQ.
  - Show the influence of these earthquakes on Caltrans' Seismic Design Criteria (SDC).

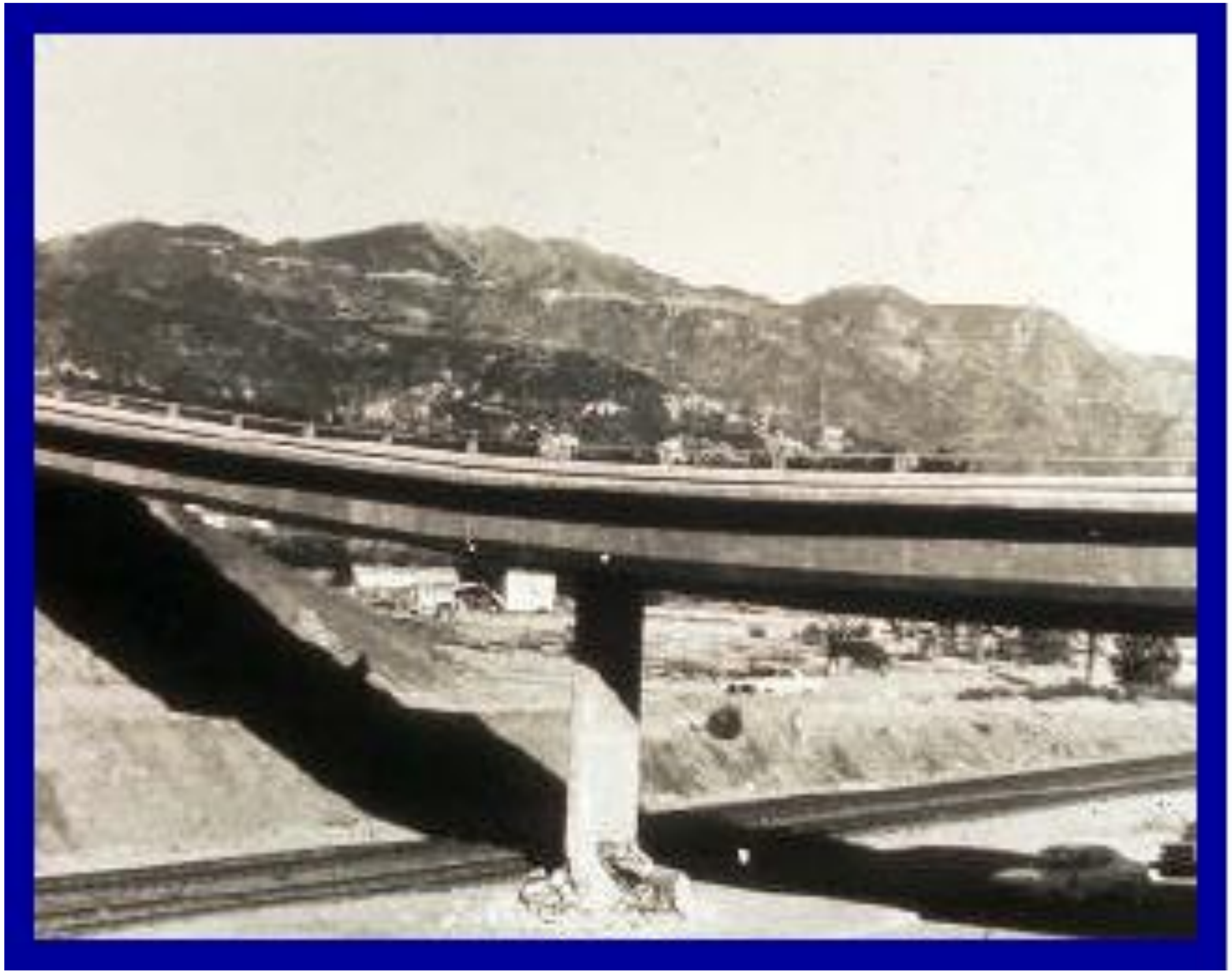
Objectives: California Experience

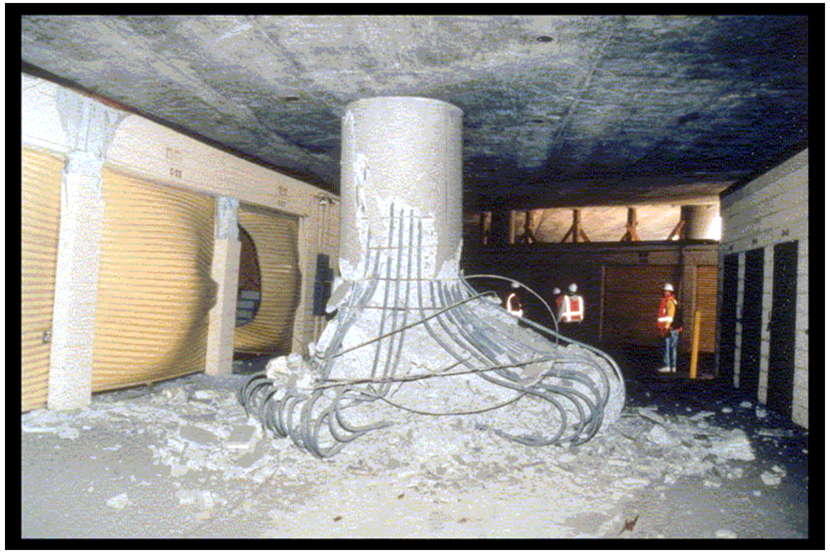
- Lessons Learned:
    - 1971 San Fernando EQ: Confinement
    - 1989 Loma Prieta EQ: Continuity
    - 1994 Northridge EQ: Balance
- Northridge EQ influence on substructure and foundation design.
- Column Isolation Casing.

1st Major California Earthquake and its Influence on SDC

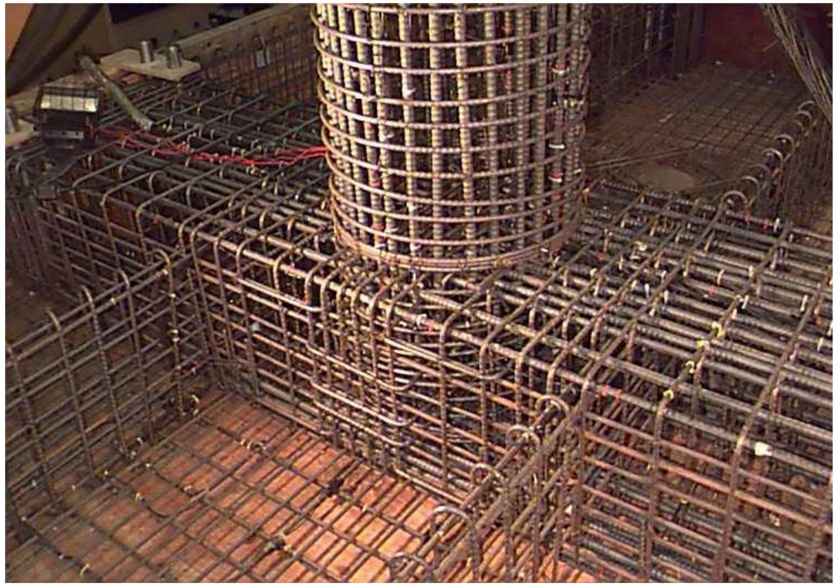
- 1971 San Fernando EQ: Collapse of multiple structures including Route I-5/I-405 Separation Structure resulted in:
- A drastic increase in “Confinement” reinforcement in columns.

1971 San Fernando earthquake





Caltrans' pre- 1971 columns,
1994 damage.



Caltrans' post-1989 test columns

Caltrans' new confined columns

Caltrans' Seismic Design Criteria

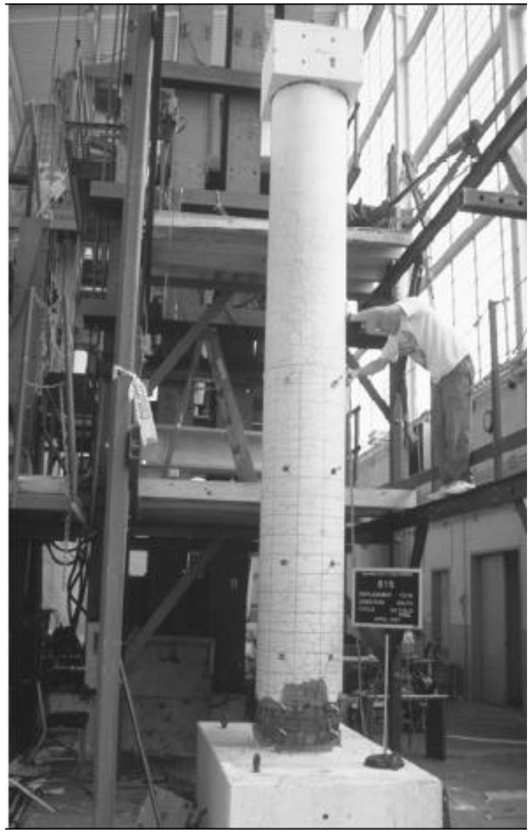
- Confinement:

  Caltrans' SDC 3.5.1

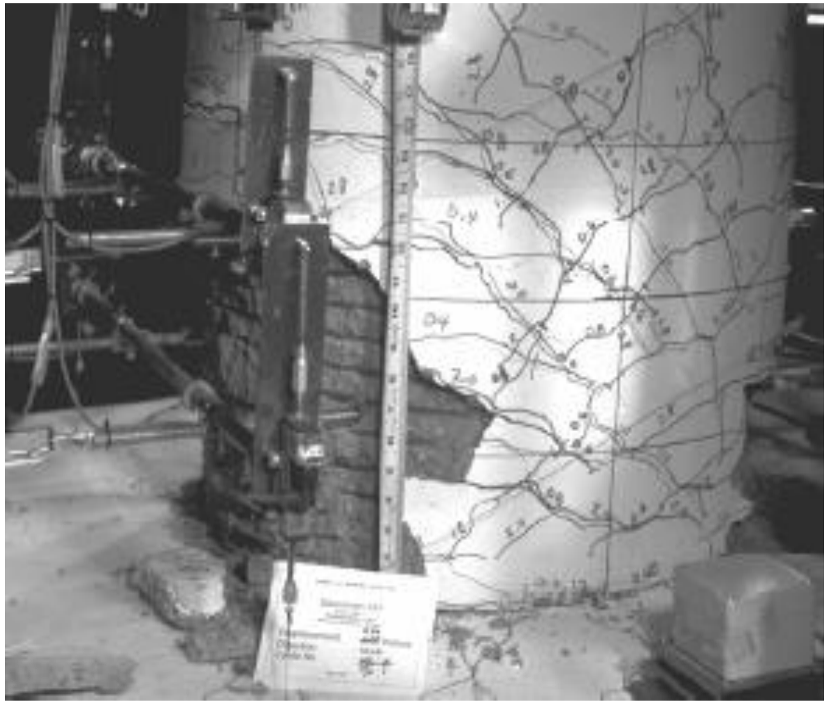
  $\Delta_C > \Delta_D$

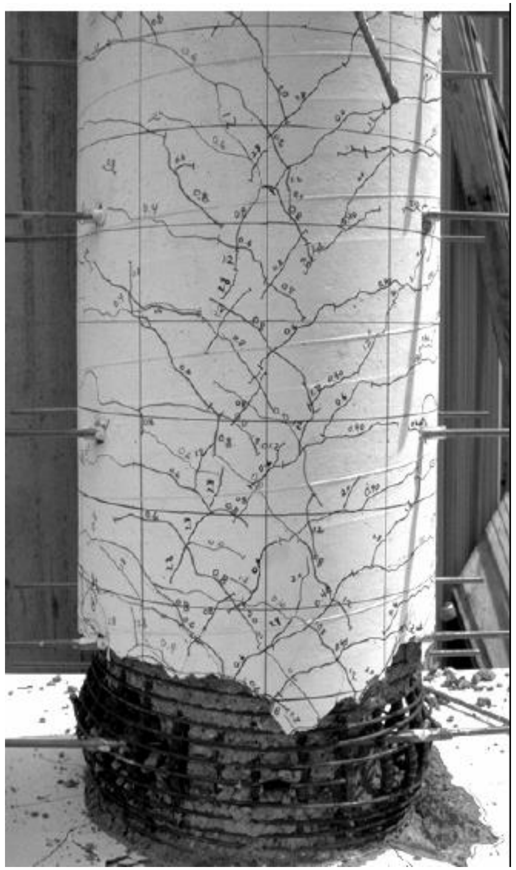
Caltrans' post- 1989 Column Testing of Plastic Hinges

Plastic Hinge: Segment of a column attracting maximum moment where the seismic energy is dissipated.

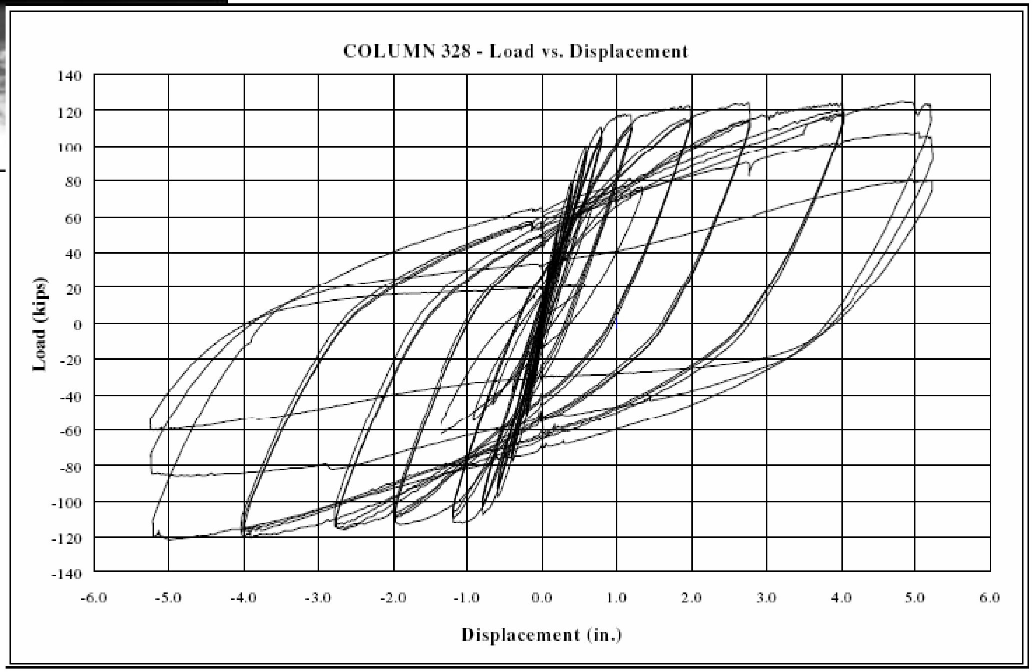


Caltrans' post- 1989 Column Testing





Caltrans' post- 1989 Column Testing



2nd Major California Earthquake and its Influence on SDC

- 1989 Loma Prieta EQ: Collapse of Bay Bridge and Cypress Street Viaduct resulted in:
  - An increase in the support seat width.
  - Better structural framing (Continuity).

1989 Loma Prieta Earthquake: The San Francisco-Oakland Bay Bridge lost a deck segment due to insufficient hinge seat

Caltrans' hinge seat, before 1971

Fairfax-Washington U.C. 53-1580 7-LA-10-R9.31 B-6-BKT
Bent 4 of WB Struc., Looking South.

Caltrans' Seismic Design Criteria

- **Continuity:**
  - Caltrans' SDC 7.2.3.2 and 6.3.3
    - Minimum 30" support length for in-span hinges abutments.
  - Caltrans' Cast-In-Place, post-tensioned box girder bridges have excellent continuity and framing. They meet the SDC requirements.
  - Improvements in Pre-Cast bridges meet the continuity requirements.

Caltrans' columns, before 1971

Caltrans' columns and shafts, new construction

Caltrans' columns and shafts, new construction

3rd Major California Earthquake and its Influence on SDC

- 1994 Northridge EQ: Collapse of I-5/SR-14 structures emphasized the concept of “Balance” in stiffness and mass from bent to bent.

1994 Northridge Earthquake: I-5/SR-14 collapse, lack of stiffness and mass “Balance” from bent to bent.

Route 14/Interstate 5 Interchange
Collapsed Connectors 53-1964F & 53-1960F

1994 Northridge Earthquake: I-5/SR-14 collapse.

14/5 Conn. Sep. & OH 53-1960F 7-LA-14/5-R14.73/R45.62 3-36-JSM
Pier #3 from above, looking East

1994 Northridge Earthquake: I-5/SR-14 collapse.

1994 Northridge Earthquake: I-5/SR-14 collapse.

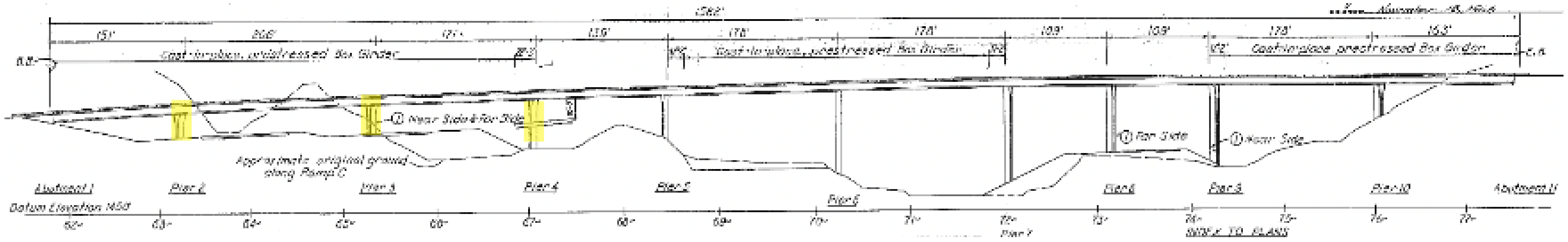
1994 Northridge Earthquake: I-5/SR-14 collapse.

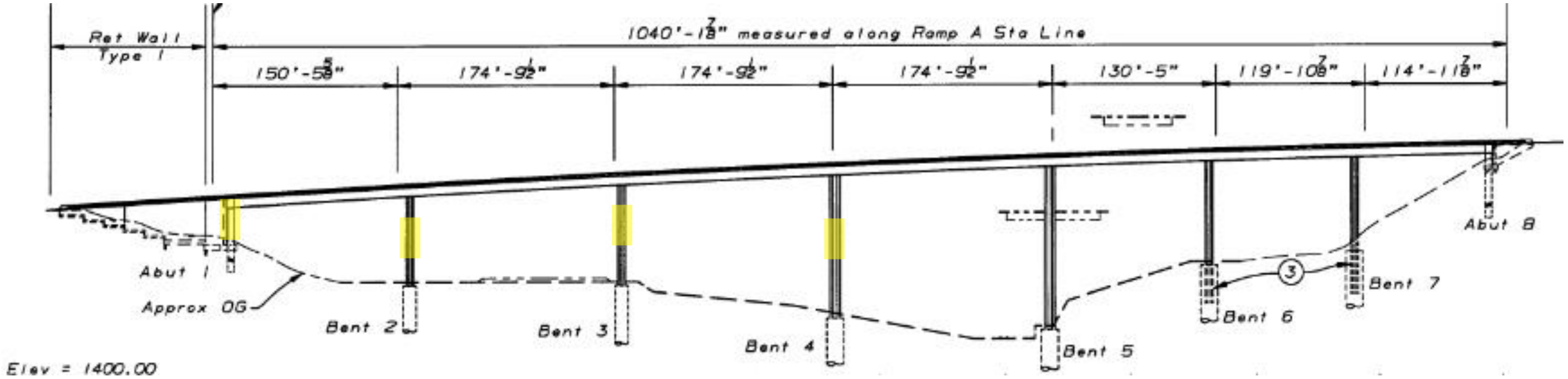
14/5 Conn. Sep. & OH 53-1960F 7-LA-14/5-R14.73/R45.62 1-8-BHM
Looking W @ pier 2

14/5 Conn. Sep. & OH 53-1960F 7-LA-14/5-R14.73/R45.62 4-23-RLI
Pier 2.

14/5 Conn. Sep. & OH 53-1960F 7-LA-14/5-R14.73/R45.62 3-26-JSM
Abutment #1.

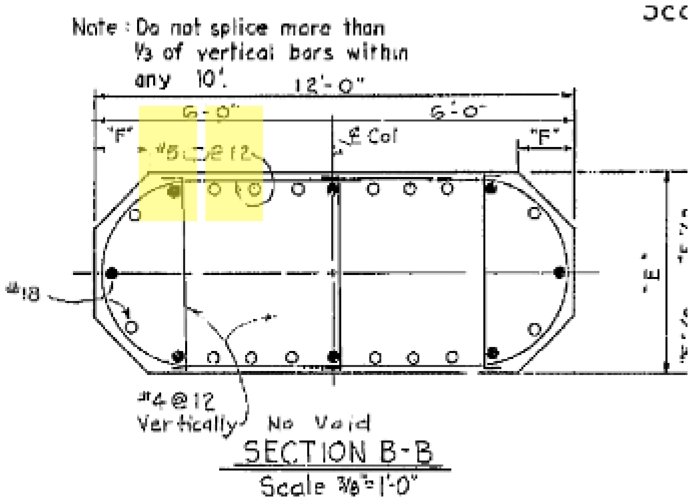
I-5/SR-14. Top: 1971 Design. Bottom: 1994 Design.



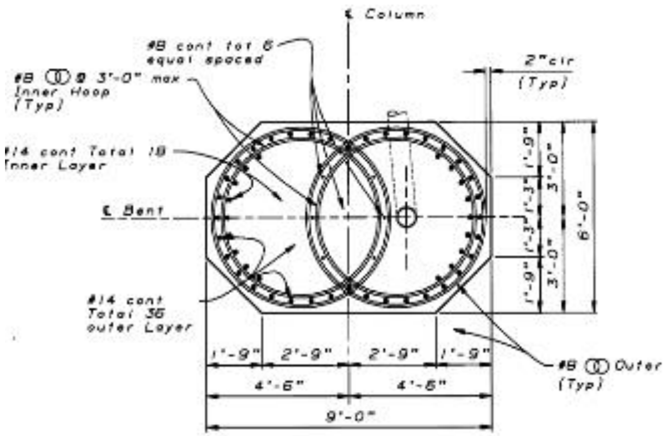


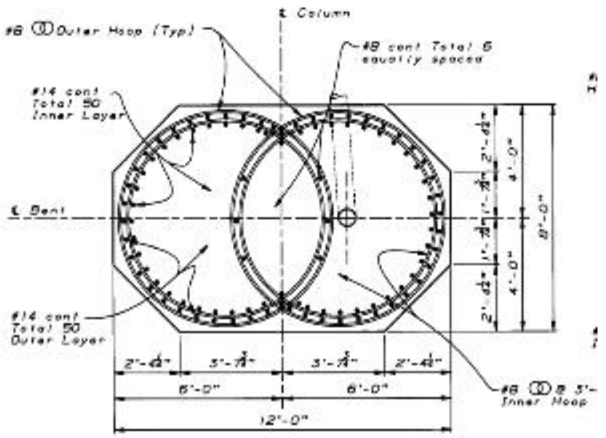
1971 to 1994 Design Upgrade

1971 Design



1994 Design





Bents 2, 3, 6, 7: 6’x9’ Columns
#8 hoops Bundled at 10”

Bents 4, 5: 8’x12’ Columns
#8 hoops Bundled at 8”

Caltrans' Seismic Design Criteria

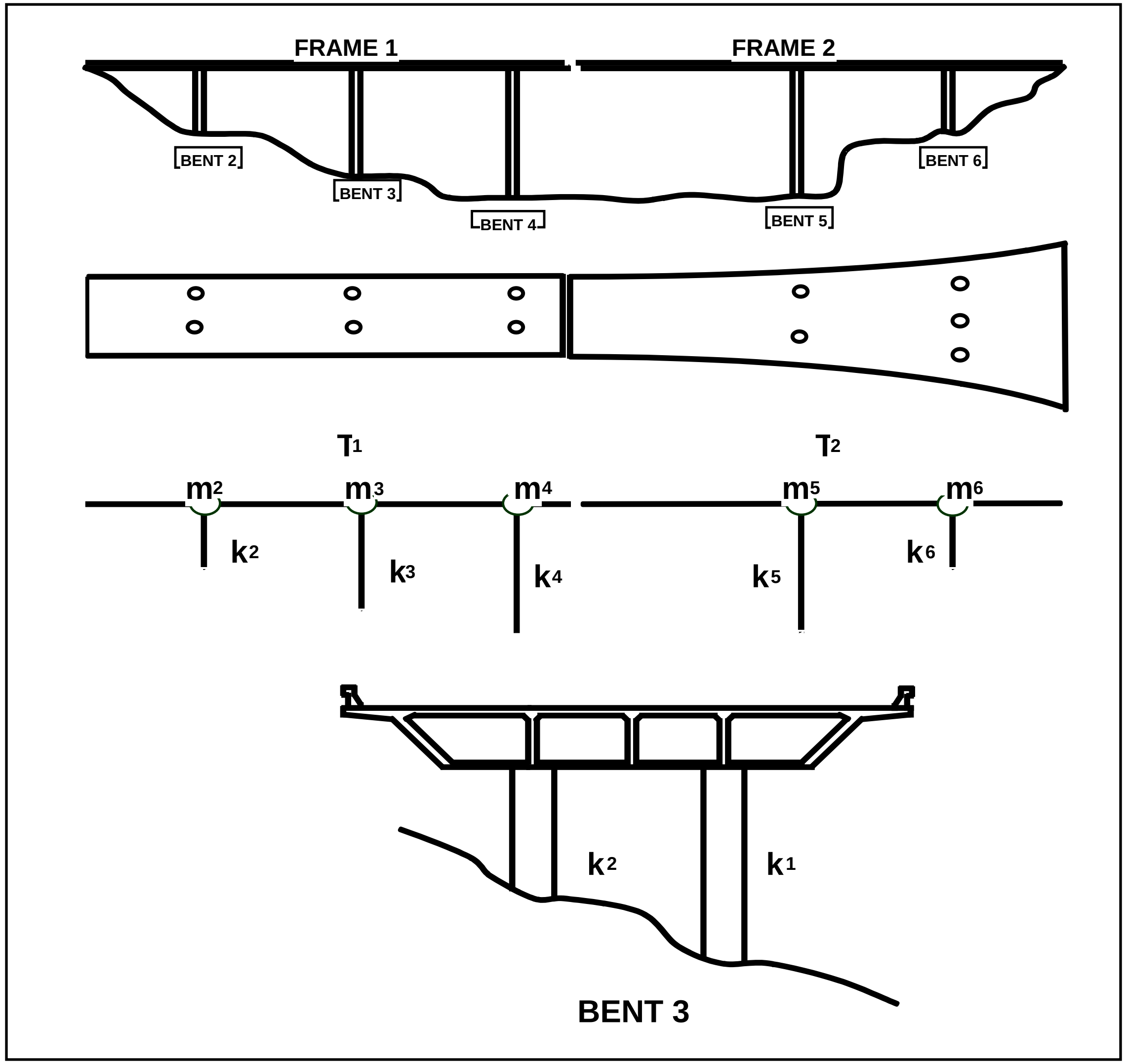
- Balance: SDC 7.1.2

Table 7.1.2-1 Column/Bent Stiffness-to-Mass Ratios for Bents/Frames

Column/Bent	Stiffness-to-Mass Ratio
For any two bents in a frame or any two columns in a Bent	$0.5 \le \dfrac{\left(\dfrac{k_i^e}{m_i}\right)}{\left(\dfrac{k_j^e}{m_j}\right)} \le 2.0$ (7.1.2-1)
For adjacent bents in a frame or adjacent columns in a Bent	$0.75 \le \dfrac{\left(\dfrac{k_i^e}{m_i}\right)}{\left(\dfrac{k_j^e}{m_j}\right)} \le 1.33$ (7.1.2-2)

Caltrans' Seismic Design Criteria

- Balance:



The Need for Balance

- Adjacent columns

Courtesy Ron Bromenschenkel

Designing for Balance

Column Isolation Casings
Southeast Connector Separation-Circa 1996

Courtesy Ron Bromenschenkel

Designing for Balance

Column Isolation Casings
New Schuyler Heim Bridge-Circa 2020

Precast Yard

Designing for Balance

Column Isolation Casings
New Schuyler Heim Bridge-Circa 2020

Precast Yard

Site Construction

Conclusions

- California earthquake history shapes Caltrans' practice.
- 3 major earthquakes dictated "Confinement, Continuity, Balance" as seismic requirements for bridges.
- CIP post-tensioned box girder and properly detailed PC bridges can meet the above seismic requirements.

END

A Successful Plastic Hinge

Ground Motions, Damage Patterns and Directivity in M_w6.7 1994 Northridge Earthquake

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Eric Elison, and Clinton Jacob
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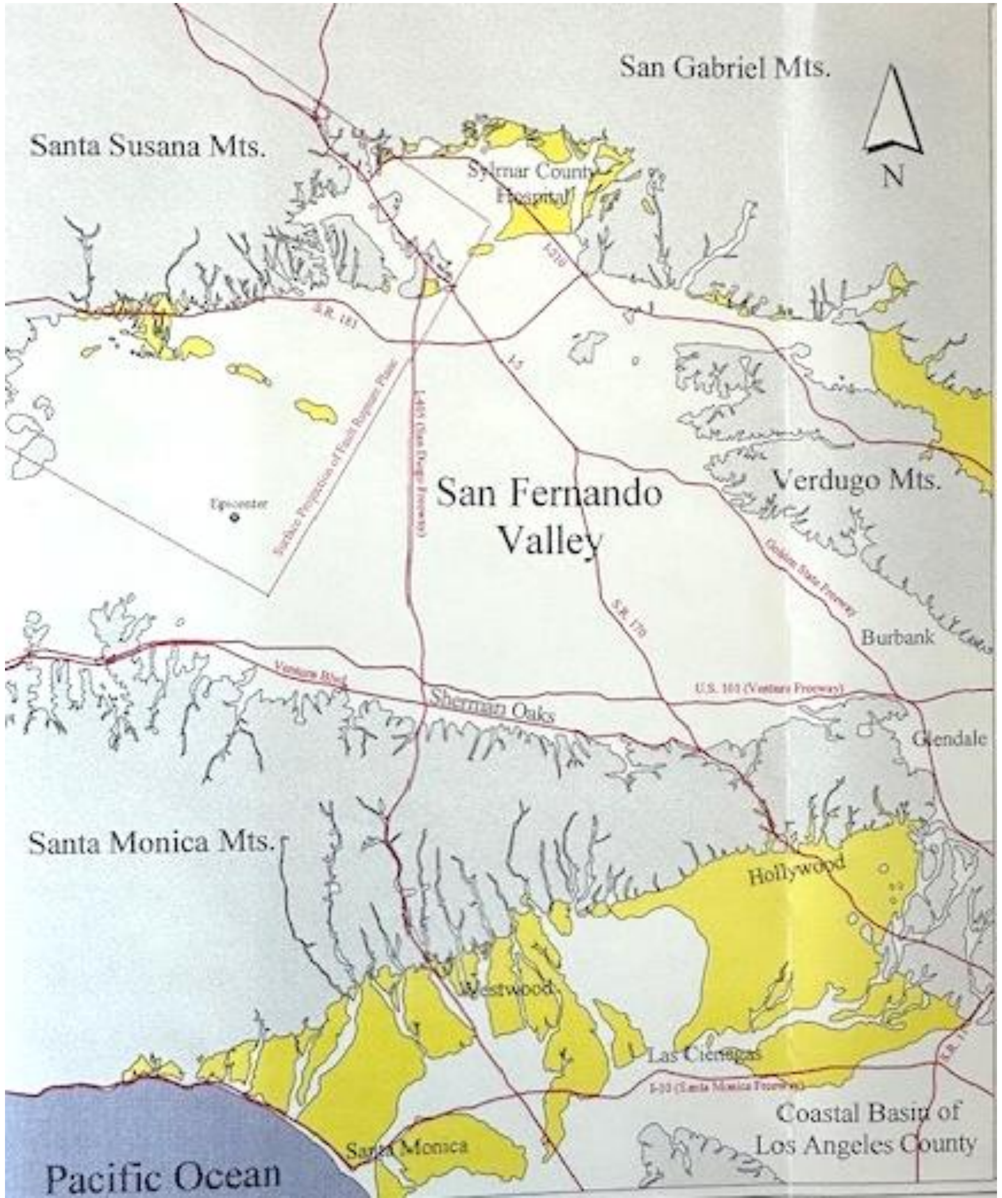
TRB Webinar
October 30, 2024

Acknowledgements

National Science Foundation Grant

Surficial Geology of San Fernando & LA Basin



Rock

Holocene

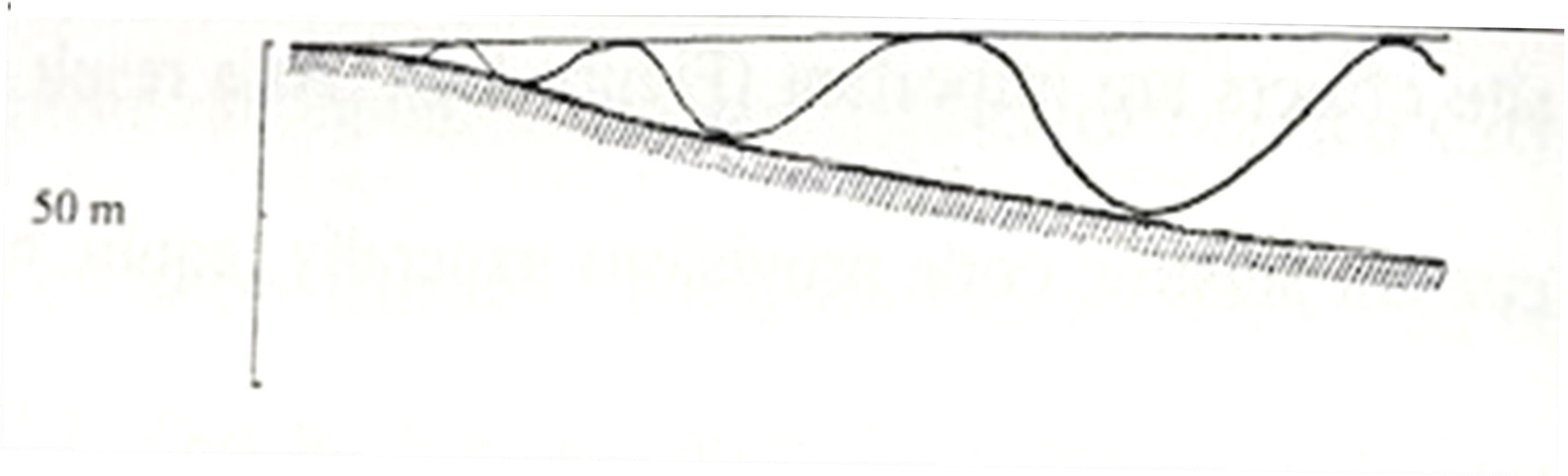
Pleistocene

Ocean

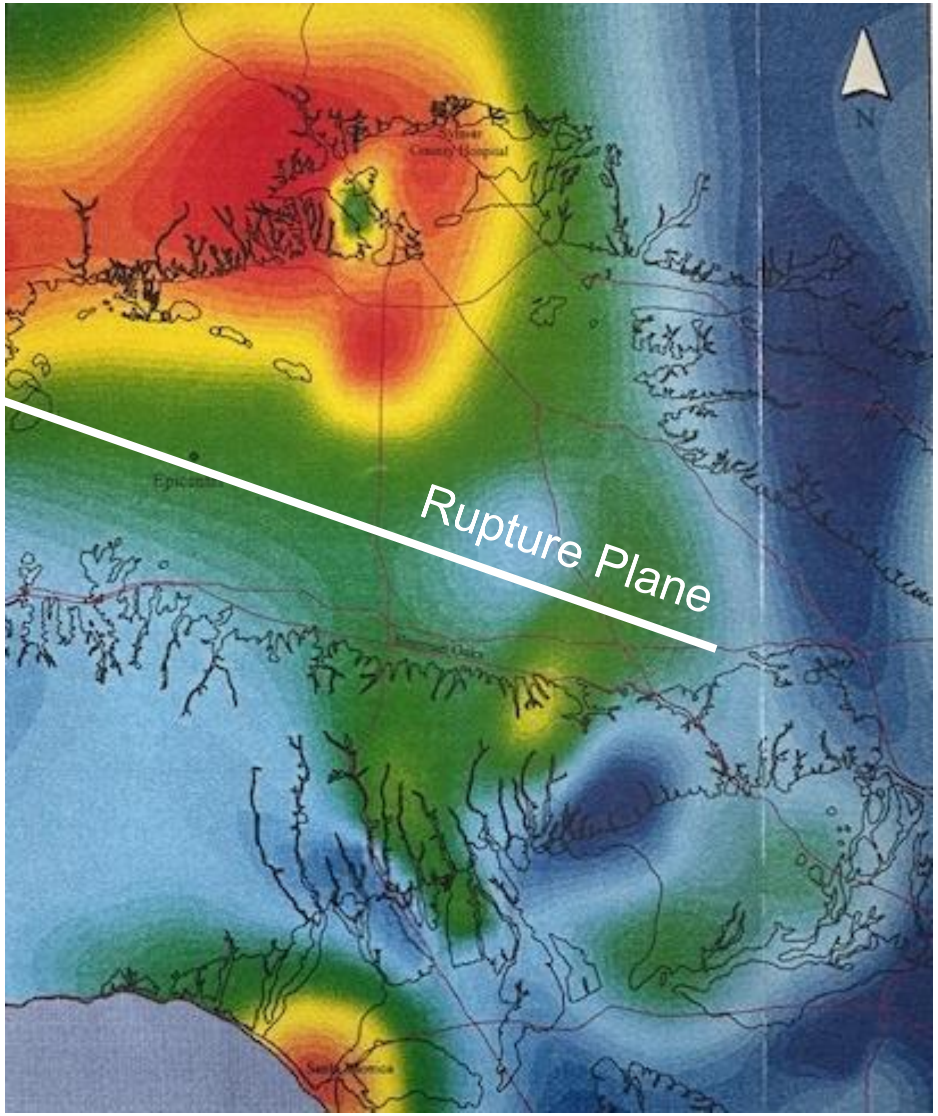
Ground Motion Issues

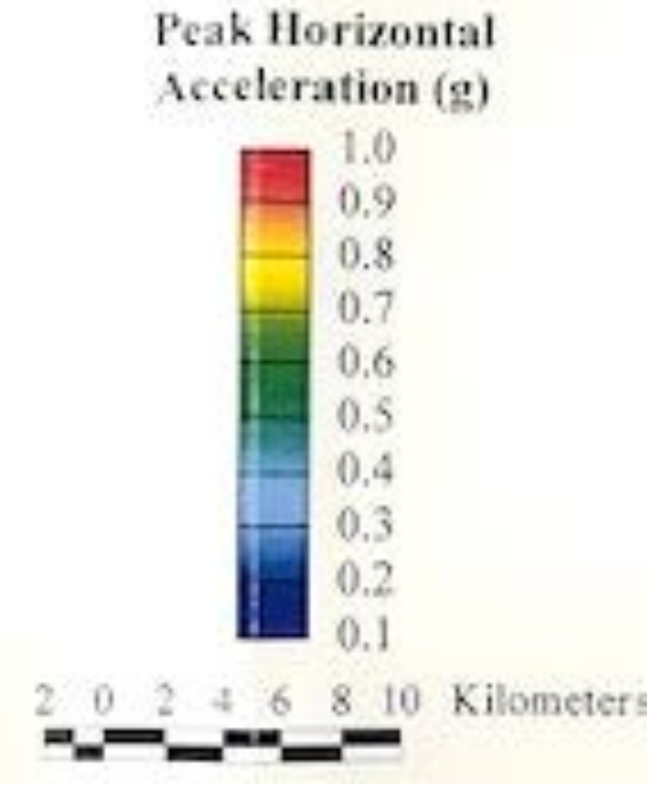
- Relatively High Peak Ground Acceleration (PGA)
- High Vertical to Horizontal Accelerations
- Directivity Effects
- Basin Edge Effects

Basin Edge Effects

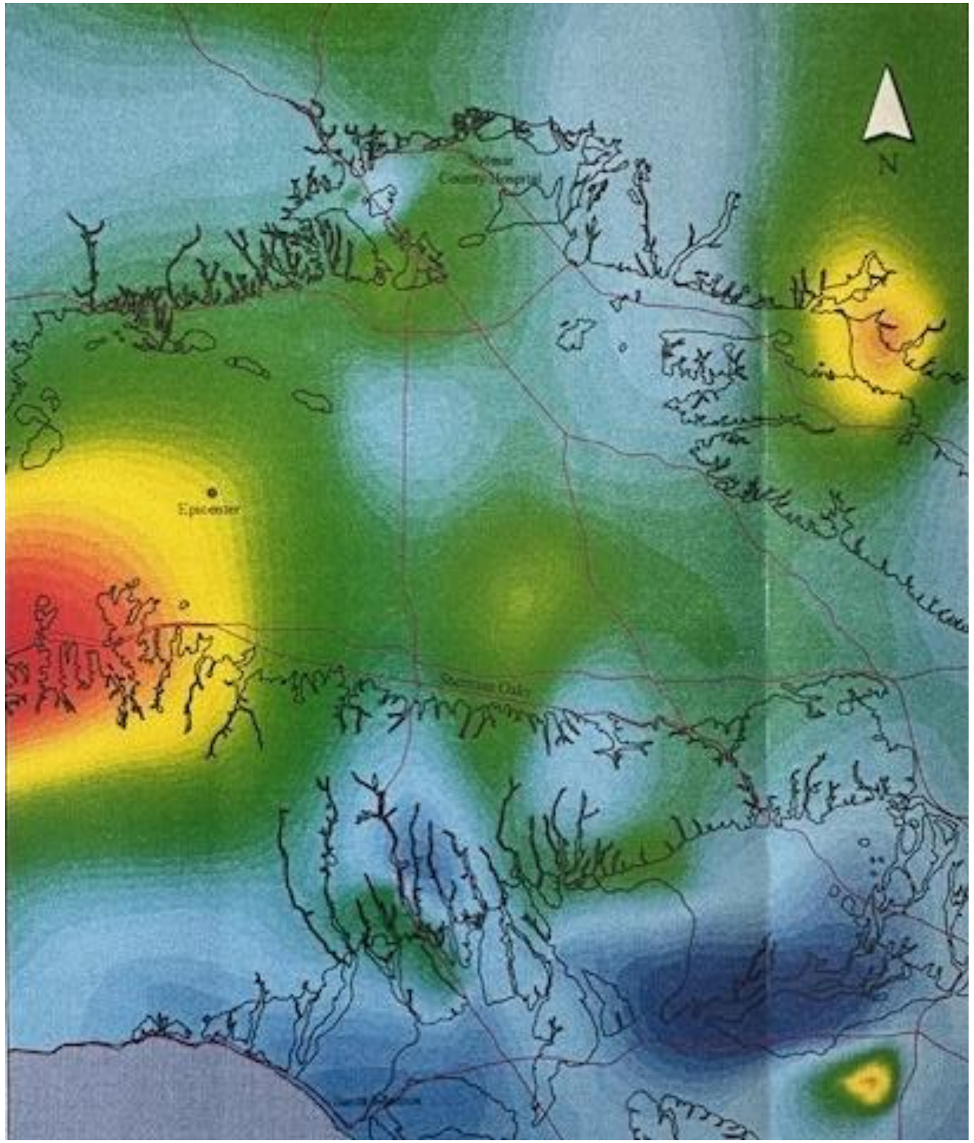


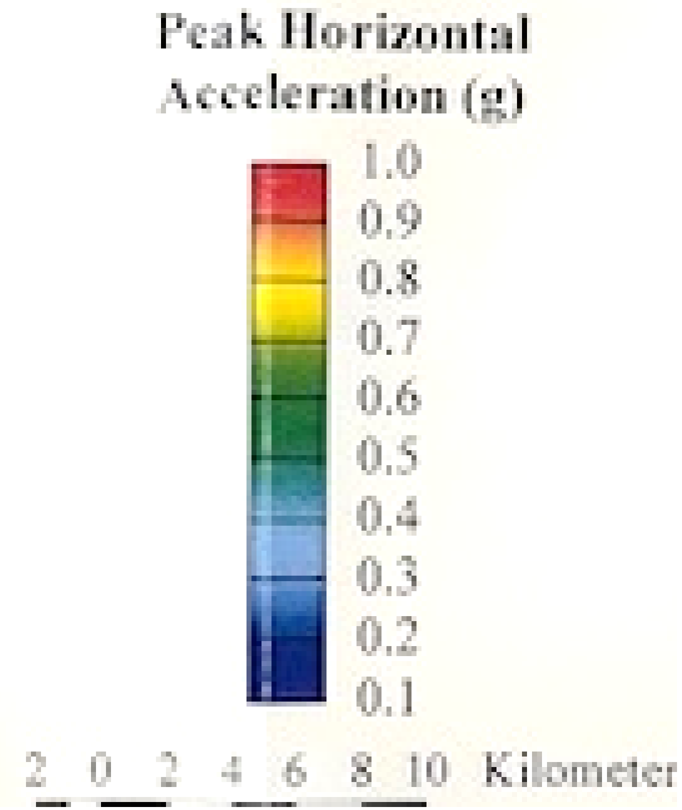
Contours of Peak Ground Acceleration



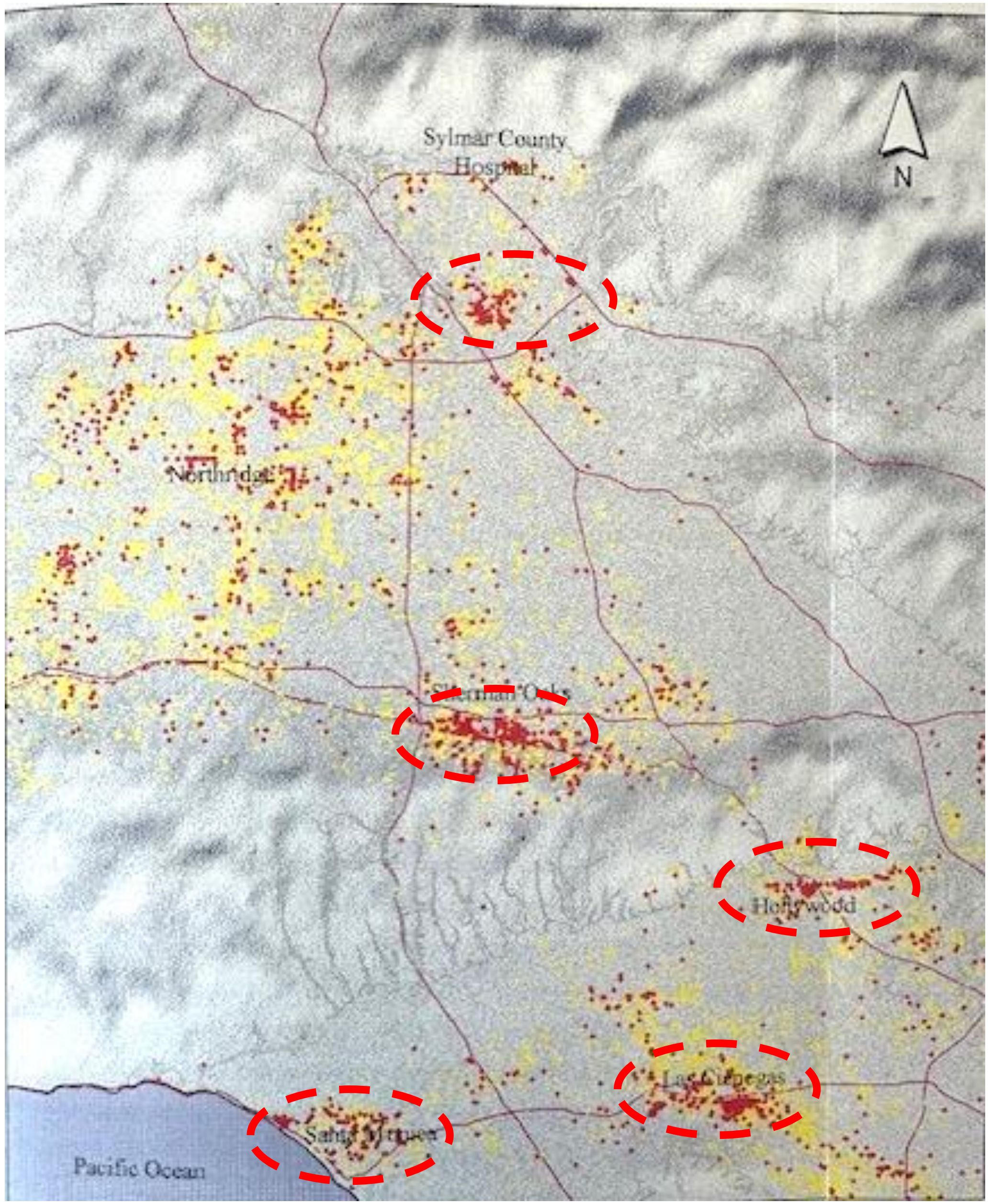


Contours of PVA to PHA





Distribution of Red and Yellow Tagged Buildings



Explanations for Damage Concentrations

Identify Damage Correlation Relative to:

- Grain Size
- Geologic Age
- Organic Content
- Impedance Contrast

Geologic History at La Cienaga

- Relatively deep soil deposits.
- Soft organic clays and silts from swamps when LA river was diverted south.
- Low-grade meandering streams deposited fine-grained soils over region.
- Dense sandy gravel (“50 ft gravel”) from LA river.

Geologic Zonation

- Zonation based on geologic age and soil gradation defined by Tinsley and Fumal (1985) mapping.
- Zonation based on organic content obtained from USDA (1915,1916) soil mapping .
- Zonation based on impedance contrast using location of “50 ft gravel layer” defined by Poland (1959).

Damage Density from ATC-20 Tag Designations

Data available from wide range of buildings types

- Red Tags - Unsafe and public entry is prohibited for any reason.
- Yellow Tag - Severely damaged but access may be possible through some entrances. Additional evaluation/repair required.
- Green Tag - Safe for continued habitation without any need for significant repair.

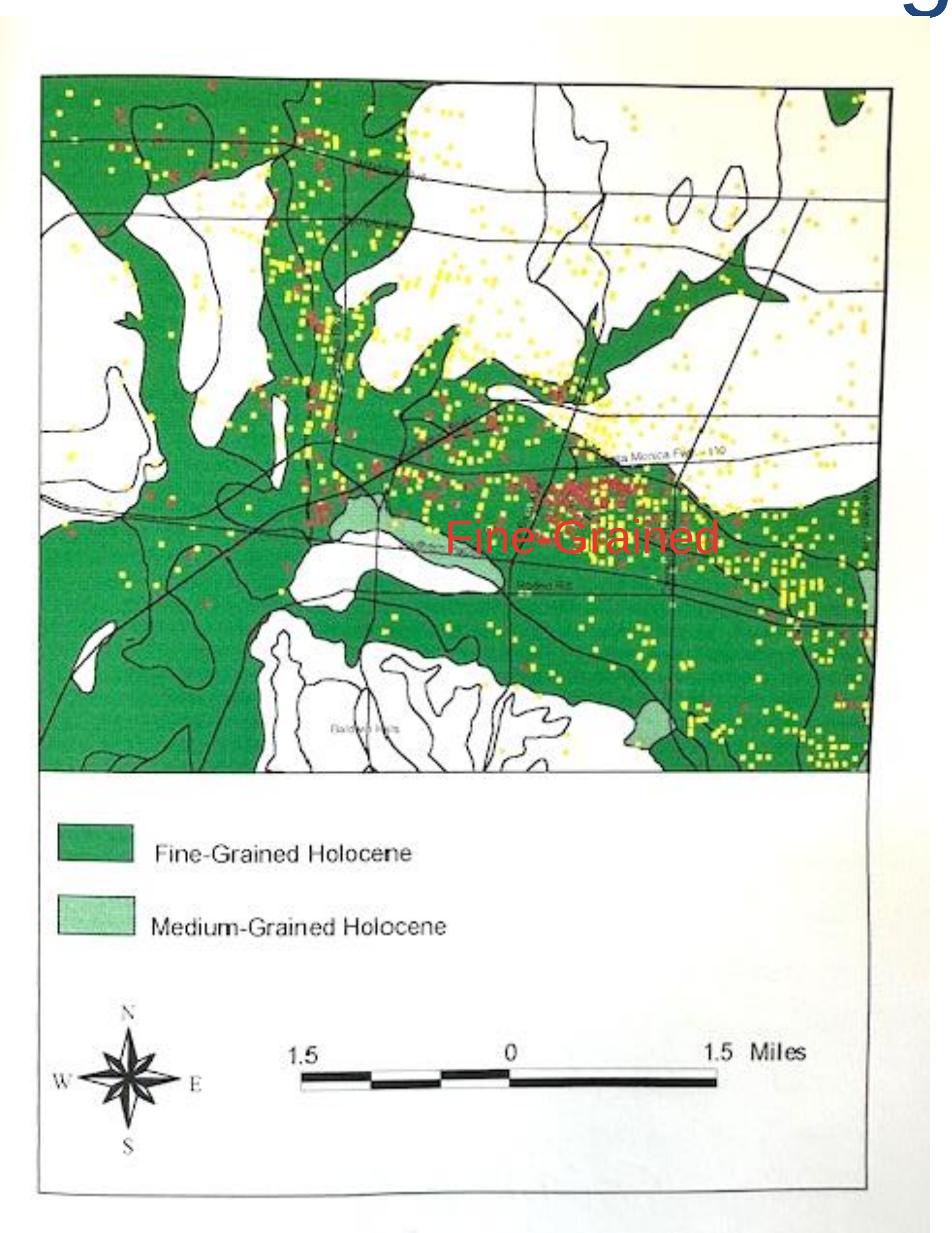
Damage Density from Insurance Company

- 96,510 buildings, 25% of all insurance policies
- 90% of buildings are 3 stories or less
- Vast majority are single family residences.
- Damage Criteria
  - Severely Damaged- Damage greater than 65% of value
  - Moderately Damaged – Damage between 35-65% of value

La Cienaga Building Inventory Characteristics

- WWII vintage residential or low-rise commercial buildings.
- Wood frame or unreinforced masonry.
- Building density (1550 per km^2) relatively uniform over 75 km^2 study area.
- Building damage based on red-, yellow-, or green-tags.

Red and Yellow Tag Distribution - La Cienaga



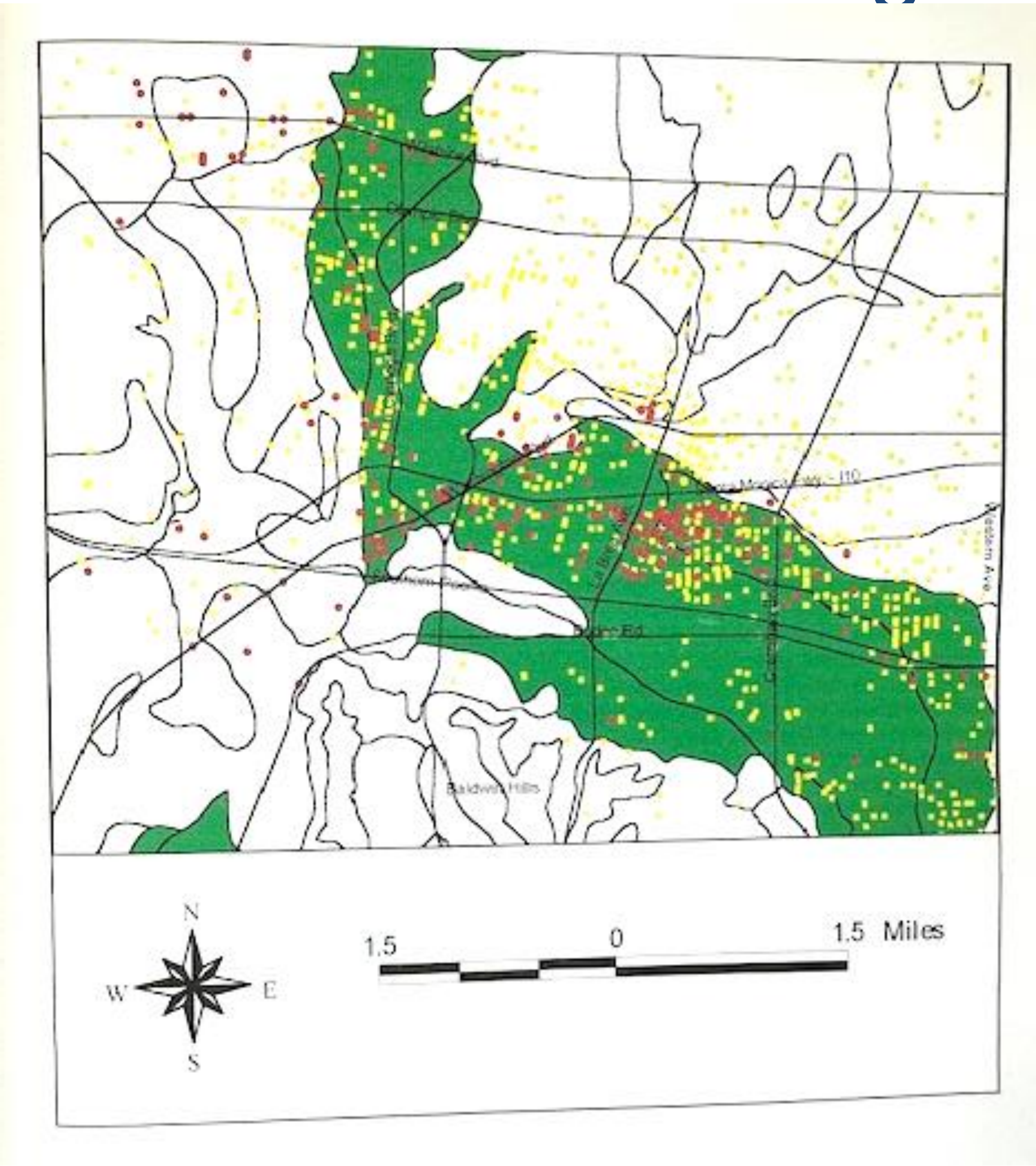
Fine-Grained Pleistocene

11.6 tags/km^2

Fine-Grained Holocene

31.3 tags/km^2

Red and Yellow Tag Distribution - La Cienaga



Fine-Grained Pleistocene

11.6 tags/km^2

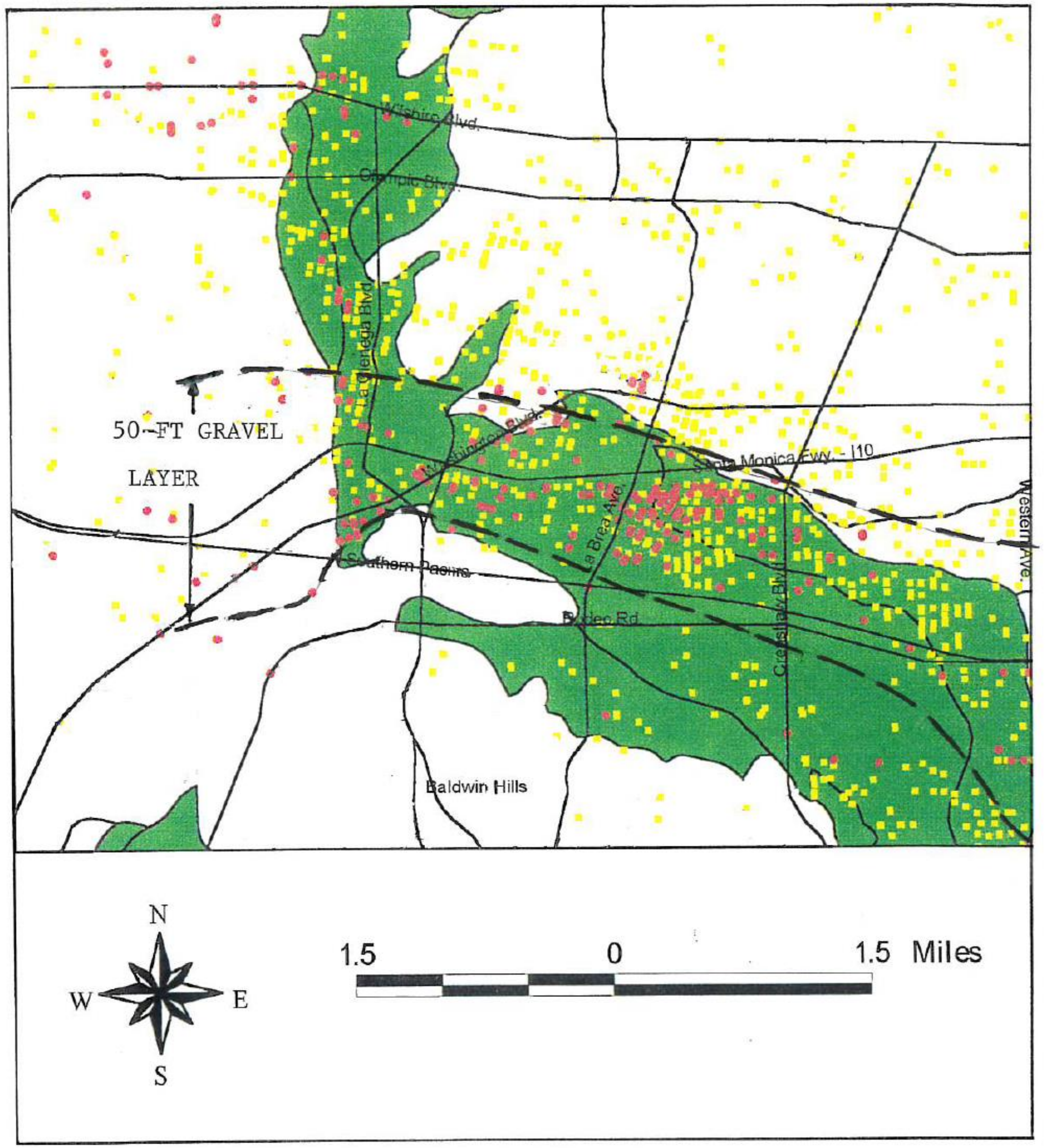
Fine-Grained Holocene

31.3 tags/km^2

Fine-Grained Holocene, Mod. To High Organic

49.8 tags/km^2

Red and Yellow Tag Distribution - La Cienaga



Fine-Grained Pleistocene

11.6 tags/km^2

Fine-Grained Holocene

31.3 tags/km^2

Fine-Grained Holocene, Mod. To High Organic

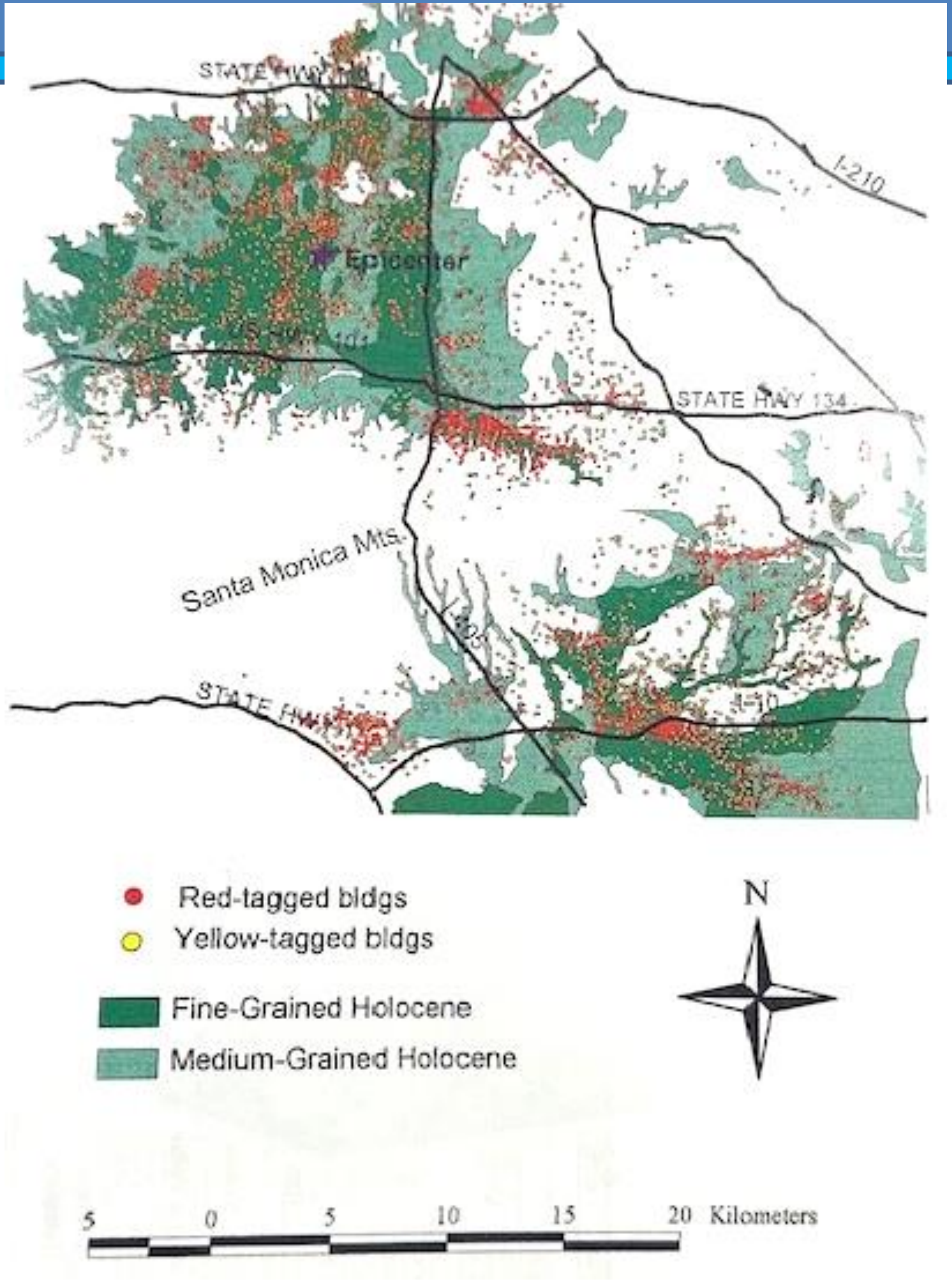
49.8 tags/km^2

Fine-Grained Holocene, Mod. To High Organic Underlain by Gravel

62.5 tags/km^2

Summary for La Cienaga Area

- Damage density was 2.7 times higher on Holocene than on Pleistocene fine-grained soil.
- Location in moderate to high organic zone increased damage density by another 60%.
- Presence of underlying gravel layer increased damage density another 25%.



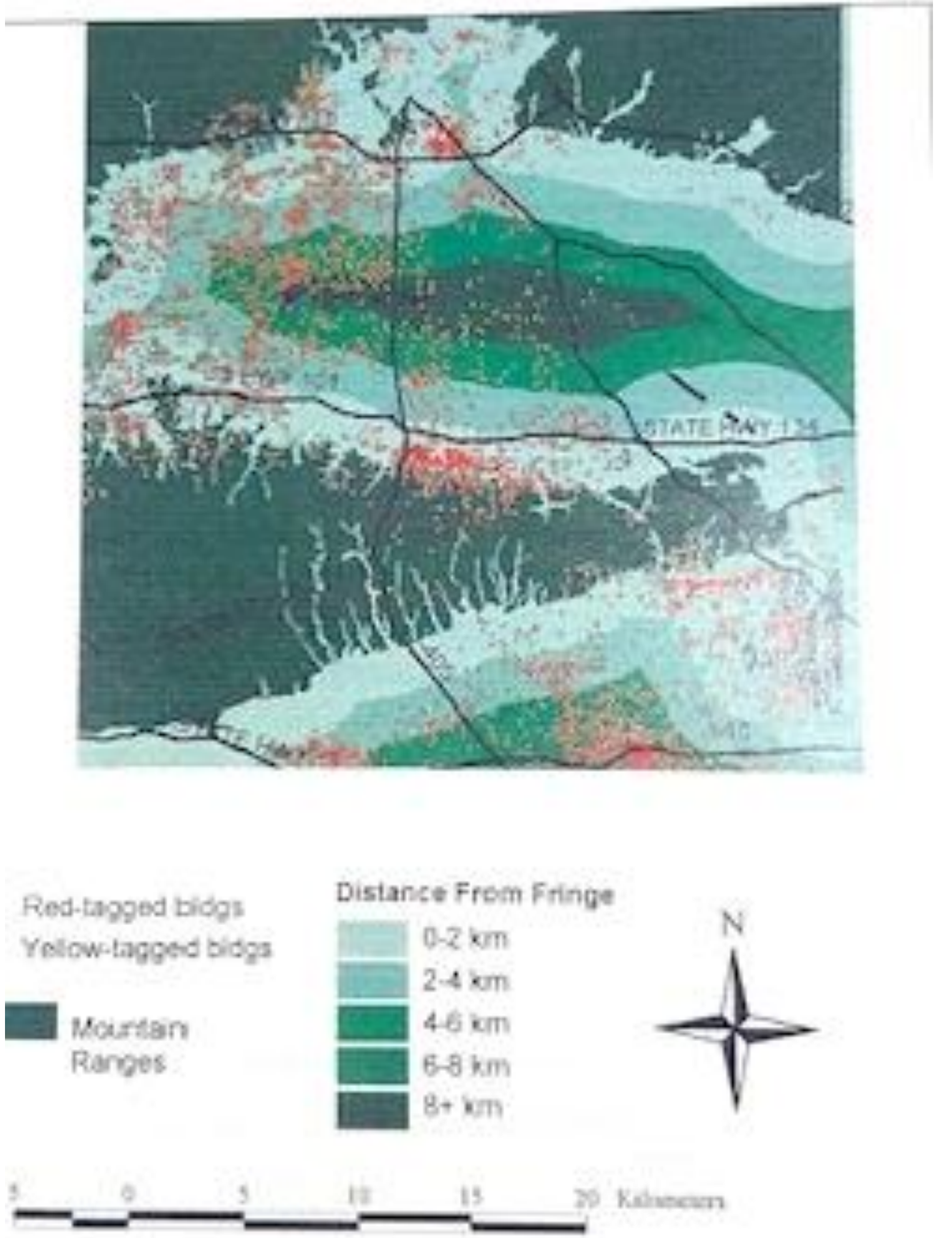
Distribution of Damage with Geologic Age

San Fernando and LA Basins

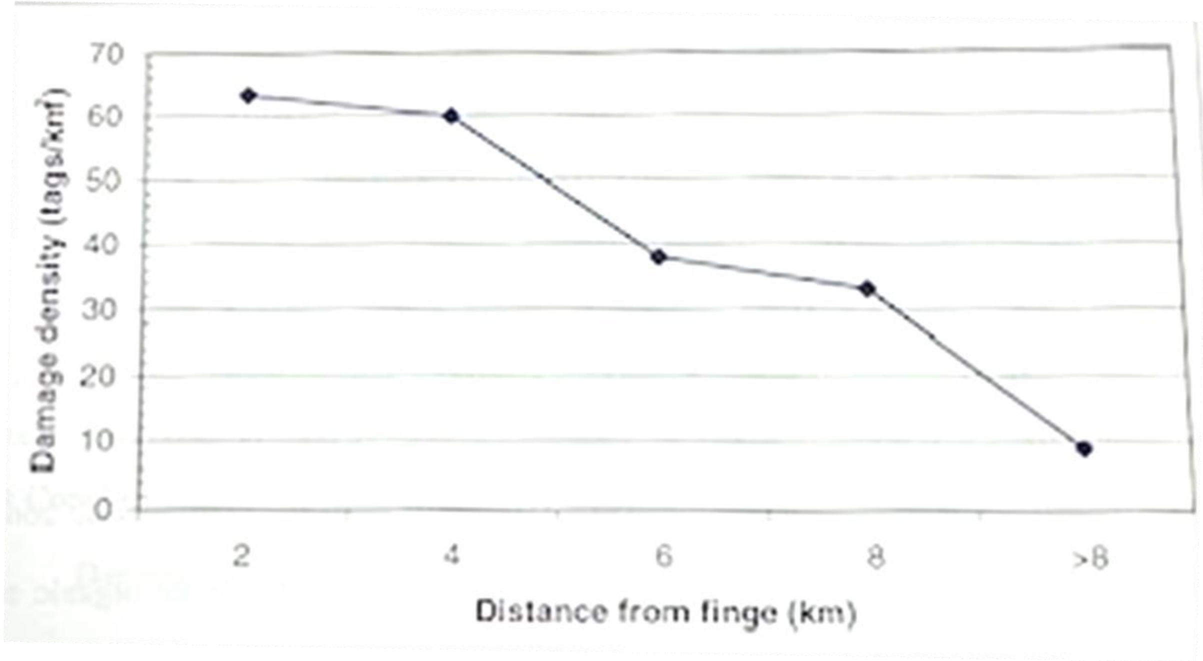
COMPARISON TO DAMAGE DENSITY STATISTICS - LA & SAN FERNANDO VALLEYS

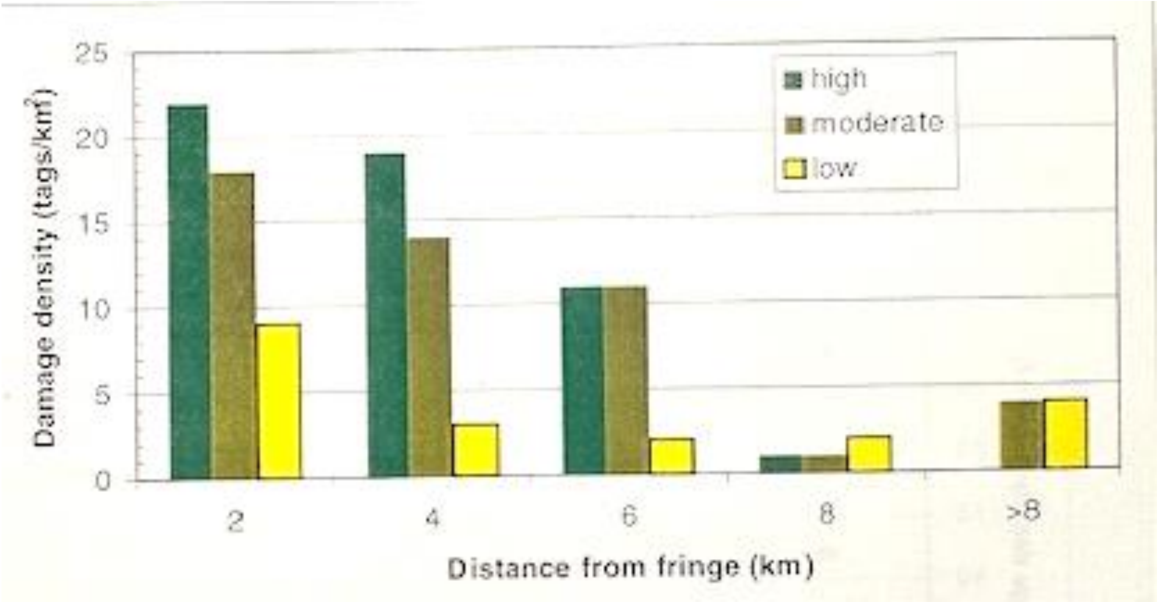
Soil Category	Category Area (mi^2)	Red and Yellow Tag Density ($tags/mi^2$)	Red Tag Density ($tags/mi^2$)	Yellow Tag Density ($tags/mi^2$)
Coarse-Very Coarse Grained Pleistocene	2	9	2	8
Coarse-Very Coarse-Grained Holocene	87	20	5	15
Medium-Grained Pleistocene	31	26	5	21
Medium-Grained Holocene	83	33	7	26
Fine-Grained Pleistocene	6	18	0	18
Fine-Grained Holocene	73	59	13	47
Low Organic Content	145	14	3	11
Moderate Organic Content	124	36	8	29
High Organic Content	45	53	10	43
Fine-Grained Holocene with High Organic Content	27.5	70	14	56

Damage Distribution at Basin Fringes

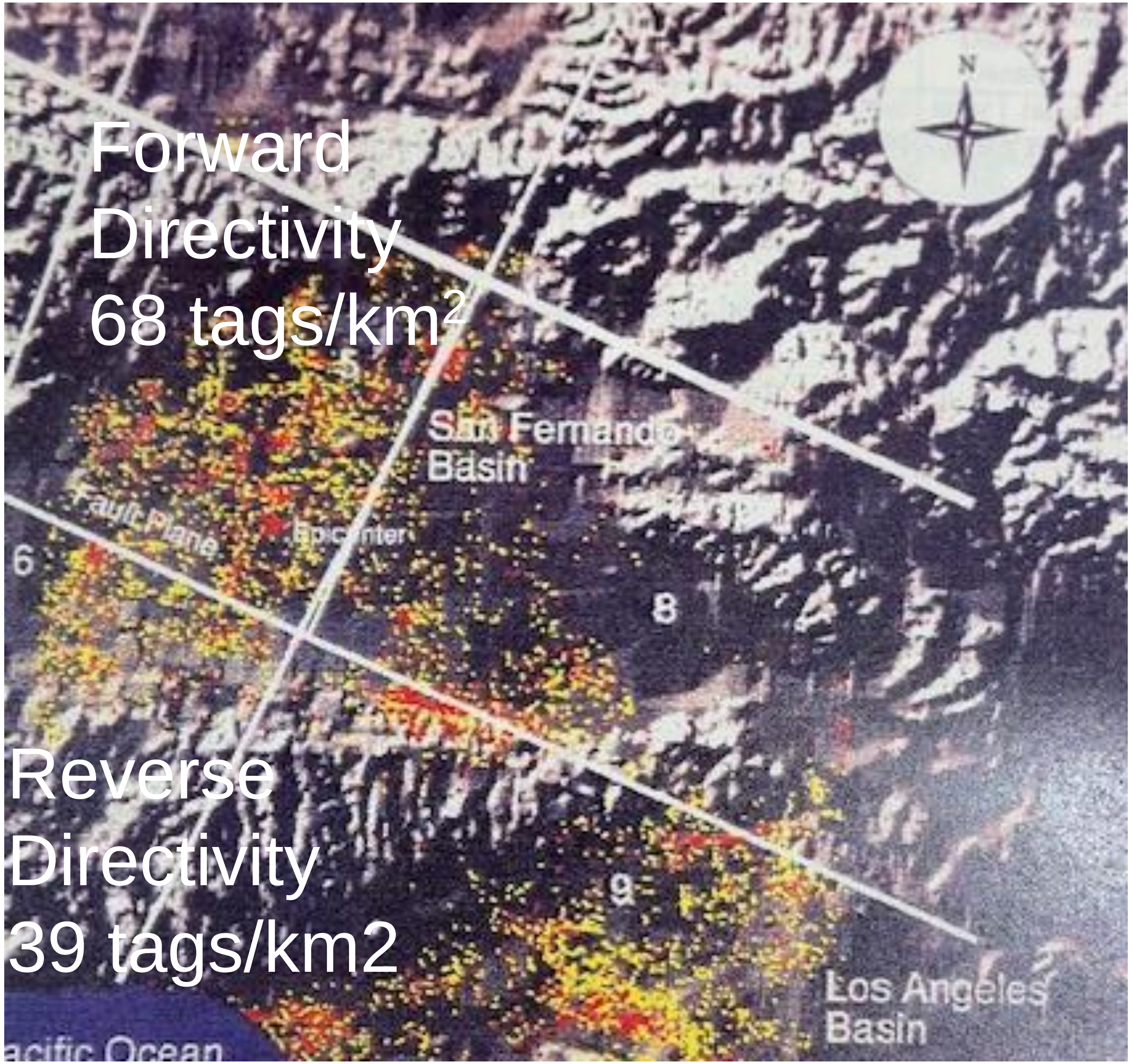


Damage Distribution at Fringes





Directivity Effects on Damage Distribution



Questions?

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From Northridge to Resilience

Innovative strategies to ensure post-earthquake functionality

Michel Bruneau

Ph.D., P.Eng., Dist.M.ASCE, F.SEI, F.CAE
SUNY Distinguished Professor
Dept. Civil, Structural and Environmental Engineering
University at Buffalo

Resilience

- The concept of resilient infrastructure, formulated nearly two decades ago, has been progressively endorsed over the years
- This has happened in parallel with an at-large shift towards resilience across many disciplines
- Two critically important steps to achieve a resilient society is to:
  - Literally build bridges
  - Figuratively build bridges

Building Bridges Toward a more Resilient Society

- Dictionary definition

bridge 1 of 3 noun (1)

ˈbrij

Synonyms of *bridge* ›

Literally: The physical infrastructure

1 **a** : a structure carrying a pathway or roadway over a depression or obstacle (such as a river)

a *bridge* connecting the island to the mainland

b : a time, place, or means of connection or transition

building a *bridge* between the two cultures

the *bridge* from war to peace

Building Bridges Toward a more Resilient Society

- Dictionary definition

bridge 1 of 3 noun (1)

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Synonyms of *bridge* >

1 **a** : a structure carrying a pathway or roadway over a depression or obstacle (such as a river)

  a *bridge* connecting the islan to the mainland

Figuratively: Connecting people

b : a time, place, or means of connection or transition

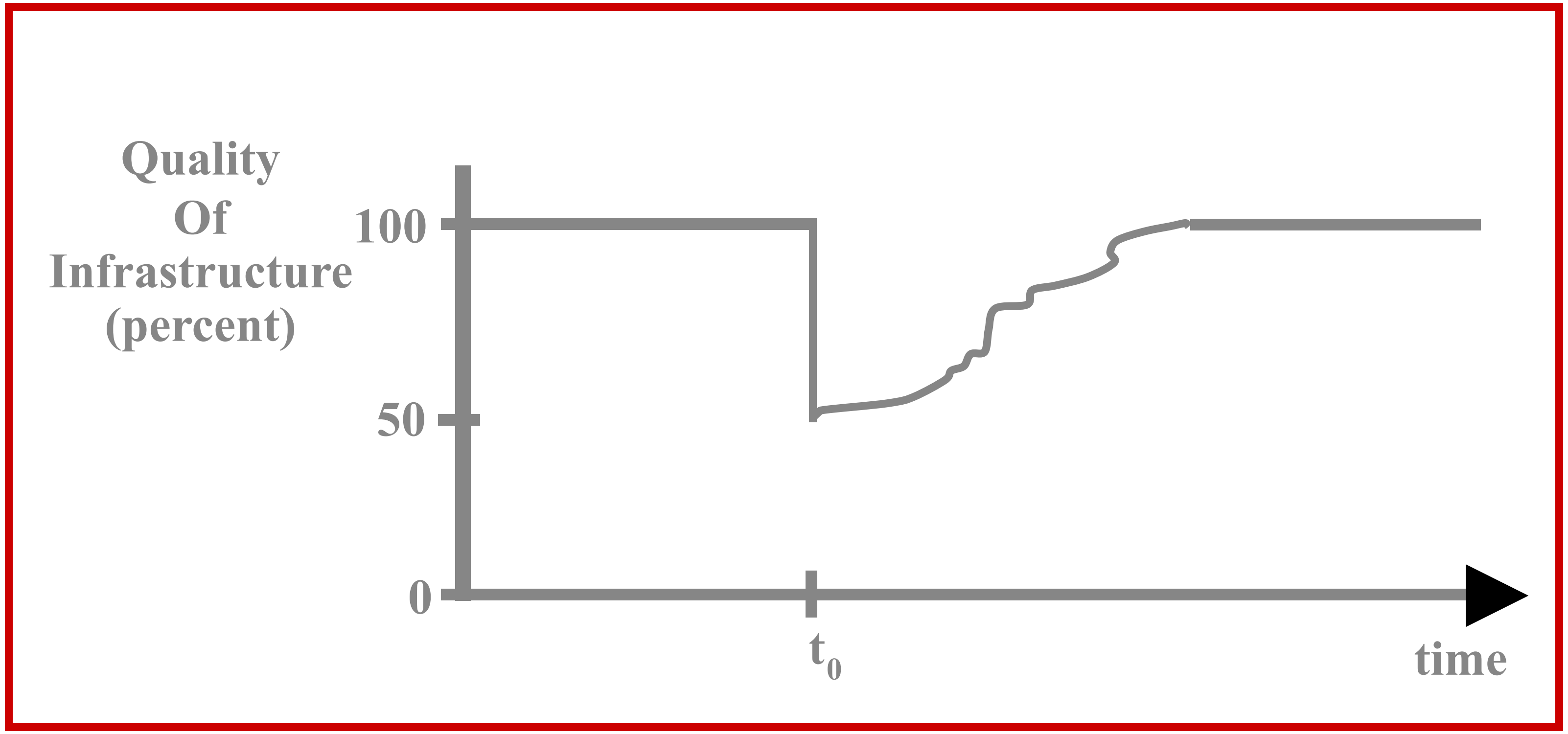
  building a *bridge* between the two cultures

  the *bridge* from war to peace

Literally

- What is Resilience?
- What is Resilience for Structural Engineers?
  - Achieving resilience with steel structural systems rapidly reparable
  - Achieving resilience with steel structural systems with low/no damage

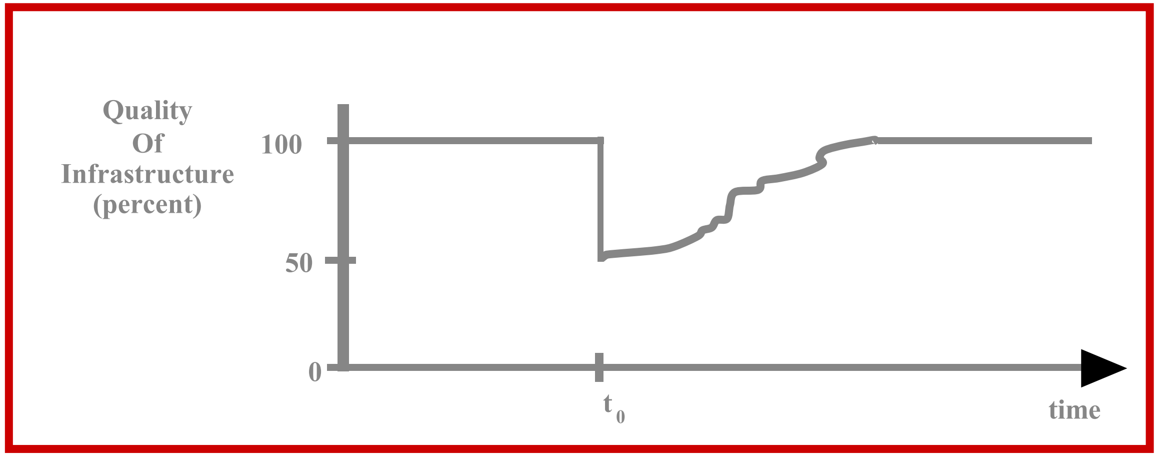
Resilience Curve (MCEER 2002)



Bruneau, M., Chang, S., Eguchi, R., Lee, G., O'Rourke, T., Reinhorn, A., Shinozuka, M., Tierney, K., Wallace, W., von Winterfelt, D., (2003). "A Framework to Quantitatively Assess and Enhance the Seismic Resilience of Communities", EERI Spectra Journal, Vol.19, No.4, pp.733-752.

Resilience Curve (MCEER 2002)

- Some colleagues embraced the concept, others confidently affirmed that “nobody will ever use the resilience concept”
- From 2002-2008, MCEER presentation to dozens of groups and federal government agencies
- The resilience figure started to appear in PPTs everywhere (the dynamic of how it happened is unknown)



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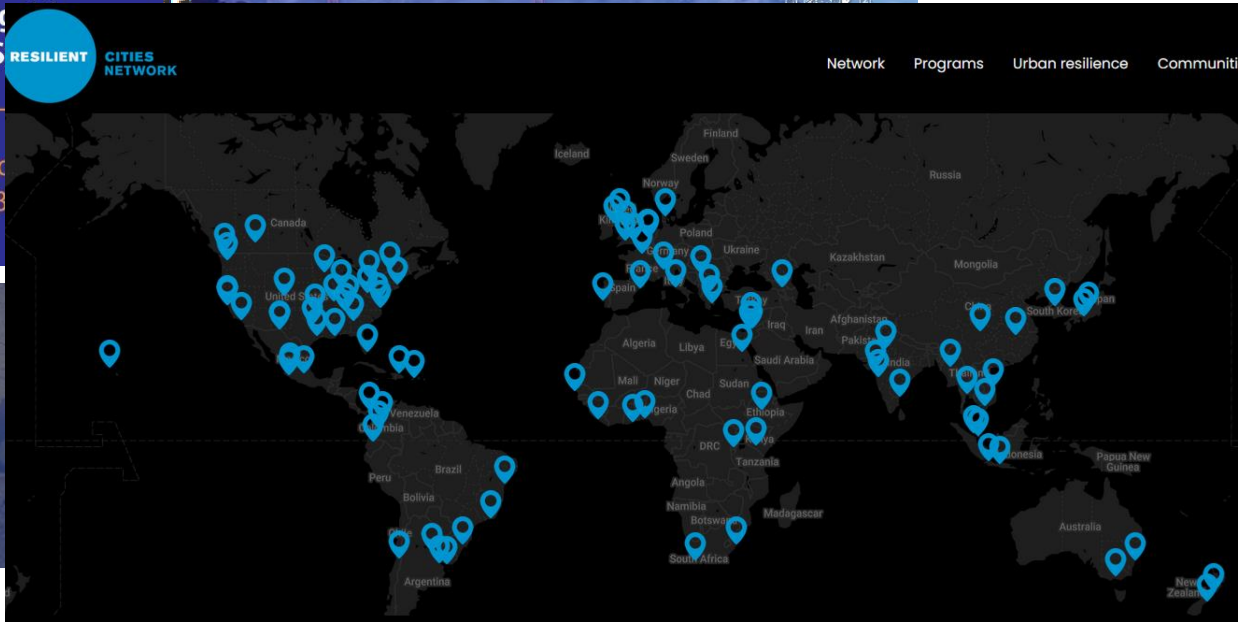
Workshop 3: Good N

Resilience since then: Selected Examples

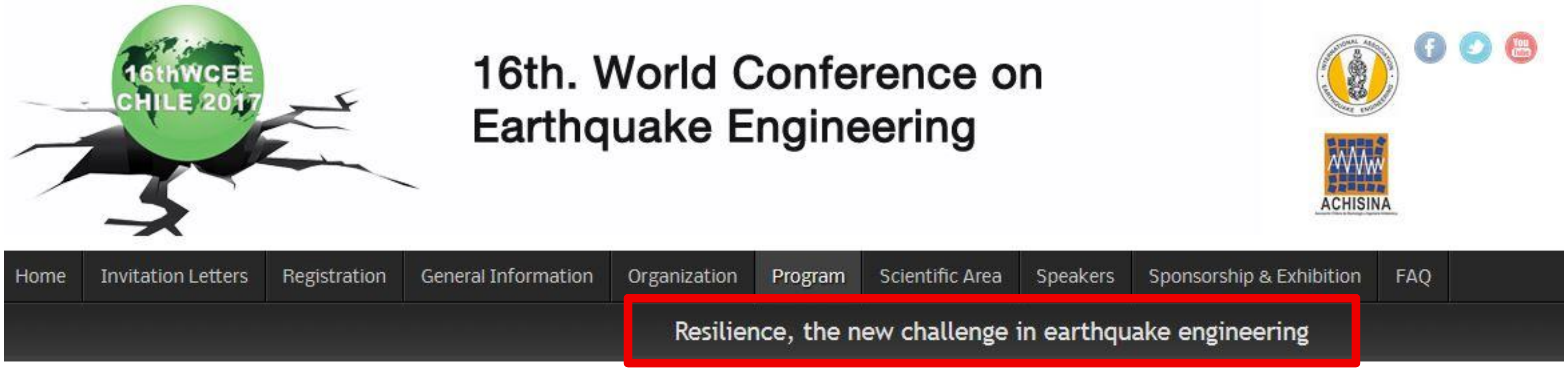
Tokyo Initiative for a Low Ca
& Resilien

The White House
Office of the Press Secretary



Resilience since then: Selected Examples

- 12CCEE: "Improving Seismic Infrastructure Performance and Community Resilience."
- 17WCEE: "Towards Disaster Resilient Society"
- Hundreds of research centers on the topic of resilience



resilience
SURVIVE and THRIVE
BALANGAY
VINTAGE 2018
BAROSSA VALLE
GRENACHE
St. John's Road
Resilience
LEBON - POUPELIN
RESILIENCE
AND
THE LOST GEMS
General
& Exhibition
eering
RESILIENT LADY
Resilient Lady.

Resilience (as of 06/2010) (07/2016) (04/2021) (09/2022)

Google “Resilience”: 7,880,000 results (47,000,000) (217,000,000) (798,000,000)

Google Obama + Resilience: 420,000 hits (719,000) (4,520,000) (9,870,000)

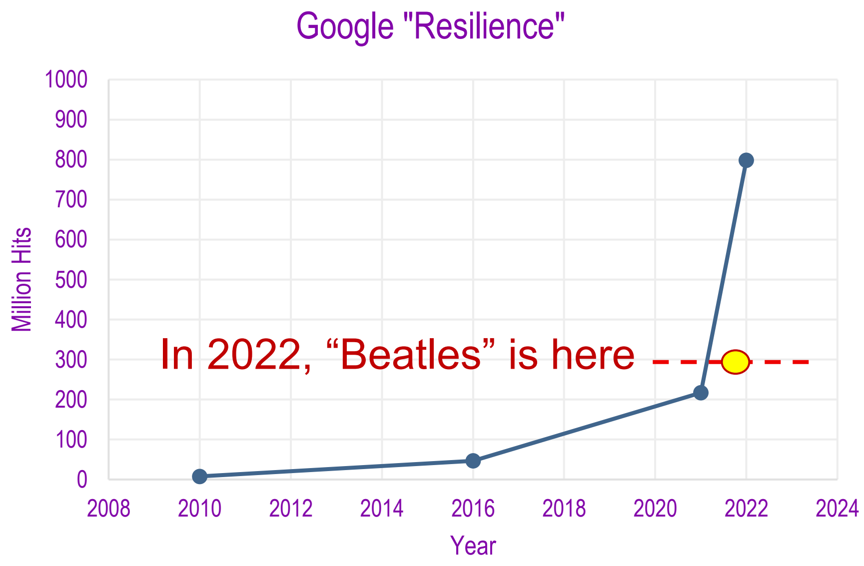
Google “Engineering Resilience”: 6,200 hits (17,300) (54,700) (81,100)

Google “Quantifying Resilience”: 953 results (2,470) (13,500) (23,100)

Google “Quantification of Engineering Resilience” : 1 result (almost a googlewhack) (3) (7) (7)

Resilience = The new Babel Tower?

Need for Rigorous Quantifiable Resilience



Definition of Resilience

(per (Dictionary.com, Merriam-Webster, American Heritage, Merriam, and Oxford dictionaries)

1. The ability of something to return to its original shape after it has been pulled, stretched, pressed, bent, etc. (some definitions use "return to the original form", "resume its original shape", "spring back into shape")
2. Ability to recover readily from illness, change, depression, adversity, misfortune, or the like (some definitions use "recover quickly", "become healthy, happy, or strong again")

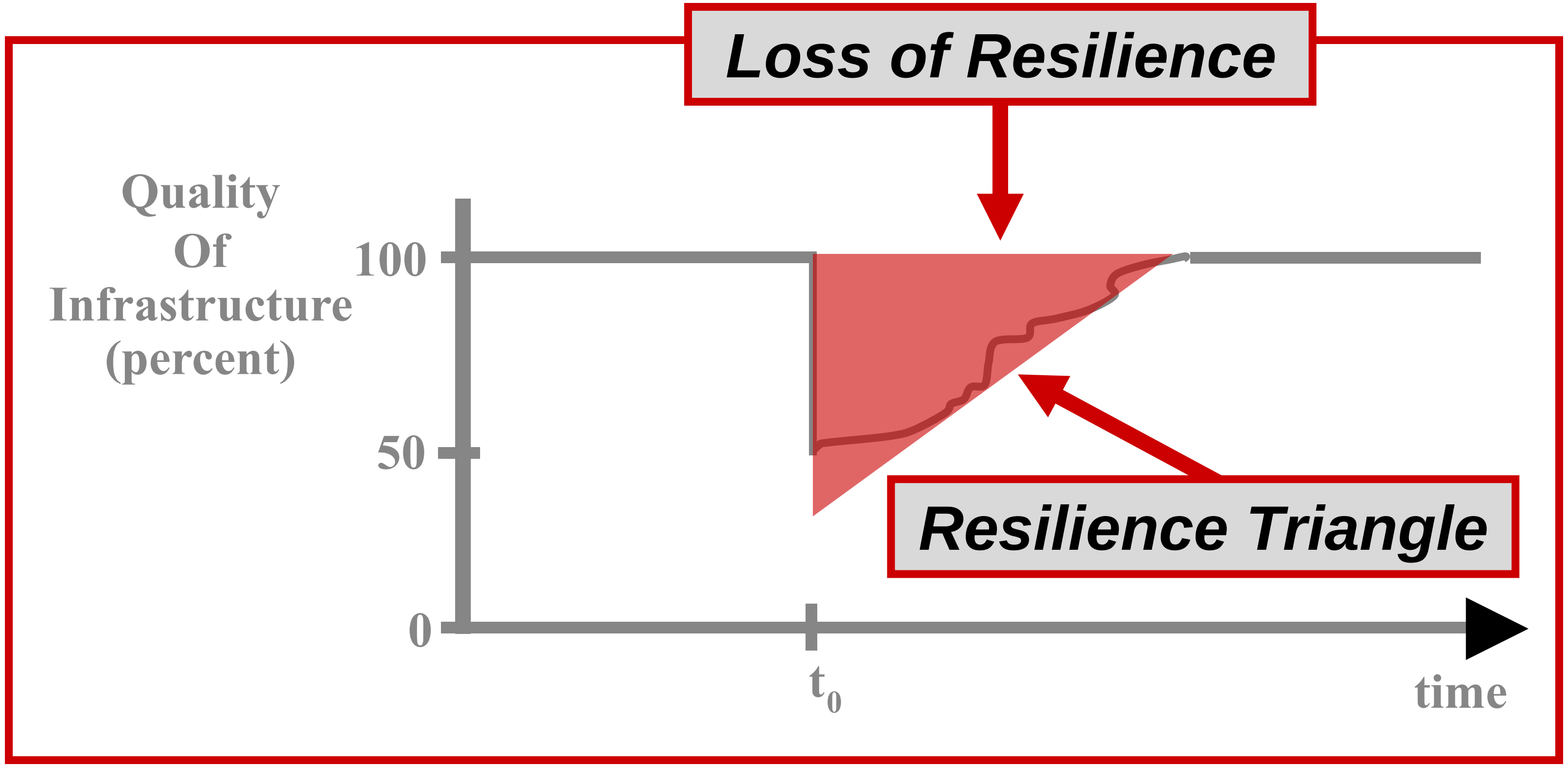
Bottom line: The quality of being able to return quickly to a previous good condition after problems (Cambridge Dictionary)

Therefore, Resilience must:

1. Address ***functionality*** to *maintain it's operations or intended function* of either, communities, services, organizations, infrastructure, physical facilities, individually, or their combined interactions

2. Address both the ***loss of functionality*** (sudden in case of a disastrous - earthquakes) and ***recovery of functionality*** (in time and space.

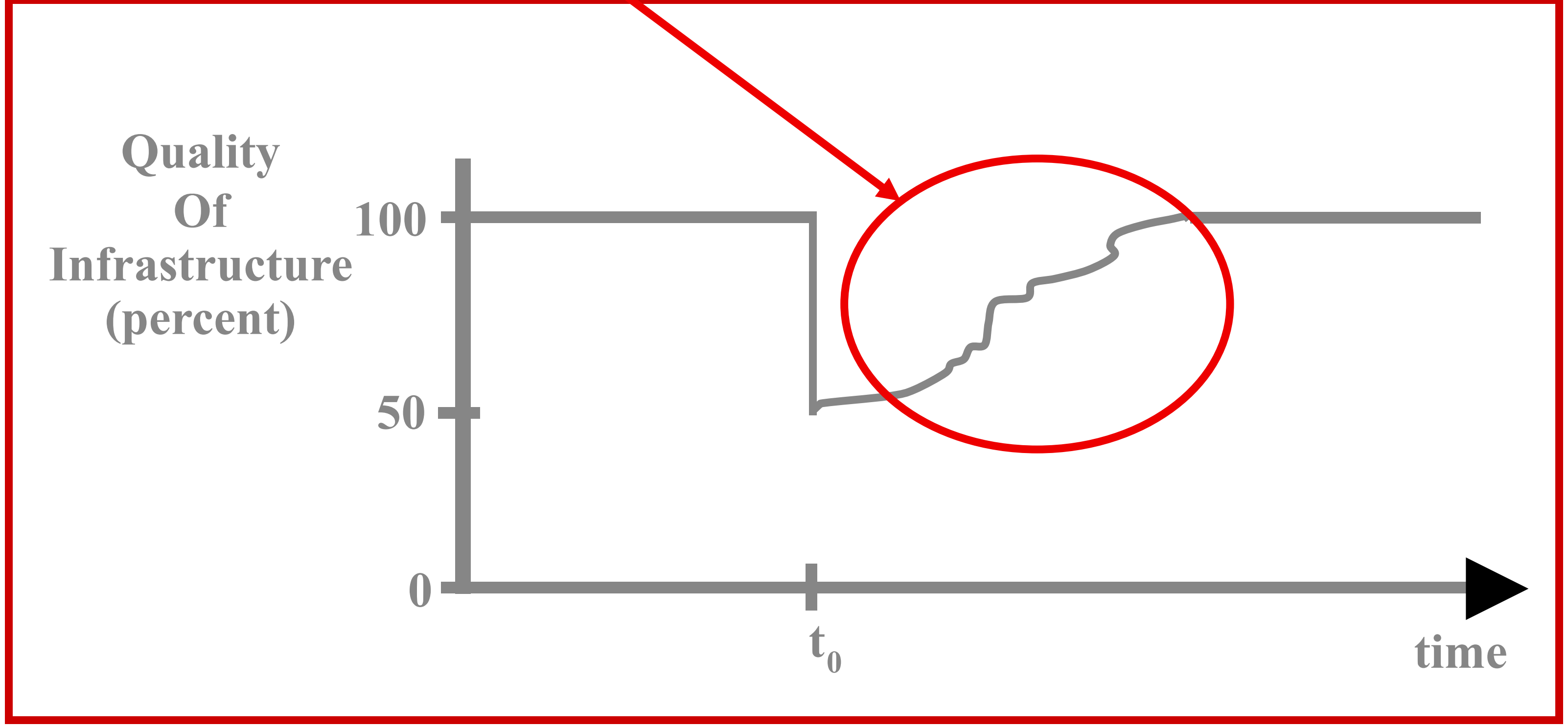
Resilience Curve (MCEER 2002)



Bruneau, M., Chang, S., Eguchi, R., Lee, G., O'Rourke, T., Reinhorn, A., Shinozuka, M., Tierney, K., Wallace, W., von Winterfelt, D., (2003). "A Framework to Quantitatively Assess and Enhance the Seismic Resilience of Communities", EERI Spectra Journal, Vol.19, No.4, pp.733-752.

Resilience Curve (MCEER 2002)

Enhance resilience by accelerating recovery after extreme events



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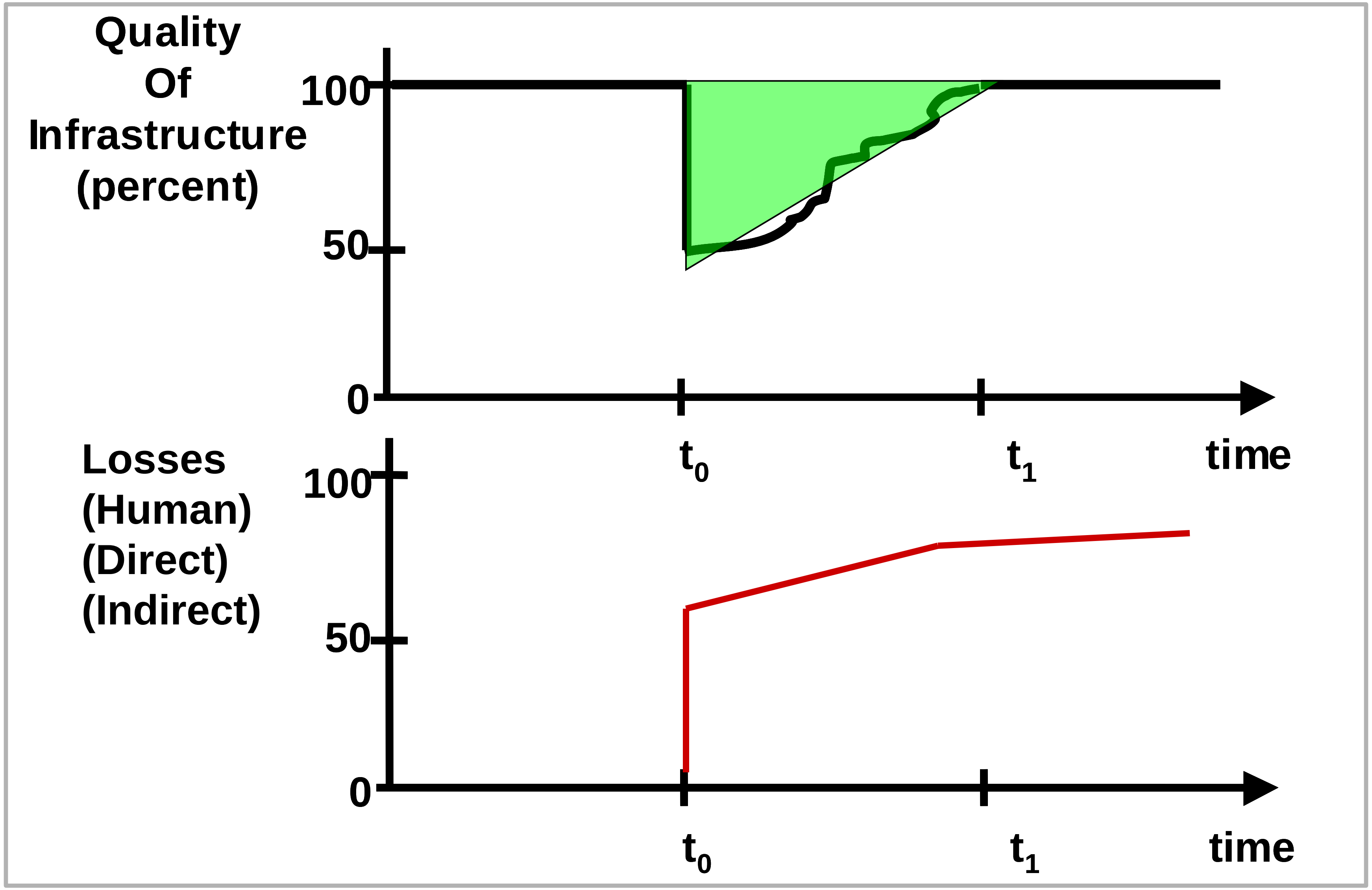
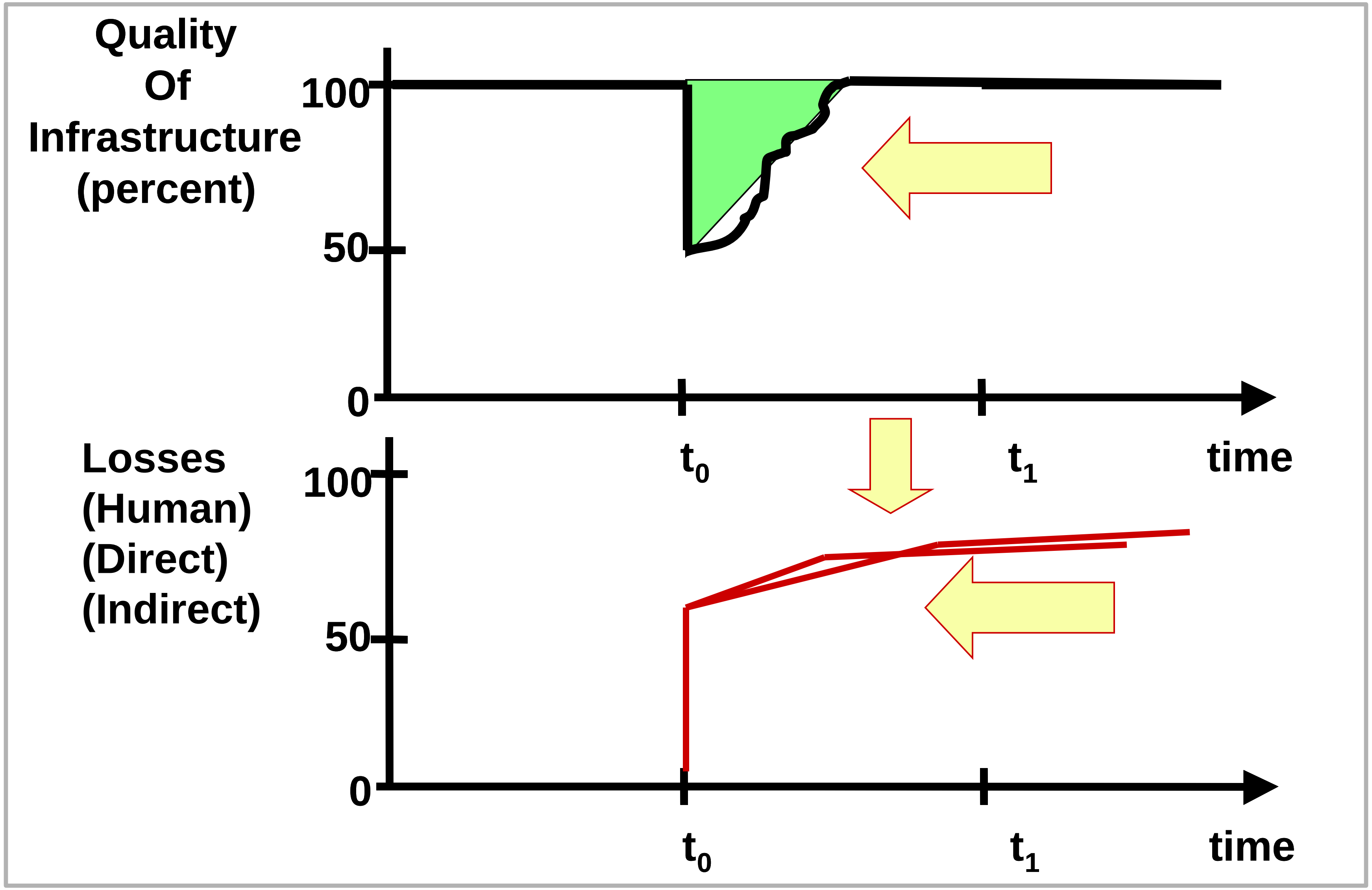
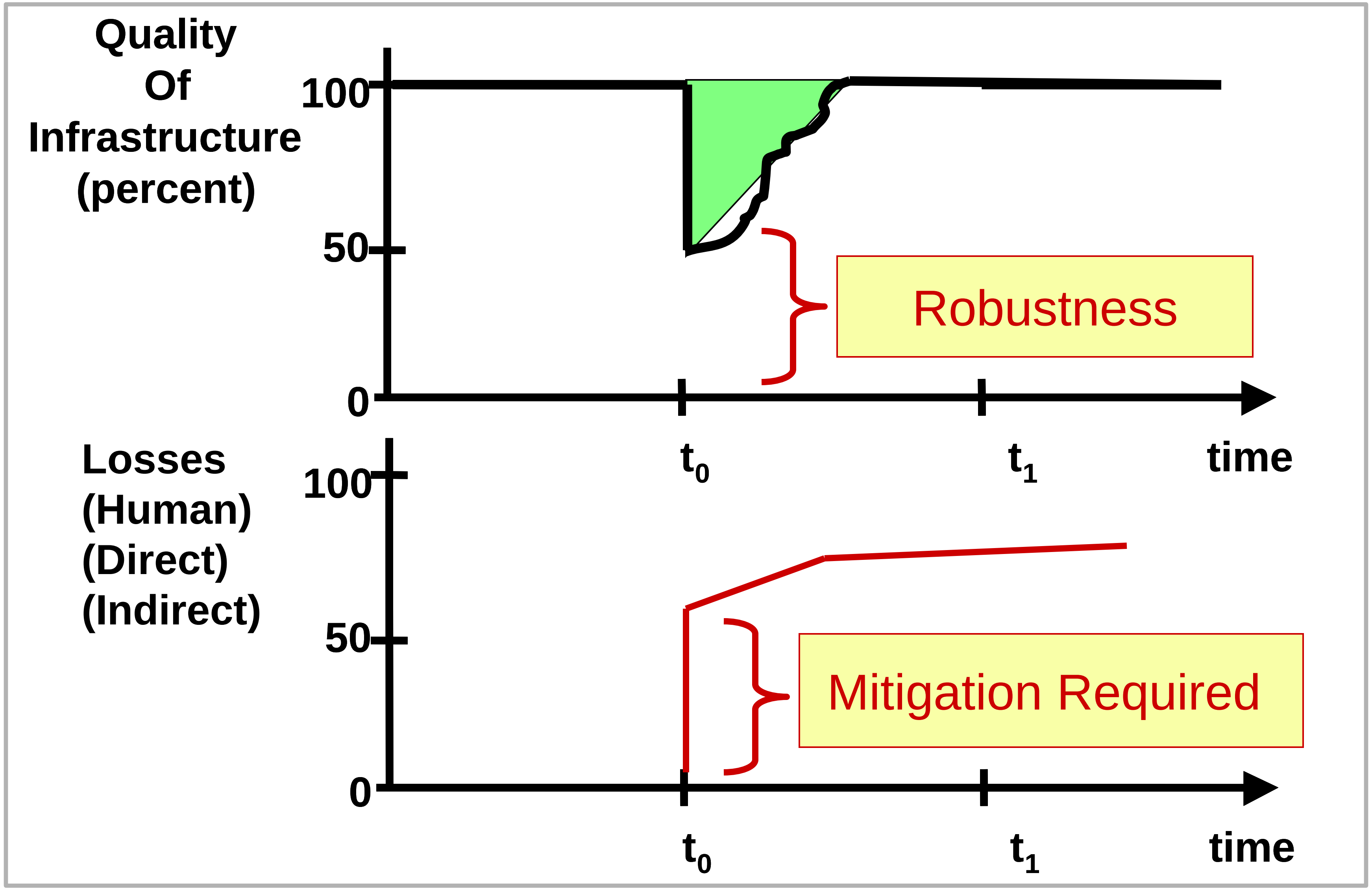
Mitigation and Response



Mitigation and Response

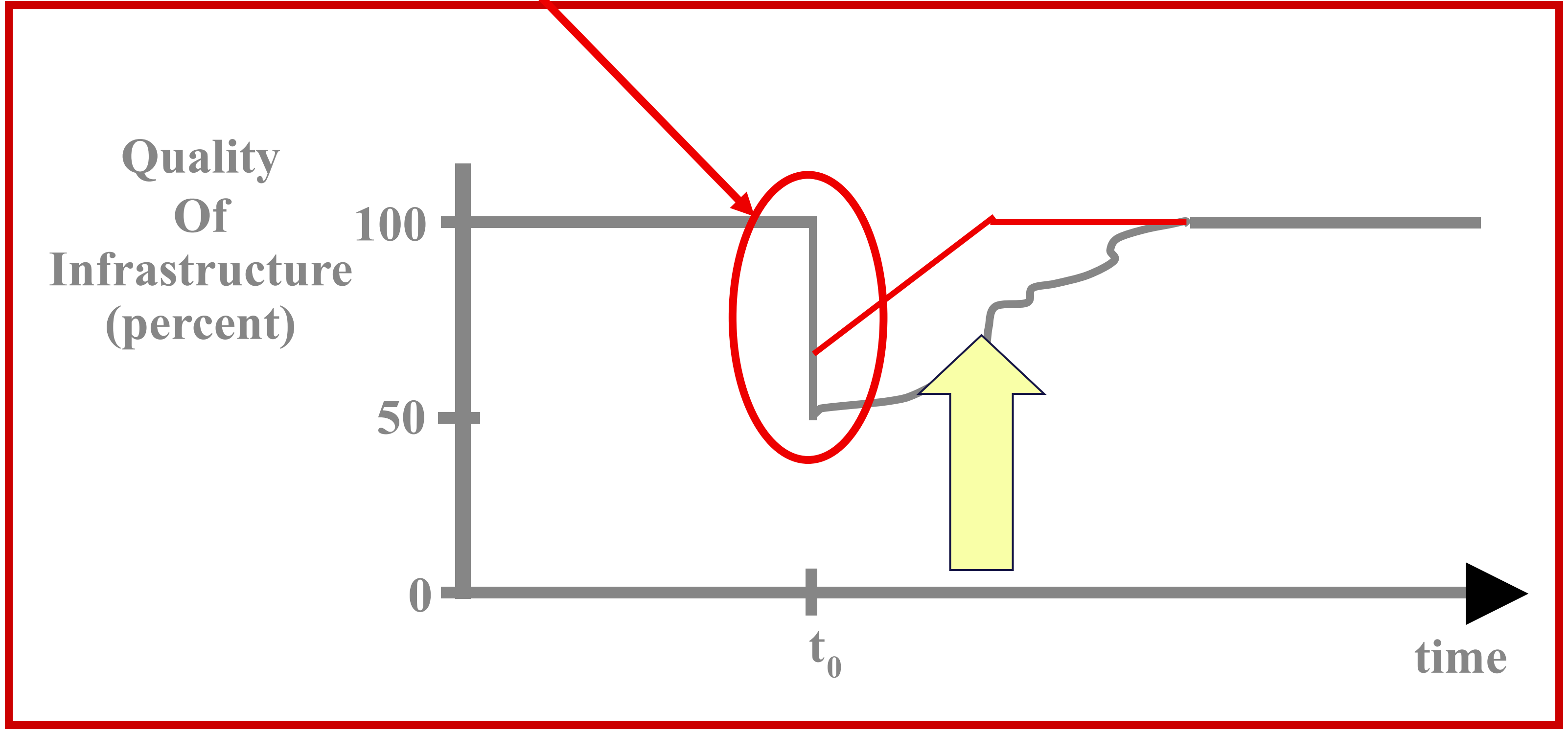


Mitigation and Response



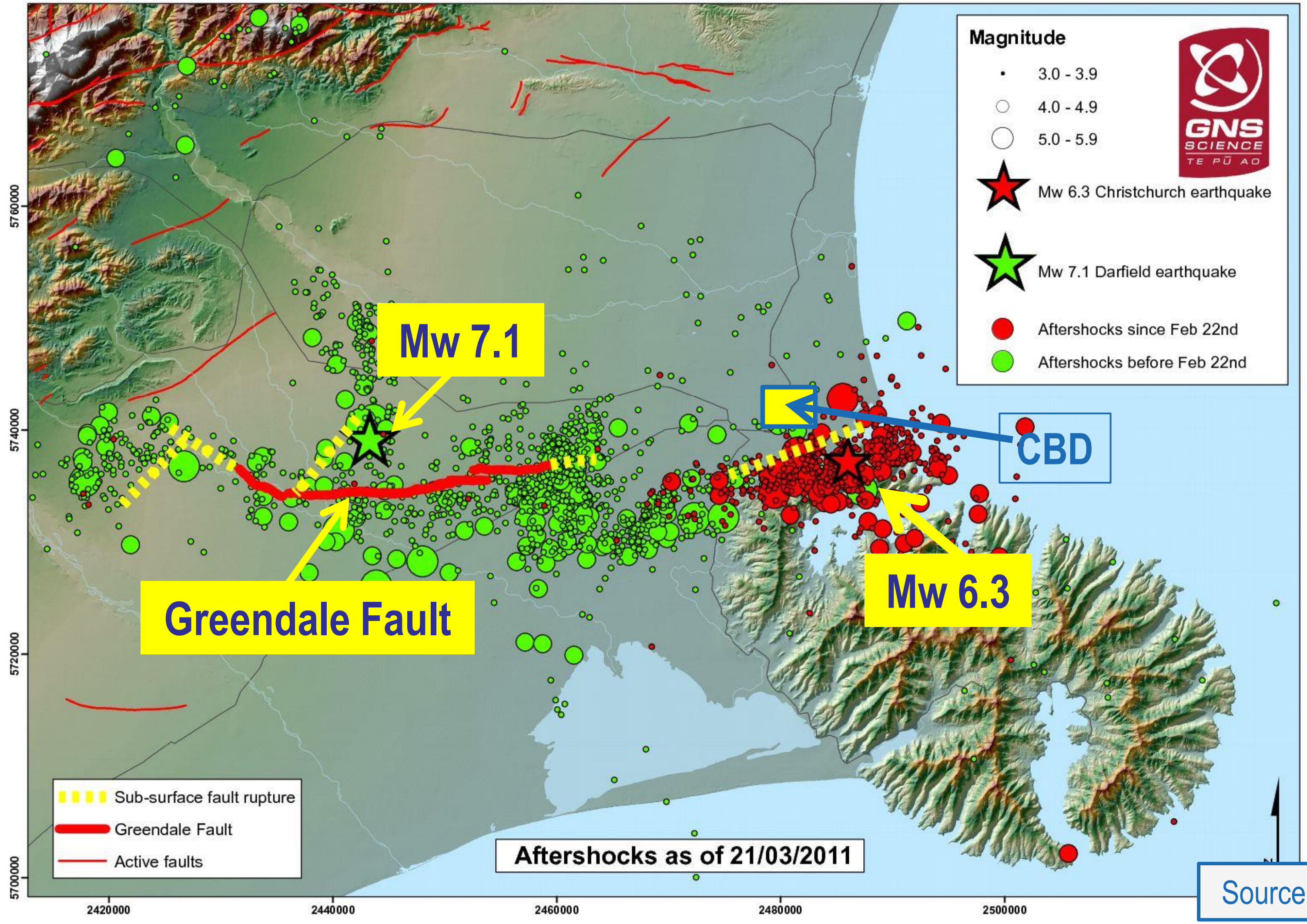
Resilience Curve (MCEER 2002)

Enhance resilience by reducing damage during extreme events

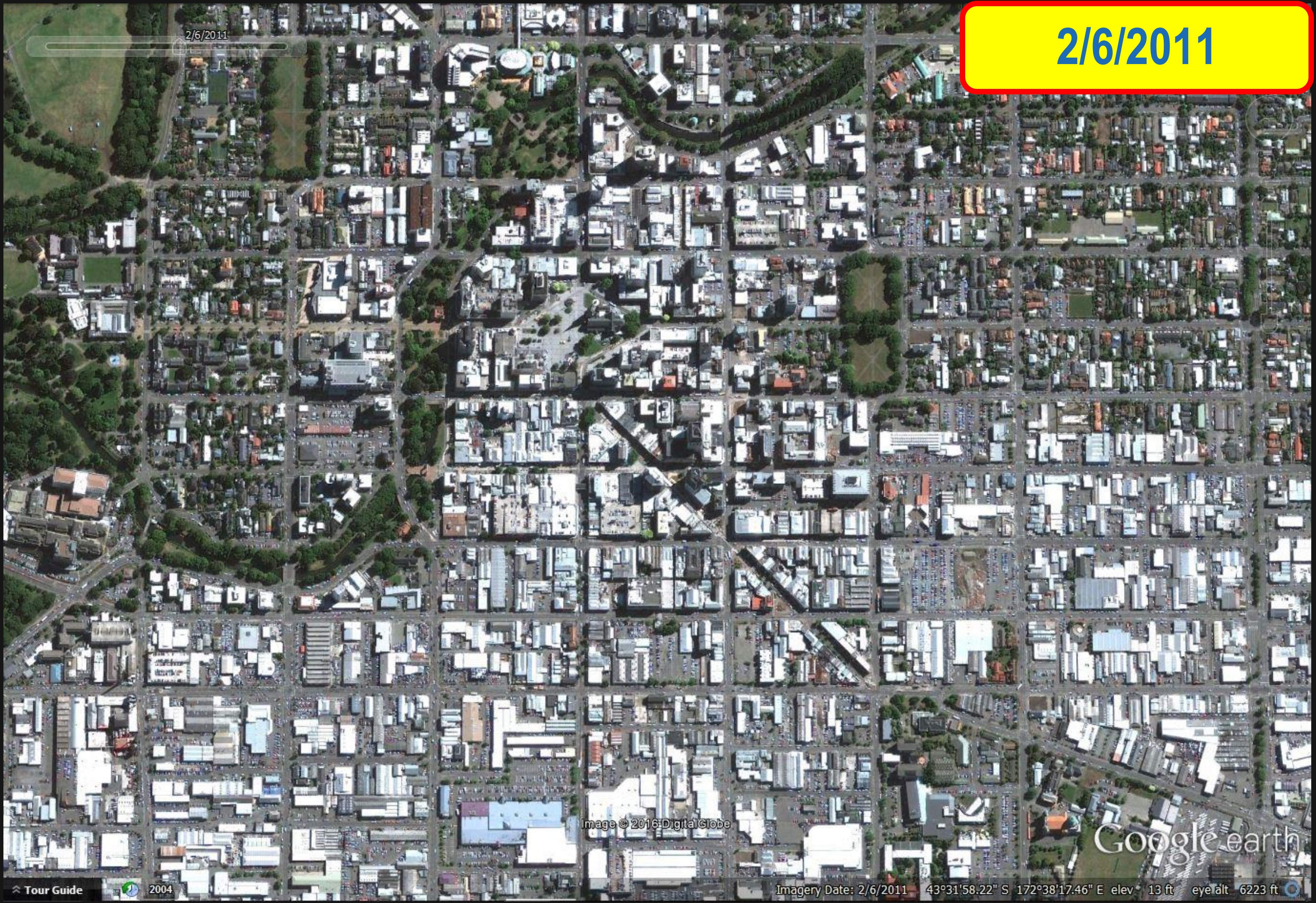


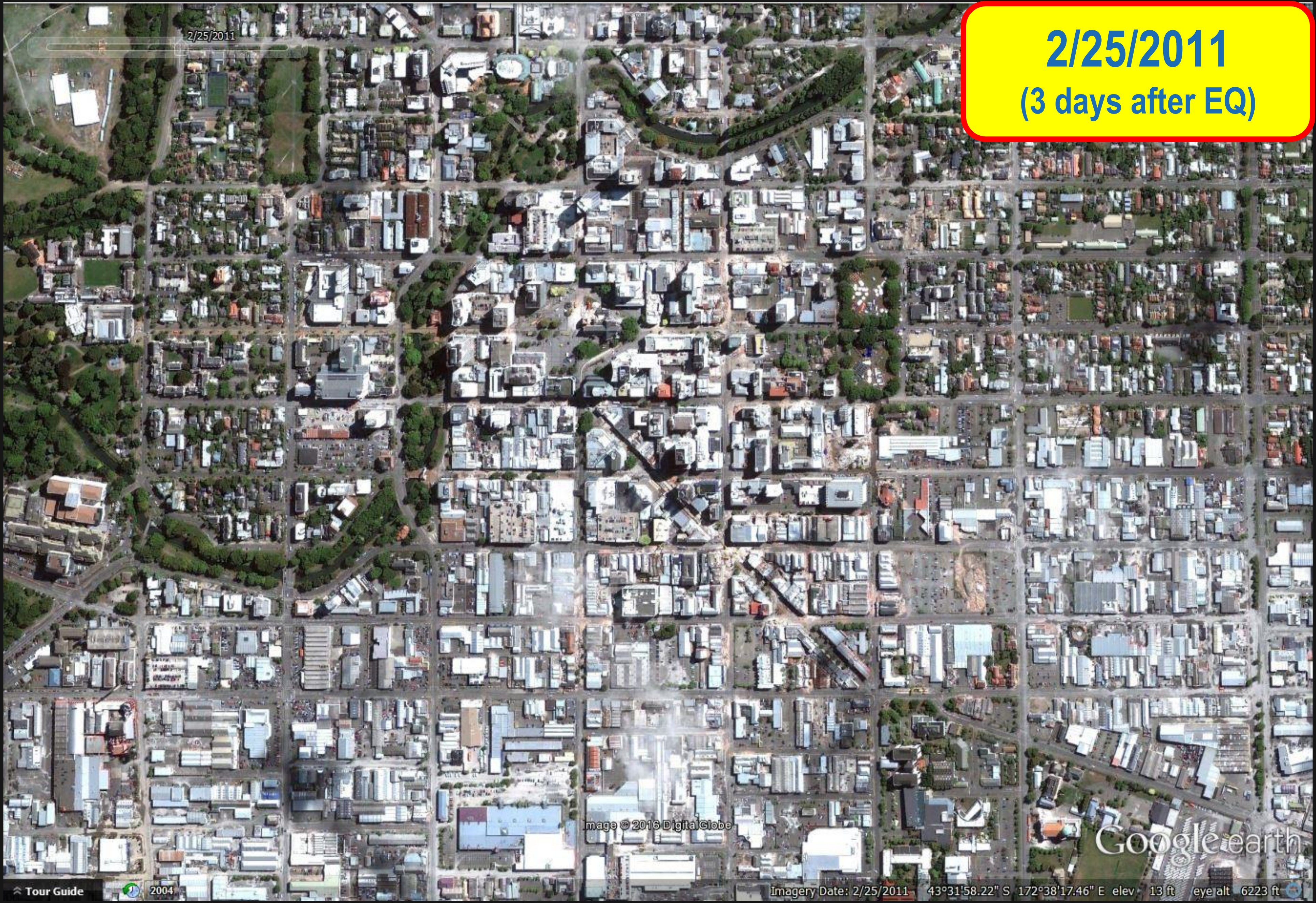
Bruneau, M., Chang, S., Eguchi, R., Lee, G., O'Rourke, T., Reinhorn, A., Shinozuka, M., Tierney, K., Wallace, W., von Winterfelt, D., (2003). "A Framework to Quantitatively Assess and Enhance the Seismic Resilience of Communities", EERI Spectra Journal, Vol.19, No.4, pp.733-752.

Mw 6.3, Lyttleton, 21 February 2011

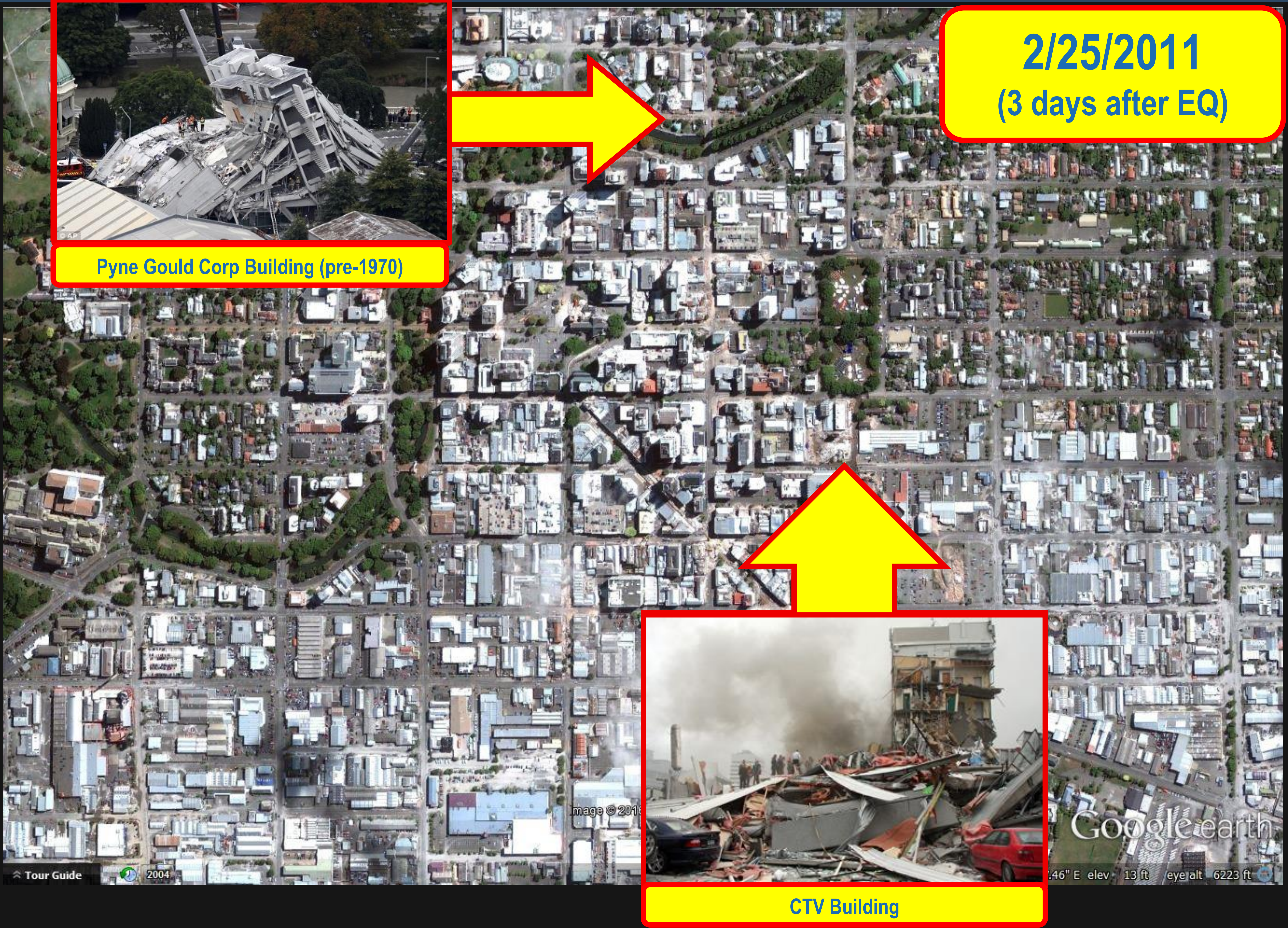


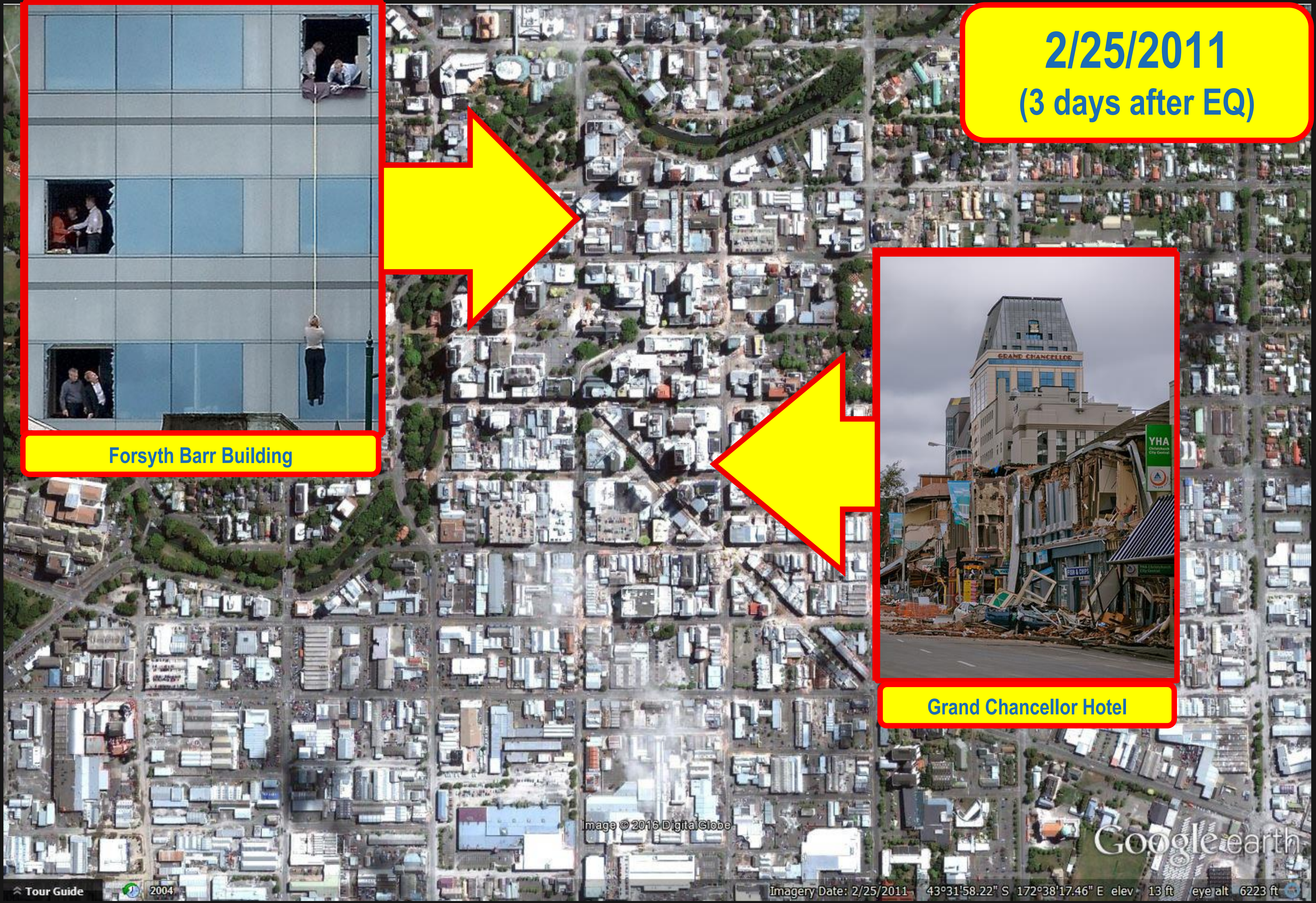
Source: GeoNet


2/6/2011
2/6/2011
Image © 2016 DigitalGlobe
Google earth
Tour Guide
2004
Imagery Date: 2/6/2011 43°31'58.22" S 172°38'17.46" E elev 13 ft eye alt 6223 ft



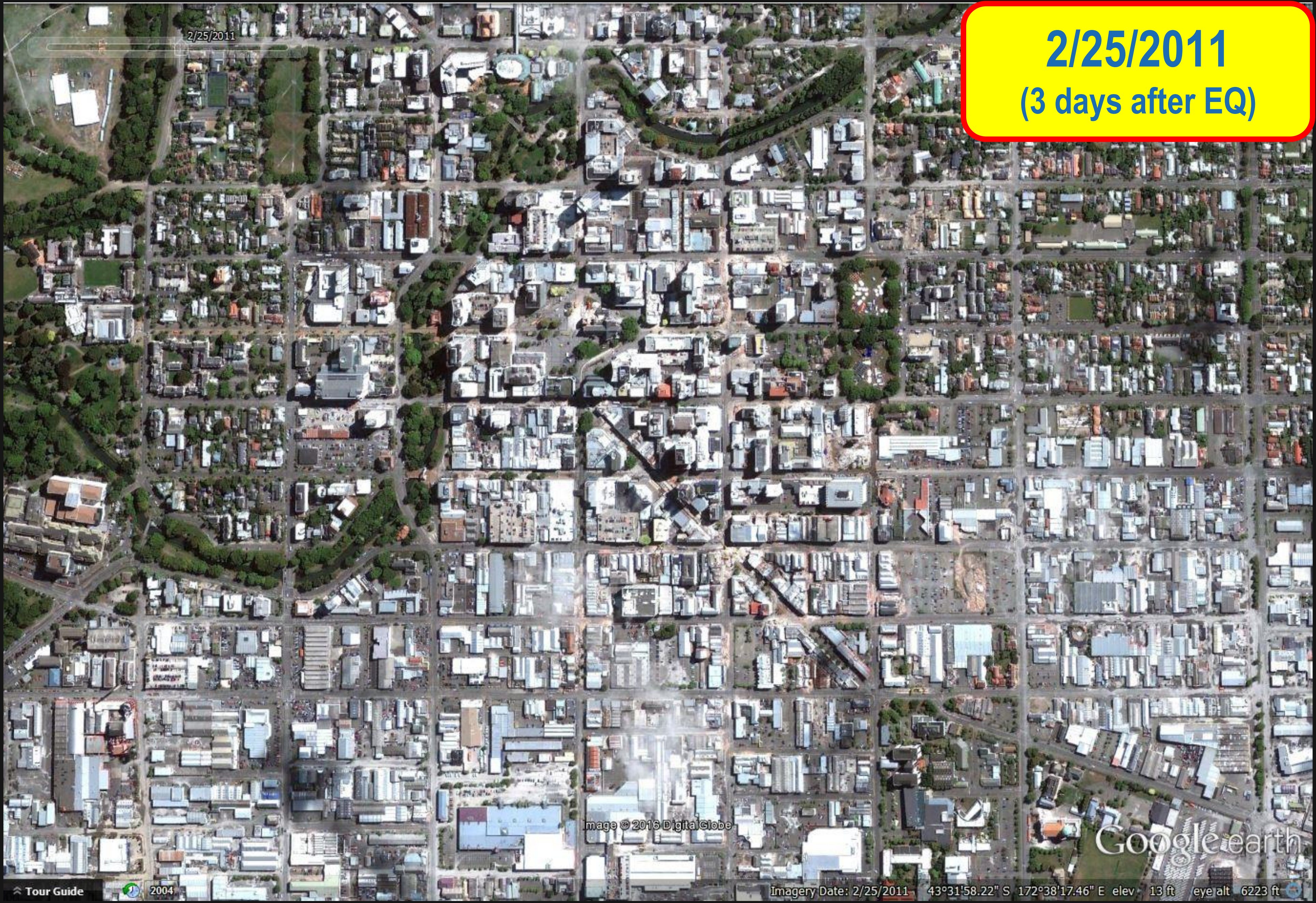
2/25/2011
(3 days after EQ)

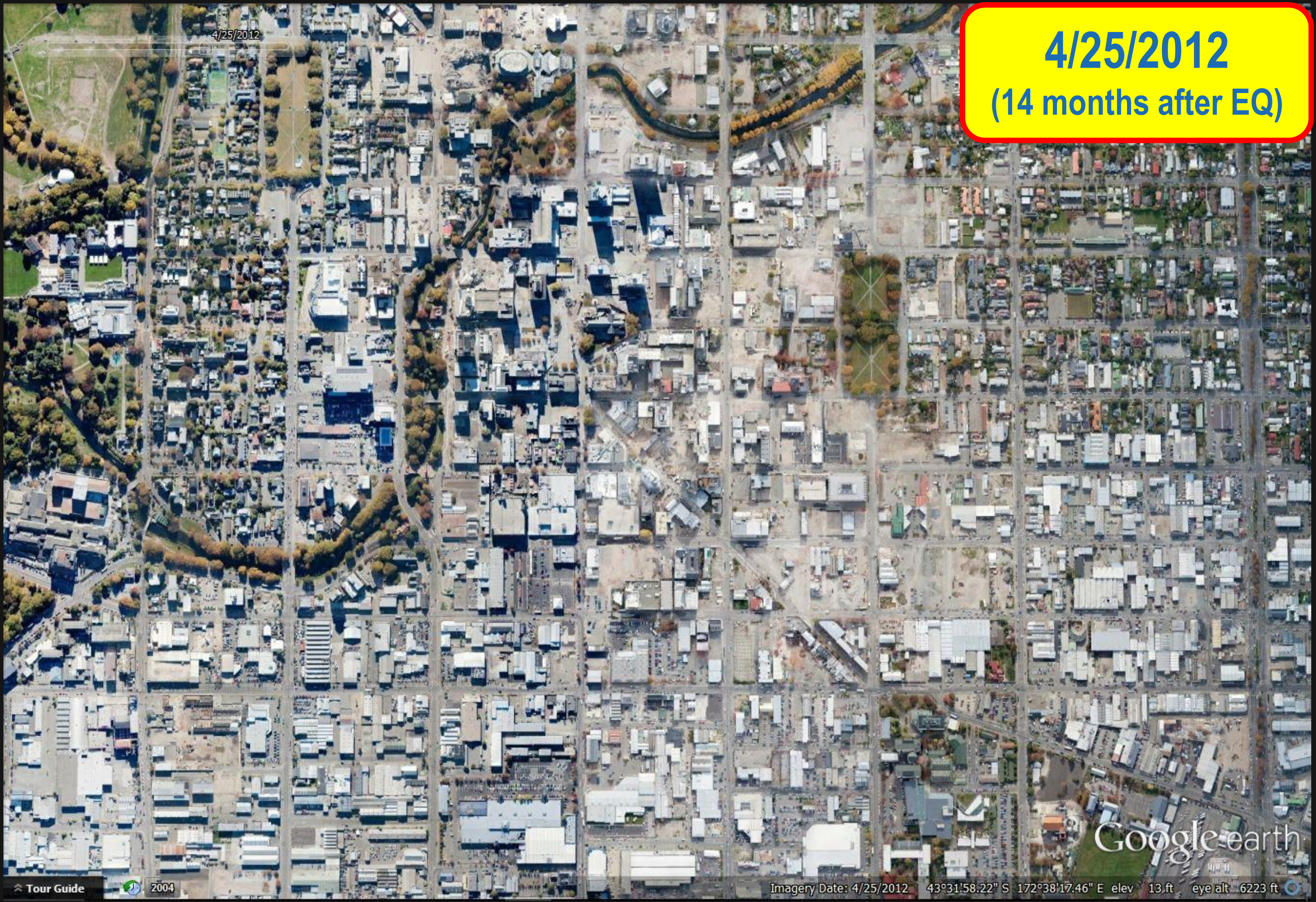

2/25/2011
(3 days after EQ)
Pyne Gould Corp Building (pre-1970)
CTV Building
Google earth
Tour Guide
2004



2/25/2011
(3 days after EQ)
Forsyth Barr Building
Grand Chancellor Hotel
GRAND CHANCELLOR
YHA
Image © 2016 DigitalGlobe
Google earth
Tour Guide
2004
Imagery Date: 2/25/2011 43°31'58.22" S 172°38'17.46" E elev 13 ft eye alt 6223 ft

2/25/2011
(3 days after EQ)




4/25/2012
(14 months after EQ)
4/25/2012
Tour Guide
2004
Imagery Date: 4/25/2012 43°31'58.22" S 172°38'17.46" E elev 13 ft eye alt 6223 ft
Google earth

The Pay-now or Pay-later Decision

It is a rational decision to bet against occurrence of an extreme event to use liquidity for other purposes, provided it is a conscientious decision, recognizing all consequences, and using insurance (or self-insurance) to cover the risk

A NHTSA crash test

What most owners are typically sold

What some owner typically think they are getting (but wouldn't pay for)

Outcome of Current Design Approach

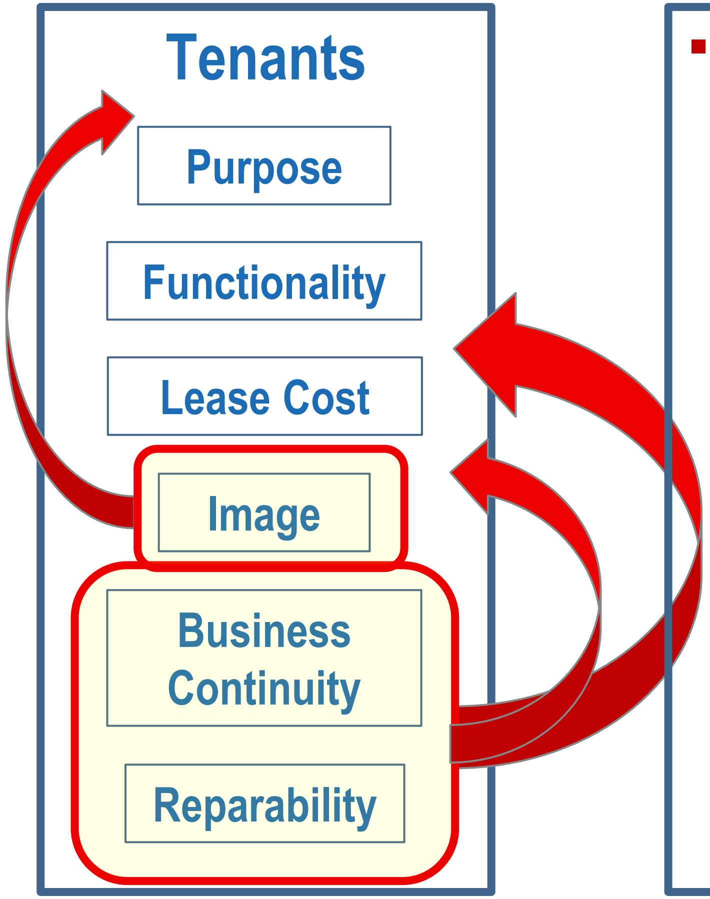
Reconstructing Christchurch: Quantitative Findings on Shift in Building Structural Systems

Michel Bruneau, Ph.D., P.Eng
Department of Civil, Structural and Environmental Engineering
University at Buffalo
Gregory A. MacRae, Ph.D.
Department of Civil and Natural Resources Engineering
University of Canterbury

Free Download

http://www.michelbruneau.com

Hierarchy of Priorities (Post-Earthquake)



- Many felt RC buildings did not perform well
  - Heavy media coverage of buildings collapses, severe damage, leaning buildings, trapped occupants (e.g. stair collapse), etc.
  - Many buildings with low damage (beam plastic hinging and rebar elongation) were deemed "irreparable" and demolished
  - Life safety seismic performance objective: buildings (generally) behaved / were damaged as engineers (but not as public) expected
  - Two tallest steel structures in Christchurch reopening relatively fast after earthquake, led many tenants and owners to conclude that steel structures are preferable

Rebuilding of Christchurch
(10+ years later)

- Some damaged buildings still there; most demolished
- Construction Types used in Reconstruction (still on-going)
  - A few base-isolated buildings
  - A few buildings with viscous dampers
  - Some EBFs with replaceable links
  - A few rocking (self-centering) frames
  - Some moment frames with friction connections
  - Multiple buildings with BRBs
  - Mostly steel construction (CHCH was a concrete town)
  - One "cardboard" church
  - One Cathedral maybe rebuilt to collapse prevention level

Resilience (Practically Speaking)

- Resilience is a tool to be used to convey a message regarding this functionality
- This can be achieved within the realm of:
  - Aspirational Resilience
    - "It is more resilient because…."
  - Quantifiable Resilience
    - "A resilience objective of # is set / has been attained / is desirable

Qualitative + Professional Judgment at the risk of a "because I say so" impression

Aspirational Resilience

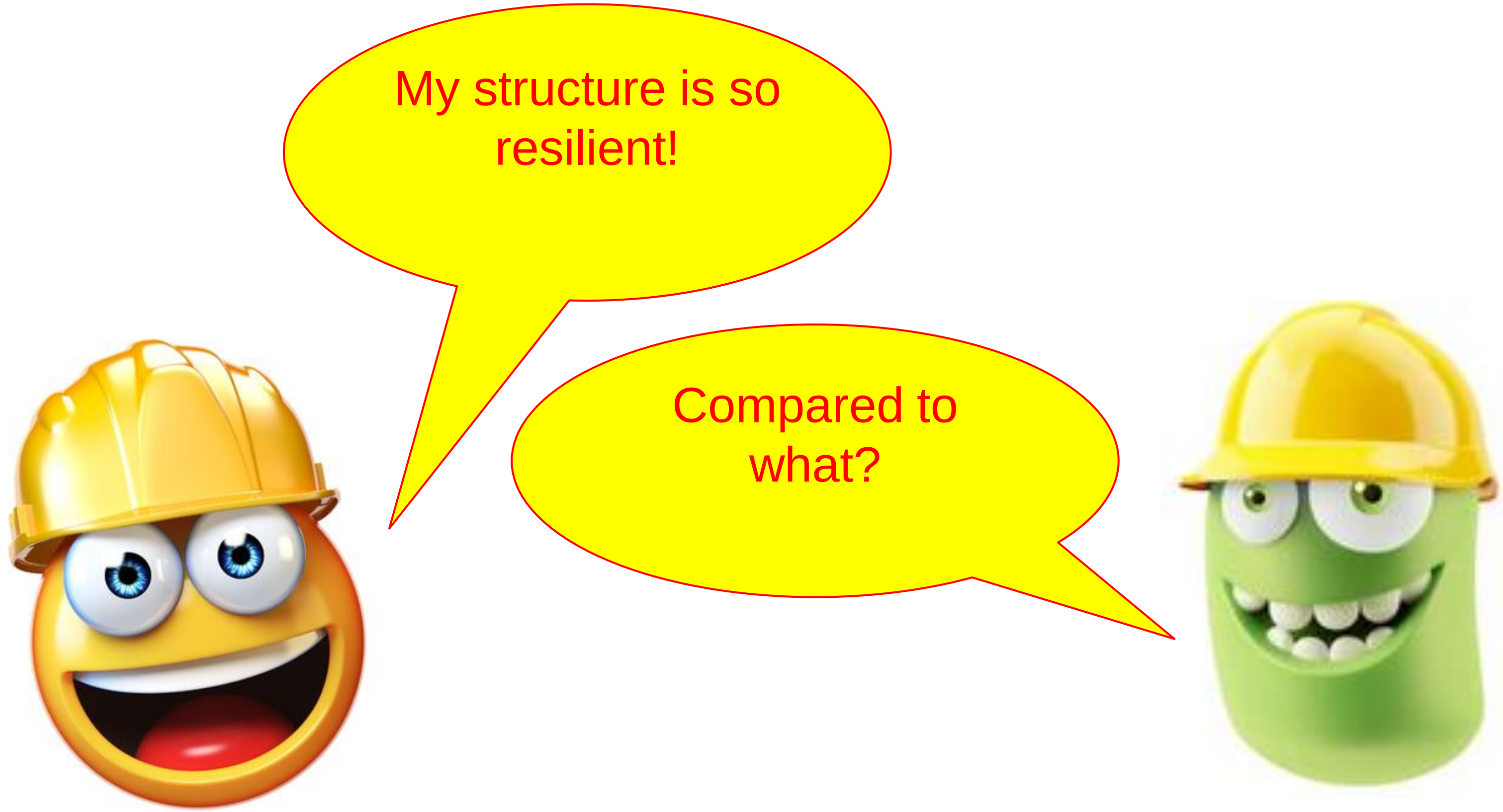


Photo by M. Bruneau

Photo by M. Bruneau


MCEER
SQ1264

Imani, R., Bruneau, M. (2015). "Effect of Link-beam Stiffener and Brace Flange Alignment on Inelastic Cyclic Behavior of Eccentrically Braced Frames", AISC Engineering Journal, Vol.52, No.2, pp.109-124.

Photo by M. Bruneau

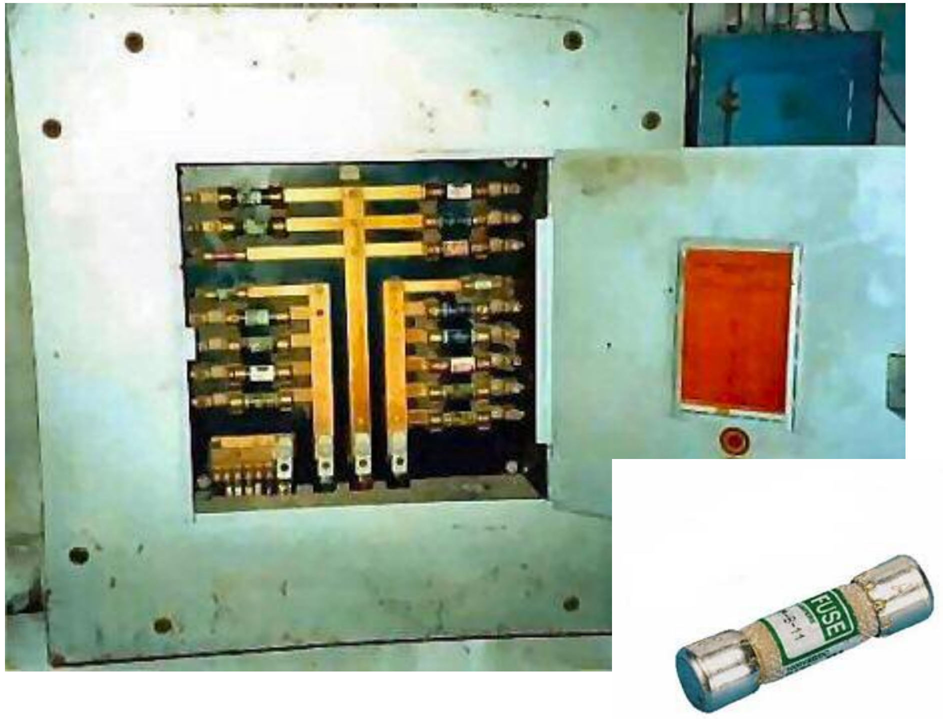
Post-Earthquake Repair

Example of Aspirational Resilience: Structural Fuses

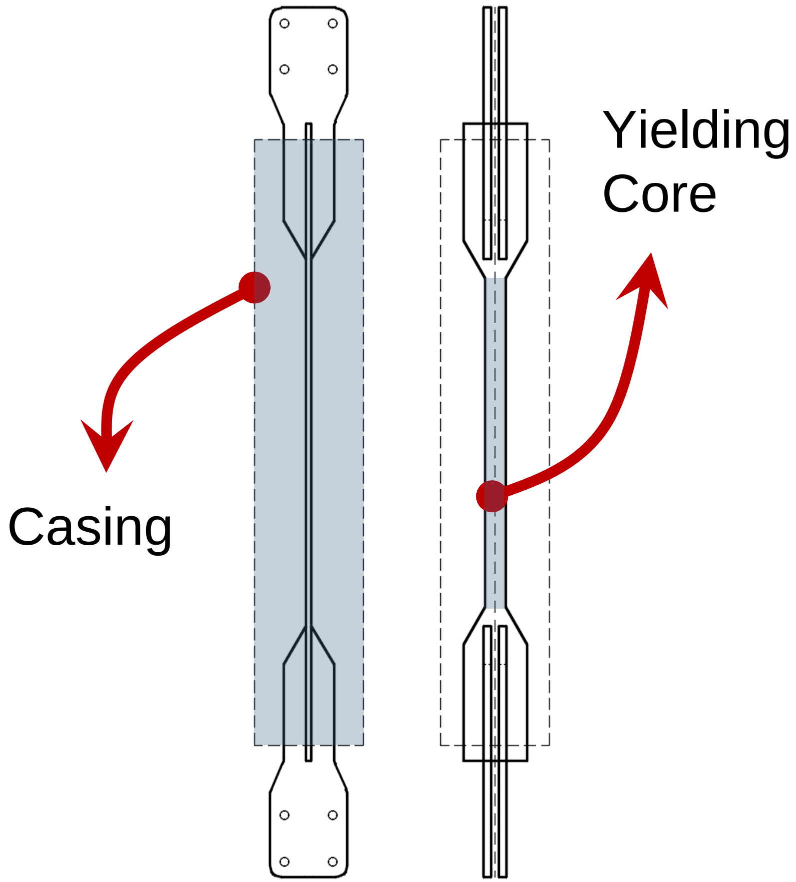
- From Energy Dissipation to Structural Fuse
  - Researchers have proposed that hysteretic energy dissipation should instead occur in “disposable” structural elements (i.e., structural fuses)

Analogy

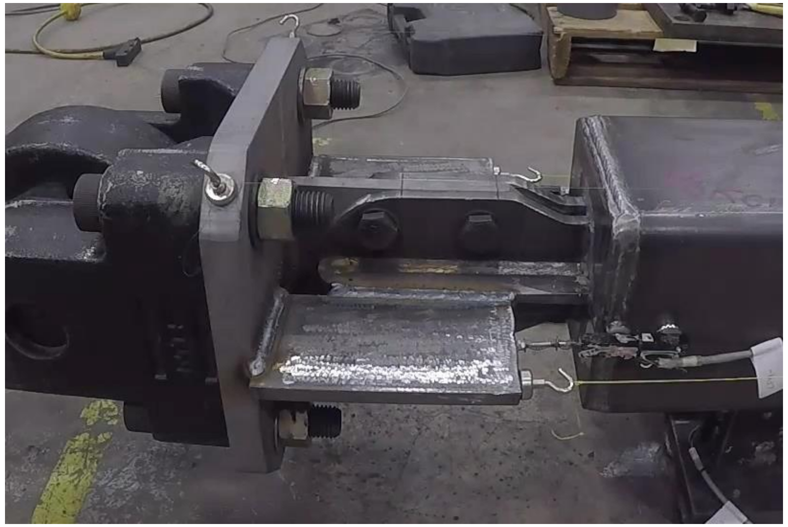
- Sacrificial element to protect the rest of the system.

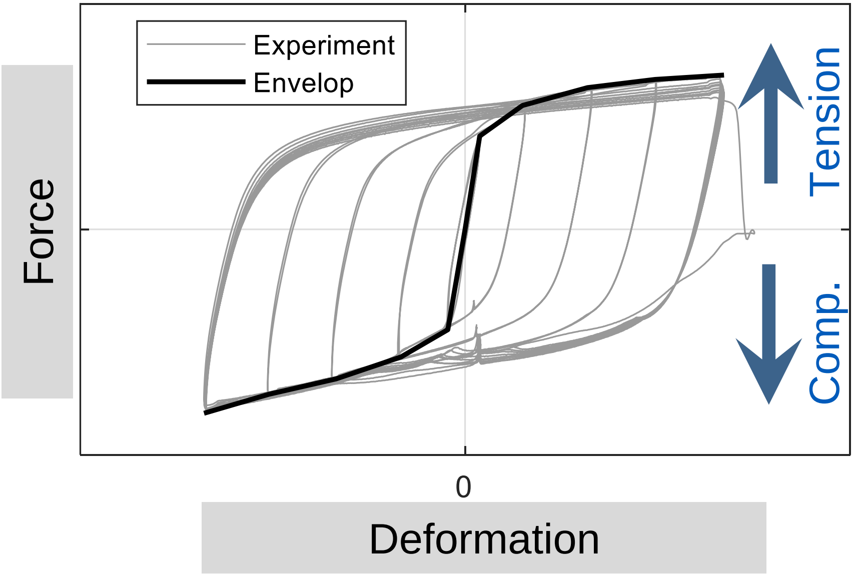


Buckling Restrained Brace (BRB)



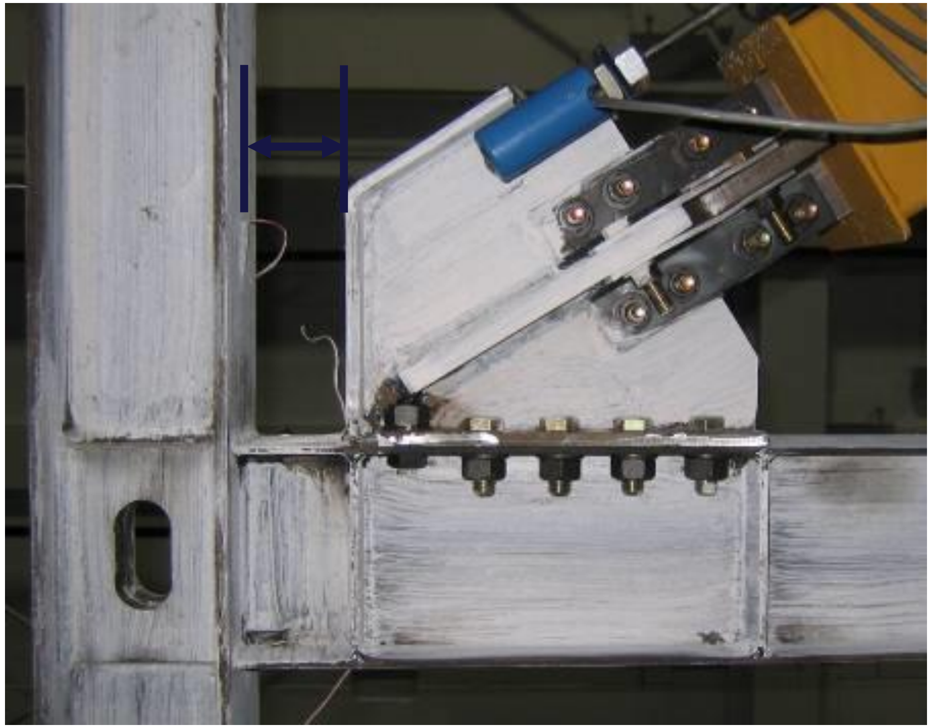
Buckling Restrained Brace (BRB)





Buckling Restrained Braced Frame

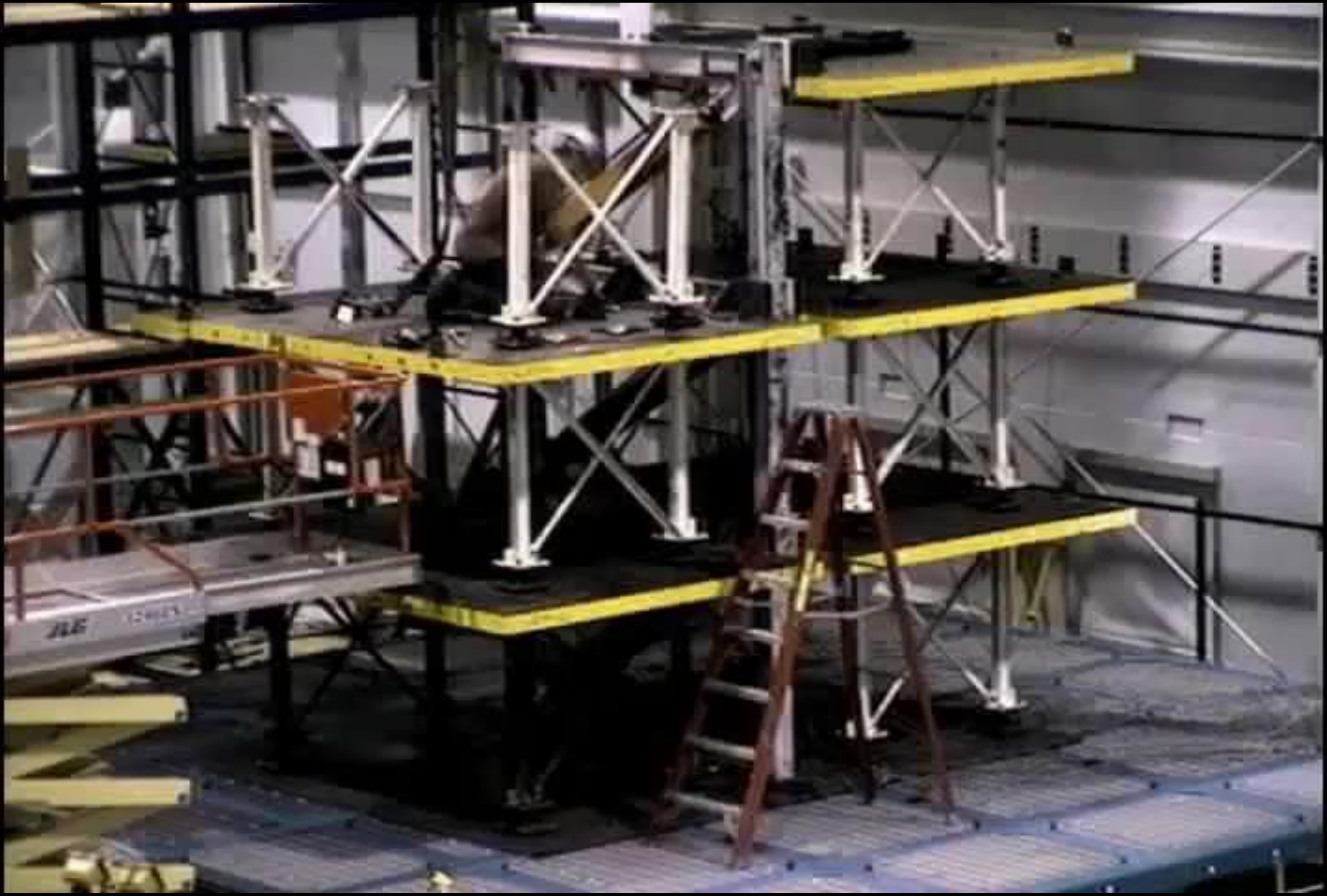
Eccentric Gusset-Plate



Vargas, R., Bruneau, M., “Experimental Investigation of the Structural Fuse Concept”, Technical Report MCEER-06-0005, Multidisciplinary Center for Earthquake Engineering Research, State University of New York at Buffalo, Buffalo, NY, 210 pages.

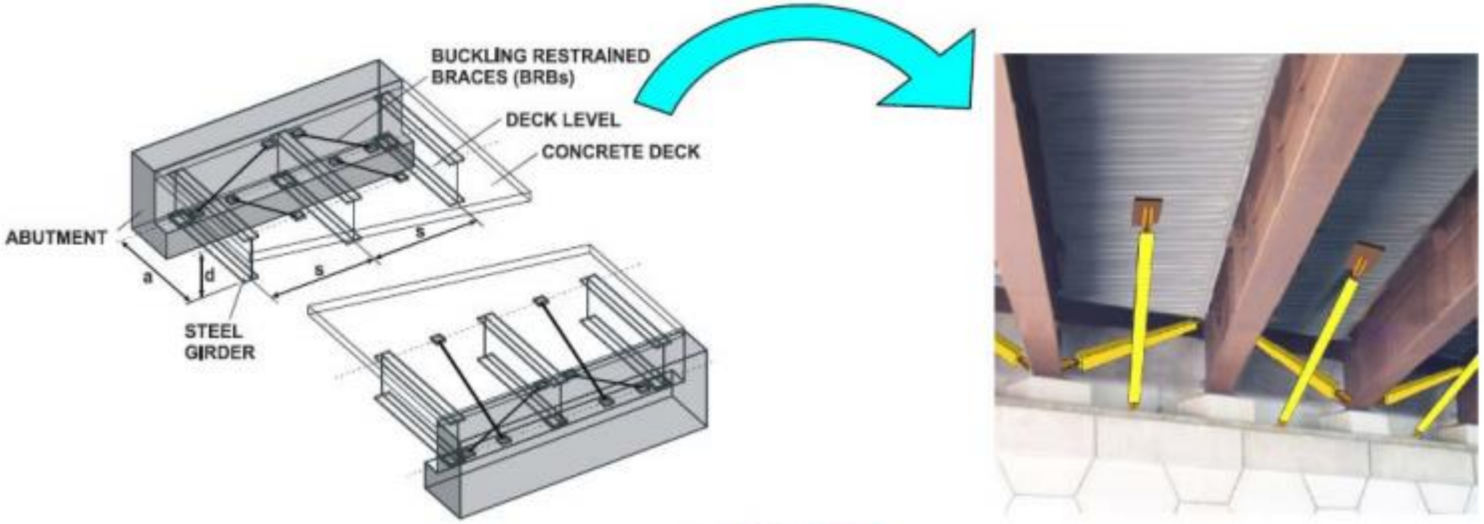
Test 1

(PGA = 1g)



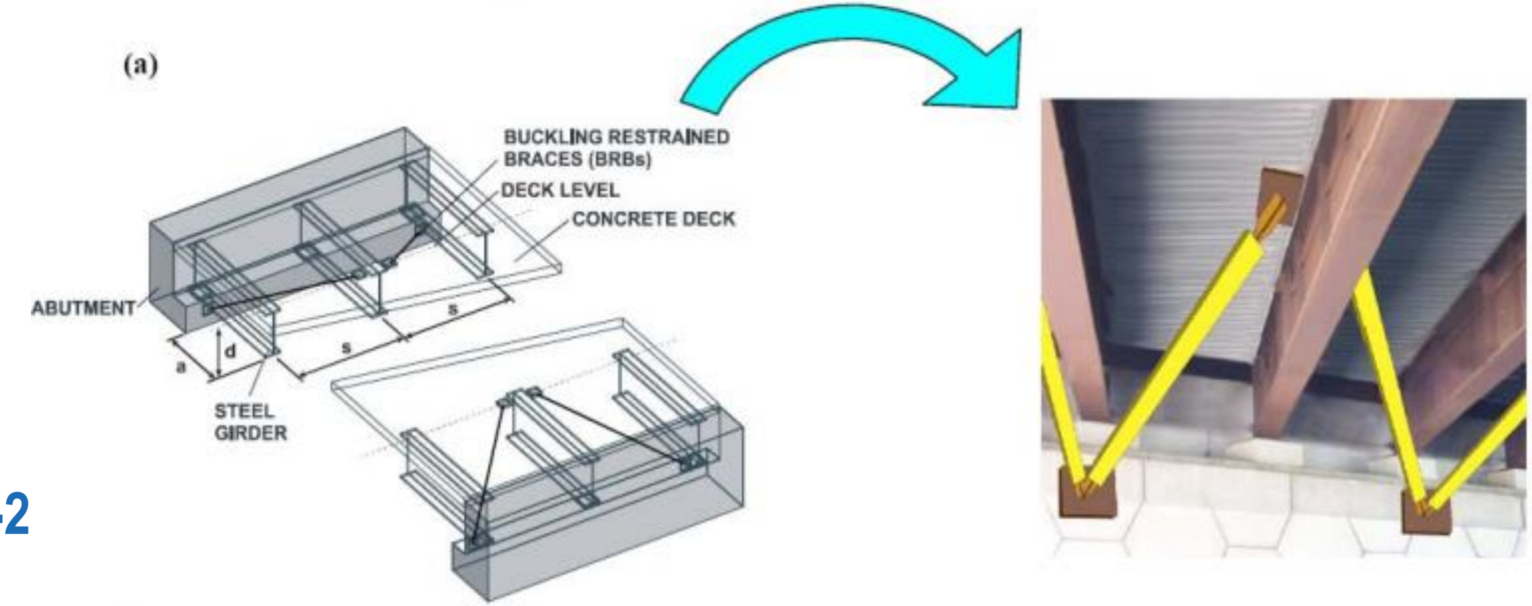
Bi-Directional Ductile Diaphragms:

EDS-1



(a)

EDS-2



(b)

Celik, O., Bruneau, M., (2011). “Skewed Slab-on-Girder Steel Bridge Superstructures with Bidirectional-Ductile End Diaphragms,” ASCE Journal of Bridge Engineering, Vol.16, No.2, pp.207-218.

Bi-Directional Ductile Diaphragms (NCHRP-IDEA)

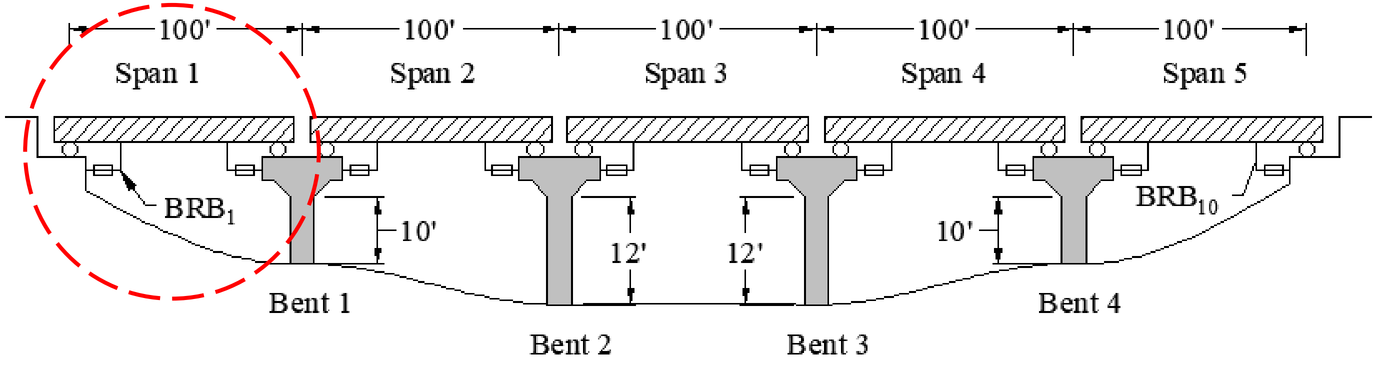
- **ANALYTICAL RESEARCH – Longitudinal behavior**
  - Parametric elastic analysis
  - Non-linear behavior and parametric analysis of bridges designed per:
    - Proposed procedure based on RSA
    - Non-linear based design method
    - Proposed equivalent lateral force method
  - Capacity design procedure
  - Irregular bridges: behavior and design
- **EXPERIMENTAL RESEARCH – Three directions of earthquake excitation**
  - Design, construction, and testing of 40-foot-long bridge span (1:2.5 scale) on two shake tables

- **Carrion-Cabrera H.**, and Bruneau M., (2024). "Asynchronous shake table testing of seismic resilient multi-span bridges having buckling restrained braces", ASCE Journal of Structural Engineering (in press)
- **Carrion-Cabrera H.**, and Bruneau M., (2024). "Equivalent Lateral Force Design Method for Longitudinal Buckling-Restrained Braces in Bidirectional Ductile Diaphragms", ASCE Journal of Structural Engineering, Vol.150, No.3
- **Carrion-Cabrera H.**, and Bruneau M. (2022) *"Longitudinal-direction design of buckling restrained braces implemented to achieve resilient multi-span bridges"*. Bridge Engineering Themed Issue: Bridge and transportation network resilience, https://doi.org/10.1680/jbren.21.00097
- **Carrion-Cabrera H.**, and Bruneau M. (2022) *"Seismic response of regular multi-span bridges having buckling-restrained braces in their longitudinal direction"*, Engineering Structures. Vol. 259, Article 114127, https://doi.org/10.1016/j.engstruct.2022.114127.

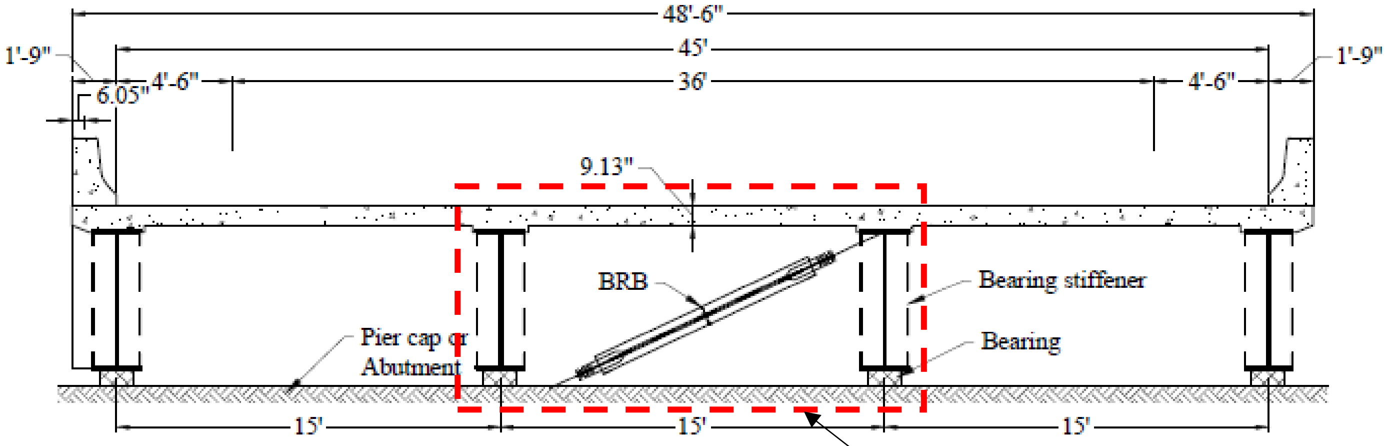
Objectives of Experimental Program

- To validate different types of BRB end connections (available in the literature or new custom connections specifically designed for this application) to accommodate 3-D motions (i.e., multi-directional displacement demands at ends of BRBs)
- To experimentally validate the behavior of BRBs in bidirectional ductile end diaphragms under seismic loads and thermal-induced demands representing life-cycle demands
- To validate the BRB design procedure proposed in the analytical part of the research

Prototype



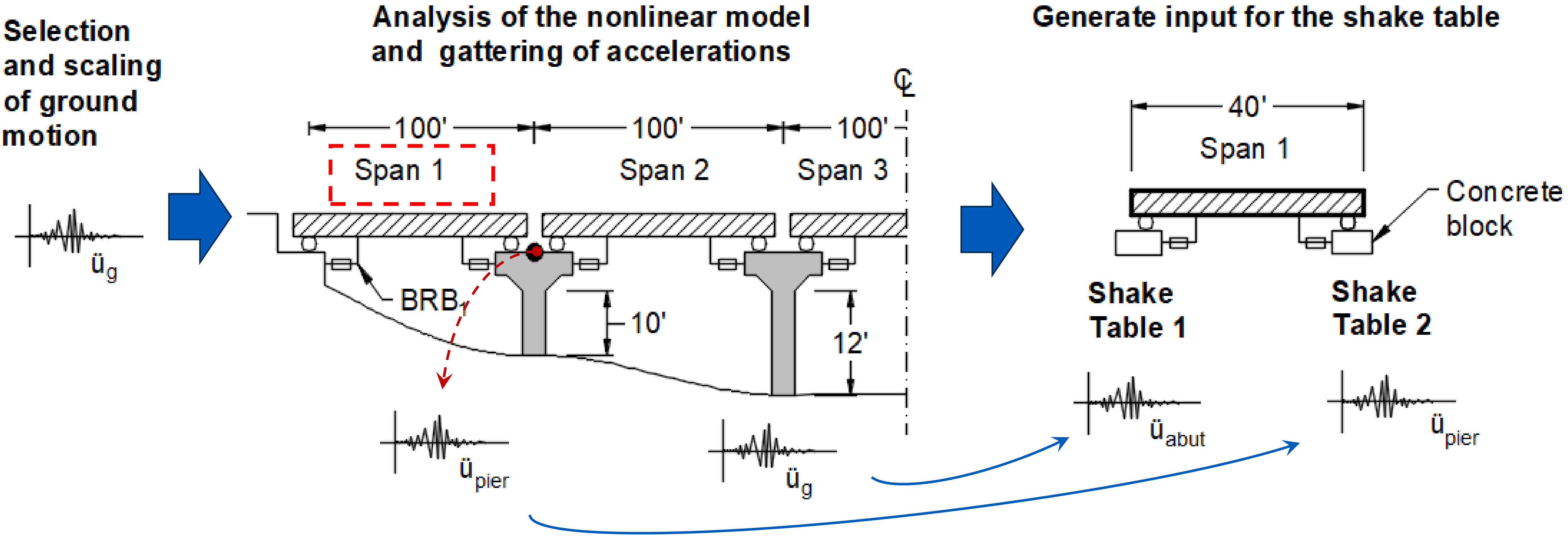
Elevation view



Cross-section

Represented by the specimen

Specimen 1 / 2.5

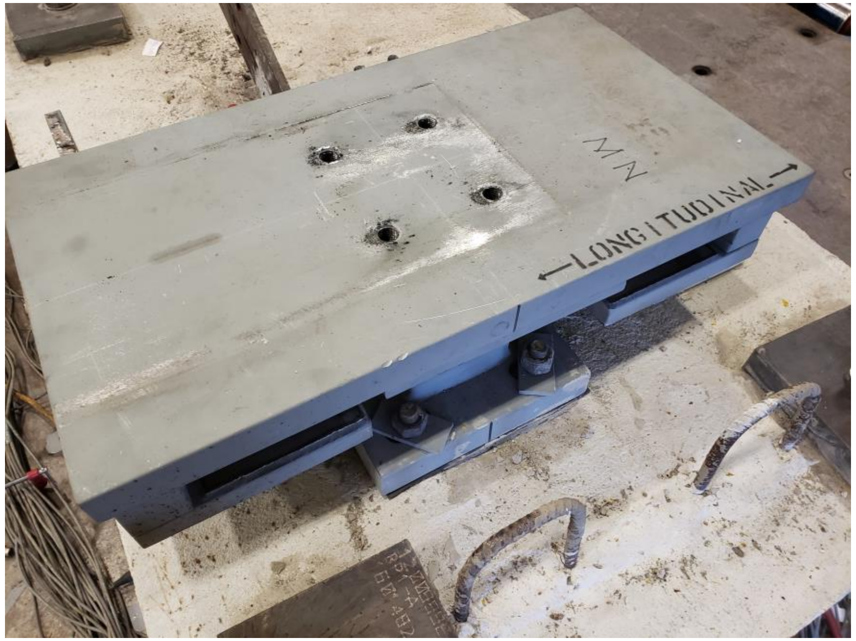


- **Carrion-Cabrera H.**, and Bruneau M., (2024). "Asynchronous shake table testing of seismic resilient multi-span bridges having buckling restrained braces", ASCE Journal of Structural Engineering, Vol. 150, No. 7,
- **Carrion-Cabrera H.**, and Bruneau M., (2024). "Equivalent Lateral Force Design Method for Longitudinal Buckling-Restrained Braces in Bidirectional Ductile Diaphragms", ASCE Journal of Structural Engineering, Vol.150, No.3

Material

- Steel by AISC
- Bridge manufacturing High Industries (High Steel, High Concrete, and High Transit)
- BRBs by CoreBrace
- Bearings by RJ Watson

BRB



Bearing

Experiment

Specifications

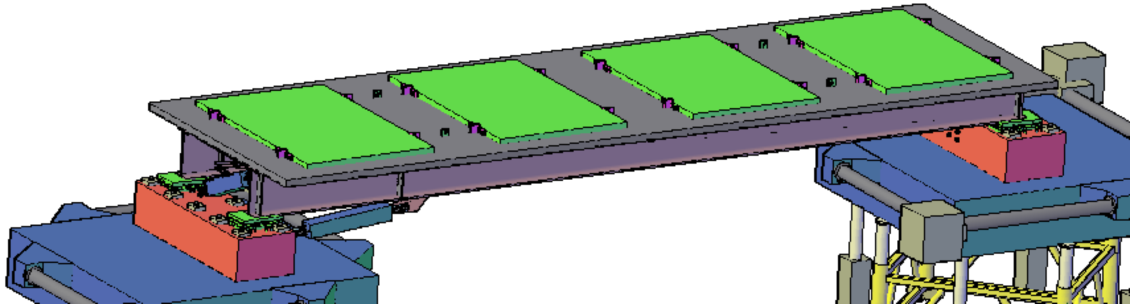
A total of:

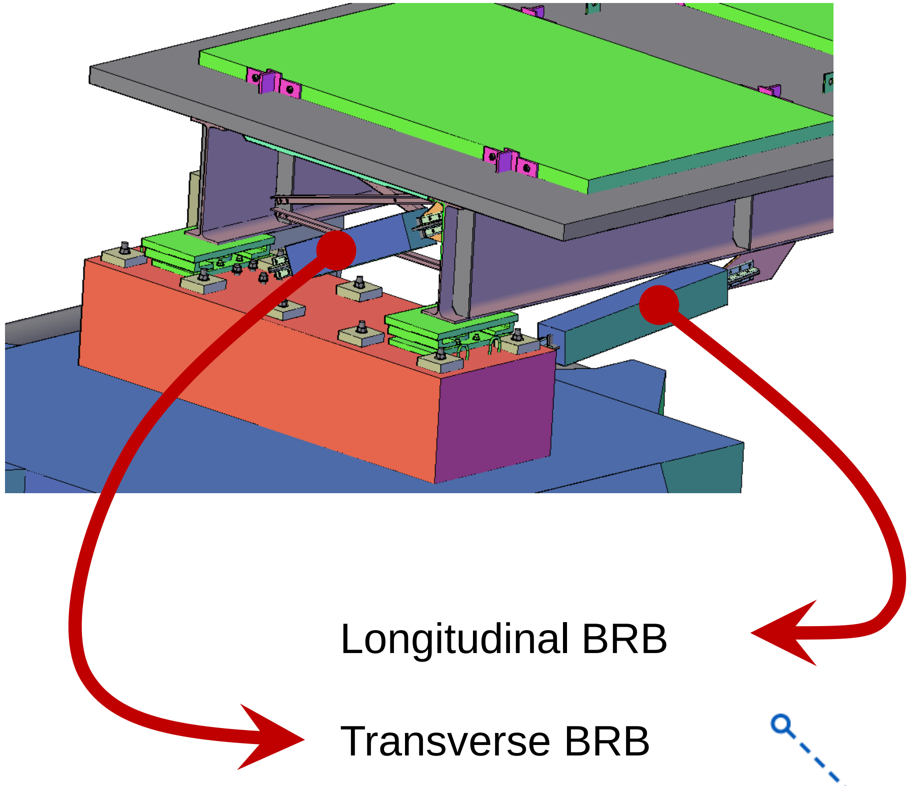
- 4 different BRB configurations
- 4 different BRB connections to gusset plates
- 8 different connections between BRB to concrete
  (6 for new structure, 2 for retrofitting)
- 4 different connections between BRB to the steel girder

Loads for each configuration

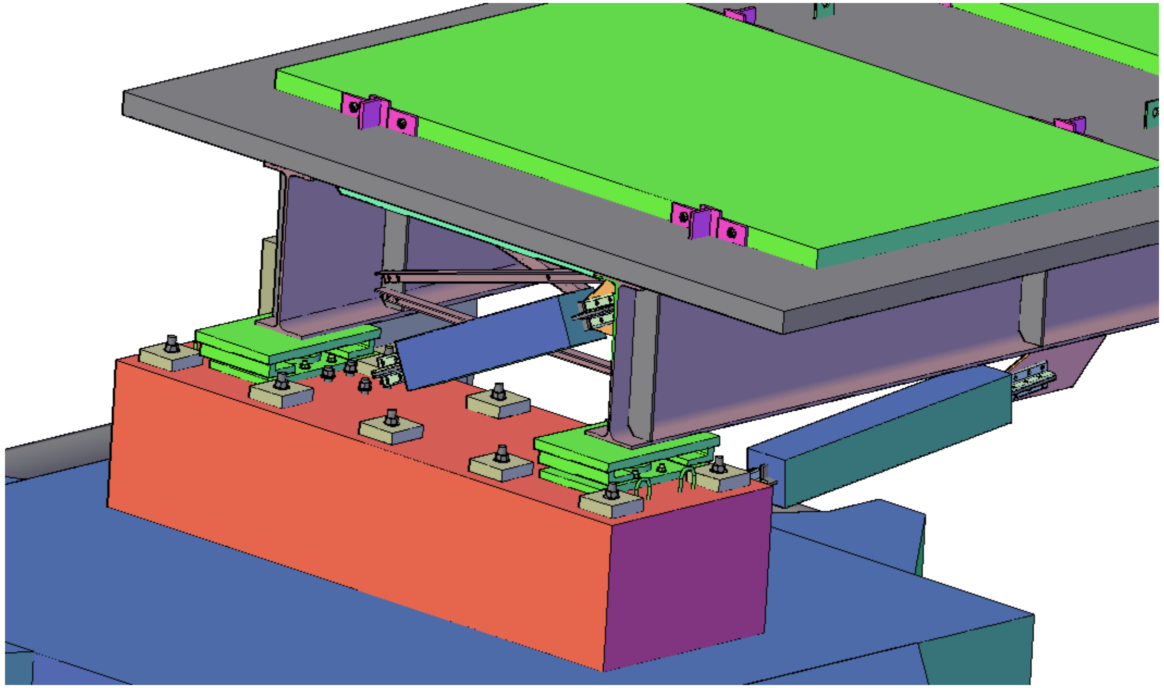
- 1 temperature sequence, representing 75 years of variation.
- 4 spectral matched ground motions, representing design spectrum (1D to 3D).
- 7 historical motions, to induce large demands. (1D to 3D)

Idealization of the experiment set up





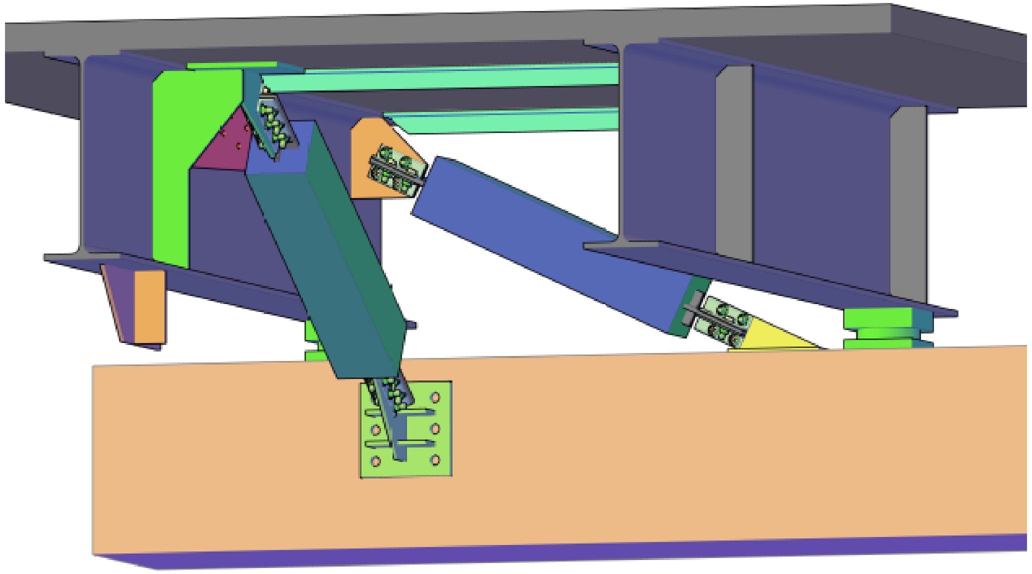
Configuration I



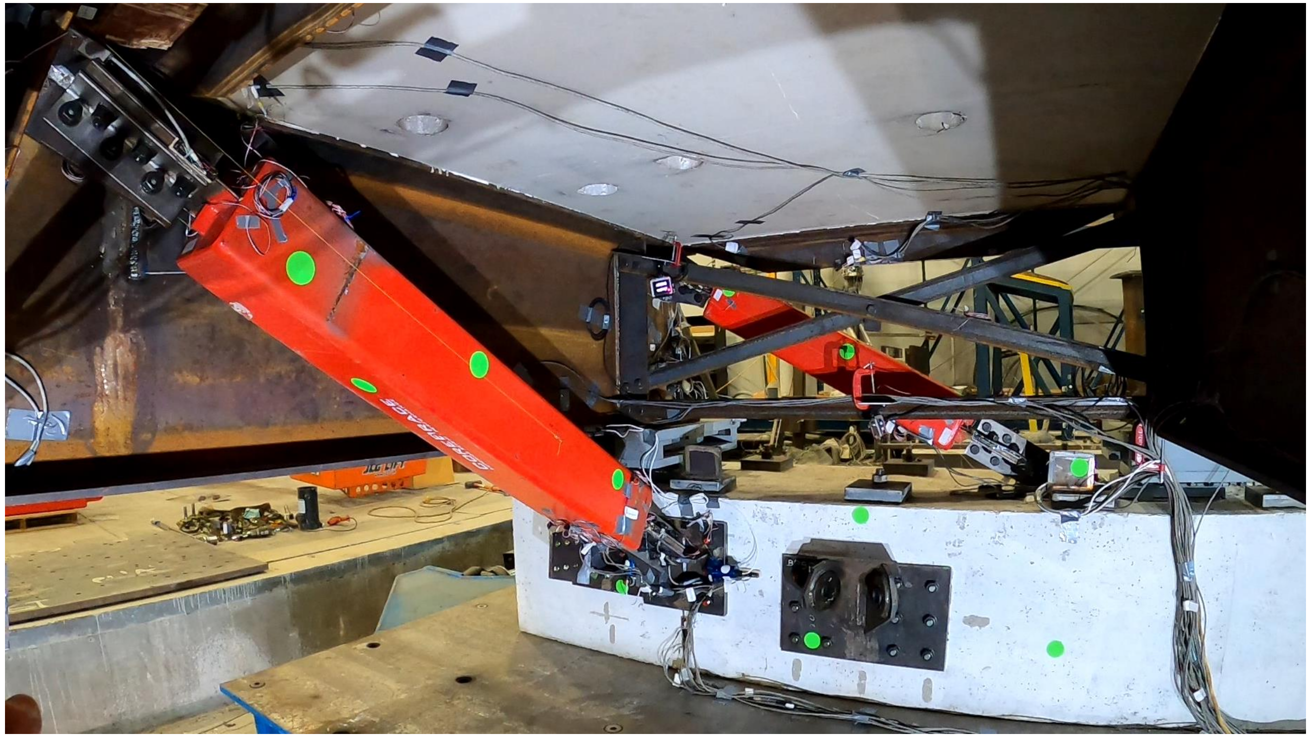
Conceptual view

Experiment

Configuration II

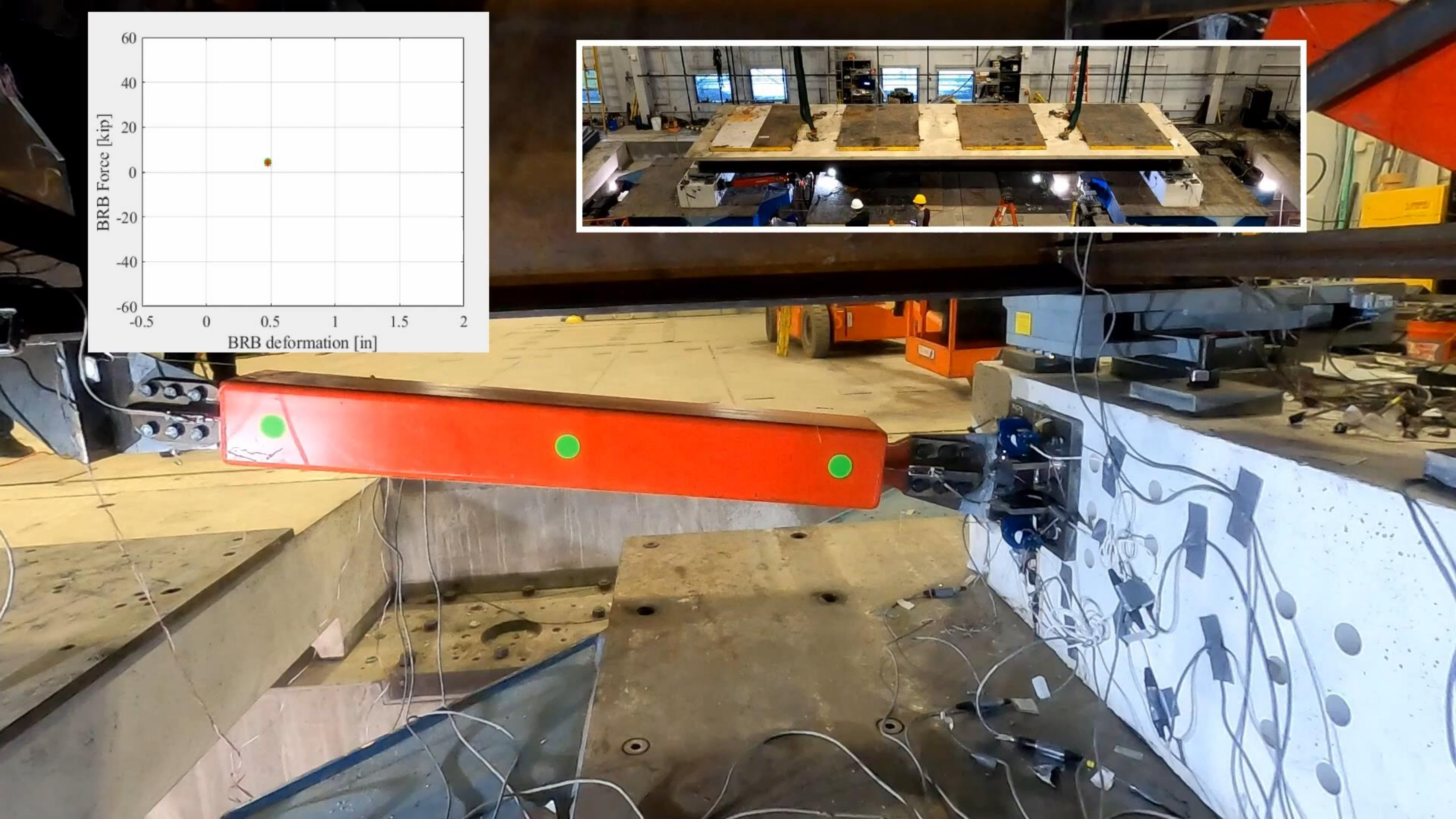


Conceptual view



Experiment

Seismic motions with three components

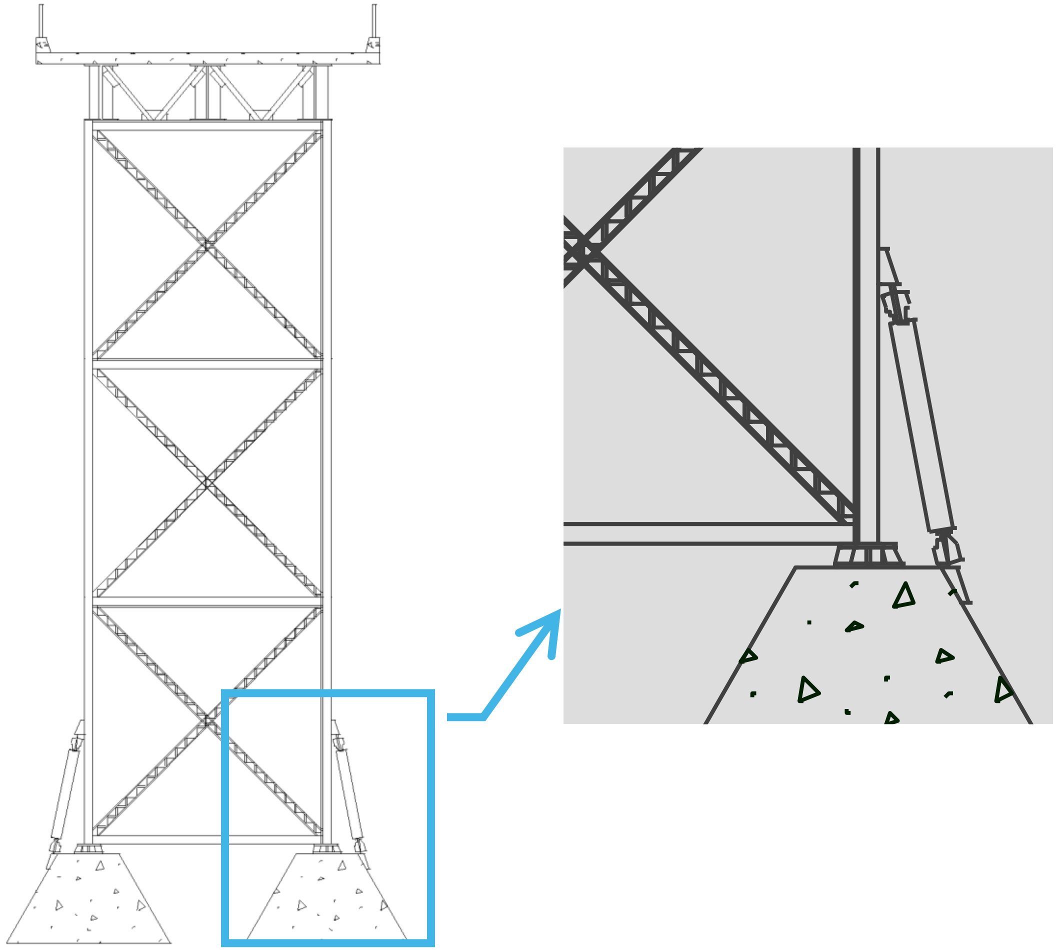

60
40
20
0
-20
-40
-60
BRB Force [kip]
-0.5
0
0.5
1
1.5
2
BRB deformation [in]

Other Examples of Resilient Bridge Concepts

- Dual Pier with Structural Fuses (i.e., Short BRBs)
- Braced Bents with Buckling Restrained Braces
- Braced Bents with Tubular-link Eccentrically Braced Frames (TEBF) a.k.a. EBF with Built-up Box Links
- Rocking Bents/Towers

Controlled Rocking/Energy Dissipation System

- Absence of base of leg connection creates a rocking bridge pier system partially isolating the structure
- Installation of steel yielding devices (buckling-restrained braces) at the steel/concrete interface controls the rocking response while providing energy dissipation

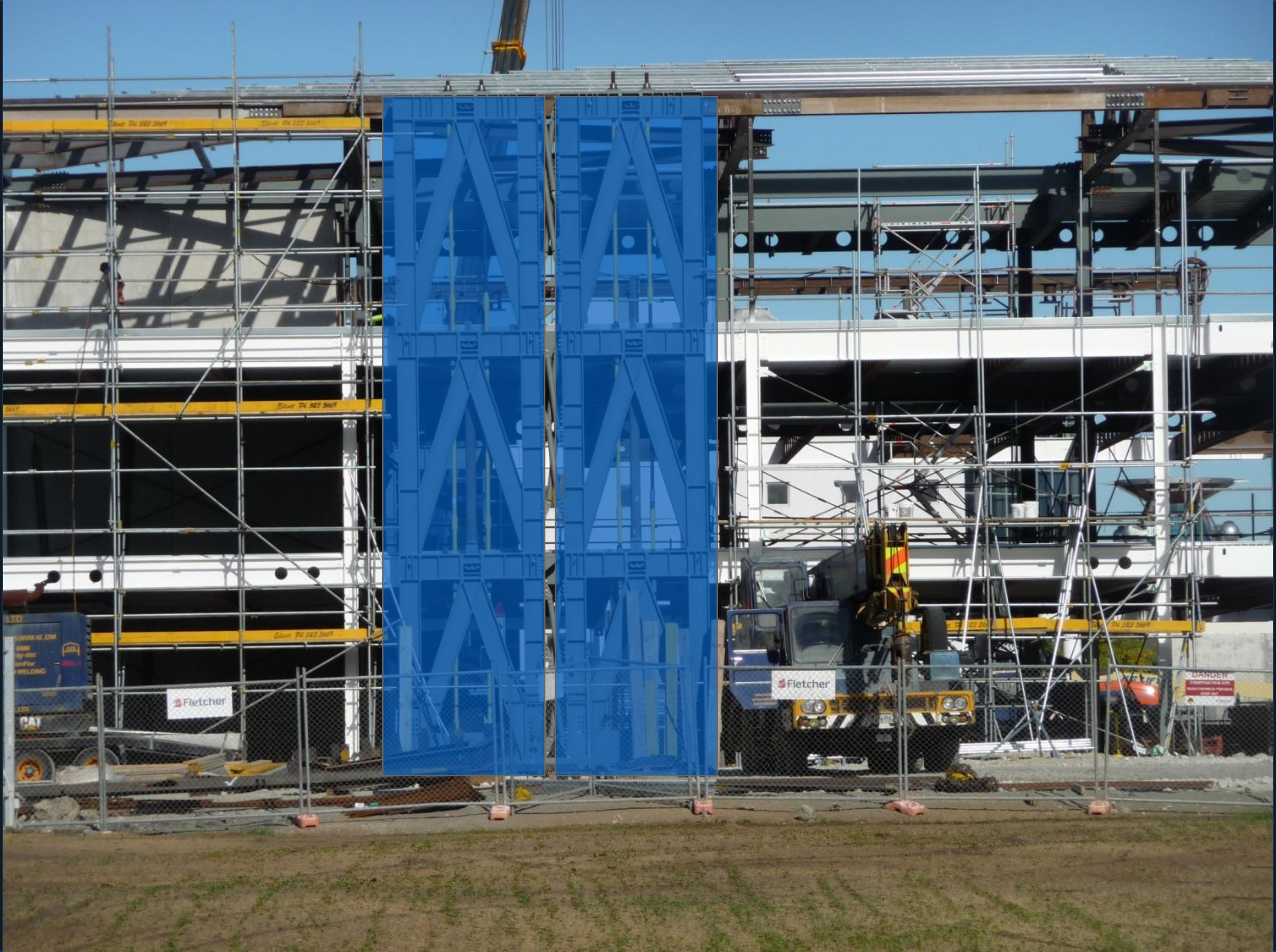


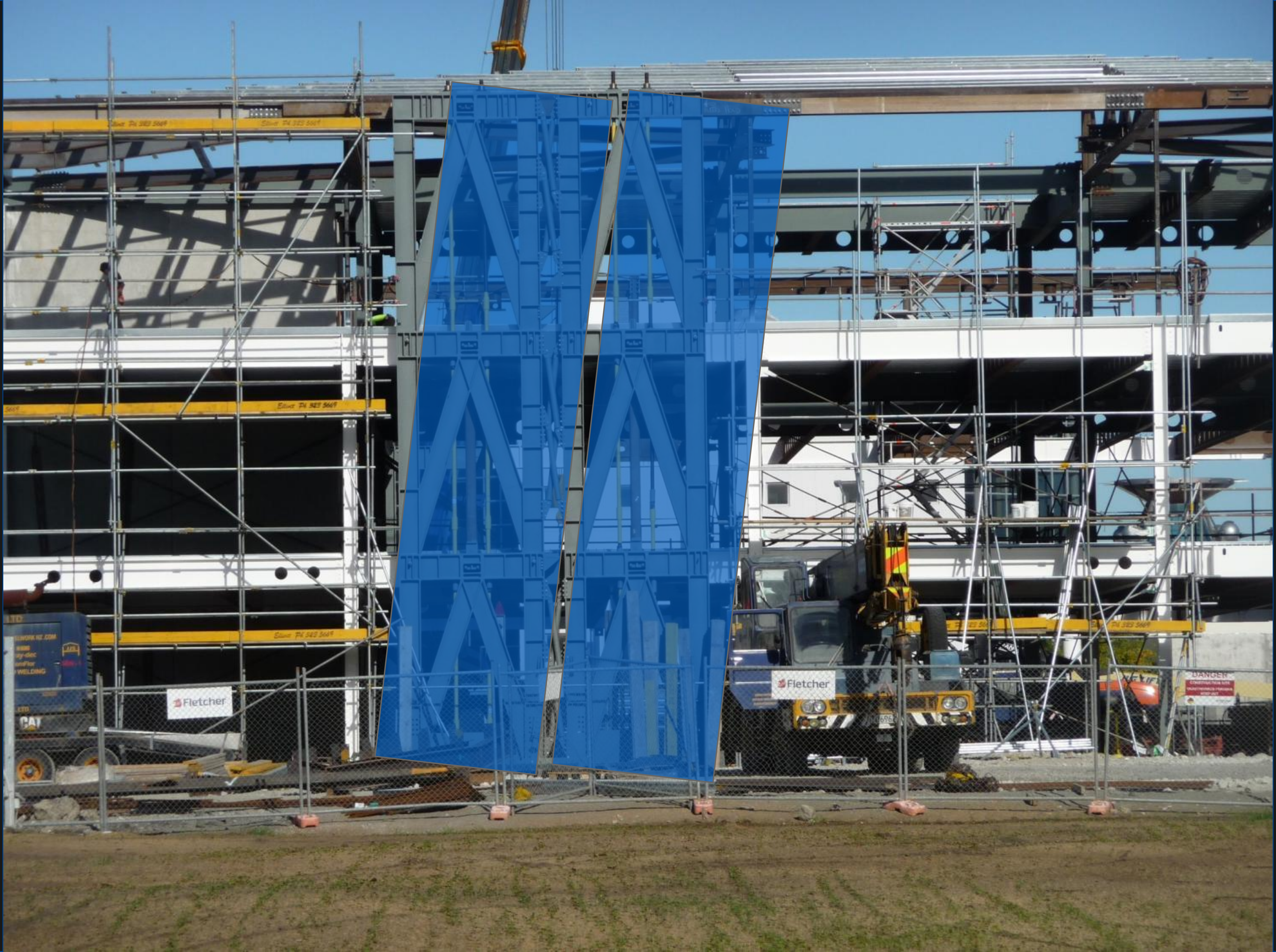
Retrofitted Tower

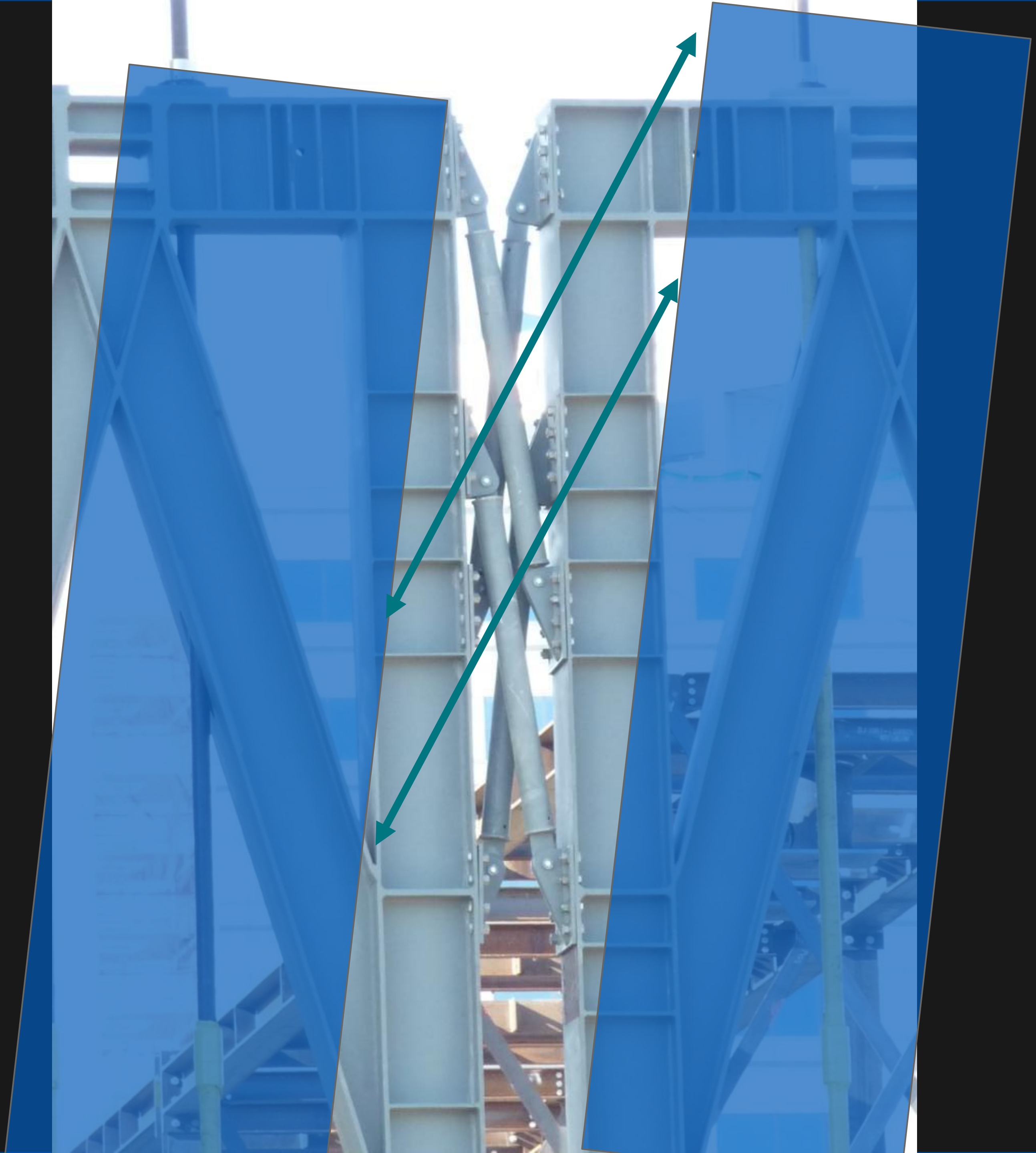
Pollino, M., Bruneau, M., (2010). "Bi-Directional Behavior and Design of Controlled Rocking 4-Legged Bridge Steel Truss Piers," ASCE Journal of Structural Engineering, Vol.136, No.12, pp.1512-1522.
Pollino, M., Bruneau, M., (2010). "Seismic Testing of a Bridge Truss Pier Designed for Controlled Rocking," ASCE Journal of Structural Engineering, Vol.136, No.12, pp.1523-1532.

Synthetic EQ 150% of Design
Free Rocking

Synthetic EQ 150% of Design
TADAS Case η_L=1.0


Fletcher
Fletcher
DANGER


Fletcher
Fletcher
DANGER



Building Bridges Toward a more Resilient Society

- Dictionary definition
- Most importantly, we need more of these bridges

bridge 1 of 3 noun (1)

ˈbrij

Synonyms of *bridge* >

1 **a** : a structure carrying a pathway or roadway over a depression or obstacle (such as a river)

a *bridge* connecting the island to the mainland

b : a time, place, or means of connection or transition

building a *bridge* between the two cultures

the *bridge* from war to peace

Building Bridges Toward a more Resilient Society

- Dictionary definition
- Most importantly, we need more of these bridges
- Because, a knowledgeable public is a “necessary condition” to achieve a resilient society

Building Bridges Toward a more Resilient Society

- Dictionary definition
- Most importantly, we need more of these bridges
- Because, a knowledgeable public is a “necessary condition” to achieve a resilient society
- This knowledge transfer is something we (engineers) need to do, because:
  - Journalists typically do not have technically training
  - Media’s objective is getting “clicks” (attention, not solutions)
  - Nobody cares about the issues (until a disaster strikes)

Questions received from NY Times after Francis Scott Key Bridge collapse

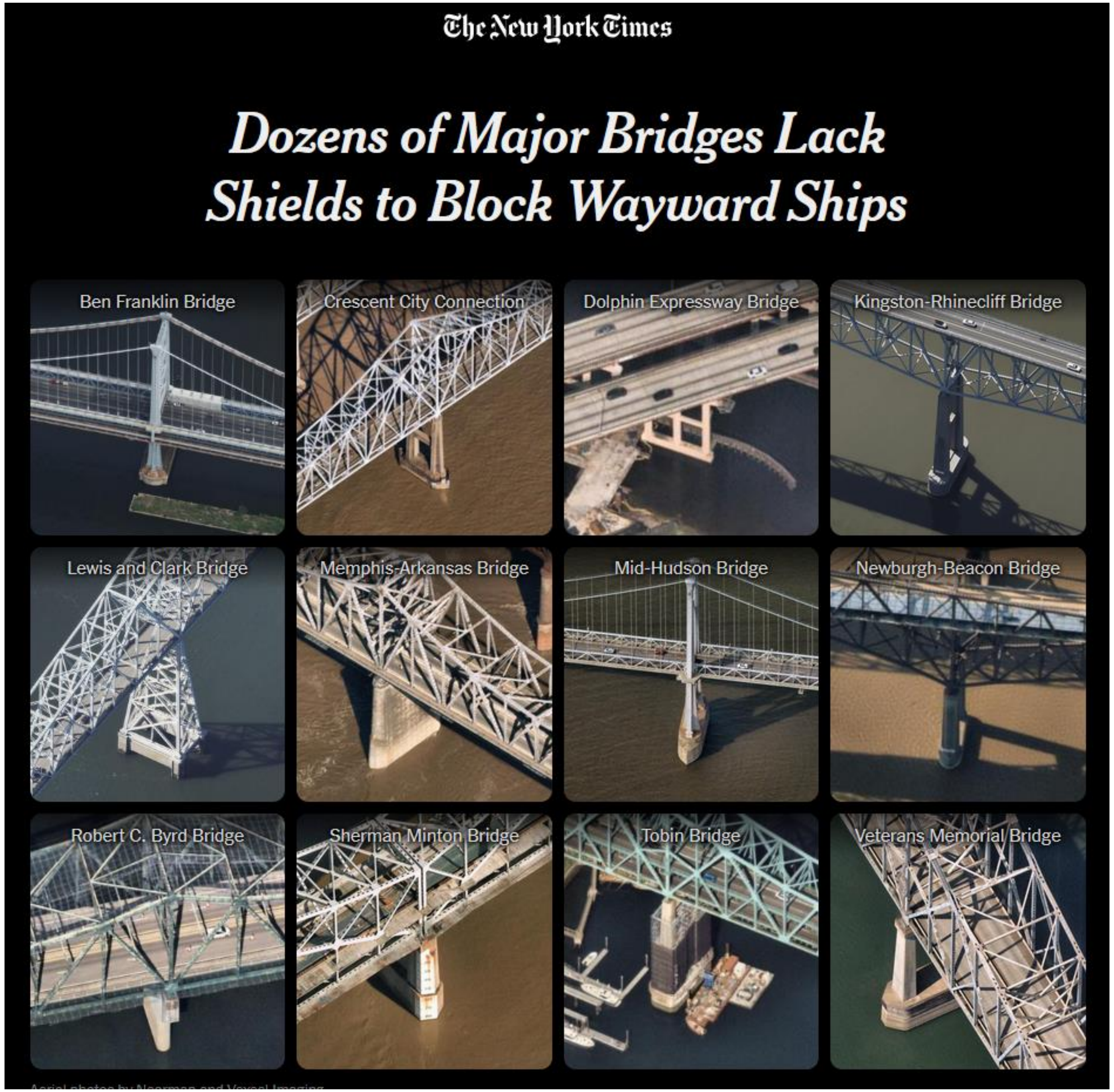
- “I'm looking at [the] Astoria-Megler Bridge, and I was wondering what you think about the pier protection there? Here's a link to some of the details of the Astoria-Megler bridge from the bridge inventory dataset https://infobridge.fhwa.dot.gov/Data/BridgeDetail/24999298”
- “Another thing I wanted to add-- this bridge is also deemed as 'Fracture critical', similar to the Baltimore bridge. I understand that there's less redundancy for 'Fracture critical' type of bridges, so I'm wondering if a big ship hits a pier of a fracture critical bridge, is the entire span likely to collapse or would it have to hit the fracture critical component of the bridge -- say the beam-- for it to come down? Are fracture critical bridges more likely to collapse than non-fracture critical types in case of a big vessel collision?”
- Note: This journalist has a Master’s degree in Urban Planning

Four-part response provided in writing (things you know, but they don't)

- 1) There has been a lot of confusion and misinformation in the press lately about "fracture-critical" and "non-fracture critical" bridges. That classification is irrelevant for the case at hand, because what drives the design of a long-span bridge is the need to support a roadway between two towers/piers as far from each other as required by the river or navigation channel to clear. As such, losing one of the towers/piers of a long-span bridge is as fatal as kicking one leg of a three-legged stool. I can't think of a single long span bridge that would survive the loss of one of its two main-span towers/piers. Adding towers only to prevent collapse if losing one tower would be counter to the objective of achieving a long clear span between towers in the first place.

Outcome

1. Somewhat failed. Article stated: *"[many bridges] have "fracture critical" designs, meaning that the failure of a key component would probably cause a wider collapse of the span. The Times found that about half of the major bridges with deficient pier protections were also fracture critical. But bridge design engineers note that the collapse of a pier would be sufficient to take out almost any bridge."*



LinkedIn Post (with link to NYT article)

Michel Bruneau • You
SUNY Distinguished Professor + Author of "The Blessings of Disaster...
3mo •

The New York Times asked me: "Are fracture critical bridges more likely to collapse than non-fracture critical types in case of a big vessel collision?" and a few other things. Here are the thoughts and basic concepts I shared with them. The 4th point, I believe, is the more important. This is for a non-technical audience.

1) There has been a lot of confusion and misinformation in the press lately about "fracture-critical" and "non-fracture critical" bridges. That classification is irrelevant for the case at hand, because what drives the design of a long-span bridge is the need to support a roadway between two towers/piers as far from each other as required by the river or navigation channel to clear. As such, losing one of the towers/piers of a long-span bridge is as fatal as kicking one leg of a three-legged stool. I can't think of a single long span bridge that would survive the loss of one of its two main-span towers/piers. Adding towers only to prevent collapse if losing one tower would be counter to the objective of achieving a long clear span between towers in the first place.

2) Because towers/piers are so critical, measures are usually taken to protect them from hazards, such as bridge collisions. The calculations to determine the level of protection provided by existing conditions are

From Engineers (via LinkedIn)

Thomas Cooper • 1st 3mo •••
National Technical Director @ WSP in Australia | Bridges Aviation ...

Thanks for the sound comments and for offering clear and attainable solutions that address the broader issues.

Ronald Spacht • 1st 3mo (edited) •••
Bridge Group Manger

As a Structural Engineer that specializes in bridge design, I could not agree more with your 4 talking points. Clear, short and to the point. Whether or not the NY Times reports it that way is another matter. One thing I would add is retro fitting a structure is never a quick nor simple task and sometimes not feasible, have retro fit several smaller structures over the years.

Benjamin Szymanski, P.E., PMP • 2nd 3mo •••
Supervising Structural Engineer at WSP USA

Thank you. This is the post I've been waiting to read since the Baltimore bridge collapsed.

Alejandro Muñoz Fonttz • 1st 3mo •••
AEC industry professional, seasoned leader, skillful engineer, scie...

Bruneau at it's best

Francesco R. • 2nd 3mo •••
Founder & Principal - Russo Structural Services

Well done Michel. I cautioned the Wall Street Journal in a similar article that first week to not chase the wild dog called fracture critical, it's an irrelevant feature of the bridge to be discussing.

Jagtar S Khinda, PD, PE, F.SEI, F.ASCE, Life Member AS... 3mo •••
• 1st
Founder of J Khinda Engineers, Civil Structural Geotechical Earthq...

I think it is very important that more NYCDOT personnel and structural engineers in general , become familiar with all the concepts raised by our distinguished professor Michel Brunesu in this post and also advocated in his famous books in this field in general.

Wagdy Wassef • 1st 3mo •••
Vice President, National Bridges and Structures Practice at WSP U...

Thank you Michel for the simple language that non technical audience can fully understand.

Edward Wasserman • 1st 3mo •••
Sr. Engr at Modjeski and Masters

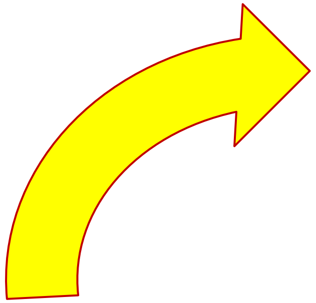
Very clearly and succinctly expressed, Michel.

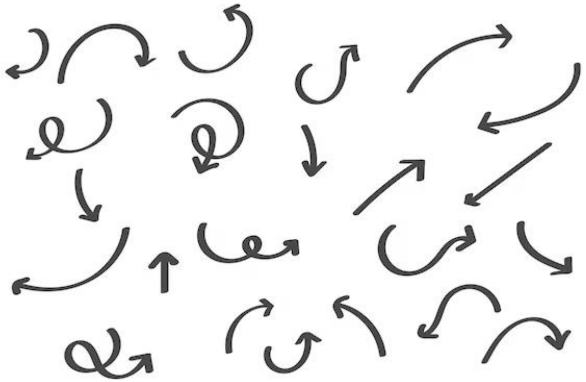
'Richard Dunne, PE' • 2nd 3mo •••
National Director Bridge Preservation at GPI / Greenman-Pederse...

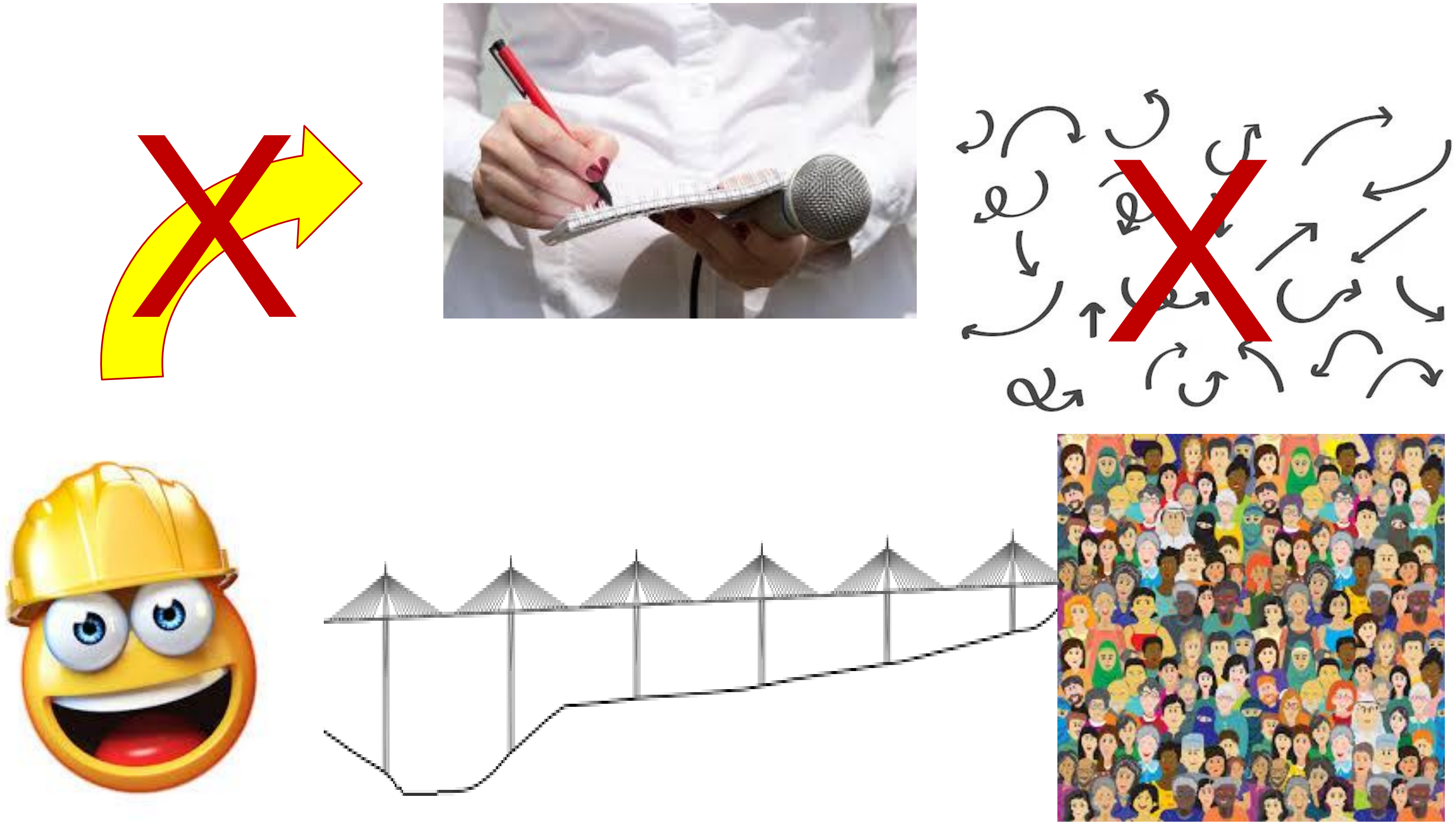
Well done!!

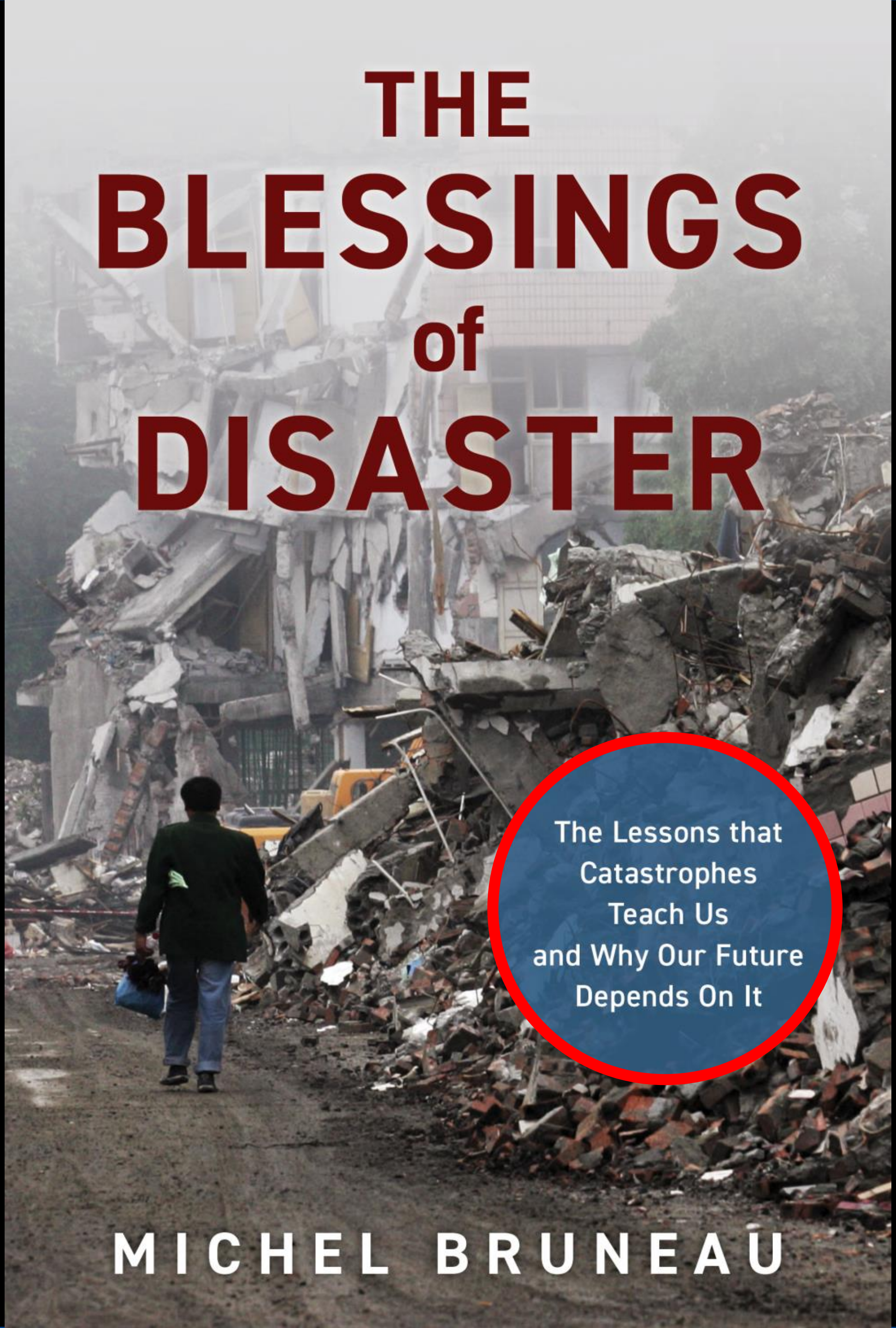
Jason B. Lloyd, PhD, PE • 1st 3mo •••
Striving to be a doer of deeds | Life full of errors and victories | Ev...

Send this post to Jennifer Homendy at NTSB too!









Lessons from past disasters are important, irrespective of causes,

Because

Our response to existential threats depends on whether we learn from, or ignore, these lessons

Audience: You, your parents, your grand-parents, your kids and grand-kids – and the whole neighborhood

- The goal in writing *The Blessings of Disaster* was to provide a truthful but effective journey through the world of disasters, and to make it enjoyable.
- Along the journey, you will discover connections between natural disasters, crooks, cows, hijackers, the Three Little Pigs, nuclear holocaust, movie reviews, viruses, scapegoats, trading stamps, real estate agents, Chinese hockey sticks, airport proctologists, and many more.

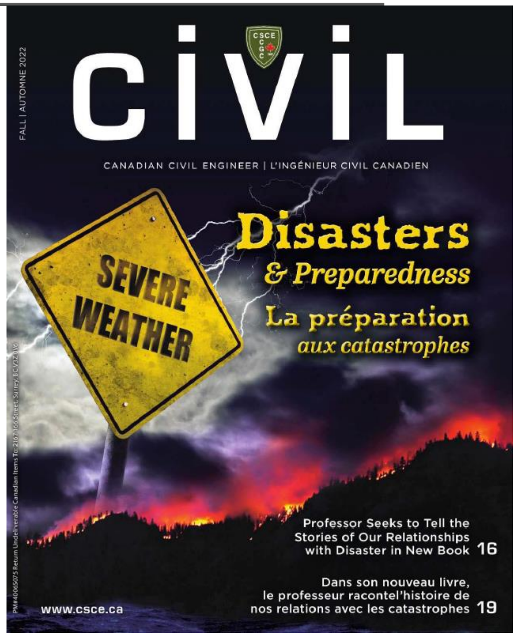
From Engineers

"The Blessings of Disaster is an interesting and unique read: informative and well versed in research across many different knowledge areas but very often breezily informal and deliberately humorous in tone. But never at the expense of Bruneau's realism; he has written a work that he hopes people will learn from — but, by his own admissions, knows they probably won't."

— ASCE, Civil Engineering Magazine

"Bruneau has tucked serious and rather involved ideas about risk, engineering, safety and society, as well as life in general, into a book that is also entertaining. He writes poignantly of the contradictions of a technologically advanced civilization. (...) The blessings of disasters are harsh lessons that show much, I'm afraid, about our own capacity for folly."

—Engineering News Record



Webinars on The Blessings of Disaster

- Links at www.michelbruneau.com :

NATURAL HAZARDS CENTER

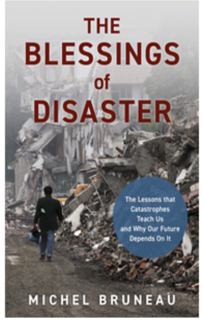
ABOUT US PUBLICATIONS TRAINING WORKSHOP

October 10, 2023, 11:00 a.m. to 12:00 p.m. MDT

The Lessons of Catastrophe: Structural Challenges and New Disaster Perspectives

Webinar Description:

Join leading catastrophe engineer and author Michel Bruneau as he examines how future successes and failures in dealing with societal threats—be they pandemics, climate change, overpopulation, or other events—can be predicted by observing how we currently cope with and react to disasters.



Bruneau will discuss ideas from his recent book, **The Blessings of Disaster: The Lessons That Catastrophes Teach Us and Why Our Future Depends on It**, which highlights the relationship between humans and disasters. Bruneau will bring experiences from his decades-long career as an earthquake and disaster engineer together to detail case studies from extreme events such as the Kobe Earthquake in Japan and Category 5 hurricanes in the United States. Along with thoughtful and practical solutions, he'll provide a thorough examination of the structural challenges that face today's (and tomorrow's) world.

ISMSE INGÉNIEURS EN STRUCTURE DE MONTRÉAL MONTREAL STRUCTURAL ENGINEERS

ÉVÉNEMENTS À PROPOS PARRAINS NOUS JOINDRE ENGLISH

LES BIENFAITS DES DÉSASTRES: CONSTRUIRE DES PONTS VERS UNE SOCIÉTÉ PLUS RÉSILIENTE

Conclusions

- Resilient designs are those that can help achieve rapid return to full functionality following an earthquake
- More resilient buildings/bridges can be achieved using steel structural systems relatively faster to repair following earthquake
- Resilient bridges can be achieved using bidirectional ductile diaphragms implemented with Buckling Restrained Braces, because
  - Bridge can remain fully functional and in-service **immediately** following earthquake
  - Bridge can resist multiples earthquakes before need to replace BRBs
- Other resilient bridge concepts also exists (some examples shown)
- The book “The Blessings of Disaster” can be used as a tool to raise awareness to need for resilient infrastructure

Acknowledgments

- Graduate students:
  - All former graduate students whose work have been cited in slides throughout this presentation
- Colleagues
  - Andrei Reinhorn, Greg MacRae, and dozens more.
- Sponsors:
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  - California Department of Transportation
  - CoreBrace, RJ Watson, High Industries (High Steel, High Concrete, High Transit)
  - National Science Foundation (EERC and NEES Programs)
  - New York State
  - University of Canterbury Quake Center
  - Multiple Project Advisory Panels

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Shake table video here

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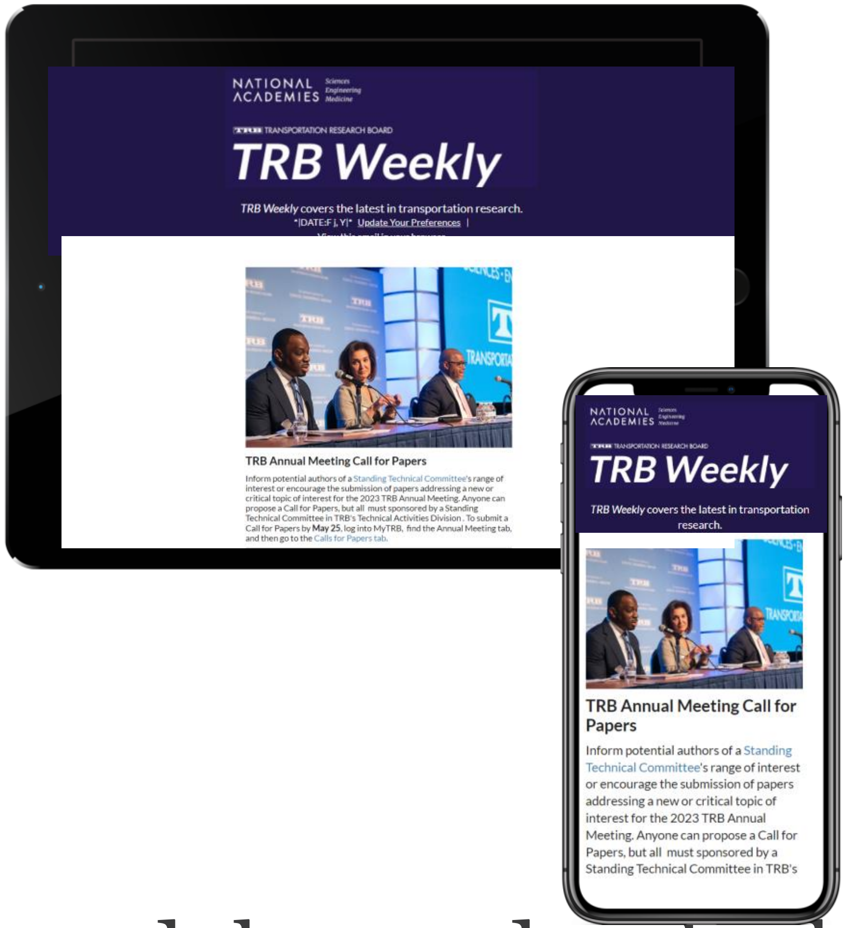

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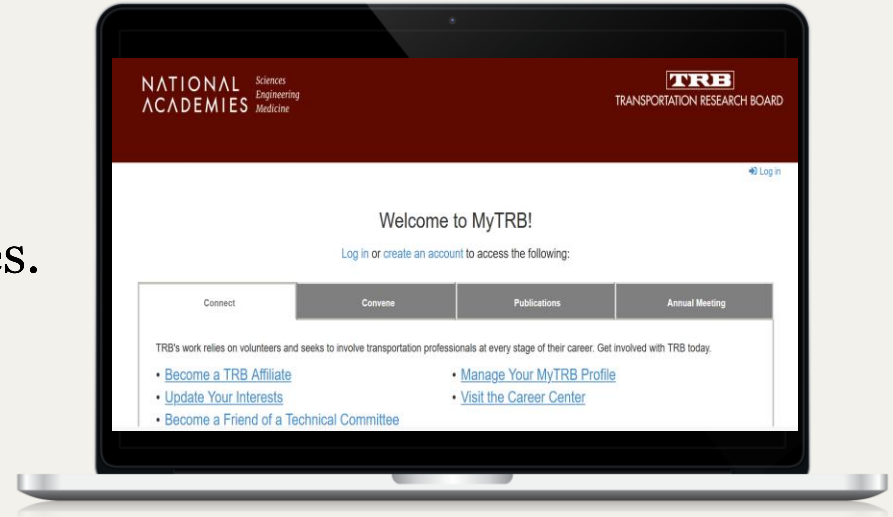

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