Earthquake Engineering

in a Flat World

- improving the performance of civil infrastructure

Ian Buckle

Foundation Professor, University of Nevada Reno

Invited Lecture

University of Auckland Centre for Earthquake Engineering Research ,

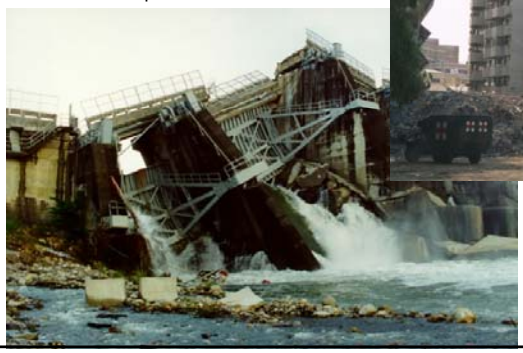
Department of Civil and Environmental Engineering , Auckland, May 24, 2012

Natural hazards

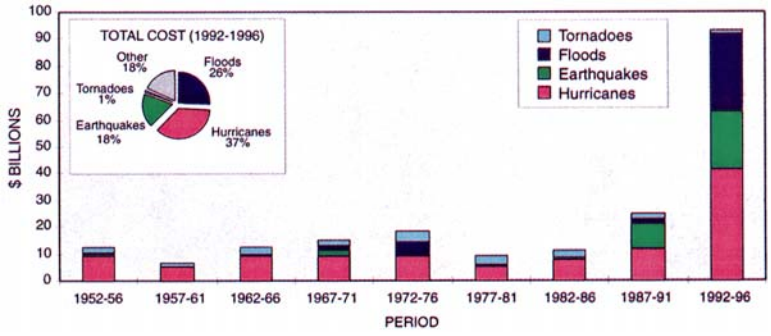
- Hurricanes
- Floods
- Blizzards
- Wildfires
- Earthquakes

Earthquakes…

- Rapid-onset disasters
- 14,000 lives lost / year
- US Annualized losses
  - FEMA: $4.4 billion
  - EERI: $10 billion



Losses due to natural hazards in the U.S: 1952-1996



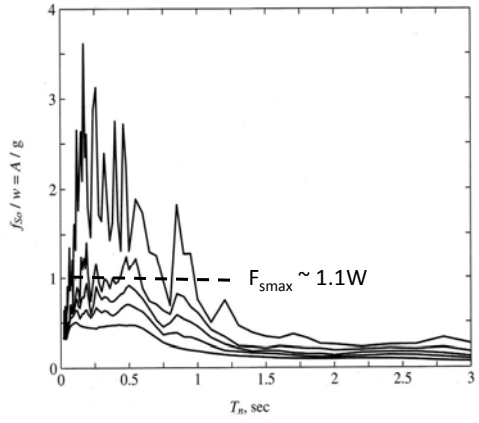
Earthquakes are costly disasters

For several reasons:

Majority of our inventory does not meet current seismic design requirements and should be retrofitted to minimize risk of collapse

But even new structures built to current standards will be damaged in the ‘design earthquake’…

Earthquake loads are high…



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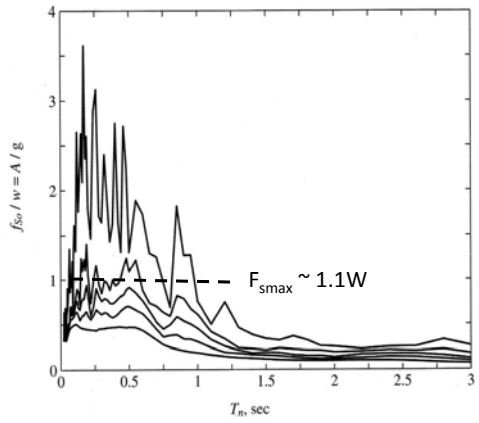

Acceptable Damage

Building codes are 'life-safety' codes

- Fundamental purpose of modern building code (or bridge code) is the protection of life, i.e.,
  - no fatalities
  - minor injuries

  during an earthquake that has a small probability of being exceeded in the life of the building or bridge (1,000-year return period)

For example, US bridge code says…

Bridges shall be designed for… life-safety… considering a seismic hazard corresponding to a…1,000 year return period.

AASHTO *Guide Specifications for Seismic Bridge Design*, 2009

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Bridges shall be designed for… life-safety… considering a seismic hazard corresponding to a…1,000 year return period.

Life safety design… shall be taken to imply that the bridge has a low probability of collapse but may suffer significant damage and that significant disruption to service is possible…. which may require closure to repair the bridge. Partial or complete replacement may be required in some cases.

AASHTO *Guide Specifications for Seismic Bridge Design*, 2009

Life safety vs. functionality

Bridges and buildings are designed to be safe but not necessarily remain in service…. continuing functionality is not assured.

Exceptions exist: critical bridges and facilities such as hospitals, schools…

But continuing functionality following a large earthquake is prohibitively expensive

Life safety vs. functionality

And for many years *life-safety* has served us well… lives lost and injuries are less, and financial losses have been 'contained'
But as Thomas Friedman recently observed…

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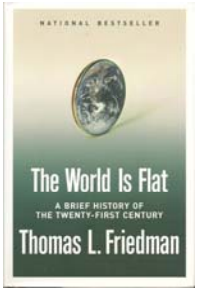

The ‘world is flat’

Interconnectedness of society greatly expands the impacted area of a damaging earthquake far beyond the epicentral region.

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Interconnectedness of society greatly expands the impacted area of a damaging earthquake far beyond the epicentral region.

A local disaster can quickly become a national/global one, which in turn leads to an escalation in financial loss not seen in earthquakes a decade ago.

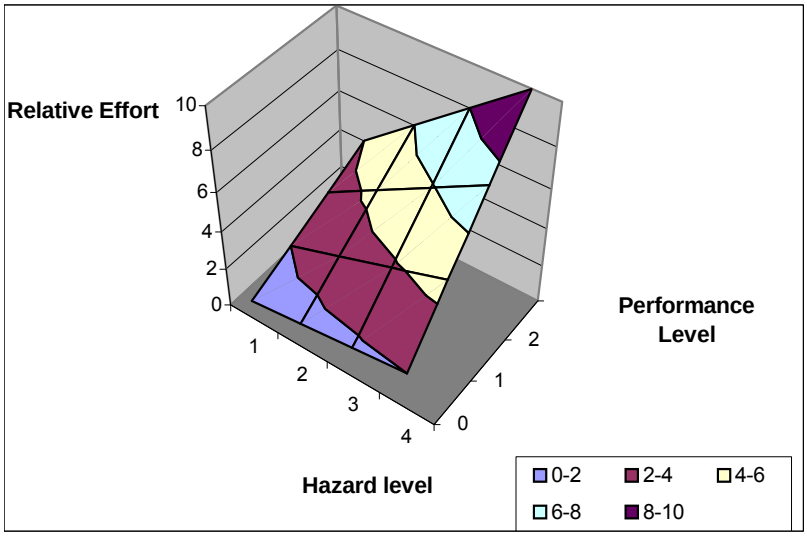
* *Securing society against catastrophic earthquake losses,* Earthquake Engineering Research Institute, Oakland CA, 2003

Escalating indirect losses

- Well-recognized problem…
- Loma Prieta Earthquake, 1989
  - SFO Hyatt Hotel just opened
  - No fatalities, no injuries despite collapsed building across street
  - Engineers called design ‘success’
  - But City of Burlingame closed the hotel because of cracks in shear walls
  - The owner was not pleased.

Escalating losses

- This and other similar incidents, as well as the interconnectedness of society, has given rise to pressing need to do better, and the concept of ‘Performance-Based Design’ has been born
- Goal is to be able to design a specific building,
  to have a specific performance,
  during a specific earthquake
  [e.g. hotel, closed no more than 7 days, M7 EQ]



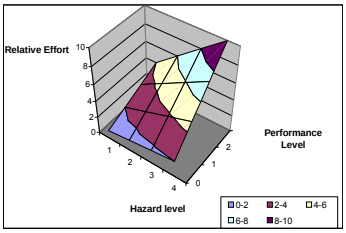
Performance-based design

Explicit attempt to satisfy public expectations of bridge performance for earthquakes ranging from small to large… for example:

Performance	Earthquake		
	Small	Intermediate	Large
No interruption	√	√	
Limited access		√	√
Closed for repairs			√

Performance-based design

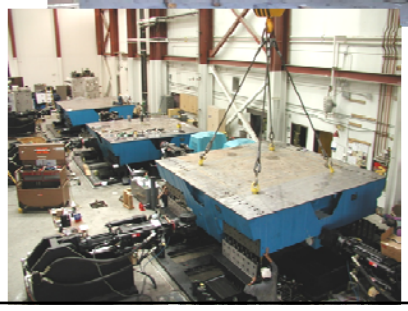
- Barriers to implementation
  - Lack of knowledge
  - No extra cost



- Currently driving the bridge-research agenda
  - Damage-free performance
  - Little or no extra cost
  - Two examples at University of Nevada Reno
    - Innovative materials
    - Hybrid isolation

Large-Scale Structures Laboratory

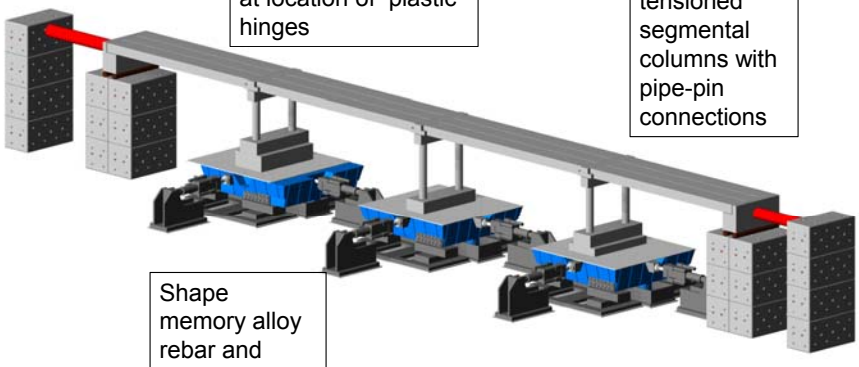
- George E Brown Jr. Network Earthquake Engineering Simulation (NEES)
- Established by the National Science Foundation
- UNR LSSL is one of 14 universities providing core facilities to the NEES network
- Multiple shake table site with telepresence capabilities
- Data repository and portals to simulation tools



104ft (31.7 m)

Elastomeric bearing embedded in column at location of plastic hinges

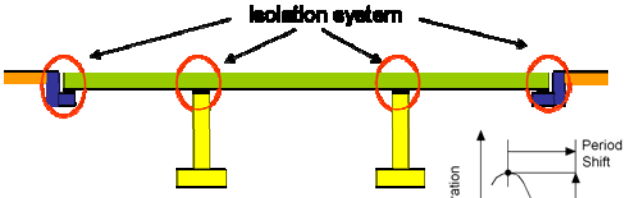
Post-tensioned segmental columns with pipe-pin connections



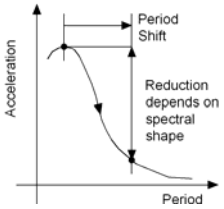
Shape memory alloy rebar and ECC concrete in hinge zones

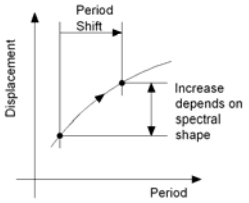
PI: M. Saiid Saiidi, UNR

Hybrid vs Seismic (Full) Isolation

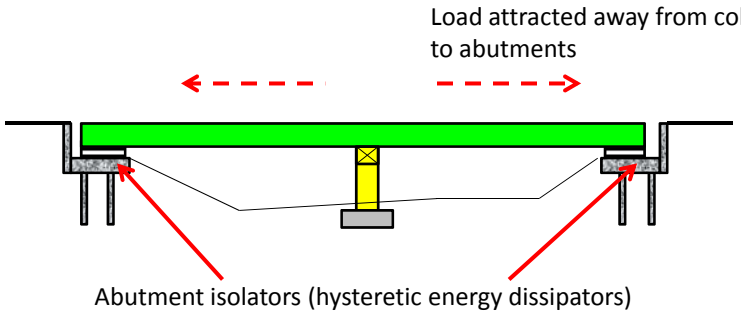


- Period shift
  - lowers spectral accelerations
  - reduces column and foundation shear forces and moments
  - but increases superstructure displacements (but not column drifts)





Hybrid (Partial) Isolation



- Reduces column forces
- Reduces superstructure displacements
- But increases abutment reactions (shear forces)

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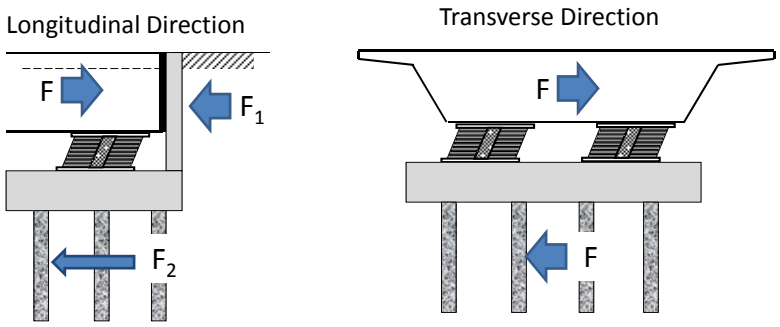
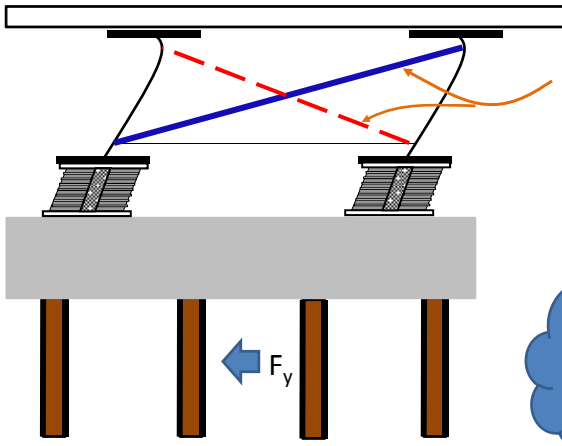


Background | Experimental study | Results | Conclusions

Hybrid Isolation + Ductile End Cross-Frames



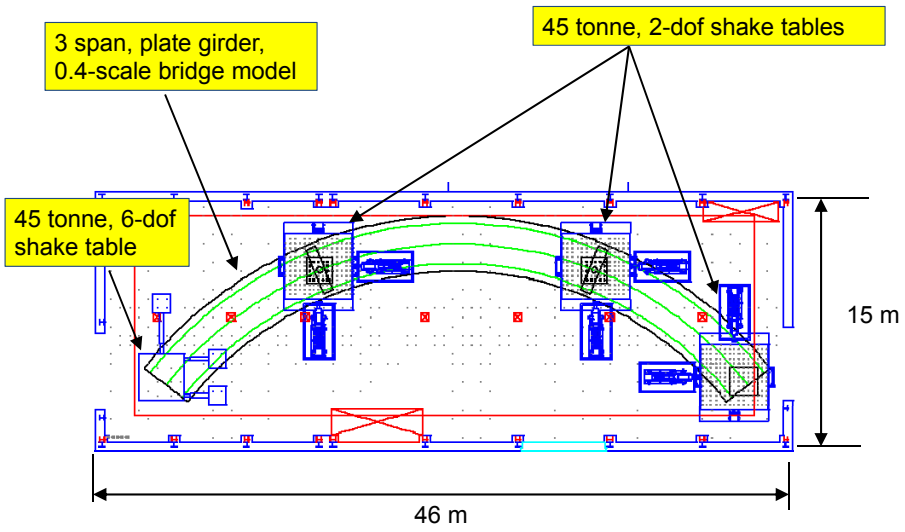
Yield (F_Y) and buckling in cross- frame

Hybrid protective system

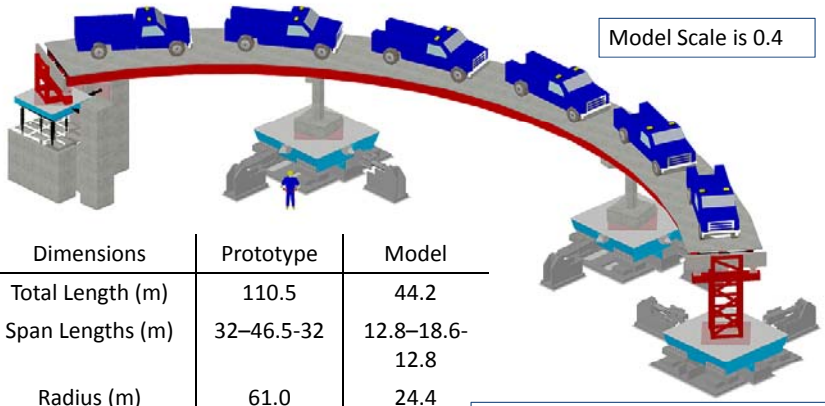
Background | Experimental study | Results | Conclusions

Curved highway bridge project at UNR

- To study, experimentally and analytically, the seismic performance of a large-scale model of a highly curved bridge using multiple shake tables
  - With and without protective systems
    - Isolated
    - Partially isolated
    - Rocking columns
  - With and without abutment interaction
  - With and without live load



Prototype and Model Dimensions



Model Scale is 0.4

Dimensions	Prototype	Model
Total Length (m)	110.5	44.2
Span Lengths (m)	32–46.5-32	12.8–18.6-12.8
Radius (m)	61.0	24.4
Total Width (m)	9.1	3.7
Girder Spacing (m)	3.4	1.4
Column Height (m)	6.1	2.4

Model weight is 1,423 kN (142 tonnes)

Model weight with live load is 1,690K (169 tonnes)

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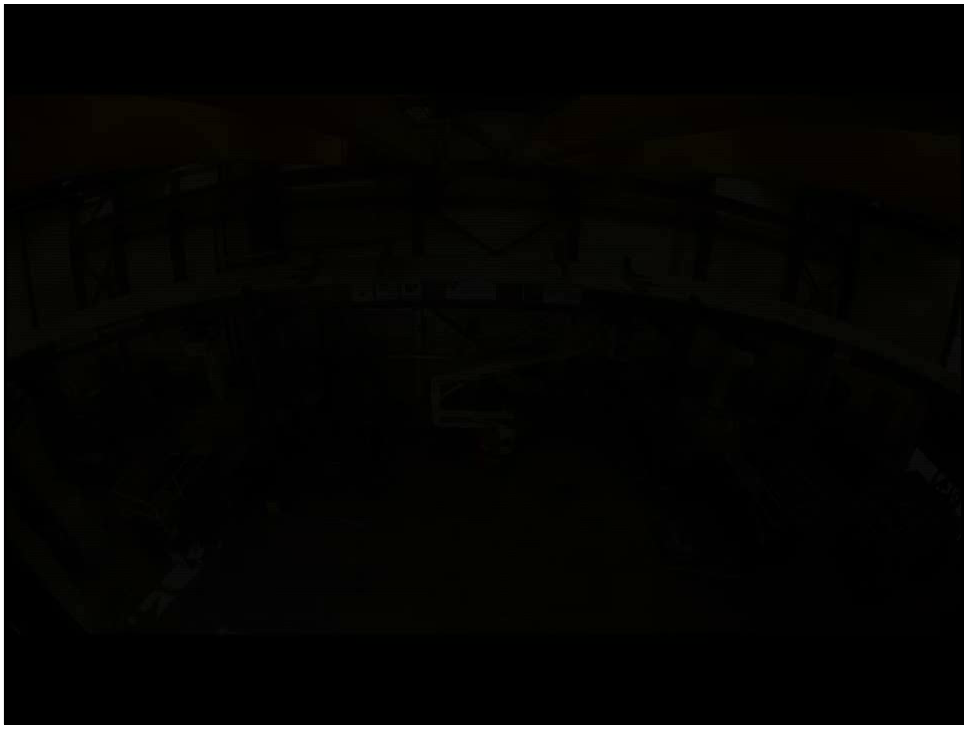


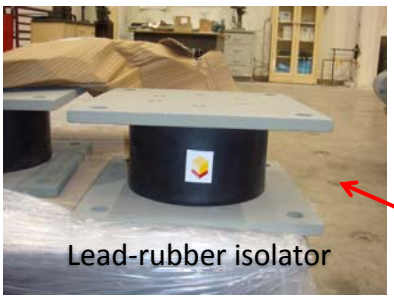
North column: 3.5 x Design Earthquake

- Curved2_Canon2_No_Col_NE_350Des_20110915140114_1(2).mpg

Curved Highway Bridge Project at UNR

1. Conventional bridge (104^0, steel bearings, 24 inch diam. columns, sacrificial shear keys at abutments)
2. Conventional bridge with live load (6 trucks)
3. Fully isolated bridge with 12 LRB isolators
4. Hybrid isolated bridge with 6 LRB isolators and ductile cross frames
5. Abutment pounding (nonlinear backfill)
6. Rocking columns

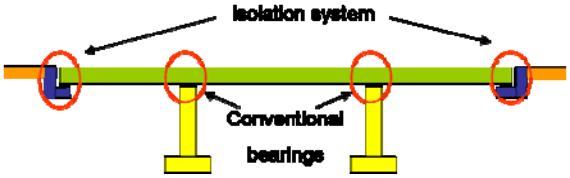
Curved Bridge: Full Isolation Case



Curved Bridge: Hybrid Protective Systems

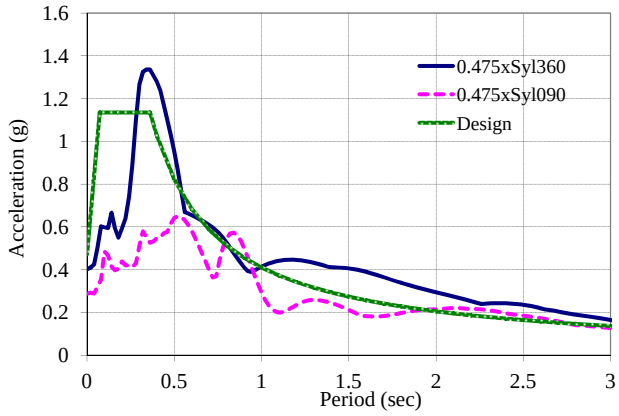
Boundary Conditions

- Abutments
  - LRB isolators effective in tangential direction only
  - Buckling Restrained Braces (BRB) in radial direction with shear key
- Piers
  - Pin connection between the superstructure and pier using steel pot bearings



Input Motion

- Design Earthquake: PGA = 0.472g; S_s = 1.135g; S_1 = 0.41g
- Sylmar record of the 1994 Northridge Earthquake selected
- SYL 360: PGA = 0.84g; S_1 = 0.87g
- Scale Factor = 0.475 (to give same S_1as Design Earthquake)



Test Protocol

- Same set of ground motions input to all 4 shake tables (synchronous motion)
- Motion applied in increments of Design Earthquake (DE):

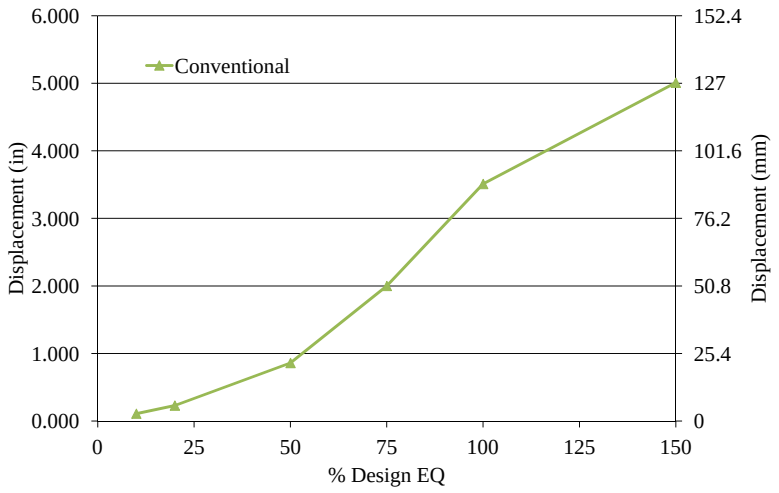
Run #	Motion (DE)	Note	Run #	Motion (DE)
1	10%		6	150%
2	20%		7	200%
3	50%		8	250%
4	75%	SK	9	300%
5	100%		10	350%

Periods of Vibration

Bridge	Longitudinal Vibration Mode	Transverse Vibration Mode
Conventional Case	0.50 sec	0.53 sec
Full Isolation	1.00 sec* 1.43 sec**	1.00 sec* 1.43 sec**
Hybrid Protective System	0.50 sec* 0.90 sec**	0.55 sec* 0.55 sec**

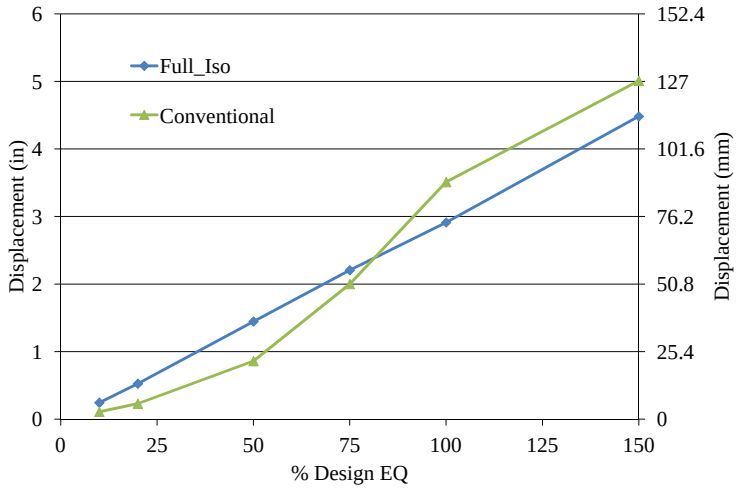
Notes: * = period at 100% Design Earthquake (DE)
** = period at 150% DE (Maximum Considered Earthquake, MCE)

Superstructure Displacement



Note: These are resultant superstructure displacements at the center of the bridge.

Superstructure Displacement



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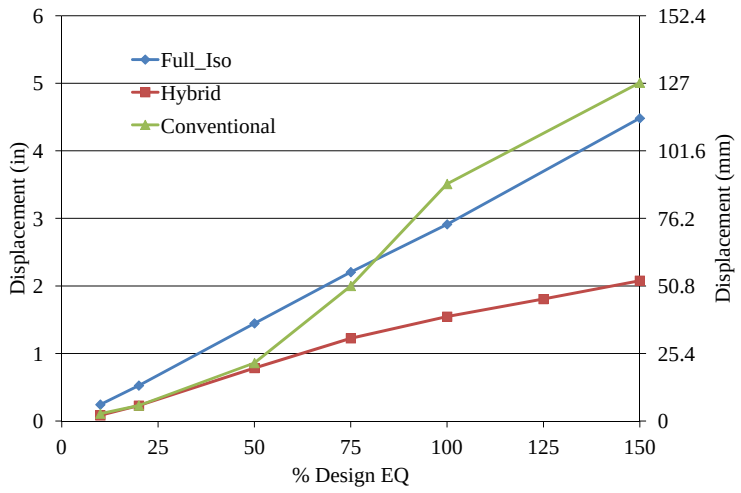

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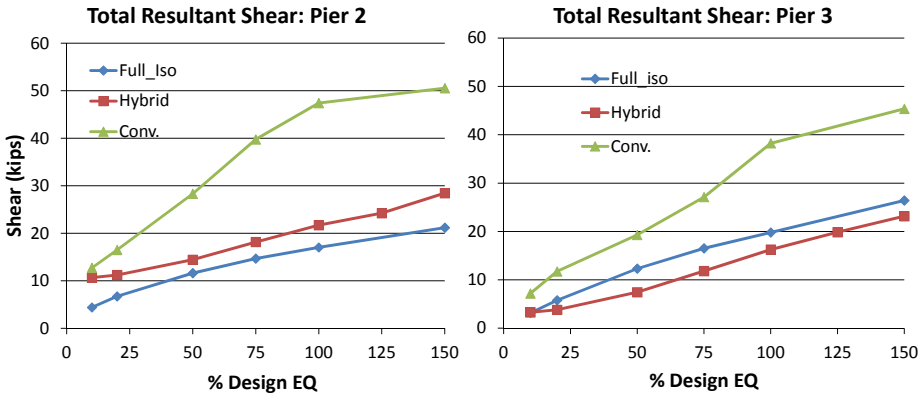
Background | Experimental study | Results | Conclusions

Pier Reactions: Resultant Shear Forces



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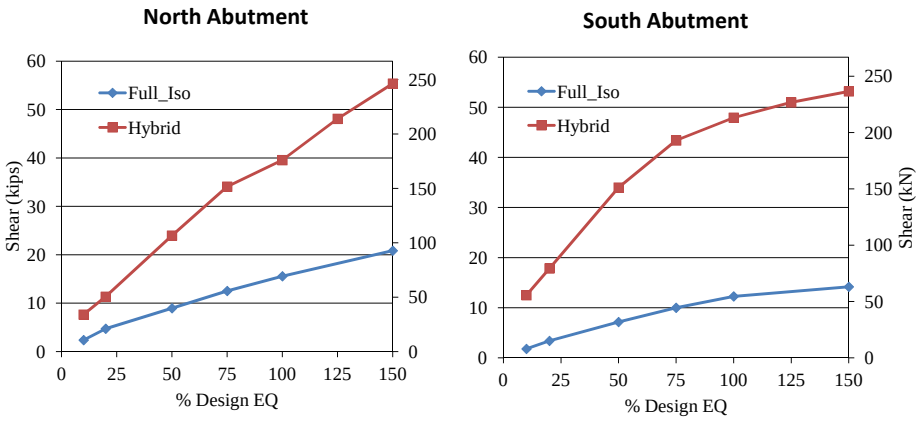
Abutment Reactions: Isolator Tangential Shear



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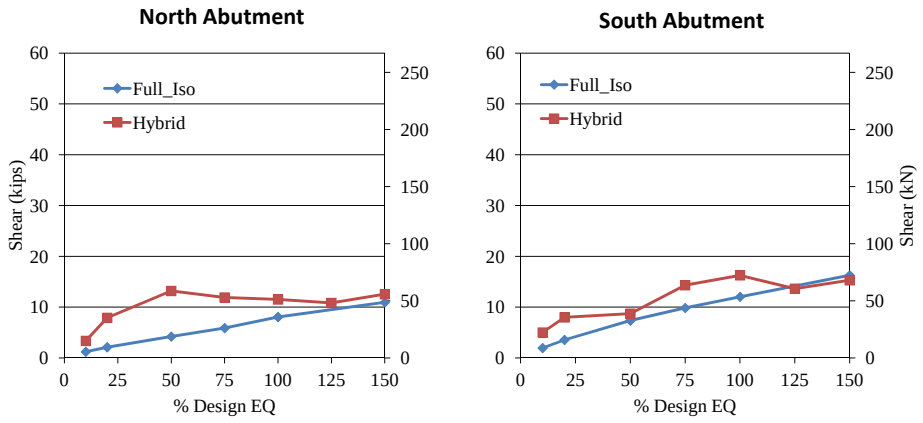
Abutment Reactions: Isolator Radial Shear



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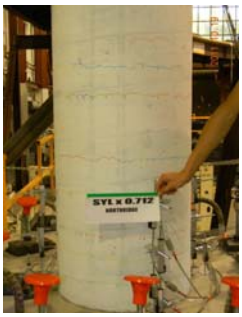
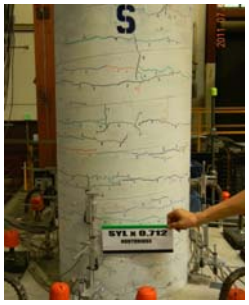
Column Damage at 150% Design Earthquake

Pier 2 Conventional Case

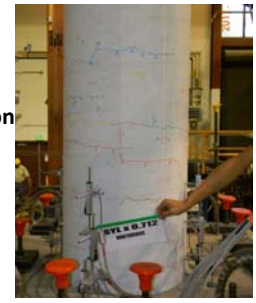
Pier 2 Full Isolation Case (Hybrid Isolation Similar)



Pier 3 Conventional Case



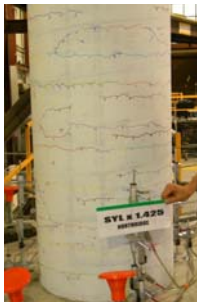
Pier 3 Full Isolation Case (Hybrid Isolation Similar)



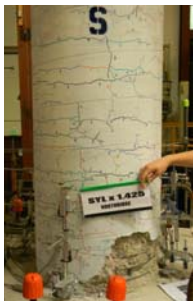
Column Damage at 300% Design Earthquake

Pier 2 Conventional Case

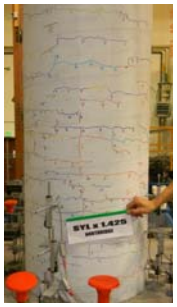
Pier 2 Full Isolation Case (Hybrid Isolation Similar)



Pier 3 Conventional Case



Pier 3 Full Isolation Case (Hybrid Isolation Similar)



Conclusions

1. Both *full* and *hybrid* isolation were effective at keeping the columns elastic under the design earthquake and essentially elastic under the maximum considered earthquake (150% DE).

2. *Hybrid* isolation was also effective at reducing the superstructure displacements (to about one-third of the displacements in the *full* isolation case).

Summary

- Earthquakes are costly disasters (in lives and dollars)
- Even though number of fatalities is falling (in the U.S.) dollar losses are increasing – it's a flat world…
- Building and bridge codes are focused on life-safety – damage is to be expected and is considered 'acceptable'
- Research is underway to remove 'acceptable damage' from our vocabulary

Acknowledgements

- University of Nevada
- Federal Highway Administration
- California Department of Transportation
- NSF-NEES and –NEESR

Thank you.