Performance of Bridge Columns Under Long Duration Ground Motions (Shake Table Tests)

Presented by :

Mohammed Saeed Mohammed

Research Assistant, PhD Student

Dept. of Civil and Environmental Engineering

David Sanders and Ian Buckle

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University of Nevada, Reno

Federal Highway Administration

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Problem Statement and Objectives

Why Long Duration ?

- **The 2010 M8.8 Chile and 2011 M9.0 Tohoku, Japan earthquakes are a reminder of the importance of the effect of ground motion duration on structural response.**

- **Chile Earthquake** → **Ruptured over ~ 500 km**
  Duration ~ 20-90 seconds

- **Tohoku Earthquake** → **Fault size ~ 500 km x 210 km**
  Duration ~ 40-110 seconds

- **Comparing these ground motion durations with other earthquakes in California which has typically lasted less than 30 seconds, shows that the durations of the Chile and the Tohoku earthquakes are very long.**

Problem Statement and Objectives

Why Long Duration ?

- **Current seismic design codes do not consider duration effects and they are mainly based on the peak response.**

AND THIS IS DUE TO :

➢ **The big differences in conclusions of previous research with regard to the effect of strong ground motion duration on structural performance.**

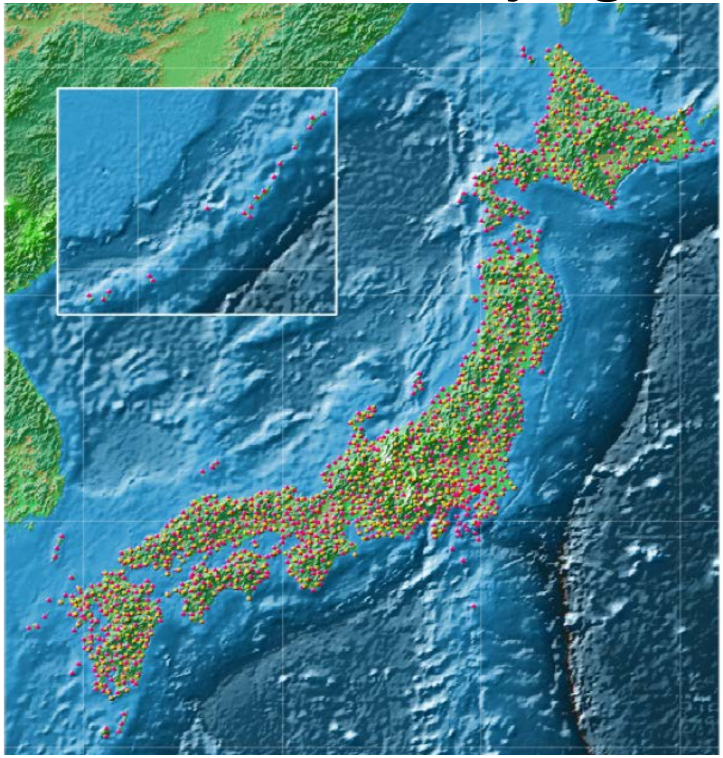
➢ **The lack of the available long duration ground motion records which made the researchers to conduct their studies using simulated records.**

Problem Statement and Objectives

Why Long Duration ?

- **But now, and after recording a number of long duration ground motions from 2008 China, 2010 Chile and 2011 Japan earthquakes, extensive data are now available for studying this topic.**

- **The Japanese event is the best recorded mega earthquake for a long time come.**
- **Japan is the best instrumented place in the world.**



Instrumentation in Japan

Problem Statement and Objectives

Why Long Duration ?

- **What makes this study even more important is the possibility of occurrence of another large magnitude long duration subduction earthquake along the Pacific Northwest coast of the United States which lies near the CASCADIA SUBDUCTION ZONE.**

➡ **More than twice the length of the Tohoku fault.**

➡ **From the literature, there are some similarities between the Japan and the Cascadia Subduction Zone.**

Research Questions

- **Should the current seismic codes be modified to take the effect of ground motion durations into account?**

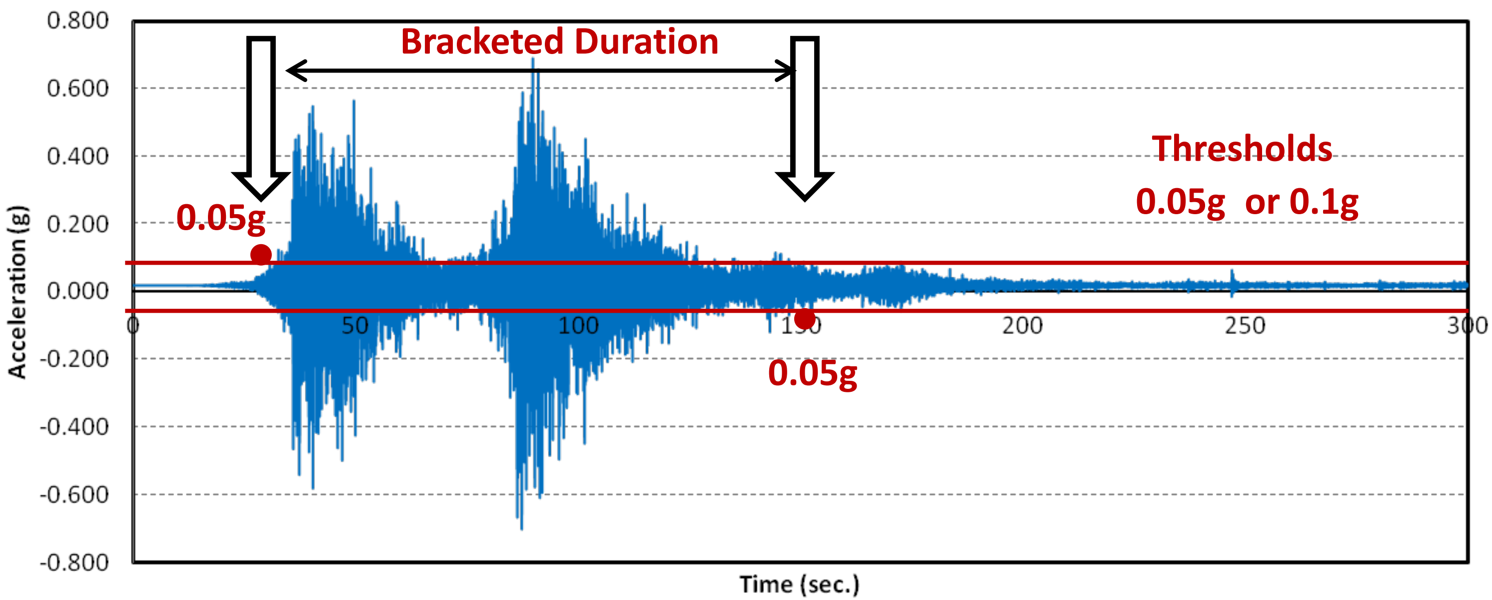
- **How do we characterize the difference in damage between a short and long duration earthquake?**

Ground Motion Duration Definitions

- **More than 30 definitions of ground motion duration in the literature.**

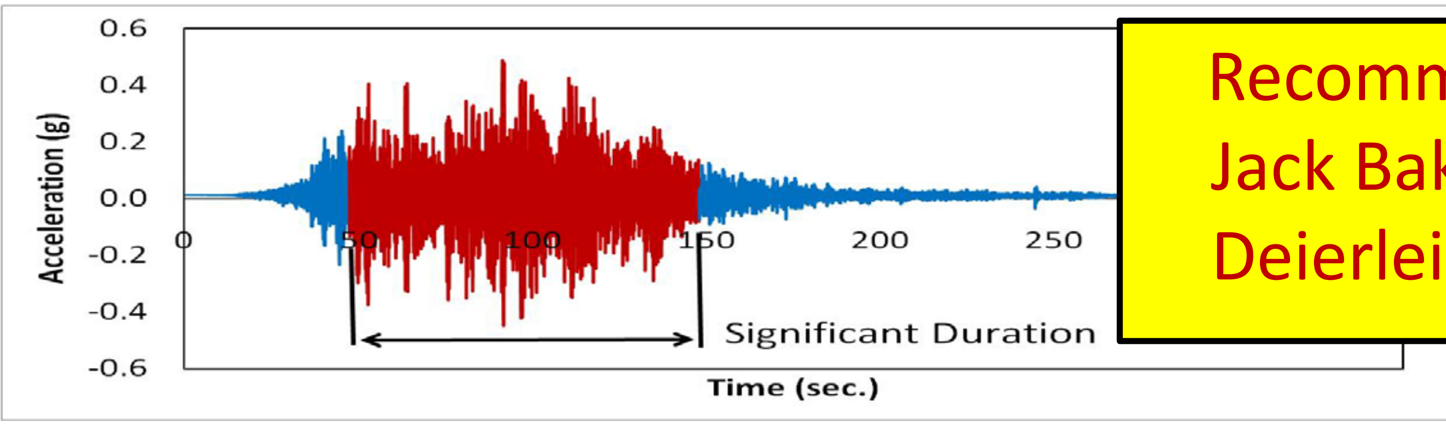
- ***Bracketed Duration***

The measure of the time interval between the first and last exceedance of an absolute acceleration threshold

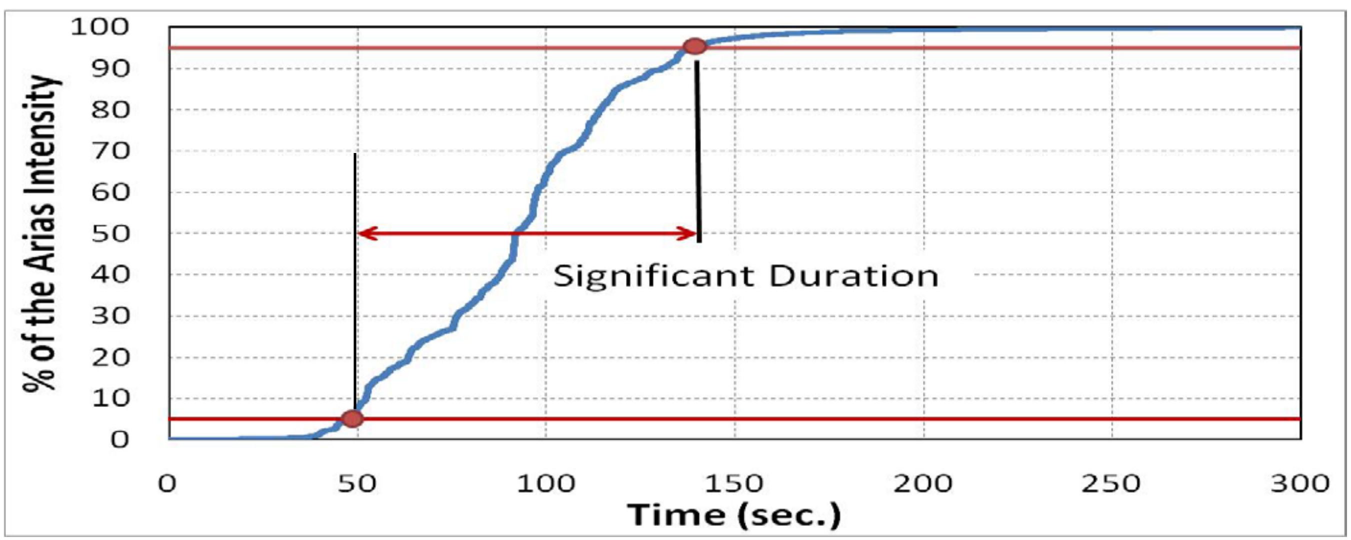


Ground Motion Duration Definitions

- ***Significant Duration (5-95% of the Arias Intensity)***



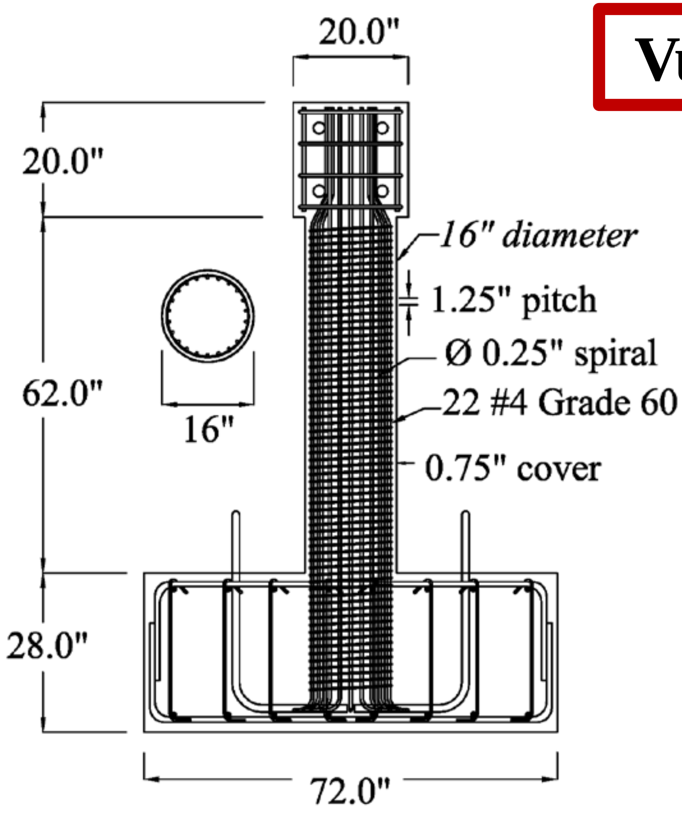
Recommended by Jack Baker and Greg Deierlein (2012)



$$I_A = \frac{\pi}{2g}\int_0^{T_d} a(t)^2 dt$$

Path to the test (Pre-test work)

1- Choose a previously tested column that was tested under regular motions to be our specimen, in this case we can know the maximum displacement capacity of the columns before testing.



Vu and Saiidi (2005) - Rinaldi - 1/3 scale

- **Design Code: AASHTO**
- **L/D= 4.5 (flexural behavior)**
- **Axial Load ratio= 8.0%**
- **Long. steel ratio= 2.2%**
- **Trans. steel ratio= 1.1%**

Path to the test (Pre-test work)

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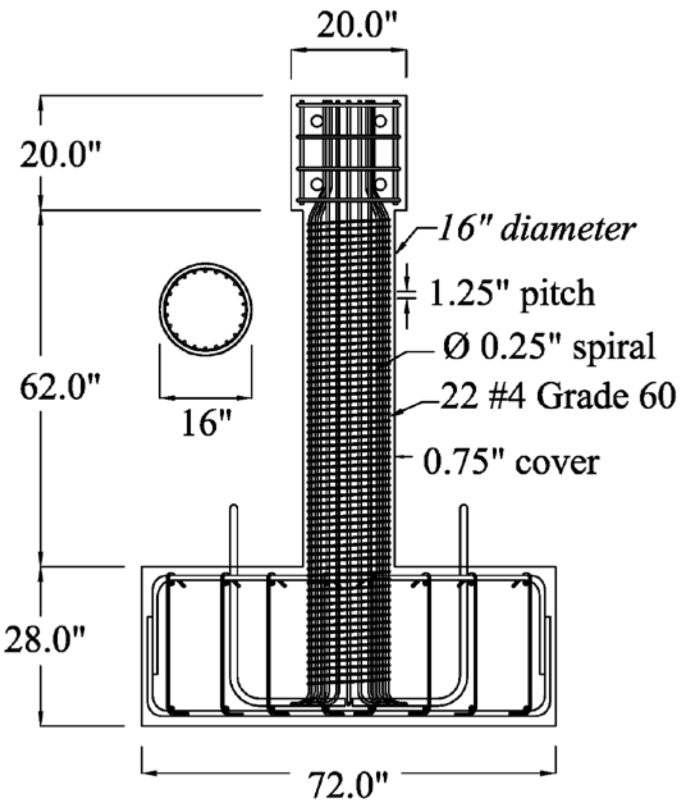
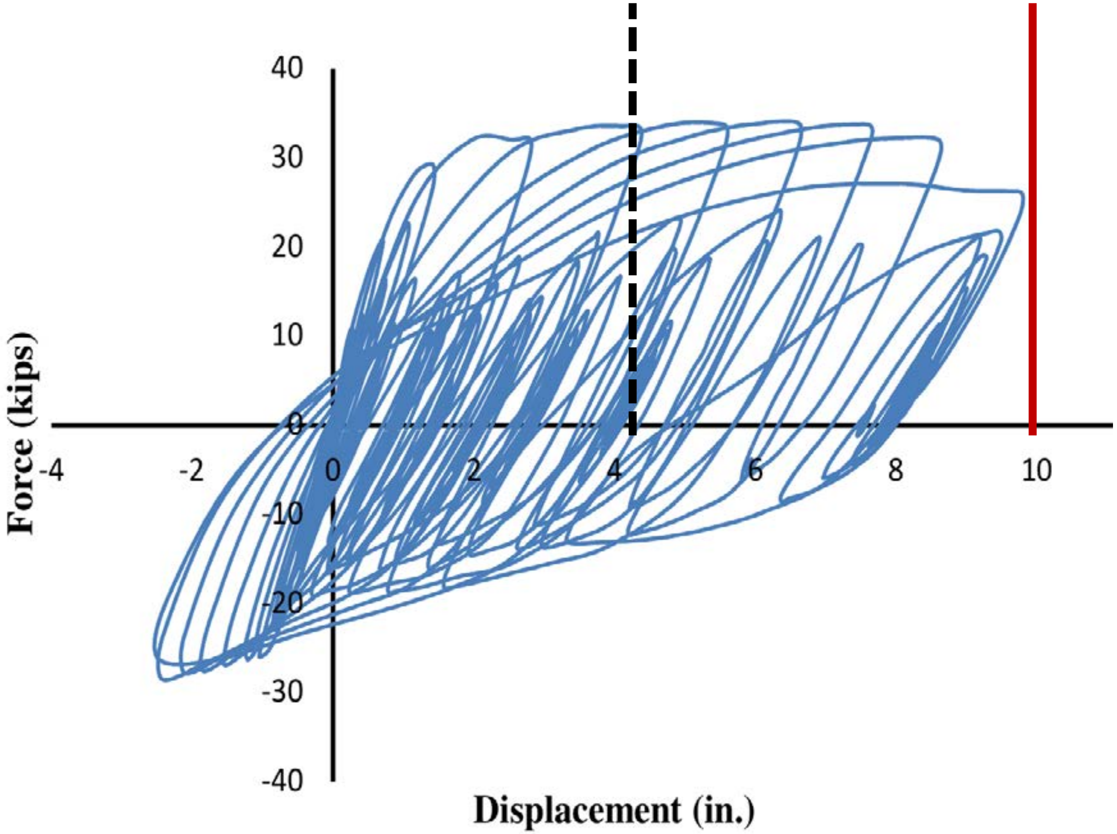


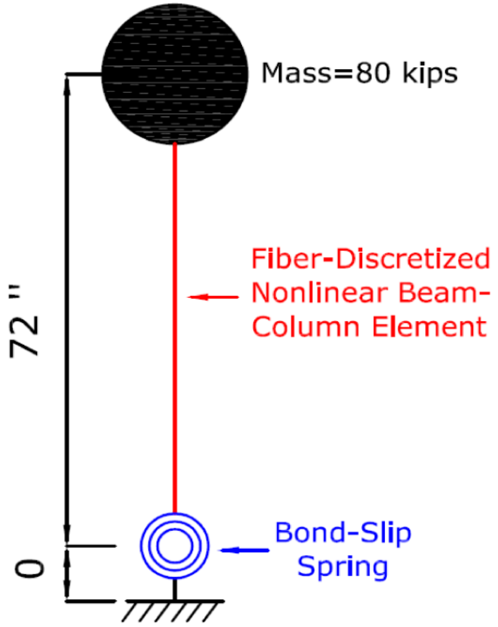
Displacement Capacity= 9.8 in.

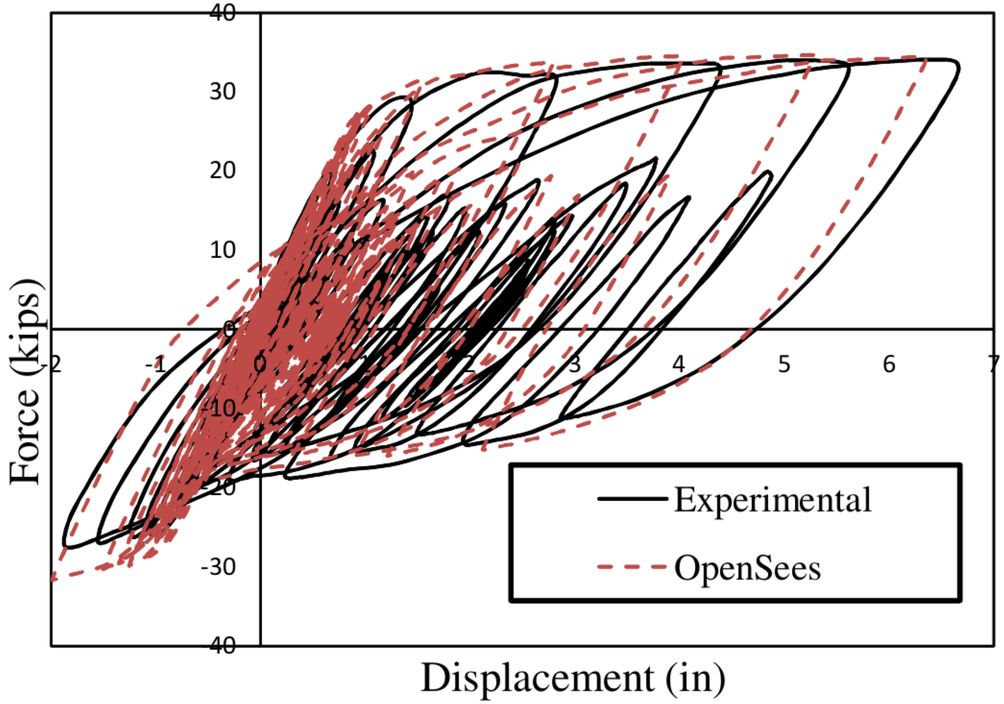


Path to the test (Pre-test work)

2- A simple OpenSees model is used to simulate Vu and Saiidi's Column.

The selection of the motions is based on this model (the displacement demands are almost half the capacity).

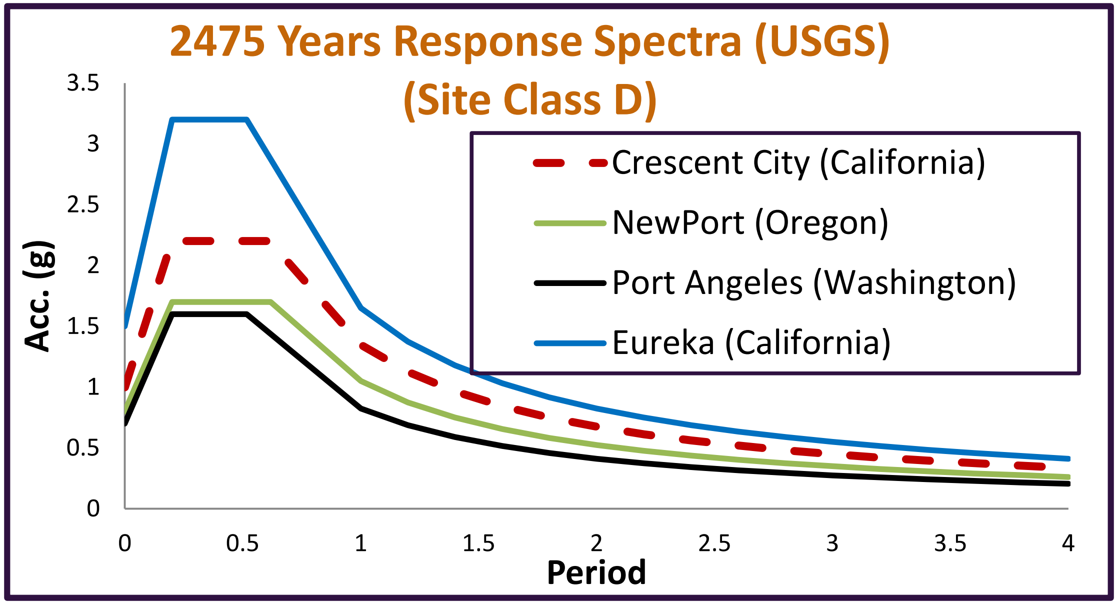




Path to the test (Pre-test work)

3- Two identical specimens are tested :

- **Long duration motion from the Japan 2011 Earthquake**
- **Short duration motion from Loma Prieta 1989 Earthquake**



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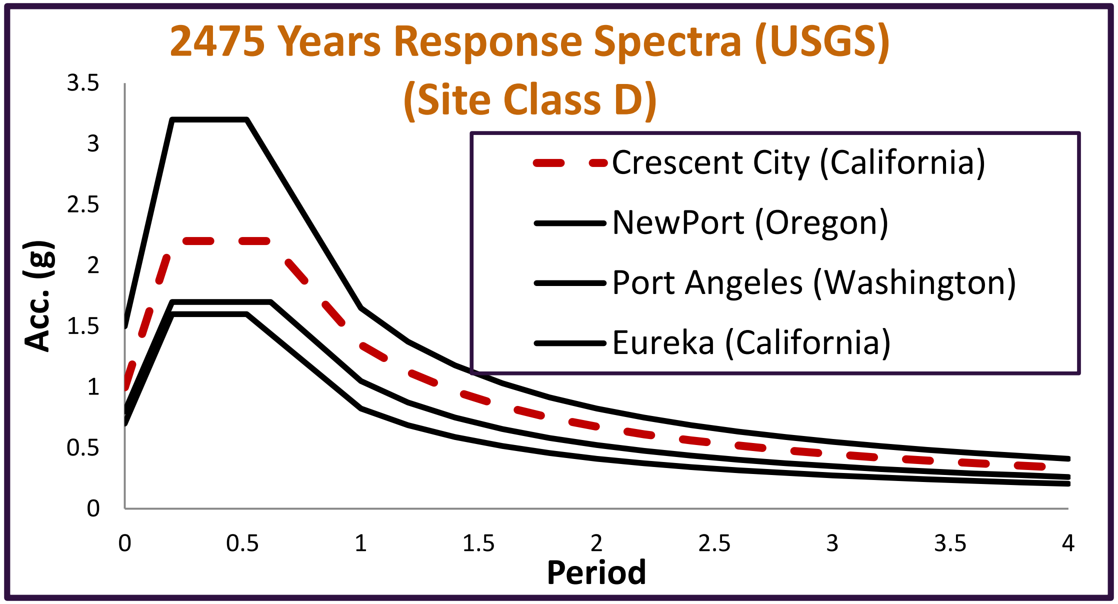
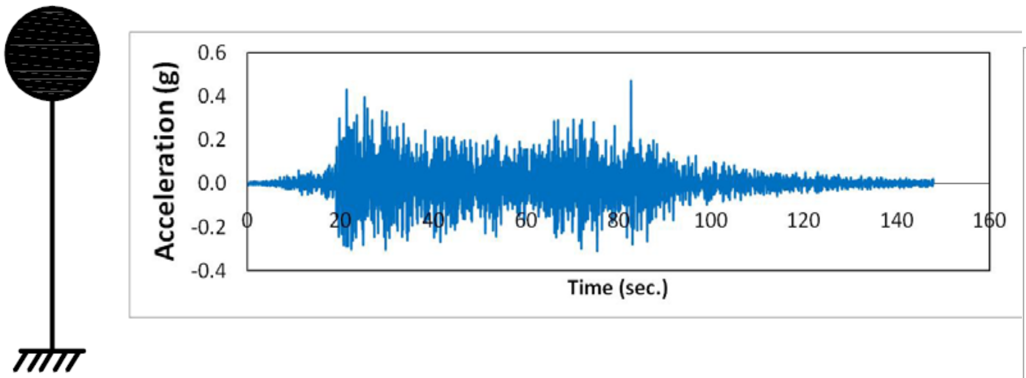
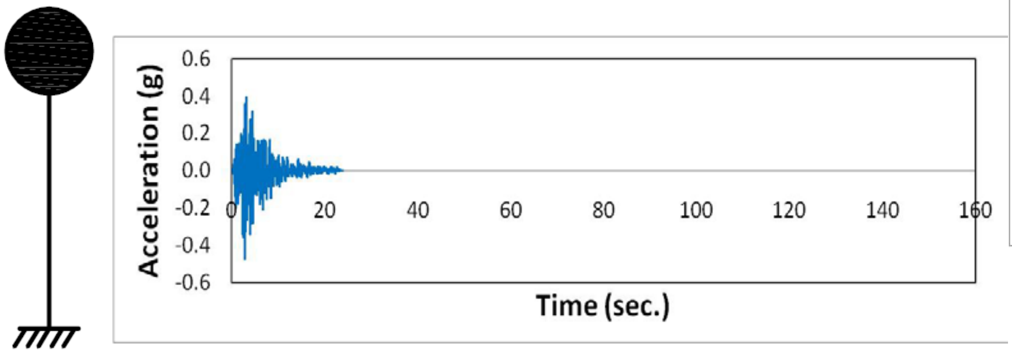
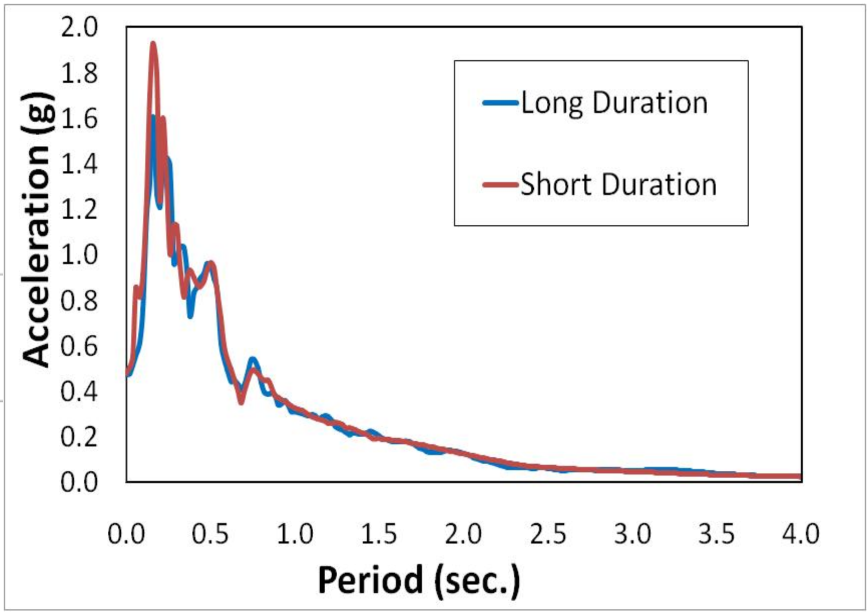


The two motions are modified to match the response spectrum of Crescent City (2475 years)

Path to the test (Pre-test work)



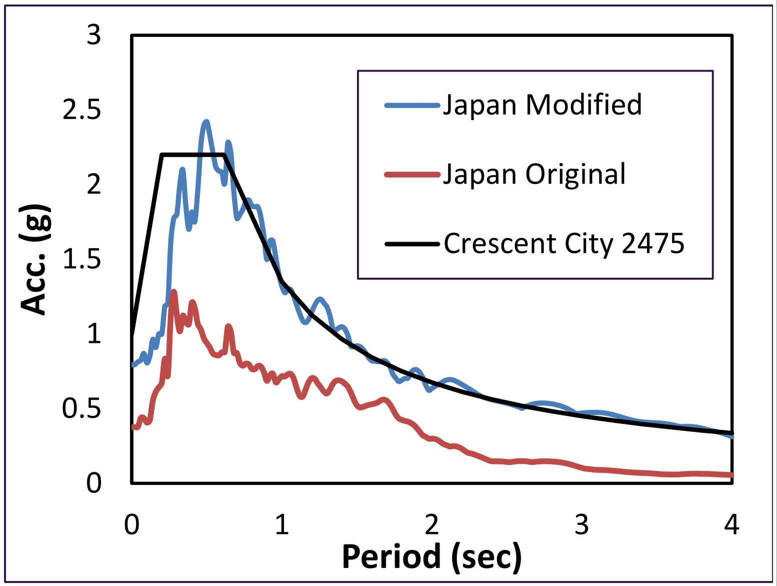


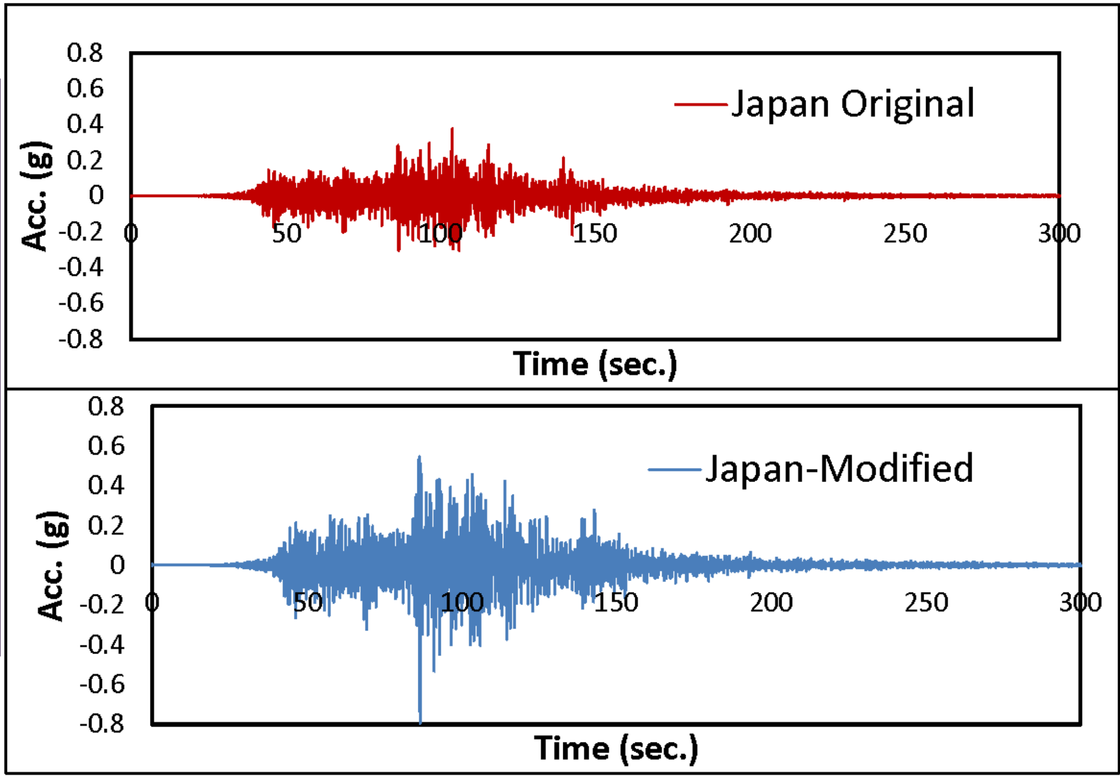


- **This approach was suggested by Deierlein (2012) .**

Path to the test (Pre-test work)

1) Japan, Tohoku 2011 /Station: FKSH20 (N-S)

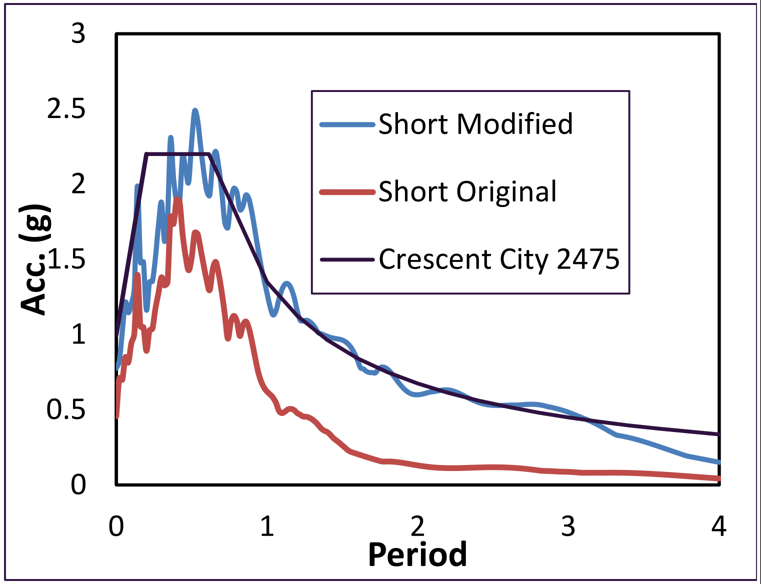


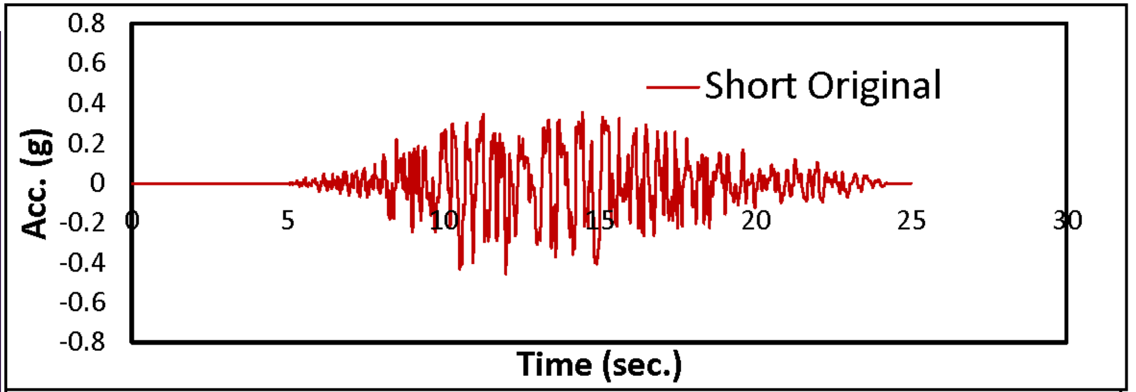


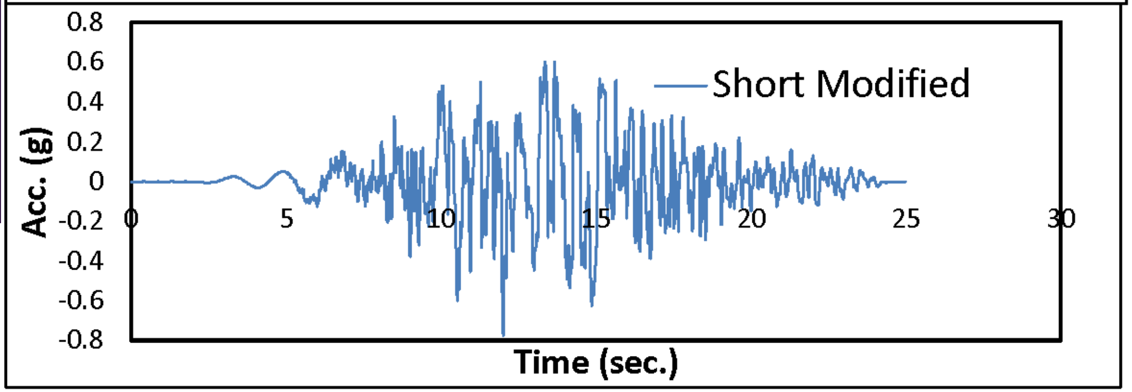
Significant Duration = 88.3 seconds

Path to the test (Pre-test work)

2) Loma Prieta 1989/Station: Bran 00



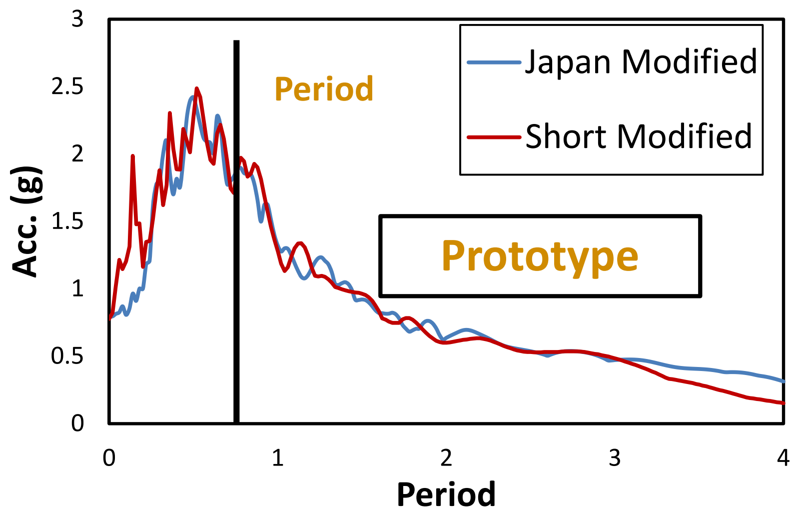


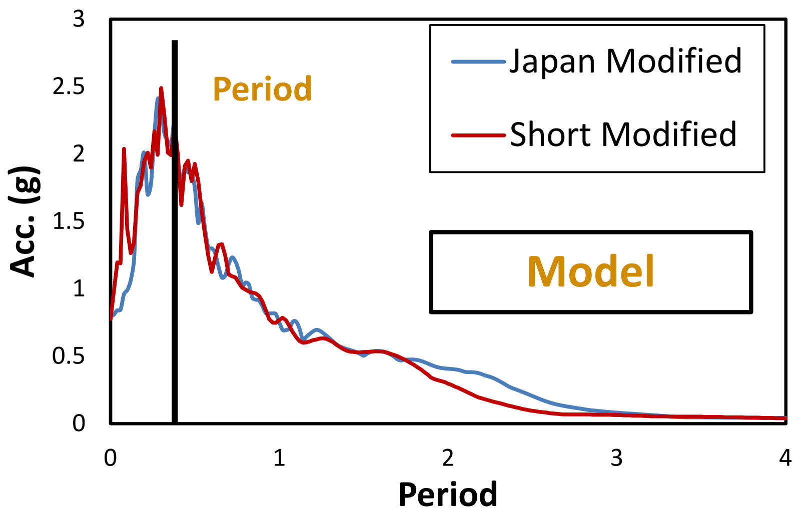


Significant Duration = 9.0 seconds

Path to the test (Pre-test work)

Final Motions





Column 1

Column 2

Japan, Tohoku

Sig. Dur. (Prototype)
= 88.3 sec
Sig. Dur. (Specimen)
= 50.9 sec

Short, Loma Prieta

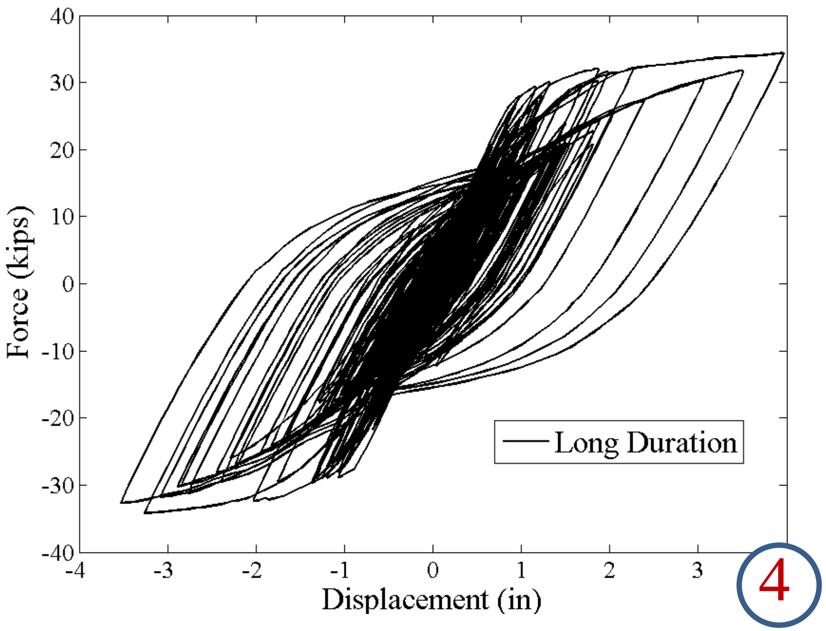
Sig. Dur. (Prototype)
= 9.0 sec
Sig. Dur. (Specimen)
= 5.2 sec

Path to the test (Pre-test work)

OpenSees Pre-Analysis

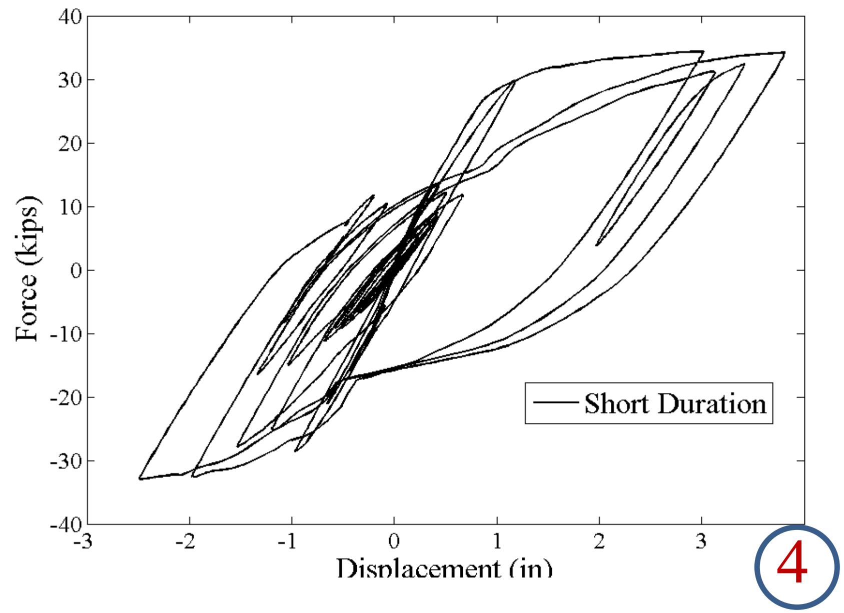
Column 1

Japan, Tohoku



Column 2

Short duration

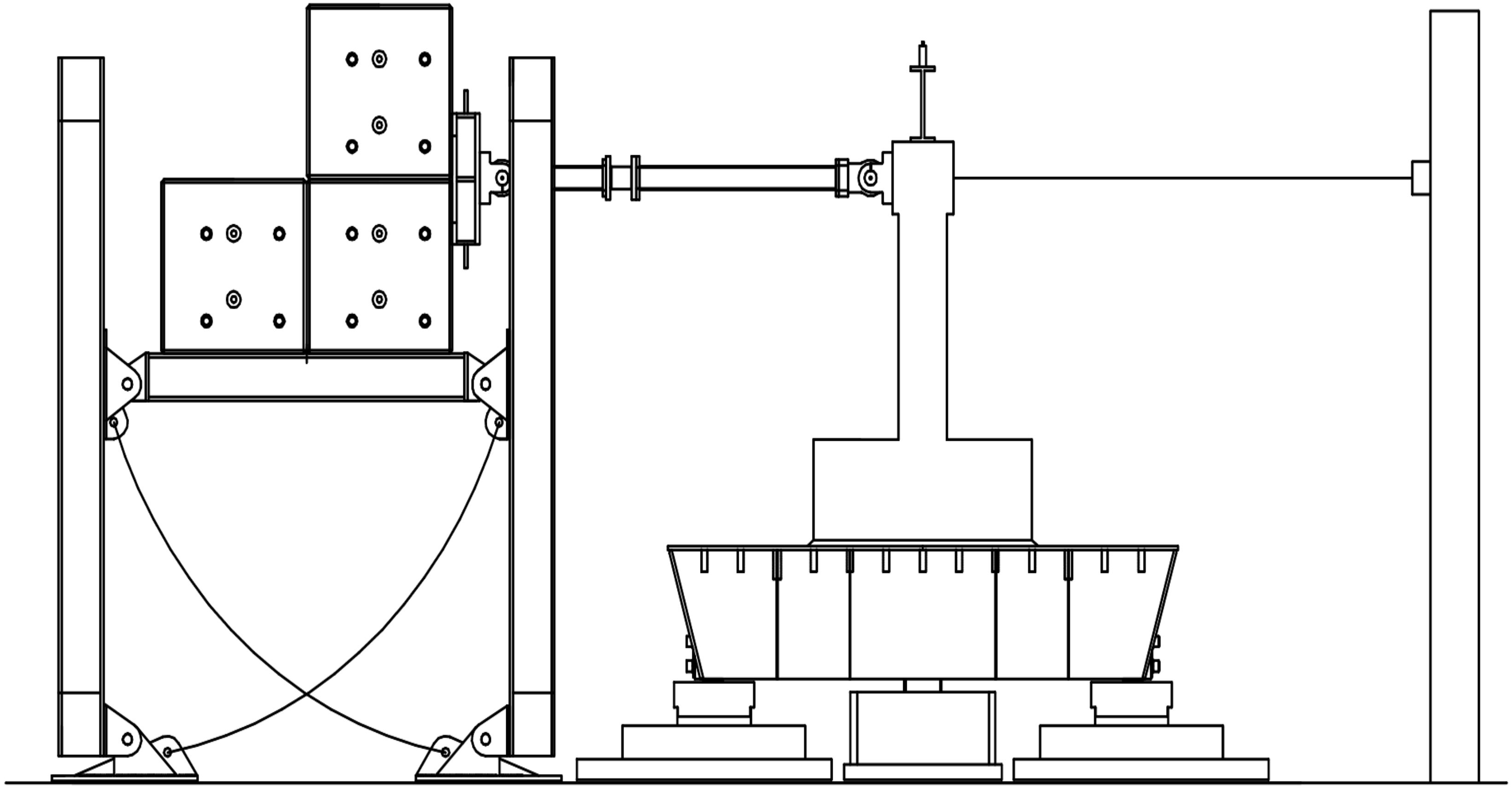


Maximum displacement demands of about 4 inches

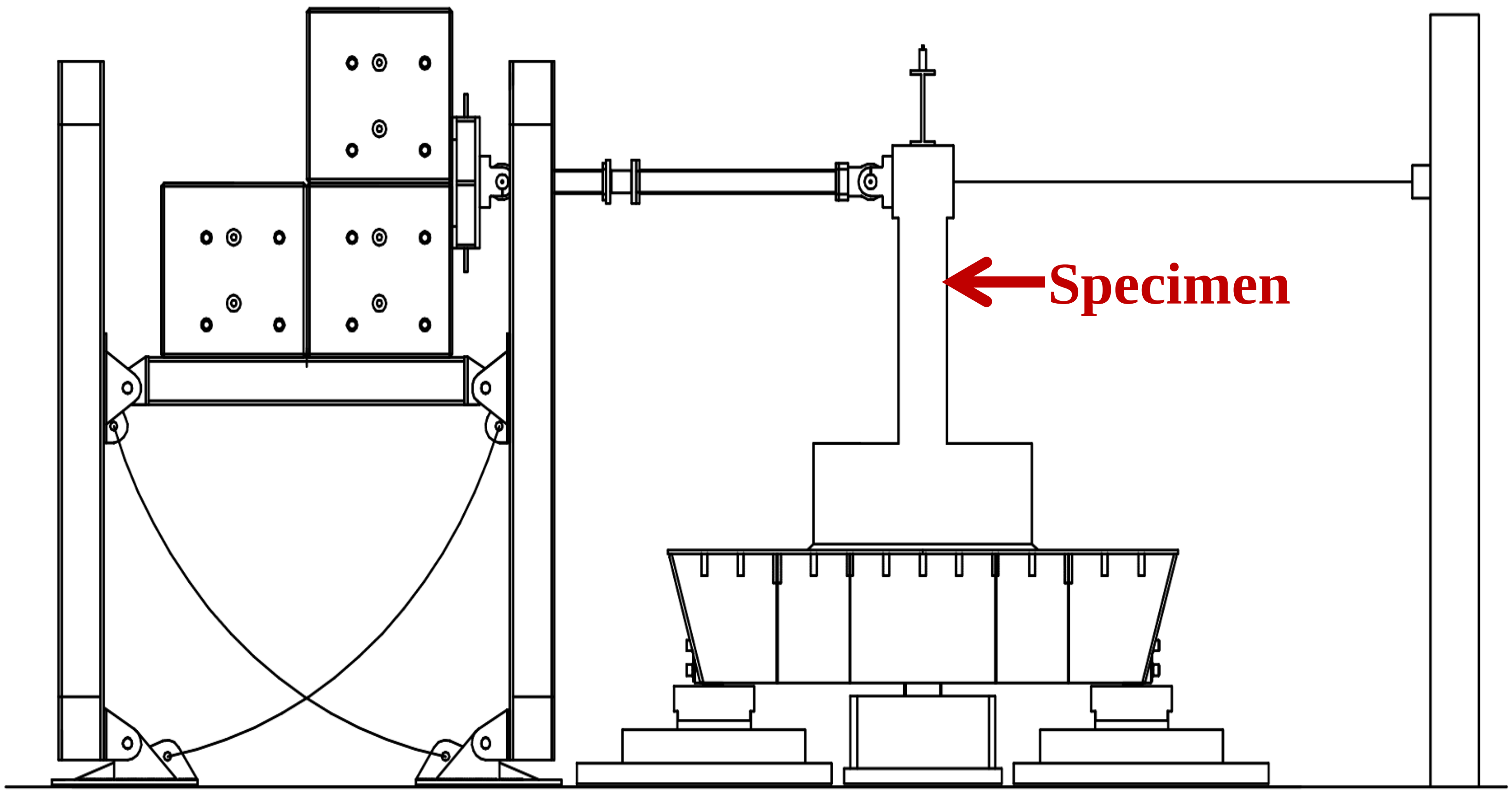
Design codes→ These motions are the same

Earthquake Engineering Laboratory

Test Setup



Test Setup



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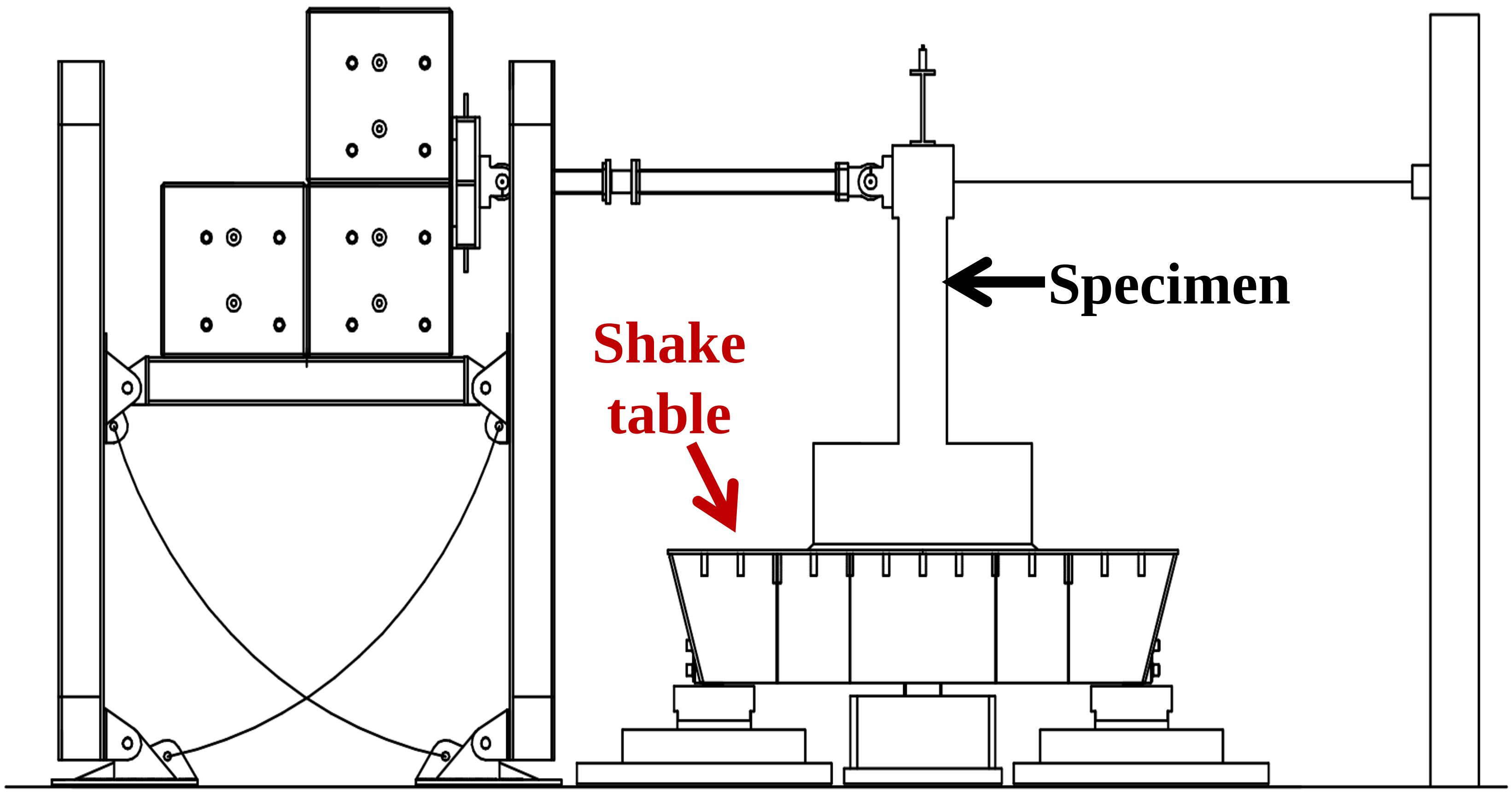

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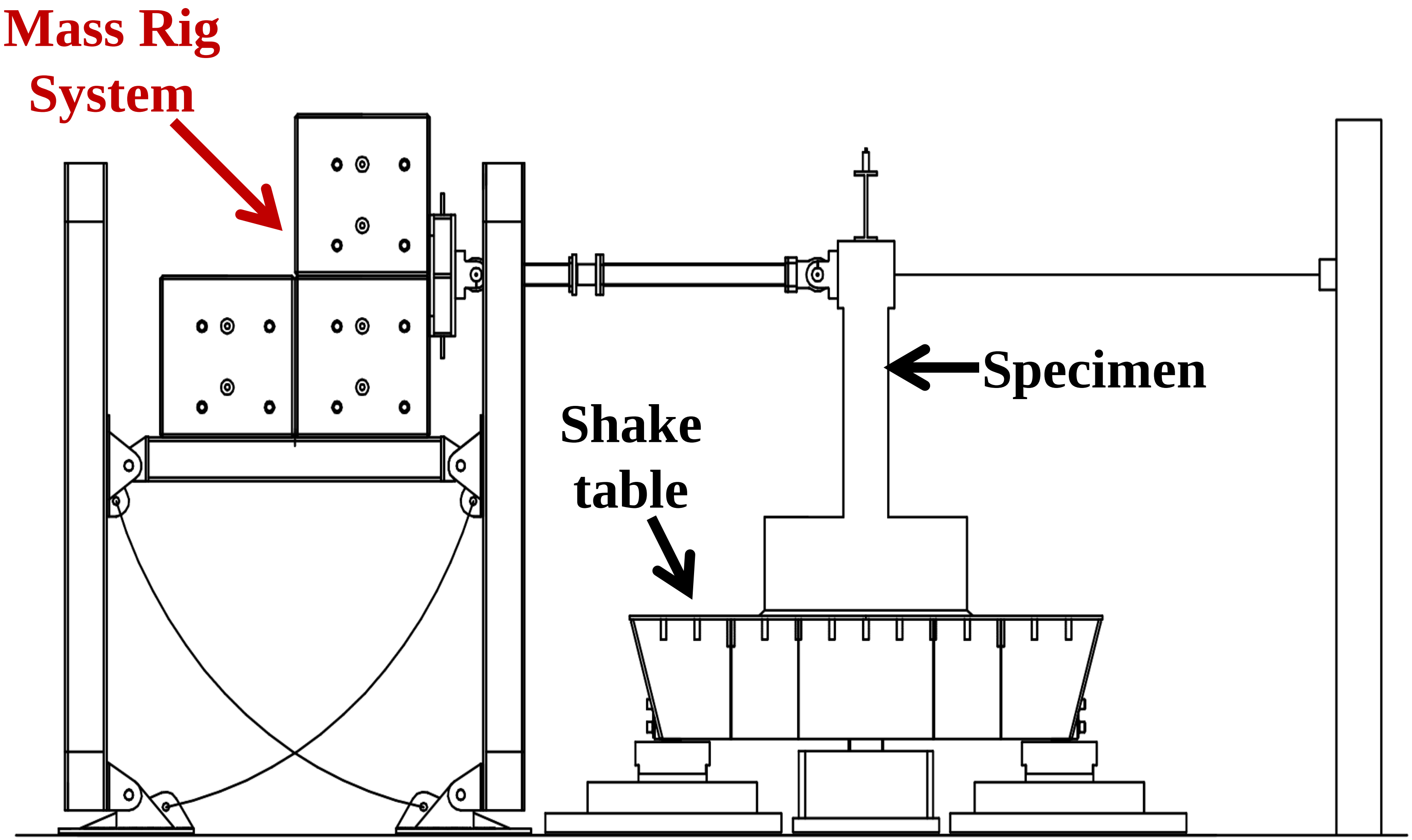
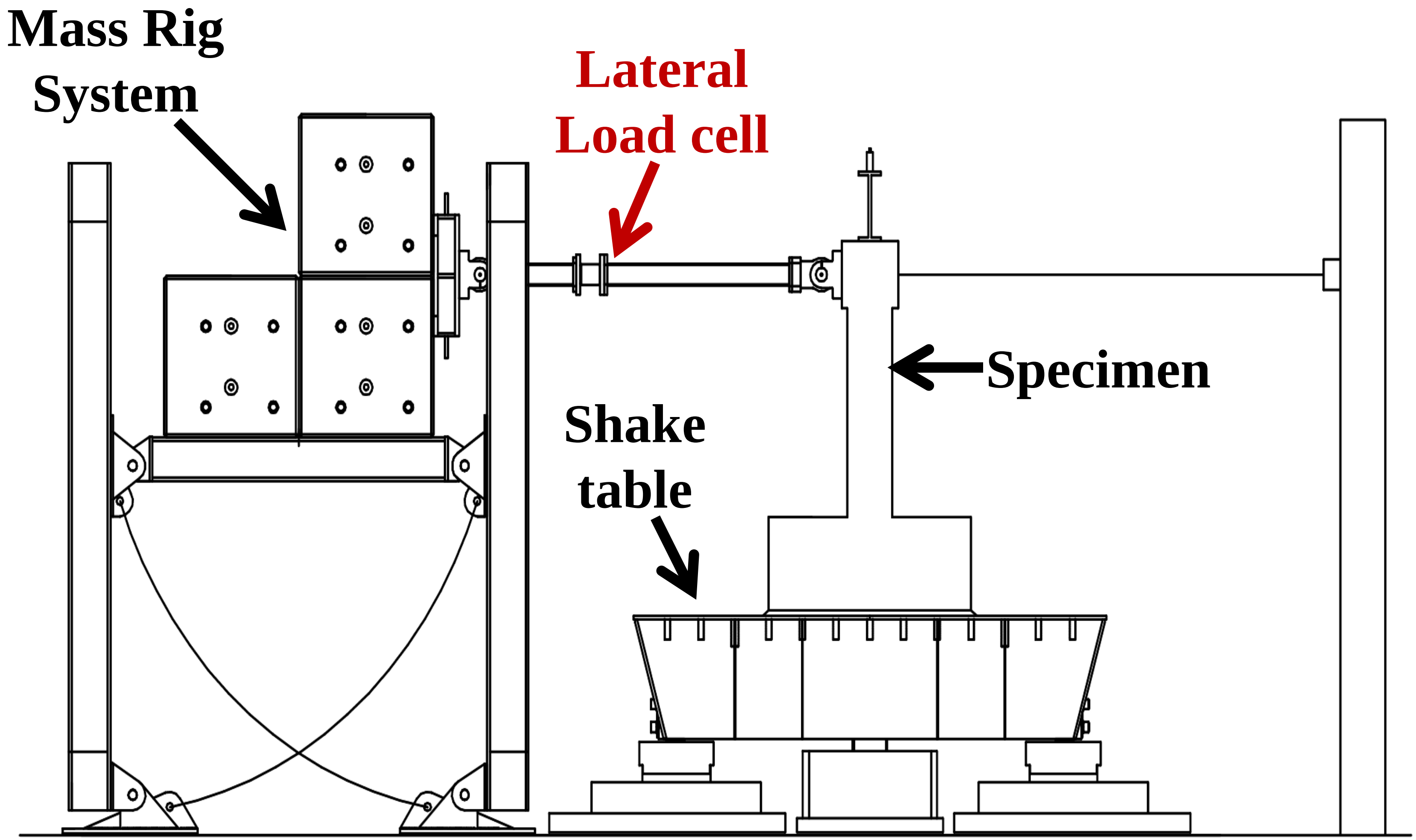
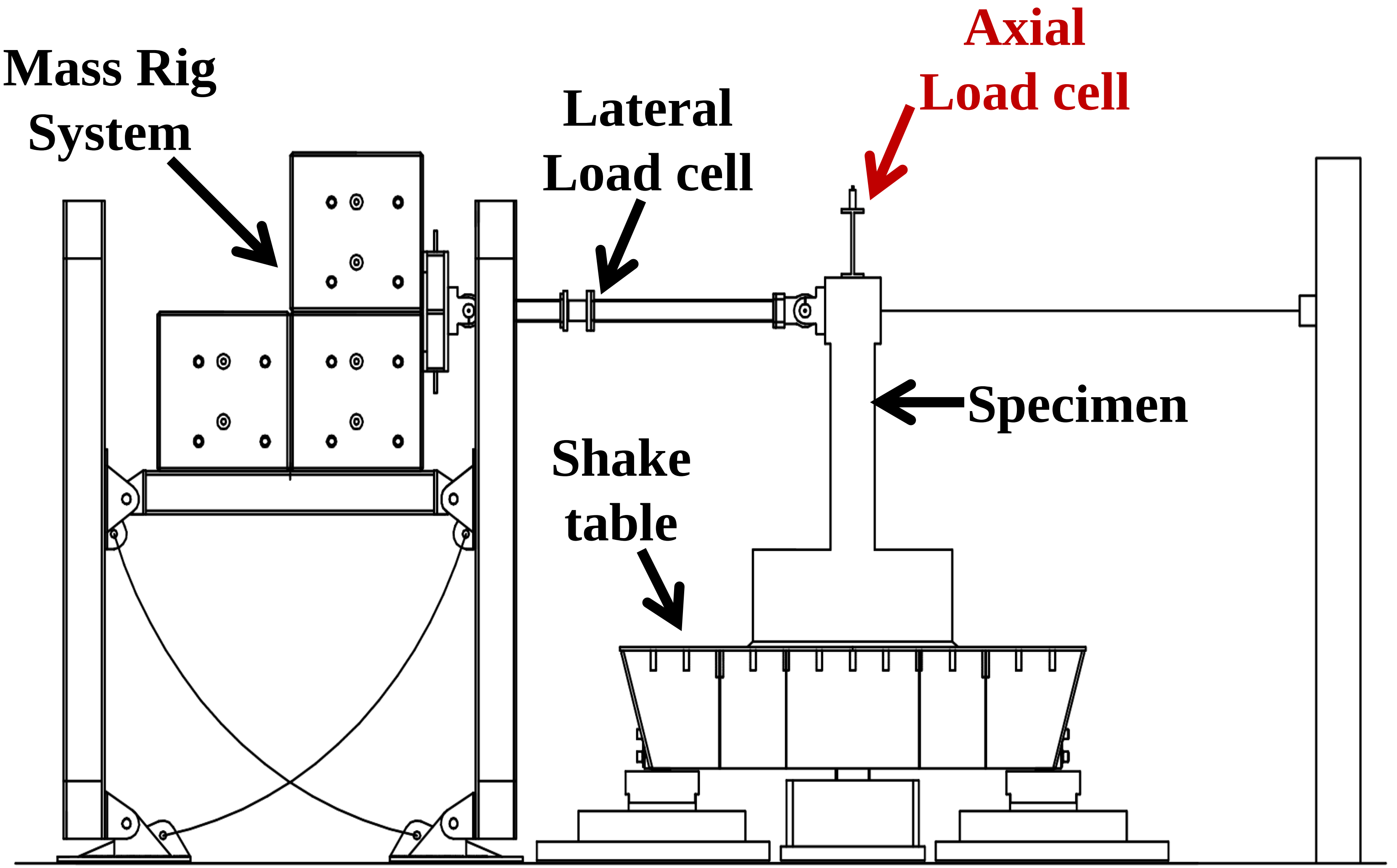


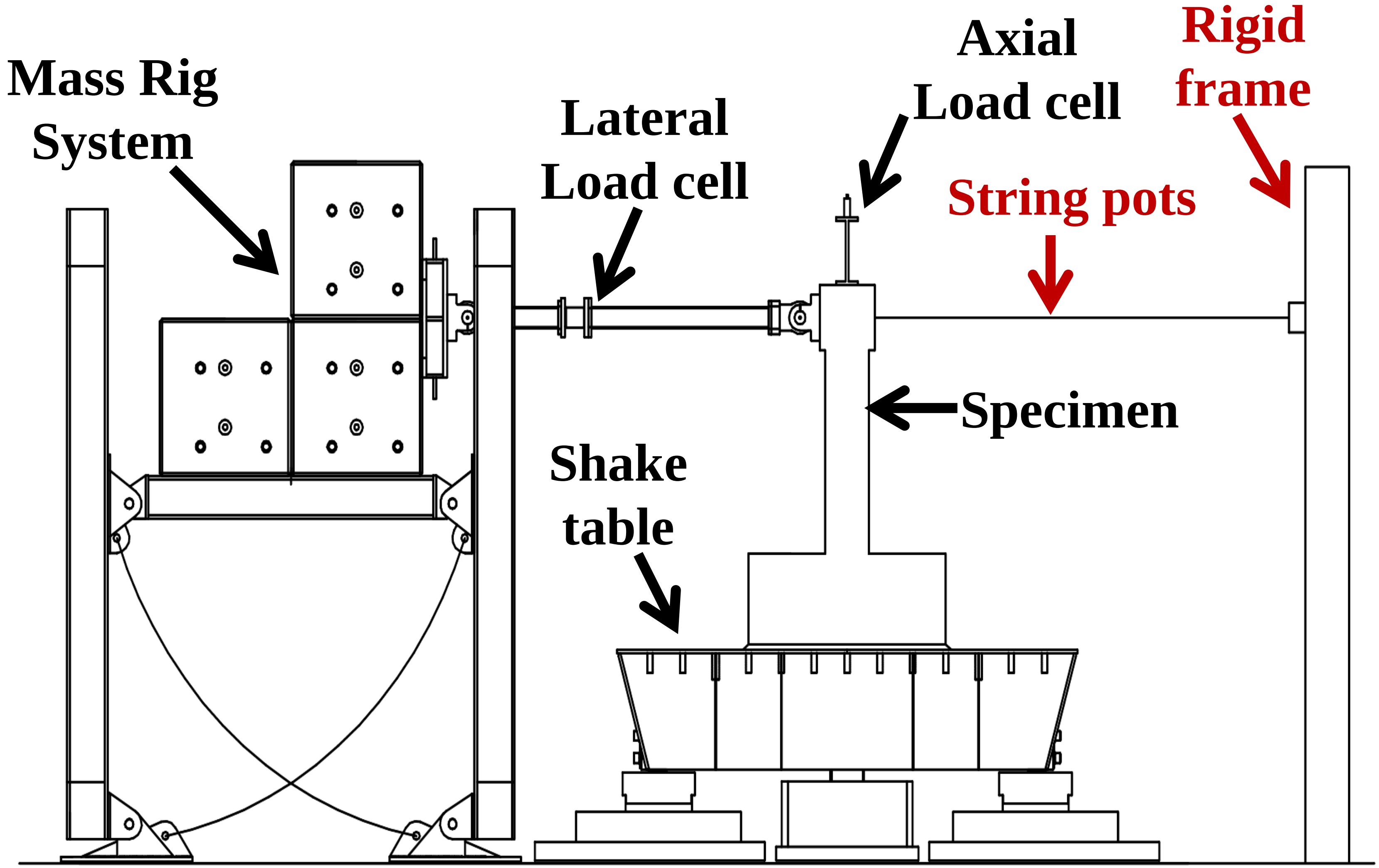
Test Setup



Test Setup

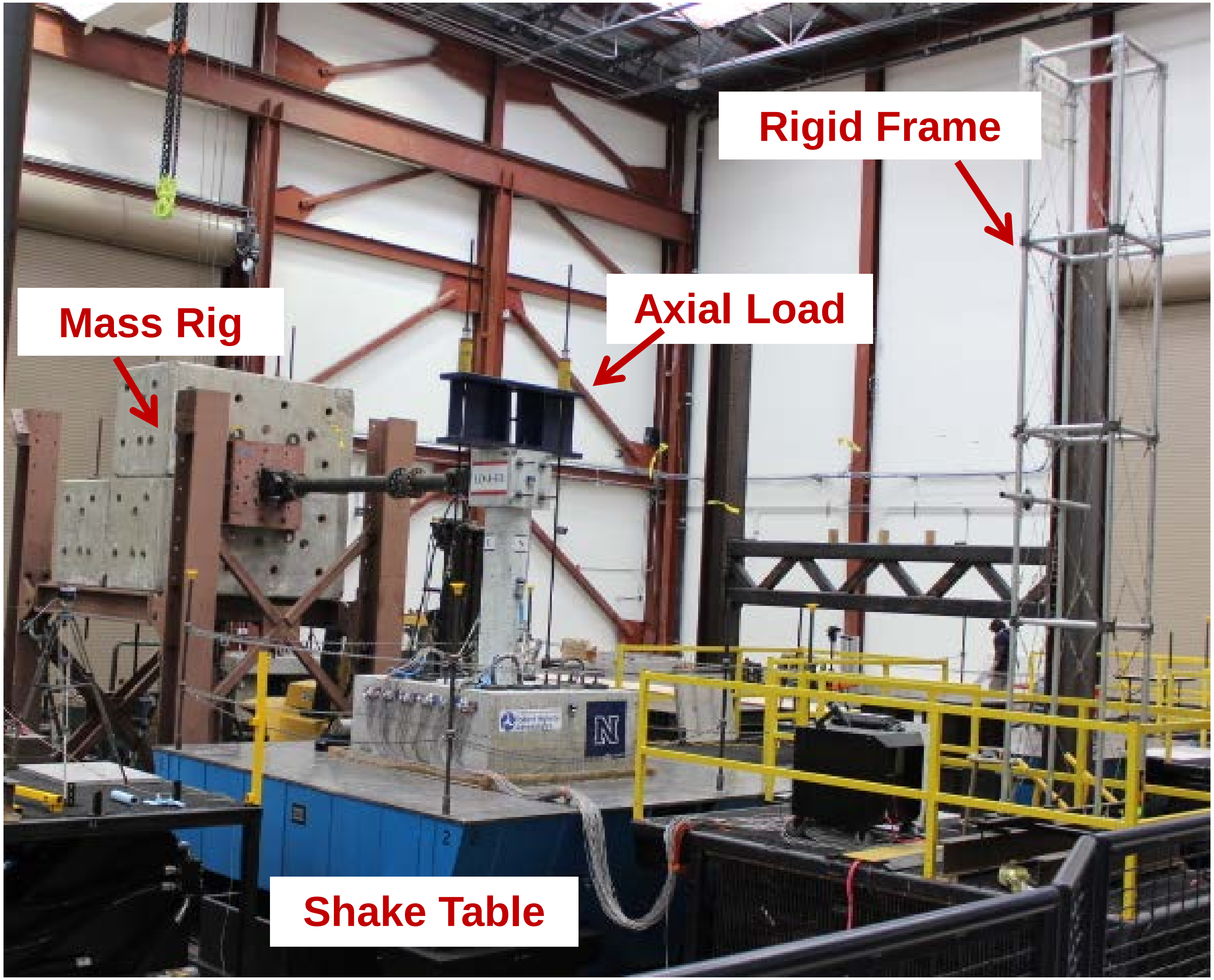

Mass Rig
System
Lateral
Load cell
Axial
Load cell
Specimen
Shake
table

Test Setup



Mass Rig System
Lateral Load cell
Axial Load cell
Rigid frame
String pots
Specimen
Shake table

Test Setup

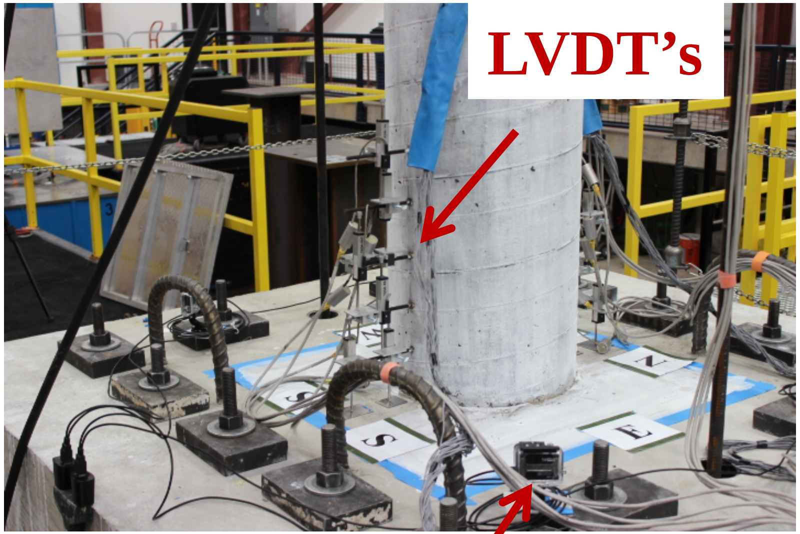


Test Setup

Instrumentation

- 48 Strain Gages
- LVDT's
- Accelerometers
- String Potentiometers
- HD and Go-Pro cameras

String pots connected to the rigid frame



Go-Pro camera in each corner

Loading Protocol

100% of GM

+

AfterShock

+

125% of GM

+

150% of GM

+

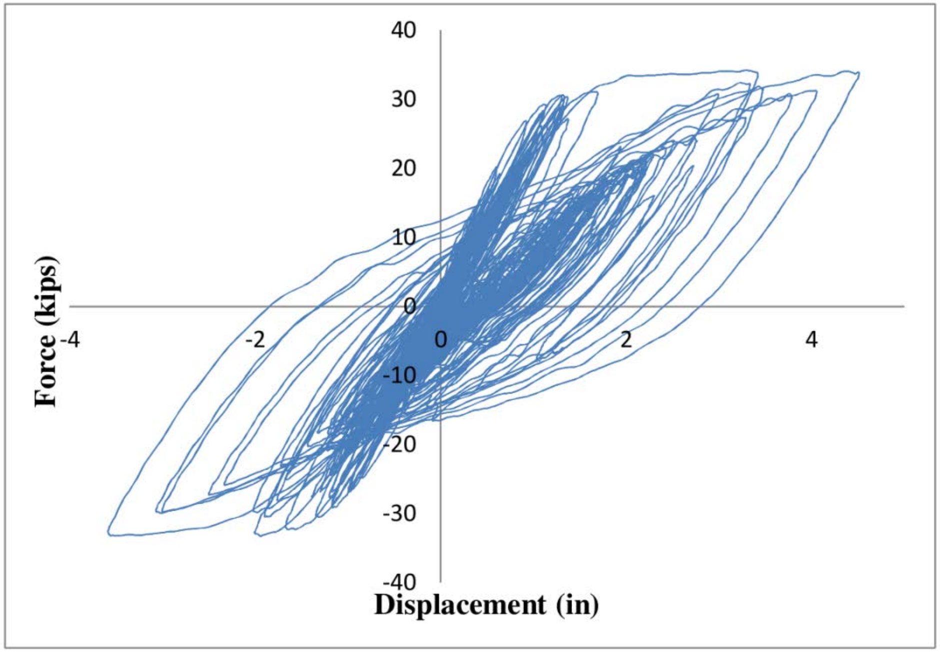
etc………

Test Results

100 % of the Ground Motion

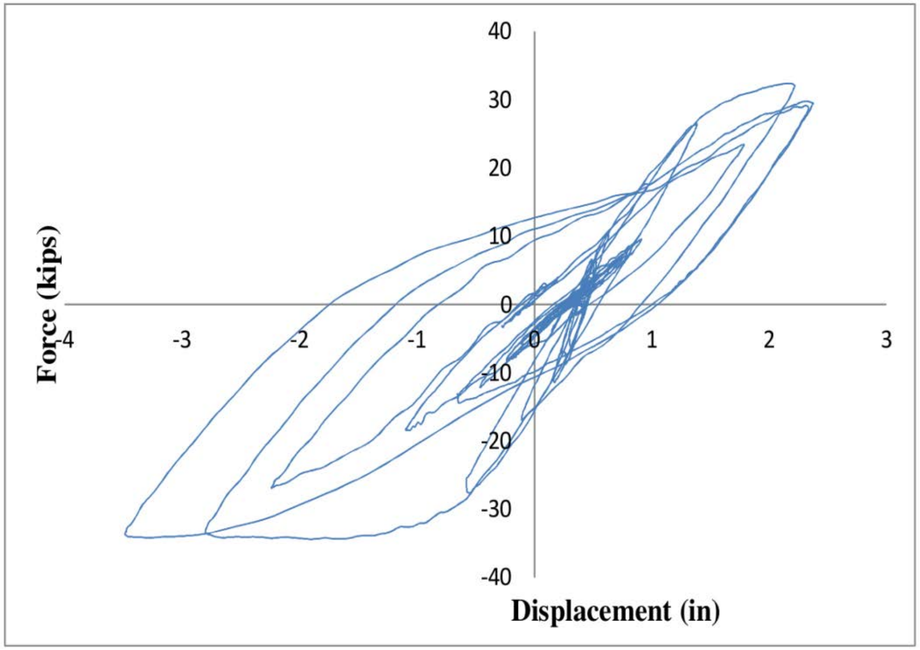
Column 1 (Japan)

Max. Disp.= 4.5 in.



Column 2 (Short duration)

Max. Disp.= 3.88 in.

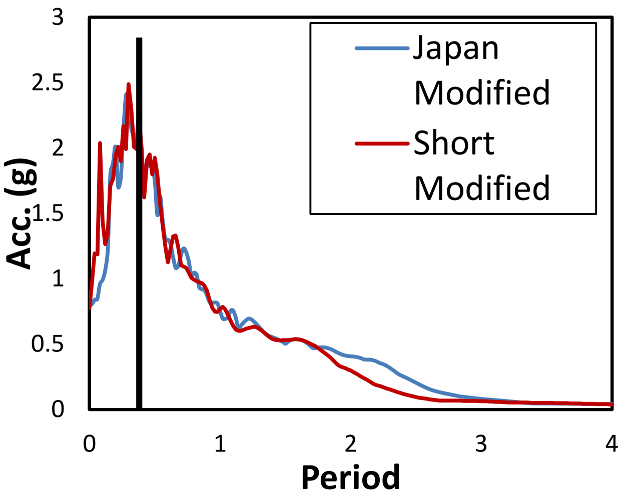


Test Results

100 % of the Ground Motion

Column 1 (Japan)

Max. Disp.= 4.5”



Column 2 (Short duration)

Max. Disp.= 3.88”

South (Column 1)

- 4.4” spalling
- Spirals Exposed

North (Column 1)

- 3.0” spalling
- Spirals Exposed

South (Column 2)

- Cracks (max width= 0.4mm)

North (Column 2)

- 4.5” spalling
- No RFT. Exposed

Test Results

125 % of the Ground Motion

Column 1 (Japan)

Max. Disp.= 4.98”

South

- 8.5” spalling
- **4 Bars fractured**

North

- 6.4” spalling
- Core Damage

Column 2 (Short duration)

Max. Disp.= 4.8”

South

- 4.5” spalling
- Spirals exposed

North

- 4.5” spalling
- Spirals exposed

Test Results

150 % of the Ground Motion

Column 1 (Japan)

Not Applicable

Bars Fractured at 125%

Column 2 (Short duration)

Max. Disp.= 7.3”

South

- 9” spalling
- Spirals exposed

North

- 6” spalling
- Spirals exposed

Test Results

175 % of the Ground Motion

Column 1 (Japan)

Not Applicable

Bars Fractured at 125%

Column 2 (Short duration)

Max. Disp.= 9.22”

South

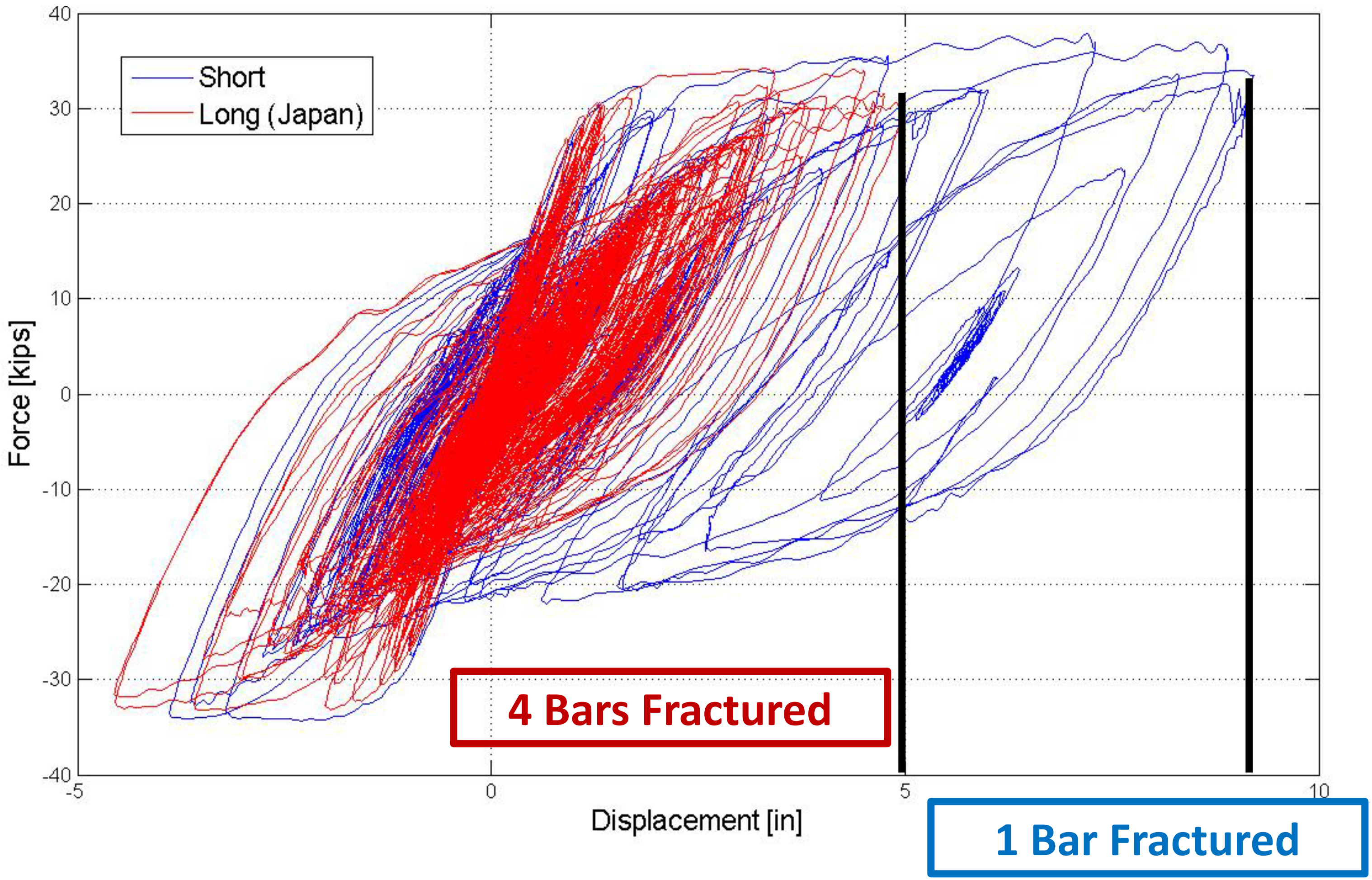
- **4 bars buckled**

North

- **1 bar fractured**
- **2 bars buckled**

Test Results

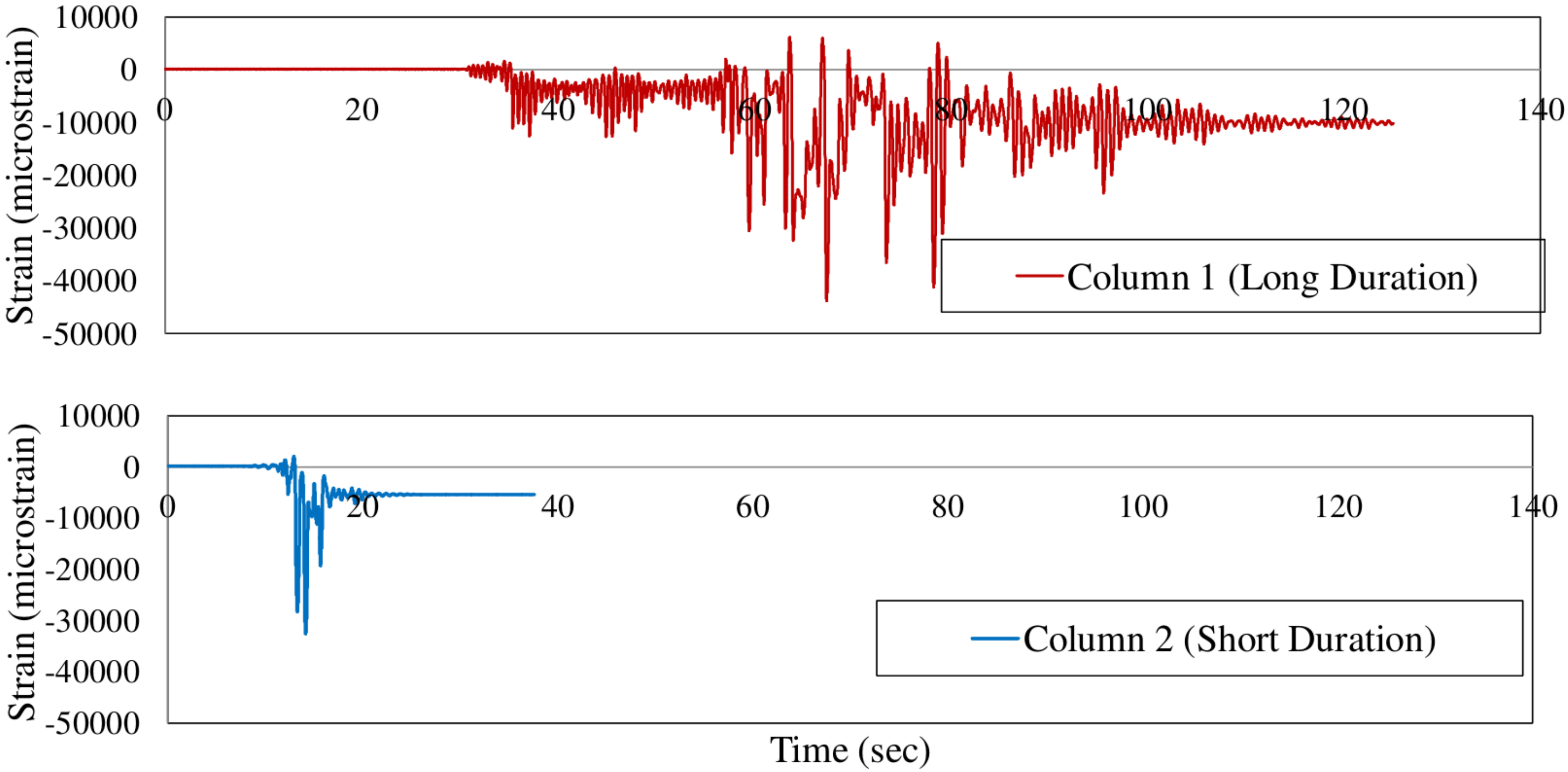
Force-Displacement Comparison



Test Results

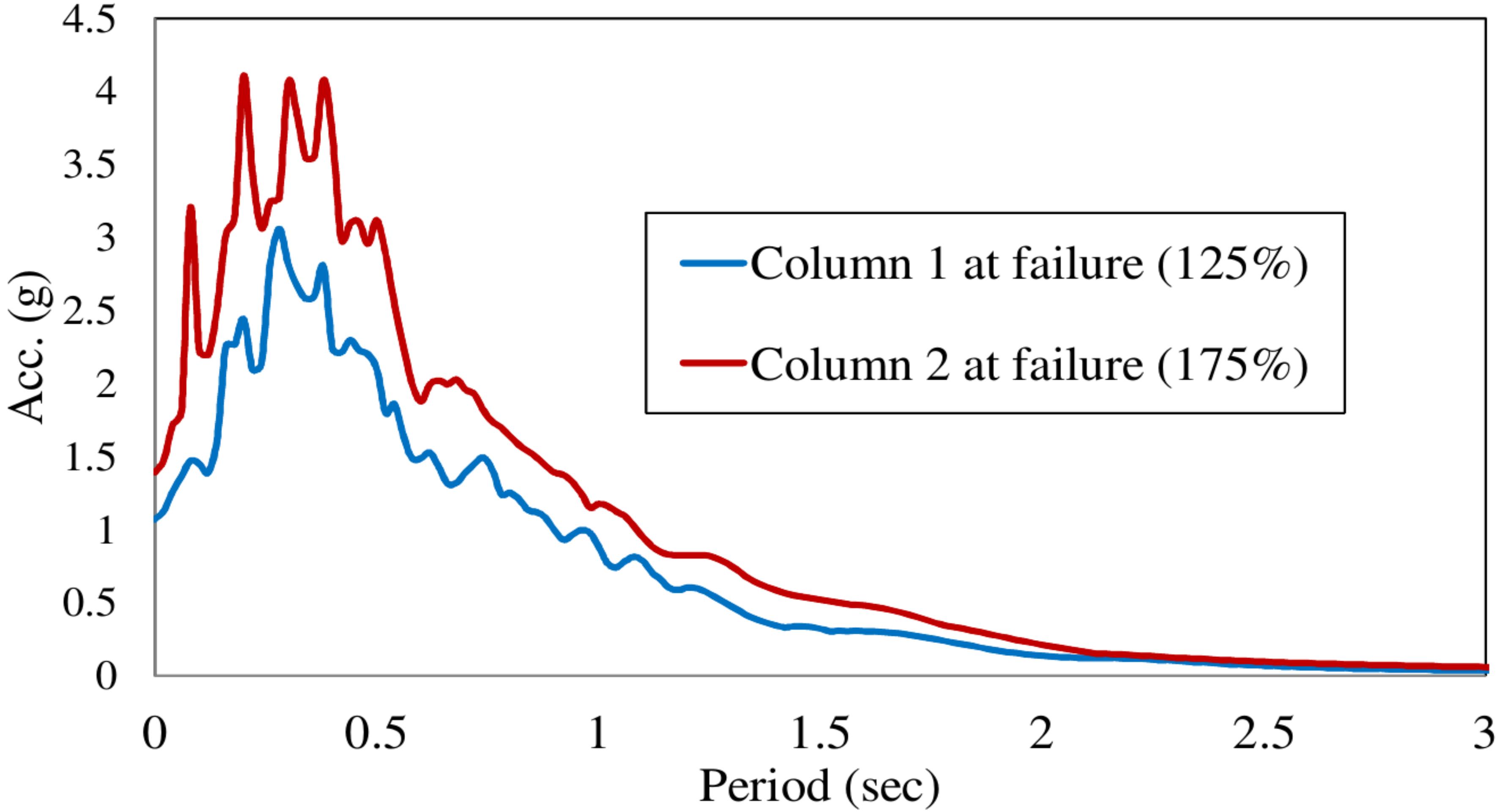
Strain Comparison (100%of GM)

4 in. above the footing



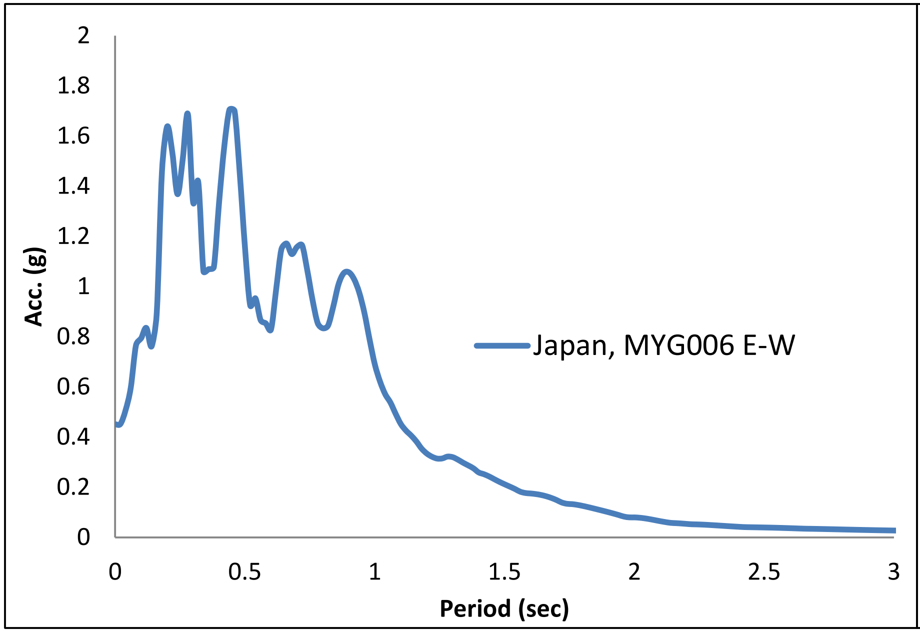
Response Spectra Comparison

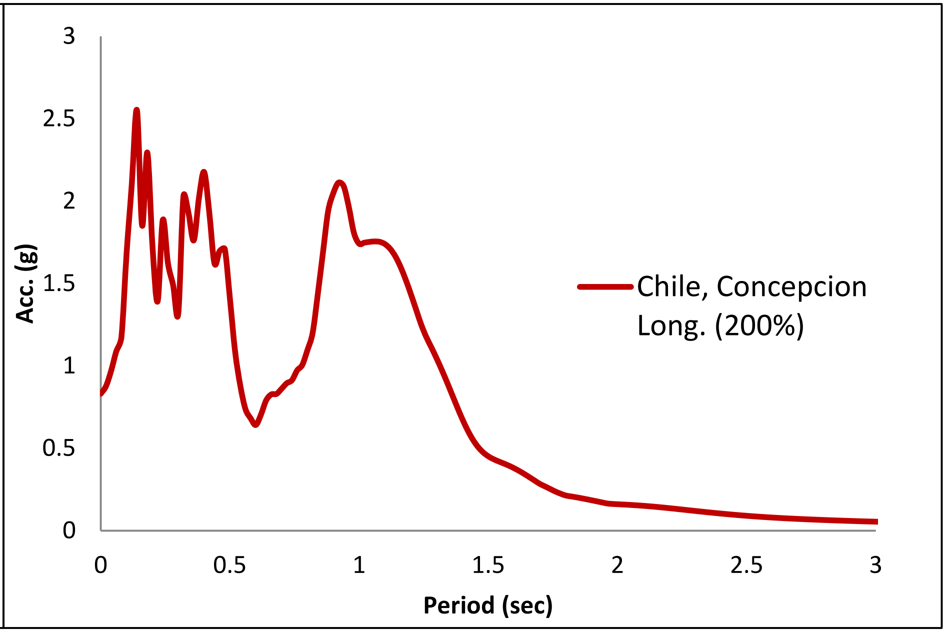
Response Spectra at final damage state



Testing Extension

- **Three more columns were tested under long duration motions from the Chile 2010 and Japan 2011 events.**
- **Two of the motions were used without modifications and real aftershocks were also used.**





Work in Progress

Extensive Analytical Work

Long Duration Ground Motion Set

Two sources of long duration ground motion → Long Rupture → Site Effects

SUBDUCTION EARTHQUAKES	CRUSTAL EARTHQUAKES
• 1985 Valparaiso, Chile M7.8	• 1999 Chi-Chi, Taiwan M7.6
• 1985 Michoacan, Mexico M8.1	• 2004 Niigata, Japan M6.6
• 2003 Hokaido (Tokachi-Oki), M8.0	• 2004 Southeast of Kii Peninsula, M7.4
• 2005 Off Miyagi Prefecture, M7.2	• 2007 Chuetsu, Japan M6.5
• 2010 Maule, Chile M8.8	• 2008 Iwate Eastern Honshu, M6.9
• 2011 Tohoku, Japan M9.0	• 2008 Wenchuan, China M8.0
• 2012 Kamaishi, Japan M7.3	• 2010 El Mayor Cucapah M7.2
•2014 Chile, M8.1	• 2011 Fukashima Hamadori, M6.7

Modified Park-Ang Damage Index

$$DI = \frac{\delta_{max}}{\delta_u} + \beta \frac{E_h}{F_y.\delta_u}$$

- δ_{max} = maximum displacement demand during the ground motion

- δ_u =*ultimate displacement capacity (taken 9.8 in. from Vu and Saiidi's test)*

- β = constant (taken 0.15 for concrete structures)

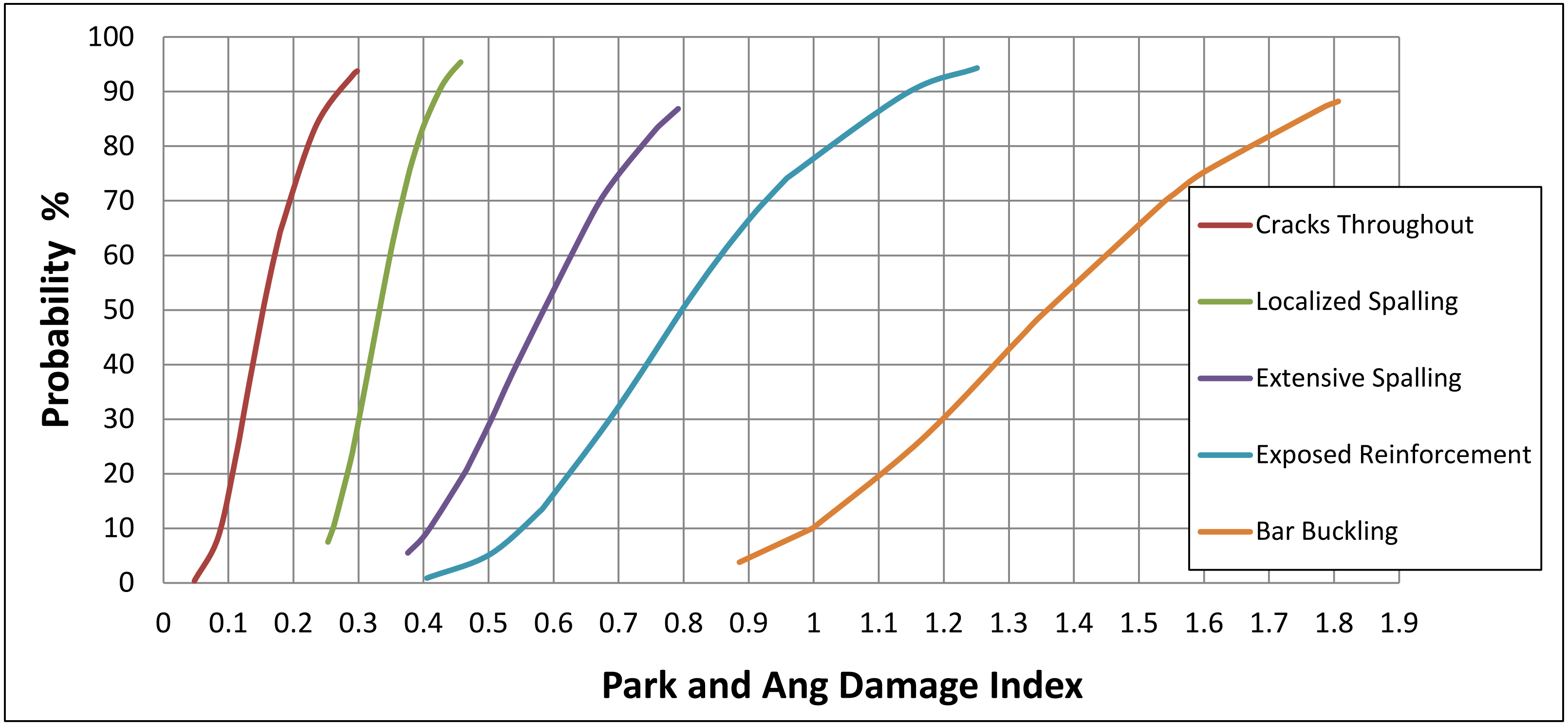
- E_h = hysteretic energy

- F_y = Force causing yield

Modified Park-Ang Damage Index

$$DI = \frac{\delta_{max}}{\delta_u} + \beta \frac{E_h}{F_y.\delta_u}$$

- Data used from past shake-table and cyclic load tests on seismically designed bridge columns (around 25 models) to correlate the damage index with different damage states.



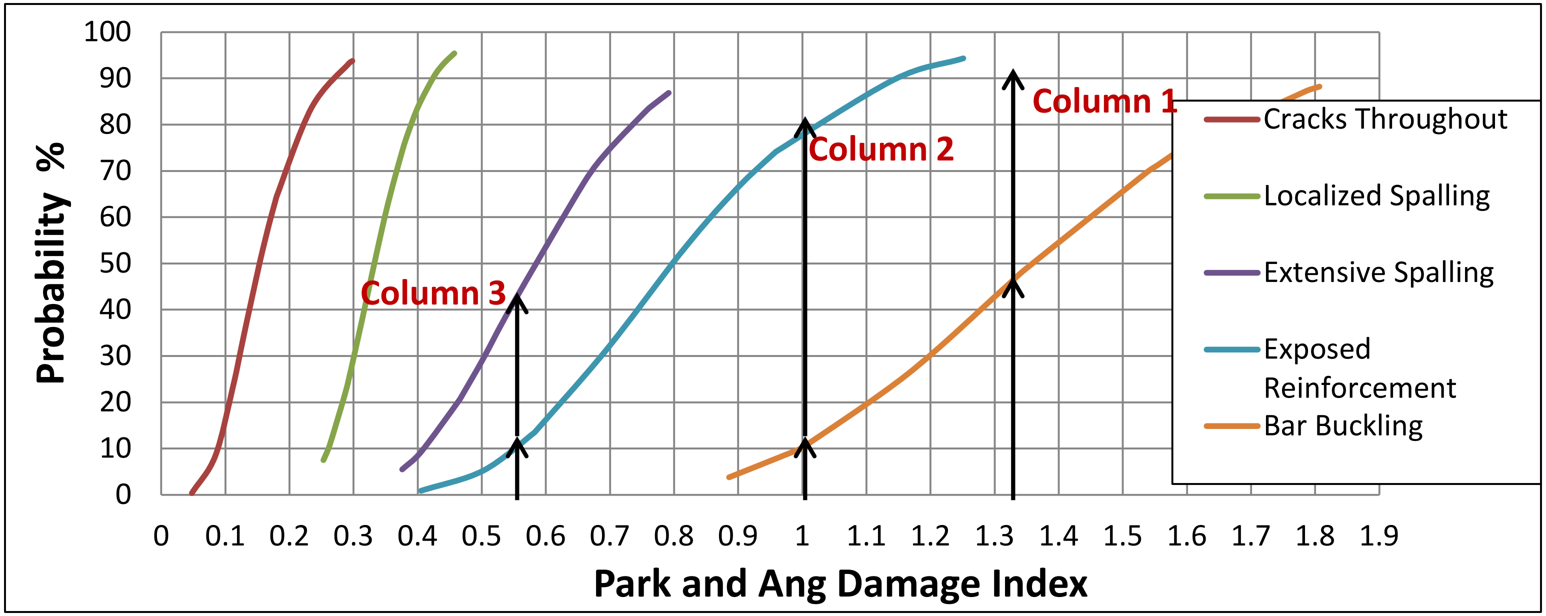
Modified Park-Ang Damage Index

$$DI = \frac{\delta_{max}}{\delta_u} + \beta \frac{E_h}{F_y.\delta_u}$$

After 100% of the ground motion

Actual Damage State

- Column 1 (Japan) → DI = 0.46 +0.87 = 1.33 → Exposed reinforcement
- Column 2 (Chile) → DI = 0.54 +0.46 = 1.00 → Exposed reinforcement
- Column 3 (Short) → DI = 0.40 +0.15 = 0.55 → Extensive Spalling



Preliminary Conclusions

- **Ground motion duration has a significant effect on the collapse capacity of bridge columns.**

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Preliminary Conclusions

- Ground motion duration has a significant effect on the collapse capacity of bridge columns.
- Reduction in the displacement capacity of about 50% is observed in case of long duration motions compared to the short duration ones.
- A significant reduction in the response spectrum at collapse (about 40%) of long duration motions with respect to short duration ones.
- Seismic design provisions are recommended take the effect of ground motion duration into account, not only design response spectra.

Preliminary Conclusions

- **Ground motion duration has a significant effect on the collapse capacity of bridge columns.**
- **Reduction in the displacement capacity of about 50% is observed in case of long duration motions compared to the short duration ones.**
- **A significant reduction in the response spectrum at collapse (about 40%) of long duration motions with respect to short duration ones.**
- **Seismic design provisions are recommended take the effect of ground motion duration into account, not only design response spectra.**
- **Ground motion duration is an important parameter when selecting ground motions for nonlinear analysis of structures.**

Tohoku, Japan 2011

Thank you

Questions ?

Modified Park-Ang Damage Index

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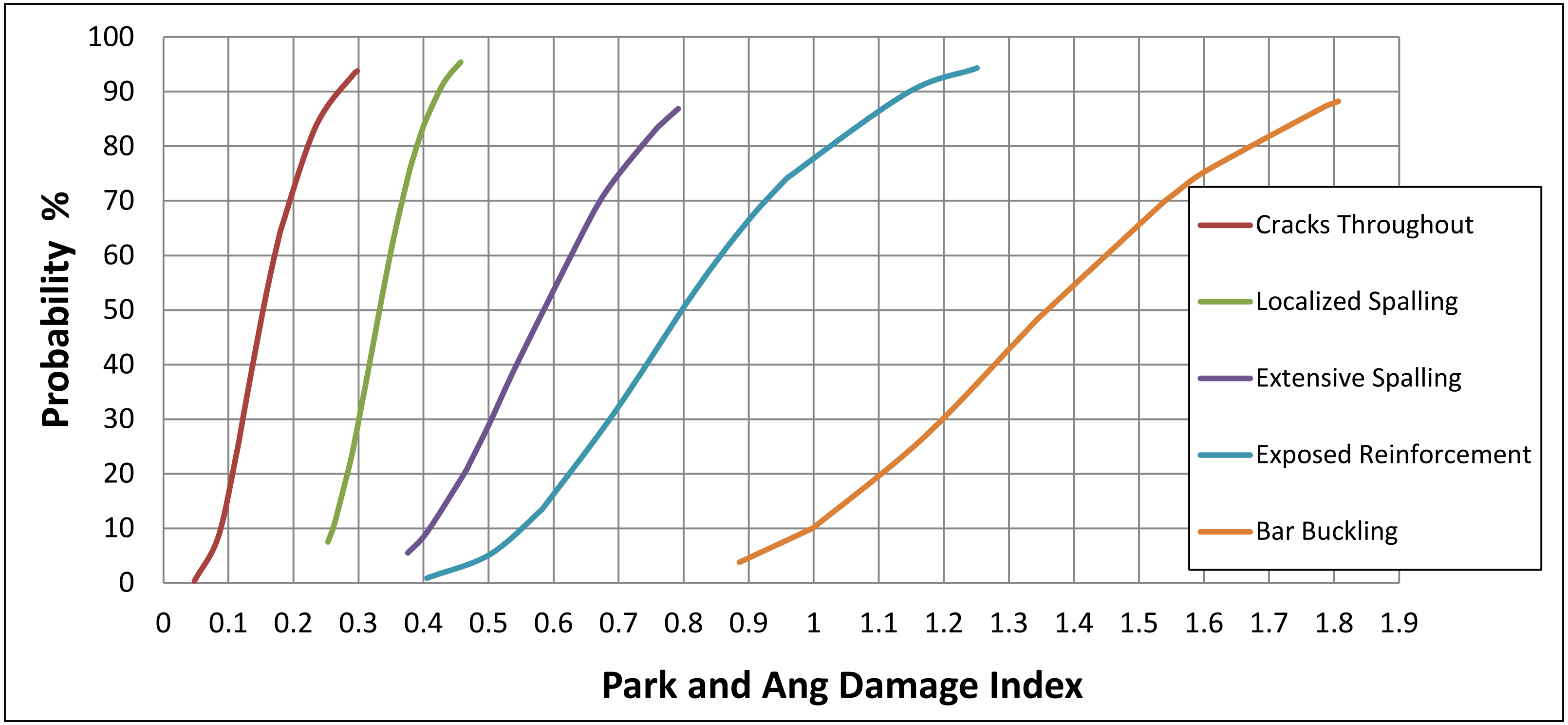
$$DI = \frac{\delta_{max}}{\delta_u} + \beta \frac{E_h}{F_y . \delta_u}$$

- Data used from past shake-table and cyclic load tests on seismically designed bridge columns (around 25 models) to correlate the damage index with different damage states.



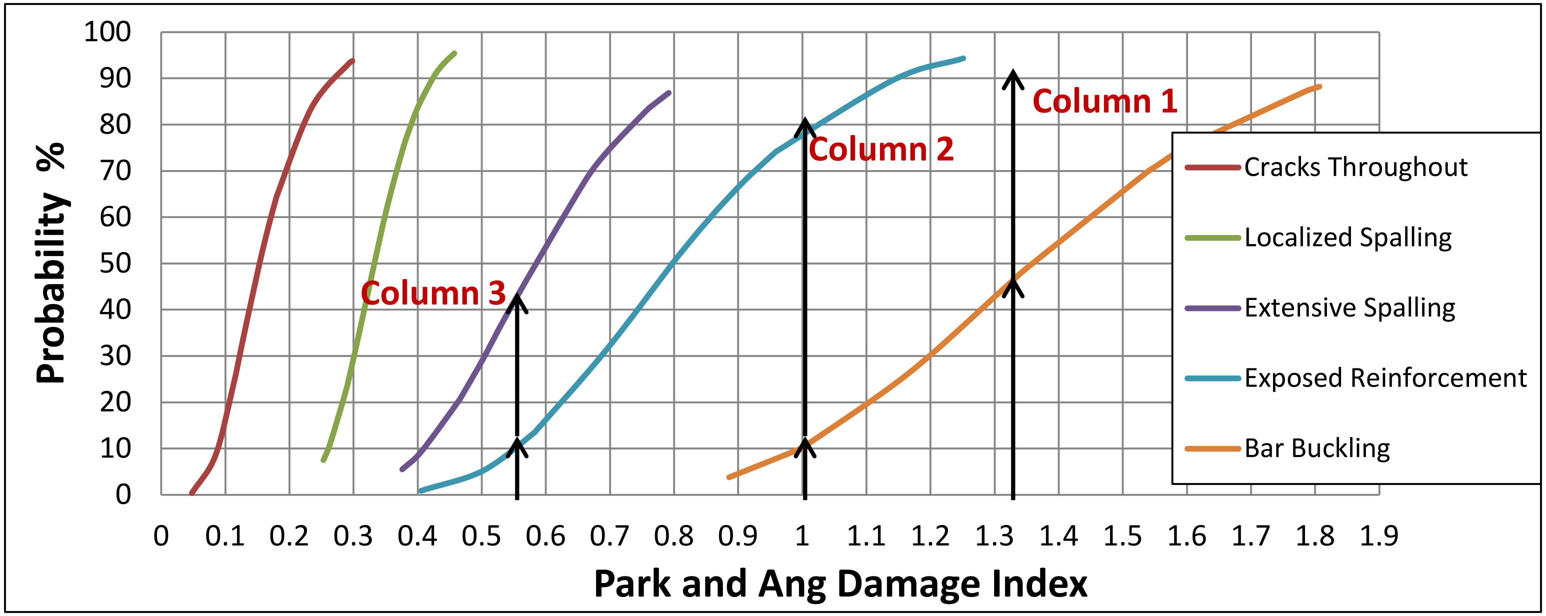
Modified Park-Ang Damage Index

$$DI = \frac{\delta_{max}}{\delta_u} + \beta \frac{E_h}{F_y . \delta_u}$$

Actual Damage State

After 100% of the ground motion

- Column 1 (Japan) → DI = 0.46 +0.87 = 1.33 → Exposed reinforcement
- Column 2 (Chile) → DI = 0.54 +0.46 = 1.00 → Exposed reinforcement
- Column 3 (Short) → DI = 0.40 +0.15 = 0.55 → Extensive Spalling



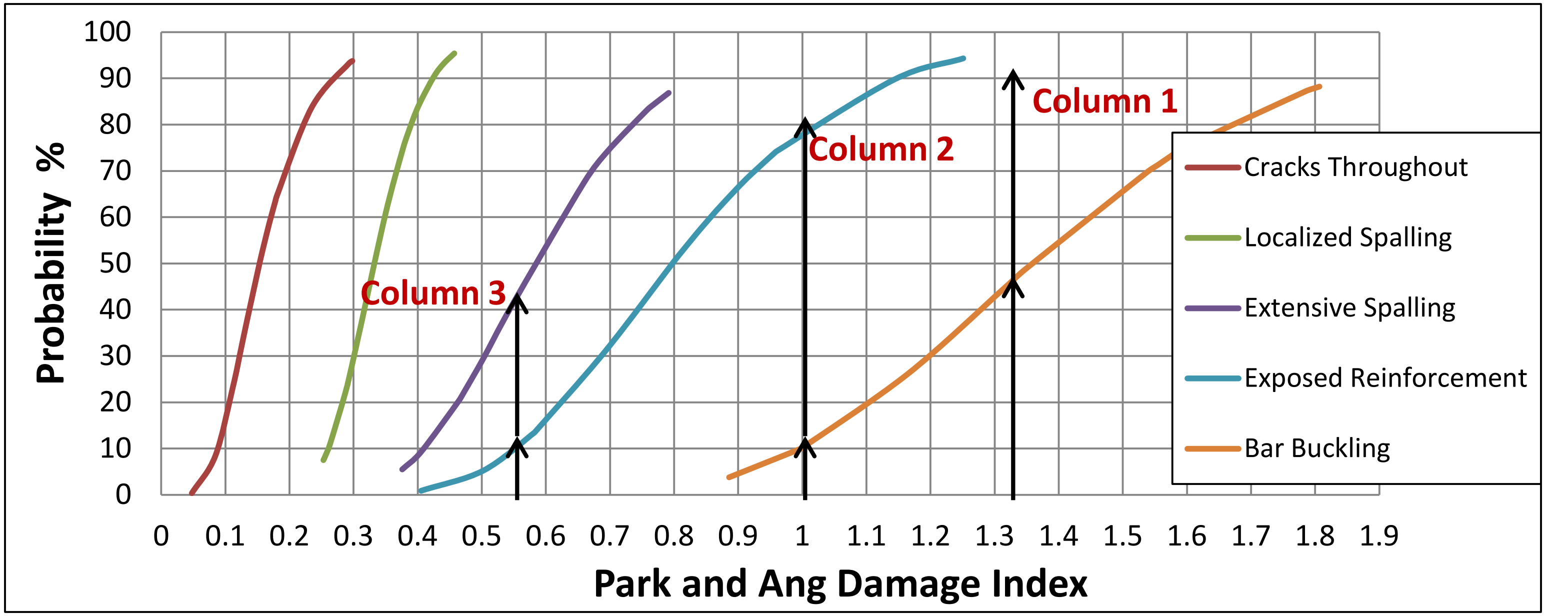
Modified Park-Ang Damage Index

$$DI = \frac{\delta_{max}}{\delta_u} + \beta \frac{E_h}{F_y . \delta_u}$$

Actual Damage State

After 100% of the ground motion

- **Column 1 (Japan)** ➡ DI = 0.46 +0.87 = 1.33 ➡ **Exposed reinforcement**
- **Column 2 (Short)** ➡ DI = 0.40 +0.15 = 0.55 ➡ **Extensive Spalling**



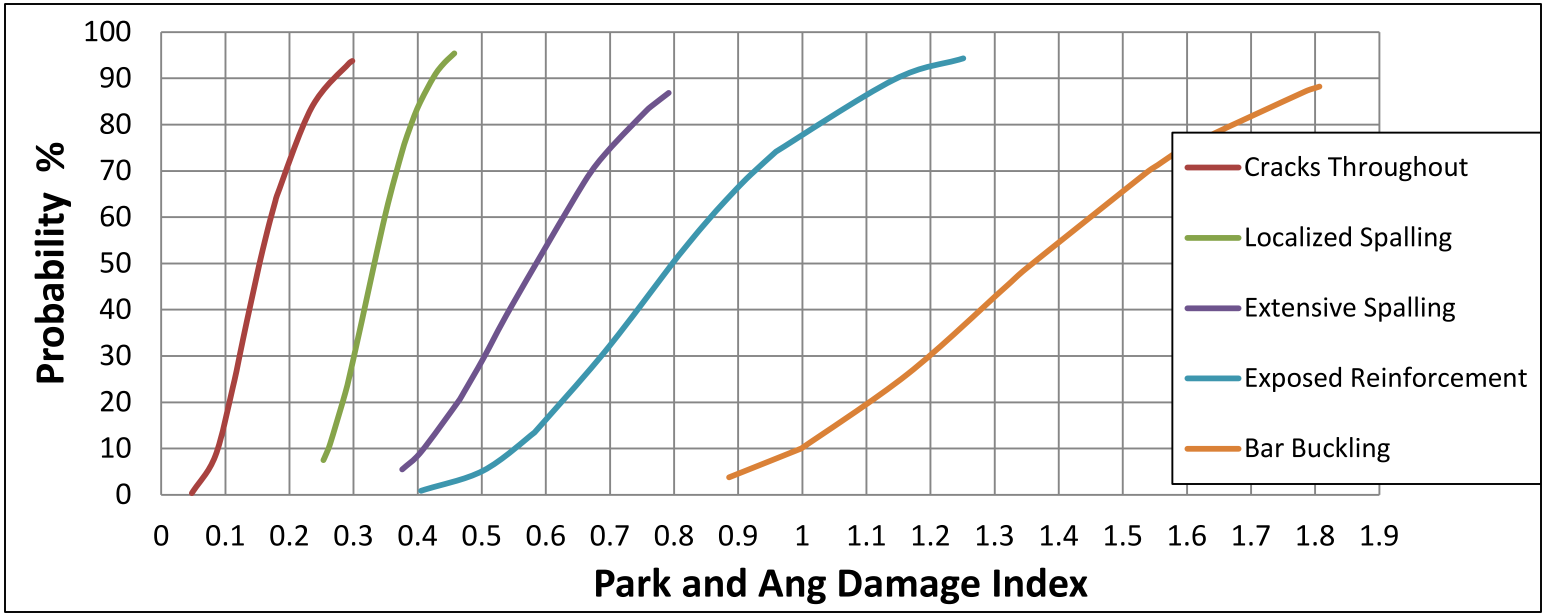
Modified Park-Ang Damage Index

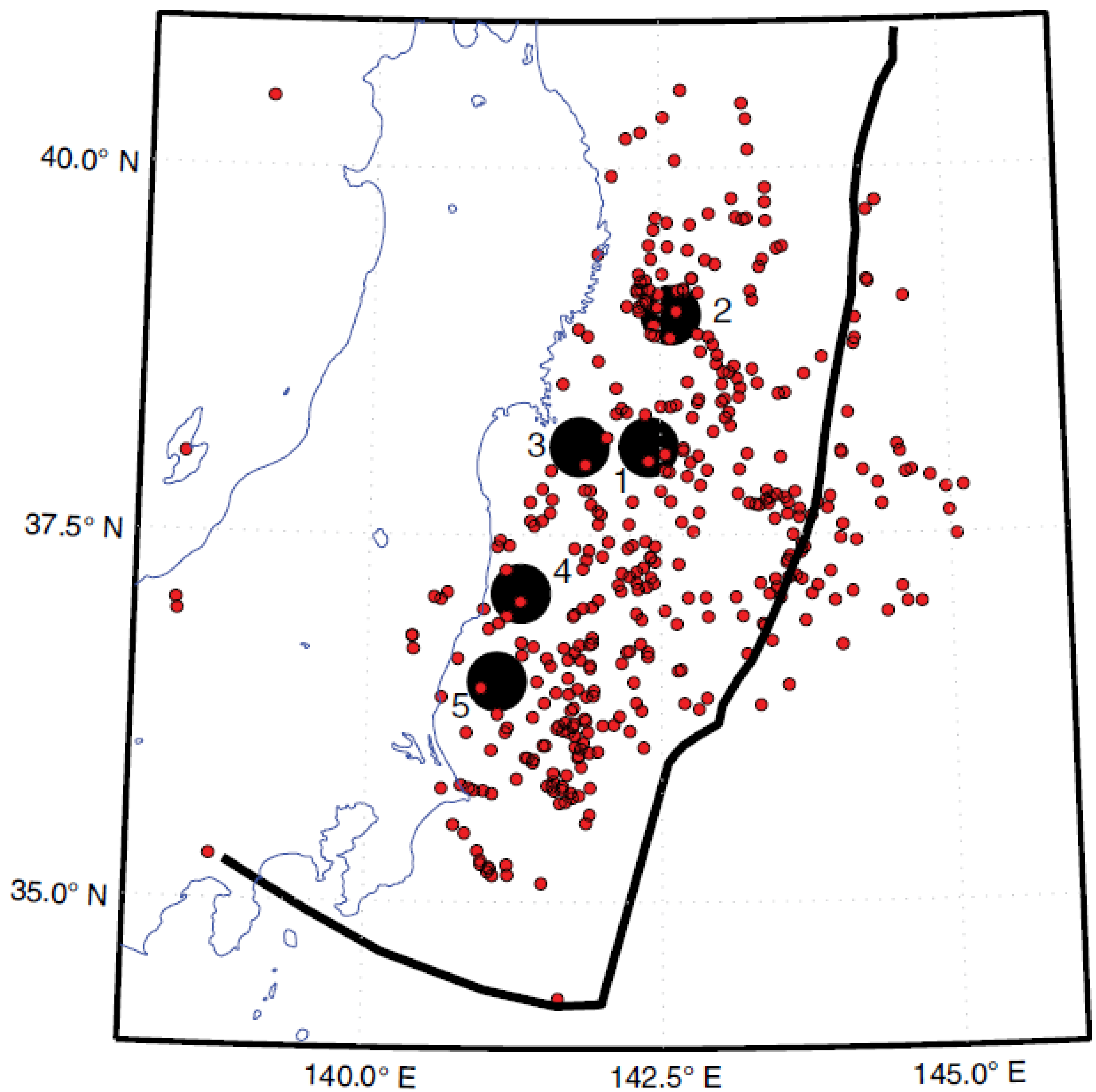
$$DI = \frac{\delta_{max}}{\delta_u} + \beta \frac{E_h}{F_y . \delta_u}$$

Actual Damage State

At the final damage state (bar fracture)

- **Column 1 (Japan)** → **DI = 0.51 +1.94 = 2.45** → **Bar Fracture**
- **Column 3 (Short)** → **DI = 0.98 +1.32 = 2.30** → **Bar Fracture**





40.0° N
37.5° N
35.0° N
140.0° E
142.5° E
145.0° E
1
2
3
4
5