Earthquake Duration Effect on Collapse Capacity of Reinforced Concrete Bridge Columns

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Problem Statement and Objectives

Why Long Duration ?

- **Chile (2015, 2014 and 2010), Japan (2011), China (2008), and Indonesia (2004) earthquakes are reminders of the importance of the effect of ground motion duration on structural response.**

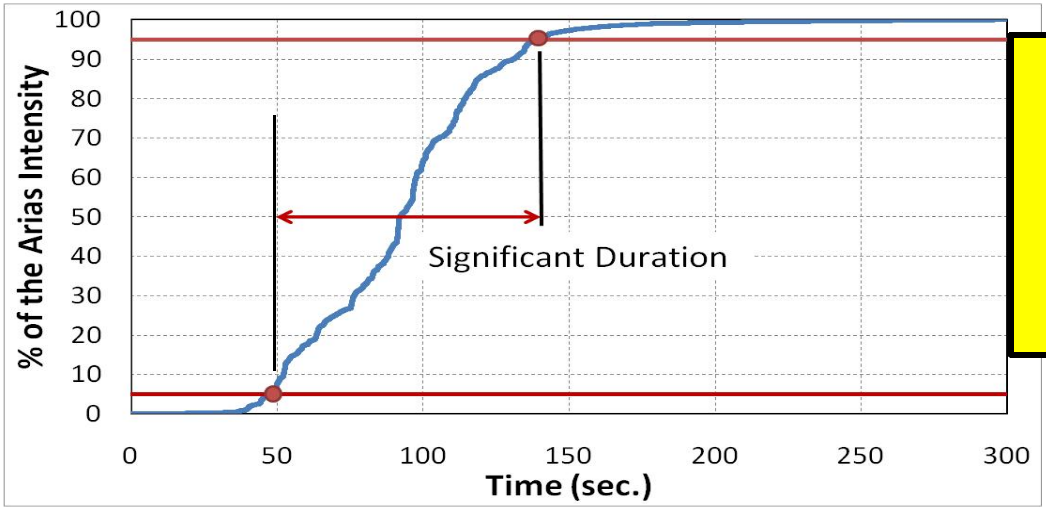
- **Chile Earthquake** ⇨ **Ruptured over ~ 500 km**
  Duration ~ 20-90 seconds

- **Tohoku Earthquake** ⇨ **Fault size ~ 500 km x 210 km**
  Duration ~ 90-270 seconds

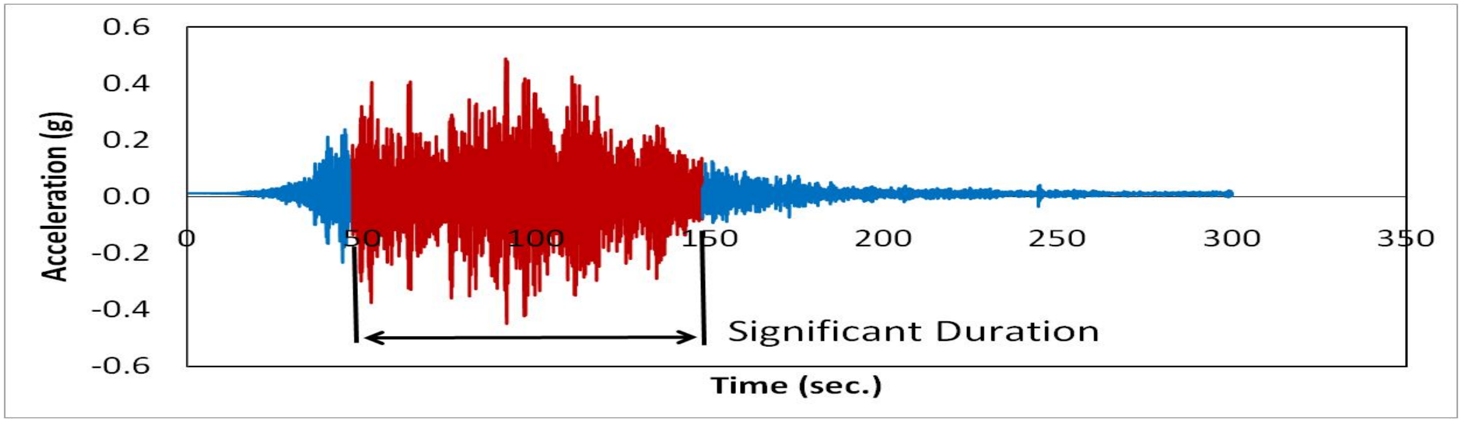
- **California** ⇨ **Earthquakes typically last less than 30 seconds**

Ground Motion Duration Definitions

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



Recommended by Jack Baker and Greg Deierlein (2012)



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 .**

- **The CASCADIA SUBDUCTION ZONE is about twice the length of the Tohoku fault and is also closer to the coastal region, so we if it ruptured over the whole length, the motions could be even stronger than what was recorded during the Tohoku earthquake.**

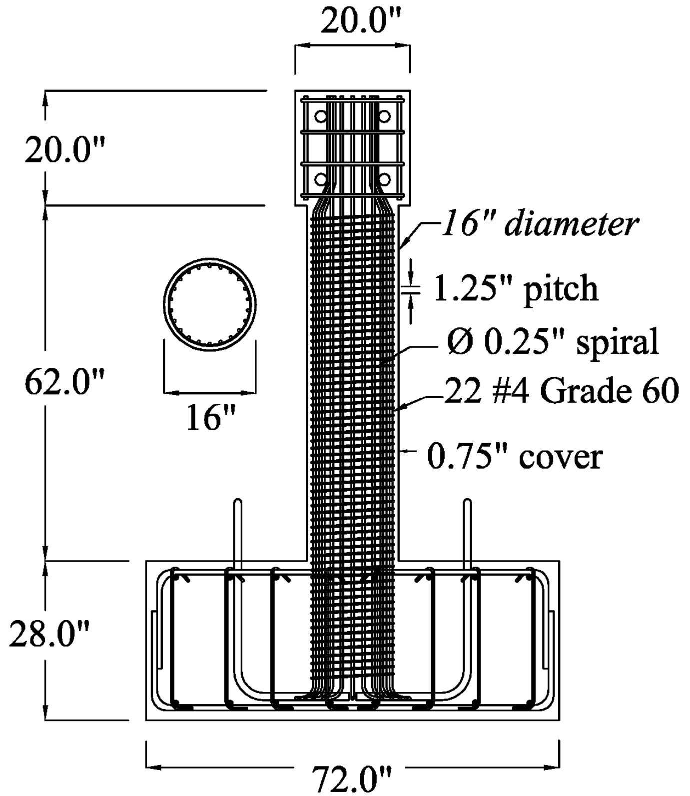
Specimen Design and Pre-test Analysis

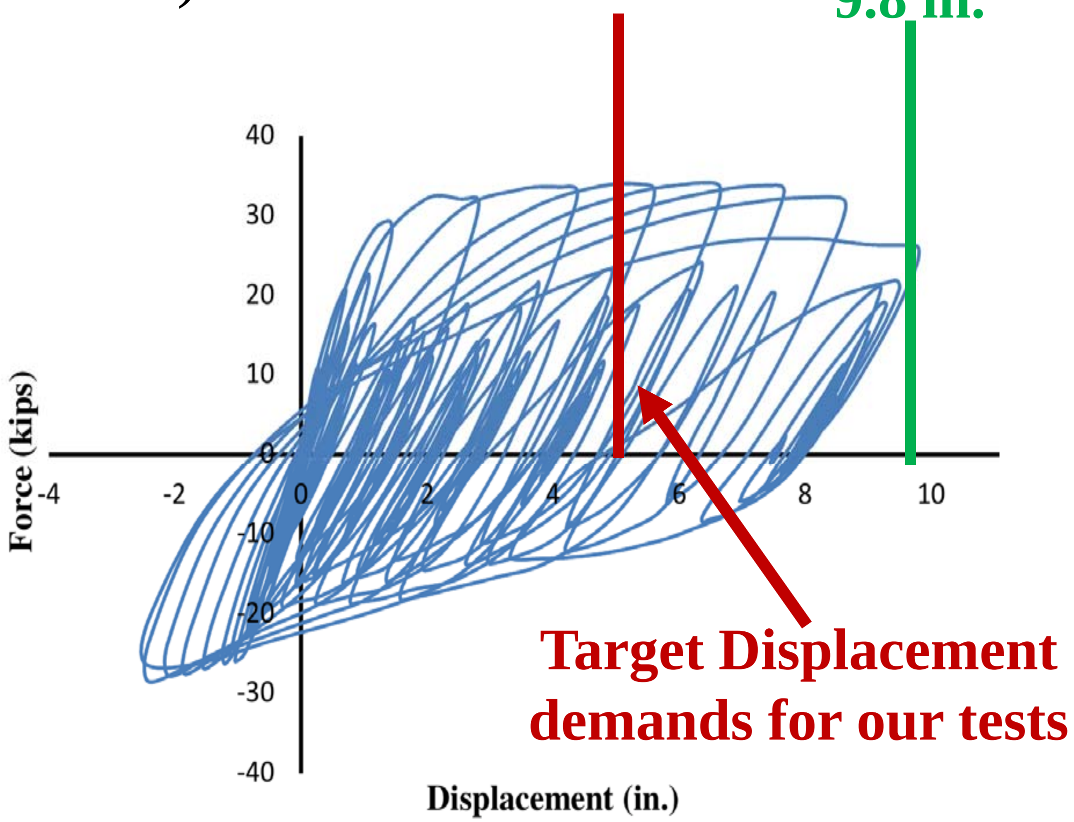
Vu and Saiidi (2005)
Rinaldi -1/3 scale

- **Design Code: AASHTO**
- **L/D= 4.5 (flexural control)**

WHY ?

we can know the maximum displacement capacity of the columns before testing. (which was **9.8 in.**)



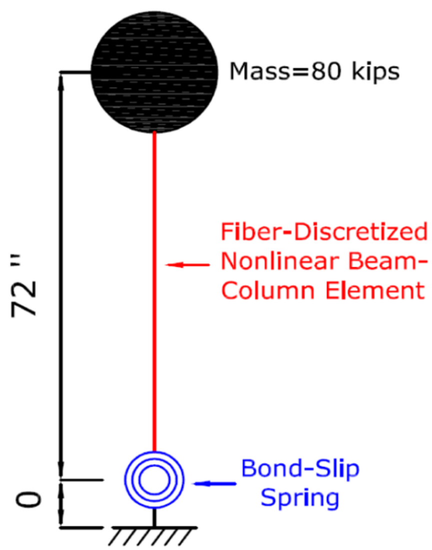


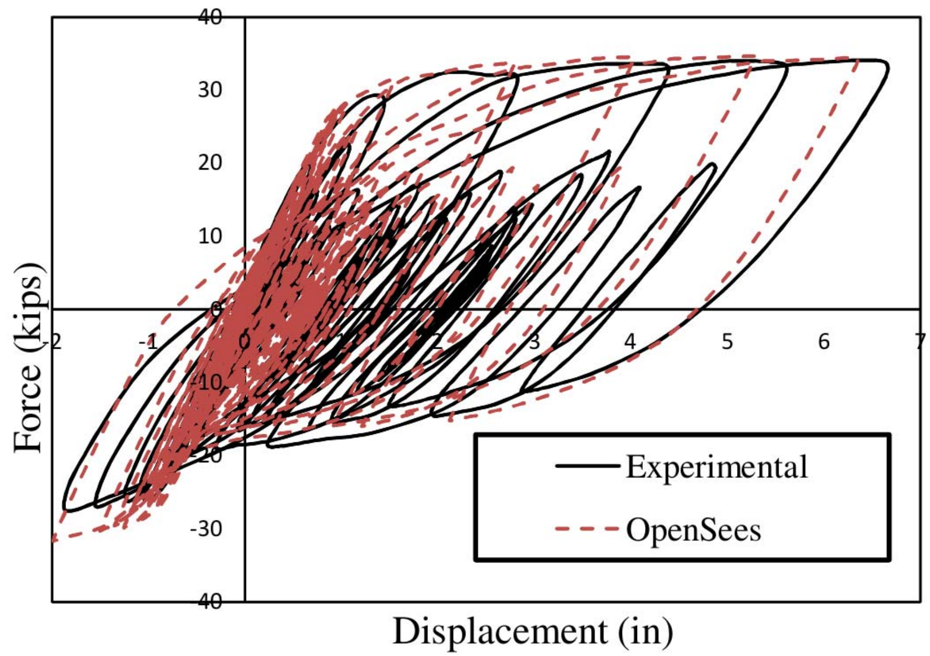
Specimen Design and Pre-test Analysis

- A simple OpenSees model was used to simulate Vu and Saiidi's Column

-The selection of the motions was based on this model (the displacement demands to be around half the capacity)

-80 long-duration ground motions from Japan 2011 and Chile 2010 were used in the pre-test analysis





Specimen Design and Pre-test Analysis

Damage Prediction Before Testing

Modified **Park-Ang damage index** was used to quantify the damage

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

- 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 = Yield force

Specimen Design and Pre-test Analysis

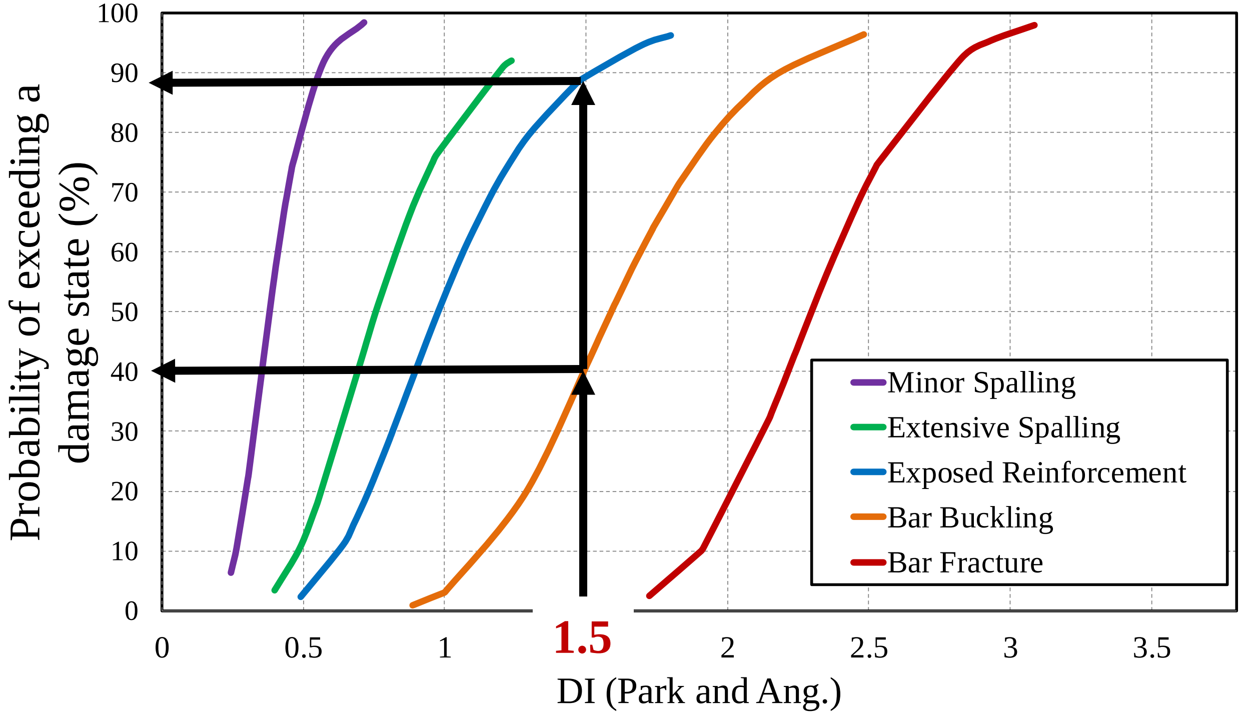
Damage Prediction Before Testing

Modified **Park-Ang damage index** was used to quantify the damage

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

→ **Experimental Fragility Curves**

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



-Example:

Run #, DI=1.5

40% Bar Buckling

90% Exposed RFT.

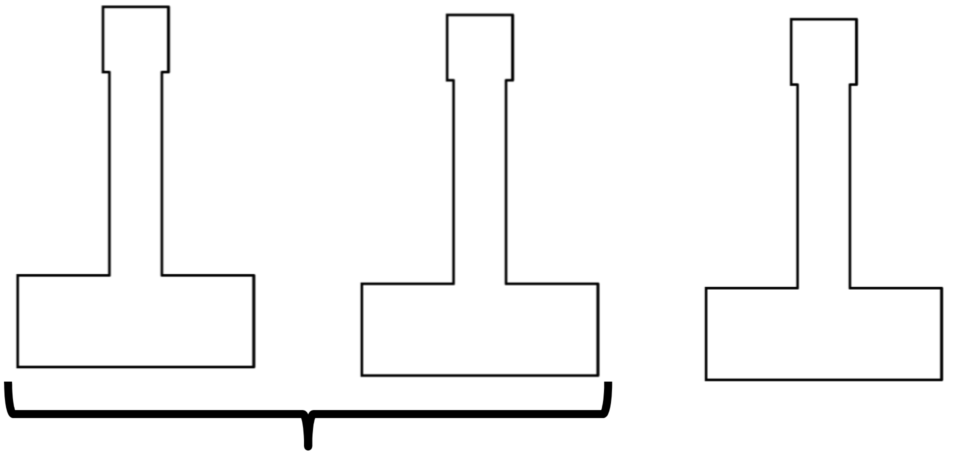
0% Bar Fracture

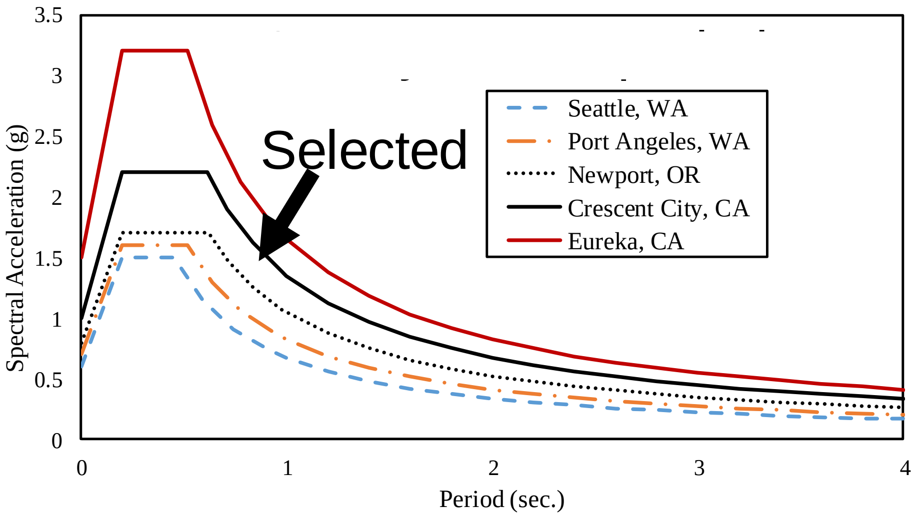
Shake Table Tests

Japan
Long-dur.

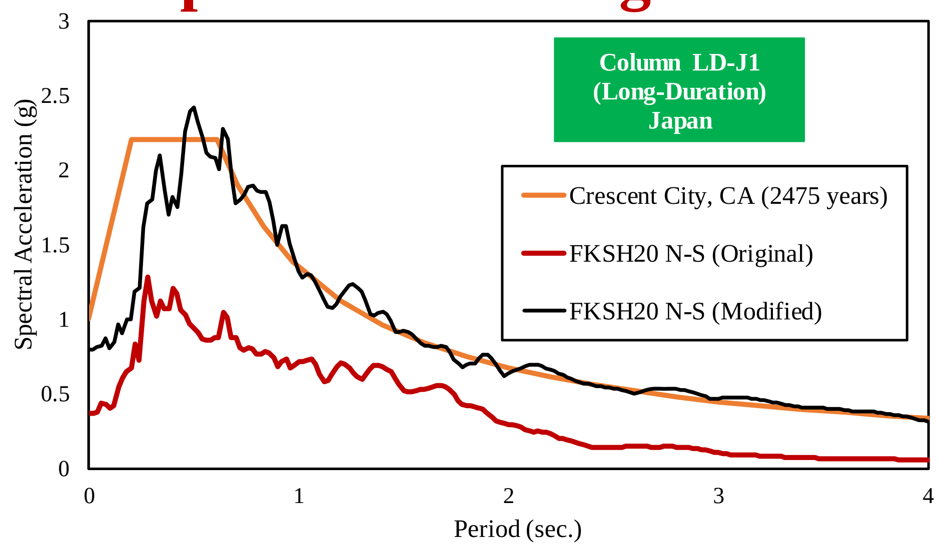
Loma Prieta
Short-dur.

Japan
Long-dur.



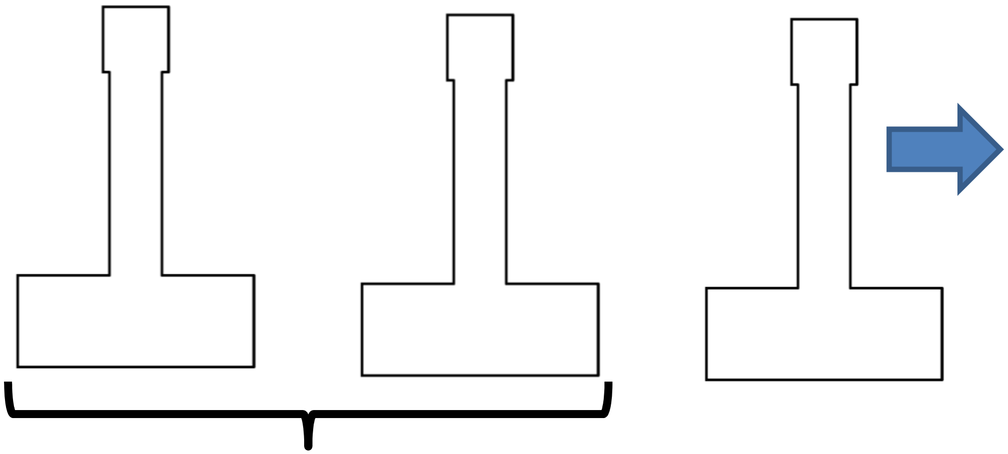


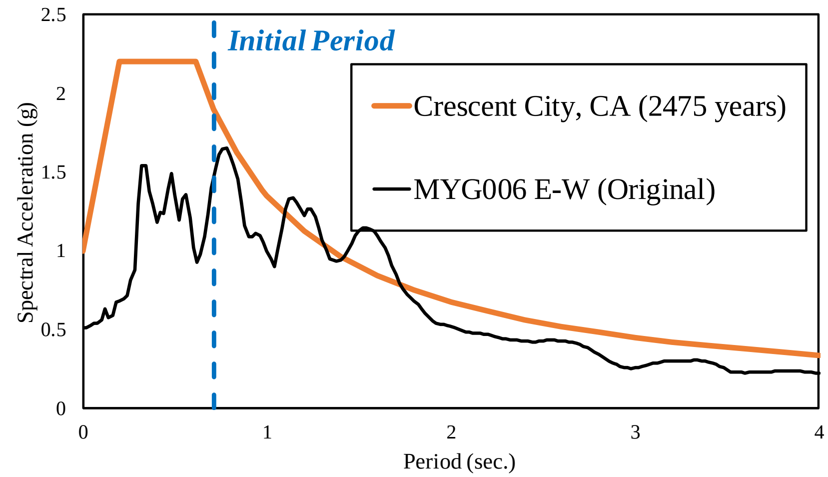
Spectral Matching

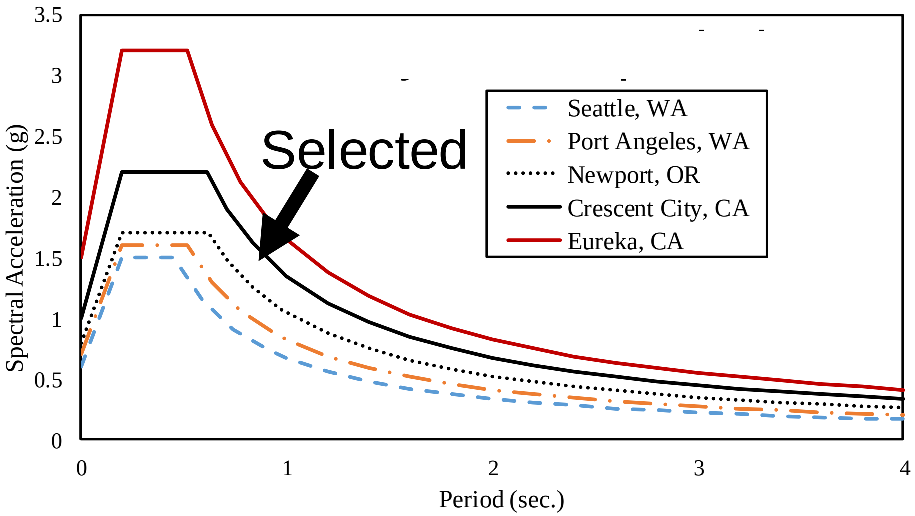


Shake Table Tests

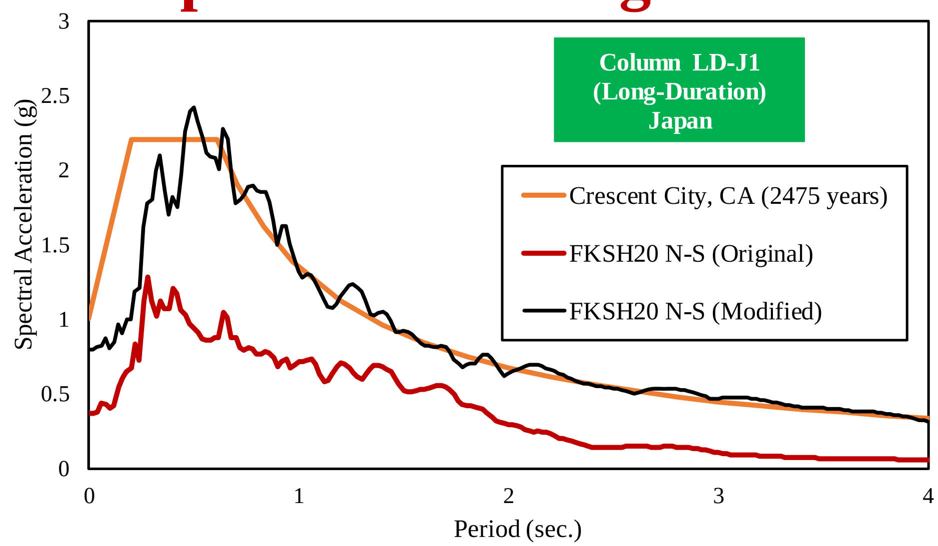
Japan **Long-dur.** | **Loma Prieta** **Short-dur.** | **Japan** **Long-dur.**



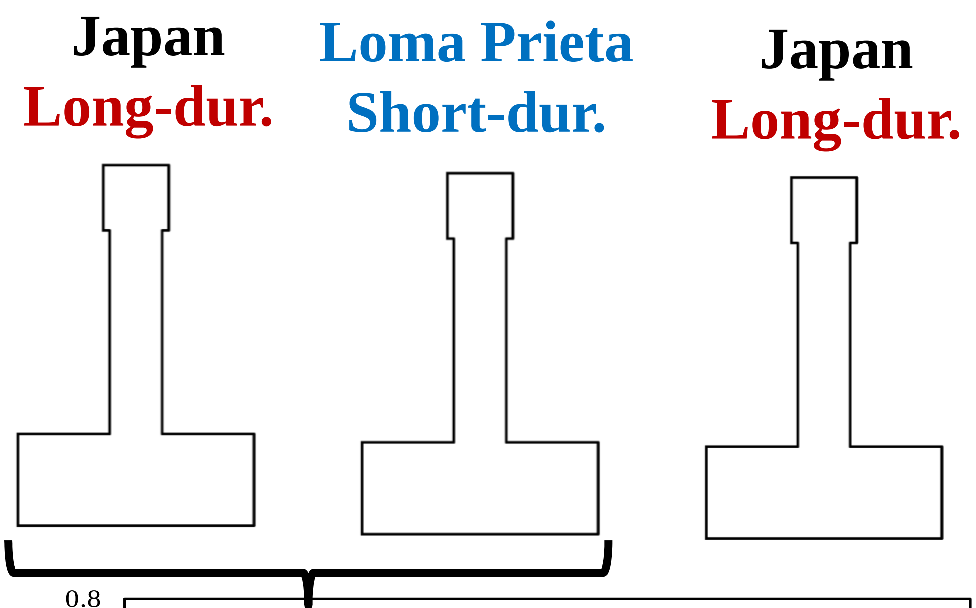


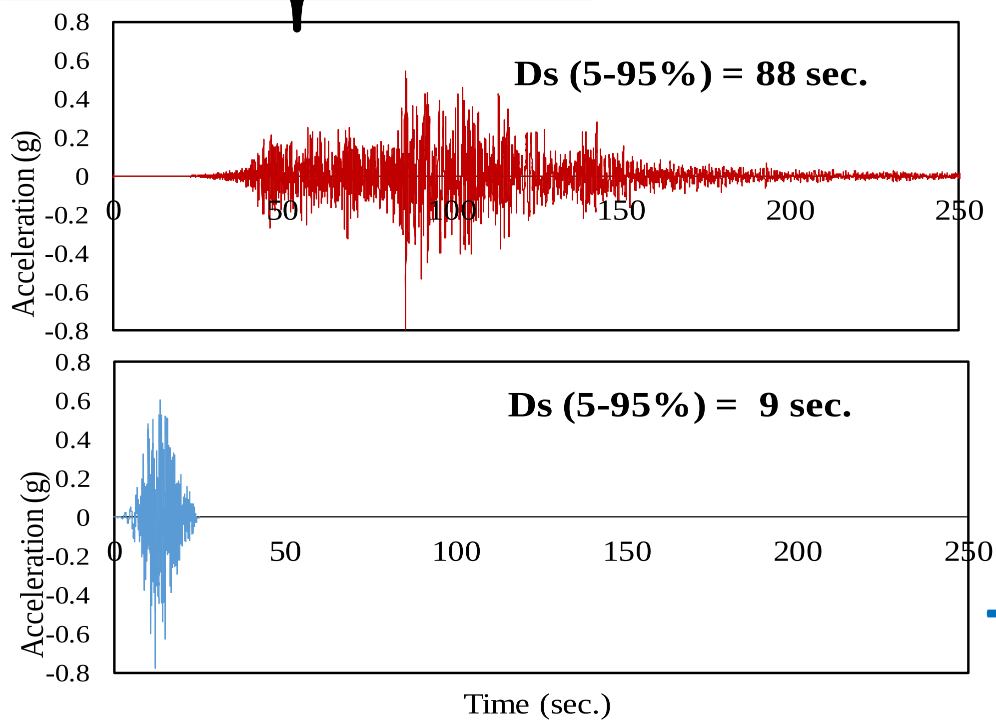


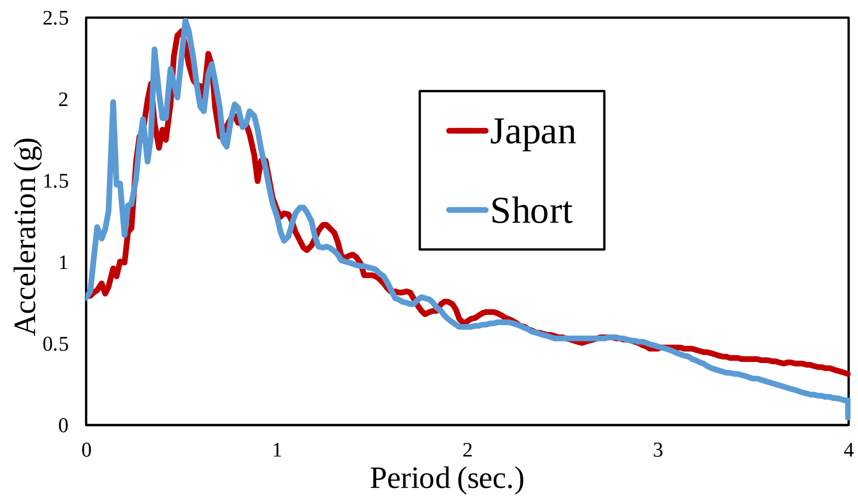
Spectral Matching



Shake Table Tests



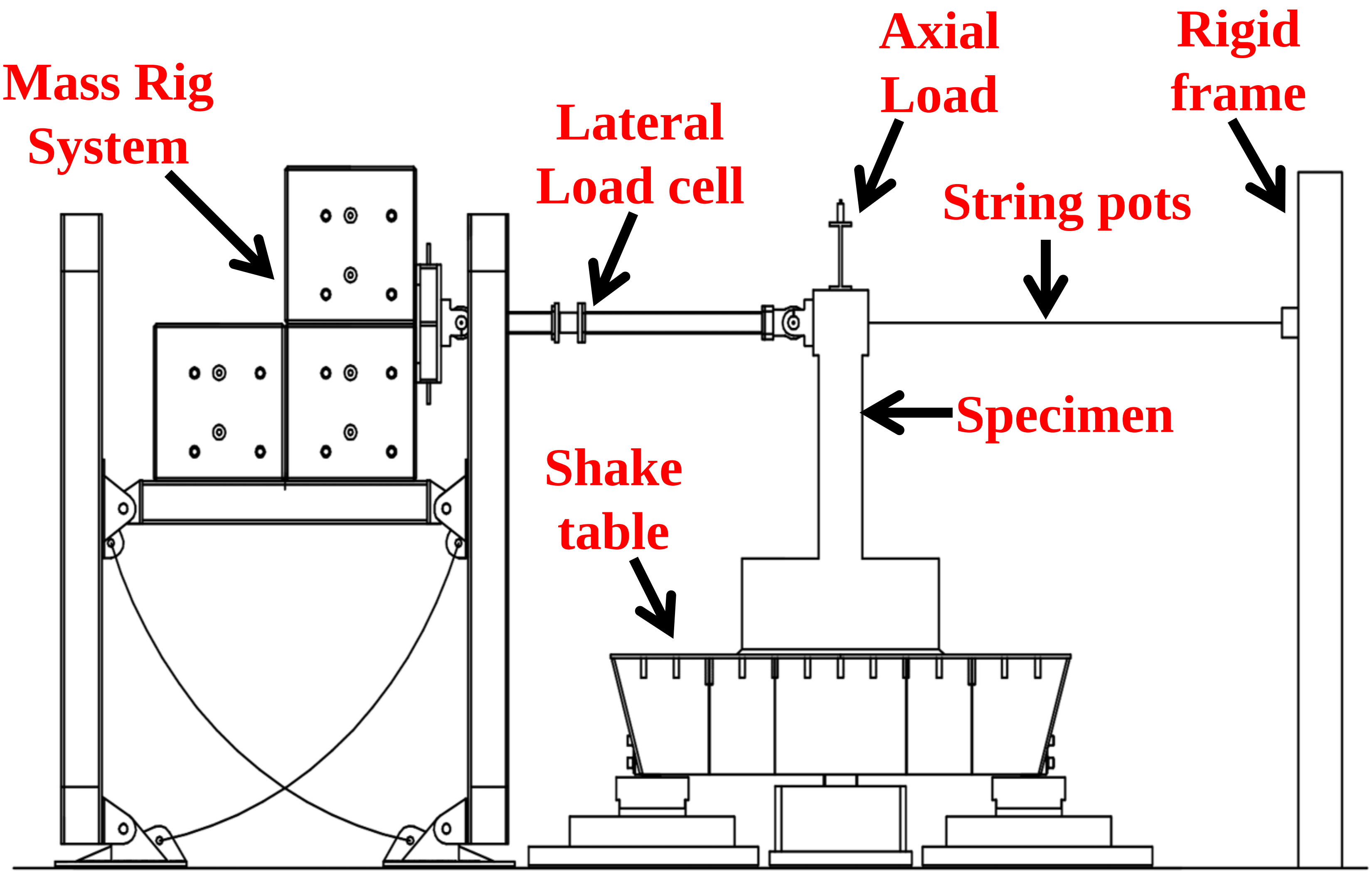




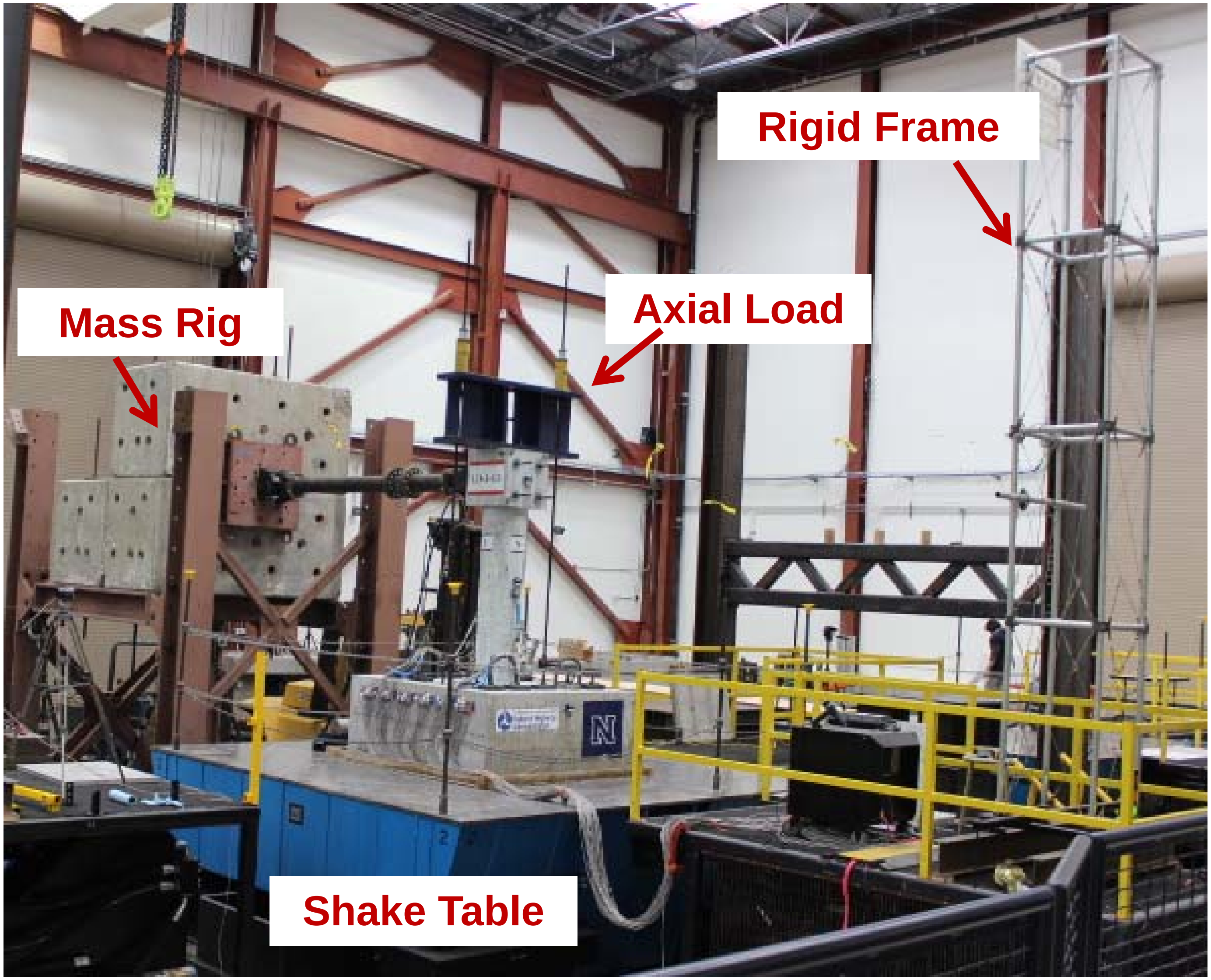
Design codes→

These motions are the same

Test Setup


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

Test Setup



Loading Protocol

100% of GM

+

AfterShock

+

125% of GM

+

150% of GM

+

etc… (Until Failure)

Test Results

100 % of the Ground Motion

Column 1 (Japan- Long Dur.)

Max. Disp.= 4.5”

South

- 4.4” spalling
- Spirals Exposed

North

- 3.0” spalling
- Spirals Exposed

Column 2 (Short-duration)

Max. Disp.= 3.88”

South

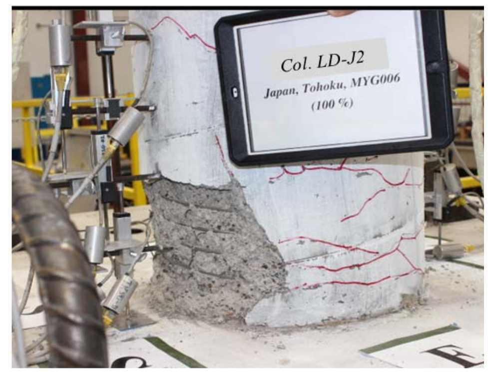
- Cracks (max width= 0.4mm)

North

- 4.5” spalling
- No RFT. Exposed

Column 3 (Japan – Long Dur.)

Max. Disp.= 4.7”



South

- 7.5” spalling
- Spirals Exposed

North

- Minor spalling
- No RFT. Exposed

Test Results

125 % of the Ground Motion

Column 1 (Japan- Long Dur.)

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

Column 3 (Japan – Long Dur.)

Max. Disp.= 7.38”

South

- 8.0” spalling
- 3 Bars buckled

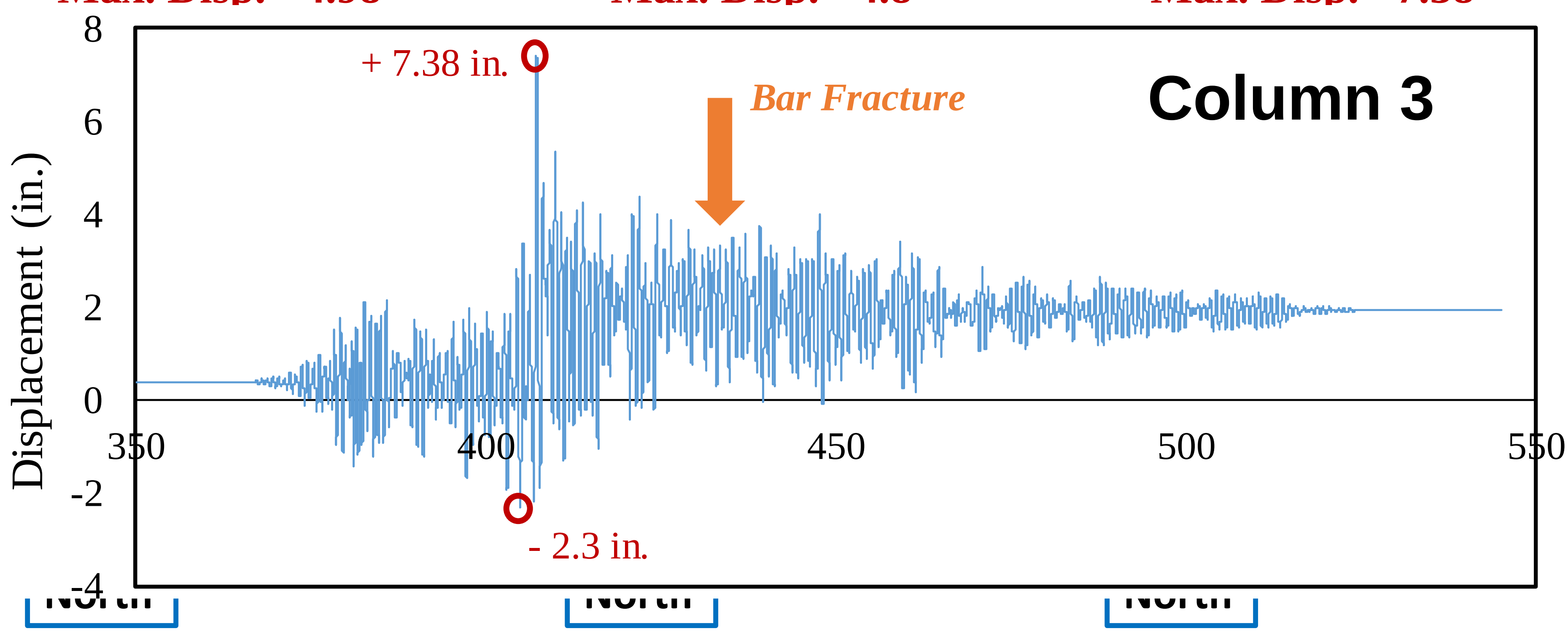
North

- 5” spalling
- 1 Bar fractured

Test Results

125 % of the Ground Motion

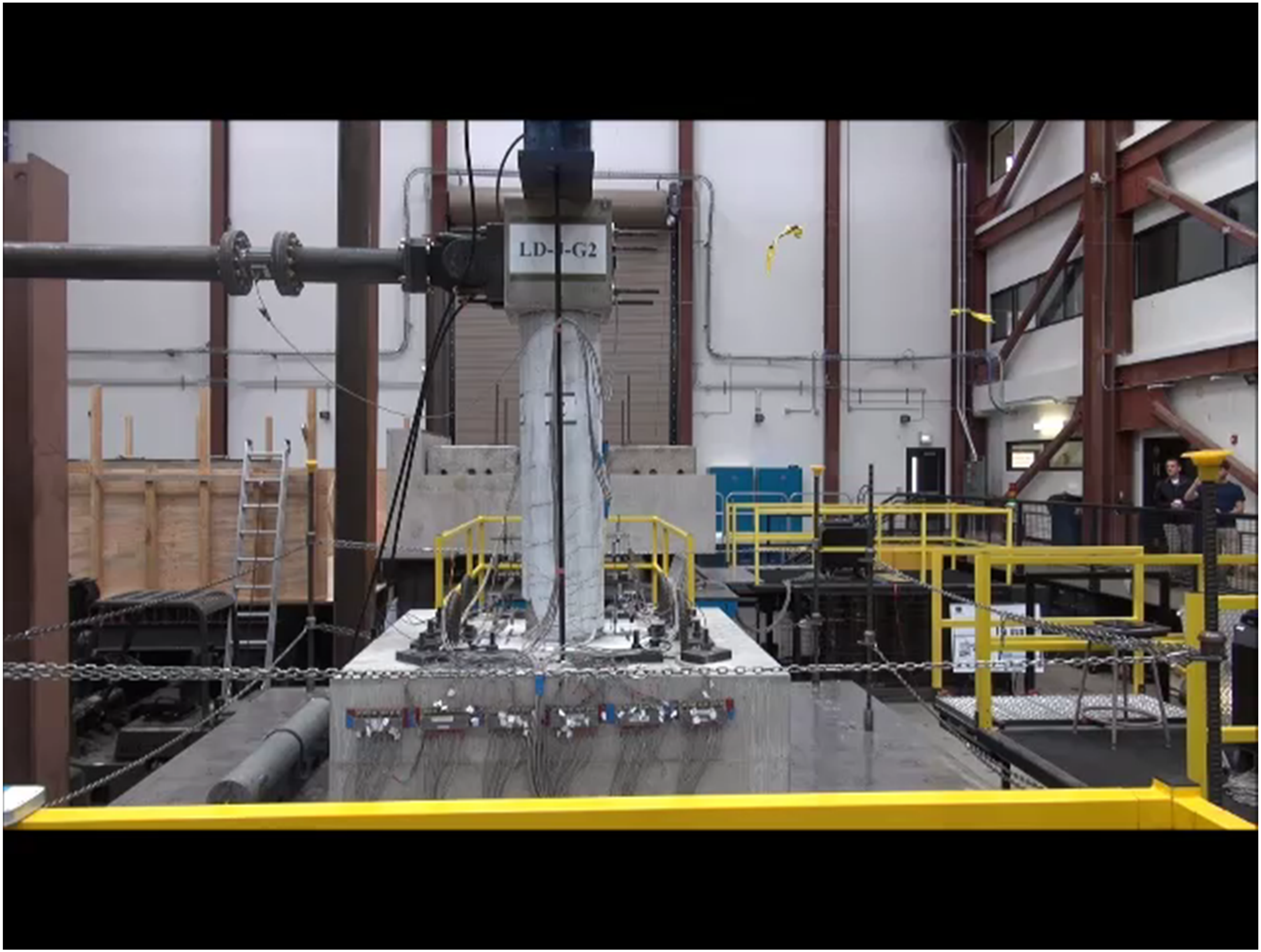
Column 1 (Japan- Long Dur.)	Column 2 (Short-duration)	Column 3 (Japan – Long Dur.)
Max. Disp.= 4.98”	Max. Disp.= 4.8”	Max. Disp.= 7.38”



- **6.4” spalling**
- **Core Damage**

- **4.5” spalling**
- **Spirals exposed**

- **5” spalling**
- **1 Bar fractured**



Test Results

150 % of the Ground Motion

Column 1 (Japan- Long Dur.)	Column 2 (Short-duration)	Column 4 (Japan – Long Dur.)
Max. Disp.= 4.98”	Max. Disp.= 7.3”	Max. Disp.= 7.38”

Column 1:

Not Applicable

Bars Fractured at 125%

Column 2:

South

- 9” spalling
- Spirals exposed

North

- 6” spalling
- Spirals exposed

Column 4:

Not Applicable

Bars Fractured at 125%

Test Results

175 % of the Ground Motion

Column 1 (Japan- Long Dur.)

Max. Disp.= 4.98”

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

Column 4 (Japan – Long Dur.)

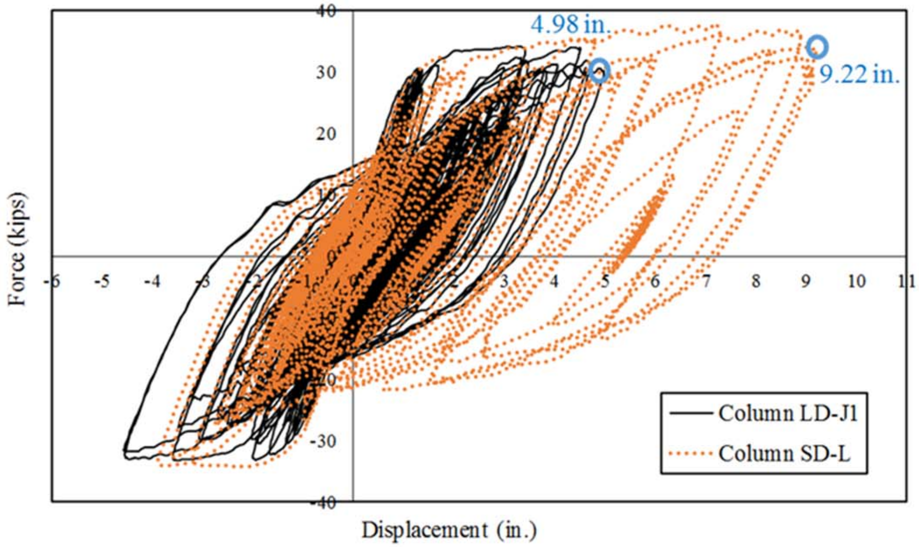
Max. Disp.= 7.38”

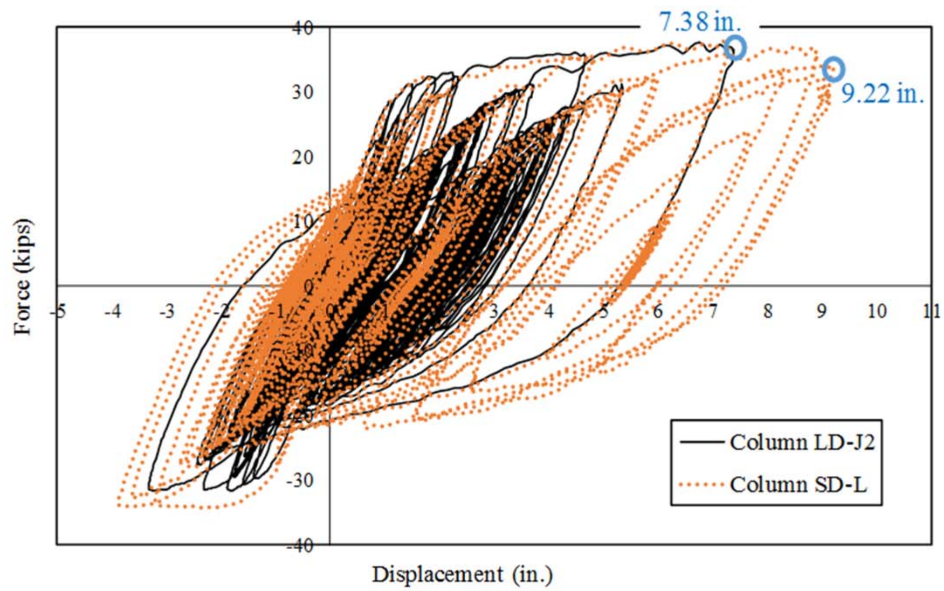
Not Applicable

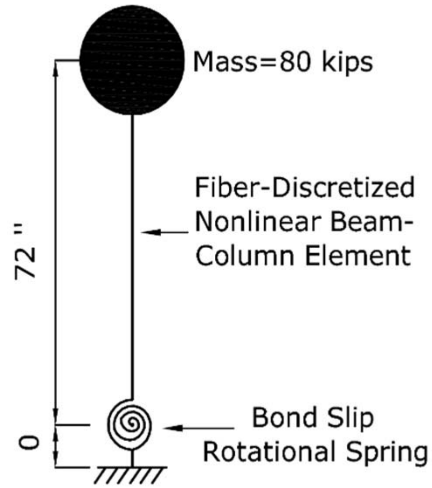
Bars Fractured at 125%

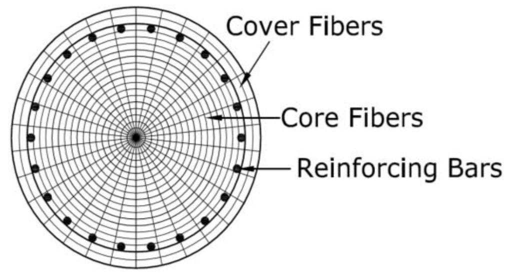
Test Results

Force-Displacement







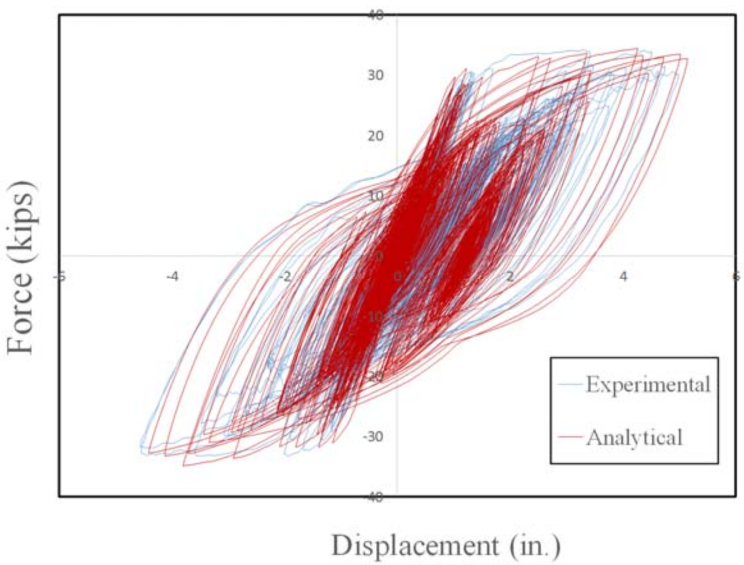


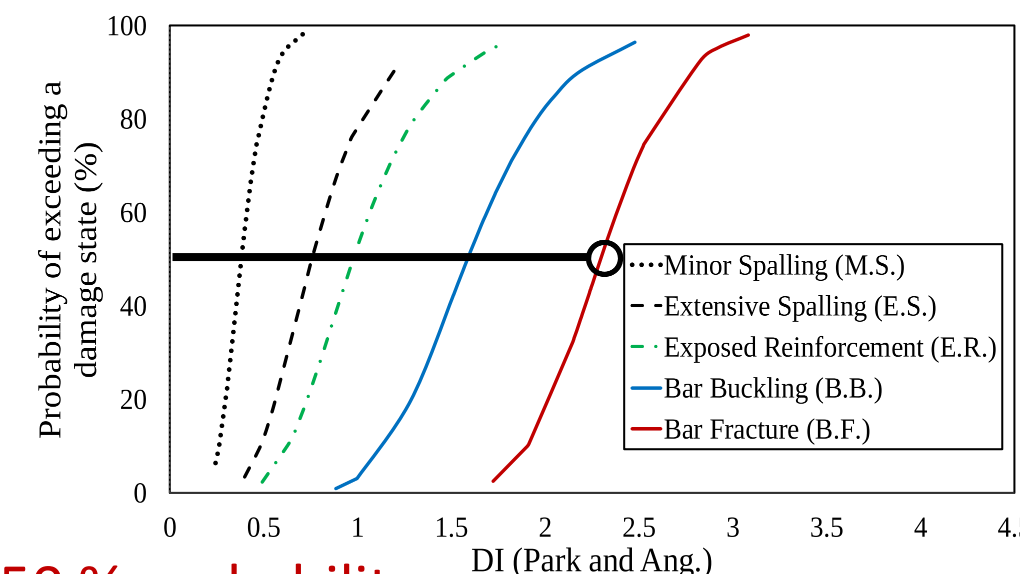
Fiber Cross Section

-Concrete01 with STC

-Steel02

-Wehbe's method for bond slip

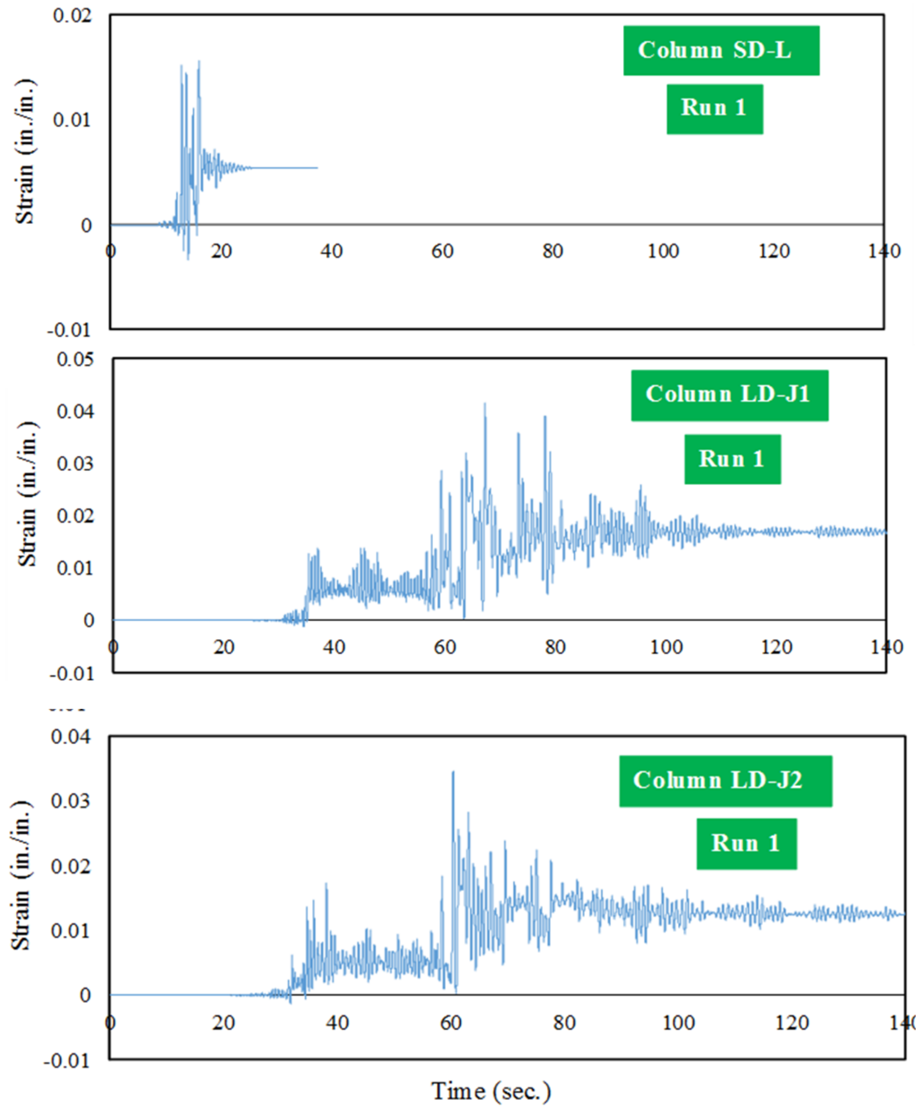




50 % probability

Test Results

Strain History



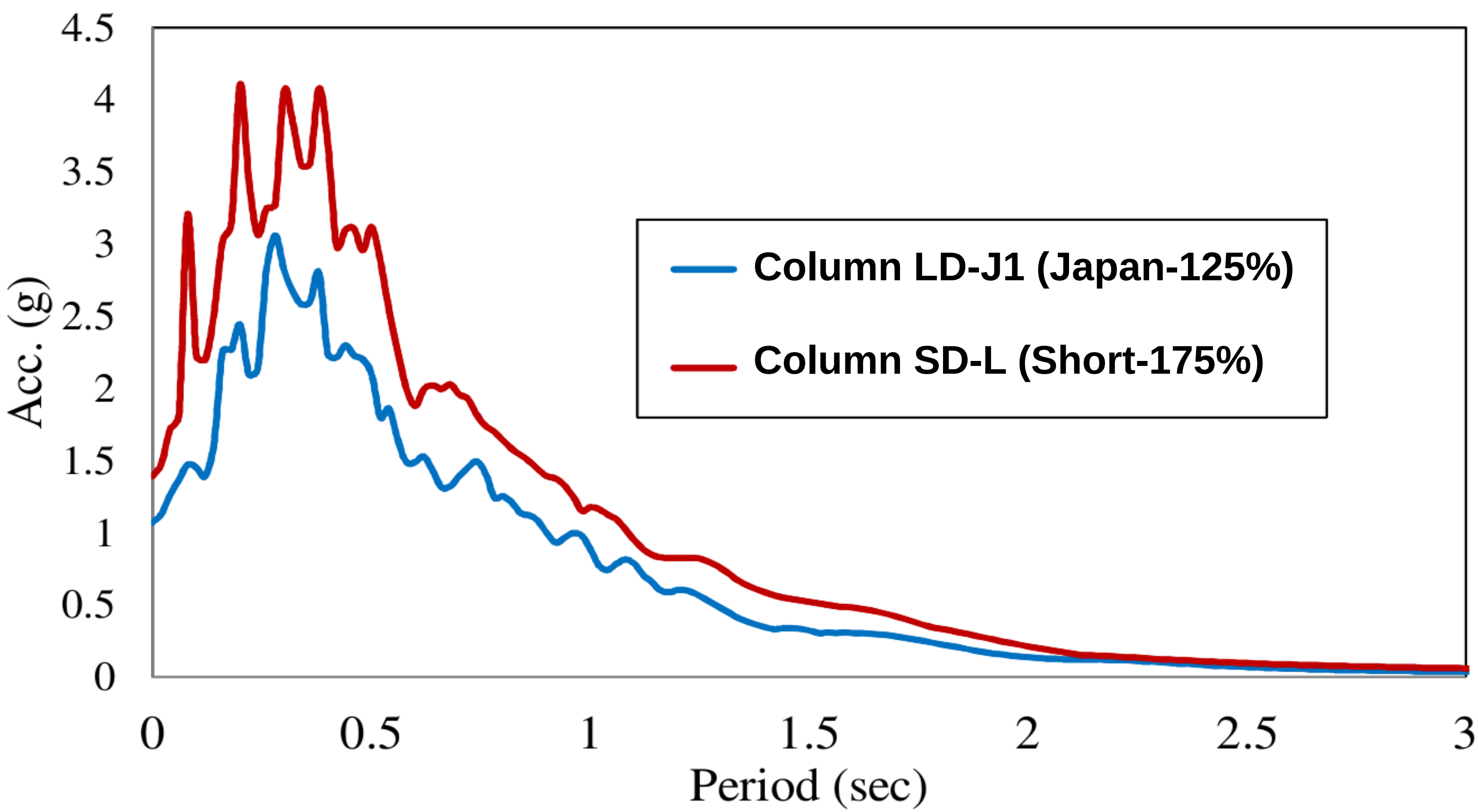
Short-Duration

Long-Duration (Japan-1)

Long-Duration (Japan 2)

Test Results

Spectral Accelerations at final damage state

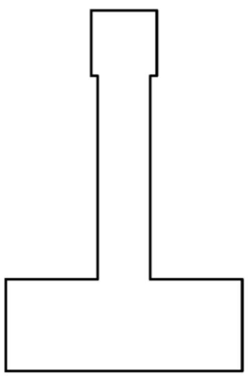


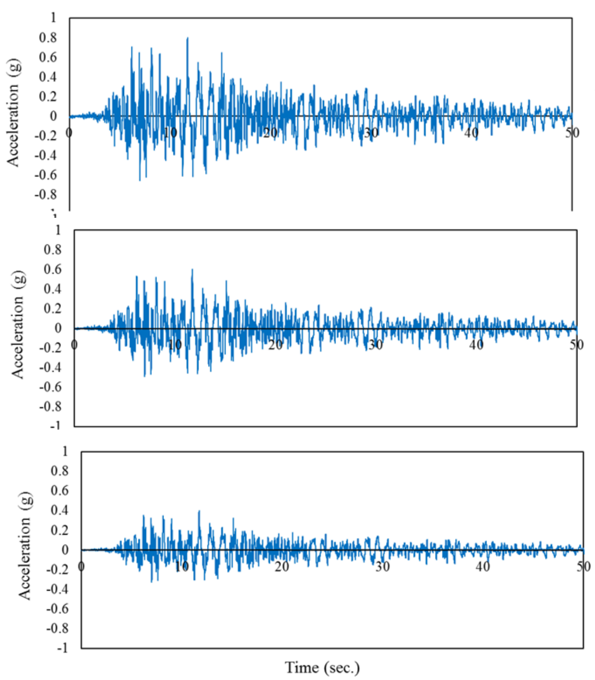
Post-Test Analysis

OpenSees Models

Ground Motions Used

Incremental Dynamic Analysis (IDA)





Scale the motions until collapse

112 motions per set

X

3 Sets

X

2 OpenSees models

=

672

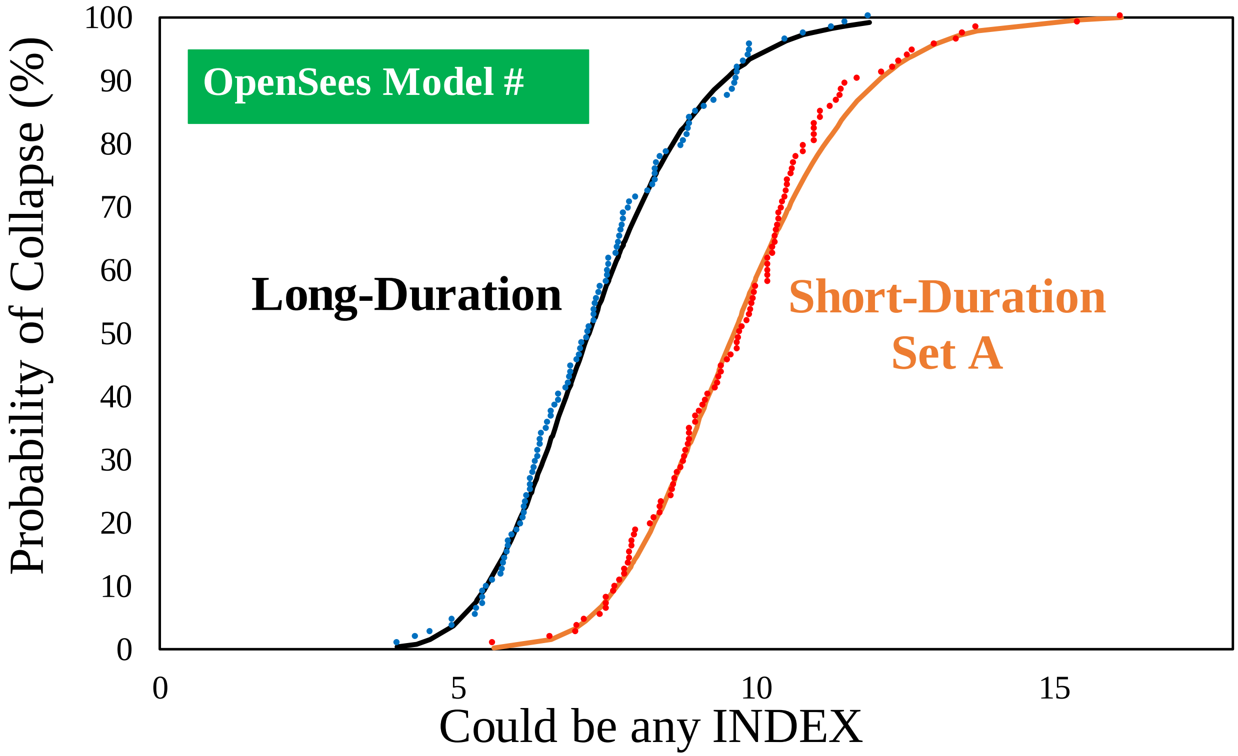
Total motions that were scaled until collapse

Post-Test Analysis

OpenSees Models

Ground Motions Used

Incremental Dynamic Analysis (IDA)



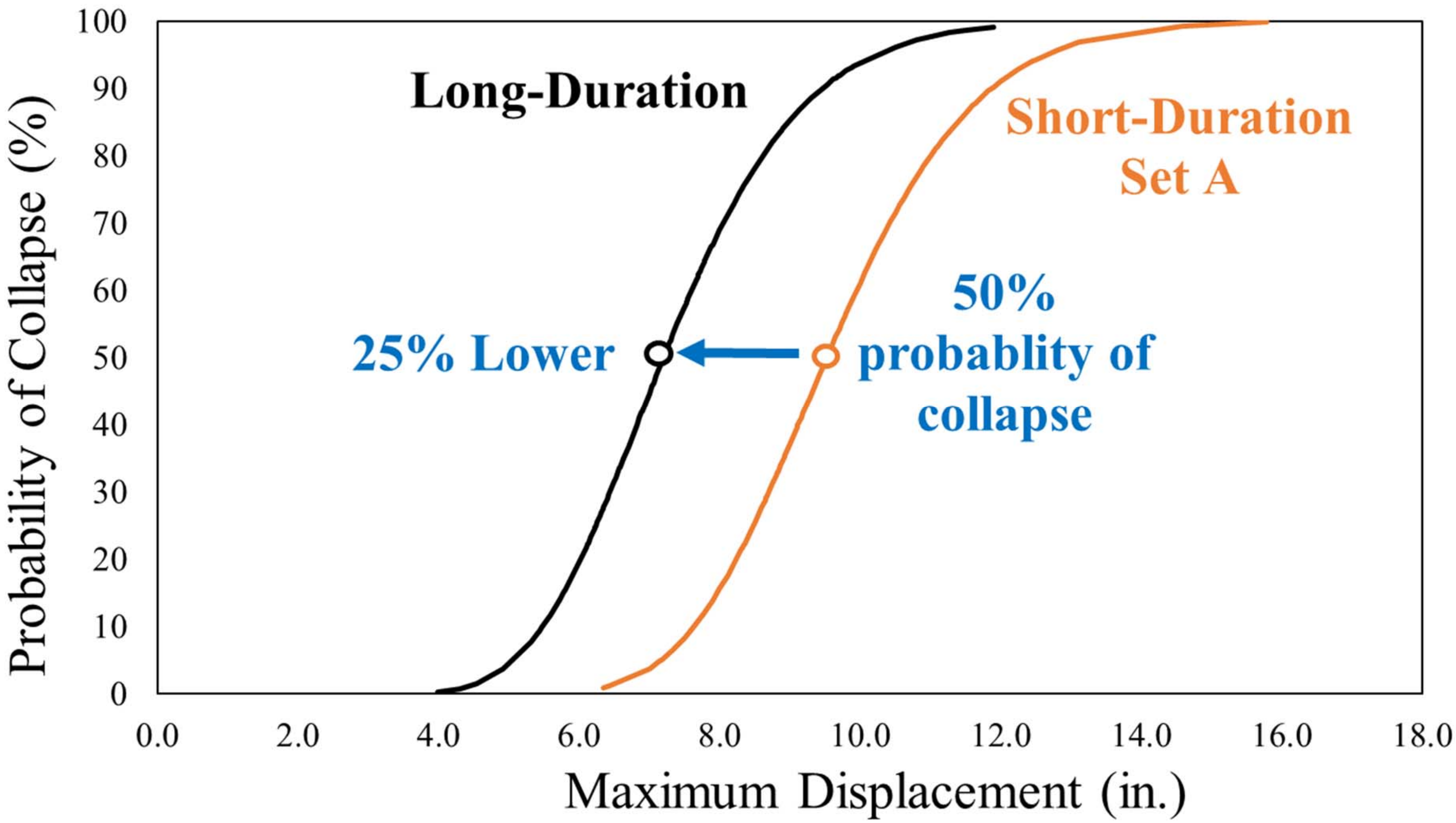
- **Example on how the comparative collapse fragility curves look like**

- **Each point represents a ground motion that was scaled until failure**

Post-Test Analysis

Maximum Displacement

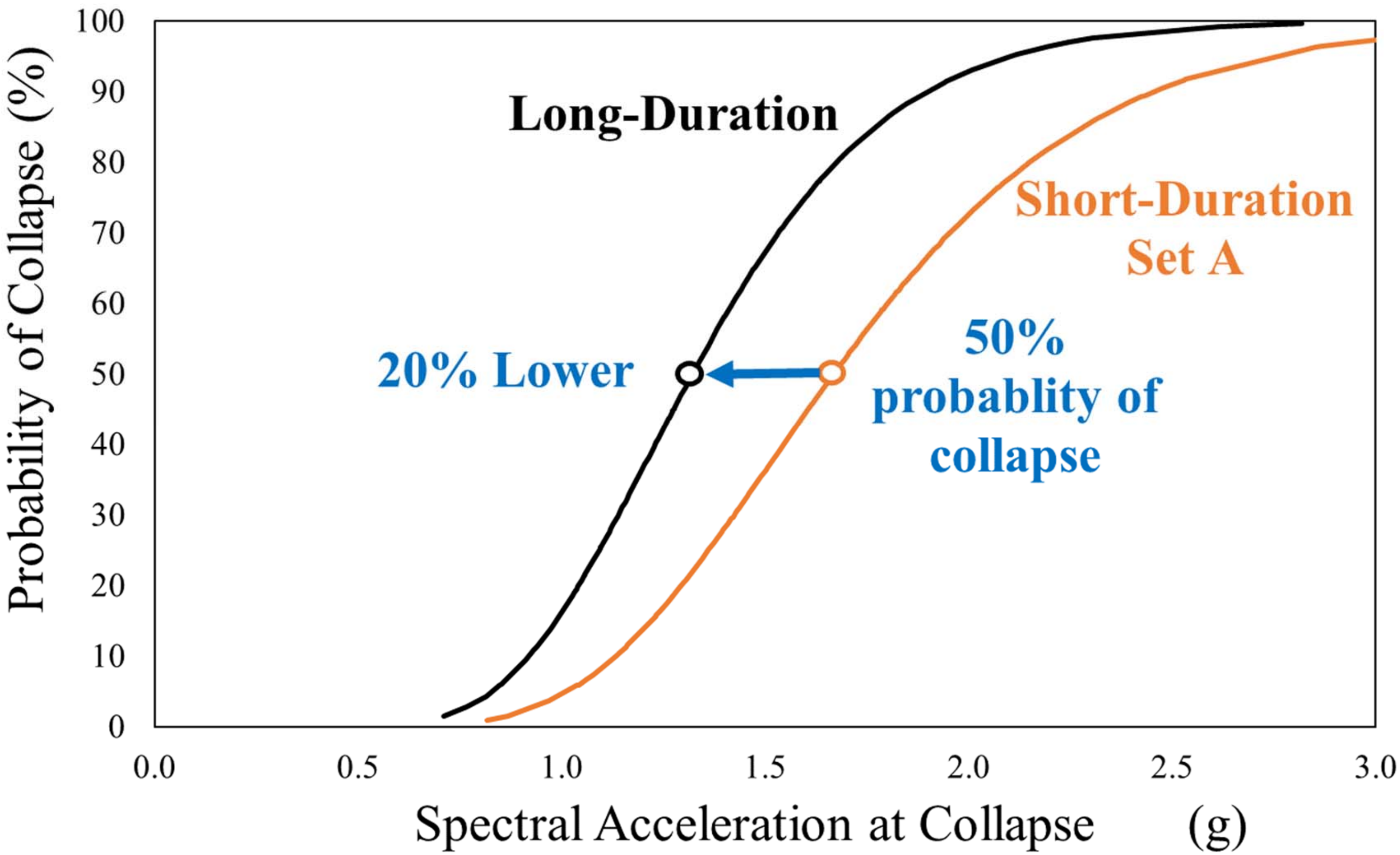
Comparative Collapse Analysis
(Collapse Fragility Curves)



Post-Test Analysis

Spectral Acceleration

Comparative Collapse Analysis
(Collapse Fragility Curves)



Conclusions

1) Ground motion duration has a significant effect on the collapse capacity of bridge columns.

2) A significant reduction in the displacement capacity was observed in case of long duration motions compared to the short duration motions for both the experimental and analytical studies.

→ Approximate reduction of about 25%

3) A significant reduction in the spectral accelerations at collapse in case of long duration motions with respect to the short duration motions.

→ Approximate reduction of about 20%

4) Ground motion duration is an important parameter when selecting ground motions for nonlinear analysis of structures.

Conclusions

5) Seismic design provisions are recommended take the effect of ground motion duration into account, not only the peak response.

Preliminary Design Recommendations

- **For displacement-based design of bridge columns, the column displacement capacity should be reduced by 25% for locations where long-duration ground motions are expected.**

- **For force-based design of bridge columns, the demand acceleration response spectrum should be increased by 25% for locations where long-duration ground motions are expected.**

Thank you

Questions ?

How failure is determined using the two OpenSees models ?

1- The OpenSees model that included low-cycle fatigue, collapse was determined by fracture of longitudinal steel bars

2- The OpenSees model that didn’t included low-cycle fatigue, collapse was determined using the experimental fragility curves and the damage index (see next slide)