ATC-15-16:
17th U.S.-Japan-New Zealand Workshop on the Improvement of Structural Engineering and Resilience

DESIGN IMPLICATIONS FOR EARTHQUAKE DURATION ON CONCRETE BRIDGE COLUMNS

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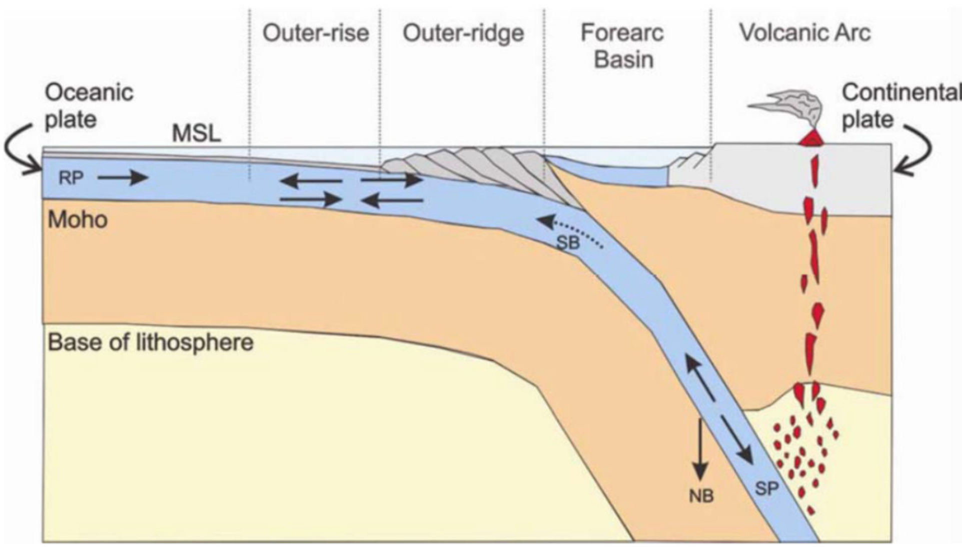
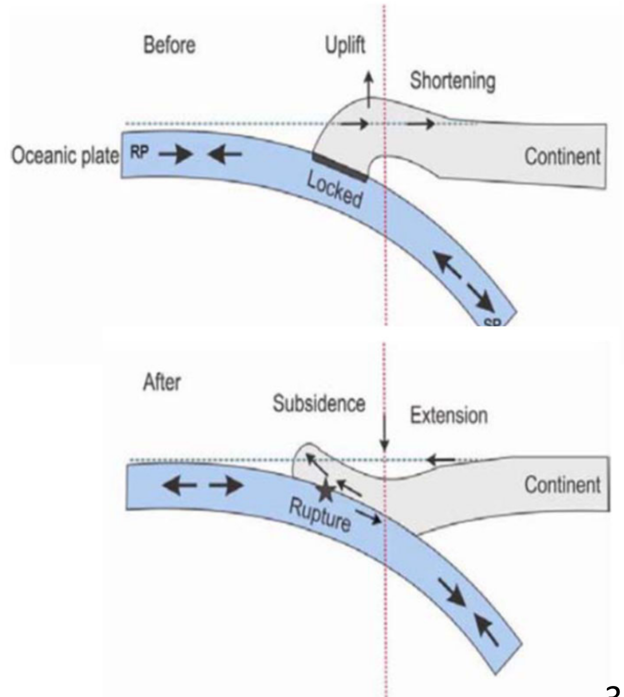
Subduction Zones

Subduction zones are plate boundaries where the world largest and longest duration earthquakes occur.

These earthquakes are shallow;
their rupture areas are very large;
and they release a large amount of energy.





Objectives

Phase I (FHWA Project):

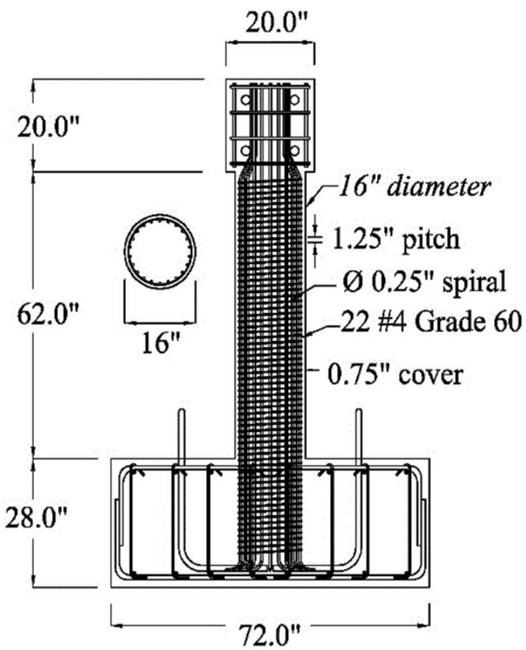
- Determine the effect of ground motion duration on collapse capacity of RC bridge columns and how to quantify this effect.
- Compare and characterize the difference in damage caused by short and long duration motions.

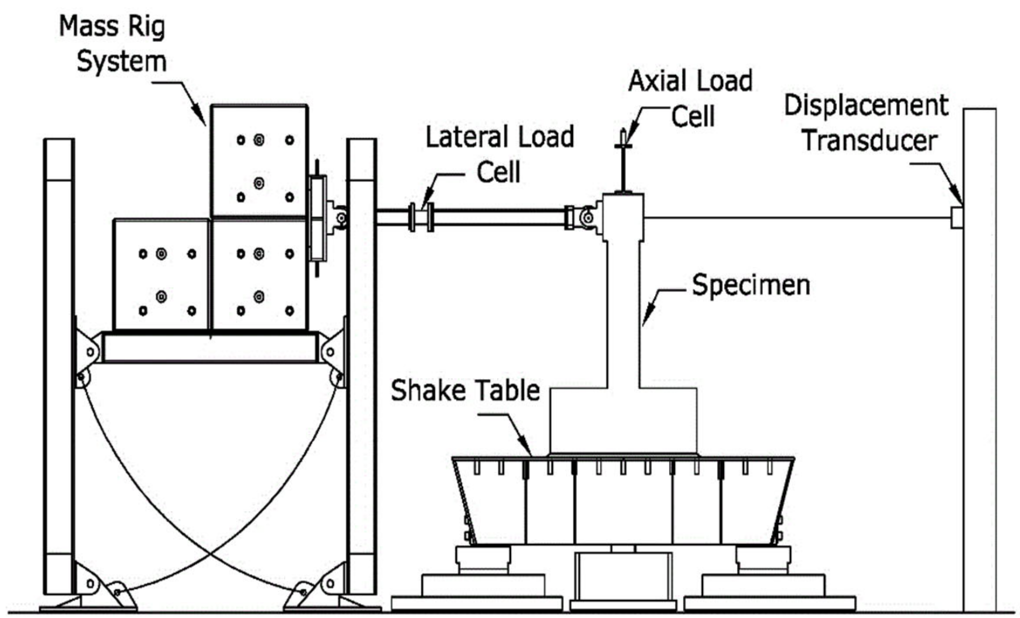
Phase II (PEER Project):

- Develop models and recommendations for considering earthquake duration in the performance assessment and design of bridges.
- Leverage research on cyclic deterioration to help qualify the use of high strength reinforcement in seismic design of bridges.

FHWA: Specimens and Test setup

- Five identical columns were tested on a shake table using long-duration motions from the Tohoku Earthquake.
- Columns where 1/3-scaled bridge columns.



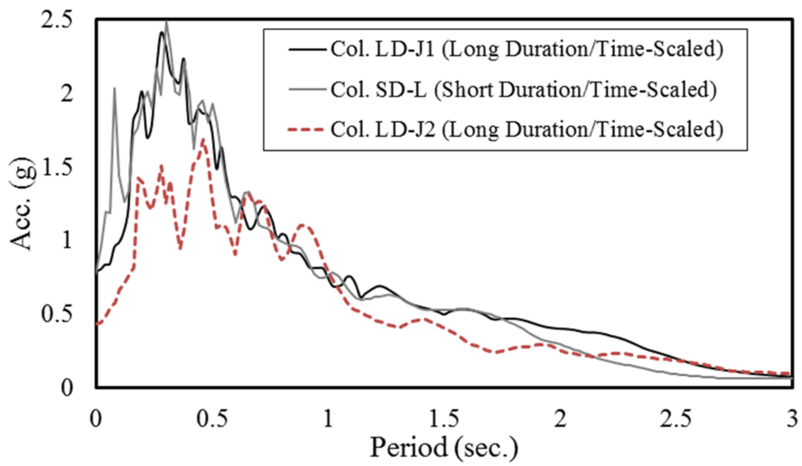


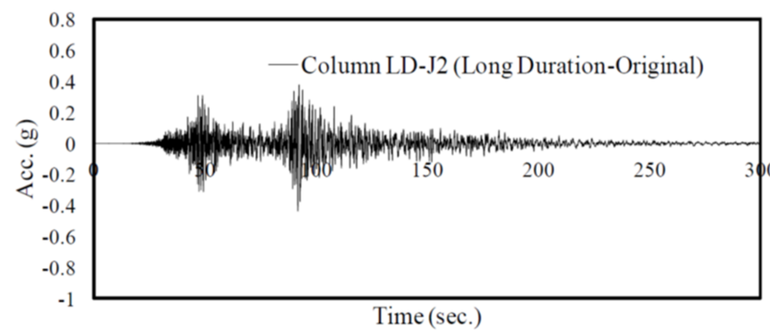
FHWA: Ground Motion Selection

- OpenSees model was used to conduct a pre-test analysis to choose ground motions in which the displacement demands on the columns are around half of its displacement capacity (9.8 in.)

Column LD-J1	Column LD-J2	Column SD-L
Tohoku 2011 earthquake (FKSH20 N-S)	Tohoku 2011 earthquake (MYG006 E-W)	Loma Prieta 1989 earthquake (Bran 00)

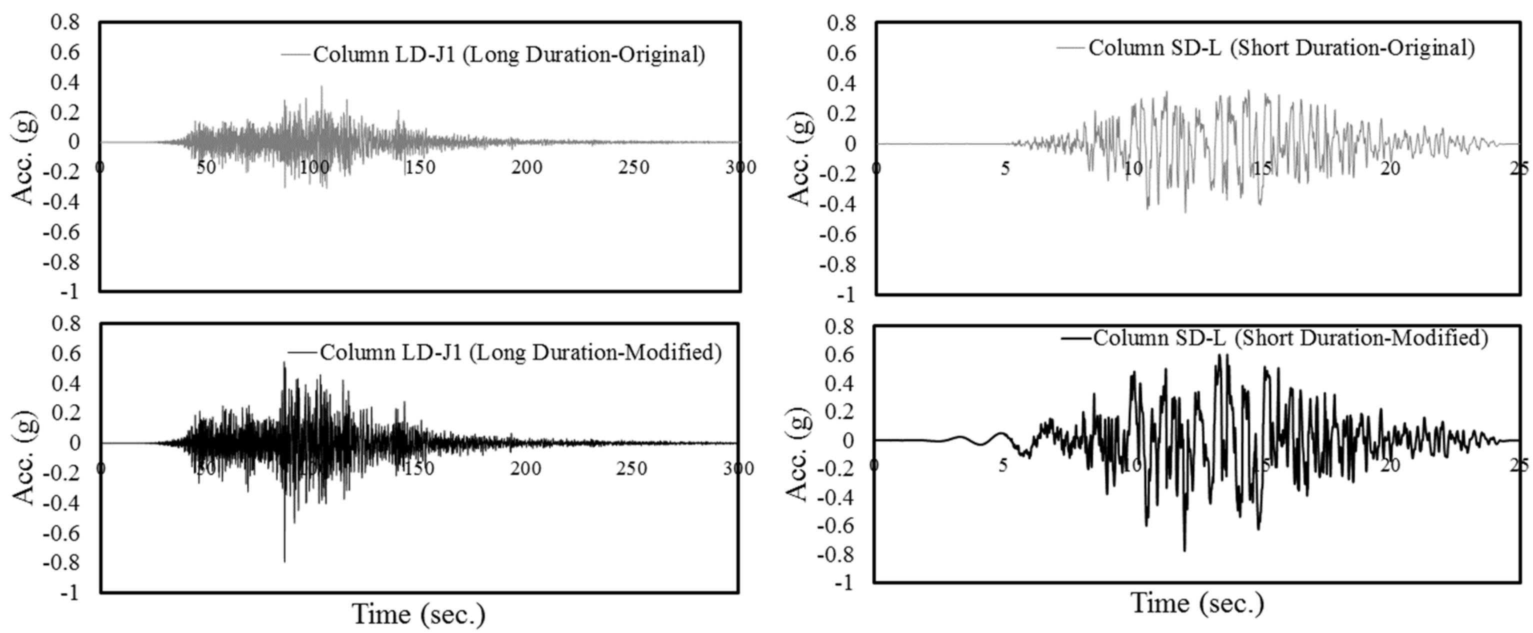
- The long and short duration motions, but LD-J1 and SD-L were modified to match the response spectrum of Crescent City.





FHWA: Loading Protocol

- Framework for the loading protocol for all columns was the same; the protocol began with the 100% of the selected motions and followed by an aftershock. Then scales of the main motions were applied until failure (125%, 150%, ..., etc.).



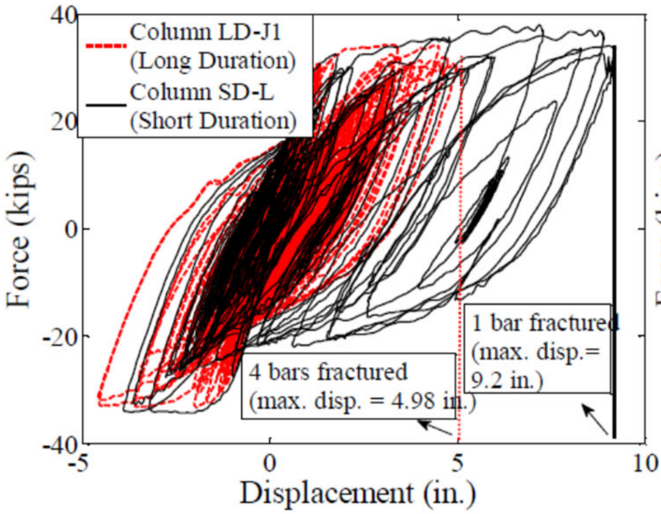
FHWA: Test Results

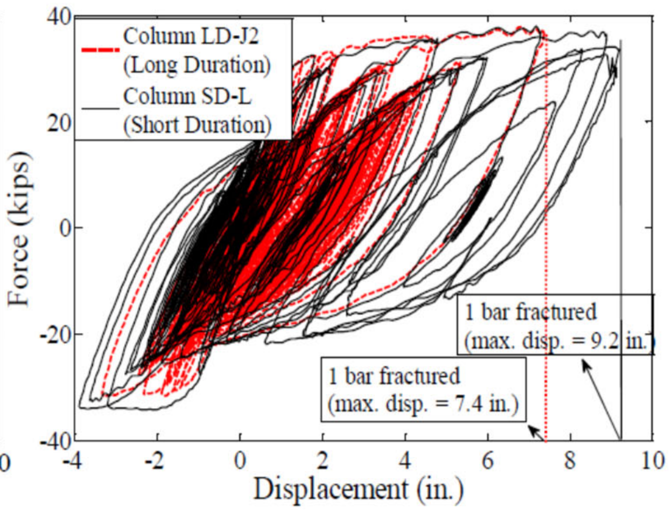
- Damage states after applying 125% of the motion:

Column LD-J1

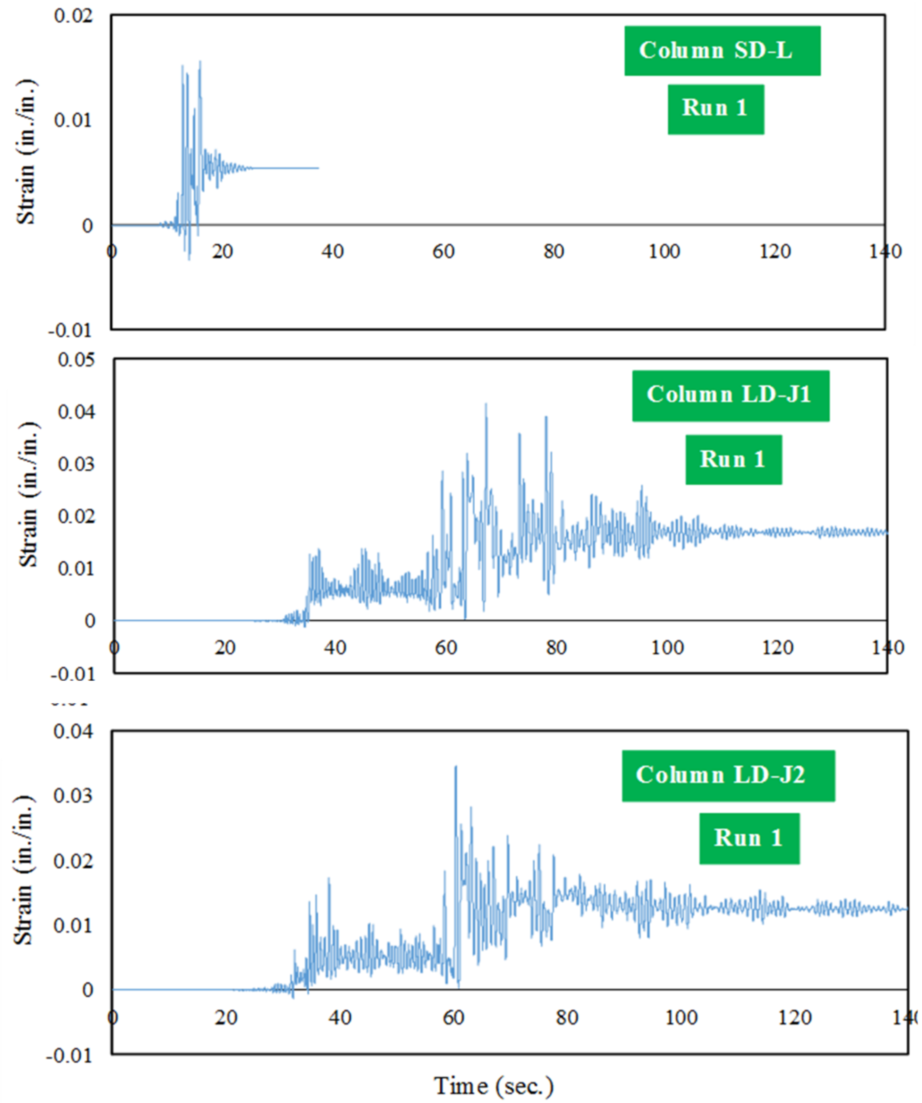
Column SD-L

Column LD-J2





Strain History



Short-Duration

Long-Duration (Japan-1)

Long-Duration (Japan 2)

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

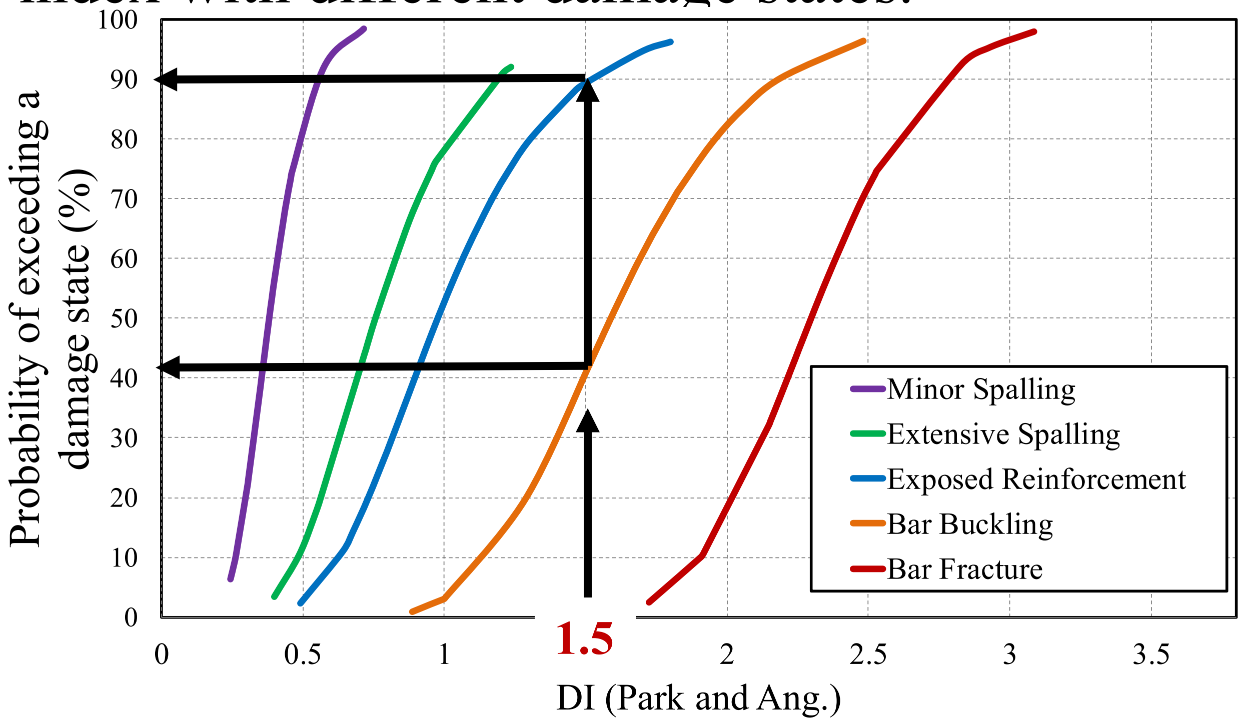
Damage Prediction Before Testing

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

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

→ **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

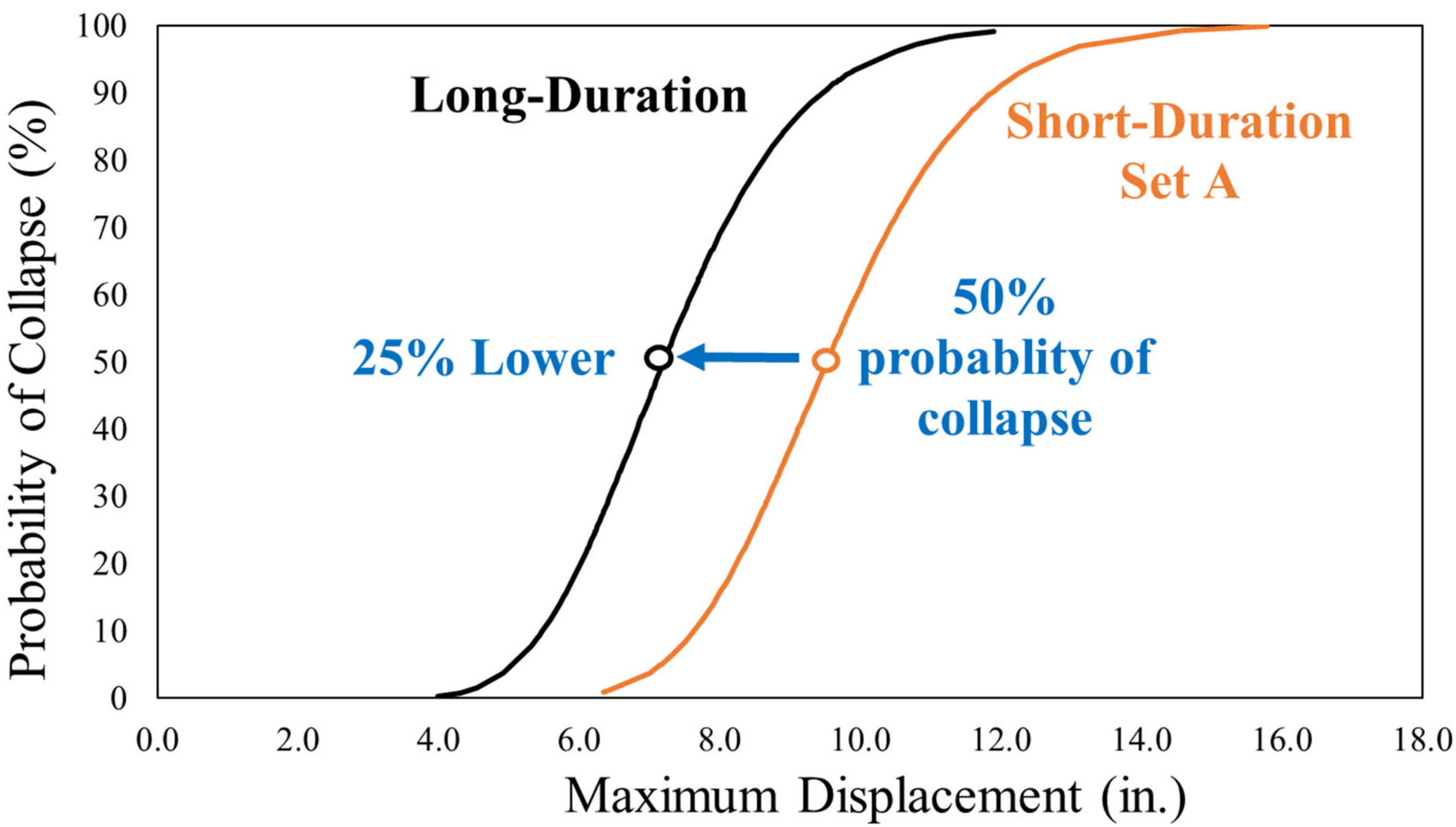
40% Bar Buckling

90% Exposed RFT.

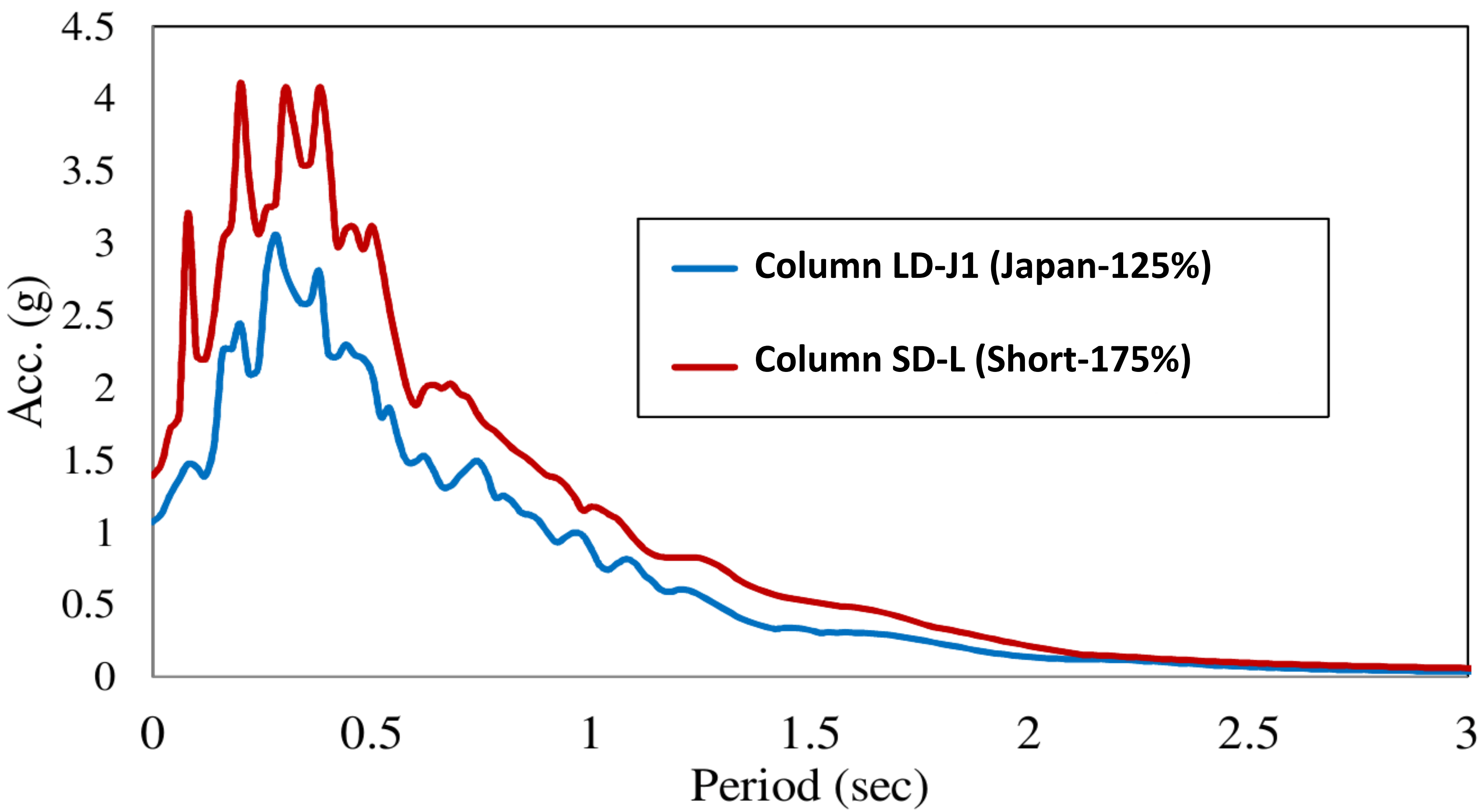
0% Bar Fracture

Comparative Collapse Analysis (Collapse Fragility Curves)

Maximum Displacement



Spectral Accelerations at Final Damage State

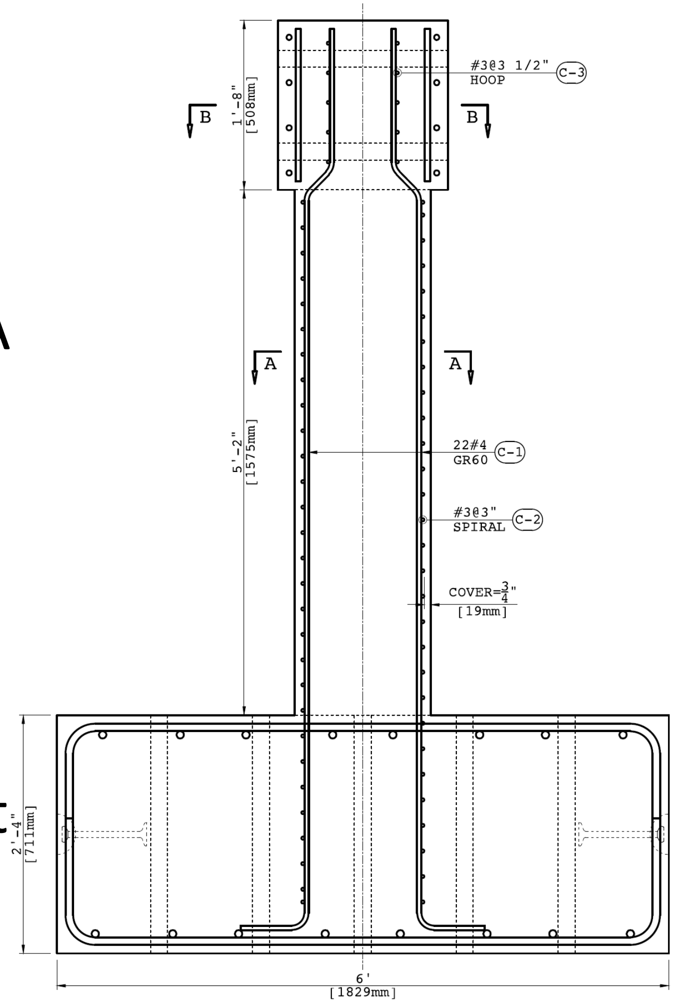


PEER Project - Specimens Description

- Four 1/3-scale CIP circular bridge column models will be tested in two groups:

First Group: two columns with different transverse reinforcement details than FHWA project's column to investigate the effect of transverse bar spacing

Second Group: two columns reinforced longitudinally with ASTM A706 Grade 80 to investigate the impact of long-duration earthquakes on high strength reinforcement



PEER Project - Specimens Description

Details of the specimens in PEER project

Specimen	LD-S3-G60	LD-S1.5-G60	LD-S1.5-G80	LD-S1.5-G80D
Diameter	16 in.	16 in.	16 in.	16 in.
Long. Reinf.	22 #4 (2.2%) Gr 60	22 #4 (2.2%) Gr 60	18 #4 (1.8%) Gr 80	18 #4 (1.8%) Gr 80
Trans. Reinf.	#3 @ 3 in. (1.04%)	#3 @ 1.5 in. (2.08%)	#3 @ 1.5 in. (2.08%)	#3 @ 1.5 in. (2.08%)
Long. Bars Clear Spacing	6 d_b†	3 d_b	3 d_b	3 d_b

† d_b: Longitudinal Bar Diameter

- Longitudinal bars in one of the columns in the second group will be debonded at the interface of the column and the footing.

PEER Project - Loading Protocol

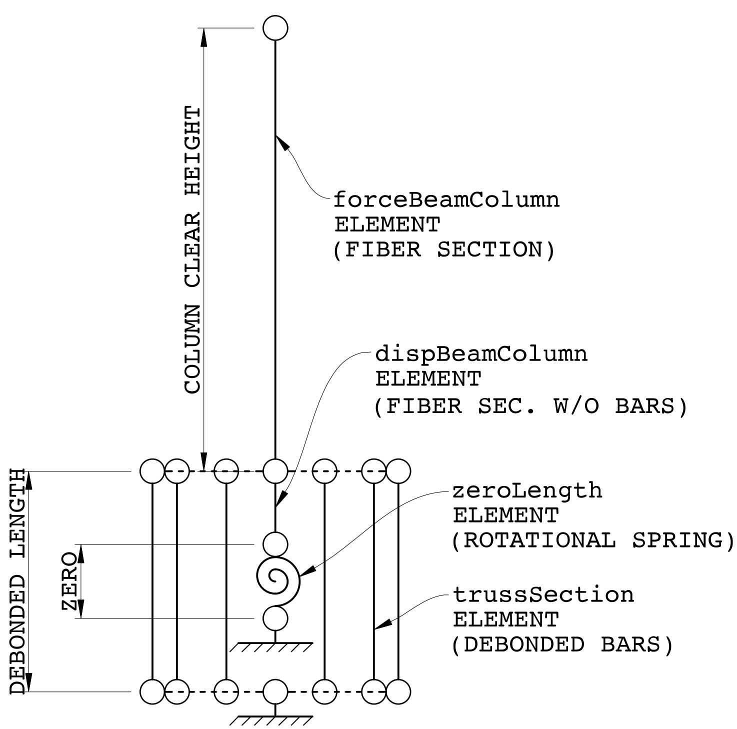
- All four columns will be subjected to a loading protocol which will be the same as the one used for the column LD-J2 in FHWA Project.

Run 1	Run 2	Run 3	Run 4
100% of the original main record	100% of the original aftershock record	125% of the original main record	150% of the original main record

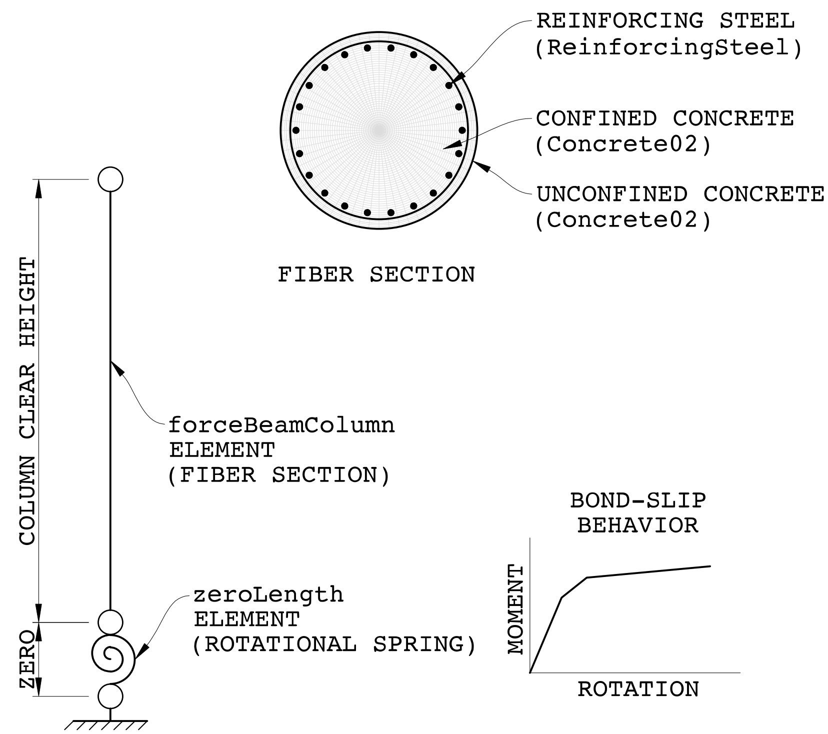
Main record: 2011 Tohoku earthquake recorded at MYG006 E-W station
Aftershock record: the aftershock that occurred one month after the main earthquake

PEER Project - Analytical Modeling

- An OpenSees model was used for pretest analytical studies.



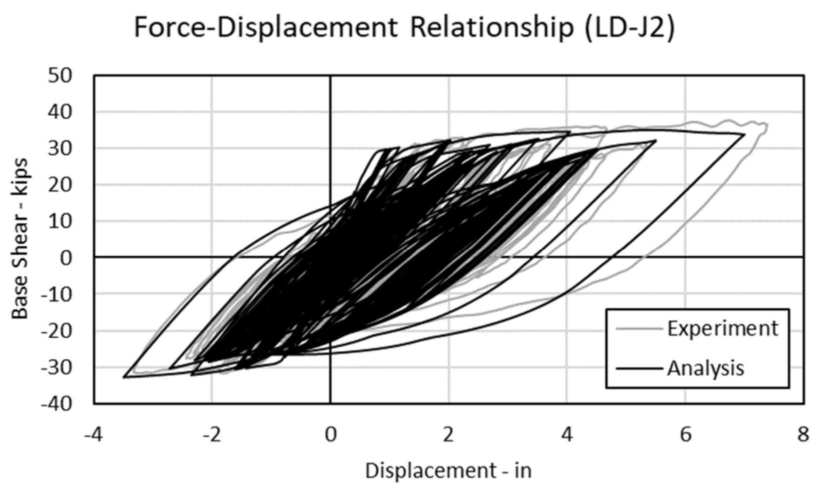
Model with debonded bars

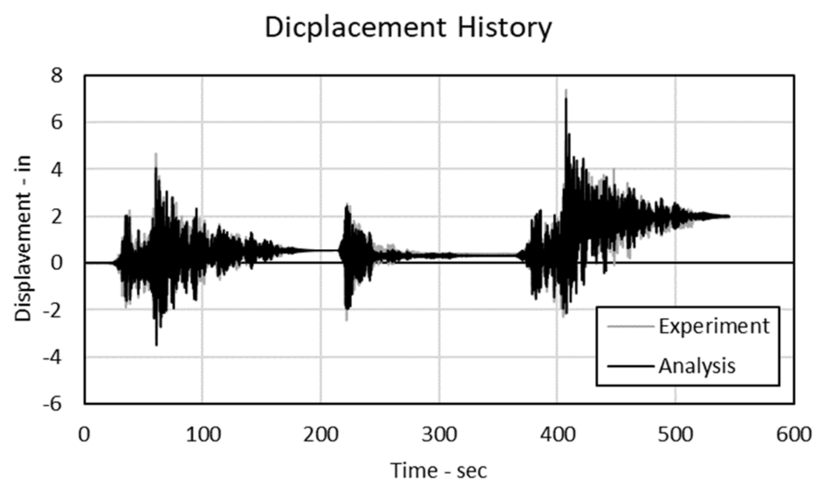


Model without debonded bars

PEER Project - Analytical Modeling

- The OpenSees model was calibrated with pervious experimental results from FHWA Project.





PEER Project - Analytical Modeling

- Nonlinear static analysis (Pushover) was conducted to determine the dominant failure mode, the displacement capacity, the initial stiffness and the fundamental period of the columns

Results of pushover analysis for PEER columns

Specimen	Yeild Disp.	Ultimate Disp.	Disp. Ductility	Plastic Moment	Effective Stiffness	Period
LD-S3-G60	0.72 in.	6.53 in.	9.05	185 kip.in	42.8 kip/in	0.44 s
LD-S1.5-G60	0.73 in.	6.74 in.	9.23	186 kip.in	42.5 kip/in	0.44 s
LD-S1.5-G80	0.90 in.	5.28 in.	5.85	182 kip.in	33.5 kip/in	0.49 s
LD-S1.5-G80D	0.83 in.	7.35 in.	8.82	170 kip.in	34.1 kip/in	0.49 s

PEER Project - Analytical Modeling

- Nonlinear dynamic response history analysis (RHA) under the loading protocol was conducted to predict the seismic performance and damage states of the columns

Predicted performance of the test columns

Specimen	Run 1 (100%)		Run 2 (aftershock)		Run 3 (125%)		Run 4 (150%)	
	DI†	DS†	DI	DS	DI	DS	DI	DS
LD-S3-G60	1.3	80% E.R.‡	1.5	90% E.R.	2.8	95% B.F.	Not applicable	
LD-S1.5-G60	1.3	80% E.R.	1.4	85% E.R.	2.7	90% B.F.	Not applicable	
LD-S1.5-G80	1.2	80% E.R.	1.4	85% E.R.	2.7	90% B.F.	Not applicable	
LD-S1.5-G80D	1.1	70% E.R.	1.2	75% E.R.	2.3	90% B.B.	>3	100% B.F.

† DI: Park and Ang Damage Index; DS: Estimated Damage State.

‡ Minor Spalling (M.S.); Extensive Spalling (E.S.); Exposed Reinforcement (E.R.); Longitudinal Bar Buckling (B.B.); and Longitudinal Bar Fracture (B.F.)

Summary and Conclusions

- Phase I - five identical columns were tested on a shake table using long-duration motions from the Tohoku Earthquake:
  - Results showed substantially reduced displacement capacity (about 25%) compared to the base specimen under the short-duration motion.

Summary and Conclusions

- Phase II - four more columns to investigate ways to mitigate the impact of long duration earthquakes and will include columns with high strength longitudinal reinforcement:
  - Pre-test analytical studies showed using the smaller spacing for transvers reinforcement can slightly help to improve the columns performance.
  - Use of Gr80 steel instead of Gr60 reduced the stiffness of columns by approximately 20%.
  - Debonding the longitudinal bars in the column-footing interface resulted in a 51% increase in the displacement ductility capacity of the column.
  - Building specimens for the Phase II PEER