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Effect of Design Details on Seismic Response of RC Bridge Columns Under Long Duration Ground Motions

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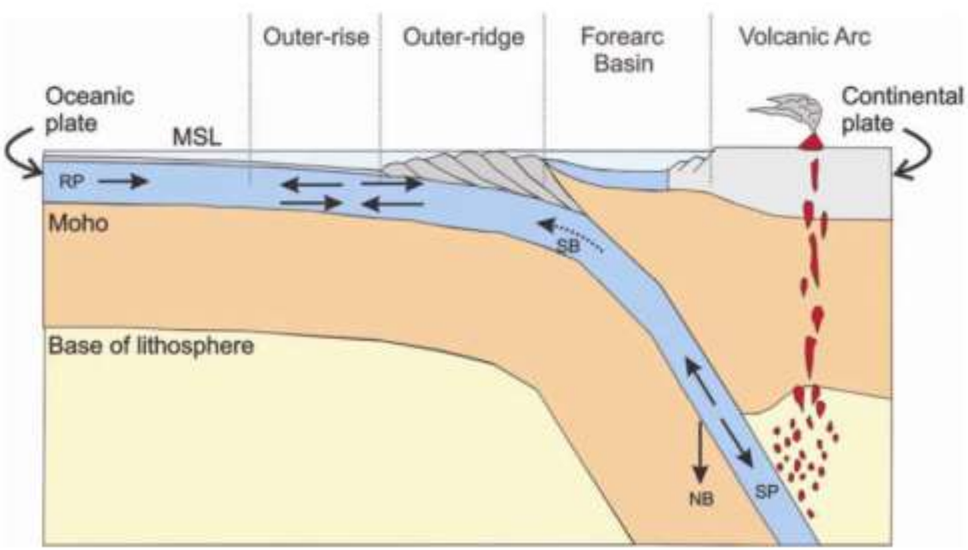
Outline

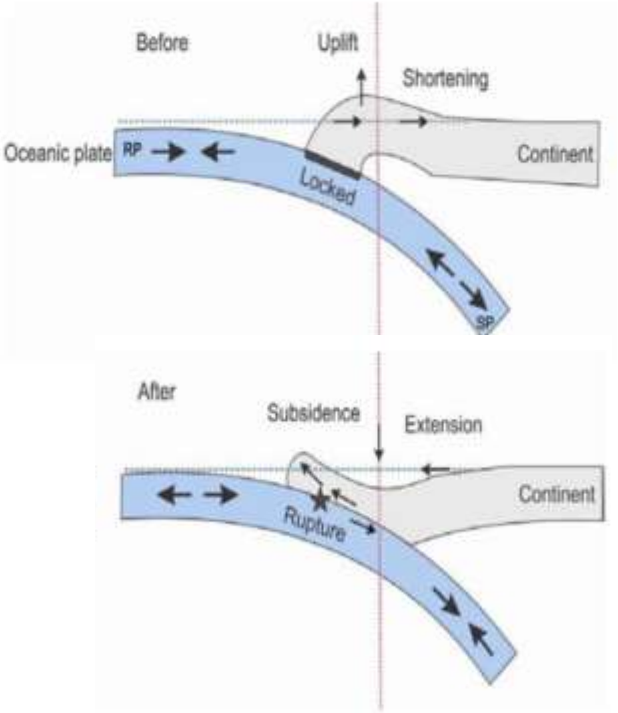
1. Introduction
2. Motivation & Objectives
3. Numerical Studies
4. Experimental Program
5. Concluding Remarks

1. Introduction
Long duration and Subduction zones

Subduction zones are plate boundaries where large magnitude and long duration earthquakes occur → Cascadia Subduction Zone, Pacific NW

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





1. Introduction
Account for duration effect

- Seismic design specifications use response spectra to identify the hazard and **do not consider duration effects**

Influence of duration on structural performance

- Damage Metric
  - Peak Response
  - Cumulative Damage
  - Energy Measures
- Duration Definition
  - Arias Intensity (AI)
  - Cumulative Absolute Velocity (CAV)
  - Bracketed Duration (D_b)
  - Significant Duration (D_s)
  - Dimensionless Duration (I_D)
- **Structural Models**

Experimental data?

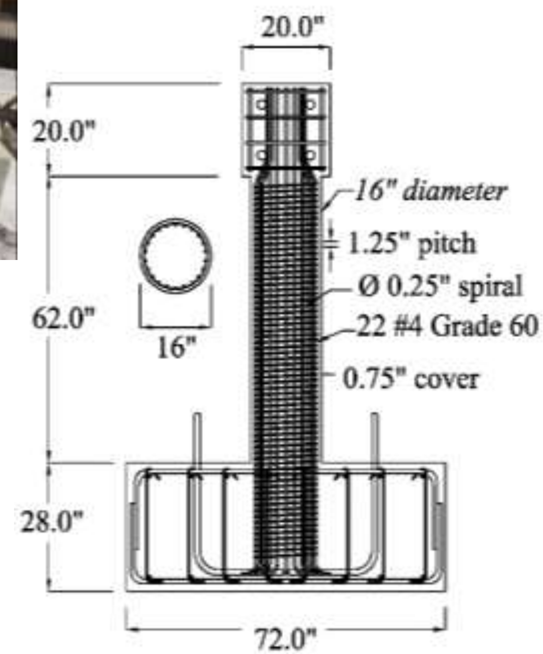
2. Motivation

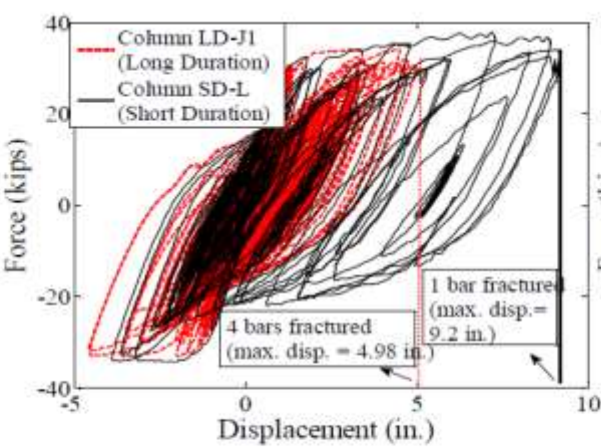
- Five identical columns were tested on a shake table using long-duration motions from the Tohoku Earthquake at UNR (Mohammed and Sanders).
- Damage states after applying 125% of the motion:

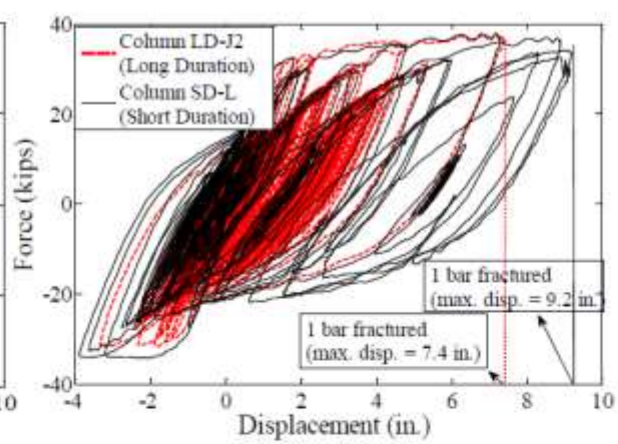
Column LD-J1

Column SD-L

Column LD-J2







2. Motivation

Experimental studies

- Examples: Kunnath et al. (1997), Stapleton (2004), Ranf et al. (2006), Ou et al. (2014), and Mohammed et al. (2017)
- Longer duration earthquakes with large number of inelastic cycles caused more damage in the plastic hinges.
- Damage is mainly attributed to the damage accumulation associated with low-cycle fatigue in the column reinforcing bars.

Analytical studies

- Examples: Mohammed et al. (2016) and Chandramohan et al. (2016)
- Main conclusion is about 20% reduction in the median collapse capacity under long duration motions

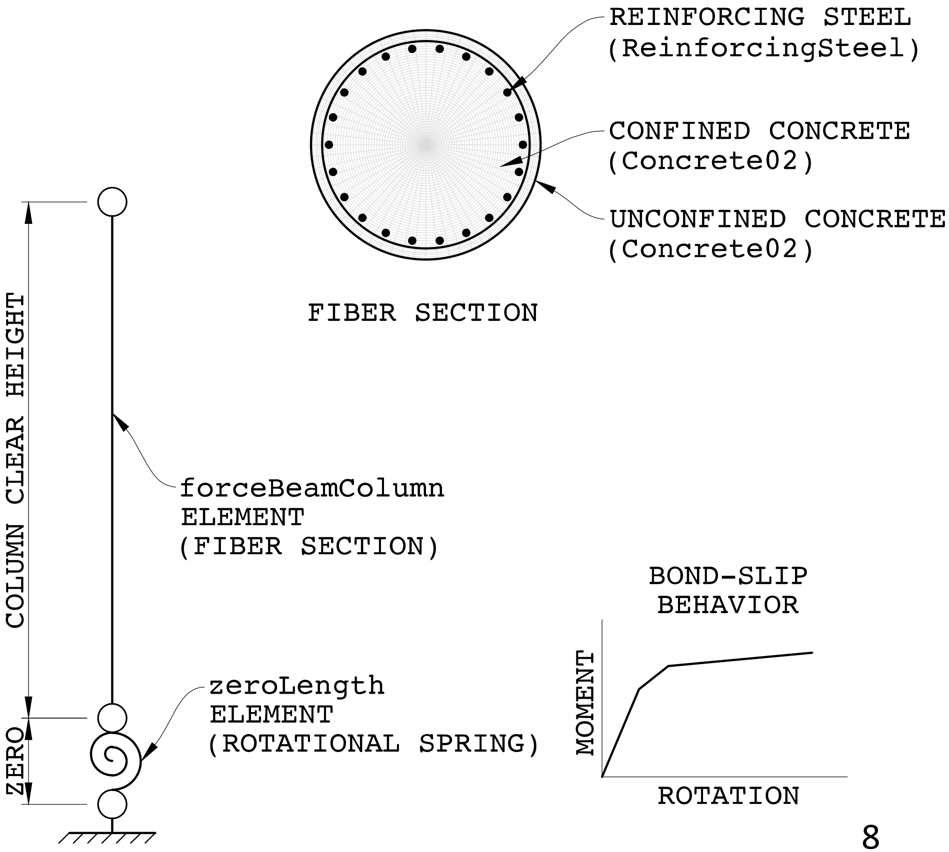
2. Objectives

- Develop improved design details to mitigate the effect of duration on reinforced concrete bridge piers that could be verified experimentally.
- 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.

3. Numerical Study
Model development

- An OpenSees model was used to conduct Incremental Dynamic Analysis (IDA) to develop fragility curves.

A full-scale, circular reinforced concrete bridge pier tested at UCSD



3. Numerical Study
Fatigue fracture model

- The fatigue-fracture model developed by **Zhong and Deierlein (2017)** was used to determine the low-cycle fatigue parameters

(Coffin-Manson) $$\varepsilon_p = C_f \left(2N_f\right)^{-\alpha_f}$$

steel ultimate strength to yield strength ratio

clear spacing of reinforcing bar

$$\alpha_f = 0.729 - 0.075\left(f_y/60ksi\right) + 0.038(s/d_b) - 0.217(T/Y)$$

nominal size of reinforcing bar

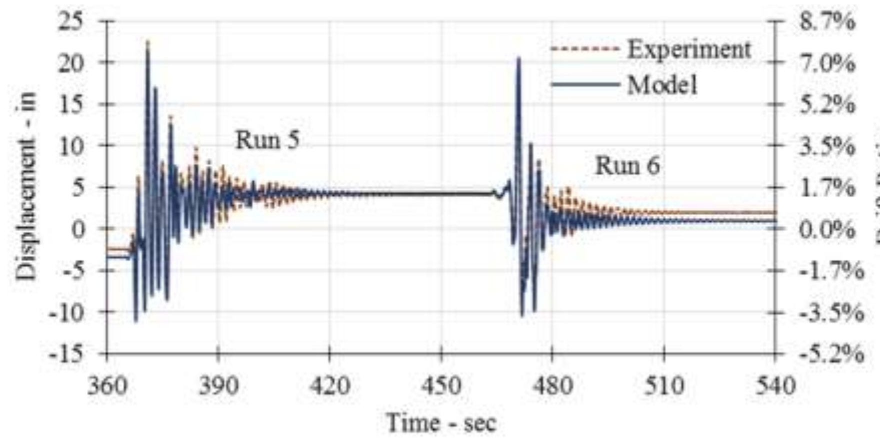
$$C_f = 0.5^{\alpha_f}\left(\varepsilon_f - f_y/E\right)$$

$$\varepsilon_f = f_y/E - 0.029\left(f_y/60ksi\right) - 0.127(T/Y)$$

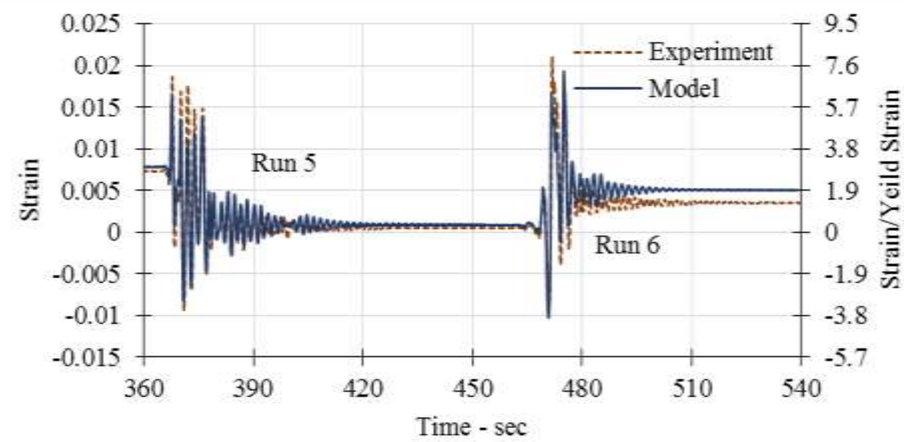
fracture strain amplitude

3. Numerical Study
Model calibration

- The OpenSees model was calibrated/verified using the experimental results from the shake table test



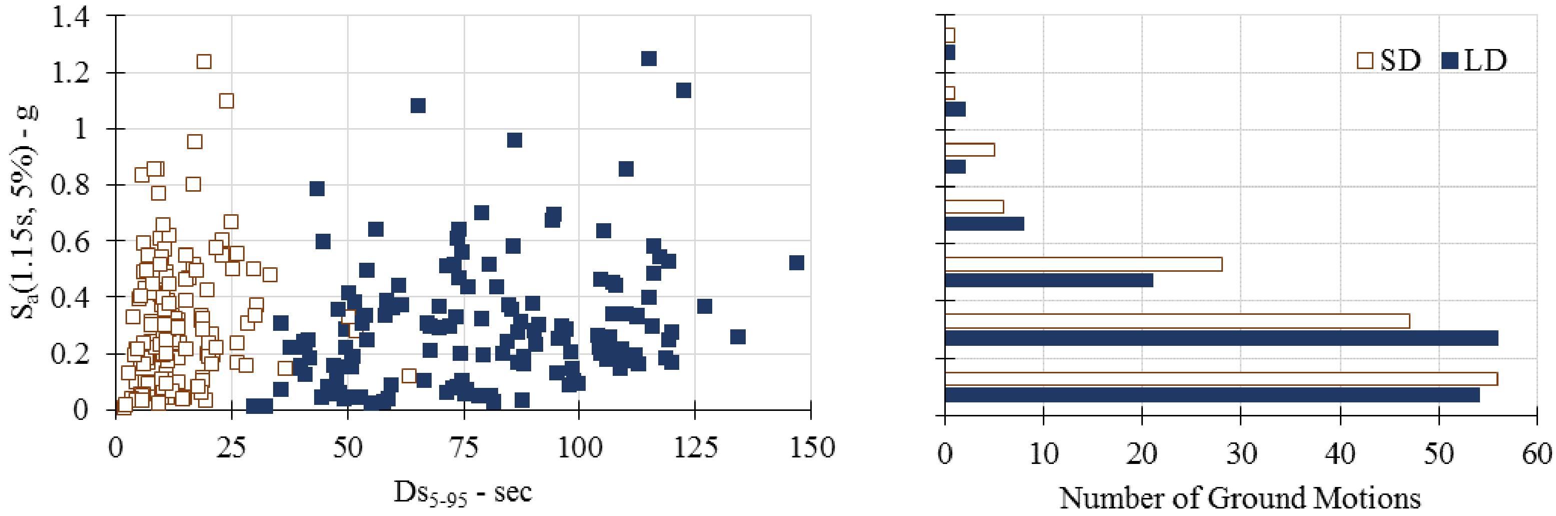
Comparison of experiment and model displacement histories



Comparison of experiment and model strain histories

3. Numerical Study
Ground motions

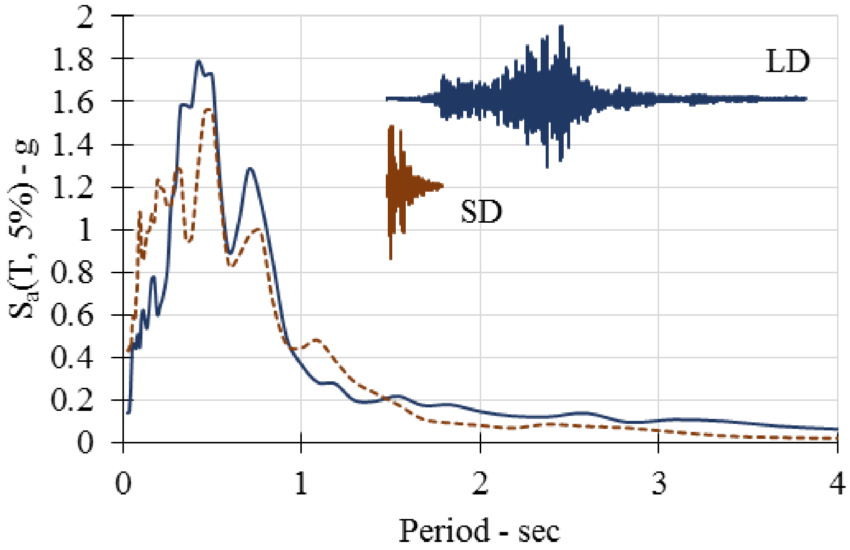
- Two suites of spectrally-equivalent long and short duration ground motions
- Each suite included 156 ground motion records
- Long duration records selected from subduction and crustal earthquakes

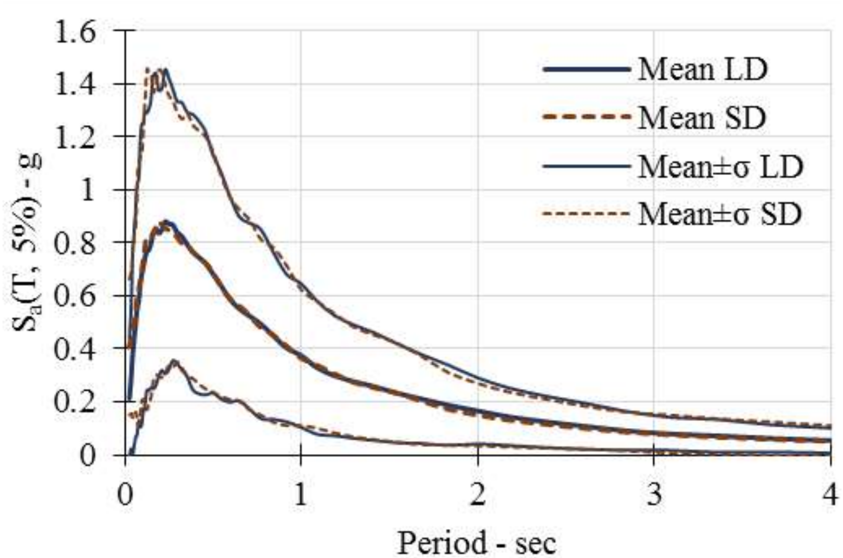


Distribution of significant duration Ds(5-95%) for the ground motion suites

3. Numerical Study
Ground motions

- Two suites of spectrally-equivalent long and short duration ground motions
- Each suite included 156 ground motion records
- Long duration records selected from subduction and crustal earthquakes

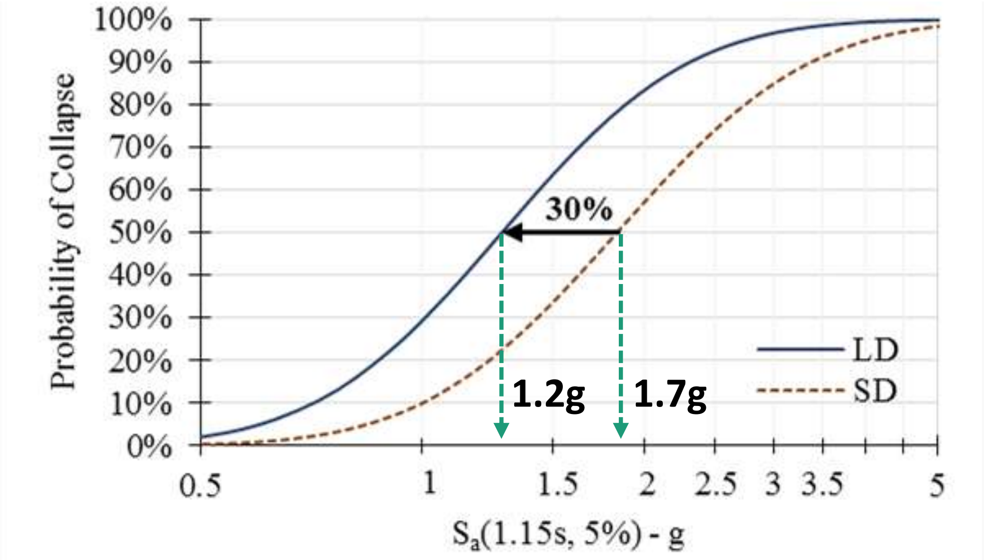




Spectral matching of short and long duration GMs: example for one pair (left) and mean of all matched GMs

3. Numerical Study
Fragility Curves

- The IDA was conducted to develop fragility curves utilizing spectrally-equivalent long and short duration records

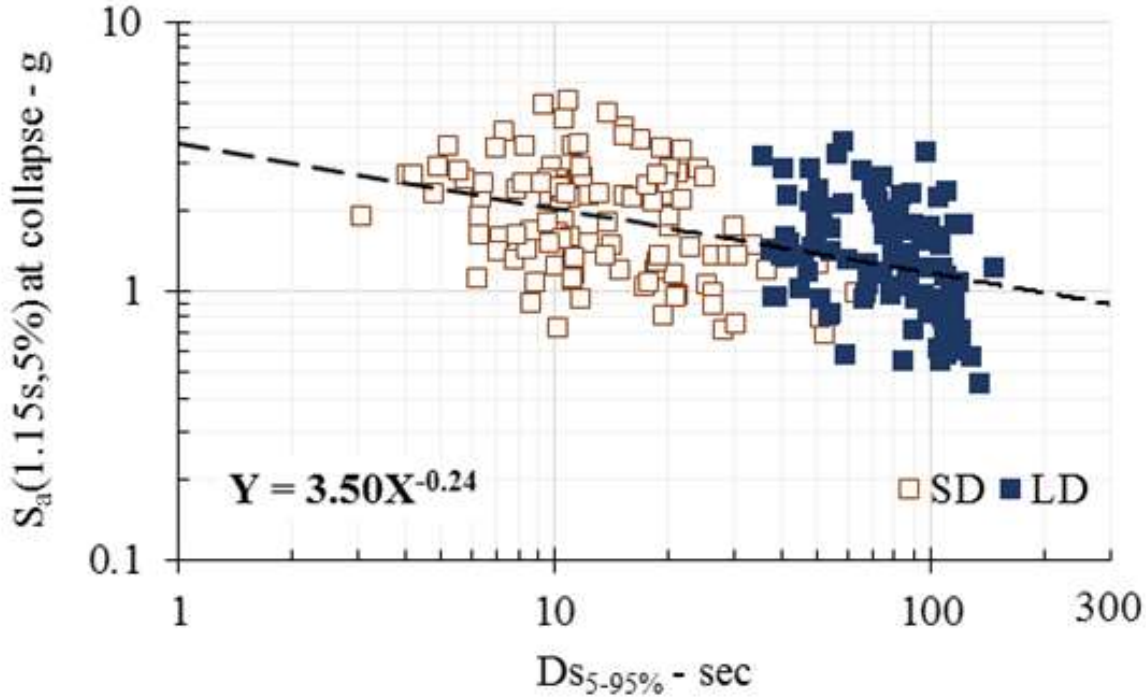


Collapse fragility curves for the short and long duration suits

Note that previous work reported 20% and 17% reduction by Mohammed et al. 2016 and Chandramohan et al. 2016

3. Numerical Study
Fragility Curves

- The lower collapse capacity of the bridge column under ground motions with longer duration



Collapse capacity of the column versus significant duration Ds(5-95%)

4. Experimental Program

Specimens

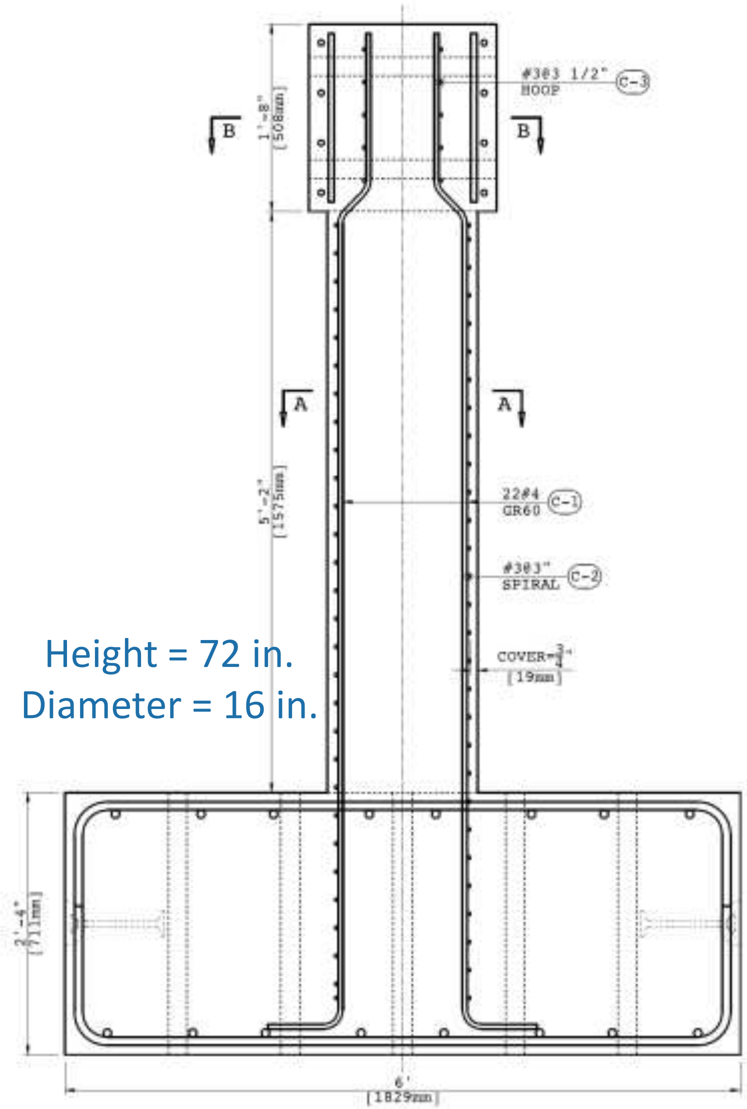
- Six 1/3-scale CIP circular bridge columns were/will be tested in two phases:

First Phase (conventional steel):

- Two columns with different trans. Reinf. details
- One column with debonding details for long. rebars

Second Phase (high strength steel):

- Two columns with different trans. reinf. details under long duration motions
- One column under a short duration motion

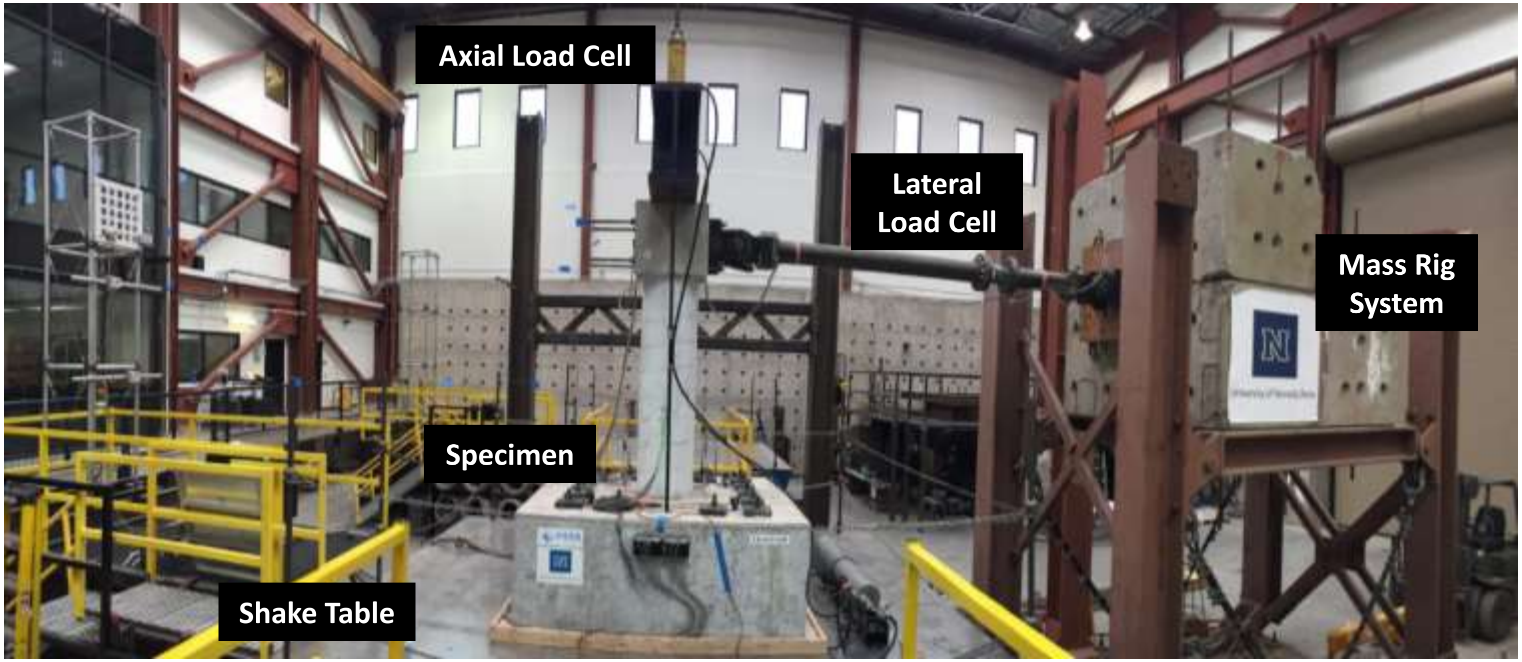


Height = 72 in.
Diameter = 16 in.

4. Experimental Program

Test matrix and setup

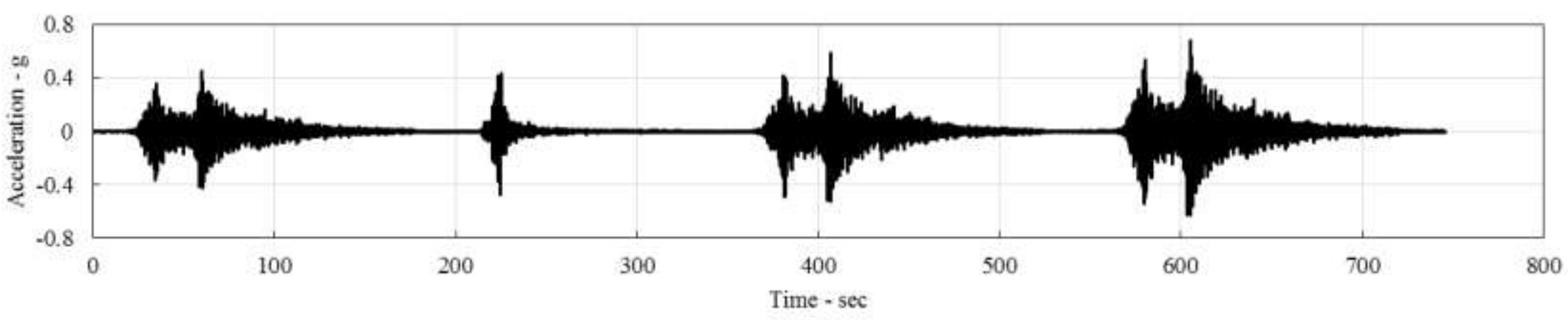
Specimens	Phase I (Completed spring 2019)			Phase II (in progress- fall 2019)		
	LD-S3-G60	LD-S1.5-G60	LD-S3-G60D	LD-S3-G100	LD-S1.5-G100	SD-S3-G100
Long. Reinf.	22 #4 (2.2%) Gr 60	22 #4 (2.2%) Gr 60	22 #4 (2.2%) Gr 60 debonded	14 #4 (1.4%) Gr 100	14 #4 (1.4%) Gr 100	14 #4 (1.4%) Gr 100
Trans. Reinf.	#3 @ 3 in. (1.04%)	#3 @ 1.5 in. (2.08%)	#3 @ 3 in. (1.04%)	#3 @ 3 in. (1.04%)	#3 @ 1.5 in. (2.08%)	#3 @ 3 in. (1.04%)
Spacing	6 d_b	3 d_b	6 d_b	6 d_b	3 d_b	6 d_b



4. Experimental Program
Loading protocol

- *Long duration motion:* 2011 Tohoku (Japan) recorded at MYG006E-W Chosen from the previous study by Sanders et al.
- *Aftershock motion:* occurred in Japan one month after the Tohoku earthquake
- *Loading protocol:*

Run 1	Run 2	Run 3	Run 4	…
100% main motion	100% aftershock	125% main motion	150% main motion	Scale until failure



FOR PHASE II → *Short duration motion:* 1999 Kocaeli (Turkey) recorded at IZN090 Scaled by 3.68 – Spectrally equivalent with the LD motion

4. Experimental Program
Construction – Phase I

Three specimens were built in parallel

4. Experimental Program
Assembly and test setup – Phase I



Placing specimen on the shake table

Instrumentation

4. Experimental Program
Shake table tests – Phase I

Column LD-S3-G60 (Run 1: 100% Tohoku EQ)

4. Experimental Program
Shake table tests – Phase I

Column LD-S1.5-G60 (Run 1: 100% Tohoku EQ)

4. Experimental Program
Shake table tests – Phase I

Column LD-S3-G60 (Run 4: 150% Tohoku EQ)

4. Experimental Program

Shake table tests – Phase I

4. Experimental Program
Observations – Phase I

LD-S3-G60

8 long. bars ruptured in run 4: **150%** Tohoku EQ
Drift capacity: **8.9%**
Base shear: **38.1 kips**

LD-S1.5-G60

1 long. bars ruptured in run 5: **160%** Tohoku EQ
Drift capacity: **13.8%**
Base shear: **36.5 kips**

LD-S3-G60D

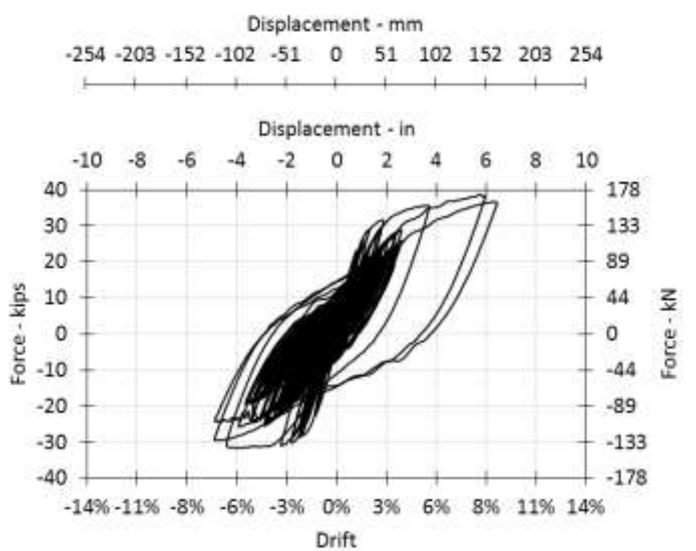
1+8 long. bars ruptured in run 3, 4: **125% & 150%** Tohoku EQ
Drift capacity: **10.9%**
Base shear: **33.7 kips**

4. Experimental Program

Results – Phase I

LD-S3-G60

Run #	**1: 100% Tohoku**	**2: 100% Aftershock**	**3: 125% Tohoku**	**4: 150% Tohoku**
Max Disp.	-4.38 in.	-2.78 in.	+5.90 in.	**+6.40 in.**
Max Drift	6.08%	3.86%	8.19%	**8.89%**
Res. Drift	0.46%	0.57%	0.60%	**1.64%**
Max B.S.	+35.43 kips	-24.79 kips	**+38.08 kips**	-36.45 kips
Max Strain	2.79%	2.01%	4.46%	Rupture
Damage State	Major spalling	Same as previous run	Long. bars were exposed	8 long. bars ruptured

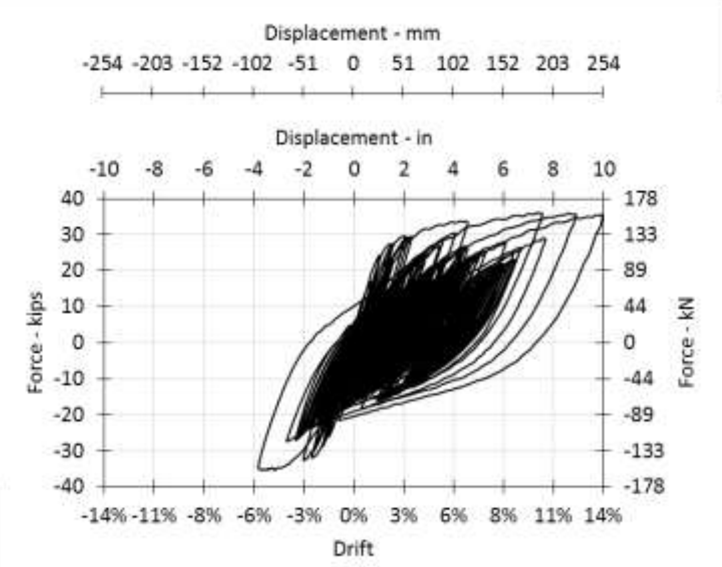


4. Experimental Program

Results – Phase I

LD-S1.5-G60

Run #	1: 100% Tohoku	2: 100% A.S.	3: 125% Tohoku	4: 150% Tohoku	5: 160% Tohoku
Max Disp.	+4.52 in.	+2.68 in.	+7.51 in	+8.87 in.	**+9.96 in.**
Max Drift	6.28%	3.72%	10.4%	12.3%	**13.8%**
Res. Drift	0.56%	0.46%	1.57%	2.99%	**5.60%**
Max B.S.	-34.78 kips	-26.04 kips	+35.25 kips	+35.21 kips	**-36.45 kips**
Max Strain	3.30%	2.31%	6.25%	7.65%	Rupture
Damage State	Major spalling	Same as previous run	Trans. bars were exposed	Same as previous run	1 long. bar ruptured

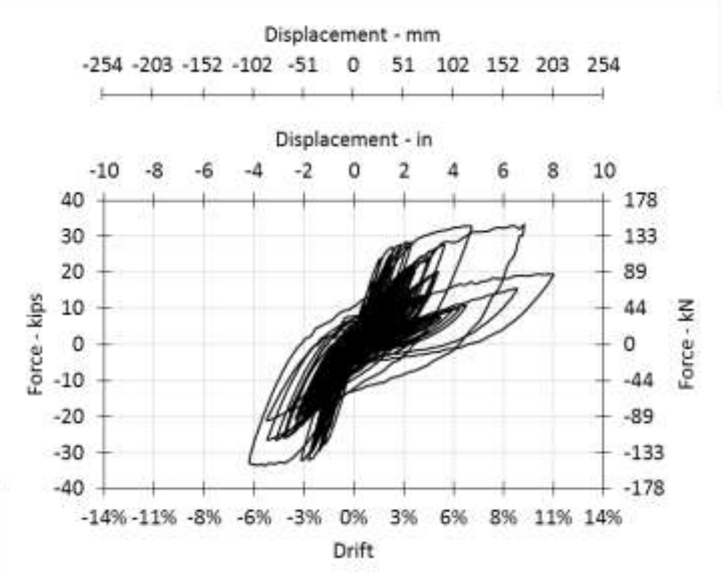


4. Experimental Program

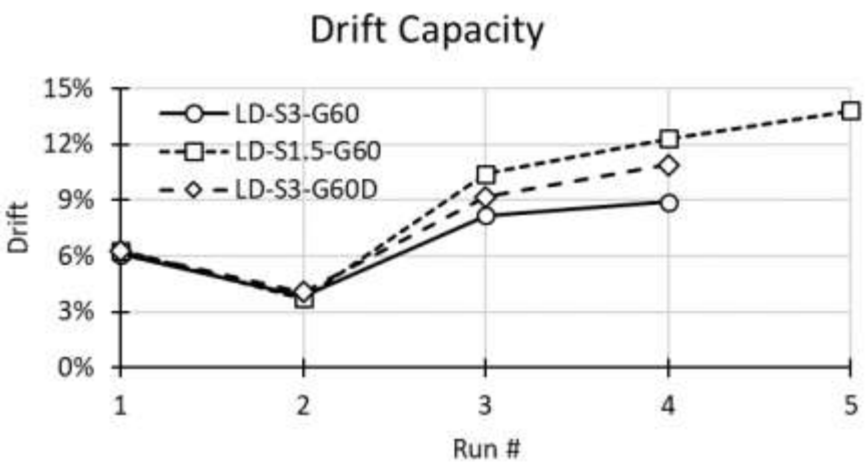
Results – Phase I

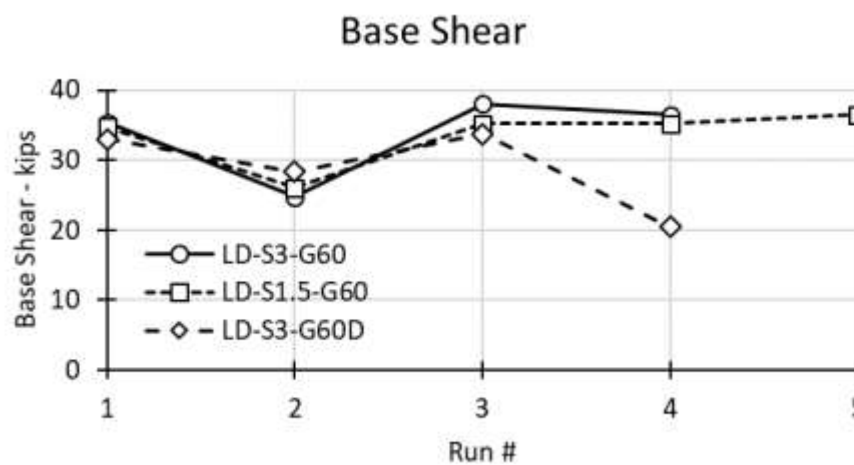
LD-S3-G60D

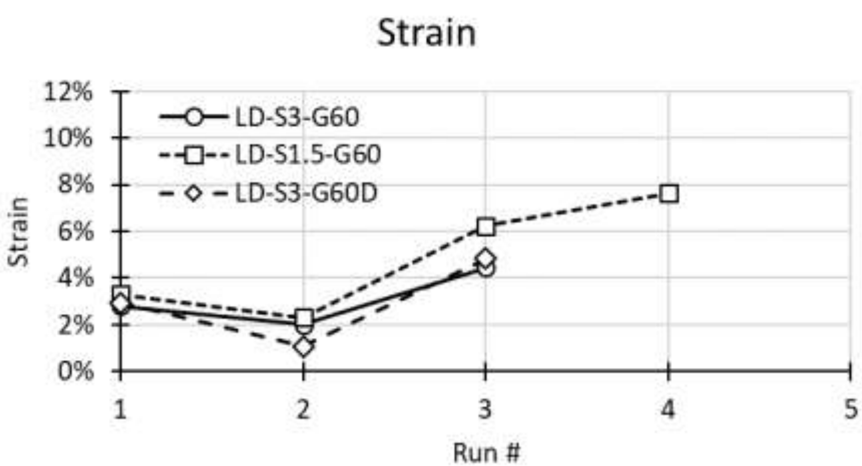
Run #	**1: 100% Tohoku**	**2: 100% Aftershock**	**3: 125% Tohoku**	**4: 150% Tohoku**
Max Disp.	+4.49 in.	-2.93 in.	+6.61 in.	**+7.82 in.**
Max Drift	6.24%	4.07%	9.18%	**10.9%**
Res. Drift	0.40%	**0.47%**	0.18%	0.28%
Max B.S.	+32.99 kips	-25.36 kips	**+33.74 kips**	-20.49 kips
Max Strain	2.95%	1.08%	4.84%	Rupture
Damage State	Major spalling	Same as previous run	Long. bars buckling, 1 bar ruptured	8 long. bars ruptured



4. Experimental Program
Comparison – Phase I







Drift Capacity

LD-S1.5-G60 $S = 3\ d_b$	**= 1.5 ×**	**LD-S3-G60** $S = 6\ d_b$ Not debonded
LD-S3-G60D Debonded	**= 1.2 ×**	

5. What is next?

- Construct three specimens for Phase II
- Conduct the shake table tests for the second phase
- Process and interpret shake table test data to understand effect of design details on mitigating duration effects
- Conduct post-test analysis using calibrated models to provide modeling guidelines on conventional and high strength steel bar rupture and low-cycle fatigue as it relates to the earthquake duration
- Evaluate and/or develop design guidelines

5. Concluding Remarks (1/2)

- Analysis results demonstrate that earthquake duration had noticeable effect on the collapse capacity of bridge columns
- The median collapse capacity under long duration ground motions is about 30% lower when compared to the short duration ground motions as obtained from fragility curves
- From shake table tests, all columns failed by developing full plastic hinges as expected from design, with rebar rupture eventually dictated by low-cycle fatigue
- Using smaller spacing for transverse reinforcement significantly helped improve the column performance with about 50% larger displacement capacity

5. Concluding Remarks (2/2)

- Debonding the longitudinal bars at the column-footing interface was less effective with about 20% increase in displacement capacity under long duration motions
- The varied design/detailing parameters affect only the seismic performance of the columns in the nonlinear range, i.e. initial stiffness and first yield were same for all cases

THANK YOU! QUESTIONS?