2020 PEER Annual Meeting

Shake Table Tests of RC Bridge Columns with Conventional and High-Strength Steel under Long Duration Earthquakes

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PEER
University of Nevada, Reno
Iowa State University
Stanford University

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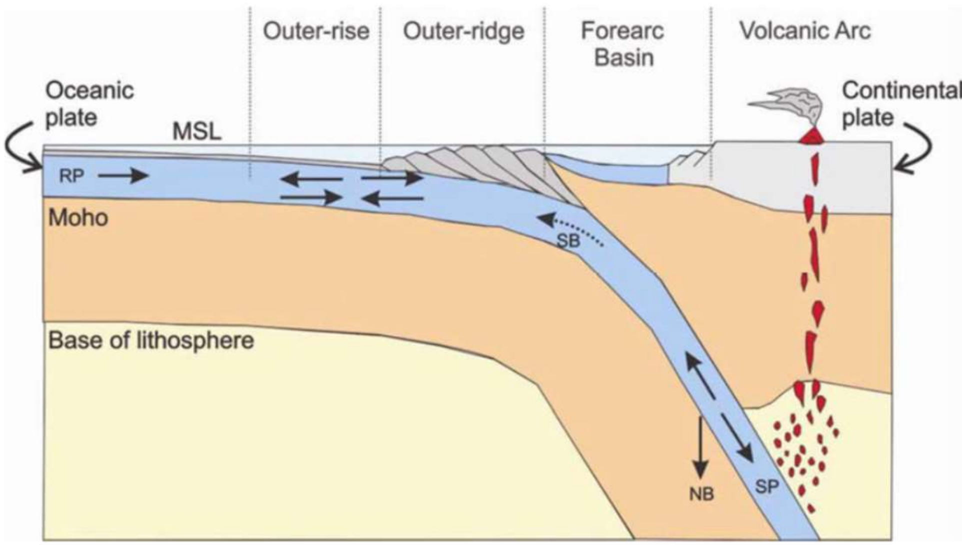
Outline

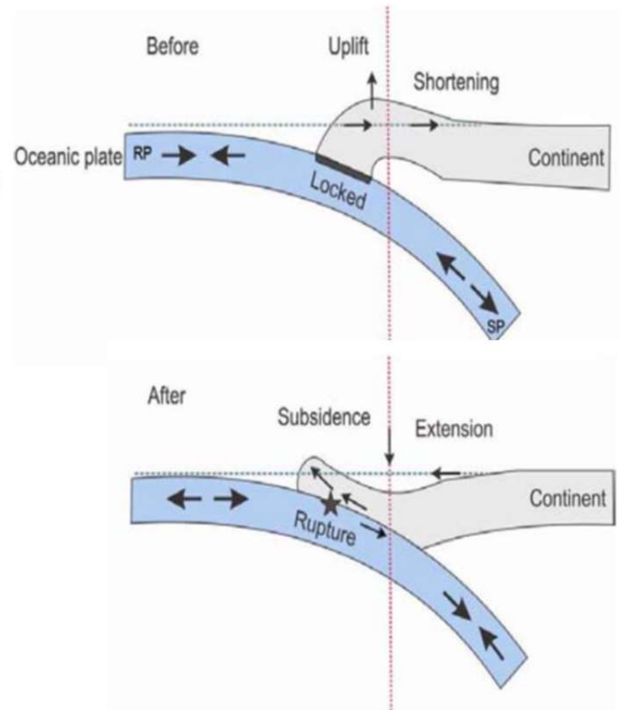
- Introduction
- Experimental Program Development
- Experimental Results: Phase I *(complete)*
- Experimental Results: Phase II *(preliminary)*
- Concluding Remarks

Introduction
Long duration and Subduction zones

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

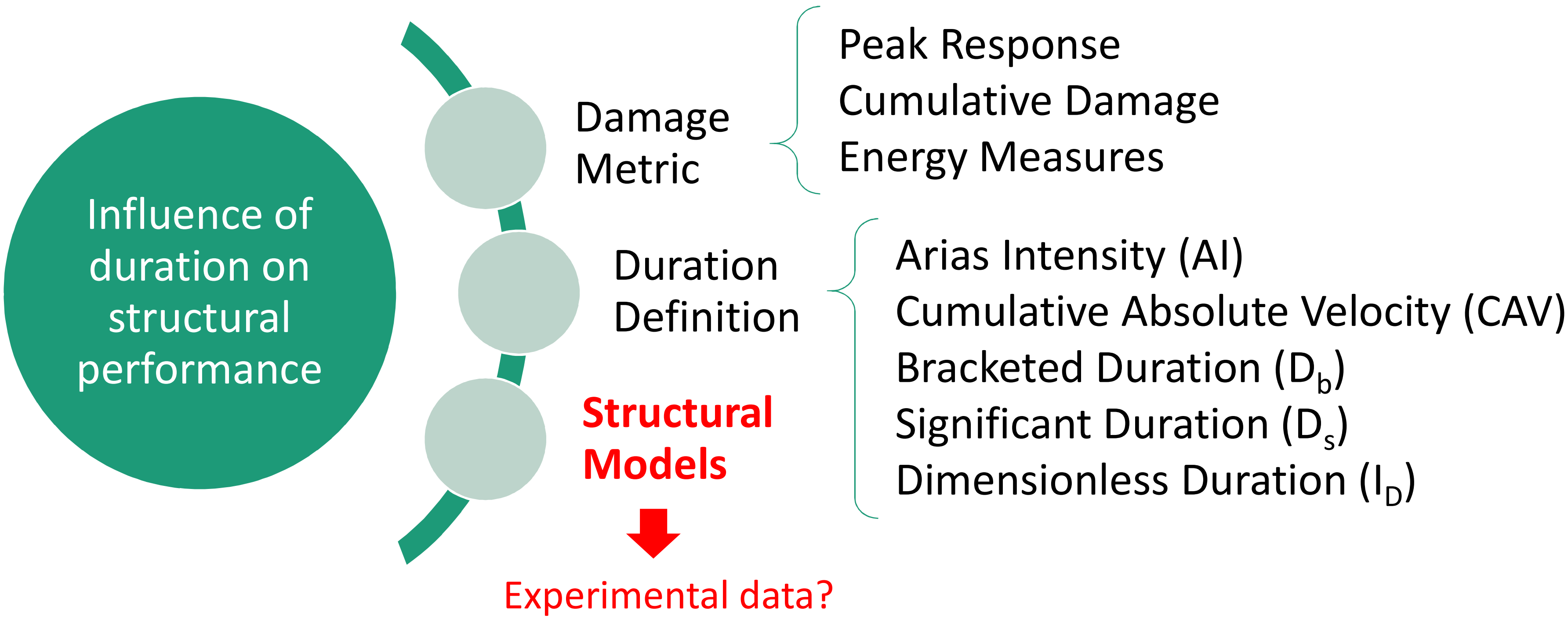
These earthquakes are shallow; their rupture areas are very large; and they release a large amount of energy





Introduction
Account for duration effect

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



Overall Objectives

- Develop models and recommendations for considering earthquake duration in the performance assessment and design of bridges.
- Develop improved design details to mitigate the effect of duration on reinforced concrete bridge piers.
- Leverage research on cyclic deterioration to help qualify the use of high strength reinforcement in seismic design of bridges.

Experimental Program

Specimens

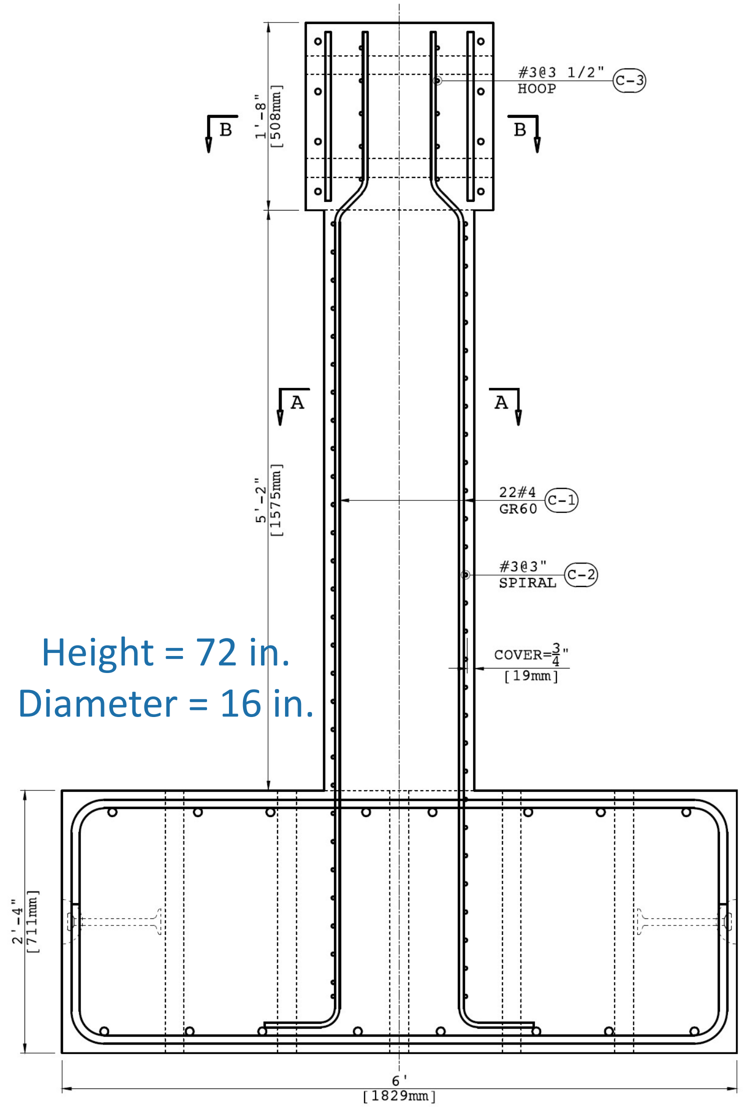
- Six 1/3-scale CIP circular bridge columns tested in two phases:

First Phase (Gr60 Steel):

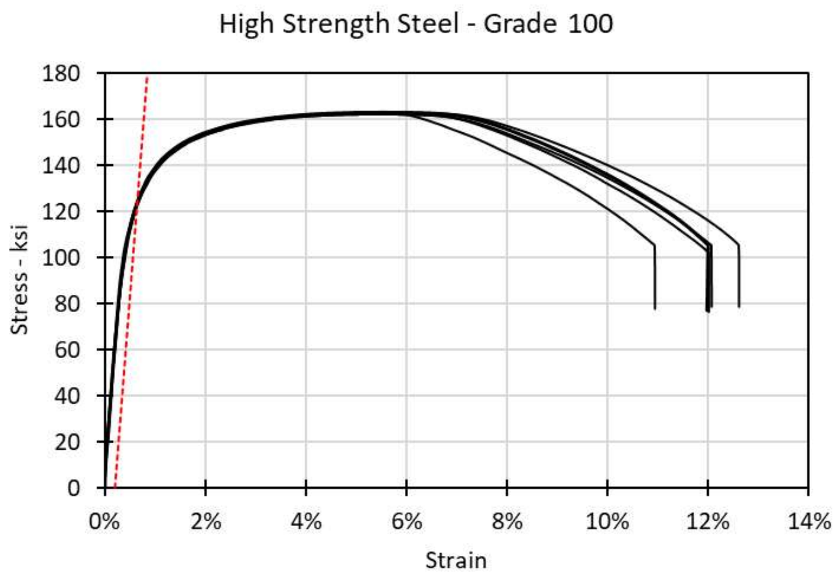
- Two columns with different transverse reinforcement details
- One column with debonding details for longitudinal bars

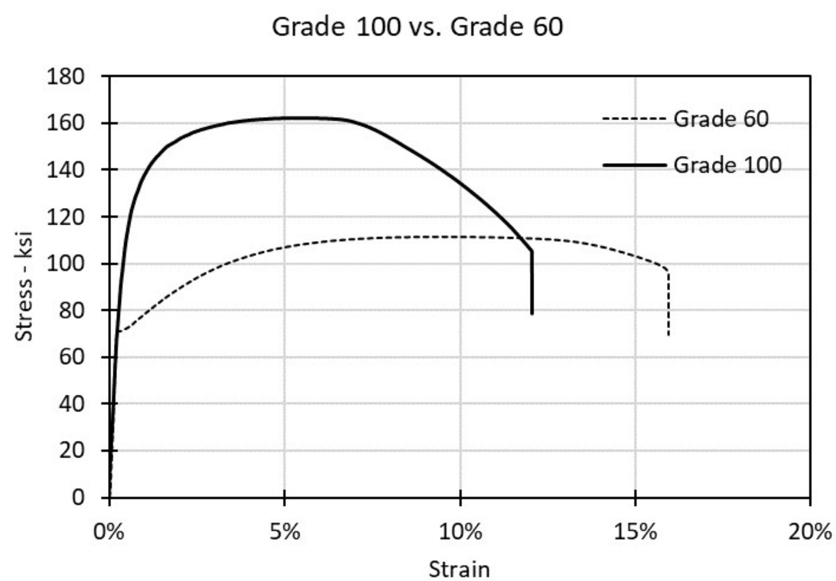
Second Phase (Gr100 Steel):

- Three columns with **HSS** long. bars and different trans. reinf. details – Tested under long and short duration motions



Experimental Program
Reinforcing steel stress-strain curves





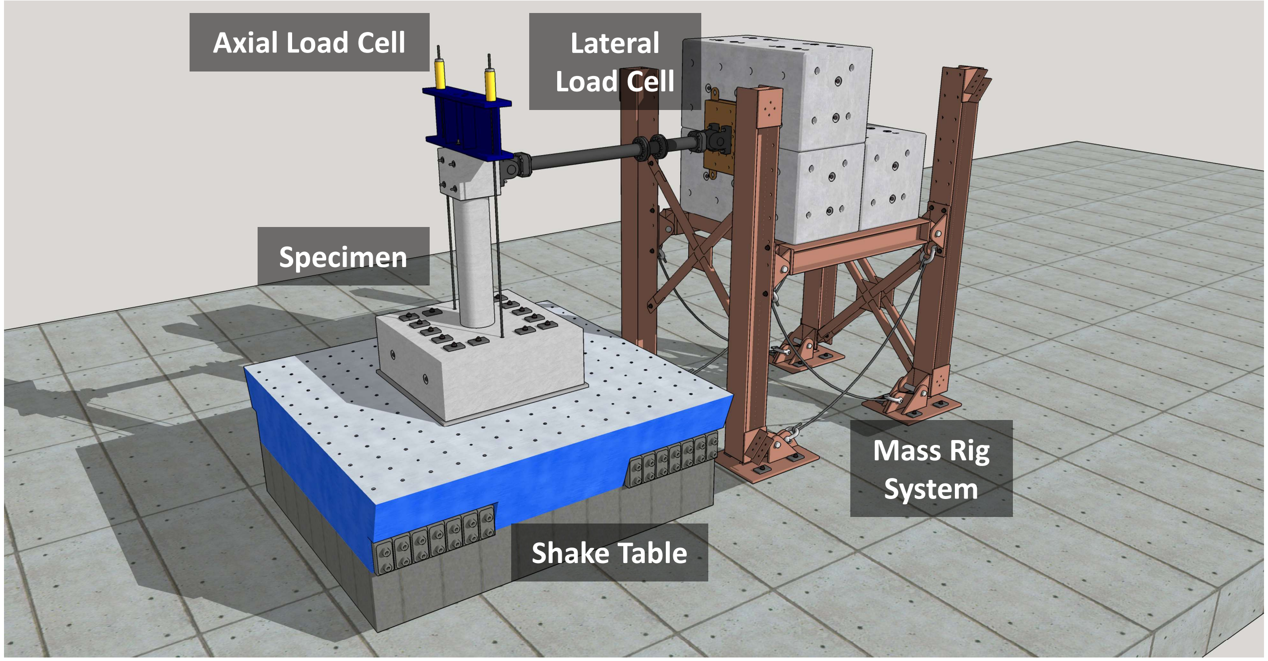
High strength steel properties

F_y (ksi)	ε_y	F_{max} (ksi)	F_u (ksi)	ε_u
124	0.64%	169	105	12%

Experimental Program

Test matrix and setup

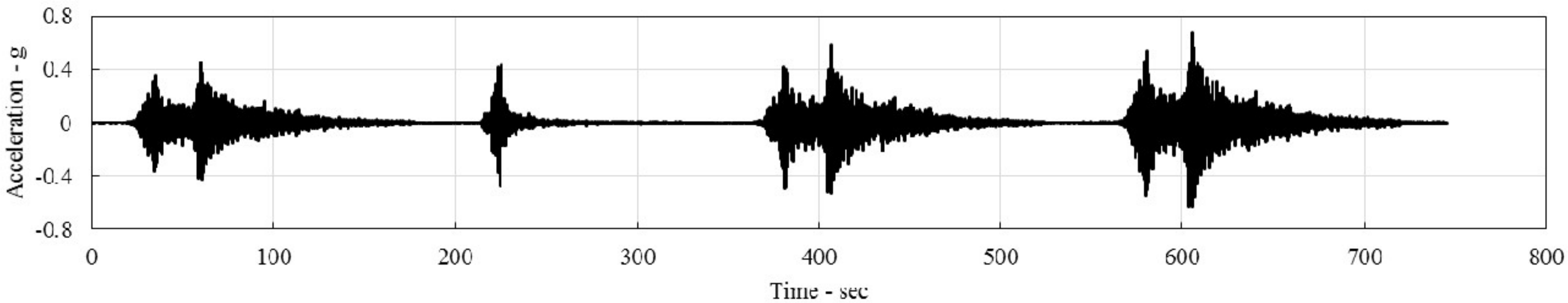
Specimens	Phase I			Phase II		
	LD-S3-G60	**LD-S1.5-G60**	**LD-S3-G60D**	**LD-S3-G100**	**LD-S1.5-G100**	**SD-S3-G100**
Long. Reinf.	22 #4 (2.2%) Gr 60	22 #4 (2.2%) Gr 60	22 #4 (2.2%) Gr 60debonded	14 #4 (1.4%) Gr 100	14 #4 (1.4%) Gr 100	14 #4 (1.4%) Gr 100
Trans. Reinf.	#3 @ 3 in. (1.04%)	#3 @ 1.5 in. (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



Experimental Program
Loading protocol

- *Loading protocol (Phase I):*

Run 1	Run 2	Run 3	Run 4	Run 5
100% main motion	100% aftershock	125% main motion	150% main motion	160% main motion



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

Experimental Program
Loading protocol

- ***Loading protocol (Phase II):***

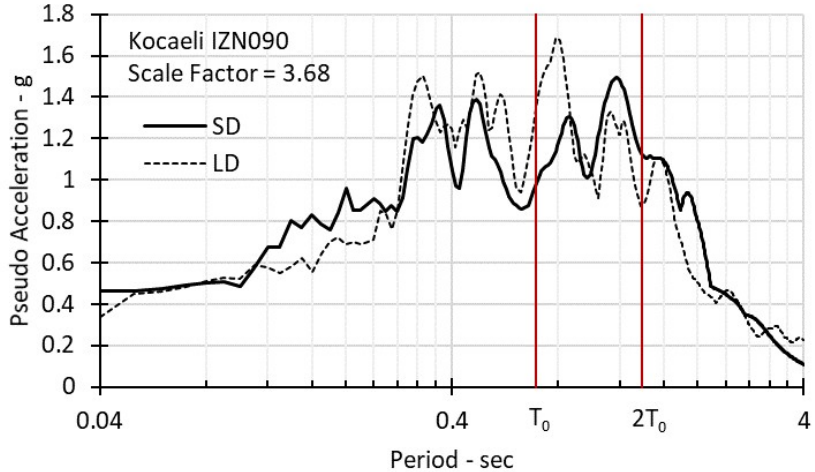
  Long duration motion: 2011 Tohoku (Japan) recorded at MYG006E-W Chosen from the previous study by Sanders et al.

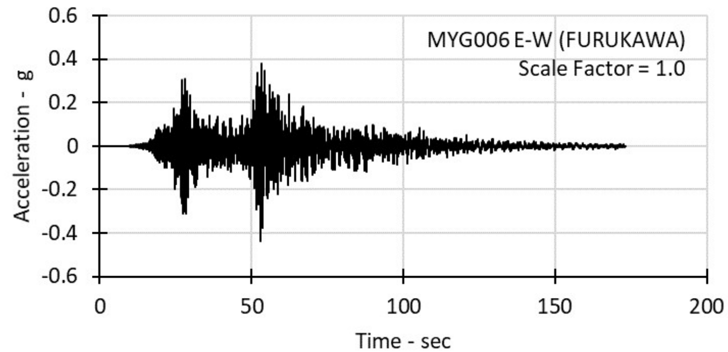
  Short duration motion: 1999 Kocaeli (Turkey) recorded at IZN090 Scaled by 3.68 – Spectrally equivalent with the LD motion

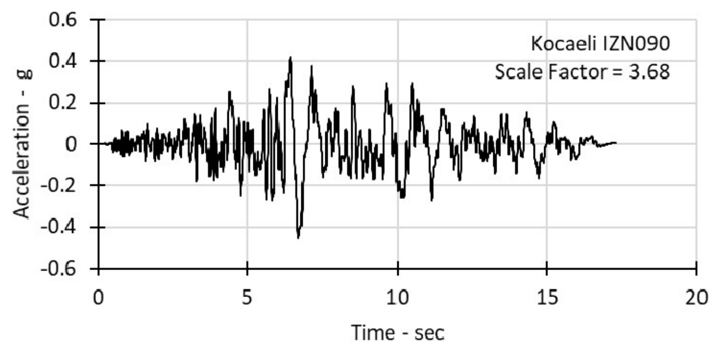
LD-S1.5-G100 & SD-S3-G100
Run 1
100% main motion

LD-S3-G100

Run 1	Run 2	Run 3
25% main motion	50% main motion	100% main motion

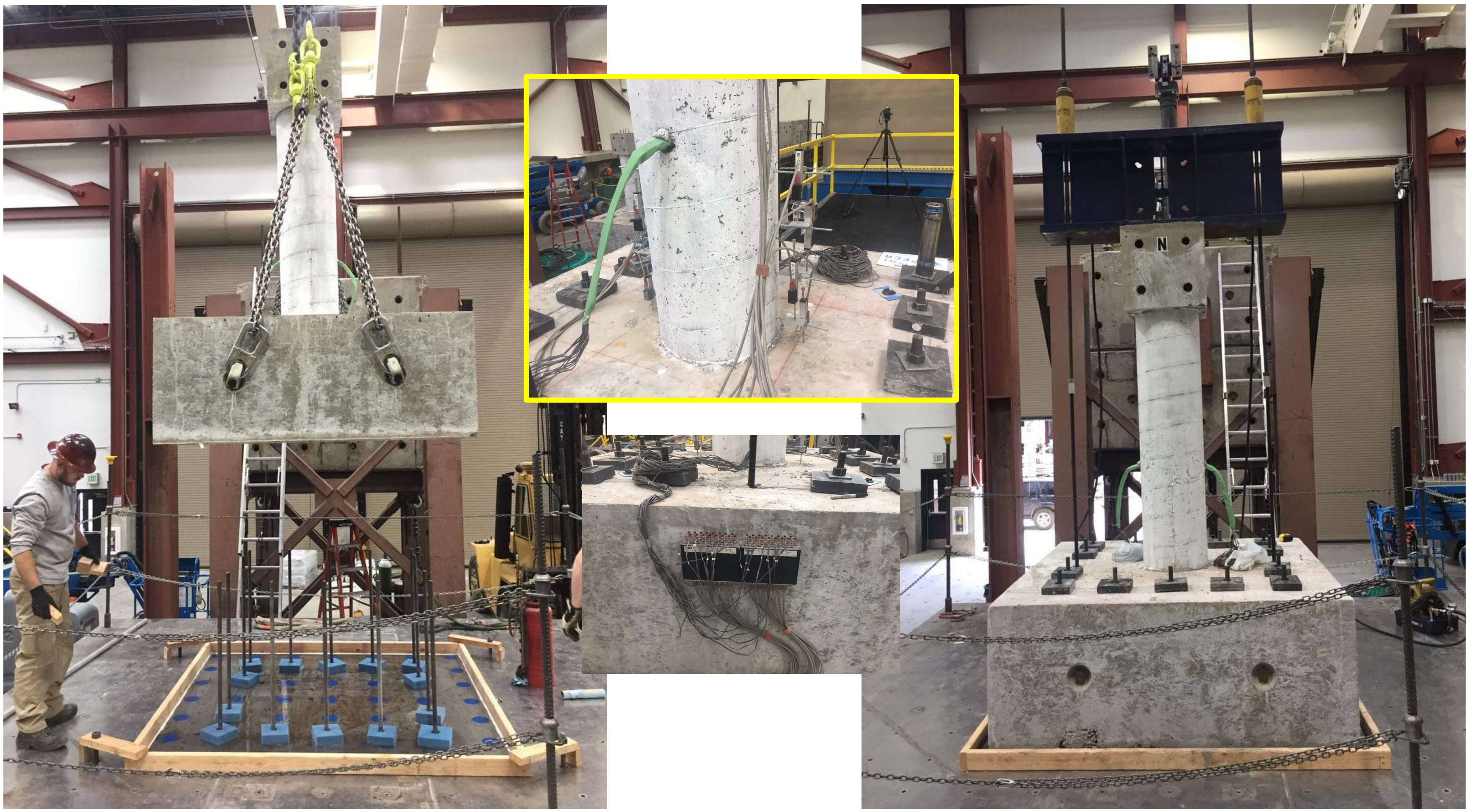






Experimental Program
Construction

Experimental Program
Assembly and test setup



Experimental Program
Assembly and test setup

Experimental Results: Phase I

Shake table tests

Experimental Results: Phase I

Shake table tests

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

Experimental Results: Phase I

Shake table tests

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

Experimental Results: Phase I

Shake table tests

Column LD-S1.5-G60 (Run 5: 160% Tohoku EQ)

Experimental Results: Phase I

Observations

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 4, 5: **150%** Tohoku EQ

Drift capacity: **10.9%**

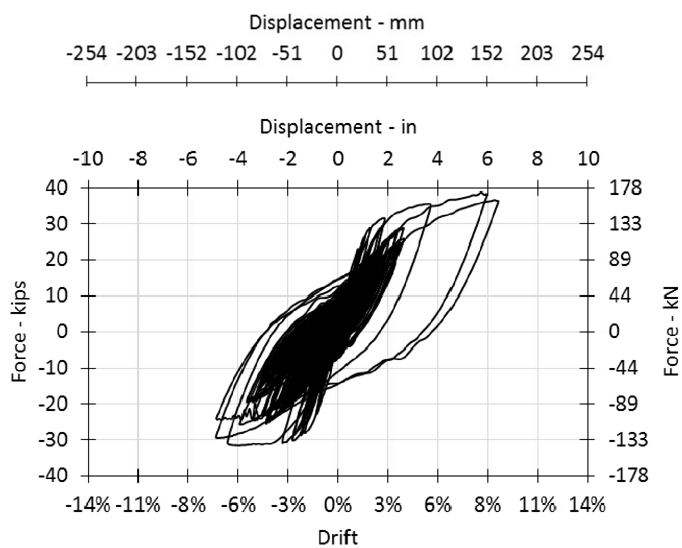
Base shear: **33.7 kips**

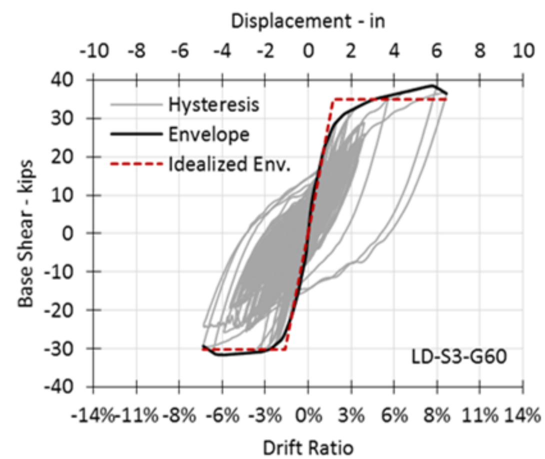
Experimental Results: Phase I

Results Summary

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



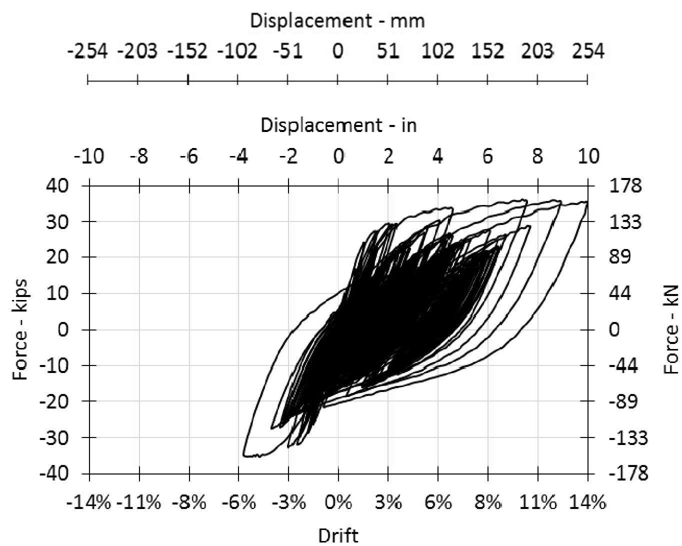


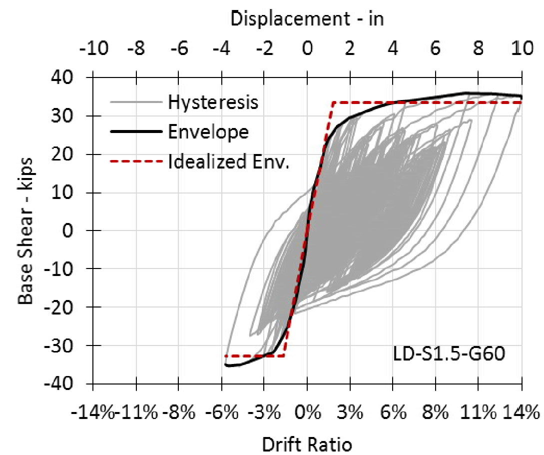
Experimental Results: Phase I

Results Summary

LD-S1.5-G60

Run #	1: 100% Tohoku	2: 100% A.S.	3: 125% Tohoku	4: 150% Tohoku	4: 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



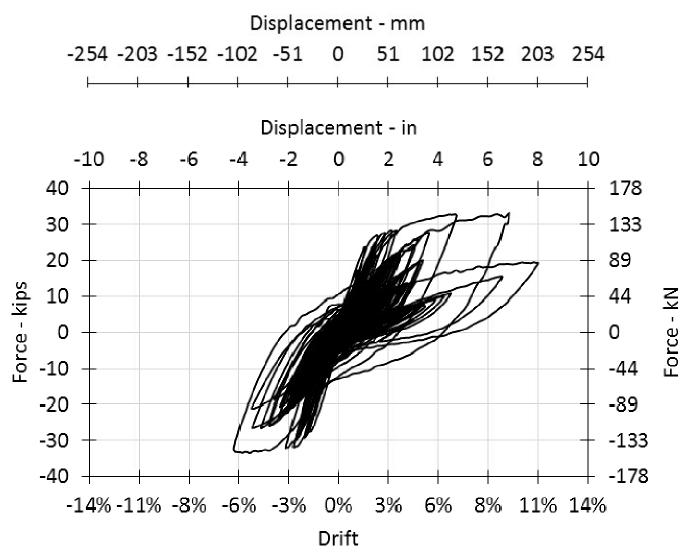


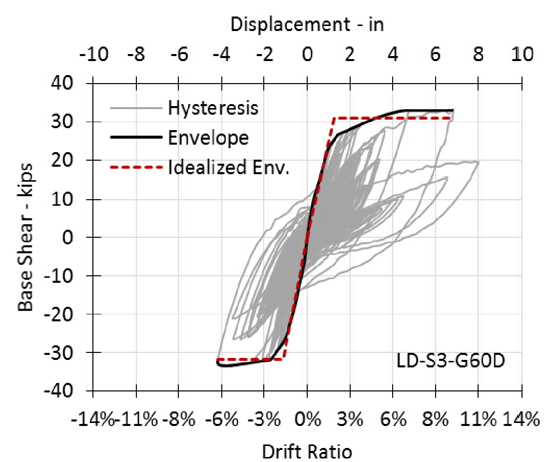
Experimental Results: Phase I

Results Summary

LD-S3-G60-Debond

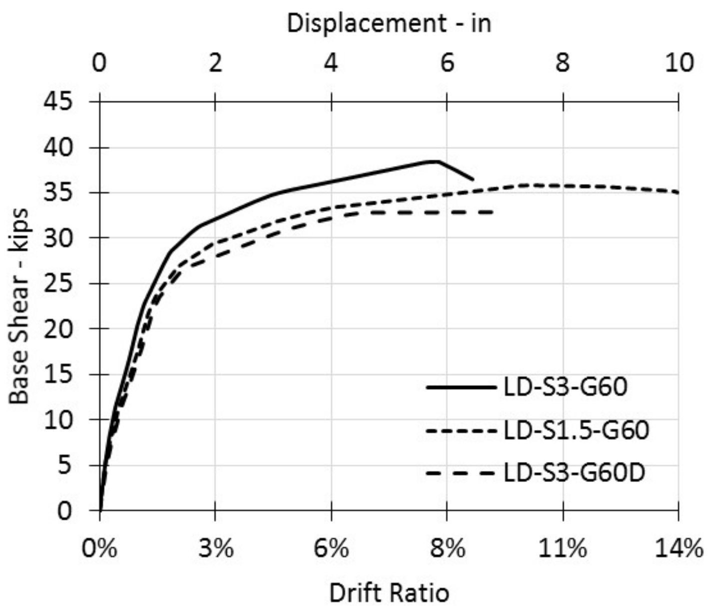
Run #	**1: 100% Tohoku**	**2: 100% Aftershock**	**3: 125% Tohoku**	**4: 150% Tohoku**
Max Disp.	+4.49 in.	-2.93 in.	+6.61 in.	**+7.82 in.**
Max Drift	6.24%	4.07%	9.18%	**10.9%**
Res. Drift	0.40%	**0.47%**	0.18%	0.28%
Max B.S.	+32.99 kips	-25.36 kips	**+33.74 kips**	-20.49 kips
Max Strain	2.95%	1.08%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

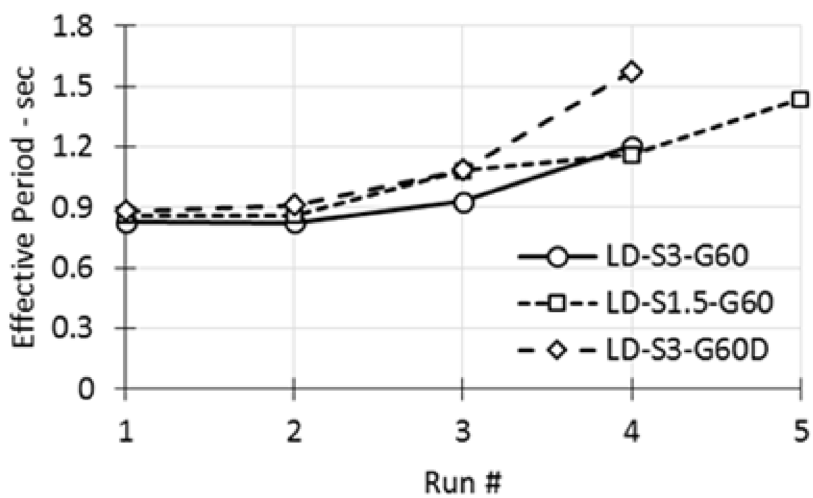




Experimental Results: Phase I
Results Summary

- Higher displacement ductility capacity in the column LD-S1.5
- Higher force capacity in the column LD-S3
- Close initial stiffness for all three columns
- Period elongation for all the test models as nonlinearity spreads

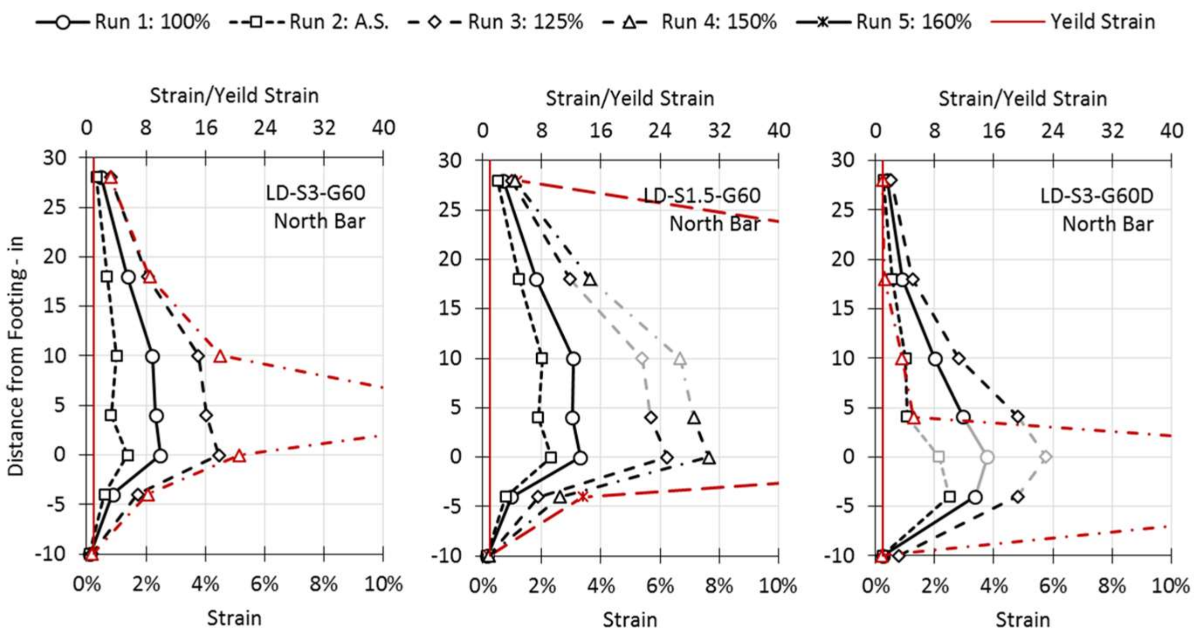




Experimental Results: Phase I

Strain Results

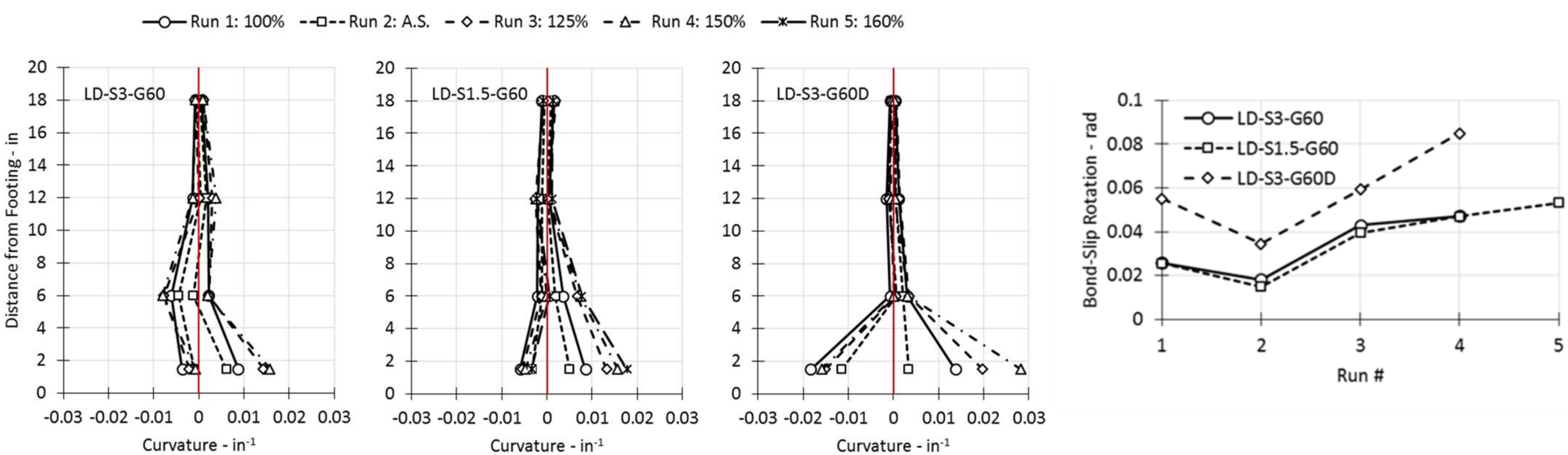
- Strains are distributed well along the length of the plastic hinge
- LD-S1.5-G60 : Larger strains due to larger displacements
- LD-S3-G60D : Strain concentration in the vicinity of the column-footing interface was reduced as a result of debonding



Experimental Results: Phase I

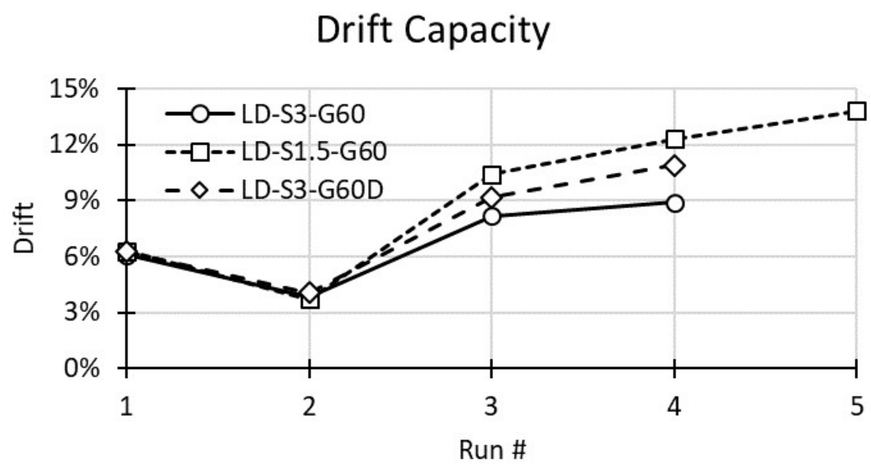
Curvature and Rotation Results

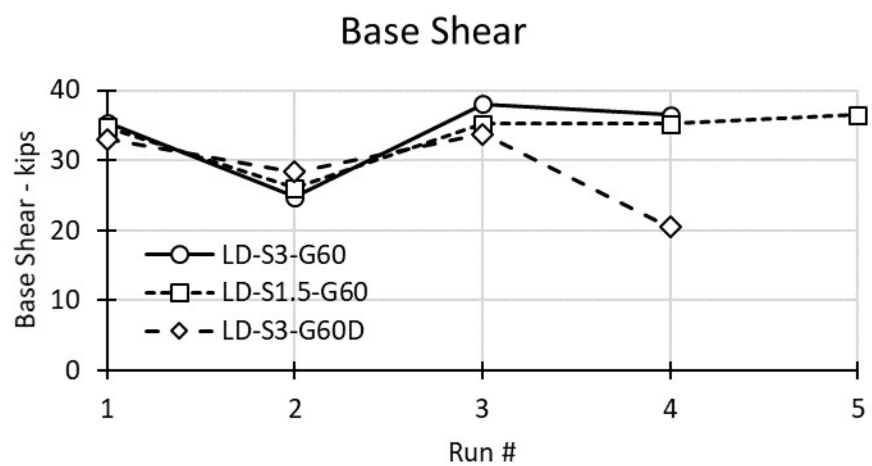
- Curvature was more concentrated at the column-footing interface
- Higher rotational capacity of the last specimen due to the intentional debonding

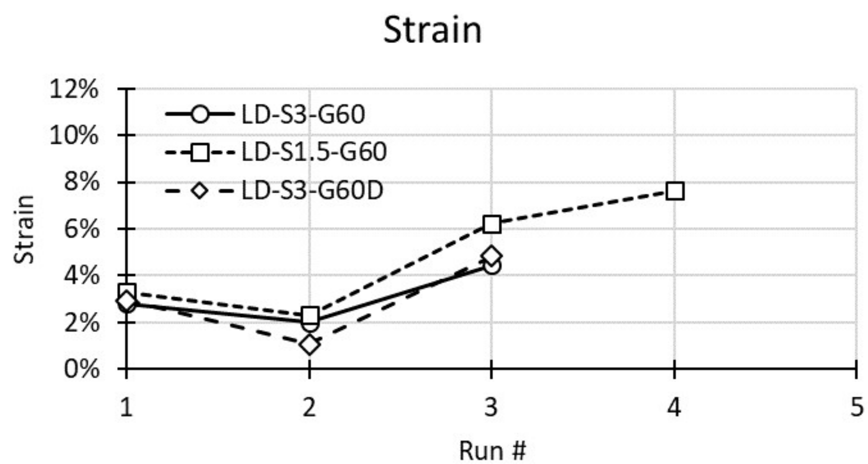


Experimental Results: Phase I

Comparisons







Displacement 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 ×**	

Experimental Results: Phase II *(prelim.)*

Observations

LD-S1.5-G100

6 long. bars ruptured in run 1: **100%** Tohoku EQ

Drift capacity: **7.7%**

Base shear: **39.4 kips**

SD-S3-G100

3 long. bars ruptured in run 1: **100%** Kocaeli EQ

Drift capacity: **9.6%**

Base shear: **39.6 kips**

LD-S3-G100

long. bars ruptured in run #: **##%** Tohoku EQ

Drift capacity: **##%**

Base shear: **## kips**

Experimental Results: Phase II

Shake Table Tests

Column LD-S1.5-G100 (Run 1: 100% Tohoku EQ)

Experimental Results: Phase II
Shake Table Tests

Column SD-S3-G100 (Run 1: 100% Kocaeli EQ)

Experimental Results: Phase II

Shake Table Tests

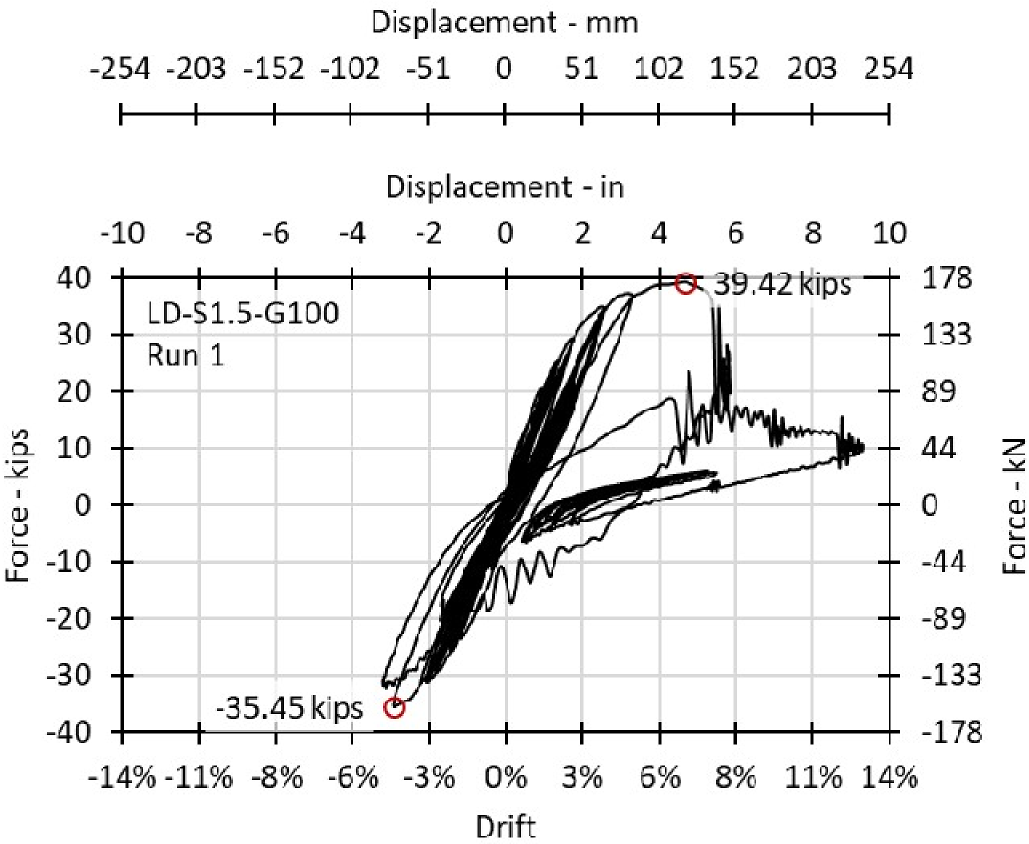
Column LD-S3-G100 (Run 3: 100% Tohoku EQ)

Experimental Results: Phase II

Results Summary

LD-S1.5-G100

Run #	**1: 100% Tohoku**
Max Disp.	5.5 in.
Max Drift	7.7%
Res. Drift	2.8%
Max B.S.	+39.4 kips
Max Strain	-
Damage State	Major spalling 5 long. Bars ruptured at time 60 sec

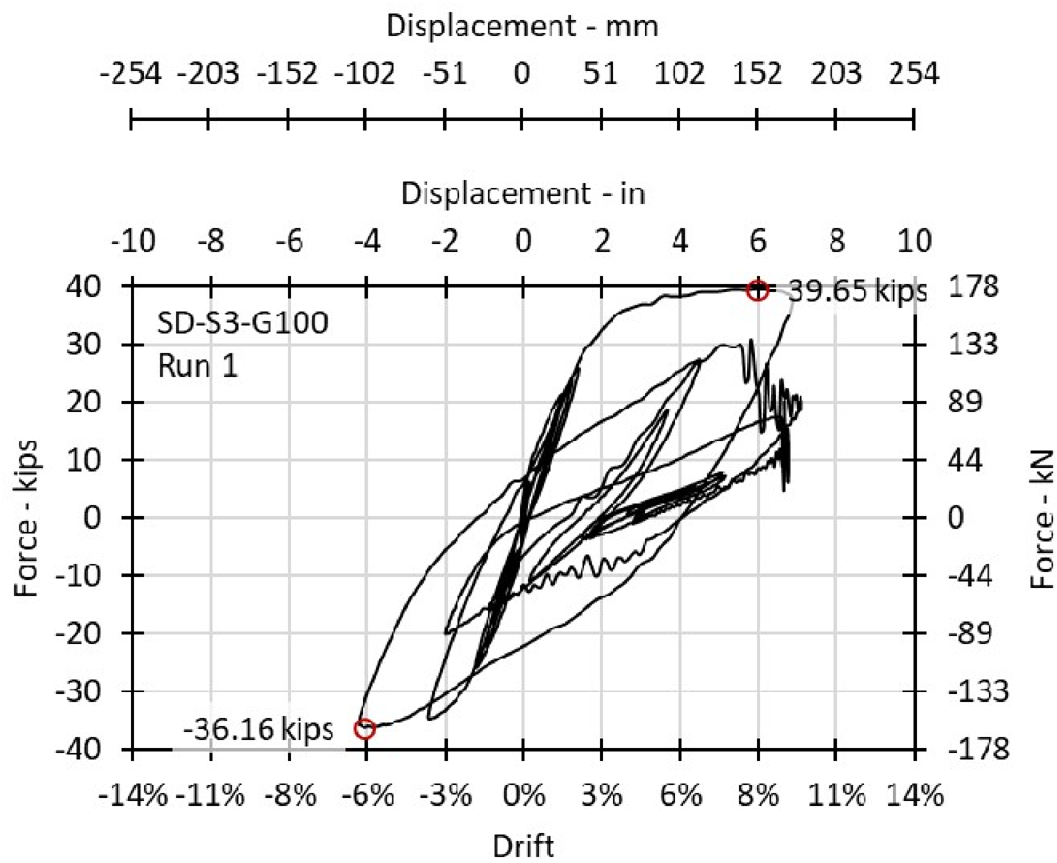


Experimental Results: Phase II

Results Summary

SD-S3-G100

Run #	**1: 100% Kocaeli**
Max Disp.	6.9 in.
Max Drift	9.6%
Res. Drift	4.2%
Max B.S.	+39.6 kips
Max Strain	-
Damage State	Major spalling 3 long. Bars ruptured

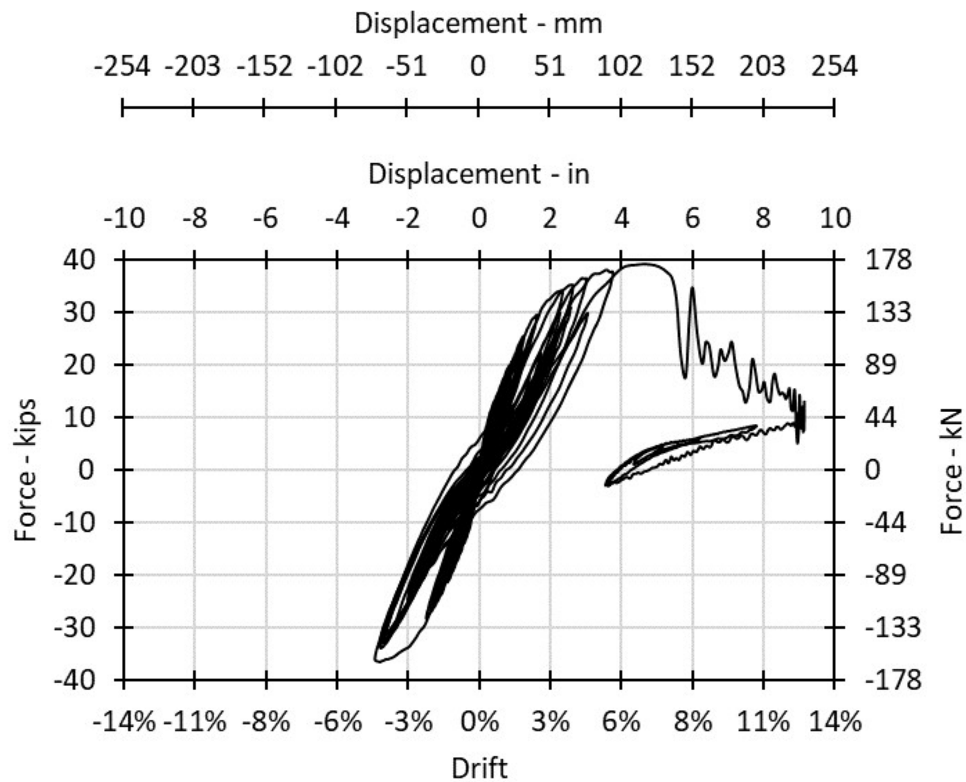


Experimental Results: Phase II

Results Summary

LD-S3-G100

Run #	1: 25% Tohoku	2: 50% Tohoku	3: 100% Tohoku
Max Disp.	0.9 in.	3.0 in.	5.5 in.
Max Drift	1.3%	4.2%	7.7%
Res. Drift	0.0%	0.2%	6.8%
Max B.S.	-21.3 kips	+36.6 kips	+39.2 kips
Max Strain	0.4%	2.7%	-
Damage State	Minor flexural cracks	Major spalling	5 long. Bars ruptured at time 60 sec



Experimental Results: Phase II

Comparisons

- Higher displacement capacity in the column SD-S3-G100
- Same displacement capacity in the columns subjected to the long duration motion
- Same force capacity for all the columns
- Close initial stiffness for all three columns
- Strain concentration in the vicinity of the column-footing interface ?

What is next?

- Process and interpret shake table test data from Phase II of testing to better understand HSS behavior
- Compile “and compare” results from previous long duration project and phase I and II of this PEER project
- 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

Concluding Remarks

- Phase I: Columns with conventional steel (Gr 60):
  - The seismic performance of the columns were satisfactory: All the columns performed in a ductile manner
  - Collapse in all specimens happened due to low-cycle fatigue
  - Using smaller spacing for transverse reinforcement significantly helped to improve the columns performance (50%)
  - Debonding the longitudinal bars at the column-footing interface was less effective (20%) on the displacement capacity of the column.
  - 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

Concluding Remarks

- Phase II: Columns with high strength steel (Gr 100):
  - All the columns showed lower displacement capacity compared to the columns in phase I, while they had slightly better force capacity
  - Using smaller spacing for trans. reinforcement did **not** help to improve the column performance
  - The column subjected to the short motion showed a 25% higher displacement capacity compared to the long motion cases
  - <u>*Interrogate possible reasons:*</u> strain concentration at the column-footing interface ? Would de-bonding help?
  - <u>*Interrogate possible reasons:*</u> HSS bars fracture does **not** seem to be heavily attributed to Low-Cycle Fatigue as suggested by comparing two columns under long duration motion?

THANK YOU! QUESTIONS?