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Seismic Performance of a Novel Corrosion-Free Beam-Column Made with UHPC, FRP, and Stainless-Steel Materials

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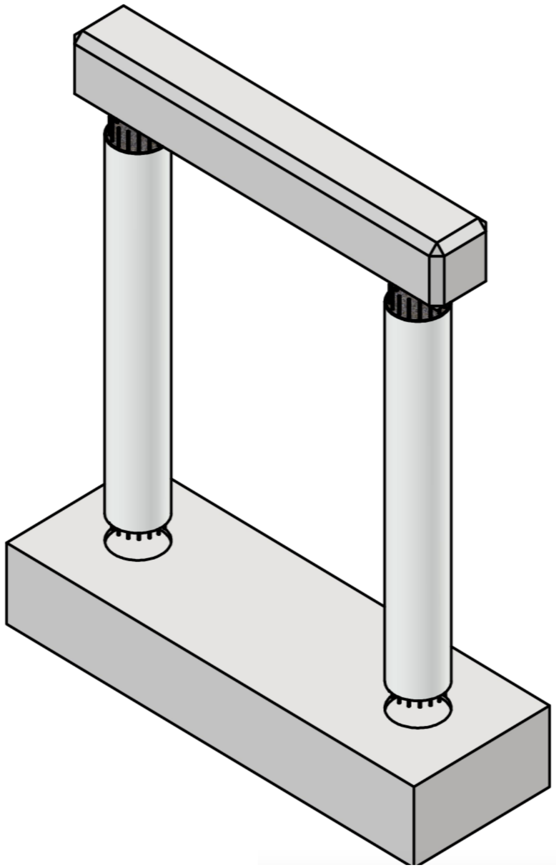
The SOURCE

Steelike®
Concrete

Sika®

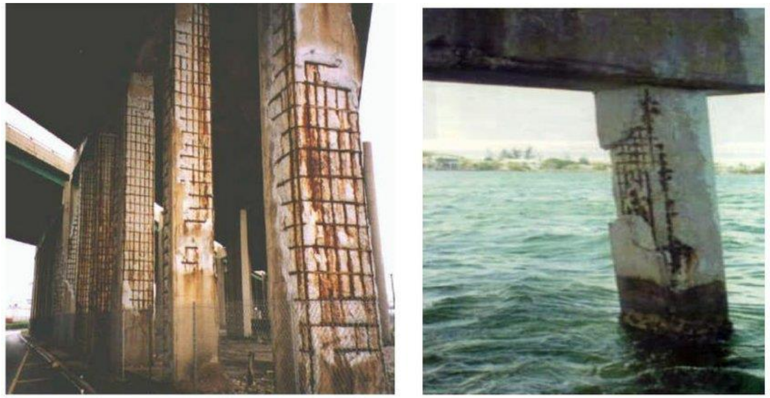
Overview

- Background
- Proposed New Configurations
- Materials
- OpenSEES Simulation
- Parametric Study: FRP Ratio
- Parametric Study: Steel Reinforcement Ratio
- Ground Motion Simulation
- Conclusions
- References



Background

- Current Reinforced Concrete (RC) bridge infrastructure is vulnerable to chloride and salt in marine environments, and de-icing application for highway bridges, and thus experiences deterioration due to reinforcement corrosion.
- According to the USDOT FHWA, more than half of the total bridge inventory in the United States are RC bridges.
  - Traditional configuration may lead to an inadequate service-life if structures are not maintained properly and/or adequately.
- Annual maintenance cost of bridge corrosion is an estimated 13.6 billion dollars (Azari et al., 2020).
- Another study by Yunovich et al. (2003) included indirect factors into the entire lifecycle cost, in which case the cost increases up to a factor of 10.



Corrosion in Typical RC Bridge Piers (Mohammed Al-Ani, 2015)

Corrosion in RC Bridge Piers and Pier Caps at Lakeshore BLVD. Crossing Yonge St. of Toronto, ON in July 2023

Background

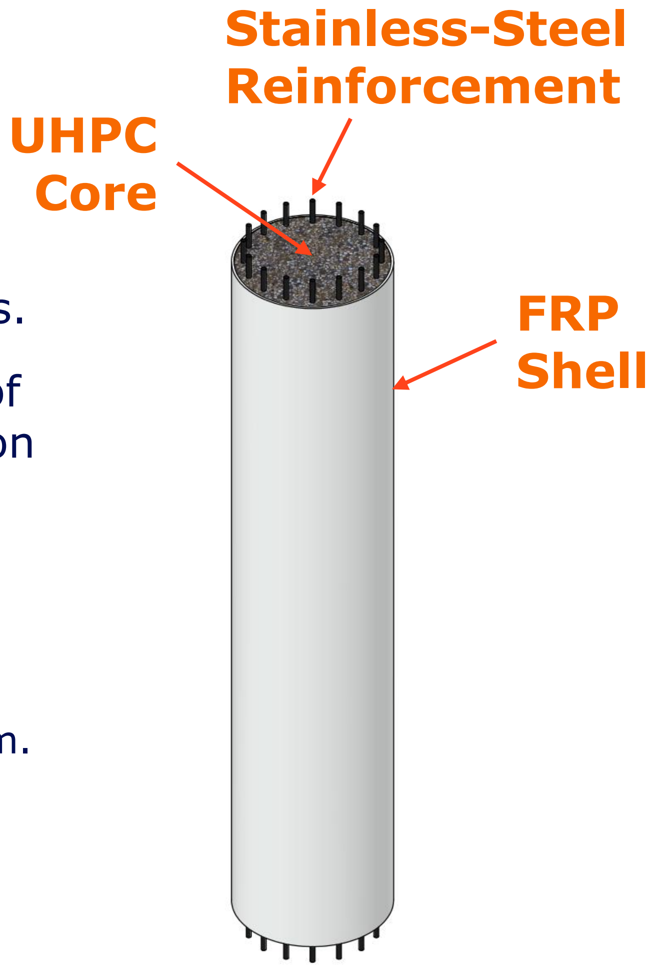
- Previous studies proposed Concrete-Filled FRP Tubes (CFFT) to address the needs for resilience against natural disasters and corrosion challenges.
- The FRP stay-in-place formwork comes with reduced construction costs, time, and workload; provides enhanced structural capacity, and protects RC core from corrosion.
- One previous study was conducted by co-author Yilei Shi, etc. with Dr. Amir Mirmiran (now Provost at UT, Tyler) at Florida International University (FIU) as part of a multi-disciplinary and multi-university NSF-NEESR research project in the last decade.
- FIU's study included cyclic and monotonic flexural tests of CFFT and RC columns, as well as CFFT/RC bridge bents, among other tasks.
- The optimized bridge substructure system was later incorporated into a four-span large-scale bridge tested on shake tables at University of Nevada, Reno (UNR), by Dr. M. Saiid Saiidi (retired).

FIU Large-Scale Bridge Pier Cyclic Tests (Shi 2009)

UNR Four-Span Large-Scale Bridge Shake Table Tests (Kavianipour 2013)

Proposed New Configurations

- Question: although the previous system boasts significant improvement on seismic performance in capacity and ductility over conventional system, it could still be subjected to corrosion by water intrusion through member joints.
- New Proposed Member: a proposed new configuration of this study consists of a UHPC core, FRP shell, & stainless-steel reinforcing bars, and is fully corrosion free, which will extend service life and reduce maintenance costs.
    - FRP shell acts as the first guard against water and chloride intrusion.
    - UHPC core has a 12x lower rate of corrosion than conventional concrete and high resistance to chloride penetration.
    - 10% of stainless-steel composition is chromium, which protects the metal like a film.
- The novel corrosion resistance of this column will provide increased durability and longevity for bridge infrastructure, reducing maintenance costs.



Materials – FRP Shell

- A filament-wound off-the-shelf product of glass FRP tube primarily used in the petroleum industry.
- The total thickness of fiberglass, resin and epoxy is 0.22 in.
- Tensile strength = 10.3 ksi
- Flexural strength = 23 ksi

FIU Large-Scale Bridge Pier Specimens with Various FRP Shells (Shi 2009)

Materials – UHPC Core

- Core diameter of 12.494 in
- Compressive Strength of 27 ksi
- Elastic Modulus of 8,250 ksi
- 2% steel fibers
- Mechanical properties provided by Steelike

TYPICAL MATERIAL PROPERTIES

According to ASTM C1856 / C1856M except where noted otherwise
70°F (21°C) curing temp, 2% load of 0.5-inch x 0.008-inch (13mm x 0.2mm) steel fiber with 435 ksi (3 GPa) tensile strength

Compressive Strength:	2 day	≥ 12 ksi (85 MPa)[1]
	3 days	≥ 14 ksi (94 MPa)
	7 days	≥ 16 ksi (108 MPa)
	14 days	≥ 19 ksi (130 MPa)
	28 days	≥ 22 ksi (150 MPa)
Sustained Post-Cracking Tensile Strength (FHWA[2])		1.07 ksi (7.38 MPa) minimum 1.50 ksi (10.34 MPa) average
Static Modulus of Elasticity		8,250 ksi (57 GPa)
Chloride Ion Penetration (ASTM C1202)		49 coulombs at 56 days
Flow (adjustable per project needs)		7-inch (18-cm) to 10-inch (25-cm) diameter
Working Time		As needed[3]
Set Time (minimum values)		75 minutes initial, 87 minutes final[3]

[1] Steelike® UHPC can be modified to reach 14 ksi compressive strength in as little as 12 hours
[2] Publication FHWA-HRT-17-053 *Tension Testing of Ultra-High Performance Concrete*
[3] Set times and working times can be customized according to project needs

Materials – Stainless Steel Reinforcement

- Grade 75, f_y = 75 ksi
- Reinforcement ratio of 1.5%
  - 16 No. 3 bars
  - A_s = 1.76 in^2
- Rebar is evenly spaced in a circular pattern with a radius of 5.30 in.
- 10% of the composition is chromium, which protects itself like a film.

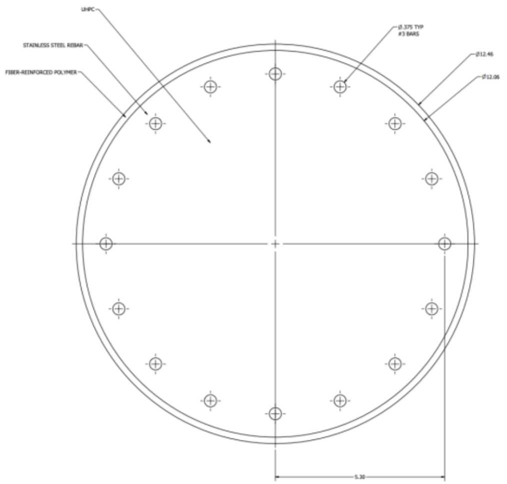


Table 4:

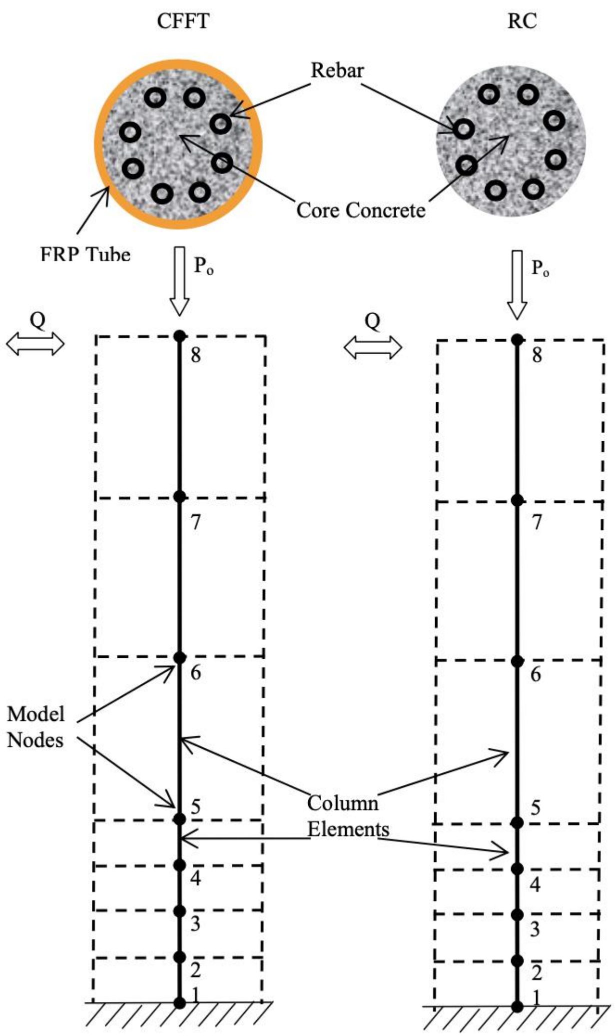
Examples of applications of different grades of SS rebars (un, unknown).

Type of SS	Structure	Location	Date	SL (years)	Reference
304	Bridge on I-696	Detroit, MI, USA	1984	un	www.nickelinstitute.org
304L	Schaffhausen bridge	River Rhine, Switzerland	1995	80	www.stainlesssteelrebar.org
304LN	Guildhall	East London	2000	750	Bertolini et al., 2013
316	Underpass	Newcastle, Tyneside, UK	1995	un	www.nickelinstitute.org
316L	Broadmeadow Bridge	Dublin, Ireland	2003	un	www.stainlesssteelrebar.org
316LN	Gladstone Bridge	Queensland, Australia		un	www.reval-stainless-steel.com
	Bridge	Ajax, Ontario, Canada	1998	un	www.nickelinstitute.org
	Thorold Tunnel	Ontario, Canada	2004	un	www.nickelinstitute.org
21-01	Gateway Bridge	South-east Queensland, Australia	2011	300	www.stainlesssteelrebar.org
	Buddhist Temple	Thailand	2013	300	www.stainlesssteelrebar.org
	Junction Värtan	Stockholm, Sweden	2015	un	www.stainlesssteelrebar.org
22-05	Ramp for Garden State Parkway	NJ, USA	1998	un	www.nickelinstitute.org
	Haynes Inlet Slough Bridge	OR, USA	2004	120	www.stainlesssteelrebar.org
	Belt Parkway Bridge	Brooklyn, USA	2004	100	www.nickelinstitute.org
	Driscoll Bridge	NJ, USA	2004	un	www.nickelinstitute.org
	Siena Footbridge	Siena, Italy	2006	120	www.nickelinstitute.org
	Stonecutters Bridge	Hong Kong, China	2009	120	www.stainlesssteelrebar.org
	Sea wall construction	Arabian Gulf	2009	un	www.nickelinstitute.org
	Little Bay Bridge	Newington, NH, USA	2011	un	Gupta, 2016
	Sakonnet River Bridge	RI, USA	2012	un	www.nickelinstitute.org
	Hurdman Bridge	Ontario, Canada	2014	un	www.stainlesssteelrebar.org
	Bayonne Breakwater	Bayonne, France	2014	un	www.stainlesssteelrebar.org
	Burgoyne Bridge	St. Catharine's, Ontario, Canada	2016	un	Gupta, 2016
23-04	Cameron Heights Dr. Bridge	Edmonton, Alberta, Canada	2010	un	www.nickelinstitute.org
	S. Saskatchewan River Bridge, Medicine Hat	Alberta, Canada	2011	un	www.nickelinstitute.org
	Caminada Bay Bridge	LA, USA	2011	un	Gupta, 2016
	Hastings Bridge	MN, USA	2012	100+	www.stainlesssteelrebar.org
	Riverwalk	Brisbane, Australia	2013	100	www.stainlesssteelrebar.org
	Allt Chonoglias Bridge	Scotland, UK	2013	120	www.stainlesssteelrebar.org
	Coastal Protection	Cromer, UK	2014	50	www.stainlesssteelrebar.org
	Kenaston Overpas	Winnipeg, Manitoba, Canada	2014	un	www.nickelinstitute.org
	Daniel Hoan Bridge	Milwaukee, WI, USA	2014	un	Gupta, 2016
	Macau Bridge	Hong Kong – Zhuhai – China	2016	120	www.stainlesssteelrebar.org
	New Champlain Bridge	Montreal, Canada	2016	un	www.stainlesssteelrebar.org
XM-28	Light rail transit	Edmonton, Alberta, Canada	2012	un	Gupta, 2016
	Osborne Bridge	Winnipeg, Manitoba, Canada	2012	un	Gupta, 2016
	Pulasky skyway	Newark, Jersey City, USA	2014	un	Gupta, 2016
	Kosciuszko Bridge	New York City, USA	2019	un	Gupta, 2016

https://doi.org/10.1515/corrrev-2017-0088 (Lollini 2018)

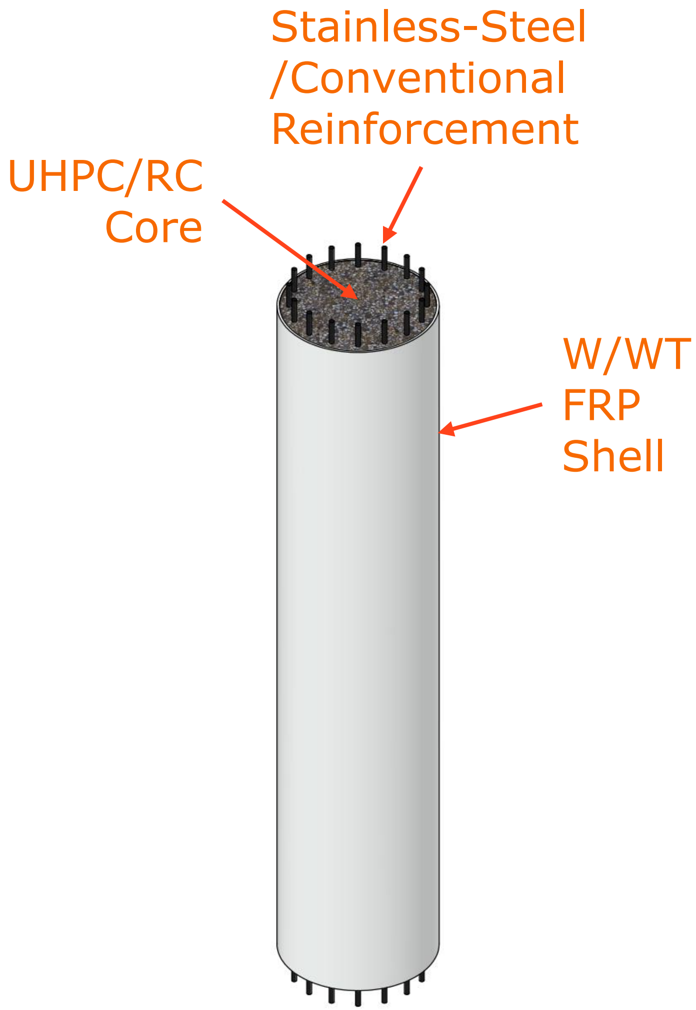
OpenSEES Simulation

- Open System for Earthquake Engineering Simulation, developed by University of California, Berkeley
- Four columns were modeled for both new and conventional configurations to compare the capacity of both types of sections.
- Cyclic lateral loading with constant axial load were induced, with increasing lateral displacement from 0.5 to 3.0 in over 6 cycles with node displacement control.
- The columns were not tested to failure, but previous work found that flexure is the most likely failure mode for long shear-span columns.
- Slippage was neglected in this model and connection to footing is assumed to be perfectly fixed.

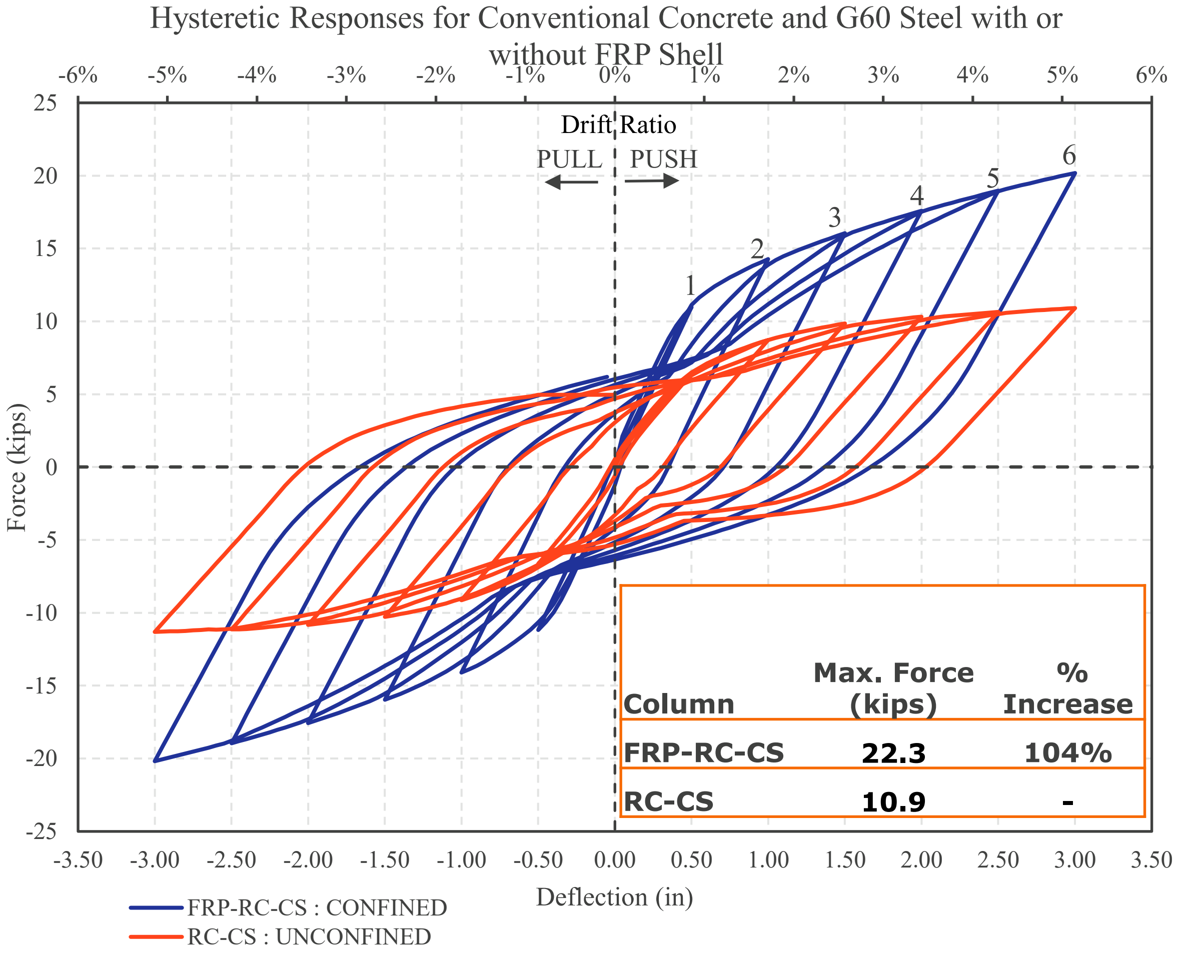


OpenSEES Simulation – Specimen Designation

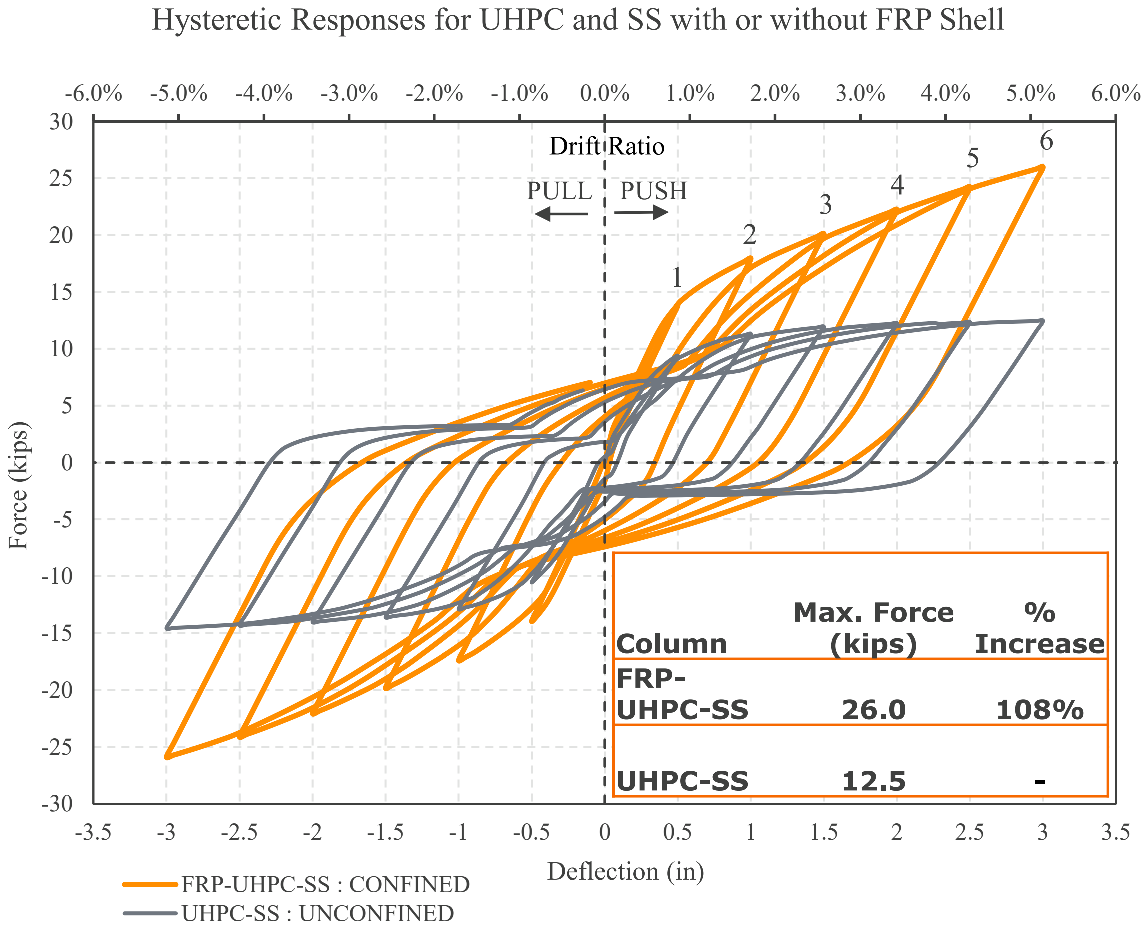
FRP-UHPC-SS	• UHPC core • FRP shell • Stainless steel reinforcement
FRP-RC-CS	• RC core • FRP shell • Grade 60 conventional steel reinforcement
UHPC-SS	• UHPC column • No FRP Shell • Stainless steel reinforcement
RC-CS	• RC column • No FRP Shell • Grade 60 conventional steel reinforcement



OpenSEES Simulation – Hysteretic Responses

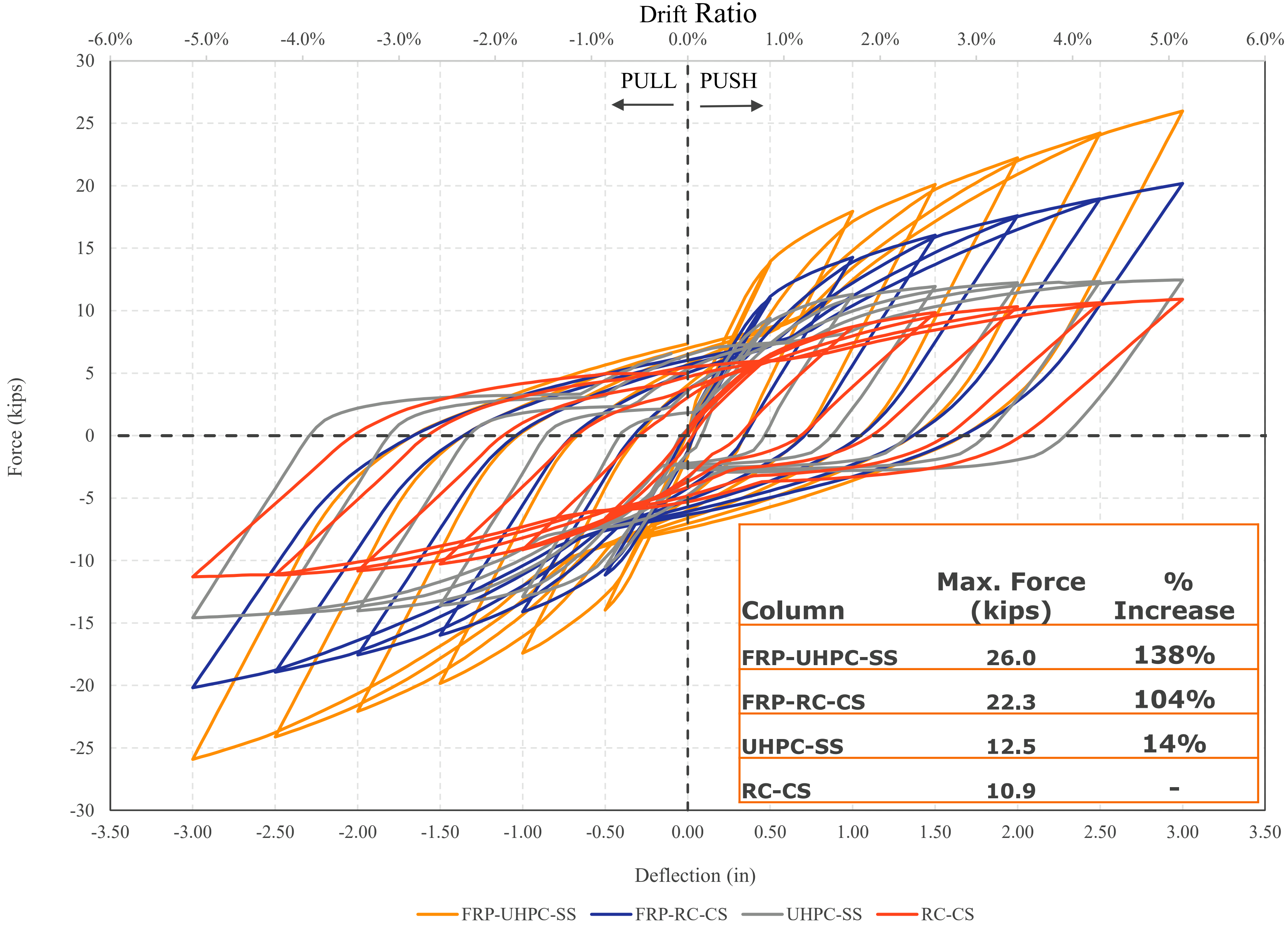


Column	Max. Force (kips)	% Increase
FRP-RC-CS	22.3	104%
RC-CS	10.9	-



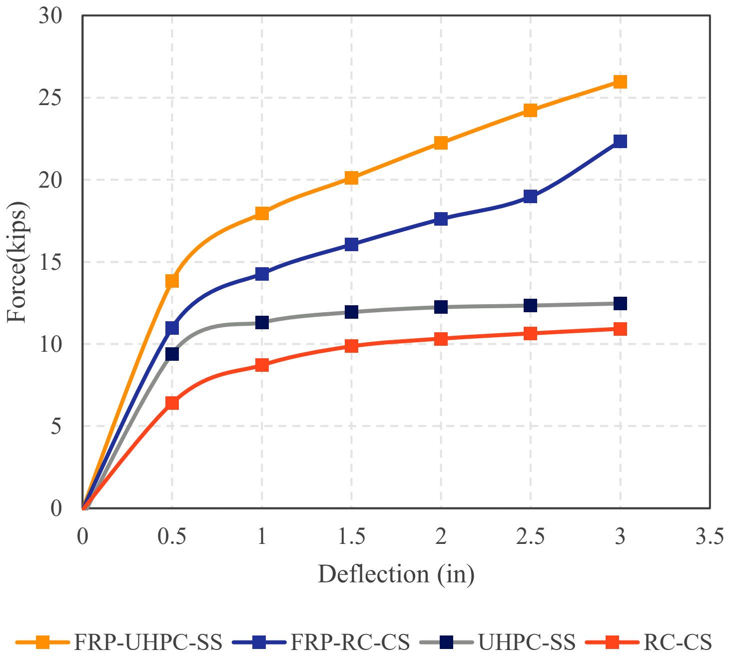
Column	Max. Force (kips)	% Increase
FRP-UHPC-SS	26.0	108%
UHPC-SS	12.5	-

Force-Deflection Hysteretic Responses

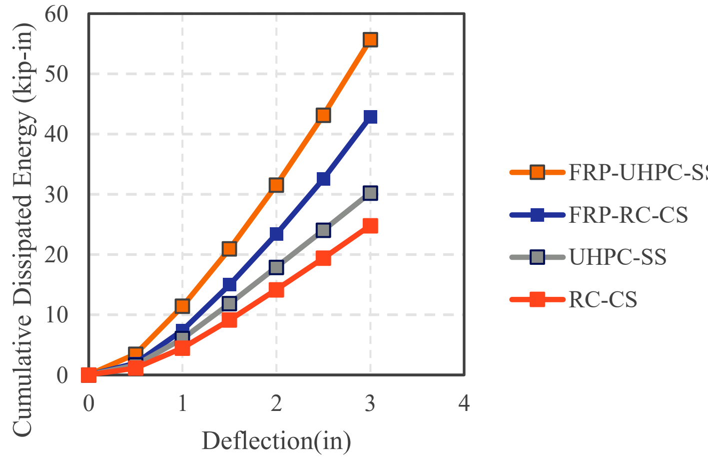


Column	Max. Force (kips)	% Increase
FRP-UHPC-SS	26.0	138%
FRP-RC-CS	22.3	104%
UHPC-SS	12.5	14%
RC-CS	10.9	-

Response Envelope Curve



Cumulative Dissipated Energy



Cyclic Simulation Results

- **Overall Performance**

FRP-UHPC-SS exhibits the best cyclic performance in initial stiffness, flexural strength, and energy dissipation among all four columns.

- **Effect of FRP Shell**

The 108% increase in cyclic performance of FRP-UHPC-SS when compared with UHPC-SS matches very well with the previous study of 104% performance increase of FRP-CS when compared with RC control specimen.

- **Effect of UHPC Core**

The increase of capacity due to the core material enhanced from RC to UHPC is not significant, with or without FRP shell, when compared with capacity increase due to FRP shell. This is attributed to the fact that the columns in this study are mainly in flexural control. The increase will obviously be significant when the columns are more controlled by compression.

- **Effect of Stainless-Steel Reinforcement**

the increase of capacity enhanced from RC to UHPC with or without FRP shell is 17% and 14%, respectively. One of the reasons for increased capacity may be due to the fact that stainless steel reinforcement for FRP-UHPC-SS is Grade 75, whereas conventional RC reinforcement is Grade 60.

Parametric Study: FRP Ratio

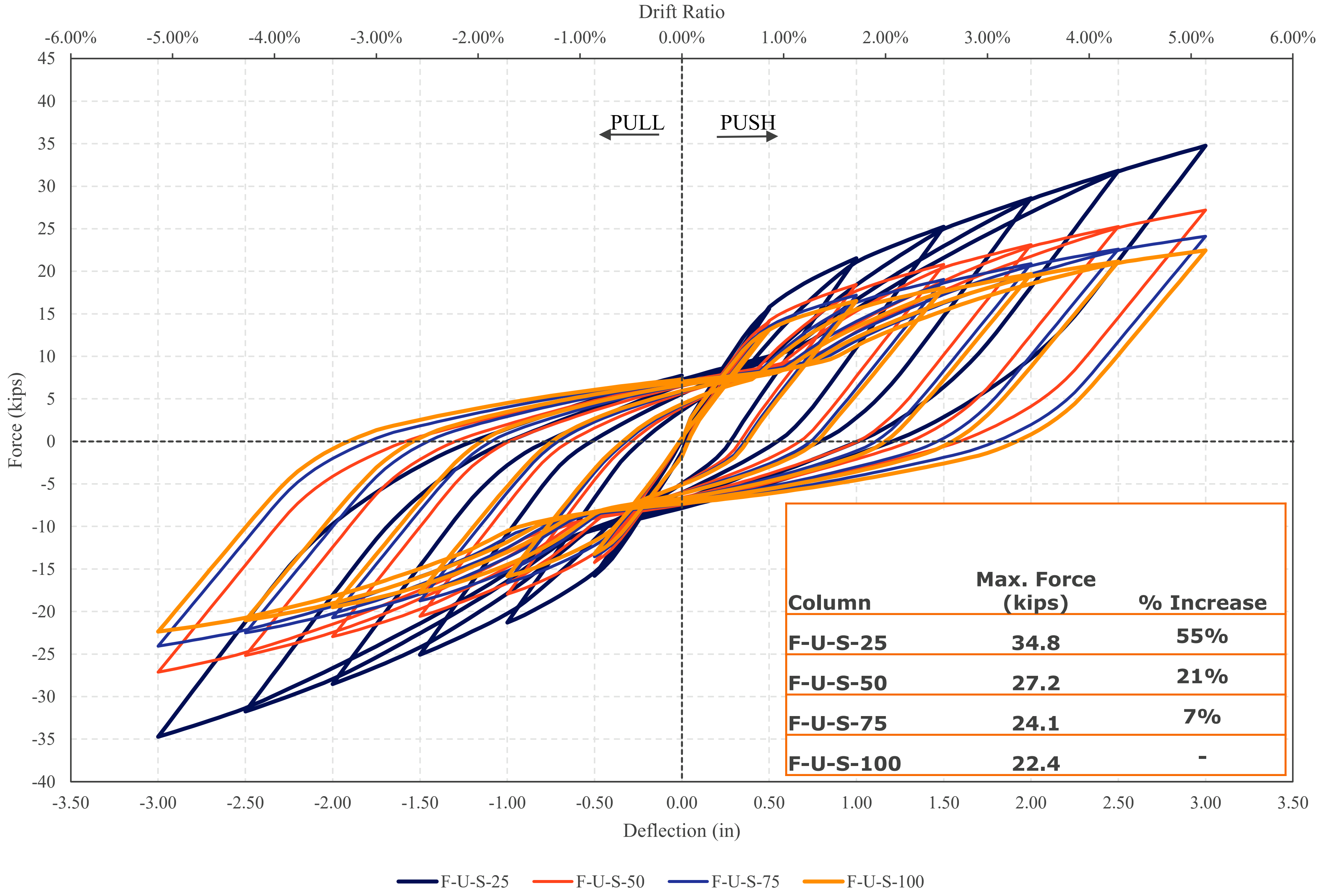
F-U-S-25
- FRP-UHPC-Stainless Steel
- D_o/t = 25
- t = 0.500 in

F-U-S-50
- FRP-UHPC-Stainless Steel
- D_o/t = 50
- t = 0.250 in

F-U-S-75
- FRP-UHPC-Stainless Steel
- D_o/t = 75
- t = 0.167 in

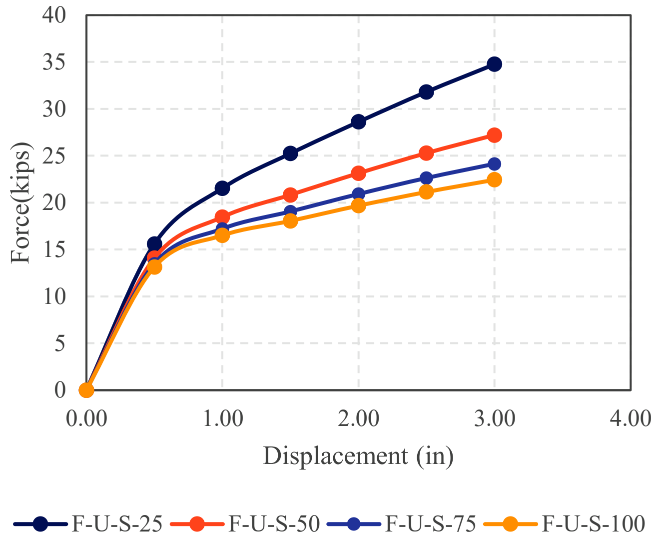
F-U-S-100
- FRP-UHPC-Stainless Steel
- D_o/t = 100
- t =0.125 in

Hysteretic Response Curve for Parametric Variation in D_o/t

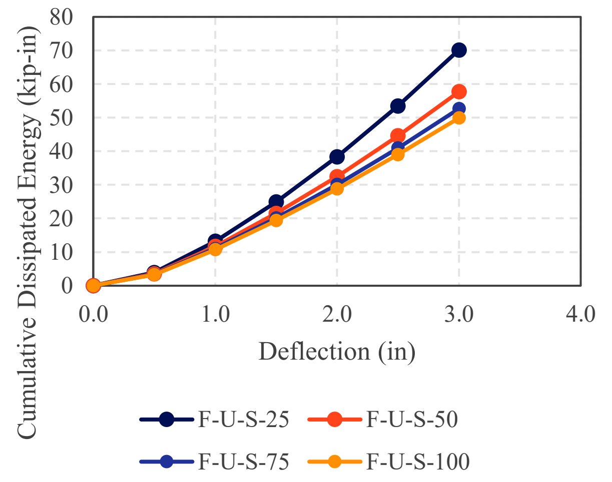


Column	Max. Force (kips)	% Increase
F-U-S-25	34.8	55%
F-U-S-50	27.2	21%
F-U-S-75	24.1	7%
F-U-S-100	22.4	-

Response Envelope Curve for D_o/t ratio



Parametric Variation in Outer Diameter to FRP Thickness Cumulative Dissipated Energy



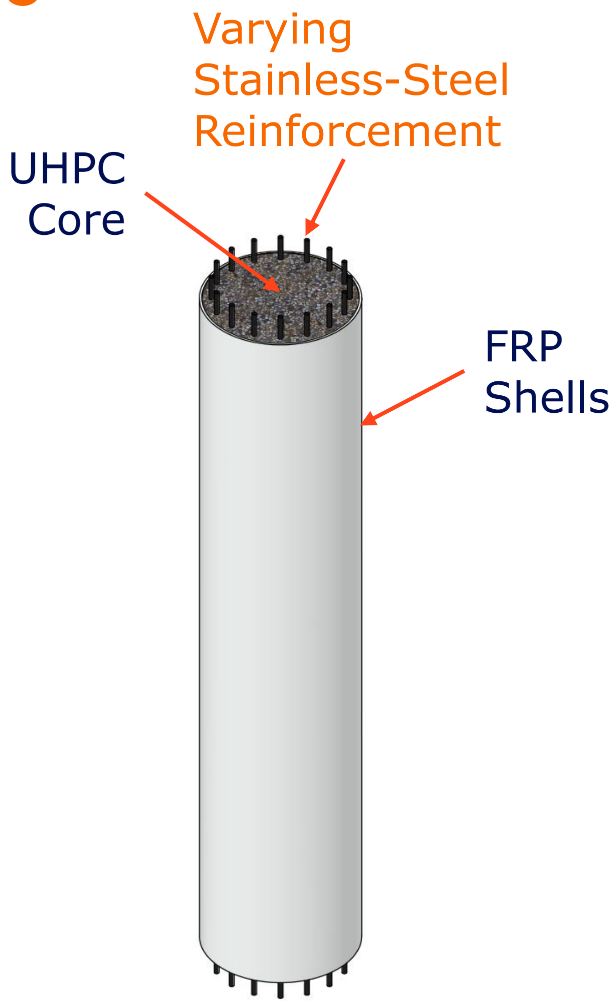
Parametric Study: Steel Reinforcement Ratio

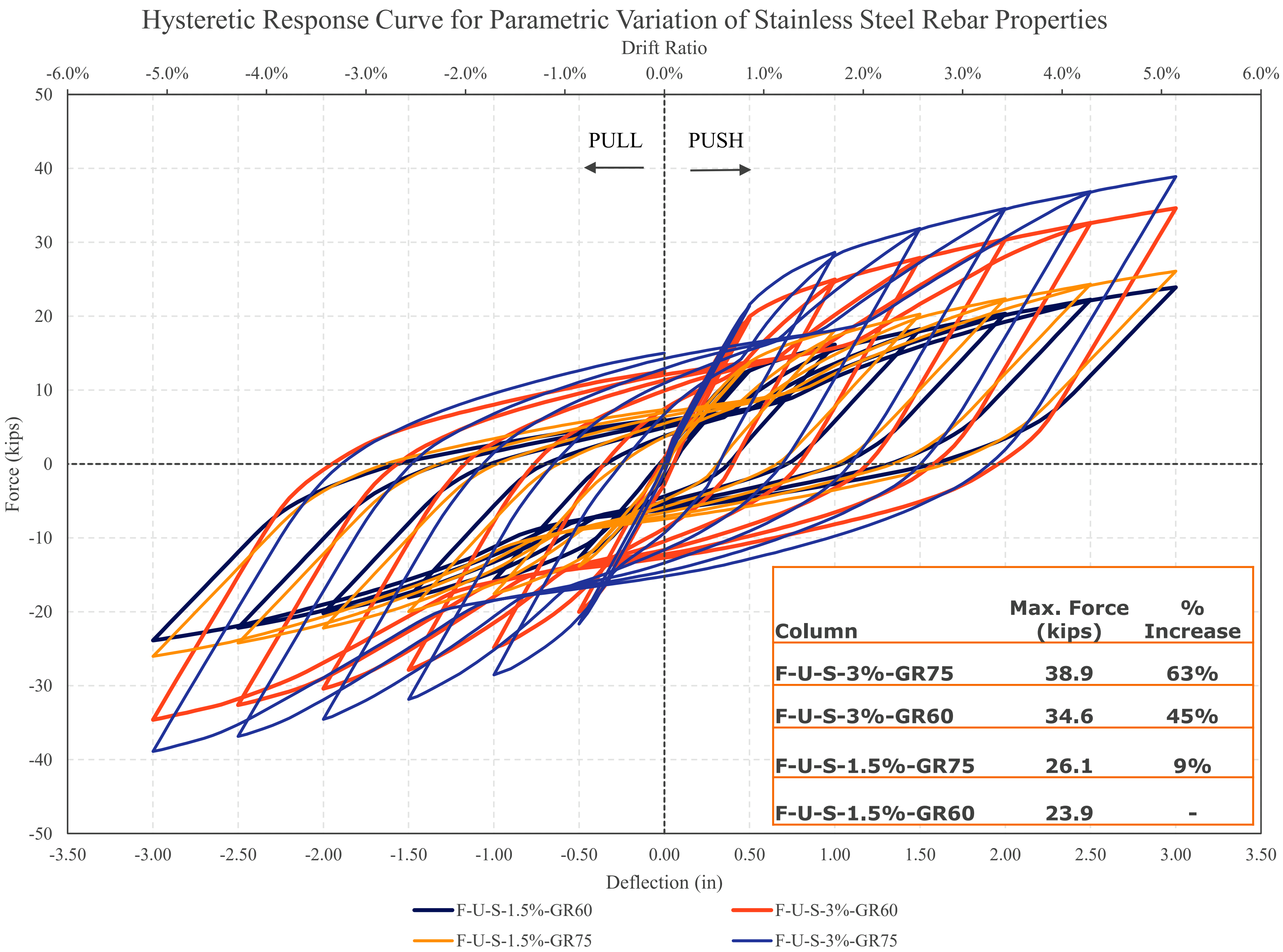
F-U-S-1.5%-GR60
- FRP-UHPC-Stainless Steel
- 1.5% volume – 16 No. 3 bars
- Grade 60 stainless steel

F-U-S-3%-GR60
- FRP-UHPC-Stainless Steel
- 3% volume – 8 No. 6 bars
- Grade 60 stainless steel

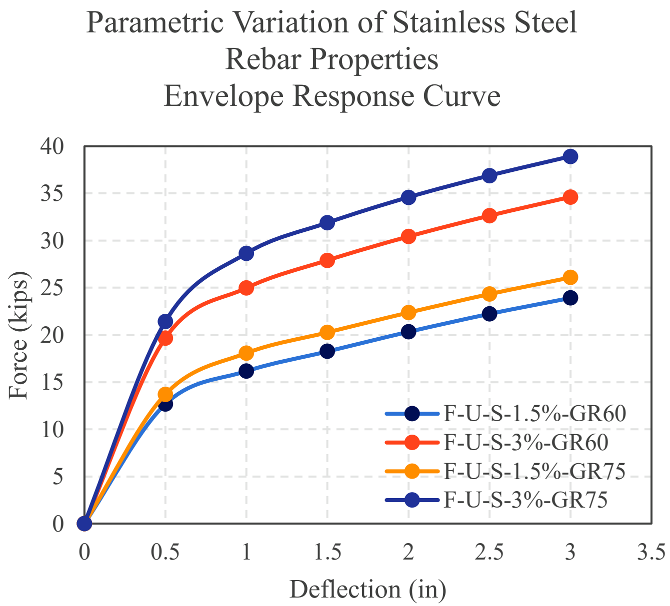
F-U-S-1.5%-GR75
- FRP-UHPC-Stainless Steel
- 1.5% volume – 16 No. 3 bars
- Grade 75 stainless steel

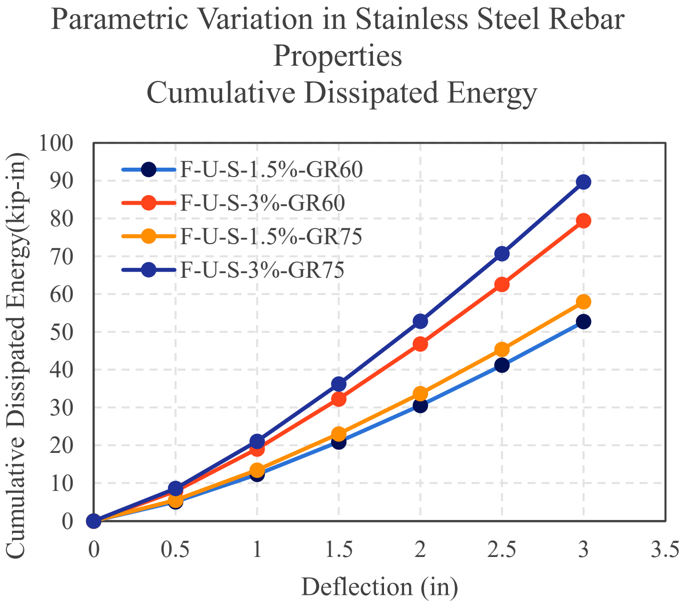
F-U-S-3%-GR75
- FRP-UHPC-Stainless Steel
- 3% volume – 8 No. 6 bars
- Grade 75 stainless steel





Column	Max. Force (kips)	% Increase
F-U-S-3%-GR75	**38.9**	**63%**
F-U-S-3%-GR60	**34.6**	**45%**
F-U-S-1.5%-GR75	**26.1**	**9%**
F-U-S-1.5%-GR60	**23.9**	**-**



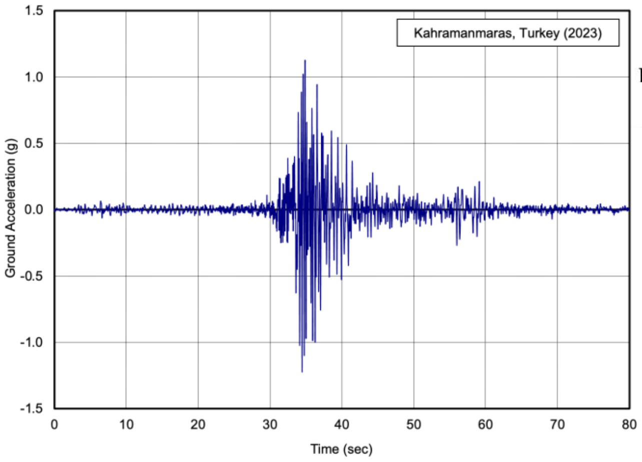


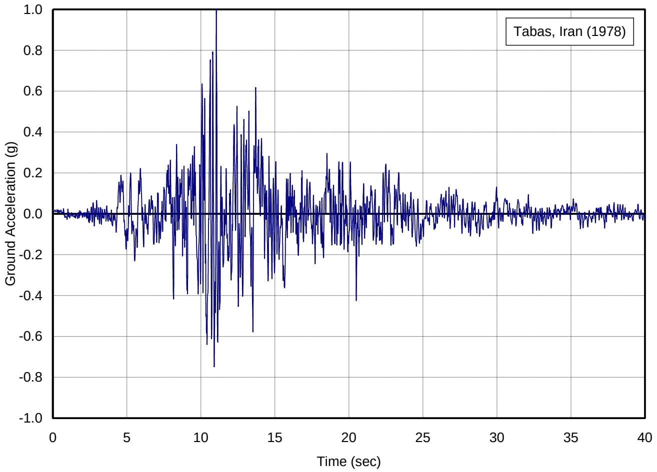
OpenSEES Ground Motion Simulation

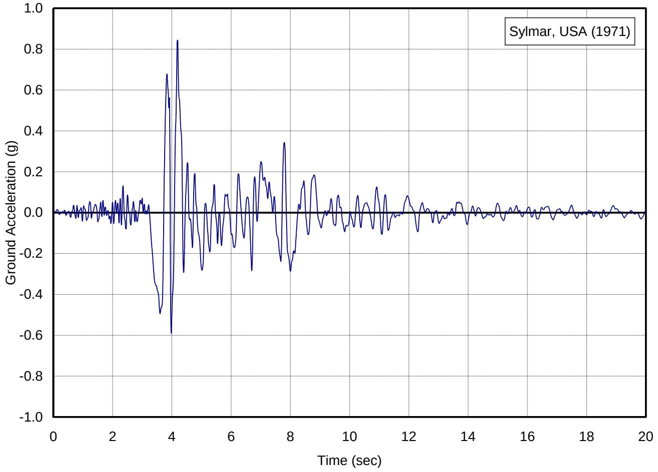
- Three Ground Motion Records

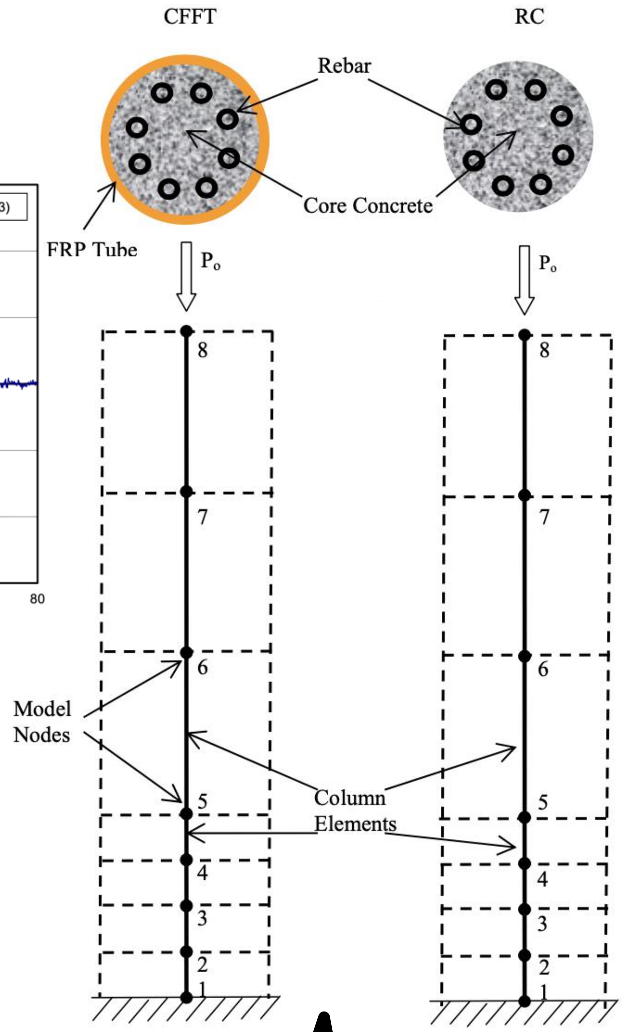
1. Kahramanmaras, Turkey Earthquake Ground Acceleration, 2023
2. Tabas, Iran Earthquake Ground Acceleration, 1978
3. Sylma, USA Earthquake Ground Acceleration, 1971

- Two Columns: FRP-UHPC-SS & FRP-RC-CS

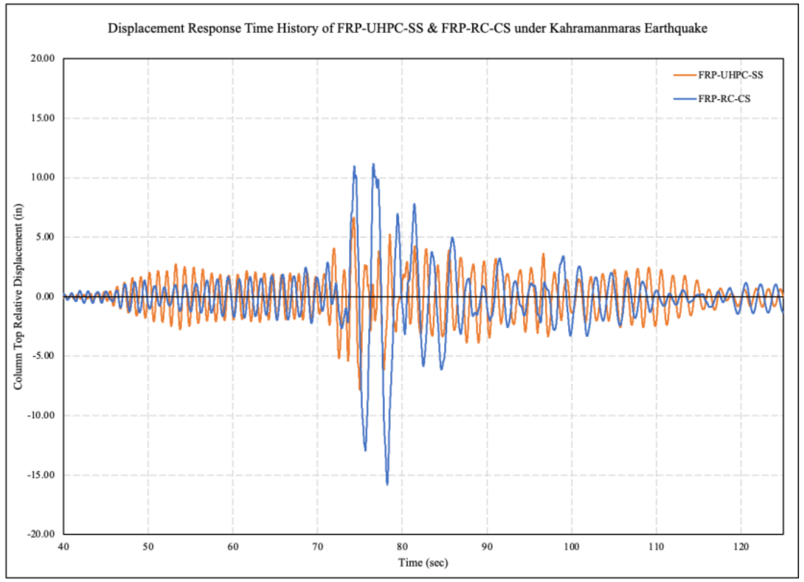


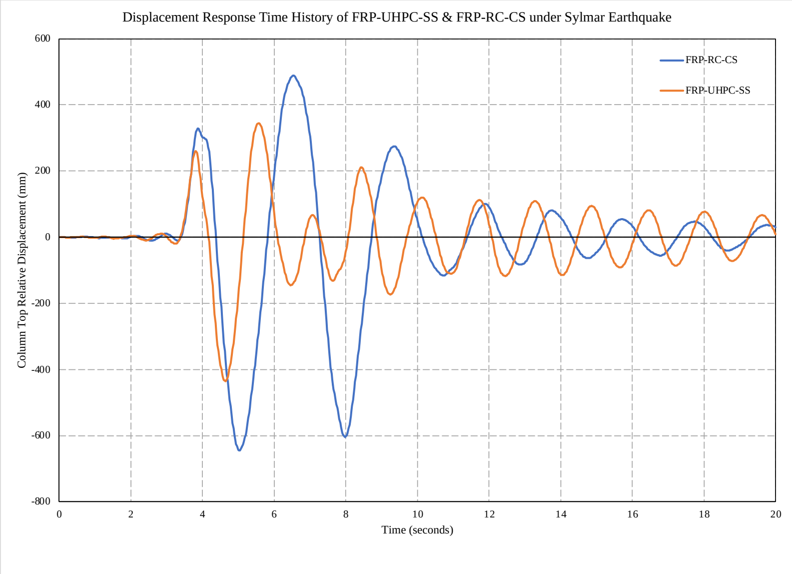


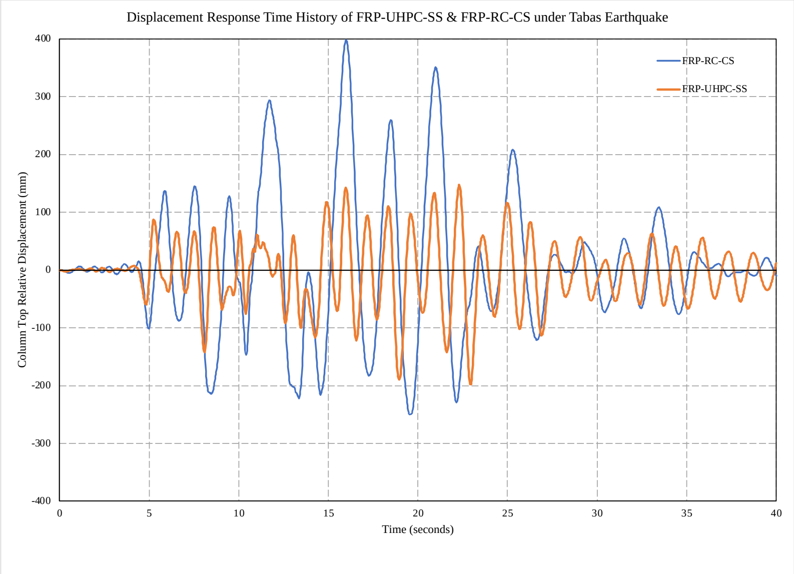


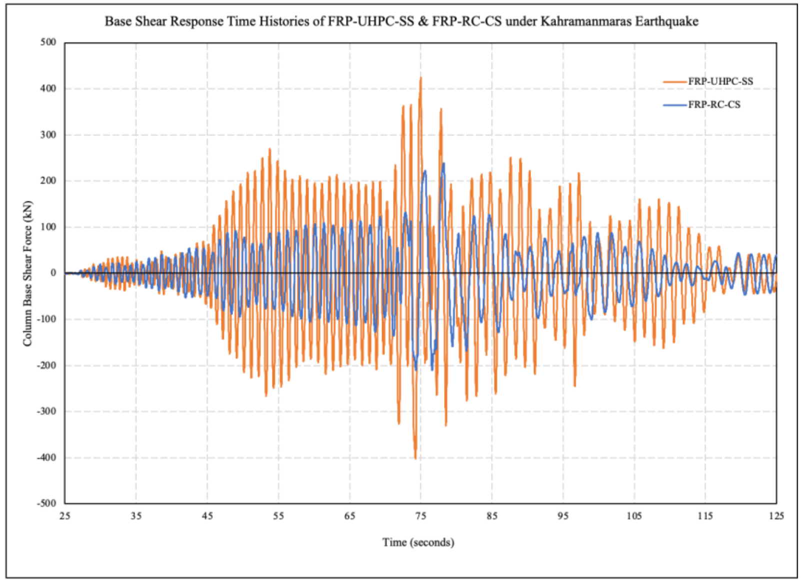


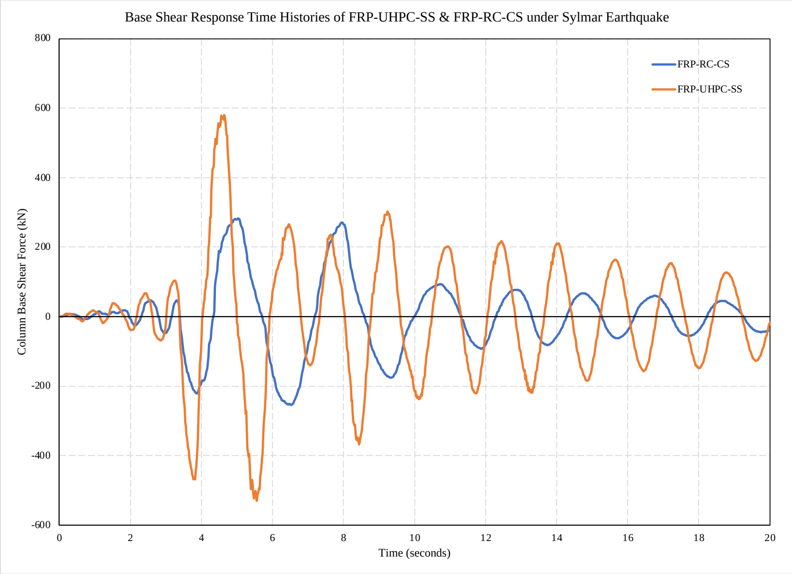
Ground Motions

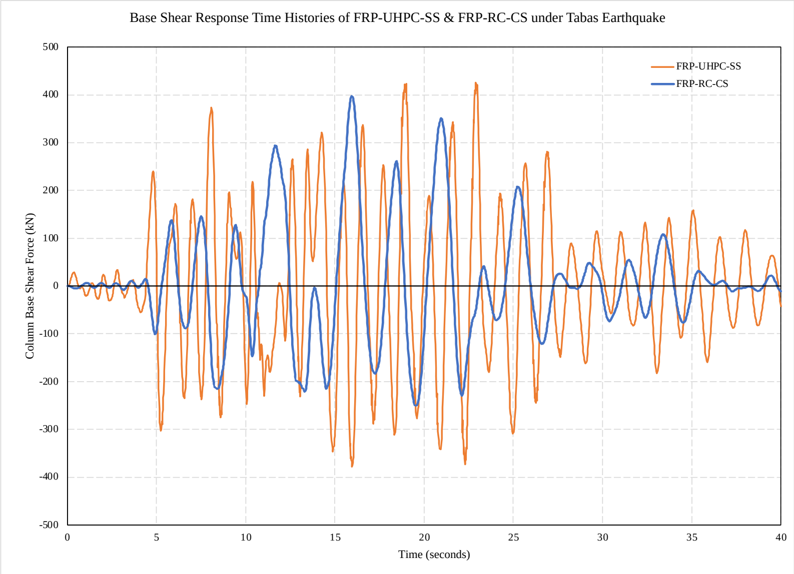

Displacement Response Time History of FRP-UHPC-SS & FRP-RC-CS under Kahramanmaras Earthquake
FRP-UHPC-SS
FRP-RC-CS
Column Top Relative Displacement (in)
Time (sec)


Displacement Response Time History of FRP-UHPC-SS & FRP-RC-CS under Sylmar Earthquake
FRP-RC-CS
FRP-UHPC-SS
Column Top Relative Displacement (mm)
Time (seconds)


Displacement Response Time History of FRP-UHPC-SS & FRP-RC-CS under Tabas Earthquake
FRP-RC-CS
FRP-UHPC-SS
Column Top Relative Displacement (mm)
Time (seconds)


Base Shear Response Time Histories of FRP-UHPC-SS & FRP-RC-CS under Kahramanmaras Earthquake
FRP-UHPC-SS
FRP-RC-CS
Column Base Shear Force (kN)
Time (seconds)


Base Shear Response Time Histories of FRP-UHPC-SS & FRP-RC-CS under Sylmar Earthquake
FRP-RC-CS
FRP-UHPC-SS
Column Base Shear Force (kN)
Time (seconds)


Base Shear Response Time Histories of FRP-UHPC-SS & FRP-RC-CS under Tabas Earthquake
FRP-UHPC-SS
FRP-RC-CS
Column Base Shear Force (kN)
Time (seconds)

Conclusions

- The novel corrosion free member composed of an FRP shell and a UHPC core with stainless-steel reinforcements generated the best seismic performance under simulated cyclic loading in terms of initial stiffness, flexural strength, and energy dissipation, among all four columns.
- The significantly enhanced flexural capacity is mainly contributed by the FRP shell in this analytical study. However, the UHPC core with Stainless-steel reinforcement is essential to constitute a corrosion free structural member.
- Parametric study shows that the higher ratios of both FRP and steel reinforcement will both lead to a better seismic performance under simulated cyclic loading. However, the optimized FRP and reinforcement ratios need to be observed so that a desired flexural failure is ensured with adequate ductility for the proposed novel corrosion free member. The optimized composition of three materials may be better obtained through more rigorous parametric studies validated by future experimental studies.
- Ground Motion Study reveals that earthquake response of the proposed new member outperforms its conventional counterpart in both base shear and displacement responses.

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Questions?

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