Quasi-Static Cyclic Test of an RC Column: Blind prediction results summary

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Working Committee

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Entries

We had 128 entries. Removing multiple predictions from the same entrant, we had 116 individuals or teams entering. This was composed of:

32 practitioners

52 academics

32 students

Entrants came from 37 different countries. We are thrilled to get such broad participation. Many thanks to all who participated.

Breakdown of entrants by country:

Argentina	1	Mongolia	1
Australia	1	New Zealand	2
Belgium	1	North Macedonia	1
Canada	6	Peru	2
Chile	1	Philippines	3
China	24	Portugal	1
Colombia	1	Republic of Korea	1
Croatia	1	Romania	1
Czechia	1	Saudi Arabia	1
Ecuador	1	South Korea	1
Egypt	1	Spain	1
Greece	3	Switzerland	2
India	2	Taiwan	3
Indonesia	2	The Netherlands	1
Iran	3	Turkey	5
Italy	3	United Kingdom	3
Japan	5	United States of America	27
Malaysia	1	Vietnam	1
Mexico	1		

Test results

The test results were as follows:

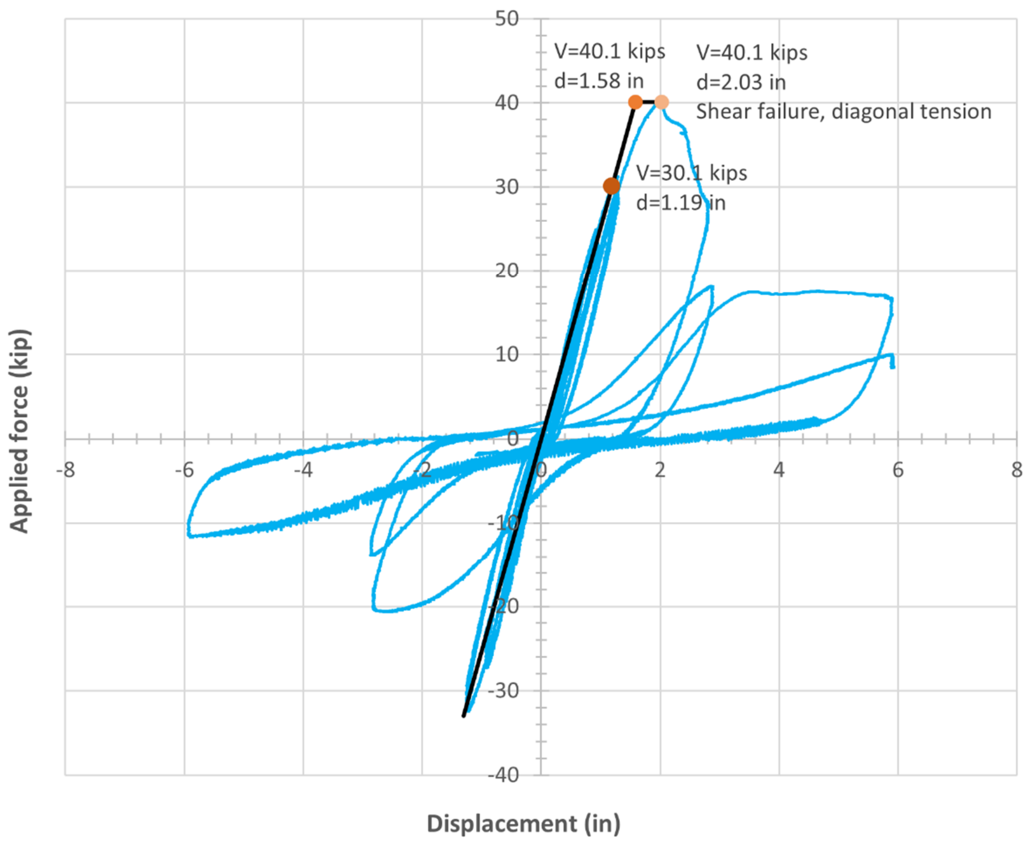
Failure mode: Preemptive diagonal tension. 42% of entries got this correct. We gave partial credit for flexural compression failure, chosen by 13% of entries, as this behavior mode occurred at larger displacements, after the shear failure in diagonal tension. See the hysteresis results. No flexural yielding occurred.

Peak strength: 40.1 kips (178 kN). 22% of the entries got within 15% of this value.

Initial stiffness: At 0.75 times the peak strength, the specimen drift was 1.13%, 1.19 inches (3.02 cm). This leads to an effective initial stiffness value of 25.3 kips/inch (44.3 kN/cm). Only 10 of entries got within 15% of this value. 22% got within 30% of this value. Of those outside the 30% margin of error 74 participants predicted higher initial stiffness, and only 16 participants predicted lower stiffness.

Ductility capacity: 1.28. 25% of entries got within 15% of this value.

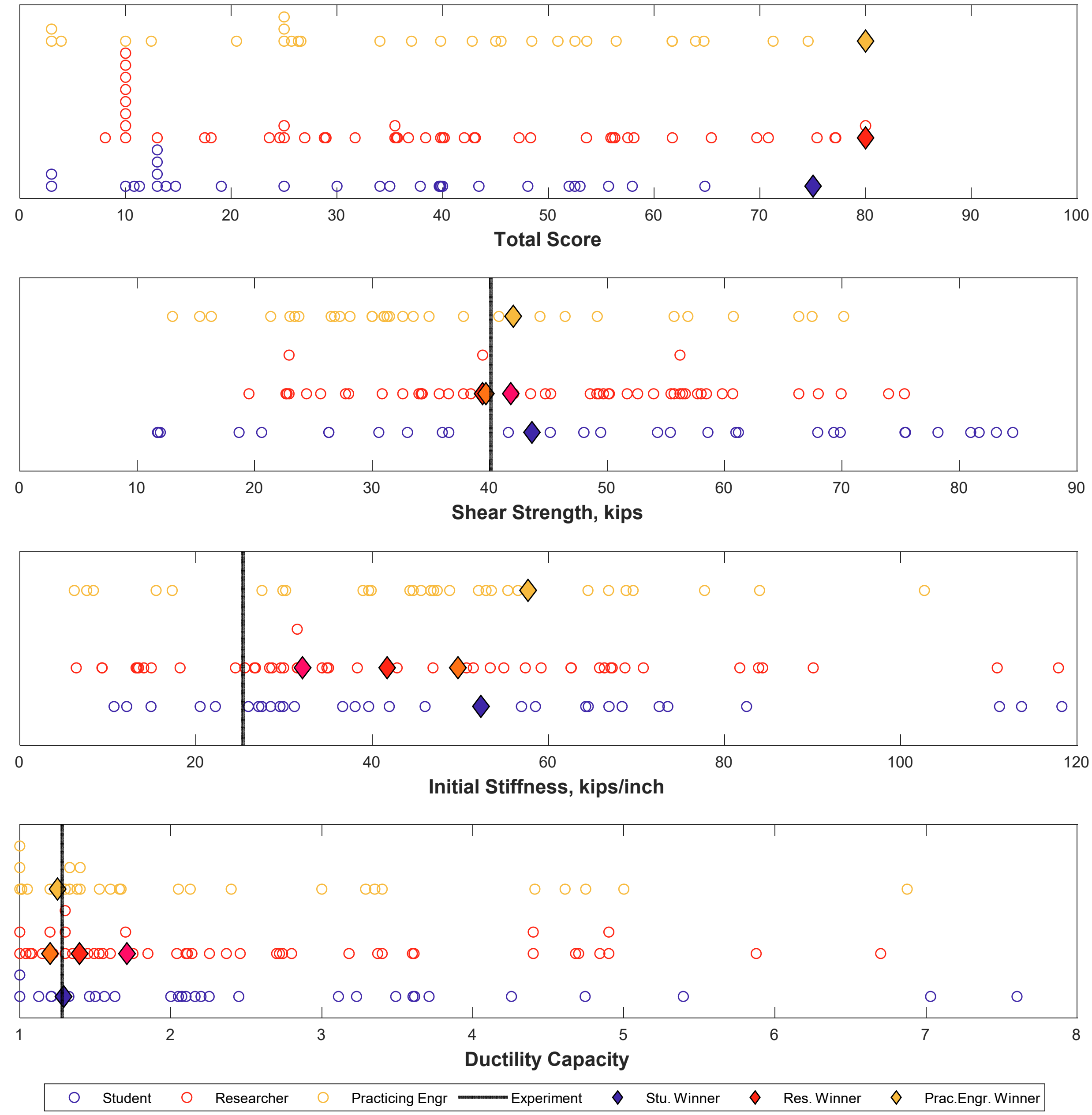
Is retrofit needed to achieve 3% drift capacity? Yes. 83% of entries answered this correctly.



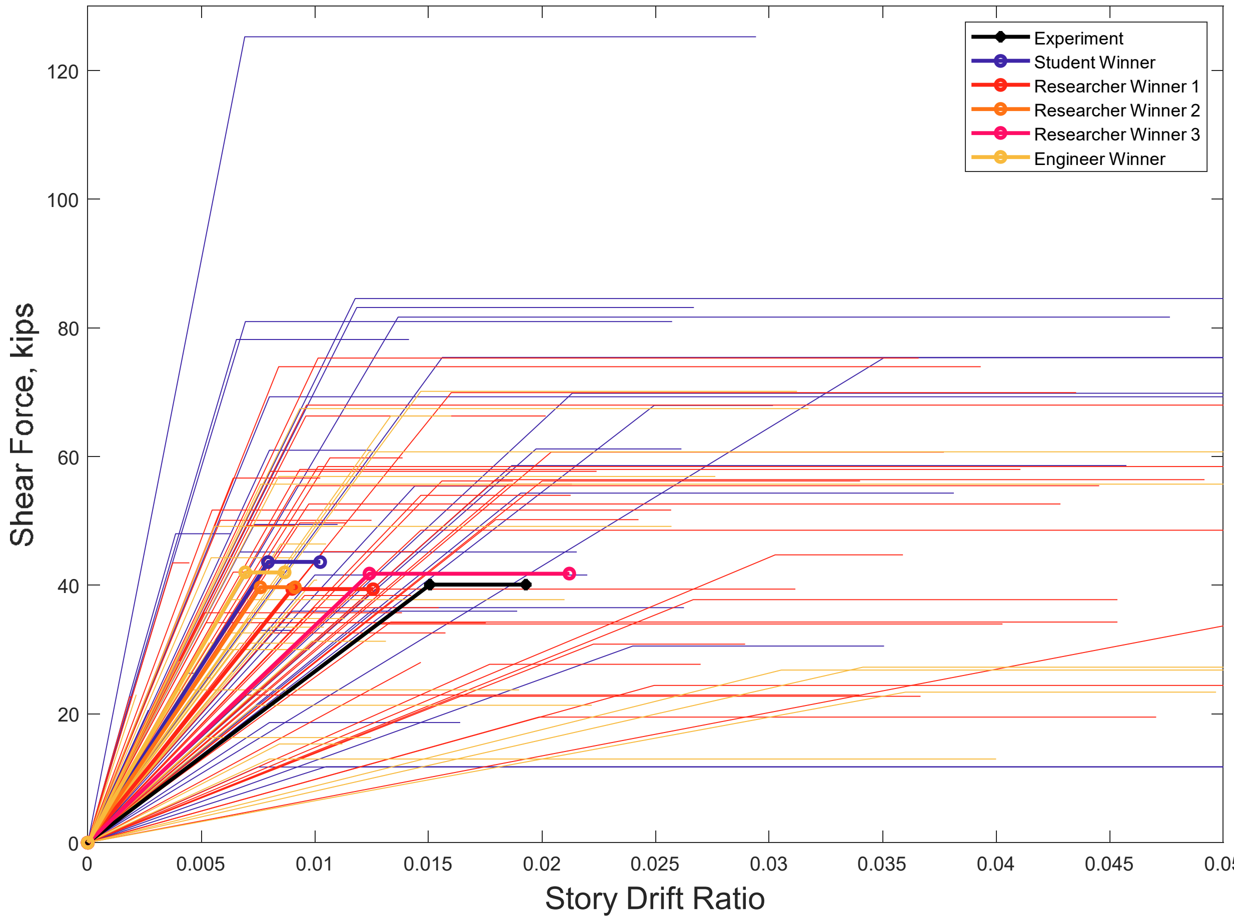
Force-displacement hysteretic output from the test, with the elastic-perfectly-plastic envelope that represents the correct answers (i.e., test results) for peak strength, effective initial stiffness, and ductility capacity.

Column specimen after shear failure in diagonal tension, shown after displacements up to 6 inches. The shear failure occurred on the first cycle to 2-inch displacement.

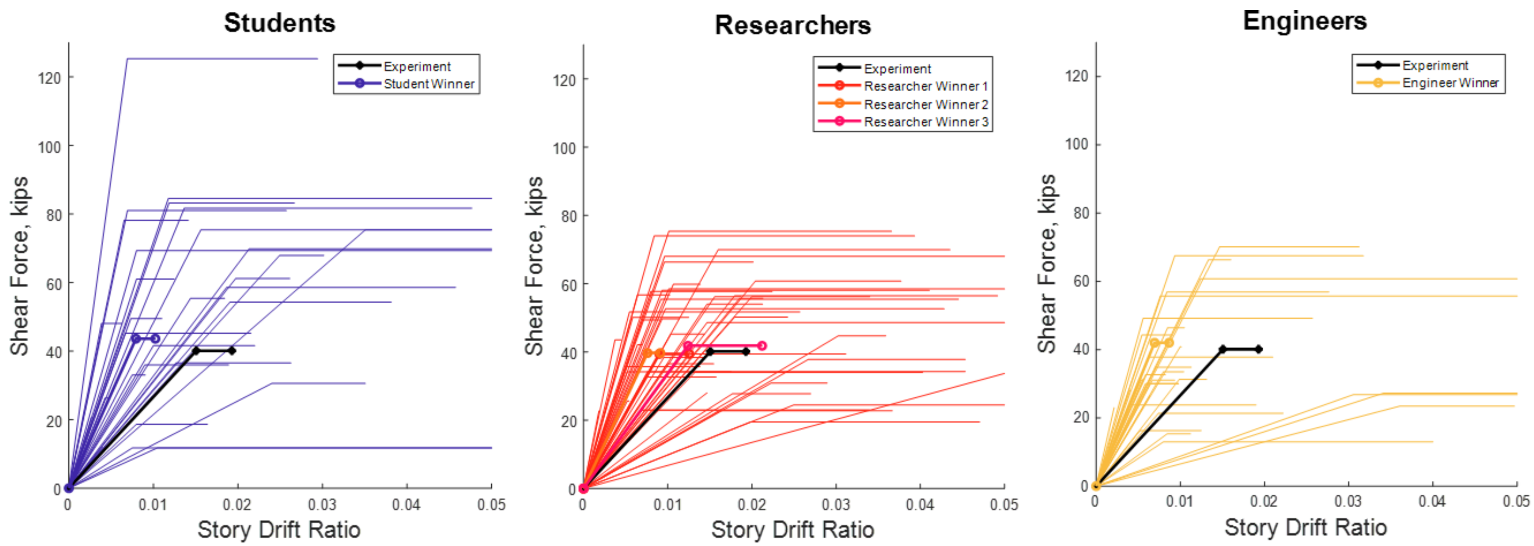
Plots of predictions



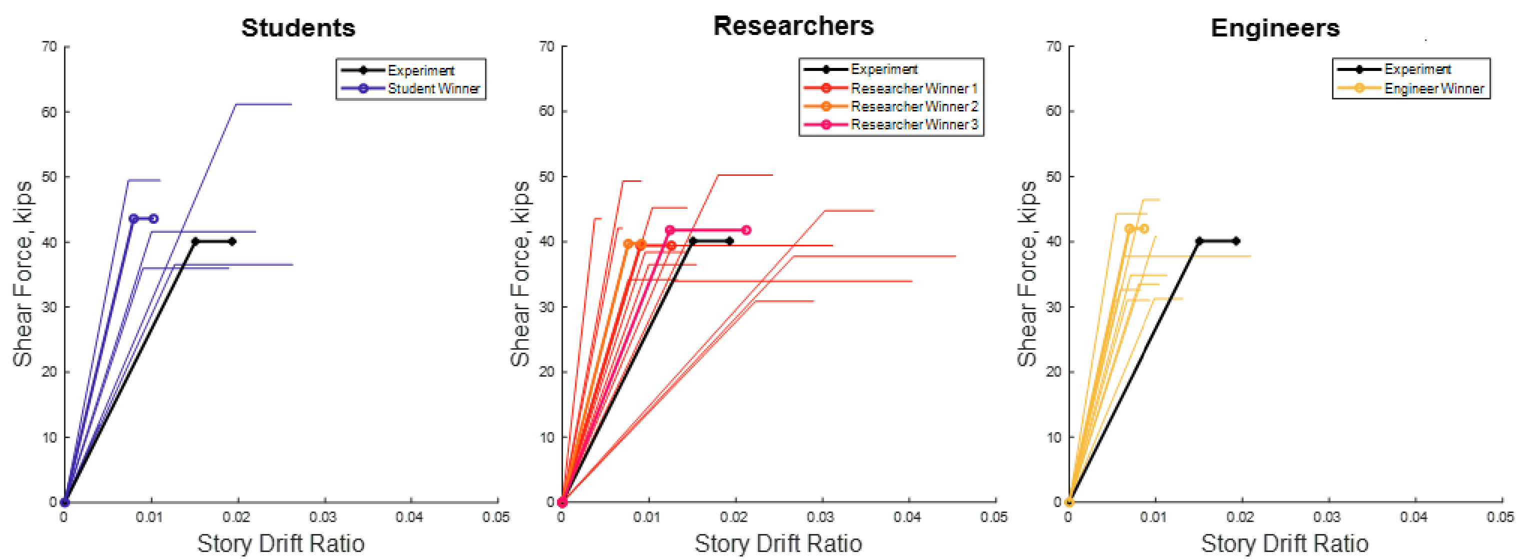
Predictions of lateral strength, stiffness, and ductility capacity, compared to the test results, along with total score (a weighted scoring of the accuracy of prediction of the strength, stiffness, ductility capacity, behavior mode and need for retrofit). As the plots show, there is significant scatter in all the predicted quantities. On average, participants overpredicted stiffness by a factor of about 2. (One outlier prediction point from each of the categories of strength, stiffness, and ductility capacity is removed from these plots for clarity.)



Predicted force-displacement envelopes for all entries (Predictions of ultimate displacement beyond 5% story-drift ratio are cut off for clarity)



Predicted force-displacement envelopes for practitioner, researcher, and student entries (Predictions of ultimate displacement beyond 5% story-drift ratio are cut off for clarity)



Predicted force-displacement envelopes for practitioner, researcher, and student entries with a total score of 50 and above. (Predictions of ultimate displacement beyond 5% story-drift ratio are cut off for clarity)

Winners

The practitioner winner is an individual entry, **Jonas Houston** of Holmes Consulting in San Francisco, CA. To predict strength, Jonas used the UCSD modified shear strength equation from the textbook *Displacement Based Seismic Design of Structures*, by Priestley, Calvi, and Kowalski (2007). Jonas used a 2D Risa model to predict stiffness, and "an assumed percentage beyond shear yield" to predict ductility capacity.

The student winner is an individual entry**, Sasan Dolati** of the University of Texas at San Antonio. Sasan used a three-dimensional finite element model in the ATENA software to predict the strength, stiffness, and ductility capacity of the specimen. Sasan's model had 5670 hexahedral elements (9 elements x 9 elements x 70 elements high) to represent the column, each element approximately a 1.5" (40 mm) cube.

<u>There were three researcher teams who tied with the same winning score. In alphabetical order:</u>

Farah Dameh, a graduate researcher, and **Stavroula Pantazopoulou,** Professor and Chair at York University, Canada submitted a team entry. The team used a three-dimensional finite element model in the ATENA software to predict the strength, stiffness, and ductility of the specimen. (The same software as used by the student winner Sasan Dolati.) The model used 50 mm (2 inch) cubes as elements, with a bilinear steel material with strain hardening, and a nonlinear concrete material using stress-strain relationships from Kent and Park (1971, 1972).

Sadik Can Girgin, Associate Professor at Dokuz Eylul University in Turkey submitted an individual entry. Sadik used a beam and truss model in the Opensees sofware to predict the strength, stiffness, and ductility capacity of the specimen. Sadik's Opensees model used Truss-type and Truss2-type elements as described in the paper:

> Moharrami, M., Koutromanos, I., Panagiotou, M., and Girgin, S.C. "Analysis of shear-dominated RC columns using the nonlinear truss analogy." *16th World Conference on Earthquake Engineering, 16WCEE 2017, Santiago, Chile*, Paper No 2593, 2017.

Mervyn Kowalsky, Professor at North Carolina State University, led a team entry with **Taylor Brodbeck, Diego Martinez, Diego Sosa, Lina Espinosa, Ana Bona**, and **Julio Samayoa**. To predict strength, the team used shear strength equations from the following paper:

> Kowalsky, M.J. and Priestley, M.J.N. (2000). "An improved analytical model for shear strength of circular RC columns in seismic regions." *ACI Structural Journal*, Vol. 97, #3, pp388-396, May.

(This is the same approach used by Jonas Houston, the practitioner winner.) The UNC team used this UCSD model along with moment-curvature analysis to predict stiffness and ductility capacity.

Background

This test came about as part of the seismic evaluation and retrofit design for a building in San Francisco. The column is like the actual building columns, except with heavier longitudinal reinforcement. Columns of the building were retrofitted with FRP wrap because they were determined to be shear-governed by criteria in ASCE 41-17.

The column represents the control specimen that was tested along with two subsequent specimens, which were retrofitted with an FRP wrap to prevent shear failure. The control specimen was designed to have a pre-emptive diagonal tension shear failure. The subsequent tests with FRP wrap prevented this shear failure, leading to ductile behavior and allowing each specimen to achieve the column's flexural strength, corresponding to a maximum lateral capacity of 52 to 60 kips (230 to 270 KN).

The retrofit tested was a three-sided FRP wrap with FRP through-anchors used on the fourth side (see figure, below). This detail was used for columns of the building for which there were obstructions to applying FRP sheets to the fourth side. Unobstructed columns were retrofitted with a more typical four-sided FRP wrap (a retrofit solution suggested by many entrants to this contest).

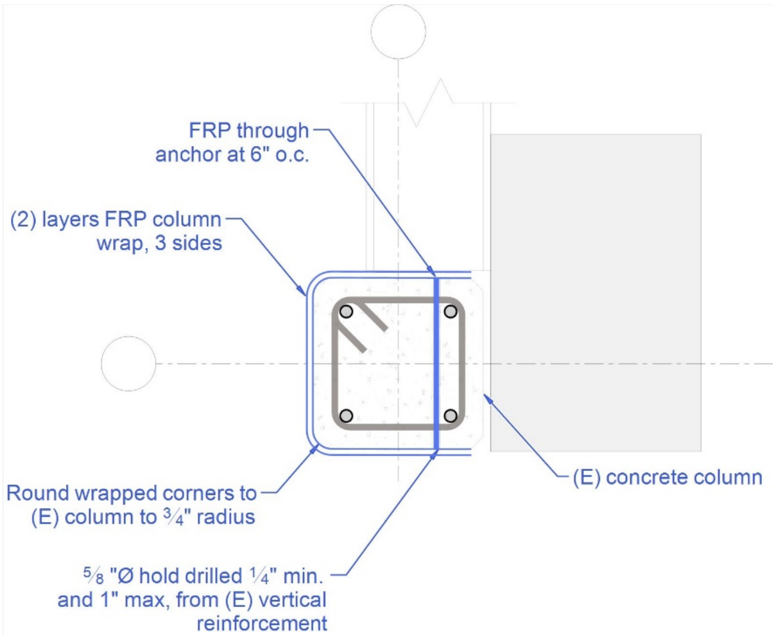


Image of three-sided FRP retrofit with through anchors that was the subject of column retrofit tests.

For the test program to succeed, the control column needed to fail in shear; otherwise, it would not be possible to show that the retrofit solution prevented shear failure. Accordingly, we were careful to look at the range of possible best estimates of shear strength and flexural strength to ensure that shear strength would govern for the control column. We were surprised to find a wide range in predicted shear strength between equations such as those in ASCE-41, ACI 318, and in the UCSD method (the latter of which was used for two of the five winning entries). Because of this, we had to substantially increase the longitudinal reinforcement in the specimen, compared to that in the actual columns, to ensure a shear failure.

Given the wide range of predictions for shear strength, and with the test result showing shear strength higher than predictions based on US Standards, it became clear that a prediction contest would be valuable. Hopefully the issues raised by this test and prediction contest can lead to improved standards for assessing concrete columns and similar members.

In addition to the question of predicting shear strength, the results show a disparity between predicted stiffness and actual stiffness. Many entrants, including practitioners who otherwise had good predictions, predicted stiffness more than twice the actual stiffness.

We plan to look further into methods that participants in this contest used in their predictions, to identify methods that are used by practitioners, as well as those that led to good predictions. We intend to produce a PEER report with more details on the testing and on this prediction contest.

Also, information on the building retrofit and the column testing will be published in a two-part article in Structure Magazine, with the first part scheduled for the January 2022 issue. We will share a link to this article when it is published.