Blind Prediction Competition of Shear Strength for Thick Concrete Foundation Elements With and Without Shear Reinforcement

Organizers

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Test Overview

A large reinforced concrete beam was constructed and tested at the University of California, Berkeley. This test was conducted to assess the adequacy of current code provisions for one-way shear strength, particularly in the context of foundation mats of tall buildings constructed with high strength reinforcement.

This test beam was constructed with no shear reinforcement in one span and minimum shear reinforcement in the other span to obtain two test results out of one beam. It was tested under a centrally located concentrated force *P* and self-weight, with roller reactions at each end (Figure 1). Failure initiated in the span without shear reinforcement. Following the failure of the span with no shear reinforcement, that span was repaired with post-tensioned external shear reinforcement such that the opposite side would fail during further testing. For a full description of the testing protocol and reinforcement layout, please refer to:

https://peer.berkeley.edu/news-and-events/2021-thick-foundation-element-blind-prediction-contest

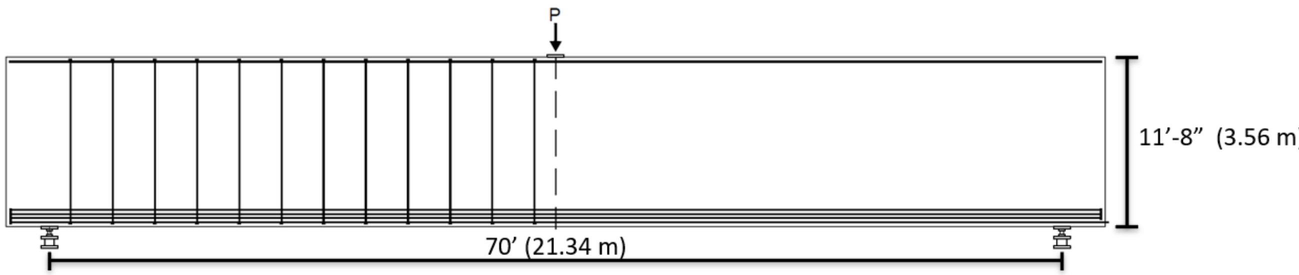


Figure 1: Test configuration.

Test Result Highlights

a) Phase 1

Phase 1 emphasizes the behavior of Span 1 without shear reinforcement because it was expected that failure would occur in that span first while Span 2 responded in the effectively linear-elastic range of response. Figure 2 shows the measured relationship between midspan applied force *P* and midspan deflection. The span had developed several nearly vertical cracks and several inclined cracks as the force *P* approached the peak value (Figure 2). The visible inclined crack near the middle of the span was predominant until the applied force reached *P* = 111 kips. With an audible sound and sudden drop in the value of *P*, a second major crack formed to the left of the one at the middle of the span, with the upper end of the new crack extending toward the point of force application *P*. The width of this new crack slowly grew to around 5 mm as the deflection increased to around 1.1 inches without substantial increase in applied force *P*. The test was then stopped out of concern to avoid a sudden failure due to loss of aggregate interlock along the major crack.

Table 1 summarizes several key variables. Notably, the major cracks near the end of the test were inclined, indicative of shear or diagonal tension cracking. The maximum flexural tension strain was well below the yield strain and flexural compression distress was not observed. Consequently, we classified the failure as a diagonal tension failure.

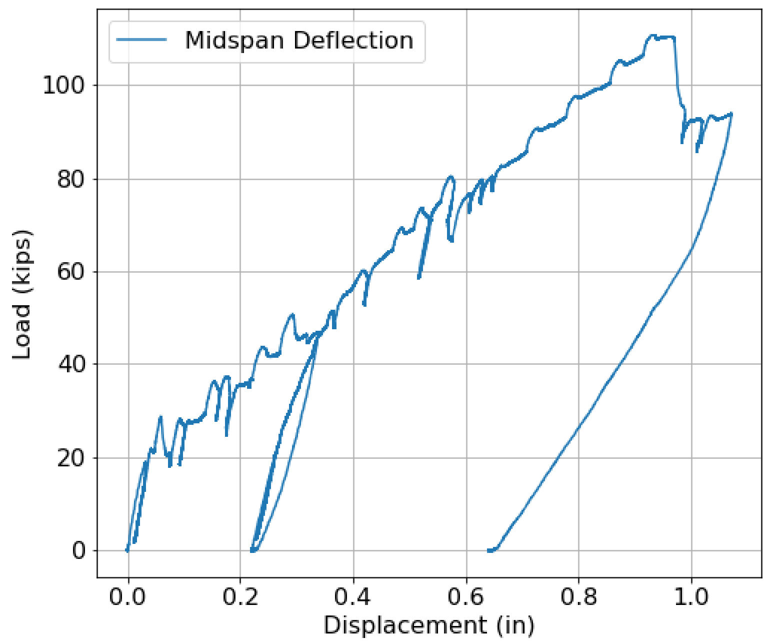


Figure 2: Measured relationship between externally applied force *P* and midspan displacement during Phase 1 testing.

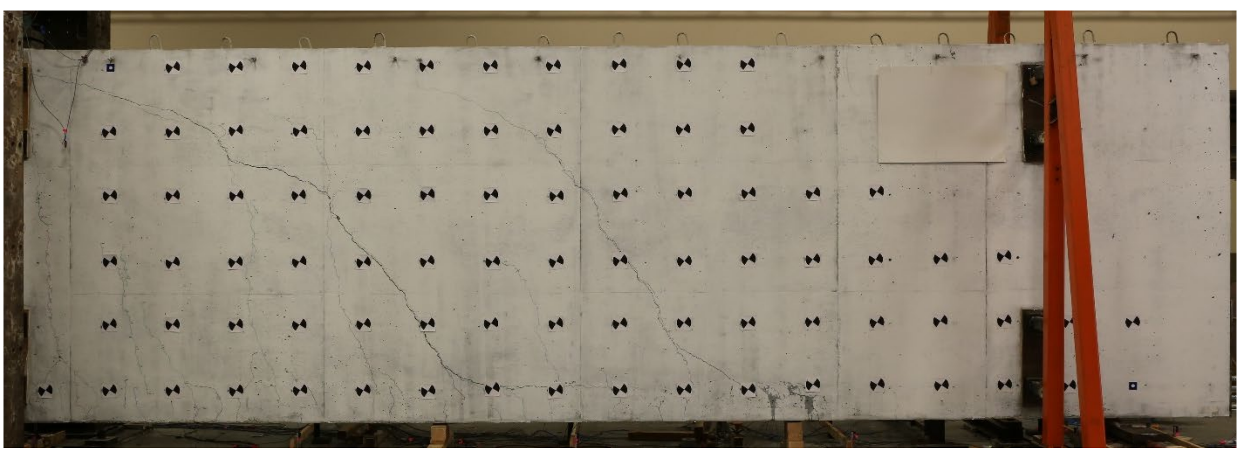


Figure 3: Crack pattern in Span 1 at the end of Phase 1 testing.

Table 1: Test Result Highlights

	Phase 1 (No Shear Reinforcement)	Phase 2 (ACI 318-19 Minimum Shear Reinforcement)
Peak Load	111 kips	501 kips
Peak Displacement	0.93”	3.91”
Max Steel Tensile Strain	1650 με ≈ 45ksi	3840 με ≈ 90 ksi
Max Crack Width Before Failure *estimated	5 mm	> 15 mm
Permitted Failure Modes	Diagonal Tension Failure	Diagonal Tension Failure Flexure-Diagonal Tension

a) Phase 2

Phase 2 emphasizes the behavior of Span 2 with shear reinforcement because it was expected that failure would occur in that span following the retrofit of Span 1 with external shear reinforcement and grouted longitudinal reinforcement. Figure 4 shows the measured relationship between midspan applied force *P* and midspan deflection. The span had developed several nearly vertical cracks and several inclined cracks as the force *P* approached around 300 kips (Figure 4). At higher values of *P* a new set of more steeply inclined cracks developed, with crack width increasing as applied force *P* increased. A sudden, explosive failure occurred involving fracture of several of the shear reinforcing bars, compressive failure at the upper end of the major inclined crack, and dowel splitting failure along the flexural tension reinforcement (Figure 5). The test was immediately stopped and the beam was braced in its collapsed position.

Table 1 summarizes several key variables. Notably, the major cracks near the end of the test were inclined and shear reinforcement fractured, indicative of shear or diagonal tension failure. The high strains in the flexural tension reinforcement during Phase 2 were also noteworthy. Since this test uses high strength longitudinal reinforcement, the 0.2% offset method prescribed in ACI 318-19 20.2.1.2 was used to determine the yield stress of the high strength reinforcement, which is determined as $\approx$3000 με or $\approx$80 ksi from material testing. Considering the apparent diagonal tension failure and the large flexural tension failure, we classified the failure as a diagonal tension failure or flexure-diagonal tension. Given the explosive compressive failure, we also decided not to disqualify any blind prediction contestants who classified the failure as flexure-diagonal compression.

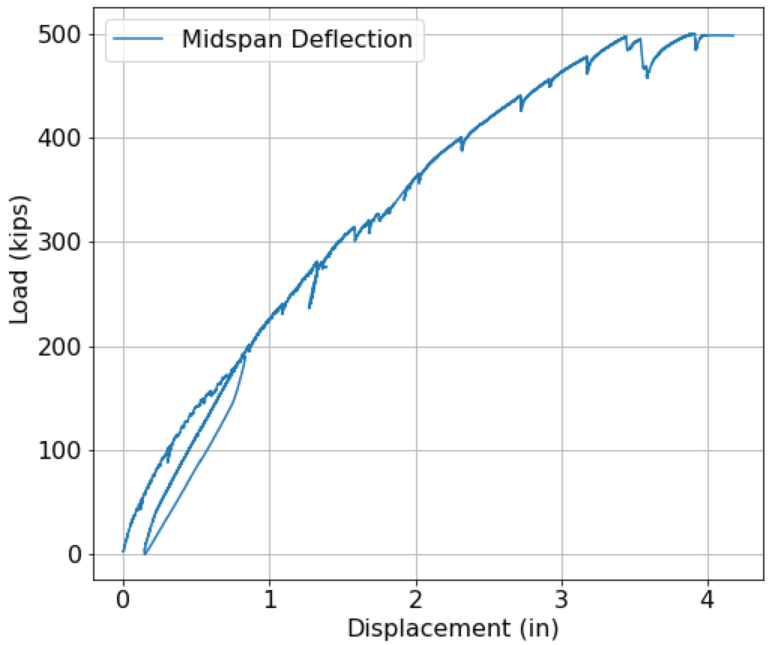


Figure 4: Measured relationship between externally applied force *P* and midspan displacement during Phase 2 testing.

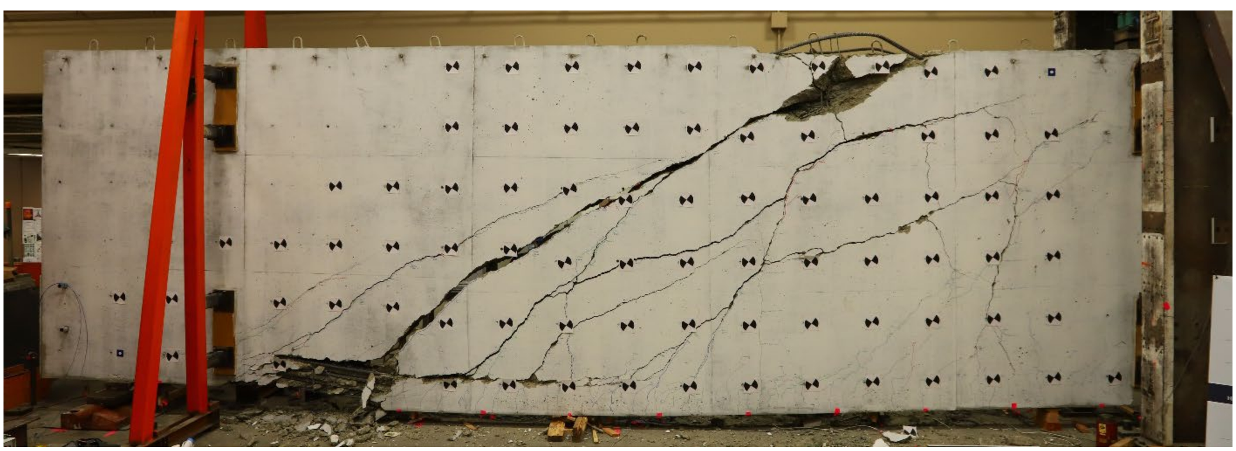


Figure 5: Crack pattern in Span 2 at the end of Phase 2 testing.

Blind Prediction Competition Participant Breakdown

A total of 59 unique participants from 23 different countries submitted an estimate for this blind prediction competition. Participants were categorized into students, practitioners, and researchers. The breakdown by country and by participant background is as follows:

- 9 students
- 23 practitioners
- 27 researchers

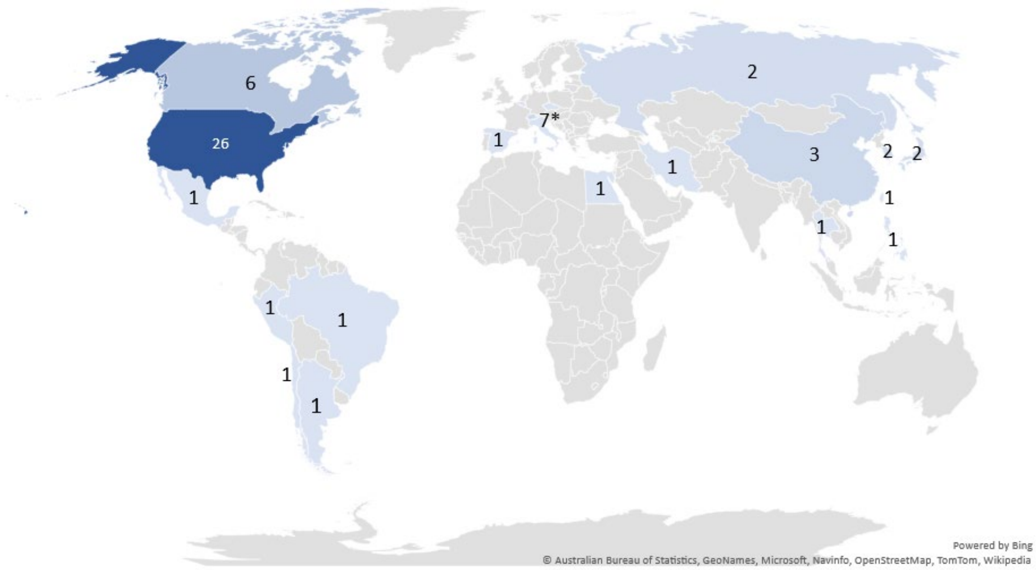
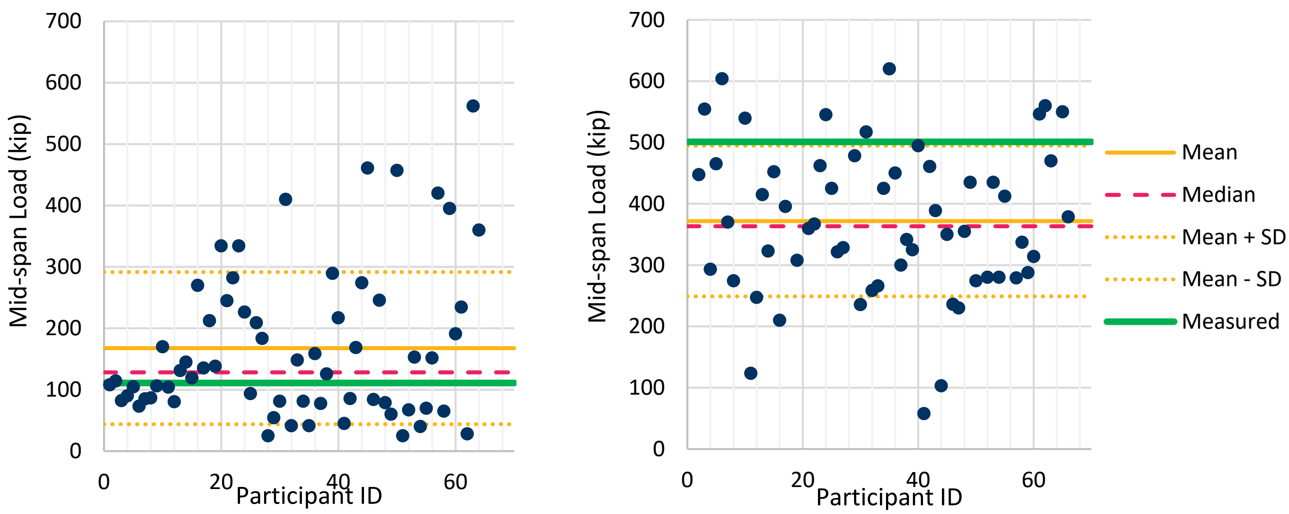


Figure 6: Geographic distribution of blind prediction competition participants.

Comparison of Measured and Predicted Strengths

Figure 7 compares the measured strengths (thicker green line) with the predicted strengths (individual black dots along with the mean, median, and mean plus or minus one standard deviation of the predictions). The graph on the left is for Phase 1 with no shear reinforcement and the graph on the right is for Phase 2 with shear reinforcement. Each prediction was assigned a Participant ID number. As some participants submitted multiple predictions, there are more Participant IDs than there are individual participants. Table 2 summarizes the measured and predicted strengths.



(a) Phase 1 (b) Phase 2

Figure 7: Measured strengths (thicker green line) and predicted strengths (individual black dots along with the mean, median, and mean plus or minus one standard deviation of the predictions).

Table 2: Prediction Competition Highlights

Parameters	**Phase 1**	**Phase 2**
Failure Load	111 k	501 k
Mean Prediction	168 k	382 k
Median Prediction	128 k	374 k
Standard Deviation	124 k	135 k
CoV	0.74	0.35

This blind prediction competition was very informative of our profession's ability to accurately predict the one-way shear strength of a thick concrete element such as a foundation mat. The median value of the estimates for Phase 1 slightly overestimated the measured value, but the mean is skewed larger due to several high overestimates. On the other hand, the median and mean estimates were very similar in Phase 2 predictions, but both values underpredicted the measured value.

Blind Prediction Competition Winners

The winners to this blind prediction competition are selected based on relative accuracy (RA) to the failure load. Participants were ranked by their % difference for Phase 1 and Phase 2 using the following formula:

$$Relative\ Accuracy\ (RA) = \frac{|Measured - Prediction|}{Measured} \times 100\%$$

The overall winner is determined by averaging the RA value between Phase 1 and Phase 2 and ranking the participants once again using the formula:

$$Overall\ Accuracy = \frac{RA_{Phase\ 1} + RA_{Phase\ 2}}{2}$$

Overall Winner and Honorable Mentions

Lawrence Burkett, of Maffei Structural Engineering in San Francisco, is awarded the overall winner of this blind prediction competition considering the overall accuracy of both estimates (108 kips and 550 kips for Phases 1 and 2, respectively). Mr. Burkett used spreadsheet calculations to determine shear and moment along the beam, including self-weight, and used the section analysis option of the Response 2000 computer program by Evan Bentz at University Toronto. He also checked his prediction against the equations in Bentz et al. (2015), which, for the unreinforced portion, gave a capacity of about 85 kips, compared to his prediction of 108 kips using Response 2000.

Adam Lubell, a project engineer at Read Jones Christoffersen LTD in Vancouver, Canada, and an Adjunct Professor at the University of British Columbia, receives an honorable mention for having a composite relative accuracy of < 15%. For Phase 1, Dr. Lubell used the general analysis procedure proposed in Desalegne & Lubell (ACI Structural J, March 2010) accounting for the measured non-linear stress-strain relationship for the reinforcement. For Phase 2, he used the analysis procedure proposed in Desalegne & Lubell (ACI Structural J, Dec 2015), with an adjustment to the crack spacing term to account for the shear reinforcement longitudinal spacing exceeding the code limit based on Lubell's 2006 PhD Dissertation (Univ of Toronto). In both cases, the critical section was evaluated dv*cot(Theta) from the concentrated load, and an upwards adjustment was made on the predicted failure load based on the expected bias of the test/model ratio.

Luis Fargier, Massman-Bavers Associate Professor of the Practice of Heavy Civil Engineering at the University of Notre Dame and his team (Christian Dennis, Emad Al-Shurman, Joseph Klatt, Oluwanifemi) also receive an honorable mention for also having a composite relative accuracy of < 15%. The team used equations of ACI 318-19 to arrive at their predictions for Phases I and II.

Phase 1 Winner

Mr. Lawrence Burkett, already noted above, had the closest estimate for Phase 1 peak load. See above for a description of the analysis method.

Phase 2 Winner

Mr. Dmitriy Roik, a practicing engineer at the firm Industrial Design Solutions in Russia, had the best estimate for Phase 2 peak load at 1.3% relative accuracy. Mr. Roik used the finite element program Lira-SAPR 2021, employing 8112 nonlinear rectangular membrane elements for the analysis.

Honorable Mentions for Students

In addition to those who had the best predictions, we would also like to commend the following students for their prediction accuracy and for their efforts in analyzing this test specimen.

- **Yongquan Li**, a PhD Student from Zhejiang University in China, for their Phase 1 prediction.
- **Junyan Xiao**, a PhD Student from the University of Toronto in Canada, for their Phase 1 prediction.
- **Amirali Bahnamiri,** a PhD Student from the University of Waterloo, for their Phase 2 prediction.

Summary

These tests were carried out to gather data on the shear strength of deep reinforced concrete members without shear reinforcement and with ACI 318-19 minimum shear reinforcement, with emphasis on beams with highly strained high-strength longitudinal reinforcement. The blind competition was designed to draw attention to the tests and to gather statistics on the ability of researchers and practitioners to predict shear strengths. The tests were successful in both regards.

The organizers of the tests are continuing analysis of the test data and considering additional tests to complement the results obtained here. The results of those tests and analyses are expected to be reported in future publications.

We thank everybody who participated in this blind prediction competition and hope that it was a rewarding learning opportunity for all.