



PCI Big Beam Competition 2021-22 IOWA STATE UNIVERSITY

Beaming with ExCYtement



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Forterra

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1. ACKNOWLEDGEMENTS

The Beaming with ExCYtement team from Iowa State University would like to acknowledge and thank the contribution of a group of people for the successful completion of the project.

We want to start by thanking Dr. Hartanto Wibowo, our faculty advisor for the competition. He periodically guided us to develop the best possible output for the competition. He had also delivered the course on prestressed concrete in the fall of 2021 to us, during which he introduced us to this unique competition.

We also want to extend our sincere gratitude to Mr. Jeff Butler and the entire team at Forterra, all of whom tirelessly worked for the successful casting and transportation of the beam. The sponsoring company, Forterra, provided us with creative mentorship throughout the competition. The casting team was highly inclusive and provided fun field facts as a takeaway from the casting experience.

The lab team at the Iowa State University Civil Engineering Department also provided their unwavering support during the assembly and testing time of the competition. We would like to recognize them for their sincere efforts.

Last, but not least, we would like to take this opportunity to thank PCI for hosting such an interesting competition for students to put into action the knowledge learned in classrooms.

2. INTRODUCTION

The Precast/Prestressed Concrete Institute (PCI) conducts the Engineering Student Design, or commonly known as the Big Beam Competition, annually to give an opportunity to students studying prestressed concrete to design, construct, and test an innovative prestressed beam. The beam has the requirements of being innovative, optimally designed, and cost effective. The competition provides a great opportunity for students to get exposure to the real-life challenges of designing and constructing such a prestressed concrete beam.

The students of Iowa State University are participating in this year's competition under the team name of "Beaming with ExCYtement", inspired by their school mascot CY, the cardinal. The team consists of Daniel Viececi, Nayana Sreekumar, and Bharath Melugiri Shankaramurthy, guided by Dr. Hartanto Wibowo.

The team is presenting in this report their design concepts and construction procedures followed to create the prestressed concrete beam for the big beam competition. To summarize the beam details, the beam cross section was finalized to be 18.5 in height and 8 in wide with 3 counts of 0.5 in prestressing strands. The total length of the casted beam was 21 ft, while the tested length was 20 ft (as per PCI competition specifications). Shear stirrups and compression rebars consisted of #3 bars.

The report begins with a discussion on the material properties and the design concepts of the beam. Followed by this discussion the fabrication details and the results from the beam test are included in the report. The report also consists of the flexural design, shear design, and deflection calculations. The report concludes with the calculation of the weight and the cost of the beam. Personal statements by the student members, expressing their learning output from the competition are also available in the report.

3. EXECUTIVE SUMMARY AND JUDGING FORMS

3.1. Executive Summary

The finalized cross section dimensions of the beam are 18.5 inches deep and 8 inches wide, with 3 numbers of 0.5"-7 wire prestressing strands. The total length of the cast beam was 21 feet, 20 feet of testing length and 6 inches on either side for providing required support in lab. Top rebars to hold the stirrup in space were 2 numbers of #3 bars. The stirrups were also constructed using #3 bars. The shear design yielded a uniform stirrup spacing of 10 inches, with additional stirrups at locations of loading and support locations. The loading was two-point equal loading at 10 feet and 13 feet from left end of the beam.

The design process was carried out in accordance with the codal provisions of ACI 318-19. The failure of the beam was as expected in flexure with the crushing of the top layer of concrete. The design of the beam was able to cautiously avoid shear failure of the beam. The details regarding the calculated and measured parameters of testing as shown in Table 3.1. The load deflection curve for the testing is as shown in Fig 3.1.

Table 3.1. Summary of test details

Testing Detail	Calculated Value	Measured Value	Percentage diff.
Cracking Load (kips)	20.14	21	-4.10
Maximum Applied Load (kips)	34.48	35	-1.49
Maximum Deflection (in)	2.5	3.6	-30.56
Total Difference:			-36.14

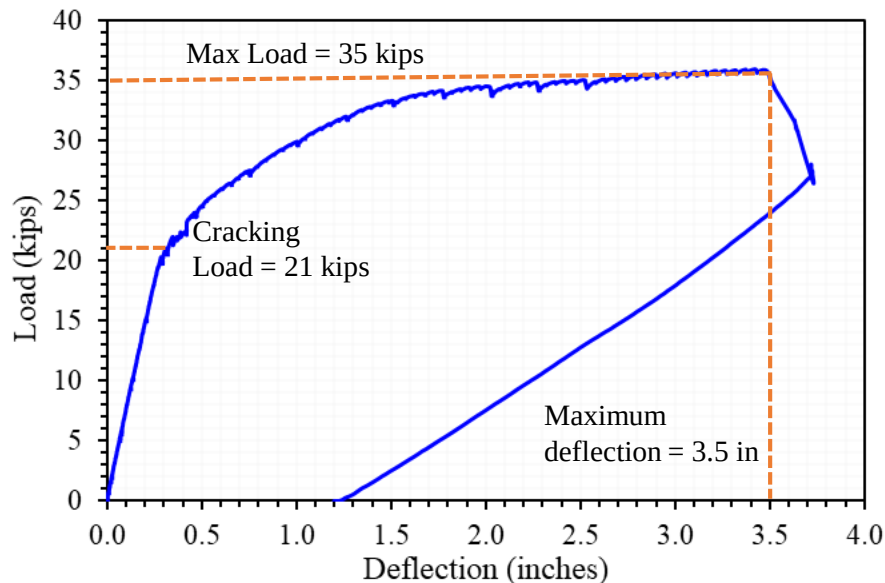


Fig 3.1. Load-deflection curve for the tested beam indicating its key properties

3.2. Judging Form- Test Summary

PCI BIG BEAM COMPETITION 2021-2022		
05/10/2022		
Date		
Beaming with ExCYtement (Iowa State University)	1	05/06/2022
Student Team (school name)	Team Number	Date of Casting
Basic Information		
1. Age of beam at testing (days)	4 days	
2. Compressive cylinder tests*		
Number tested	3 cylinders	
Size of cylinders	4 in diameter, 8 in length	
Average (psi)	9912.33	
3. Concrete properties		
Unit weight of concrete (lb/ft ³)	148.4	
Slump or spread (in.)	17	
Air content (%)	1.8	
Tensile strength (psi)	737	
Circle one: ☒ Split cylinder ☐ MOR beam		
4. Pretest calculations		
a. Applied load (total) to cause cracking (kip)	20.14	
b. Maximum applied point load at midspan (kip)	34.48	
c. Maximum anticipated deflection due to applied load only (in.)	2.5	
Pretest calculations MUST be completed before testing.		
* International entries may substitute the appropriate compressive strength test for their country.		
Judging Criteria		
Teams MUST fill in these values.		
1. Actual maximum applied load (kip)	35	
2. Measured cracking load (kip) [†]	21	
3. Cost (dollars)	213.09	
4. Weight (lb)	3202.97	
5. Largest measured deflection (in.)	3.6	
6. Most accurate calculations		
a. Absolute value of (maximum applied load – calculated applied load)/calculated applied load	0.02	
b. Absolute value of (maximum measured deflection – calculated deflection)/calculated deflection	0.44	
c. Absolute value of (measured cracking load – calculated cracking load)/calculated cracking load	0.04	
Total of three absolute values (a + b + c) = 0.5		
[†] Measured cracking load is found from the "bend-over" point in the load/deflection curve. Provide load/deflection curve in report.		
Test summary forms must be included with the final report, due July 15, 2022.		
Sponsored by:		
 		

3.3. Judging Form- Member Certification



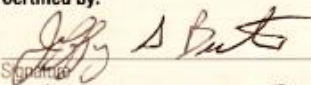
PCI BIG BEAM COMPETITION 2021-2022

CERTIFICATION

FORTERRA
As a representative of (name of PCI Producer Member or sponsoring organization)
Fowa State University
Sponsoring (name of school and team number)

I certify that:

- The beam submitted by this team was fabricated and tested within the contest period.
- The calculations of predicted cracking load, maximum load, and deflection were done prior to testing of the beam.
- The students were chiefly responsible for the design.
- The students participated in the fabrication to the extent that was prudent and safe.
- The submitted test results are, to the best of my knowledge, correct, and the video submitted is of the actual test.

Certified by:

Signature
JEFFREY S BUTLER
Name (please print)
5/10/22
Date

17.24 kips / per point load (34.48 kips total)
Predicted Maximum Load
10.07 kips / per point load (20.14 kips total)
Predicted Cracking Load
2.5 in
Predicted Deflection at Midspan

THIS CERTIFICATION MUST BE PART OF THE FINAL REPORT

Sponsored by:

ASPIRE **ALP**
SUPPLY

4. MATERIAL DETAILS

4.1. Concrete Mix Design

Considering the available effective space between the designed steel reinforcement bars and the prestressing strands within the formwork which needs to be filled with a good quality concrete (meeting the strength requirement of 10 ksi, the target strength that was assumed for the structural design calculations), a semi-flowable self-consolidating concrete (semi-SCC) was deemed necessary and efficient because of its adequate filling ability, passing ability, segregation resistance, and relatively lower cost as compared to a conventional SCC.

Accordingly, a semi-SCC with a water-to-binder ratio of 0.33 was produced in a precast concrete production facility (at Forterra plant, Iowa Falls). A combination of Type III cement and slag (in weight ratio: 70:30) was used as binders to ensure quicker strength development of concrete. The aggregate combination included 3/4" limestone as coarse aggregate and concrete sand as fine aggregate in the volume ratio of 55:45. A hydration stabilizer- Recover®, and a polycarboxylate based high-range water reducer (HRWR)-Adva® 585 were used, respectively, to meet the requirements of the mix in terms of its hydration stability, high workability, and strength. Table 4.1. gives the material proportions (pounds per cubic yard of concrete) used for the semi-SCC production (additional details regarding the concrete materials can be found in Appendix B).

Table 4.1. Material proportions for producing 1 cubic yard of concrete

	Cement	Slag	Coarse Aggregate	Fine Aggregate	Water	Air*
Weight Proportions (lbs)	577	248	1562	1331	269	\
Volume Proportions (cf)	2.93	1.38	9.78	7.98	4.31	0.54

*As no air entraining admixture was used, the air content given is the entrapped air volume

The produced concrete had an average spread (i.e., slump flow) diameter of 17 inches tested in compliance with inverted slump mold test (ASTM C1611). The concrete was homogenous with no segregation or evidence of bleeding, and hence, it was deemed ‘highly stable’. Accordingly, the semi-SCC was assigned a visual stability index (VSI) value of 0 on a typical visual evaluation scale (of 0-3) used for fresh SCC mixtures in accordance with ASTM C1611. Fig. 4.1. compares the quality of the tested semi-SCC to other standard conditions. The fresh concrete unit weight (density) tested in accordance with modified ASTM C138 was 148.4 pcf, and the fresh concrete temperature was recorded to be 82°F. Table 4.2 summarizes the tested fresh concrete properties.

Table 4.2. Summary of fresh concrete properties

	Spread diameter (in.)	Unit weight (pcf)	Visual stability index	Air (%)	Temperature (°F)
Value	17	148.4	0 (highly stable)	1.8	82

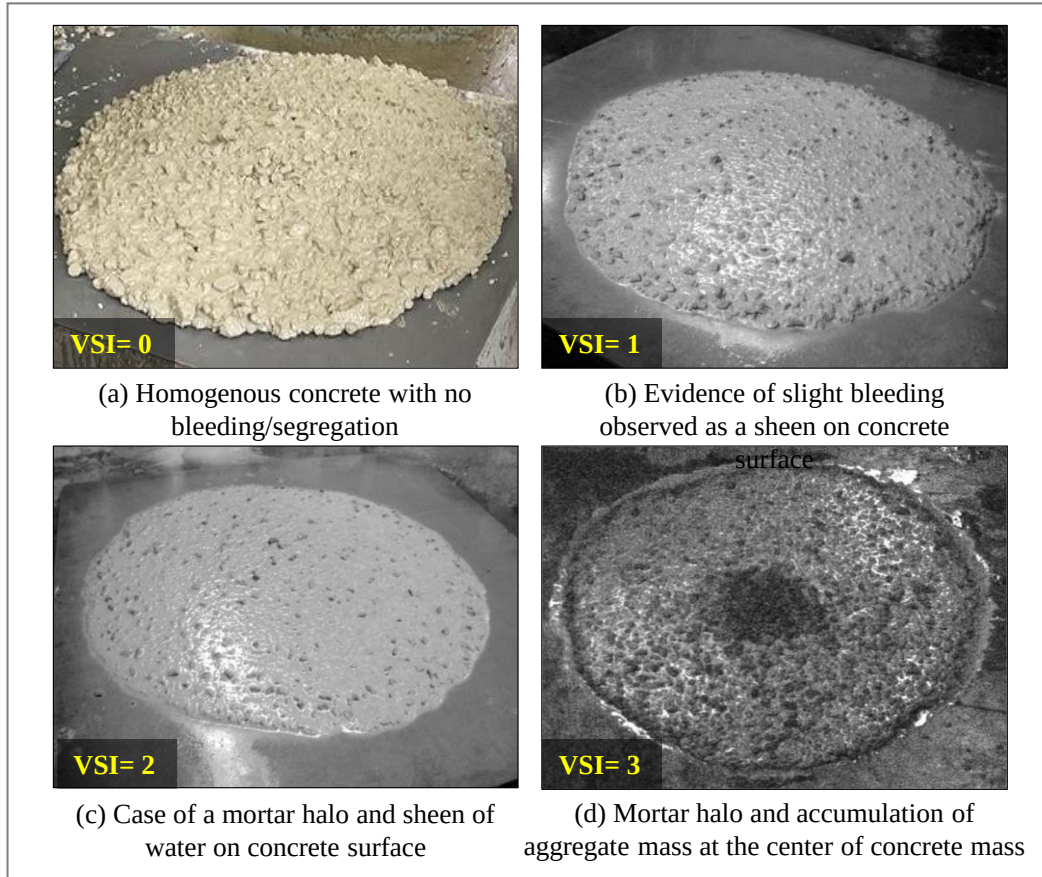


Fig 4.1. Stability of the semi-flowable SCC (a) used for casting the beam as compared to other standard conditions (shown in (b)-(d), compiled from ASTM C1611)

4.2. Rebar Specifications

Top rebars were provided to support the shear reinforcements in the beam. Shear reinforcements were provided in the beam to resist the shear demand at locations of loading and at support locations. All the rebars used in the beam were Grade 60 #3 mild steel reinforcement.

4.3. Prestressing Strands Specifications

The prestressing strands used were 0.5"-7-wire low relaxation 270 ksi strands. The strands were jacked to 75 percent of the ultimate stress. The strands were straight throughout the length of the beam and placed at 15.88 in from top of the beam.

5. MATERIAL DETAILS

5.1. Preliminary Assumptions

The first step in the structural design was to draw the bending moment diagram due to the applied point loads to know what the maximum moment was needed to be designed. A design load value of 10 kips was selected to make sure the beam would not crack before the service limit but also provide room to fail before the upper strength limit.

We consulted with Forterra to discuss options for materials and fabrication requirements and limitations. During these discussions, we determined what clear covers to use, concrete strengths to use for design, type of prestressing strands, size and shapes of stirrups, and more. We initially wanted to use harped strands to be more efficient in our design but learned that only straight strands could be used due to restriction in constructability.

5.2. Flexural Design

One of the most interesting and challenging part of the whole competition was to determine the cross section of our beam. While most prestressed beams in industry are designed with standard shapes, we had to design our own cross section from scratch. Multiple sizes and shapes were tried to obtain a certain section modulus based on the required stresses, and Magnel diagrams were utilized to design the prestressing force and eccentricity. The iterative nature of the design process was evident at this stage of designing.

The initial decision of the team was to design a I-section to achieve the desired section modulus while minimizing the weight of the beam. However, constructability issues in designing the shear reinforcements that needs to be bent into smaller shapes to fit within the beam and that can be fabricated by the supplier redirected the design to a rectangular cross section.

As the shape of the cross section was finalized as rectangular, the next step was to determine the exact dimensions of the cross section. The section was highly optimized, keeping in mind the usage of 3 prestressing strands, minimum spacing between strands and concrete cover. Once the width of the cross section was determined to be 8 in, iterations were done to determine the height based on the stress conditions in the cross section. This yielded our final dimension of 18.5 in x 8 in rectangular cross section.

The final steps of the flexural design were to design the prestressing force and eccentricity to balance the live load such that the beam would not crack below the minimum service load and fail before the ultimate load. With the cross section being completed, the prestressing steel design and stress checks were straightforward and quick to complete.

5.3. Prestress Losses

The losses in prestressing strands do play a significant role in the behavior of the beam upon loading since the resistance from the prestressing strands are vital for keeping stress and

6. BEAM FABRICATION

6.1. Building the Formwork

The real-life implementation of the beam design and construction started with the formwork building. It required plenty of coordination to determine when, where, and how the formwork needs to be built. It was a challenge by itself given the distance between the Forterra plant and the lab at Iowa State University, where the testing was scheduled to take place.

Multiple options were discussed on the formwork fabrication. Option one, have materials transported to Forterra plant and the team and plant workers assisting in the formwork fabrication and option two was to make the forms in the Iowa State University Structures' lab with steel forms to save money on currently expensive wood. The option finally implemented was the one where the formwork was made at the Forterra plant, but with recycled wood panels. We reduced a considerable amount of material wastage in this stage of our construction and would like to highlight that as one of our key achievements of the project.

The wood panels were assembled within the prestress strand stressing bed at the Forterra plant to make the formwork as shown in Fig 6.1 and Fig 6.2. The formwork was well oiled prior to casting to ensure easy removal of the casted beam. The inner dimensions of the formwork were checked to ensure the dimensions match the required dimensions of the beam.



Fig 6.1. Side panels of formwork

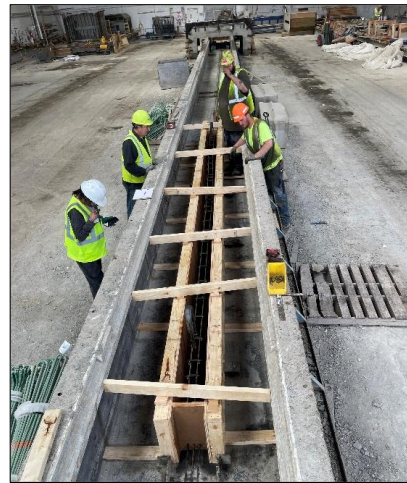


Fig 6.2. Completed formwork

6.2. Strand Jacking Details

The first wood panel supporting the length of the beam and the end panels was securely placed before the three 0.5"-7-wire strands were run through the length of the stressing bed as shown in Fig 6.3. At the opposite end of the prestressing strand spool, the strands were placed through chucks to lock them in place during the jacking stage (Fig 6.4). Three strands were used in the beam, and they were all looped in through the set of shear stirrups, placed throughout the length of the beam.

Once the three strands had been run down the bed and chucked at either end, the strands were ready to be jacked. A hydraulic jack and heavy hardware were used to pull the strands back a certain distance that would achieve the required jacking stress in the steel.



Fig 6.3. Prestressing strand through end panel



Fig 6.4. End chucks for locking strands

6.3. Building the Rebar Cage

The rebar cage for the beam consisted of the three prestressing strands, two top rebars (#3 bars), and the shear reinforcements (#3 bars) as shown in Fig 6.5. The stirrups consisted of rectangular hoops that would help with shear resistance and confinement to the strands in concrete. Once the strands were chucked in place, the stirrup locations were marked on the side of the forms. Using wire ties and a nifty rotating hand tool the stirrups were secured to at the bottom to the strands that were already placed. The instability of the stirrups, which were only tied to the bottom strands, was resolved by tying them to the top rebars (Fig 6.6). With each stirrup tied at its four corners to the flexural reinforcement, the rebar cage was locked in place and ready to be poured with concrete.

In addition to the rebar cage for the beam, there were two rebar loops placed near the beam ends to help transport the beam to the testing lab. These loops consist of a multiple rebars bunched together and bent to form the rectangular loop (Fig 6.7).



Fig 6.5. Completed rebar cage



Fig 6.6. Stirrup tie down



Fig 6.7. Transport hook

6.4. Casting and Curing

The concrete was batched at the plant and a hopper brought it over from the mixer to the bed where the beam formwork (Fig 6.8) along with the rebar cage and prestressing strand was assembled. The concrete was poured into the forms around the reinforcement and consolidated using a vibrator. Once the concrete reached the top of the forms, a screed was used to give the beam a smooth finish on top as shown in Fig 6.9. The volume of the beam was less than one cubic yard of concrete, and the casting operation was finished in a span of ten minutes.



Fig 6.8. Concrete Pour



Fig 6.9. Finishing the concrete beam surface

Given the nonsymmetric loading on the beam, the shear stirrup locations were also nonsymmetric. To identify the left and right ends of the beam, a tie was placed on top of the poured concrete at the right end of the beam (Fig 6.10). Learning such minute skills were big learning outcomes of the project. Along with the concrete used to cast the beam, sufficient concrete was also prepared to determine its unit weight, air content, and spread (Fig 6.11). Control cylinders were also made so we could track the concrete's strength as it aged.



Fig 6.10. Identification tie placed at right end of the beam



Fig 6.11. Casting concrete cylinders for strength testing

Once the concrete pouring was finished, the cast beam was covered with a plastic sheeting and was left undisturbed to cure for three days. The beam was cast indoors and let to air-cure on its own, without utilizing any additional curing techniques such as for instance the traditional steam curing method that Forterra uses for conventional precast bridge girders. The choice of letting the beam air-cure without external assistance was to achieve the sufficient, but not exceeding the required strength (as assumed in the design calculations) on the day of beam testing.

At the end of the three-day air-curing process, the strength of the concrete was tested to determine the release time for the strands. As the cast concrete had gained sufficient strength, the strands were cut on the third day from casting, and arrangements were made to transport the beam from the casting plant to the University's structural engineering laboratory located at the Town Engineering Building. Fig 6.12 shows

the overall sequence of tasks and operations carried out using the freshly mixed concrete at the plant.



Fig 6.12. An overview of tasks performed at the concrete plant

7. TESTING

7.1. Cylinder Strength Test

The strength of the concrete used for the beam construction was closely monitored to ensure the accuracy of the predicted test values. The design calculation assumptions on the strength of concrete had to be as close as possible to the actual strength of concrete used. The gain in concrete strength was considerably rapid and therefore multiple tests were carried out on the cylinders in the laboratory. Fig 7.1 shows the concrete strength gain with time and the corresponding tensile strength of concrete on the day of testing.

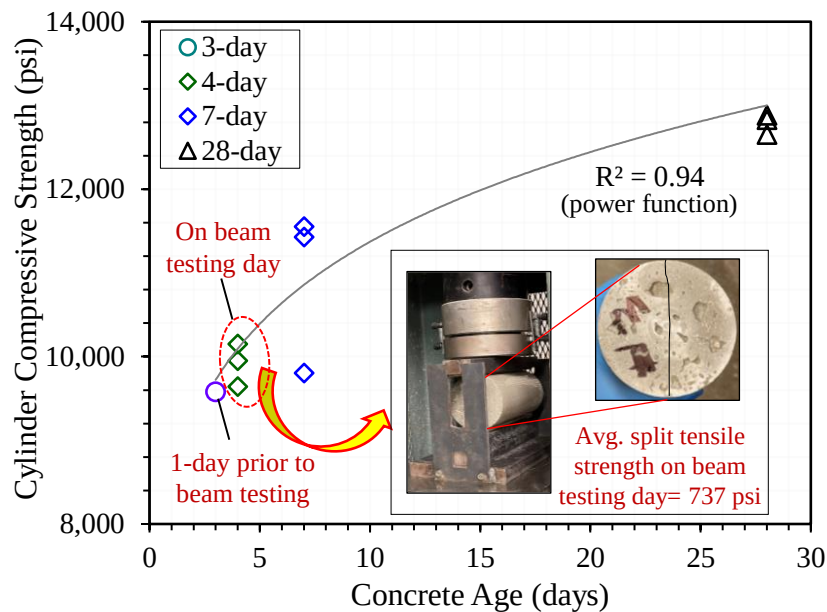


Fig 7.1. Development of concrete strength with time

The two tests conducted on the cylinders were the compressive strength and split-tensile (indirect tensile) strength test. For the compression test, the cylinders were placed between two bearing caps/pads to evenly distribute the applied load, then placed into a hydraulic machine that would apply uniaxial compressive force/load on the cylinder until failure (Fig 7.2). The machine recorded the stress values as the load was applied and displayed the maximum stress value at failure, which was taken as the concrete's compressive strength at a particular testing age. Once the compressive strength reached its desired level, three split cylinder tests were performed to measure the concrete's tensile strength capacity according to the competition requirements. The cylinder was placed in the same hydraulic machine, but this time it was loaded in the transverse direction to obtain the indirect tensile strength (Fig 7.3).



Fig 7.2. Compressive strength test setup



Fig 7.3. Split-tensile strength test setup

7.2. Prestressed Beam Test

The beam was transported to the structure's laboratory at Iowa State University, where it was set up for the test as per the competition requirements. The beam was placed on roller supports 20 feet apart, and a spreader beam was used to apply the live loads at midspan and 3 feet from midspan. A hydraulic jack was used to apply the loads by pushing down on the spreader beam. The jack was also connected to a computer to measure the loading values. To measure the midspan deflection, a strain gauge was attached to the bottom of the beam, which was also connected to the computer to measure the deflection values. These worked together to measure the load and deflection simultaneously to produce a load-deflection diagram.

Measurements and mark ups were conducted at multiple locations to set up the beam for testing. The span lengths, spreader beam locations, and strain gauge location were three of the most important mark up, along with additional details for the testing.

Multiple cameras were set up to record the test. First camera was set up with a view at midspan of the beam, at eye level with the bottom of the beam to show how much the beam deflected along with a reference tape measure (Fig 7.4). Two sets of cameras were recording the testing from the front view and the aerial view of the test (Fig 7.5). These multiple views of the testing provided us with sufficient recording to incorporate in the beam testing video submitting along with the report. The details provided in the video closely capture the multiple stages of the beam loading until failure.



Fig 7.4. Reference tape for beam deflection measurement



Fig 7.5. An overview of the setup for big beam testing

Once the test began, the loading was paused periodically while we listened and monitored for cracks. The first crack was observed at 21 kips of total loading (Fig 7.6). Newer cracks were observed with continued loading and all the cracked were marked with markers, as they started becoming more visible. The cracks showed a mirroring pattern across the midpoint of the loading locations, which was a good indication of the accurate load application. As the load kept increasing, there was an evident growth of cracks in addition to greater beam deflection. Eventually the maximum capacity of the beam was reached at 35 kips of total load. The beam failed due to the concrete crushing at the top of the beam near midspan as shown in Fig 7.7. Notes were kept during the test as well in addition to the computer monitoring to track the loads and deflections, including the cracking and ultimate load.



Fig 7.6. First crack as observed



Fig 7.7. Cracked beam

8. PERSONAL STATEMENTS AND CONTACT DETAILS

Daniel Vieceli:

I learned a lot of lessons and important information about the design process, construction, and communication through participating in this competition. First, I learned how iterative the design process is. There are a lot of assumptions that need to be made before any analysis or calculations can be done, then afterwards you check the assumptions and see if they hold up and change as necessary. The biggest iterative challenge we faced was trying to design a cross section for the beam. I also learned the importance of knowing the practical limitations and requirements to construct something. We communicated early on with Forterra to get base information of what to use and consider in our design, such as shapes for the beam and stirrups, types of strands, concrete initial and final strengths, clear covers, etc. And this ties in with the most important thing I learned, which is effective communication. There are a lot of parties involved in construction projects, and every decision made affects someone else who needs to be kept informed. I am very thankful to PCI, Iowa State University, Forterra, and my teammates for getting the opportunity to participate in this competition where I learned valuable information that will assist me in my career designing bridges.

Nayana Sreekumar:

I personally am grateful to the team at PCI for conducting the competition and screening through the innovative design submittals. The whole project was a learning curve for me to take the subject matters that I learn in school to field implementation. As a PhD student my world is more academic driven and less influenced by the industry, but this project gave me a good exposure to the challenges and freedom of working in field. It was a lovely experience to interact and learn from the folks involved in the casting at the plant and lab support team. Each of them had great insights to provide to junior people like our team. The iterative nature of the design procedure was another learning outcome from this project, which has formed a certain sense of dimensioning and other design parameters in our minds. The team we formed was also such a diverse and supportive one that each of us got an opportunity to showcase our strength and work on our weak spots. Thank you, team Beaming with ExCYtement!

Bharath Melugiri Shankaramurthy:

As a Ph.D. candidate working in cement and concrete-based materials since few years, I always questioned myself as to how the fundamental material properties and their behavior influence the real-world construction. Although, I always got some answers from professors or research articles, I never had a first-hand experience. Through this competition, I not only got clarity regarding this but also understood how the material terminologies translate to the structural behavior of the constructed member. This also was an endorsement on the key role the concrete formulations play in real-world structures. Although the structural design is perfect, if the material formulation is not put together well, the as-built structure would not perform the way it is expected to during its service life. Having worked as the only member with construction materials background and the two other teammates from structural engineering major, I had a unique learning experience understanding the stepwise design approach and the iterative process involved in arriving at the final calculations for loads, deflections etc., Hands-on experience pouring the beam, testing material properties, and maintaining records of all the key aspects to bring out as a technical report, all helped to revise the concepts, pay attention to details and also enjoy the adrenaline rush to take part in the prestigious competition. Shooting the informal video was joyful. Overall, it is an experience that I cherish forever. Thank you for all the support and the opportunity.

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397, Town Engineering Building

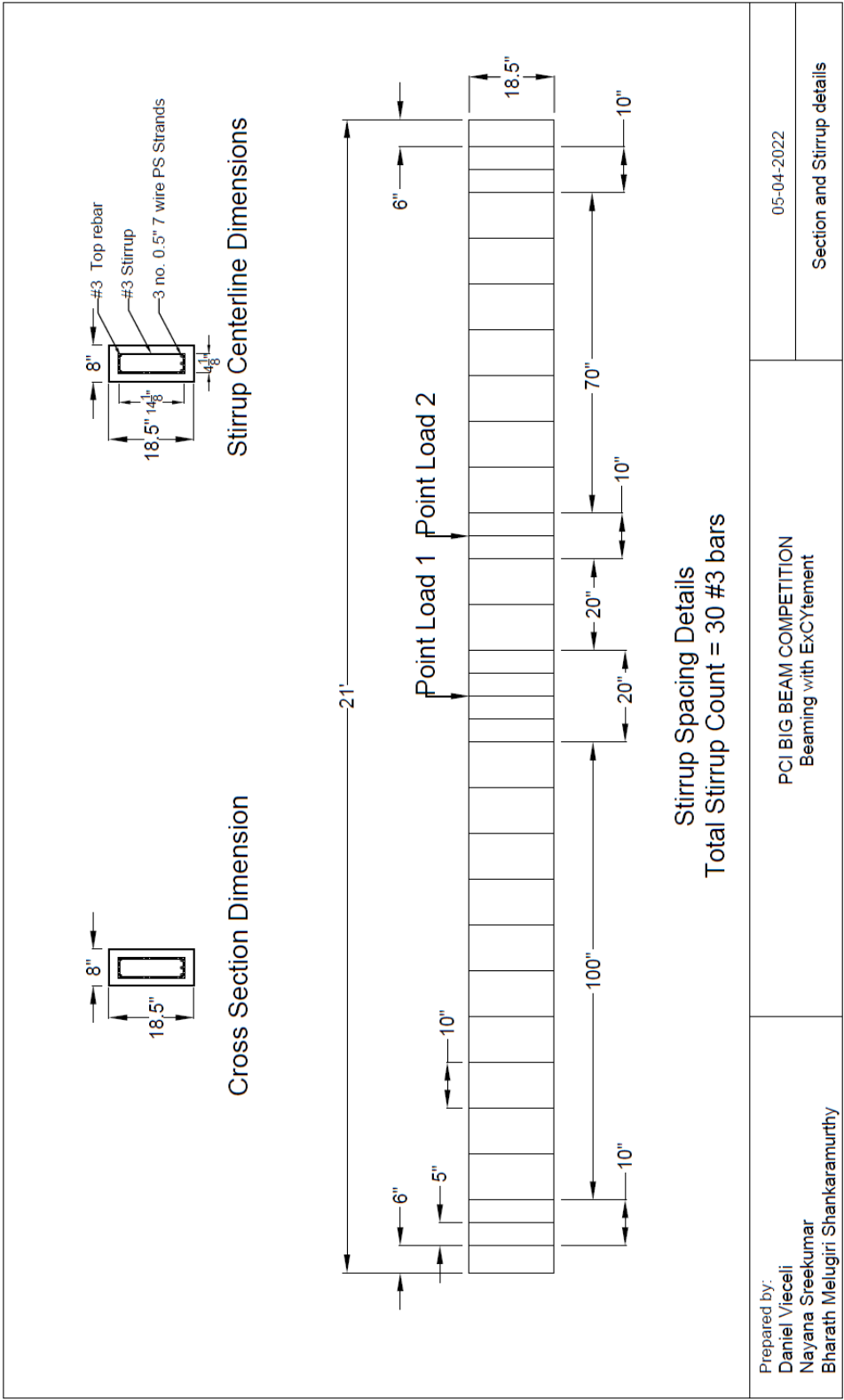
813 Bissel Road

Ames, Iowa - 50011

9. REFERENCES

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2. ASTM C1611/C1611M-21, Standard Test Method for Slump Flow of Self-Consolidating Concrete, ASTM International, West Conshohocken, PA, 2009
3. ASTM C138-17a, Standard Test Method for Density (Unit Weight), Yield, and Air Content (Gravimetric) of Concrete, ASTM International, West Conshohocken, PA, (2017)
4. ASTM C39/C39M-21, Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens, ASTM International, West Conshohocken, PA, (2021)
5. ASTM C496-496M-17, Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens, ASTM International, West Conshohocken, PA, (2017)
6. E.P. Koehler, D.W. Fowler, E.H. Foley, G.J. Rogers, S. Watanachet, M. Jae Jung, Self-Consolidating Concrete for Precast Structural Applications: Mixture Proportions, Workability, and Early-Age Hardened Properties (Report No. FHWA/TX-08/0-5134-1), 2007

10.APPENDIX A: STRUCTURAL DETAILING



11.APPENDIX B: MATERIAL DETAILS

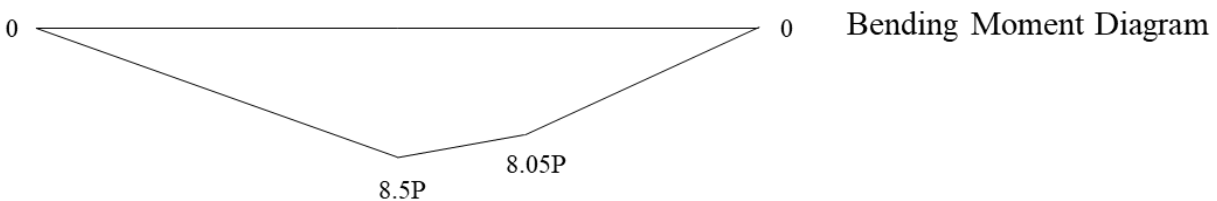
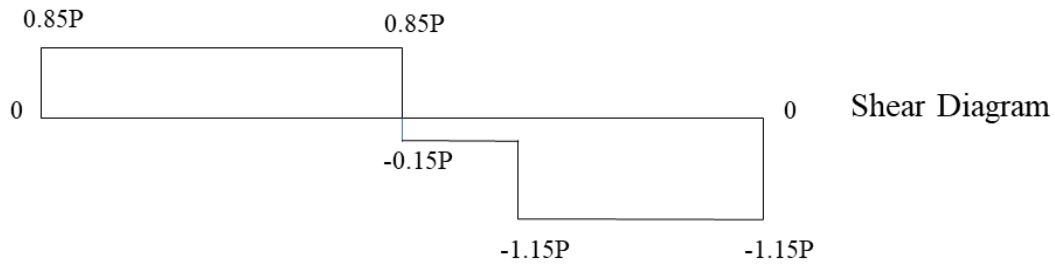
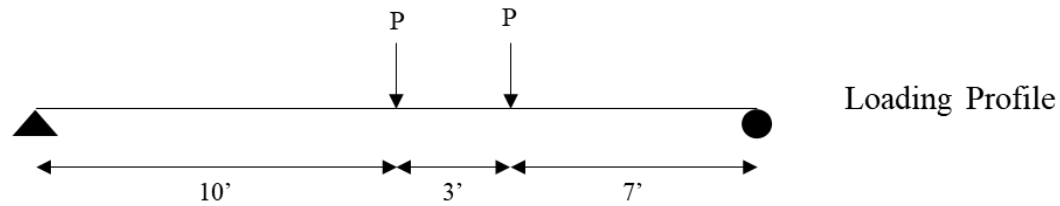
Material proportions and concrete mix design:

		Concrete Mix Design Data for Iowa Falls		
Mix Designation PS 825 19A		Targets (psi) 1 Day: 8000 28 Day: 10000		Date 3/4/2020
	Material	Cubic Yard Quantity	Specific Gravity	Cubic Yard Volume
Cement	Cement, Type III	577 lbs	3.150	2.93 ft³
	Slag, GranCem	248 lbs	2.870	1.38 ft³
Cementitious Materials				
	Coarse Aggregate, 3/4" Limestone	1562 lbs	2.560	9.78 ft³
	Fine Aggregate, Concrete Sand	1331 lbs	2.670	7.98 ft³
Aggregates				
Chemical Admixtures	HRWR	8.0 oz/CWT	1.065	66.0 oz
	Hydration Stabilizer	1.5 oz/CWT	1.125	12.4 oz
Water	Water	269 lbs	1.000	4.31 ft³
Air	Air Content, %	2.0%	+ 1.5% - 1.5%	0.54 ft³
Batch Properties	Pozzolans, %	30%	Total Volume 27.01 ft³	
	Total Cementitious	825 lbs	Yd³ Weight 3993 lbs/yd³	
	Water Cement Ratio*	0.33	Unit Weight 147.88 lbs/ft³	
	Spread	19 in	+/-	3 in
	*Water Cement Ratio includes water from liquid admixtures			
Material	Type/Classification	Supplier		
Cement	Type III	Lehigh, Mason City		
Slag	GranCem	Skyway Cement Co., Skyway		
Coarse Aggregate	3/4" Limestone	Martin Marietta, Alden, IA		
Fine Aggregate	Concrete Sand	Martin Marietta, H and M		
HRWR	ADVA 585	GCP Applied Technology		
Hydration Stabilizer	Recover	GCP Applied Technology		

Contact:

Name	Title	Phone	Email
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12.APPENDIX C: FLEXURAL DESIGN



Section Properties		
b =	8	in
h =	18.5	in
d _p =	15.875	in
A =	148	in ²
I =	4221	in ⁴
y _t =y _b =	9.25	in
e =	6.625	in
r ² =	28.52	in ²

Material Properties								
Concrete			Steel					
f'c =	10	ksi	no. of strands =	3		A _s ' = 2 #3 bars =	0.22	in ²
f'ci =	8	ksi	A _{PS} =	0.459	in ²	d' =	2.5625	in
f _r =	-0.750	ksi	f _{pu} =	270	ksi	E _s =	29,000	ksi
f _{ri} =	-0.671	ksi	f _{pi} =	189	ksi			
E _c =	5700	ksi	f _{py} =	243	ksi			
E _{ci} =	5098	ksi	E _{PS} =	28,000	ksi			

Losses:

1st Relax:

$t = 24 \text{ hrs}$

$f_{pi} = 189 \text{ ksi}$

$f_{py} = 243 \text{ ksi}$

Strand cut off time

$$\Delta f_{PR1} = f_{pi} * \frac{\log t}{45} \left[\frac{f_{pi}}{f_{py}} - 0.55 \right]$$
$$\Delta f_{PR1} = 189 * \frac{\log 24}{45} \left[\frac{189}{243} - 0.55 \right]$$

$$\Delta f_{PR1} = 1.32 \text{ ksi}$$

$f_{p,transfer} = 187.68 \text{ ksi}$

$P_{transfer} = 86.33 \text{ kips}$

Stress after 1st relaxation

Strand force after 1st relaxation

Elastic shortening:

$e = 6.63 \text{ in}$

$M_{DL} = 92.5 \text{ kip-in}$

$I = 4221.08 \text{ in}^4$

$A = 148 \text{ in}^2$

$n_{ps} = 7.77$

$$f_{cgp} = \frac{P}{A} - \frac{Pe * e}{I} + \frac{M_g e}{I}$$
$$f_{cgp} = \frac{86.33}{148} - \frac{86.33 * 6.63^2}{4221.08} + \frac{92.5 * 6.63}{4221.08}$$
$$f_{cgp} = 1.63 \text{ ksi}$$

$$\Delta f_{P,ES} = n_{ps} * f_{cgp}$$
$$= 7.77 * 1.63$$
$$= 12.64 \text{ ksi}$$

Stress after elastic shortening

Strand force after elastic shortening

$f_{P,ES} = 175.04 \text{ ksi}$

$P_{ES} = 80.52 \text{ kips}$

2nd Relax:

$t_n = 96 \text{ hrs}$

$$\Delta f_{PR2} = f_{pi} * \left[\frac{\log t_n - \log t_i}{45} \right] \left[\frac{f_{pi}}{f_{py}} - 0.55 \right]$$
$$\Delta f_{PR2} = 189 * \left[\frac{\log 96 - \log 24}{45} \right] \left[\frac{189}{243} - 0.55 \right]$$
$$\Delta f_{PR2} = 0.58 \text{ ksi}$$

Stress after 2nd relaxation

Strand force after 2nd relaxation

$f_{P,PR2} = 175.04 \text{ ksi}$

$P_{PR2} = 80.52 \text{ kips}$

Loads:

$$w_{sw} = \frac{A * \gamma_{concrete}}{148in^2} = \frac{144in^2/ft^2 * 150pcf/1000}{148in^2/ft^2} = 0.154 klf$$

Uniformly distributed load due to self-weight of beam

$$M_{DL} = w_{sw} * L^2 / 8 \\ = (0.154klf)(20ft)^2 / 8 * 12 in/ft \\ = 92.4 kip in$$

Moment due to dead load

$$M_{PS} = P_e * e = f_{pe} * A_{PS} * e \\ = (175.04ksi)(0.459in^2)(6.625in) \\ = 532.2 kip in$$

Moment due to prestress

Stresses in Concrete:

Stresses at Prestress Transfer

$$\sigma_{top} = \frac{P}{A} - \frac{M_{PS}y}{I} + \frac{M_{DL}y}{I} \\ = \frac{80.34 kip}{148in^2} - \frac{(532.2 kip in)(9.25in)}{4221in^4} + \frac{(92.4 kip in)(9.25in)}{4221in^4} \\ = -0.421 ksi = 0.421 ksi (T) < -0.671 ksi (O.K.)$$

Stress in top fiber of beam at prestress transfer.

Stress is less than the cracking stress at transfer.

$$\sigma_{bot} = \frac{P}{A} + \frac{M_{PS}y}{I} - \frac{M_{DL}y}{I} \\ = \frac{80.34 kip}{148in^2} + \frac{(532.2 kip in)(9.25in)}{4221in^4} - \frac{(92.4 kip in)(9.25in)}{4221in^4} \\ = 1.507 ksi (C) < 8 ksi (O.K.)$$

Stress in bottom fiber of beam at prestress transfer.

Stress is less than the initial compressive strength.

Check stresses at service loading to determine when the beam will crack

$$\sigma_{bot} = \frac{P_e}{A} + \frac{M_{PS}y}{I} - \frac{M_{DL}y}{I} - \frac{M_{LL}y}{I} \\ -0.750 ksi = \frac{79.97 kip}{148in^2} + \frac{(529.80 kip in)(9.25in)}{4221in^4} - \frac{(92.4 kip in)(9.25in)}{4221in^4} - \frac{M_{LL}(9.25in)}{4221in^4} \\ -0.750ksi = 0.540ksi + 1.161ksi - 0.202ksi - 0.00219M_{LL}$$

$$M_{LL} = 1026.94 kip ft = 85.58 kip ft$$

$$\text{From moment diagram, } M_{max} = 8.5P$$

$$85.58 kip ft = 8.5P \rightarrow P = 10.07 kip \text{ per point load}$$

$$P_{total} = 20.14 kips$$

Cracking load

Ultimate Moment:

Calculate the ultimate moment, M_n , using strain compatibility method

$$\begin{aligned}\varepsilon_{pe} &= \frac{f_{pe}}{E_{ps}} \\ &= \frac{174.23 \text{ ksi}}{28,000 \text{ ksi}} = 0.00622\end{aligned}$$

Strain due to prestress

$$\begin{aligned}\varepsilon_d &= \frac{P_e}{A_c E_c} \left(1 + \frac{e^2}{r^2} \right) \\ &= \frac{79.97 \text{ kip}}{(148 \text{ in}^2)(5700 \text{ ksi})} \left(1 + \frac{(6.625 \text{ in})^2}{28.52 \text{ in}^2} \right)\end{aligned}$$

Decompression strain

$$= 0.000241$$

Assume $c = 2.7 \text{ in}$

$$a = \beta_1 c = 0.65(2.7 \text{ in}) = 1.755 \text{ in}$$

$$\begin{aligned}\varepsilon_f &= 0.003 \left(\frac{d_p}{c} - 1 \right) = 0.003 \left(\frac{15.875 \text{ in}}{2.7 \text{ in}} - 1 \right) \\ &= 0.0146\end{aligned}$$

Strain due to flexure

$$\begin{aligned}\varepsilon_{ps} &= \varepsilon_{pe} + \varepsilon_d + \varepsilon_f \\ &= 0.00622 + 0.000241 + 0.0146 \\ &= 0.0211 > 0.0085\end{aligned}$$

Total strain in prestressing strands

$$\begin{aligned}f_{ps} &= 270 - \frac{0.04}{\varepsilon_{ps} - 0.007} \\ &= 270 - \frac{0.04}{0.0211 - 0.007} = 267.16 \text{ ksi}\end{aligned}$$

Stress in prestressing strands

$$\begin{aligned}\varepsilon_s &= 0.003 \left(\frac{c - d'}{c} \right) = 0.003 \left(\frac{2.7 - 2.5625}{2.7} \right) \\ &= 0.000153 < 0.00207\end{aligned}$$

Strain in top steel does not yield

$$T = C_c + C_s$$

$$f_{ps} A_{ps} = 0.85 f'_c b \beta_1 c + \varepsilon_s E_s A'_s$$

Use equilibrium equation to calculate c and check assumption.

$$\begin{aligned}(267.16 \text{ ksi})(0.459 \text{ in}^2) \\ &= 0.85(10 \text{ ksi})(8 \text{ in})(0.65c) \\ &\quad + 0.000153(29,000 \text{ ksi})(0.22 \text{ in}^2)\end{aligned}$$

$$122.63 \text{ kip} = 44.2c + 0.976 \text{ kip}$$

$$c = 2.75 \text{ in} (\sim 1.9\% \text{ diff. from assumption} - \text{O.K.})$$

$$a = 0.65(2.75 \text{ in}) = 1.79 \text{ in}$$

$$M_n = T(d_p - a/2) - C_s(d' - a/2)$$

$$\begin{aligned}&= (122.63 \text{ kip})(15.875 - 1.79/2 \text{ in}) - ((0.976 \text{ kip})(2.5625 \\ &\quad - 1.79/2 \text{ in}))\end{aligned}$$

$$= 1835.37 \text{ kip in}$$

$$= 152.92 \text{ kip ft}$$

Assumption is O.K.

Take moment about C_c to get the beam's moment capacity

$$M_n = 154.258 \text{ kip ft}$$

From the moment diagram, $M_{max} = 8.5P$

$$\left(154.258 \text{ kip ft} - \frac{92.4 \text{ kip ft}}{12 \text{ in/ft}}\right) = 8.5P$$

$$P = 17.24 \text{ kips per point load}$$

$$P_{ult} = 34.48 \text{ kips}$$

Moment capacity calculated using Response 2000 software.

Subtract off dead load moment from total moment.

Maximum applied load

13.APPENDIX D: SHEAR DESIGN

Location (ft)	Shear, Vu (kips)	Moment, Mu (kip-ft)	Vudp/ Mu	Eqn a term	Eqn b term	Eqn c term	Min Vc term	Final Vc term, with min Vci term	Vci (kips)	fpe	fpc	Vcw (kips)	Vc (kips)	Vs (kips)
0.00	16.38	0.00	0.00	60.00	760.00	500.00	60.00	126.49	18.72	0.00	0.00	44.45	18.72	3.11
0.71	16.27	11.11	1.94	1416.01	760.00	500.00	500.00	500.00	74.00	59.38	0.18	51.47	51.47	-29.78
0.77	16.26	12.05	1.79	1309.53	760.00	500.00	500.00	500.00	74.00	64.47	0.20	52.07	52.07	-30.39
2.50	16.00	39.12	0.54	438.75	760.00	500.00	438.75	438.75	64.93	174.24	0.54	65.04	64.93	-43.60
5.00	15.63	78.23	0.26	244.96	760.00	500.00	244.96	244.96	36.25	174.24	0.54	65.04	36.25	-15.42
10.00	14.88	156.25	0.13	148.16	760.00	500.00	148.16	148.16	21.93	174.24	0.54	65.04	21.93	-2.09
11.50	2.86	152.17	0.02	77.38	760.00	500.00	77.38	126.49	18.72	174.24	0.54	65.04	18.72	-14.91
13.00	3.09	147.70	0.03	79.35	760.00	500.00	79.35	126.49	18.72	174.24	0.54	65.04	18.72	-14.60
16.50	21.13	73.94	0.38	324.59	760.00	500.00	324.59	324.59	48.04	174.24	0.54	65.04	48.04	-19.87
20.00	21.63	0.00	0.00	60.00	760.00	500.00	60.00	126.49	18.72	174.24	0.54	65.04	18.72	10.11

Location (ft)	Vs max = 8bw*d*sqrt(fc)/(kips)	Vs < Vs_max?	S, from Av,min	Smax =min(3/4h,24)	S req = (Av*fyrt*dp)/Vs	S_chosen (calculated)	S_Chosen (final)	0.5*phi* Vc	Vu>0.5 *phi*V c?	Shear rft requirement	Location remark
0.00	78.93	Yes	64.02	13.875	55.1	13.0	10.0	7.02	Yes	Rft required	
0.71	78.93	Yes	64.02	13.875	5.8	5.0	10.0	27.75	No	No rft required	Vcw = 5*sqrt(fc)
0.77	78.93	Yes	64.02	13.875	5.6	5.0	10.0	27.75	No	No rft required	Critical location
2.50	78.93	Yes	64.02	13.875	3.9	3.0	10.0	24.35	No	No rft required	
5.00	78.93	Yes	64.02	13.875	11.1	11.0	10.0	13.60	Yes	Rft required	
10.00	78.93	Yes	64.02	13.875	81.9	13.0	10.0	8.22	Yes	Rft required	
11.50	78.93	Yes	64.02	13.875	11.5	11.0	10.0	7.02	No	No rft required	
13.00	78.93	Yes	64.02	13.875	11.7	11.0	10.0	7.02	No	No rft required	
16.50	78.93	Yes	64.02	13.875	8.6	8.0	10.0	18.01	Yes	Rft required	
20.00	78.93	Yes	64.02	13.875	17.0	13.0	10.0	7.02	Yes	Rft required	

14.APPENDIX E: DEFLECTION CALCULATION

Dead Load and Camber:

$$\begin{aligned}\delta &= \frac{-5}{384} \frac{wl^4}{EI} + 2 \left[\frac{M_o x}{6EI L} (L^2 - x^2) \right] \\ &= \frac{-5}{384} \frac{(0.154/12)(20 * 12)^4}{5098 * 4221} \\ &\quad + 2 \left[\frac{532.3 * (10 * 12)}{6 * 5098 * 4221 * 20 * 12} ((20 * 12)^2 - (10 * 12)^2) \right] \\ &= -0.0258 + 0.356 \\ &= 0.3302 \text{ in } \uparrow\end{aligned}$$

After strands are cut at transfer

Deflection at service load of P=10 kips (before cracking)

$$\begin{aligned}\delta &= -\frac{10 * (20 * 12)^3}{6 * 5706 * 4221} \\ &\quad - \frac{10 * (7 * 12) * (10 * 12)}{6 * 5706 * 4221 * (20 * 12)} ((20 * 12)^2 - (7 * 12)^2) \\ &\quad - (10 * 12)^2) \\ &= -0.958 - 0.105 \\ &= -1.063 \text{ in}\end{aligned}$$

Total deflection, before cracking:

$$\begin{aligned}\delta_{total} &= \delta_{camber} - \delta_{DL} - \delta_{LL} \\ &= 2 * .178 - 0.0258 - 1.063 \\ &= 0.7325 \text{ in } \downarrow\end{aligned}$$

Deflection from maximum curvature (after cracking)

$$\begin{aligned}\delta &= 0.5 * 0.00104 * (10 * 12) * (1/3 * 10 * 12) \\ &= 2.5 \text{ in } \downarrow\end{aligned}$$

Maximum curvature from
RESPONSE 2000 software

15. APPENDIX F: WEIGHT AND COST CALCULATION

The materials utilized for the construction of the prestressed beam includes concrete, prestressing strands (1/2 in diameter), rebar steel (#3 bars), shear stirrups (#3 bars) and formwork (wood panels). The following table presents the calculation of the total unit of each material used for the beam:

Total Unit Calculation per material				
Sl. No.	Material Description	Calculation description	Total unit	
1	Concrete	= Strength on test day = height * width * length	= 9.92 = 18.5 in * 8 in / 144 in ² /ft ² * 21 ft	9.92 ksi 0.80 yd ³
2	1/2 in Prestressing Strand	= Total length of PS strand	= 21 * 3	63 ft
3	Rebar Steel	= no. of rebars * length * unit weight	= 2 * 21 ft * 0.376 lb/ft	15.79 lb
4	Shear Stirrups	= no. of stirrups * length * unit weight	= 30 * (2*4.125) * (2*14.125) * (1/144) ft * 0.376 lb/ft	18.26 lb
5	Forming	= height * width (of cross section)	= 18.5 in * 8 in * (1/144)	1.03 ft ²

The calculation of the total cost of the beam construction is based on the unit rate provided by PCI as part of the competition specifications. The following table presents the calculation of the total cost based on the above-mentioned rates:

Cost Calculation				
Sl. No.	Material Description	Total Unit	Cost per unit	Cost for current beam
1	Concrete	0.80yd ³	\$100 < \$20 + \$10*strength (ksi) < \$200	\$95.36
2	1/2 in Prestressing Strand	63 ft	\$0.30/ft	\$18.90
3	Rebar Steel	15.79 lb	\$0.45/lb	\$7.11
4	Shear Stirrups	18.26 lb	\$0.45/lb	\$8.22
5	Forming	66.81 ft ²	\$ 1.25/ft ²	\$83.51
Total Cost:				\$213.09

16.APPENDIX G: GALLERY

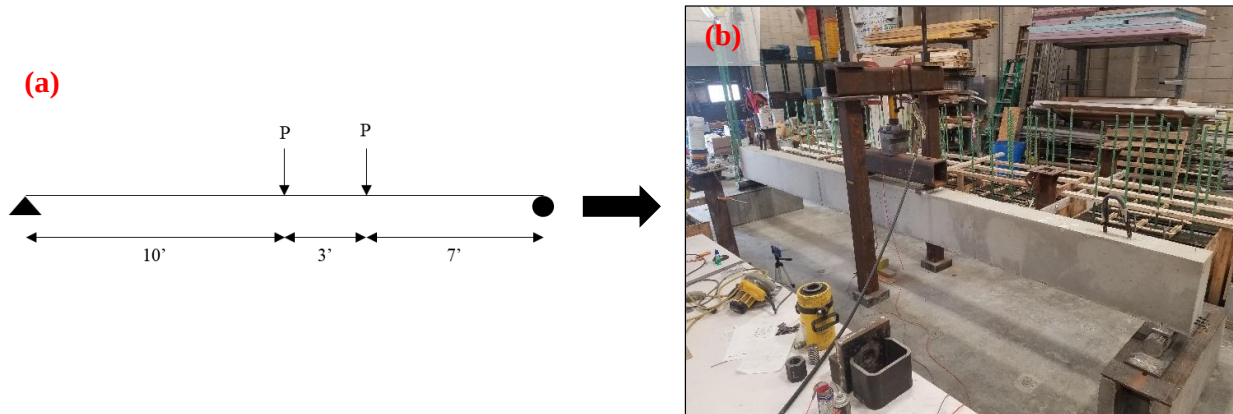


Fig 16.1. Physical transformation of the designed beam



Fig 16.2. Measurement check for the formwork dimensions

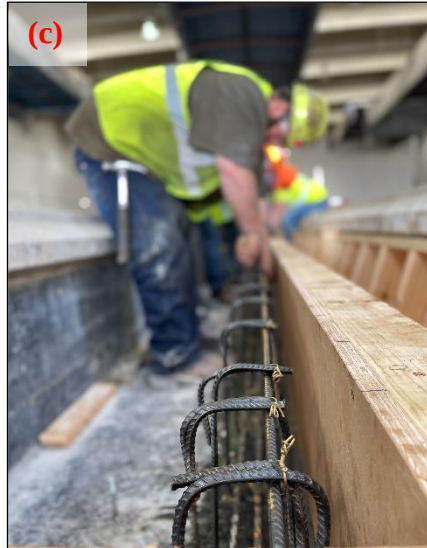
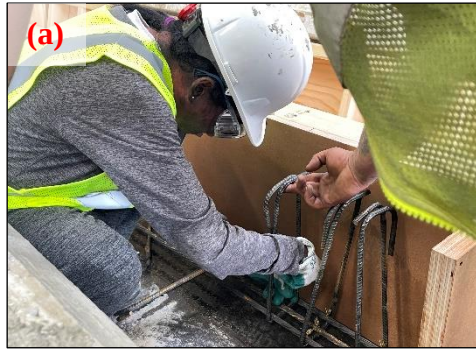


Fig 16.3. Measurement check for the formwork dimensions



Fig 16.4. Concrete pouring and finishing operation



Fig 16.5. Casted beam and cylinders



Fig 16.6. Casting team



Fig 16.7. Beam setup with camera



Fig 16.8. Camber measurement

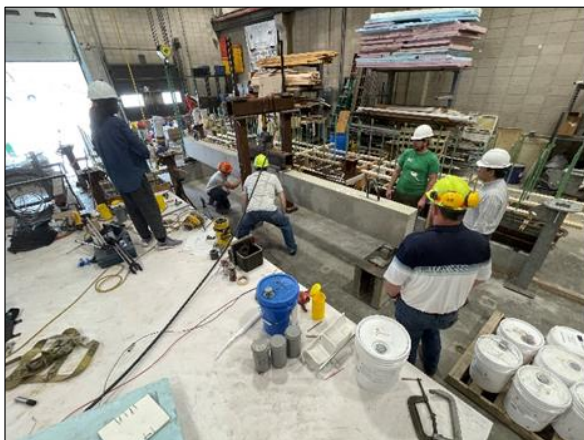


Fig 16.9. Crack inspection

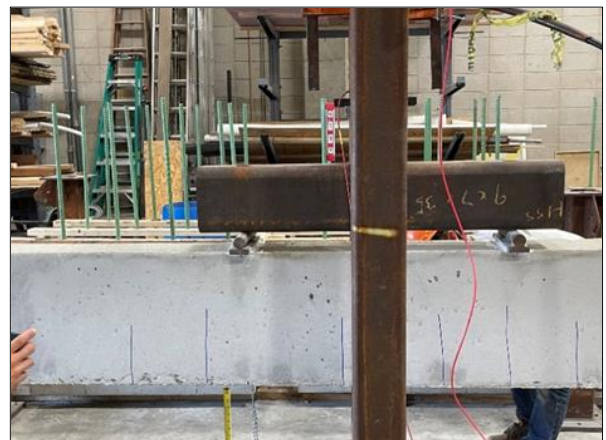


Fig 16.10. Uniformly developing cracks

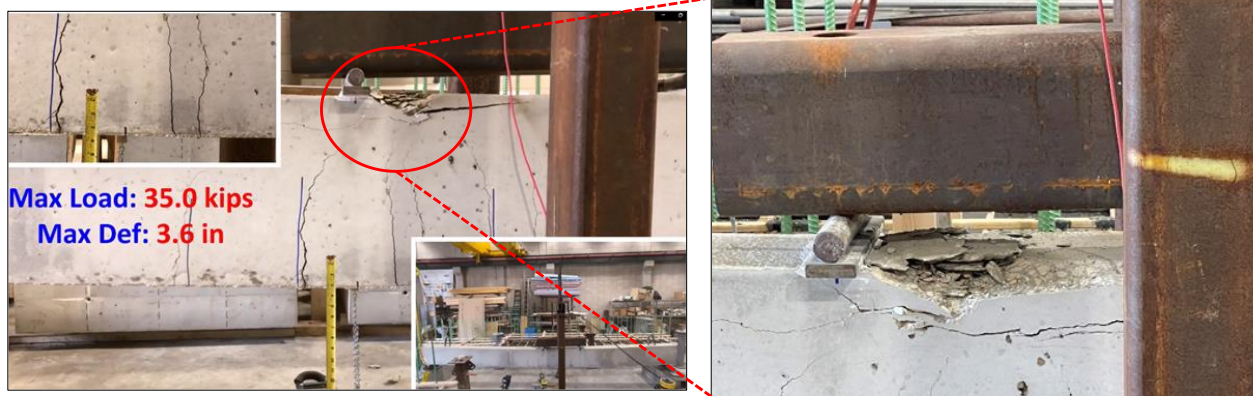


Fig 16.11. Details of the cracked beam and failure



Fig 16.12. Final toast to the project