

2024

PCI Big Beam Competition



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Raleigh, NC

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Introduction

The team from North Carolina State University in Raleigh, NC is proud to submit this report to the Precast Concrete Institute's (PCI) Student Education Committee for consideration in the 2023-2024 Big Beam Competition. With the help and guidance of Tindall Corporation in Spartanburg, South Carolina, a prestressed UHPC beam was designed, fabricated, and tested to failure. The beam, optimized for cost, weight, and deflection at ultimate load, was tested in four-point bending with the goal of reaching a service load of 20 kips and an ultimate load of 32 kips. Our team sought to optimize the cross section for ultra-high performance concrete (UHPC), which exhibits large compressive strengths and contains steel fibers to enable tensile capacity beyond concrete cracking. The first section of this report covers the mix design and mixing procedure. Next, the structural design is discussed, which resulted in our 10.5 in. deep I-shaped beam with a cross sectional area of 53.5 in². The structural design is followed by a summary of the testing, instrumentation, and results. To conclude, the team members share lessons learned from the competition. Detailed calculations are presented in the appendix.

Executive Summary

The North Carolina State University 2024 Big Beam Team had two main goals when designing the beam: 1) optimize the cross section through maximum utilization of material strengths to minimize calculated cost, and 2) pursue an innovative idea to maximize potential for points in that category. Both goals were achieved by creating the prestressed UHPC beam with the cross section shown in Figure 1.

The cross section has a height of 10.5 in. and flange widths of 8 in. and 7 in. at the top and bottom, respectively. Three 9/16" diameter prestressing strands were used as the longitudinal reinforcement. The beam was constructed with UHPC containing steel fibers, allowing for the exclusion of discrete shear reinforcement. The specified UHPC compressive strength was 17.5 ksi, and the expected peak tensile strength (from data provided by Tindall on their UHPC mix design) was 2.67 ksi. The 18 ft. required clear span was loaded in four-point bending, with both point loads applied towards one end of the beam at 3 ft. and 6 ft. from the midspan. The total beam length was 20 ft., which allowed for the necessary overhang length to fully develop the prestressing strands. The total cost for the UHPC, prestressing steel, and formwork was \$209.42, and the overall calculated beam weight was 1122 lbs.

The provisions of ACI 318-19 (ACI, 2019) were conservatively followed for cover and bar spacing requirements, although ACI 318-19 is not directly applicable to UHPC. Innovative use of UHPC allowed for highly optimized member geometry, and the methods outlined in the PCI R&D UHPC Report (Tadros et. al., PCI, 2021) were followed to achieve accurate predictions of capacity. The predicted failure mode was a tension-dominated flexural failure under the point load located 3 ft. from the midspan. A summary of predictions and results is provided in Table 1, followed by the measured and predicted load-deflection behaviors in Figure 2. The pre-test predictions were based on moment-curvature analysis and finite element modeling.

The completed test summary form and certification are shown below, followed by the engineering drawings in Figure 3 and the cost calculation in Table 2.

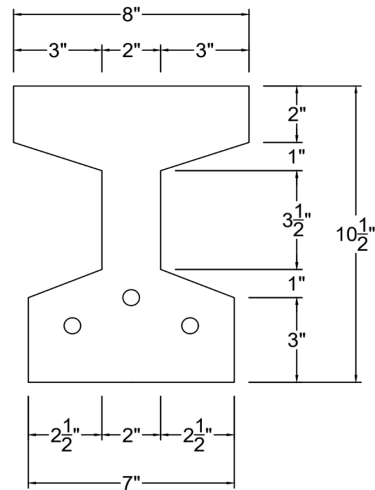


Figure 1: Cross Section Dimensions

Table 1. Predictions and Experimental Results

	Official Predictions	Experimental Results	Percent Error
Cracking load	20 kips	20.8 kips	4.0%
Maximum load	35 kips	35.4 kips	1.1%
Midspan deflection at maximum load	4.5 in.	2.53 in.	43.7%

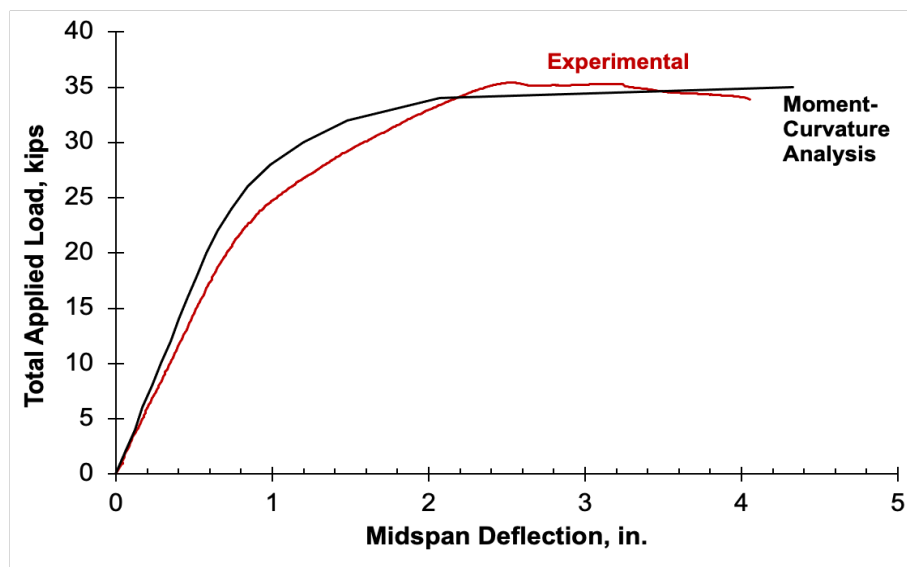


Figure 2: Experimental and Predicted Load Deflection Behaviors

PCI BIG BEAM COMPETITION 2023-2024

6/13/2024

Date

North Carolina State University

4/12/2024

Student Team (school name)

Team Number

Date of Casting

Basic Information

1. Age of beam at testing (days) 39
2. Compressive cylinder tests*
- Number tested 3
- Size of cylinders 3 in. x 6 in.
- Average (psi) 17230
3. Concrete properties
- Unit weight of concrete (lb/ft³) 151
- Slump or spread (in.) 11
- Air content (%) 5%
- Tensile strength (psi) 2670
- Circle one: ☐ Split cylinder ☐ MOR beam
4. Pretest calculations
- a. Applied load (total) to cause cracking (kip) 20
- b. Maximum applied point load at midspan (kip) 35
- c. Maximum anticipated deflection due to applied load only (in.) 4.5

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. Center to center span (ft) 18.5
2. Actual maximum applied load (kip) 35.4
3. Measured cracking load (kip)[†] 20.8
4. Cost (dollars) 209.42
5. Weight (lb) 1122
6. Largest measured deflection (in.) 2.53
7. Most accurate calculations:
- a. Absolute value of (maximum applied load – calculated applied load)/calculated applied load 1.14%
- b. Absolute value of (maximum measured deflection – calculated deflection)/calculated deflection 43.8%
- c. Absolute value of (measured cracking load – calculated cracking load)/calculated cracking load 4.0%
- Total of three absolute values (a + b + c) = 48.9%**

[†] 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 digital report, due June 14, 2024.

Sponsored by:



PCI BIG BEAM COMPETITION 2023-2024

CERTIFICATION

Tindall Corporation

As a representative of (name of PCI producer member or sponsoring organization)

North Carolina 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

Name (please print)

Date

35.0 kips

Predicted maximum load

20.0 kips

Predicted cracking load

4.50 inches

Predicted deflection at midspan

THIS CERTIFICATION MUST BE PART OF THE FINAL REPORT.

Sponsored by:

ASPIRE

ALP
SUPPLY

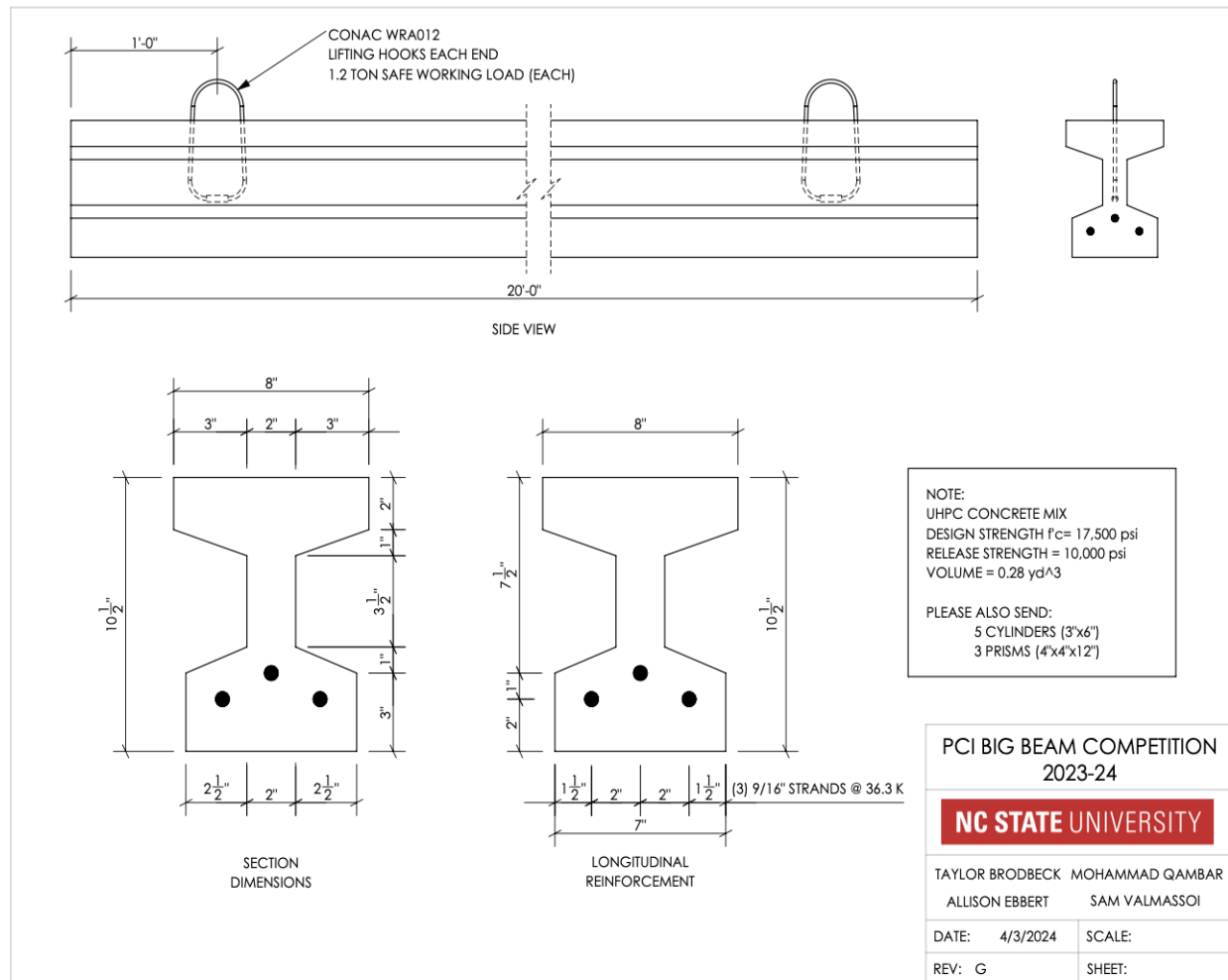


Figure 3: Loading Schematic (above) and Engineering Drawing (below)

Table 2. Cost Calculation

	Unit Cost	Amount	Cost
UHPC	400 \$/yd ³	0.272 yd ³	\$108.90
3 - 9/16 Prestressing Strands	0.42 \$/ft	60 ft	\$25.20
Formwork	1.25 \$/ft ²	60.26 ft ²	\$75.32
Total			\$209.42

Mix Design and Fabrication

The NCSU Big Beam utilized an Ultra-High Performance Concrete (UHPC) mix design. UHPC is characterized by both its high compressive strength and its superior tensile properties relative to traditional concrete. This superior performance is accomplished by utilizing a high packing density, achieved by foregoing coarse aggregate and using a low water-to-cement (w/c) ratio. In addition, the inclusion of well-distributed steel fibers throughout the mix bridges any cracks that form, and provides strength and ductility. A UHPC mix typically results in a member that has relatively high compressive, tensile, and shear strengths, such that traditional mild steel reinforcement may be foregone, and member geometry may be optimized further than would otherwise be possible using traditional reinforced concrete. For these reasons, UHPC was an ideal material for this competition.

Mix Design Proportions and Properties

For the NCSU Big Beam mix, 5.0 yd³ of UHPC were batched. Although the volume of the Big Beam was only 0.28 yd³, a separate UHPC “bigger beam” was being cast by Tindall at the same time for a research project, thus requiring the larger batch size. Table 3 below shows the mix design proportions used in NCSU Big Beam.

Table 3. Mix Design Proportions

Material	SSD Weight, lb/yd³	Volume, yd³	Total Volume, %
Type IL Cement	1360	1.29	25.8%
Silica Fume	350	0.47	9.4%
Coarse Aggregate	0	0.00	0%
Fine Aggregate (white washed Sand)	1781	2.01	40.1%
Steel Fibers	265	0.10	2.0%
Hydration Stabilizer/Retarder	8.95	0.02	0.5%
High-Range Water Reducer/Plasticizer	54.41	0.14	2.9%
Air Detrainers	0.07	0.00	0%
Water	279	0.82	16.4%
Air	0	0.15	3.0%
Total		5.00	100%

The mix design shows that 1360 lb/yd³ and 350 lb/yd³ of Type IL Cement and Silica Fume were used, respectively. This total amount of cementitious material is compared to 279 lb/yd³ of water, resulting in a w/c ratio of 0.16. Additionally, 1781 lb/yd³ of fine washed sand was used, comprising 40.1% of the total volume of the mix. Conversely, no coarse aggregate was used, as is typical for UHPC. Finally, note the use of 2.0% by volume of 0.5-inch long, 7.9x10⁻³-inch diameter steel fibers.

Additional materials include a retarder to delay the setting of the mixture (0.5% by volume), as well as a very high dose of high-range water reducer (2.9% by volume) and an air detainer to keep total air content from exceeding 3.0% by volume. These admixtures were particularly important due to both the low w/c ratio of the mix, as well as the fact that the 5.0 yd³ of material had to be produced in two sequential 2.5 yd³ mixing operations, combined as a composite batch in a slowly-revolving mixing truck. Mixed material from the first batch had to remain workable in the mixing truck while the second batch was produced and the composite batch blended.

Table 4 shows the measured properties of the fresh mix. The flow test, conducted during batching, measured a flow of 11.25 in. The measured air content was 5%. The w/c ratio was 0.16, as specified during batching. Finally, the unit weight of the material was 150.2 lb/ft³, determined by weighing a cylinder cast from the mix.

Table 4. UHPC Mix Properties

Property	Value
Spread	30 in.
Flow	11.25 in.
Air Content	5.0%
Unit Weight	151 lb/ft ³
w/c Ratio	0.16

Mixing Procedure

The general mixing procedure used is as follows:

The sand was added to the mixer pan. Then, air detrainer and 33% of the specified water were added, “pre-wetting” the sand. The air detrainer acts as a defoaming agent during mixing, keeping the air content from rising to undesirable levels. Silica fume was then manually added to the pan, and the mixer was allowed to mix for a few minutes to ensure that the additions were well blended. The cement and all but 8 gallons of the remaining water were then added, followed by the plasticizer and retarder, and the batch was mixed until the material is fluid. The 8 gallons of water held back were used to fine tune workability at the end of the mixing process and to rinse out the remaining plasticizer from the buckets used to dispense it.

At this point, a flow test was conducted to determine how much of the remaining water was needed, with the target flow diameter being at least 11 in. Once the flow test was passed, the fibers were added to the pan manually, with care taken to avoid adding large clumps of fiber. Once mixing was complete, the two 2.5 yd³ batches, mixed subsequently, were combined together in a mixing truck, and were transported to the casting area. Figure 4 shows the various stages of mixing in the Tindall plant.



Figure 4: Stages of Mixing in the Tindall Spartanburg Plant

(a) addition of silica fume, (b) addition of retarder and plasticizer, (c) flow test conducted prior to addition of fibers, (d) emptying the pan mixer into a mixing truck below, and (e) NCSU Big Beam team in the batch plant

Overall, the entire procedure took approximately one hour for both batches, or about 30 minutes per 2.5 yd³ batch. According to Mr. Taylor Nunamaker, Engineer Lead for Tindall Spartanburg, this was a substantial increase in mixing time compared to their traditional mixes, which typically take less than five minutes per batch. Increased mixing time was attributed to the low water-cement ratio, which requires a longer time in the mixer to become fluid, and to the fact that many of the materials had to be manually added into the pan mixer. Tindall does not produce UHPC routinely, so their batching and mixing processes are not optimized for this material.

Fabrication

After the UHPC was mixed and combined, it was taken to the prestressing bed and poured into the forms. The forms were constructed by Tindall, using their CNC machine to precisely cut plywood pieces and rigid foam, that was used to form the I-shaped cross section. Because the UHPC had sufficient shear strength, the only discrete reinforcement used were the longitudinal prestressing strands. The three 9/16" strands were laced through the forms and stressed to 36.3 kips per strand using hydraulic jacks reacting against the bulkhead of the prestressing bed. All gaps and cracks in the formwork were filled with silicone to prevent leaks, and lifting loops were placed at each end of the beam to allow for handling after casting. The formwork is shown in Figure 5 along with the NCSU Big Beam team ready to cast concrete.



Figure 5: Formwork with Strands (left) and Ready to Cast (right)

The UHPC was transferred from the mixing truck into a large bucket that was suspended over the formwork while concrete was slowly poured into the form. Because the mix was highly flowable, no vibration was necessary during casting. There was also concern that heavy vibration, if used, could settle the fibers. The concrete flowed throughout the form until it reached the final height. The UHPC mix being cast into the form is shown in Figure 6.



Figure 6: UHPC being poured into formwork.

Screed boards were used to ensure a level top surface, and the beam was covered with plastic to prevent moisture loss. Casting occurred on a Friday, with de-tensioning and demolding taking place the following Monday, once the UHPC had easily reached sufficient release strength. In addition to the Big Beam itself, UHPC was cast into a series of 3 in. x 6 in. cylinder molds and 4 in. x 4 in. x 14" rectangular prism molds. The cylinders and prisms were cured alongside the Big Beam, and were tested to determine the as-cast material properties.

Material Testing

Once the NCSU Big Beam and associated material samples were shipped from the Tindall Corporation plant in Spartanburg, SC to the NCSU Constructed Facilities Laboratory in Raleigh, North Carolina, material tests were conducted to determine the structural properties of the mix as-cast, and to aid in the final prediction of beam behavior.

To determine UHPC compressive strength, 3 in. x 6 in. concrete cylinders were tested in accordance with ASTM C39 and ASTM C1856. The ends of the cylinders were ground flat and parallel using a cylinder grinding machine to ensure a level bearing surface, and during testing load was applied at a rate of 14.8 kips/min (35 psi/sec). The cylinders were tested 29 days after casting. The results of the compression tests are tabulated in Table 5, with average compressive strength determined as 17.2 ksi. The left portion of Figure 7 shows a concrete cylinder in the test machine.

Table 5. Cylinder Strengths

Cylinder	Compressive Strength, ksi
1	15.7
2	18.0
3	18.0
Average	17.2

To determine the tensile properties of the UHPC, a critical factor in determining beam capacity, flexural prism tests were conducted on 4 in. x 4 in. rectangular prisms in accordance with ASTM C1609. Load was applied at the third-points, in accordance with the Standard, at a rate of 0.002 in./min. Cross-head deflection was measured to determine the load-displacement response of the prism, which would be used later to calibrate a finite-element material model. Table 6 shows the tensile properties of the prisms, with average first peak flexural strength of 2.55 ksi and average peak strength of 2.67 ksi. Note that it is typical for UHPC concrete prisms to display a first peak, which signifies initial cracking, and a second peak, which signifies peak capacity of the steel fibers. The right portion of Figure 7 shows a flexural prism test. The load-displacement plots of the prism tests are shown in the Appendix.

Table 6. Prism Tensile Properties

Property	Prism 1	Prism 2	Average
First peak strength, ksi	2.47	2.63	2.55
Peak strength, ksi	2.61	2.73	2.67
Residual strength at L/150, ksi	0.93	0.96	0.95
First peak displacement, in.	0.006	0.012	0.009
Displacement at peak strength, in.	0.012	0.018	0.015



Figure 7: A Concrete Cylinder Test (left) and a Flexural Prism Test (right)

Mix Design Discussion

The use of a UHPC mix was an attractive choice for this competition for a variety of reasons. UHPC has a superior compressive strength relative to traditional concrete, meaning we could mobilize a larger compression block in flexure, ultimately resulting in a smaller cross section (and thus, lower weight and reduced cost). Additionally, the vastly superior tensile properties of UHPC meant we could rely on the contribution of fibers in flexure, and, forego the use of discrete mild shear reinforcement per the PCI-UHPC Report (PCI, 2021). Eliminating discrete shear reinforcement enabled further optimization of the member geometry, as cover requirements over shear reinforcement were no longer relevant. Additionally, the superior mechanical properties of UHPC enabled strand development lengths significantly shorter than they would be in traditional concrete, allowing for shorter support overhangs that further lowered weight and reduced cost.

Ultimately, the mix design performed very well for the NCSU Big Beam. In terms of the numbers, the PCI-UHPC Report requires a compressive strength of at least 17.5 ksi for a material to be considered PCI-UHPC; the average compressive strength of the three cylinders tested was 17.2 ksi, with one of these cylinders an outlier from the other two at 15.7 ksi. The remaining two cylinders averaged 18 ksi, with both breaking at 18 ksi. Additionally, the PCI-UHPC Report requires a flexural strength of 1.5 ksi. The flexural prism tests yielded a peak flexural strength of 2.67 ksi, with two flexural peaks observed in the load-displacement plot, as expected. Thus, overall, the mix design performed as expected, and ultimately was a significant contributor to the success of the NCSU Big Beam.

Structural Design

The objectives of the structural design of the beam were to support a service live load of 20 kips without cracking, and to support a factored live load of 32 kips without failing. The beam was tested in four-point bending with a clear span of 18 feet, and two load points spaced 3 feet and 6 feet to one side of the midspan. This portion of the report describes the process followed by the NCSU team to design a beam that accomplishes the structural goals while optimizing cost, weight, strength, and deflection at maximum applied load.

After reviewing the required criteria, the first step in the design process was to select which materials would be used. UHPC, known for its superior performance in compression and tension compared to traditional concrete, seemed uniquely qualified to achieve the objectives of the competition. Despite the increased cost per cubic yard, UHPC allowed for an optimized design by reducing the cross-section size. Additionally, having load points shifted to one side of the midspan created a relatively high shear demand in the short span. Using UHPC allowed for eliminating shear reinforcement altogether. While the clear span between supports was fixed, the overall length of the member was allowed to be varied. The length of the overhang was chosen to allow for the full development of the prestressing strands to mobilize their full capacity in regions of high moment demand. Once the materials and loading were defined, a combination of finite element models and sectional hand calculations were used to determine the optimal cross-section, the design methodology of which is described later in this report. The initial design presumed flexural failure at the point of maximum moment would control over shear failure, with shear capacity later checked to verify this assumption.

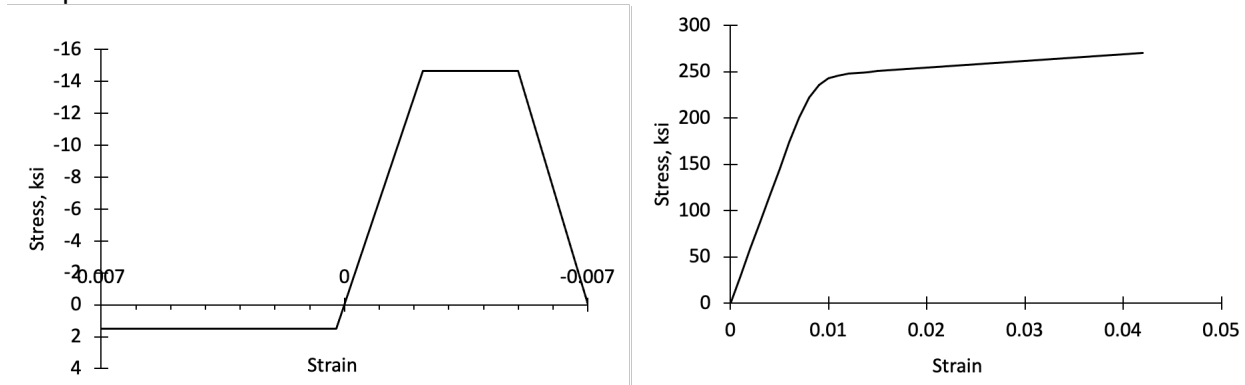
The beam cross section shown in Figure 1 was finalized after many design iterations between hand-calculations and finite-element analyses. The beam is 10.5 in. high with a top flange width and thickness of 8 in. and 2 in., respectively, and a bottom flange width and thickness of 7 in. and 3 in., respectively. The cross-sectional area of the member is 53.5 in². The UHPC had a specified design compressive strength of 17.5 ksi and a test-day strength of at least 17.2 ksi. The beam was reinforced with three 9/16 in. prestressing strands placed in a triangular configuration with each stressed to 36.3 kips ($0.7f_{pu}$). The high compressive capacity of UHPC meant that the member could ultimately be significantly less deep than a traditional concrete member, which ultimately reduced cost and weight, and increased deflection (beneficial for this competition). These factors were also the driving motivation behind selecting the I-shaped section, which was optimized to mitigate transfer stresses, maximize deflection, and minimize cost and weight. By calculation and analysis, no shear reinforcement was required in the member. The hand-calculation predictions, finite-element predictions, officially submitted NCSU Team predictions, and ultimate experimental results are shown in Table 7 below.

Table 7. Predictions and Experimental Results

	Moment Curvature Predictions	Finite Element Predictions	Officially Submitted Predictions	Experimental Results
Cracking load	20 kips	22.5 kips	20 kips	20.8 kips
Maximum load	35 kips	32.5 kips	35 kips	35.4 kips
Midspan deflection at maximum load	4.33 in.	3.8 in.	4.5 in.	2.53 in.

Hand Calculations

To efficiently iterate on design options, hand calculations were used to conduct a layered sectional analysis. The cross-section was divided into 0.5-inch thick layers, and the strain at the midpoint of each layer was used to determine the stress in the layer. The relationships for each material are shown in Figure 8. The PCI UHPC report (PCI, 2021) was used to determine the full stress-strain response of the UHPC, which was accounted for to realize the full capacity of the member. To satisfy Code compliance, the provisions set forth in ACI 318-19 governing reinforcement spacing and concrete cover were conservatively followed. The PCI UHPC Report was also used due to the lack of an official building code governing the use of UHPC. PCI's recommended UHPC tensile strength for use in design is 0.75 ksi, which the PCI UHPC report recommended for use, as it was conservatively equal to half of the PCI minimum tensile strength for UHPC (1.5 ksi). We ultimately designed for a tensile plateau of 1.5 ksi, the PCI minimum tensile strength for UHPC, which showed good agreement in predicting capacities consistent with our finite element analysis. The stress strain curve for the UHPC combined the models proposed by Graybeal (2006), assuming a tensile strength of 1.5 ksi from cracking to 0.007, and Gowripalan and Gilbert (2000) to capture the plateau and eventual decrease in compression strength associated with larger compressive strains.

**Figure 8: Stress-strain Relationships for UHPC (left) and Prestressing Strands (right)**

The final cross section was checked for the limit states of cracking and ultimate moment capacity to determine the strain distribution satisfying force equilibrium and the corresponding moment. Cracking was predicted when the strain in the bottommost tension fiber reached 0.00023. The ultimate moment capacity was determined by taking the higher moment for two strain limits, concrete crushing at a strain of 0.005 at the top of the section or a tension limit of 0.007 at the bottom of the section, at which point the steel fibers within the UHPC were predicted to no longer contribute to the tensile capacity due to large crack widths.

The layered sectional analysis resulted in moment capacities of 64 kip-ft at cracking and 113 kip-ft at ultimate, governed by the 0.007 tension limit. Using those moment capacities and the required loading arrangement allowed for the calculation of maximum predicted applied loads. The resulting loads were 20 kips predicted at cracking and 35 kips predicted at ultimate (both split evenly between the two load points). The moment distribution for both limits is shown in Figure 9. The full moment-curvature (M-C) response was calculated, and the curvature distribution along the length of the beam was integrated to determine the vertical deflection at midspan at ultimate load, using the moment area method, resulting in a predicted deflection of 4.5 in.

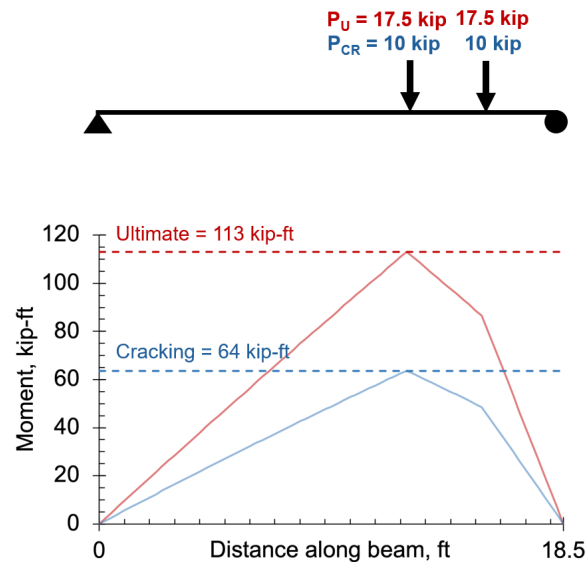


Figure 9: Moment Distribution at Predicted Cracking and Ultimate Loads

Finite-Element Modeling

In addition to hand-calculations, a finite-element model was constructed to further validate the moment-curvature (M-C) analysis both during the design phase and the prediction phase. This model was constructed in the nonlinear finite-element modeling program ATENA Engineering 3D. As part of this process, a UHPC material model was created and calibrated against the tested prisms. Prism tests were modeled in the finite-element software, and the tensile and compressive responses of the material model were varied methodically such that the load-displacement response of the analytical model matched that of the experimental prism tests; a plot showing the agreement between the load-displacement plots of the finite-element model and the experimental test data is found in the Appendix. This agreement ensures that the tensile response of the analytical material model matches that of the UHPC mix used experimentally, which is a critical parameter in determining the response of the member.

The calibrated concrete material model was then used in the finite-element model of the experiment. The UHPC section was modeled with 1.5 in. quadratic brick elements, and the prestressing strands as one-dimensional truss elements. A bond model calibrated as part of a separate research program was applied to the prestressing strands such that the effect of partial development was accounted for. The beam supports and load points were modeled as steel plates using linear tetrahedral elements. Results of the finite-element modeling were tabulated in Table 7. The cracking load was predicted as 22.5 kips, the ultimate load as 32.5 kips, and the

midspan deflection at peak load was predicted as 3.8 in. The predicted failure mode was rupture of the prestressing strands. These results showed good agreement with the moment-curvature analysis, and gave us confidence in our predictions. The graphical output of the finite-element model is found in the Appendix, along with the analytical load-displacement response.

Testing

Testing of the NCSU Big Beam was conducted at North Carolina State University Constructed Facilities Laboratory in Raleigh, North Carolina on May 21, 2024, 39 days after the cast date in Spartanburg, South Carolina. This portion of the report will discuss the test setup used, the instrumentation, and the test results.

Test Setup

Figure 10 shows the test setup used with pin-roller support conditions. On the loaded end of the beam (right end in the figure), a roller supports a 6x7x1 in. steel plate which in turn provides a bearing reaction for the beam. The roller rests on a steel support stand that is post-tensioned to the laboratory strong floor. The opposite end of the beam (left end in the figure) is supported on a pin, also through a 6x7x1 in. steel plate, with the clear span set to 18 ft. The pin support, like the roller support, rests on a post-tensioned I-beam fixture. Four hydraulic cylinders apply equal loads to the beam, two at each selected load point. The hydraulic cylinders react against the laboratory floor below, pulling downward on the Big Beam through steel spreader tubes placed on top of the beam. A hydraulic pump was used to pressurize the four cylinders equally, applying the load.

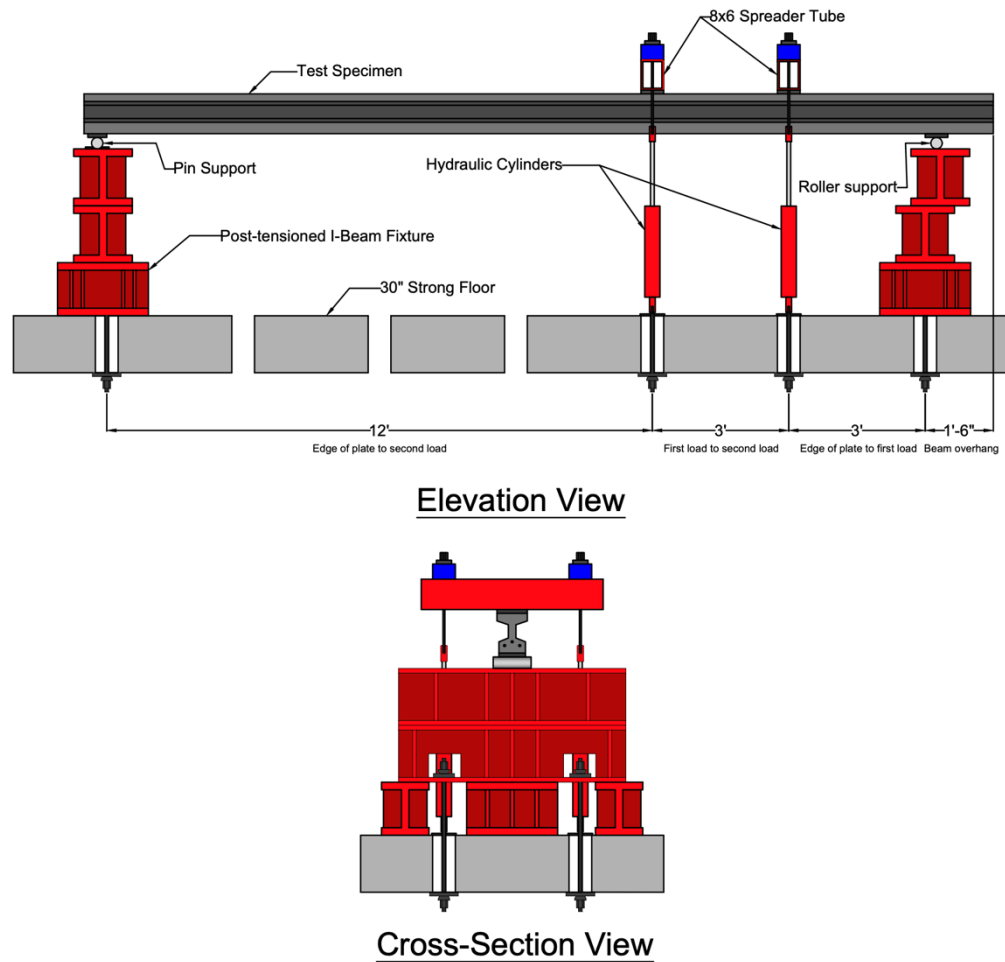


Figure 10: Test Setup Elevation (top) and Cross Section (bottom)

Instrumentation

Figure 11 illustrates the instrumentation used in this test. To measure displacement, string potentiometers were placed beneath the member at midspan, measuring vertical deflection of the beam from the laboratory floor. To correct for any support deformations, spring potentiometers were placed on the beam above each support, measuring against an external unloaded fixture, also supported on the laboratory floor. Applied load was measured by two loadcells integrated into two of the four hydraulic cylinders. Total load was determined by averaging the two loadcell readings and multiplying the value by four to account for the four identical hydraulic cylinders plumbed in parallel. Data were collected using an electronic data acquisition system (DAQ) recording at a rate of 2 Hz.

The beam was also instrumented with a digital image correlation (DIC) system. DIC uses two or more cameras to capture images of an area throughout loading. The area must be painted with a speckled pattern, consisting of a series of randomly distributed black dots against a white background. Prior to capturing images, the cameras must be placed in their respective locations and calibrated with a calibration plate, enabling the system to calculate each camera location. The lighting and focus of the cameras must be adjusted to ensure the best quality images. After the test, the DIC software post-processes the images during loading to determine the movement of the speckle pattern relative to a reference image taken before any load is applied. This method

allows for mapping measured displacement and strain fields on images of the test specimen. In this case, two DIC cameras were used, and data were recorded at a rate of 2 Hz.

To synchronize the timing between the DAQ and the DIC, a simultaneous voltage pulse is sent to both, with the time of the pulse recorded to enable synchronization of the data.

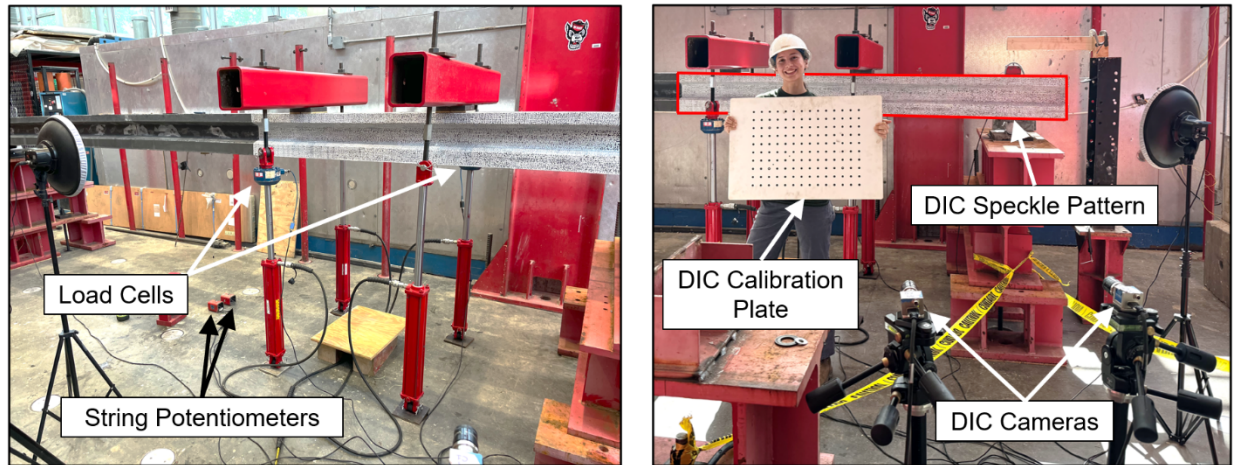


Figure 11: Traditional (left) and DIC (right) Instrumentation

Testing

The NCSU Big Beam was tested on May 21, 2024 at an age of 39 days. Figure 12 shows the measured load-displacement response of the tested beam, with the x-axis showing the midspan deflection and the y-axis showing the applied load, including the weight of the test fixtures. As load was applied, the load-displacement response followed the uncracked elastic stiffness until a total applied load of approximately 20.8 kips cracked the beam. Note that this cracking load was determined by drawing the two dotted green lines in the figure tangent to the cracked and uncracked stiffnesses, respectively, with their intersection defining the cracking load. After cracking, the inelastic cracked response dominated behavior, with the stiffness of the member softening considerably. The member achieved a peak applied load of 35.4 kips at a displacement of 2.53 in. The load-displacement response then plateaued, with the load dropping slightly before climbing back up to virtually the same peak load level at a midspan displacement of 3.24 in. The load then began to slowly drop to 34 kips, at which point the beam failed due to strand rupture.

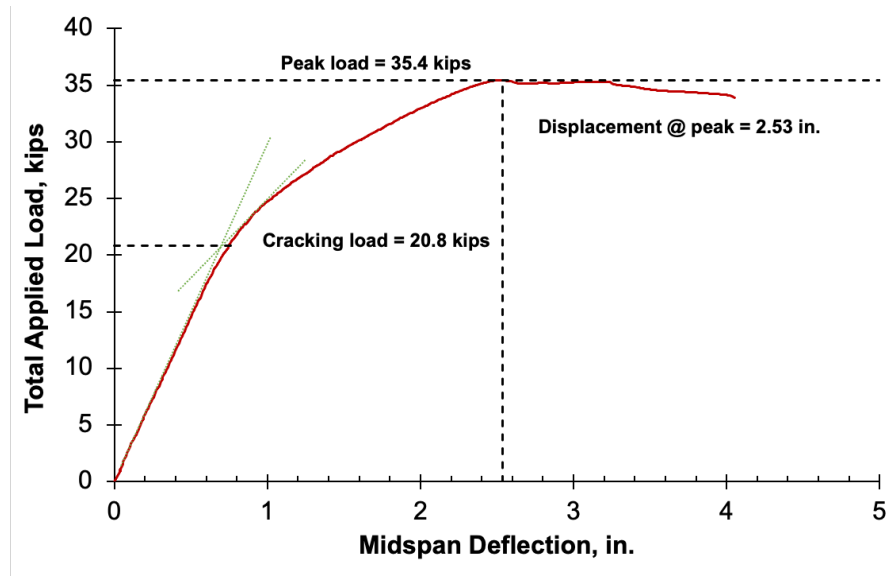


Figure 12: Experimental Load vs. Midspan Deflection

Figure 13 shows images of the beam after failure. Once the strands ruptured, the beam lost all load-carrying capacity, as the flexural crack extended to the top of the section. This resulted in the beam splitting into two pieces. Figure 13c shows the ruptured strands in the cross-section, with no indications of splitting or bond distress, highlighting the significant ability of UHPC to bond with steel strand. It is also worth noting, as can be seen in the image, that only one flexure crack formed in the specimen, as opposed to a more traditional well-distributed crack pattern. This finding is corroborated by DIC data in the subsequent section.

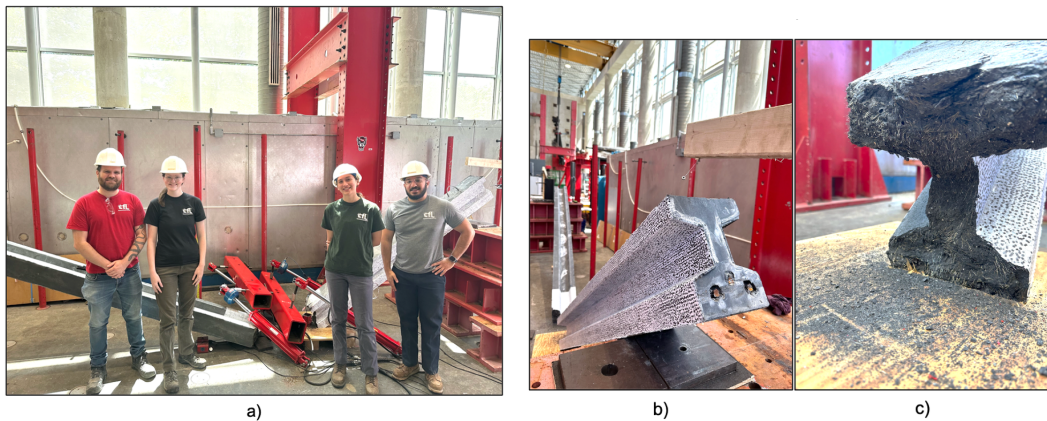


Figure 13: Beam after Failure (a, b) and Cross Section after Failure (c)

Results Discussion

The NCSU Big Beam ultimately performed excellently with respect to the design and the pre-test predictions. The beam achieved a total load capacity of 35.4 kips across both load points, with a cracking load of 20.8 kips. The vertical midspan displacement at the first occurrence of the peak load was 2.53 in.; however, the load-displacement response of the member plateaued at a nearly constant load level until a displacement reached 3.24 in. After this level, the applied load began to decrease as the displacement continued to increase to failure.

The cracking response of the member was characterized by a single flexural crack that formed and widened as loading increased. No significant additional flexural cracks were observed, no shear distress was noted in the specimen, and no shear cracks were observed.

Principal tensile strains on the side surface of the NCSU Big Beam were mapped at various levels of loading from data measured by the DIC system. Figure 14 shows maps of measured principal tension strains overlaid images of the beam at selected load levels. The strains shown range from low (or zero) tension in purple to relatively high values in red of up to 0.007. Strains mapped at the edges of the area being captured should be neglected, as these regions tend to exhibit high levels of noise in the data.

Large principal tensile strains are observed localized in the region of highest moment between the two loading points. Tensile strains in this region range from approximately 0.003 to 0.007. Cracking is inferred to correspond with regions exhibiting localized relatively high levels of strain. The strains shown at the cracking load indicate the first formation of cracks, with tensile strains of approximately 0.003 measured beneath the second load point. At higher load levels, principal tensile strains highlight the formation of a single crack beneath the second load point (on the left), which is outlined in red. This behavior is opposed to the well-distributed crack pattern expected from a traditional prestressed concrete member under flexural distress. This finding is likely due to the vastly superior bond performance of UHPC relative to traditional concrete. No slip of the strands was observed during testing, and the bond stresses between UHPC and strands near cracks are likely high enough to concentrate strand strains and to prevent additional cracking from developing beyond the first primary crack. At the post-peak load level, additional straining was observed in the region of high moment, along with significant widening of the lone flexural crack. No shear cracks were observed in the region of high shear between the roller support and the first load point.

An additionally noteworthy observation from the measured principal tension strains is the lack of splitting stresses or longitudinal cracks in the member along any of the prestressed reinforcement. This finding further reinforces the conclusion of superior bond performance between the UHPC and strands, which justifies the decision to use a small support overhang length in this beam.

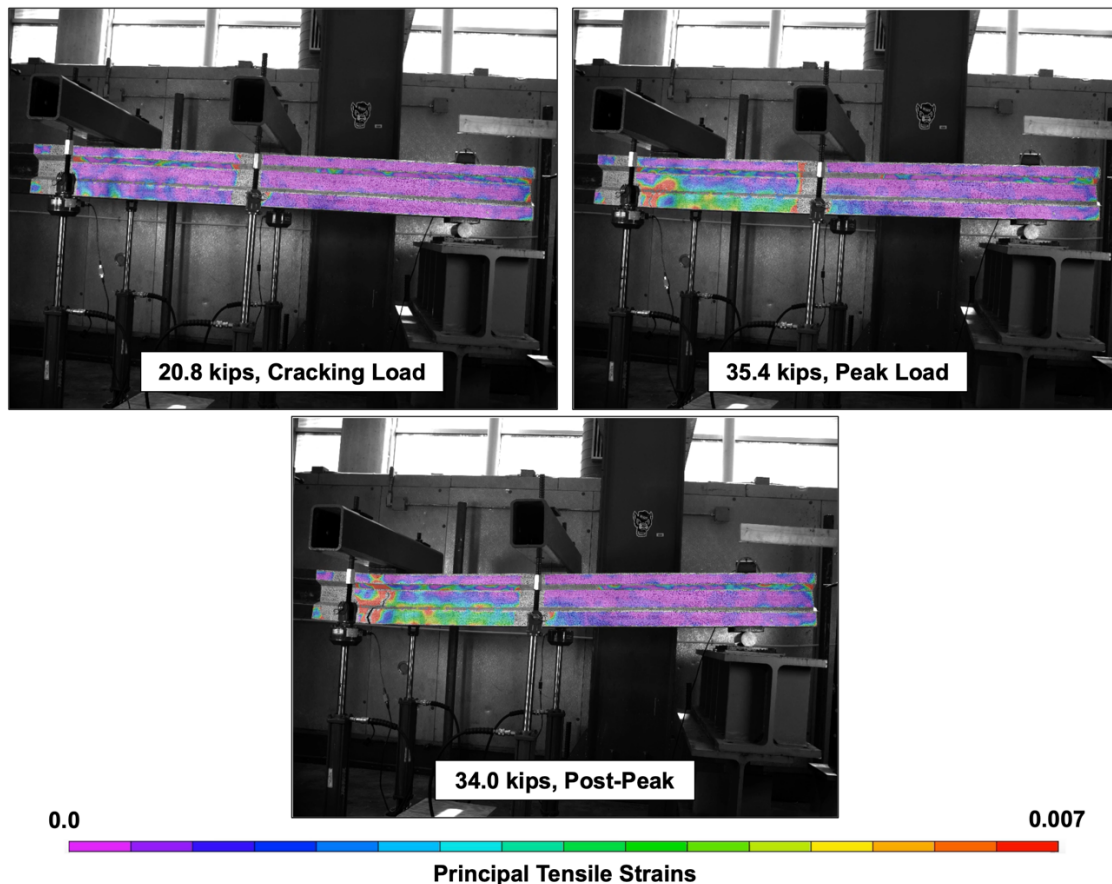


Figure 14: DIC Output of Principal Tensile Strains throughout Loading

Figure 15 shows the principal compressive strains measured by the DIC system at selected stages of loading. Compression strains ranging from 0 to -0.003 (compression sign convention negative) are mapped. Larger compressive strains appeared where expected in the top flange of the member between the two load points, where the applied moment was highest. Noteworthy is the absence of large diagonally oriented compressive strains in the region of high shear, which would be typical of a member highly stressed in shear. This finding reiterates the observation that UHPC has excellent resistance to shear stresses relative to traditional concrete. Note that even near failure, the measured principal compressive strains in the top flange did not generally exceed -0.002, indicating member capacity was limited by the loss tension across the critical crack and not by crushing of concrete.

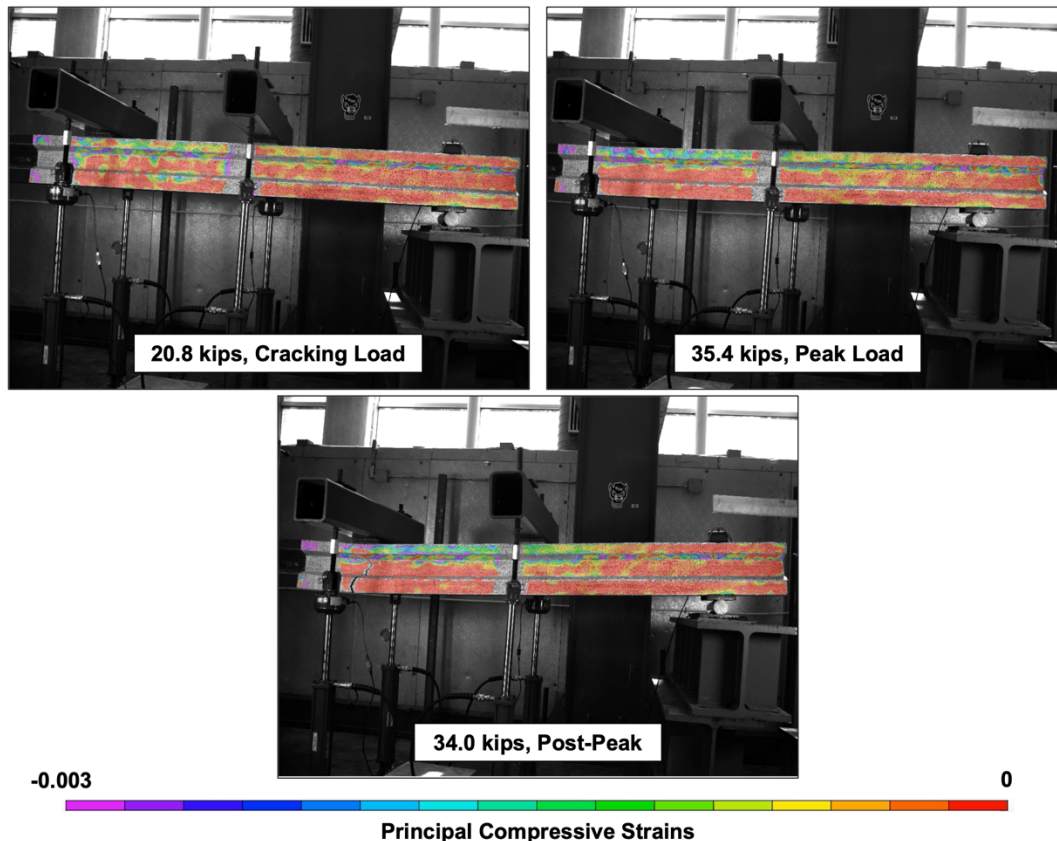


Figure 15: DIC Output of Principal Compressive Strains throughout Loading

Team Statements

Allison Ebbert: This competition taught me a lot about how precast concrete works and the challenges faced when innovating. Being able to work with Tindall's engineers and being able to go to the Spartanburg plant was a great introduction to precast. Precast is so versatile and can be as precise as the application demands. Watching the concrete be batched and transferred into a truck was really impressive compared to how I have seen lab specimens cast in-situ.

It was such a privilege to be able to design and work with UHPC. Although the tensile and compressive strengths of UHPC are very impressive, it's important to remember that it takes time for new materials to gain acceptance. There were a few issues with batching, including constituents clumping together early in the mixing process, and long mix time. These issues will be worked through with time as UHPC is used more frequently. Overall, I am excited to see how UHPC is used in the future, and I can really see its application in the precast industry.

Mohammad Qambar: The most enjoyable portion of this project for me was the aspect of the unknown associated with UHPC. While there has, of course, been a large amount of excellent research on the topic, for all intents and purposes, there is still not an official consensus on all details of UHPC design. As a result, having some more liberty to interpret the relevant research and using engineering judgement to make design predictions was very rewarding. Additionally, working with our producer, Tindall, and coordinating different aspects of our project with them was a greatly positive experience.

While learning to design and analyze a UHPC beam was a challenge, I think we all felt we could not have been better equipped with the team we had assembled. Undertaking the Big Beam project was always going to be a challenge, since you're competing against some of the best schools in the country - the fact that my group wanted to do that while also learning to design with a material they had never touched before speaks both to their ambition and intelligence. To me, the most rewarding portion of this project was taking on this challenge with them.

Sam Valmassoi: Participating in the PCI Big Beam competition has been a wonderful experience. It provided a platform for us to bridge the gap between theoretical knowledge acquired in school and its practical application in the precast industry. I was particularly excited about our use of UHPC in our design, and the unique challenges and opportunities that arose from using this material. Using UHPC allowed us to push the limits of what is possible in design. I am thankful for the assistance our team received from Tindall throughout the process, as well as their hospitality during our visit to their Spartanburg, SC plant. I am also grateful for my wonderful teammates who were a pleasure to work with throughout the project, and whose knowledge, dedication, and enthusiasm inspires me. I am proud of what we were able to accomplish together.

Taylor Brodbeck: Designing and testing a UHPC beam is something I would never have had the opportunity to do without the PCI Big Beam Competition. The competition allowed me to apply my knowledge of prestressed concrete design to a new material that I had no prior experience with. It was rewarding to see how well we were able to predict the behavior of the beam. Visiting Tindall's facility in Spartanburg, SC was a great opportunity to learn about the world of precast concrete. We got to see firsthand the batching and mixing process which was impressive at such a large scale. Additionally, we were able to tour Tindall's facility and see a variety of the projects they work on. The knowledge and experience gained from this competition have been invaluable, providing me with practical skills and a deeper appreciation for structural engineering.

Acknowledgments

The NC State University team extends their thanks to the whole team at Tindall Corporation for assistance with this project. We gratefully acknowledge Mr. Matt Thorne and Mr. Tyler Maynor for their guidance through the design process, assistance with fabrication, and encouragement to think out of the box with our UHPC beam. We also want to thank Mr. Taylor Nunamaker who was instrumental to the mixing and batching efforts, as well as explaining the process along the way.

We would also like to thank the students and Mr. Johnathan McEntire at NC State University's Constructed Facilities Laboratory, with special thanks to our faculty advisor Dr. Greg Lucier for his enthusiasm and support in tackling interesting challenges.

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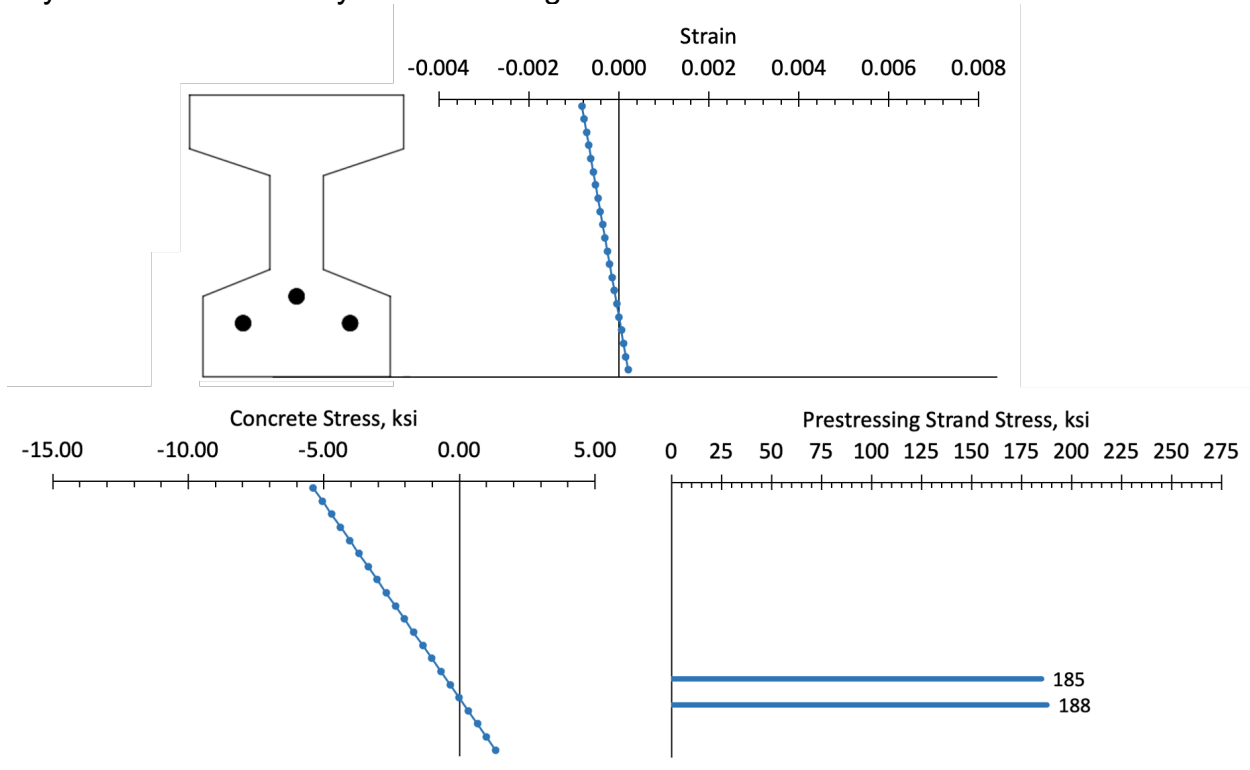
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Appendix

Appendix A: Hand Calculations

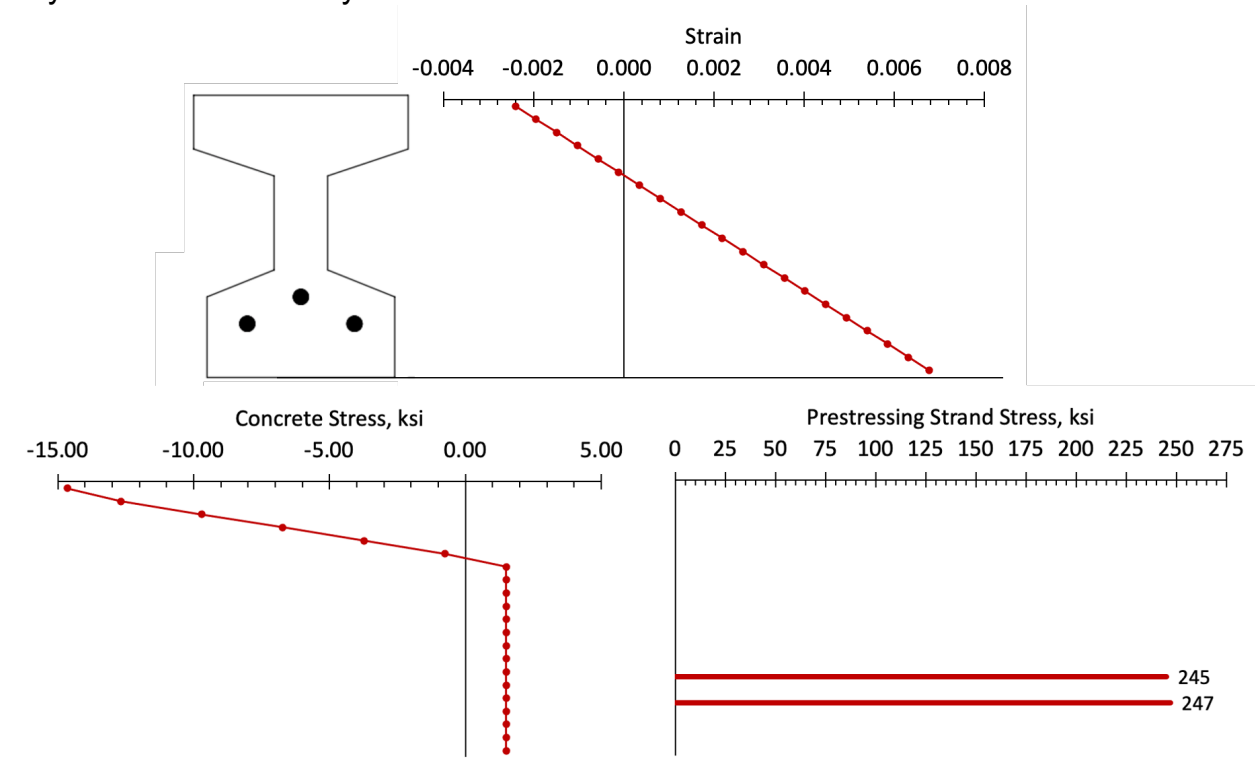
Layered Sectional Analysis at Cracking:



cracking	
et	-0.000855
c	8.27
delta ep	0.0065
eb	0.000231

	Layer	b, in.	h, in.	Top	Bottom	Midpoint	Area, in2	Strain	Stress, ksi	Force, kips	M, kip-in
UHPC layers	1	8	0.5	0	0.5	0.25	4	-0.00083	-5.39	-21.6	-5.39
	2	8	0.5	0.5	1	0.75	4	-0.00078	-5.05	-20.2	-15.16
	3	8	0.5	1	1.5	1.25	4	-0.00073	-4.72	-18.9	-23.59
	4	8	0.5	1.5	2	1.75	4	-0.00067	-4.38	-17.5	-30.67
	5	8	0.5	2	2.5	2.25	4	-0.00062	-4.05	-16.2	-36.41
	6	2	0.5	2.5	3	2.75	1	-0.00057	-3.71	-3.7	-10.20
	7	2	0.5	3	3.5	3.25	1	-0.00052	-3.37	-3.4	-10.96
	8	2	0.5	3.5	4	3.75	1	-0.00047	-3.04	-3.0	-11.39
	9	2	0.5	4	4.5	4.25	1	-0.00042	-2.70	-2.7	-11.48
	10	2	0.5	4.5	5	4.75	1	-0.00036	-2.36	-2.4	-11.23
	11	2	0.5	5	5.5	5.25	1	-0.00031	-2.03	-2.0	-10.65
	12	2	0.5	5.5	6	5.75	1	-0.00026	-1.69	-1.7	-9.73
	13	2	0.5	6	6.5	6.25	1	-0.00021	-1.36	-1.4	-8.48
	14	2	0.5	6.5	7	6.75	1	-0.00016	-1.02	-1.0	-6.89
	15	7	0.5	7	7.5	7.25	3.5	-0.00011	-0.68	-2.4	-17.37
	16	7	0.5	7.5	8	7.75	3.5	-0.00005	-0.35	-1.2	-9.45
	17	7	0.5	8	8.5	8.25	3.5	0.00000	-0.01	0.0	-0.35
	18	7	0.5	8.5	9	8.75	3.5	0.00005	0.32	1.1	9.92
	19	7	0.5	9	9.5	9.25	3.5	0.00010	0.66	2.3	21.36
	20	7	0.5	9.5	10	9.75	3.5	0.00015	1.00	3.5	33.99
	21	7	0.5	10	10.5	10.25	3.5	0.00020	1.33	4.7	47.78
Reinf.						7.5	0.192	0.00642	185	35.5	266.55
						8.5	0.384	0.00652	188	72.2	613.30
Sum:										0.00 kips	63.6 kip-ft

Layered Sectional Analysis at Ultimate Load:



0.007												
et	-0.002641											
c	2.88											
delta ep	0.0065											
eb	0.007											
	Layer	b, in.	h, in.	Top	Bottom	Midpoint	Area, in ²	Strain	Stress, ksi	Force, kips	M, kip-in	
UHPC layers	1	8	0.5	0	0.5	0.25	4	-0.00241	-14.65	-58.6	-14.65	
	2	8	0.5	0.5	1	0.75	4	-0.00195	-12.69	-50.8	-38.07	
	3	8	0.5	1	1.5	1.25	4	-0.00149	-9.70	-38.8	-48.52	
	4	8	0.5	1.5	2	1.75	4	-0.00103	-6.72	-26.9	-47.04	
	5	8	0.5	2	2.5	2.25	4	-0.00057	-3.74	-14.9	-33.63	
	6	2	0.5	2.5	3	2.75	1	-0.00012	-0.75	-0.8	-2.07	
	7	2	0.5	3	3.5	3.25	1	0.00034	1.50	1.5	4.88	
	8	2	0.5	3.5	4	3.75	1	0.00080	1.50	1.5	5.63	
	9	2	0.5	4	4.5	4.25	1	0.00126	1.50	1.5	6.38	
	10	2	0.5	4.5	5	4.75	1	0.00172	1.50	1.5	7.13	
	11	2	0.5	5	5.5	5.25	1	0.00218	1.50	1.5	7.88	
	12	2	0.5	5.5	6	5.75	1	0.00264	1.50	1.5	8.63	
	13	2	0.5	6	6.5	6.25	1	0.00310	1.50	1.5	9.38	
	14	2	0.5	6.5	7	6.75	1	0.00356	1.50	1.5	10.13	
	15	7	0.5	7	7.5	7.25	3.5	0.00402	1.50	5.3	38.06	
	16	7	0.5	7.5	8	7.75	3.5	0.00448	1.50	5.3	40.69	
	17	7	0.5	8	8.5	8.25	3.5	0.00493	1.50	5.3	43.31	
	18	7	0.5	8.5	9	8.75	3.5	0.00539	1.50	5.3	45.94	
	19	7	0.5	9	9.5	9.25	3.5	0.00585	1.50	5.3	48.56	
	20	7	0.5	9.5	10	9.75	3.5	0.00631	1.50	5.3	51.19	
	21	7	0.5	10	10.5	10.25	3.5	0.00677	1.50	5.3	53.81	
Reinf.						7.5	0.192	0.01075	245	47.1	353.21	
						8.5	0.384	0.01166	247	94.9	806.58	
Sum:										0.00 kips	113.1 kip-ft	

Shear Capacity:

Calculated following the PCI UHPC report

$$V_u = V_{cf} + V_s$$

$$V_{cf} = \left(\frac{4f_{rr}}{3}\right)b_v d_v \cot \theta$$

$$\text{where } \theta = 29 + 3500\varepsilon_s \text{ and } \varepsilon_s = \frac{|M_u|/d_v + 0.5N_u + |V_u - V_p| - A_{ps}f_{po}}{E_p A_{ps}} \leq 0.006$$

$$V_s = 0$$

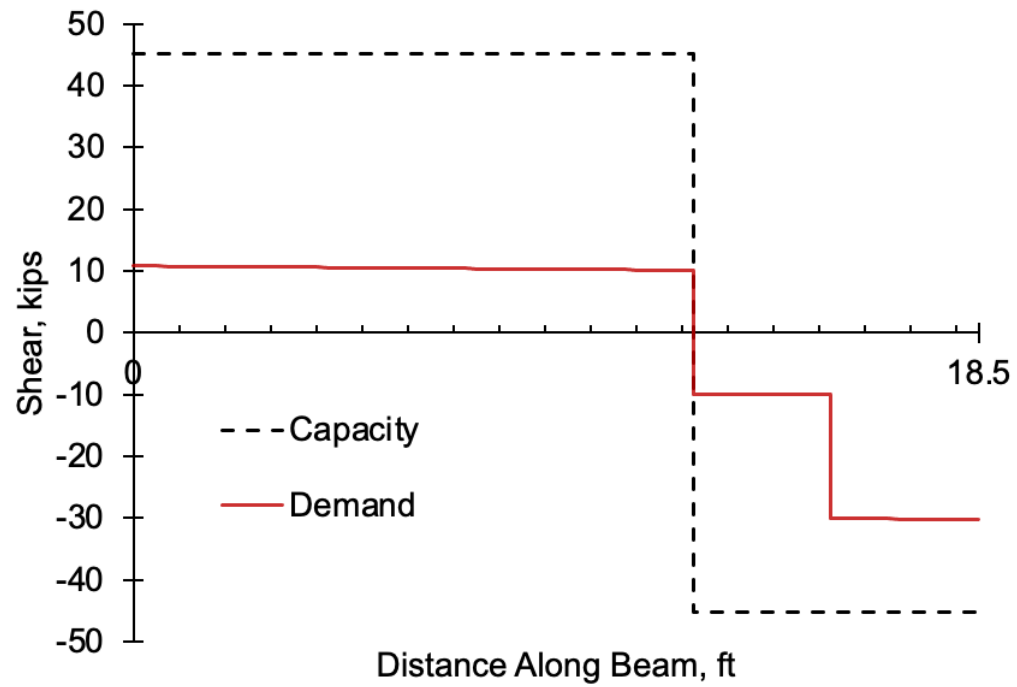
@ x = 11 ft (High Moment, Low Shear)

Vu	45.2	kips
M/V	132	in.
Mu/dv	789.2	kips
dv	7.56	in.
Mu	5966.4	kip-in
Nu	0	kips
As	0.576	in ²
es	0.006	
theta	50.00	degrees
b	2	in.
fc	17.2	ksi
frr	2.67	ksi
Vc	45.2	kips
Vs	0	kips
V	45.2	kips
V/V	1.00	

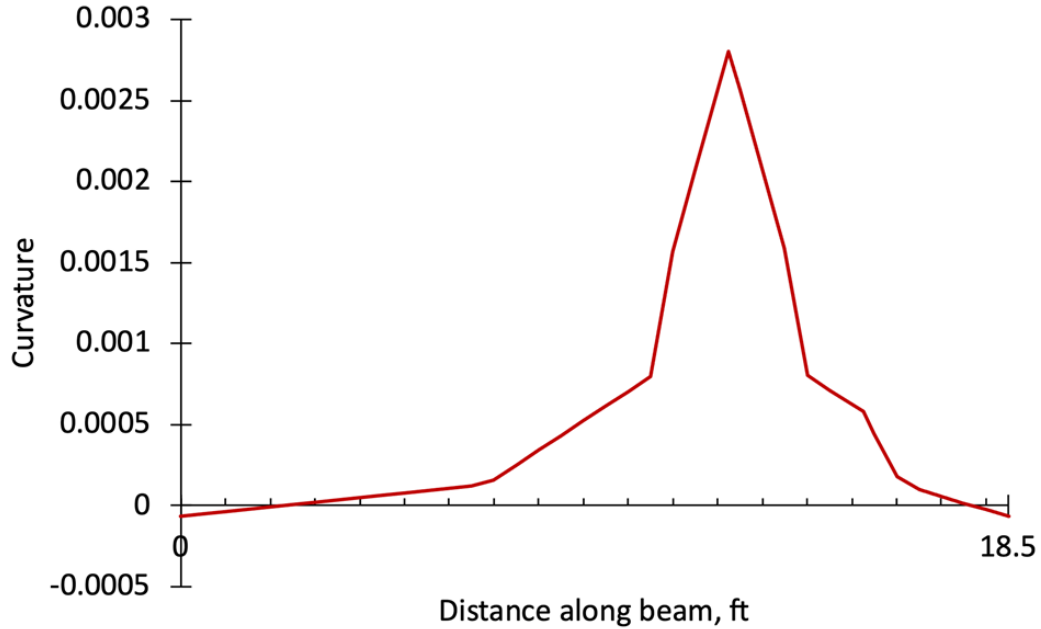
@ x = 15 ft (Lower Moment, High Shear)

Vu	45.2	kips
M/V	30	in.
Mu/dv	179.4	kips
dv	7.56	in.
Mu	1356	kip-in
Nu	0	kips
As	0.576	in ²
es	0.006	
theta	50.00	degrees
b	2	in.
fc	17.2	ksi
frr	2.67	ksi
Vc	45.2	kips
Vs	0	kips
V	45.2	kips
V/V	1.00	

Shear Capacity and Demand at Maximum Allowable Load (40 kips)

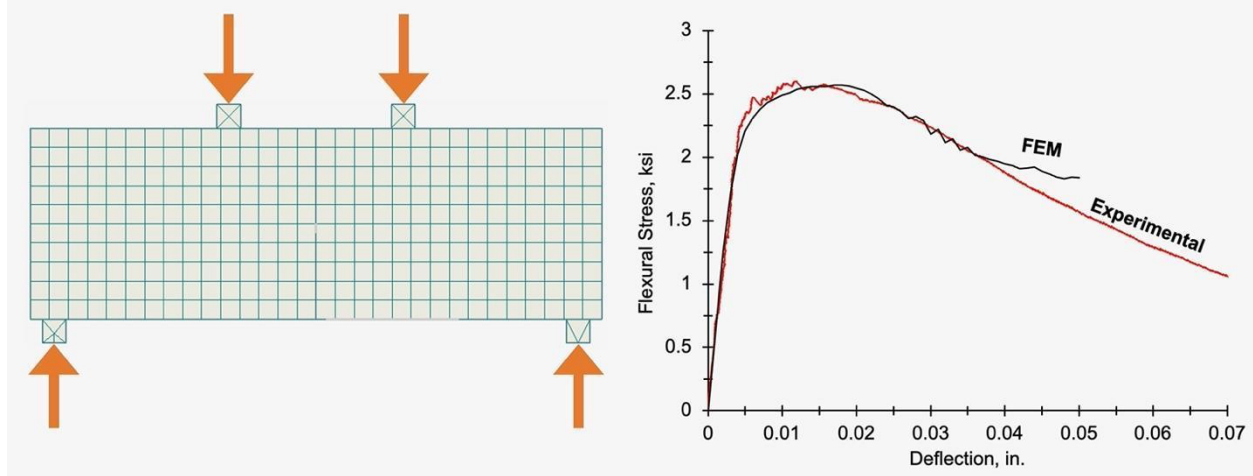


Curvature Distribution at Ultimate Load for Moment Area Method:

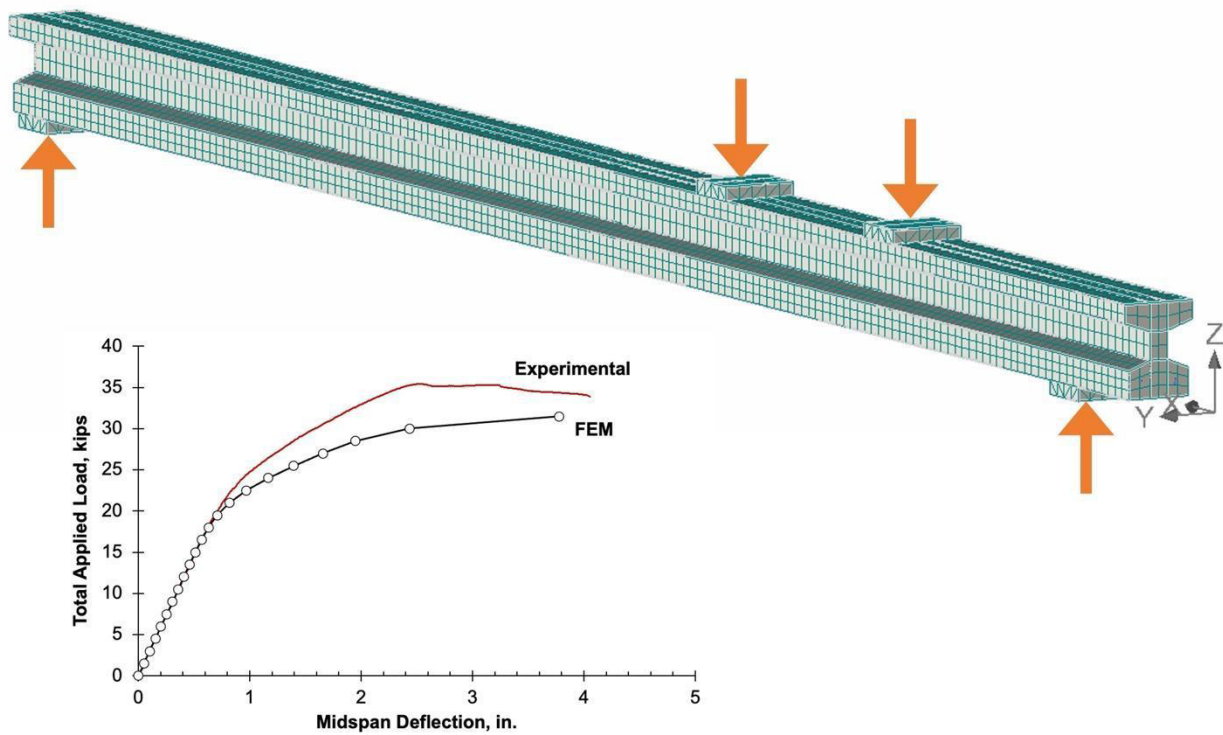


Appendix B: Finite Element Analyses

UHPC tensile response, calibrated against material tests:



Full beam FEM and predictions compared to Experimental Results



Appendix C: Cost and Weight Calculations

	Area, in ²	Volume, yd ³	Cost, \$	Weight, lb
Total Cross Sectional Area	53.5	0.275		1122.0
Prestressing Strands	0.576	0.003		
UHPC Area	52.92	0.272	108.90	

	Unit Cost		Unit Weight		Amount	Cost	Weight
UHPC	400	\$/yd ³	151	pcf	0.272 yd ³	\$108.90	1122 lb
3 - 9/16 in. Prestressing Strands	0.42	\$/ft			60 ft	\$25.20	
Formwork	1.25	\$/ft ²			60.26 ft ²	\$75.32	
Total						\$209.42	1122 lb