

2022

PCI Big Beam Competition



School:	The University of Alabama
Team:	B
Student Team:	Monica Lages Do Amaral Bipul Poudel Revanth Naidu Vasireddy
Faculty Advisor:	Dr. Sriram Aaleti
PCI Producer Member:	Gate Precast Company

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PCI Big Beam Competition 2021-22

Predictions and Certifications

PCI BIG BEAM COMPETITION 2021-2022

06/24/2022

Date

The University of Alabama

Student Team (school name)

B

Team Number

06/02/2022

Date of Casting

Basic Information

1. Age of beam at testing (days) 23

2. Compressive cylinder tests*

Number tested 3

Size of cylinders 4" x 8"

Average (psi) 11418

3. Concrete properties

Unit weight of concrete (lb/ft³) 150.2

Slump or spread (in.) 24"

Air content (%) 2.4%

Tensile strength (psi) 892

Circle one: ☒ Split cylinder ☐ MOR beam

4. Pretest calculations

a. Applied load (total) to cause cracking (kip) 19.15

b. Maximum applied point load at midspan (kip) 32.26

c. Maximum anticipated deflection due to applied load only (in.) 4.342"

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) 35.40

2. Measured cracking load (kip)[†] 20.80

3. Cost (dollars) \$ 222.78

4. Weight (lb) 2095.5

5. Largest measured deflection (in.) 5.045"

6. Most accurate calculations

a. Absolute value of (maximum applied load – calculated applied load)/calculated applied load 0.0973

b. Absolute value of (maximum measured deflection – calculated deflection)/calculated deflection 0.1619

c. Absolute value of (measured cracking load – calculated cracking load)/calculated cracking load 0.0862

Total of three absolute values (a + b + c) = 0.3454

[†]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.

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PCI BIG BEAM COMPETITION 2021-2022

CERTIFICATION

GATE PRECAST

As a representative of (name of PCI Producer Member or sponsoring organization)

The University of Alabama, Team B, Tuscaloosa

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:

Harris Carter

Signature

Harris Carter

Name (please print)

7-8-22

Date

32.26 kip

Predicted Maximum Load

19.15 kip

Predicted Cracking Load

4.342"

Predicted Deflection at Midspan

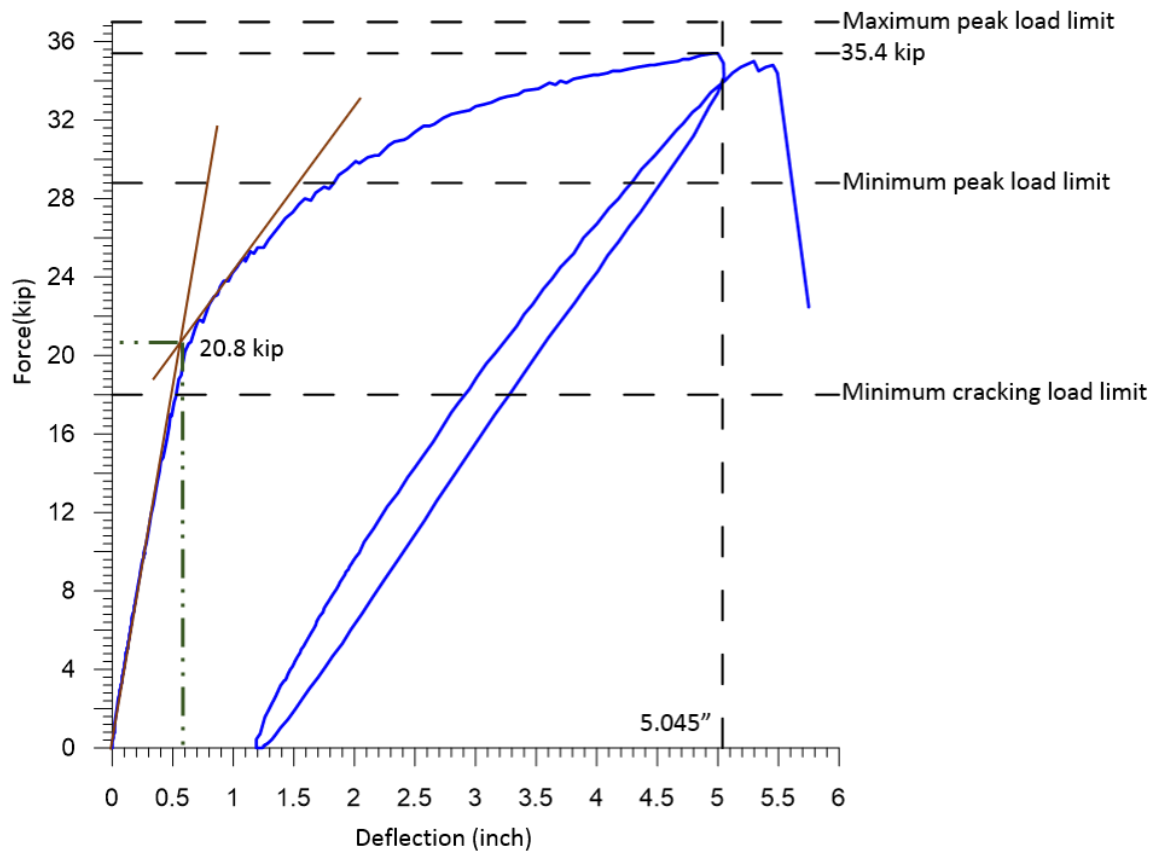
THIS CERTIFICATION MUST BE PART OF THE FINAL REPORT

Sponsored by:

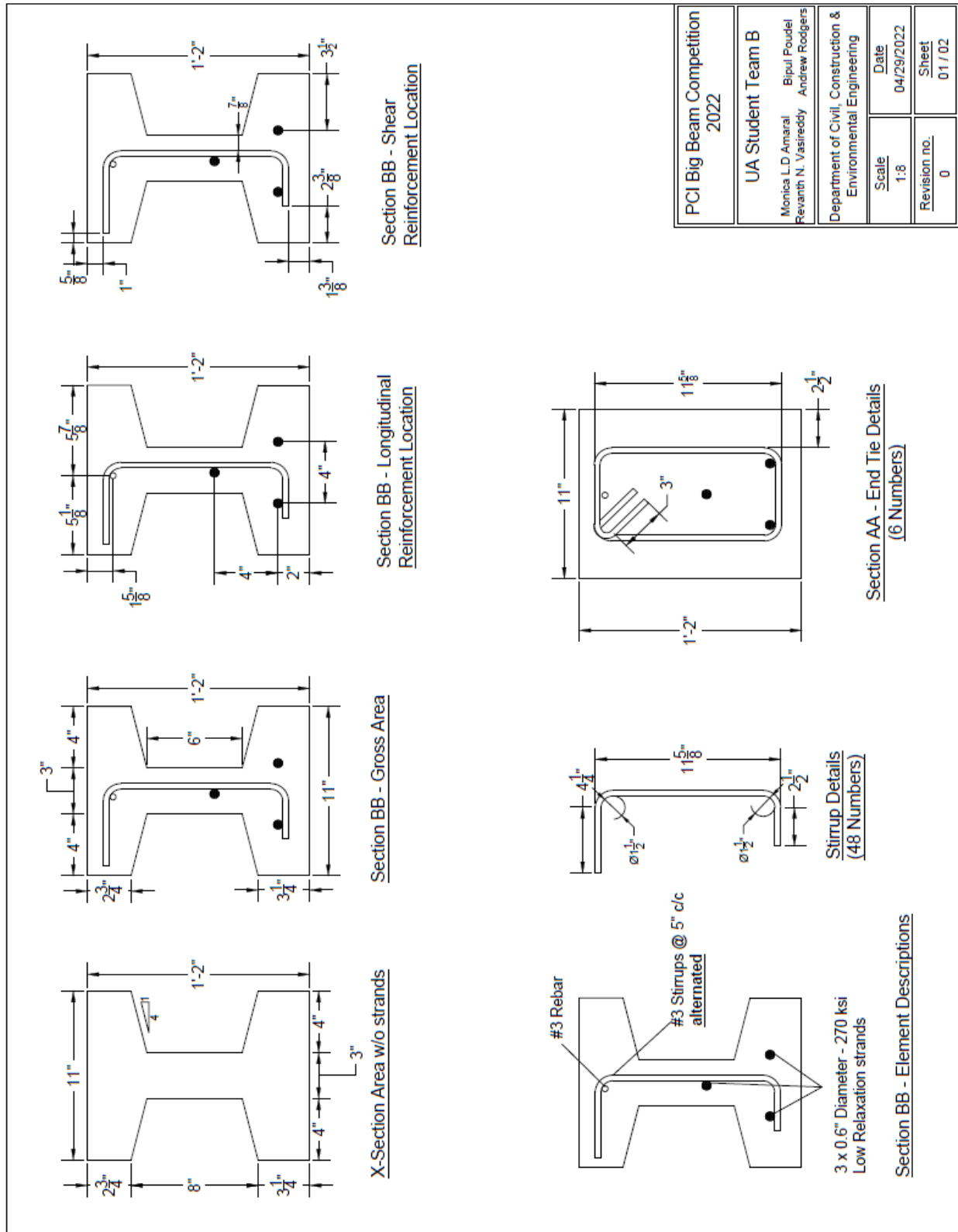
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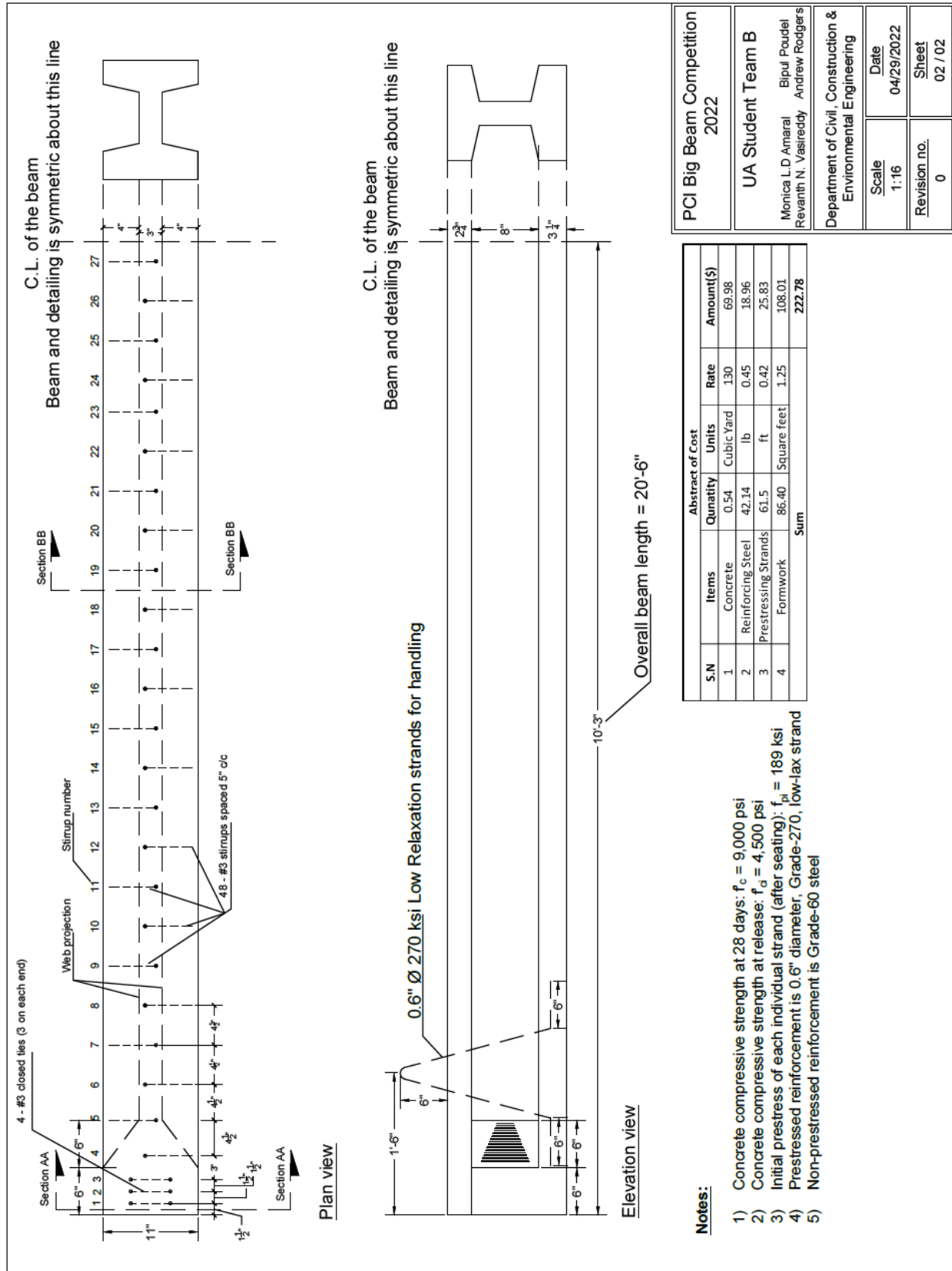
ALP
SUPPLY

Force Vs Mid-span Deflection Graph



Big Beam Drawings





PCI Big Beam Competition 2022	
UA Student Team B	
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Department of Civil, Construction & Environmental Engineering	
Scale 1:16	Date 04/29/2022
Revision no. 0	Sheet 02 / 02

Introduction

Prestress concrete structures are now widely used in civil infrastructures all over the world. It is especially useful for constructions with long spans.. It is also more durable than reinforced concrete structures. Typically, prestressed concrete structures are produced in a precast facility, which provides for a higher level of quality control. One of its significant benefits is the reduction of building time.

This report is prepared accepting the invitation of Precast Concrete Institute's (PCI) Student Education Committee for participation in Engineering Student Design (Big Beam) Competition for the 2021-2022 academic year. GATE® Precast Company in Monroeville, Alabama is the PCI partner for **Team B of The University of Alabama** and aided in the fabrication of the beam. This report first describes the concrete mix design used in the beam. It is followed by structural design process, experimental test setup and test results. The report concludes with lessons learned by the team members while taking part in competition. The Appendix contains the summary of design calculation, cost estimation of the beam and result obtained from commercial software.

Concrete Mix Design

The concrete mix design had to meet several requirements. One of the judging criteria for the competition was low cost which was proportional to concrete strength. From the past experience of Big Beam Competition, the team determined that to have the beam failure between a load of 28.8 kips to 37 kips, a compressive strength of 8000-10000 psi would be adequate. The mix also needed to have a high flow so that the concrete could fill the formwork easily. To account for all of these, with discussions and interactions with the plant QA/QC engineers, we chose a 9000 psi self-consolidating concrete (SCC) for design purpose. The proportions used for mix design is summarized in Table 1.

Table 1: Concrete mix proportions

Material	Quantity (per 1 cu. Yd.)
# 7 Lithonia	1450 lbs
#67 Atmore Gravel	400 lbs
Atmore Concrete sand	1000 lbs
Type III Portland cement (Hocim Grey III)	752 lbs
Water	283.22 lbs
Water Reducer	34 oz
Air Entrainment	2 oz
Plasticizer	35 oz

The Big beam specimen was cast on xxx at the GATE precast plant in Monroeville, Alabama. During the casting of the Big Beam at the Plant, wet concrete tests were performed as per ASTM standards. The unit weight of the concrete mix was measured as 150.2 pcf, spread as 24” and air content as 2.4%. Nine, standard 4” x 8” cylinders were casted during the concrete pour day. Compressive strength test of 3 cylinders each were done at 14 days and 22 days (day before test day) respectively as per ASTM C39. Split cylinder test of 3 cylinders were done at 22 days (day before test day) for determining tensile strength concrete. The big beam was tested to failure on 23rd day after casting. Summary of measured strength of the concrete is presented in Table 2.

Table 2: Summary of Test Results

Test	No. of specimen tested	Days	Average Strength (psi)
Compressive Strength	3	14	10637
Compressive Strength	3	22	11418
Split Tensile Strength	3	22	892

Structural Design

The structural design of the beam was conducted using conventional flexure and shear design. The objective of the design process was to come up with an efficient design section meeting Big Beam 2022 competition rules and ACI 318-19 Code provision. The primary constraint for the design process was meeting minimum cracking load of 18.8 and peak load within (28.8-37.0) kips range. The beam section also had to be optimized to reduce cost and weight of the design.

Preliminary initial beam section was selected based on Magnel Plot. From the Magnel plot, minimum section modulus required for the section was obtained as 314 in³. An I-section with flange width 11 in., web width 3 in. and overall height 14 in. was selected after several iterations, which give top sectional modulus as 319 in³. Compressive strength of concrete was kept as 9000 psi and required compressive strength at prestress release was kept as 4500 psi. For the ease of construction purpose, for ease of demolding the formwork, chamfers were added afterwards at the inward junction of web and flange. The beam cross-section consisted of three, 0.6 in. diameter, grade 270 strand. Prestress losses calculations were performed using standard methods and the

stress in beam section immediately after release of prestress was checked in accordance with sections 24.5.3.1 and 24.5.3.2 of ACI 318-19.

The team members developed a design program in MATLAB and Microsoft EXCEL sheet which was later used to conduct beam design. The program could take in different variation of I-shapes; location of prestressing strands; prestressing forces etc. and calculated stresses in beam after release of prestress, cracking capacity, ultimate capacity, maximum deflection, cost, and weight of the beam. The cracking moment was calculated using section 24.2.3.5b of ACI 318-19. The ultimate capacity was calculated at strain value of 0.003 at extreme fiber in compression zone. Conventional rectangular stress block was used to calculate ultimate flexural capacity of the beam.

The moment capacity of the section was checked so that the section would not crack below 18 kips and would not exceed its ultimate capacity greater than 37 kips. Moment curvature graph was plotted for initial condition, cracking condition, and ultimate condition. Based on the moment curvature graph, midspan deflection was calculated using moment-area theorem.

The shear capacity of the section was determined based on ACI 318-19. Both web shear capacity and flexural shear capacity were determined at every one foot interval and minimum of those was selected as shear capacity. Shear demand was calculated from the loading condition. Based on these shear stirrups requirement was determined. “C” shaped stirrups of #3 bar with standard bend requirement were used and its spacing was varied along the span of the beam based on the requirement. For constructability, a single #3 bar was provided as compression reinforcement. Special attention was provided to the transfer length portion while calculating shear demand. At last, the criterion for development length was also checked.

Beam Analysis and Prediction

As mentioned previously, the analysis of the beam was done using the MATLAB program and excel sheet. Only elastic shortening loss was considered for analysis, as the testing of the beam was planned be done within 15 to 20 days from casting. Both tensile stress and compressive stress provisions after transfer of prestress and service condition were checked using MATLAB program as per ACI 318-19. After that, the cracking moment and ultimate load were determined in Excel sheet. The curvature corresponding to initial point, cracking moment and ultimate moment were

determined. Linear line was used to join the three points. Based on the curvature obtained, moment area theorem was used to calculate the midpoint deflection of the beam.

The deflection and ultimate load capacity of the beam was again cross-checked with a commercial software named Response-2000. Response-2000 is a free and user-friendly section analysis software developed at the University of Toronto, which calculates the strength of reinforced and prestressed concrete cross-sections using modified compression field theory. We compared the results obtained from our programming with Response-2000 to establish final prediction for the Big Beam. For the final prediction, values obtained from excel sheet and theoretical calculation were adopted rather than result of Response 2000.

The initial design was based on a target compressive strength of 9000 psi. However, the compressive strength from cylinder tests done a day before the beam test was found to be 11418 psi. Split cylinder test was done to determine the tensile strength of the concrete. Tensile strength was obtained as 892 psi. Hence, the prediction was again updated based on measured compressive strength and tensile strength.

The summary of the updated prediction is presented in the table below.

Table 3: Summary of the predicted values for deflection and loads

	Excel Worksheet	Response-2000	Prediction
Cracking load (kips)	19.15	23.98	19.15
Maximum load applied (kips)	32.26	31.82	32.26
Deflection at Maximum load (inch)	4.342	3.693	4.342

Beam Fabrication

GATE Precast Company constructed the beam formwork, placed the strands and rebars in required number and position as per the detailed beam drawing submitted by the Team. The company invited us for casting of the beam on June 2, 2022. On casting day, before team's arrival; the prestressing strands were already stressed to the required initial prestressing stress of 189 ksi. The team quickly checked the formwork dimensions, spacing of the stirrups and strands positioning before pouring. With supervision of GATE Precast Company, the team used an overhead crane hopper to pour concrete into the formwork. Concrete was then further vibrated for consolidation.

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The beam was finished with trowel after casting. In addition to this, nine 4"x8" cylinders were casted for determination of test day tensile strength and compressive strength of the beam.



a) Formwork of the beam



b) Stirrup arrangement at end



c) Concrete pouring



d) Beam finishing after completion of casting

Figure 1: Big Beam Fabrication Steps

Test Setup

As per the competition rules, the beam was supported at 20 ft. span measuring center to center of the supports and two-point loads were applied, one at the center and another at 7' from the support. The beam was supported on two six inches wide steel plate with rollers; which was eventually resting on huge concrete blocks. A hydraulic loading jack was used to apply the load. The load from the loading jack was distributed to two points along the span using a spreader beam, as per

the rules of competition. A load cell of capacity 100 kips was installed between the load jack and spreader beam to record the load applied. The loads were eventually transferred as a point load to the beams through rollers attached at the bottom of the spreader beam.

Deflection was measured using string potentiometers. In addition to this, LED sensors were also installed at the midspan of the beam, to aid in measuring the curvature in the constant bending region. The data from the load cell and string potentiometers were collected using an NI DAQ system. The LED sensors used an NDI Oprotrak System to measure the change in X, Y and Z position of each LED sensor. Figure 2 shows the arrangement of test setup.



Figure 2: Test Setup of Big Beam

Test Results

The beam was initially loaded to 10 kips, and loading was paused for few moments to check for any cracks. Checking for cracks were done at every 5 kips interval. As per PCI Big Beam Competition rules, crack was checked after 18 kips service load as well. No cracks were observed

at 18 kips. First flexural cracks were observed during the load cycle where the beam was loaded to 21.3 kips. After marking those cracks, the beam was loaded and marking of cracks were done either when a cracking sound was heard, or some distinct cracks were observed. Flexural shear cracks were initiated after 25 kips of load, but it was observed more prominently after 28 kips (see Figure 3). Then, the loading was continued. More flexural shear cracks were observed. At 35.4 kips, decrease in load carrying capacity was observed (See Figure 4). But in the meantime, we were heading toward the risk of exceeding the stroke available for the hydraulic jack. Hence, it was decided to unload the beam and add 2 in. steel plate between the hydraulic jack and steel spreader beam. After resuming loading of the beam, the capacity of the beam didn't exceed beyond 35.4 kips and the beam failure occurred with concrete in the top flange crushing. No bond failure and web shear failure were observed. Almost symmetrical crack distribution was observed around the midspan region of the beam.

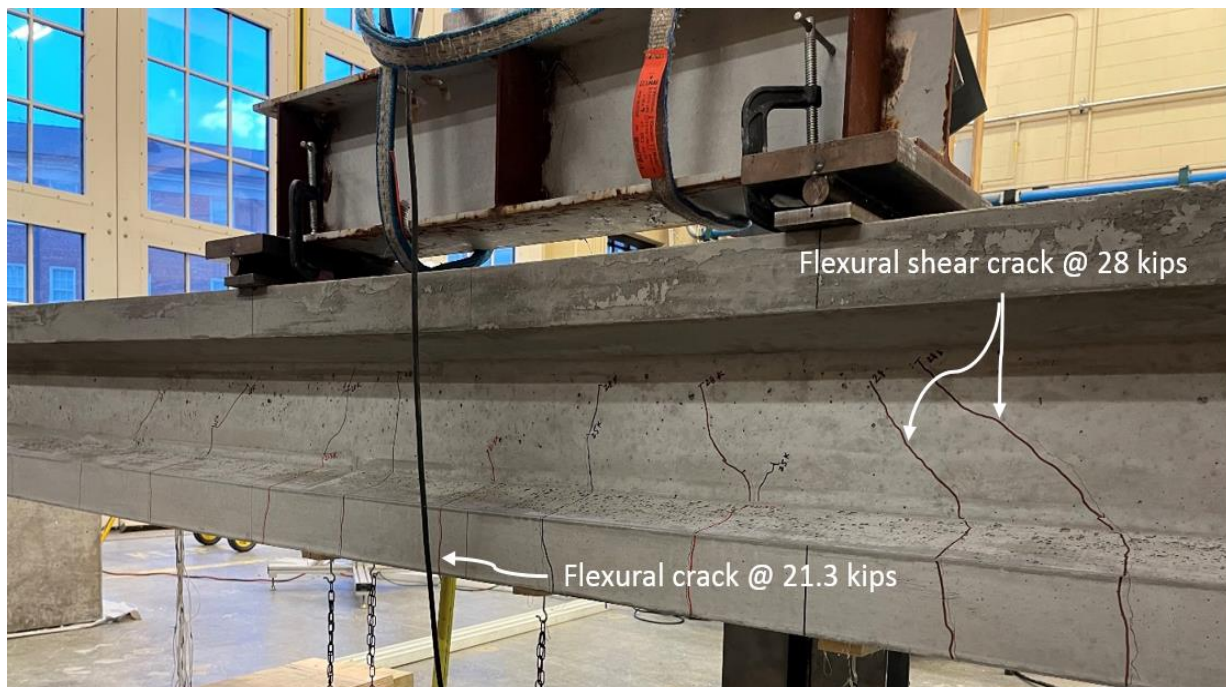


Figure 3: Crack distribution in Big Beam

The measured force-deflection response of the beam at the midspan, with minimum and maximum permissible load limit as per PCI Big Beam Competition Rules is shown in Figure 4.

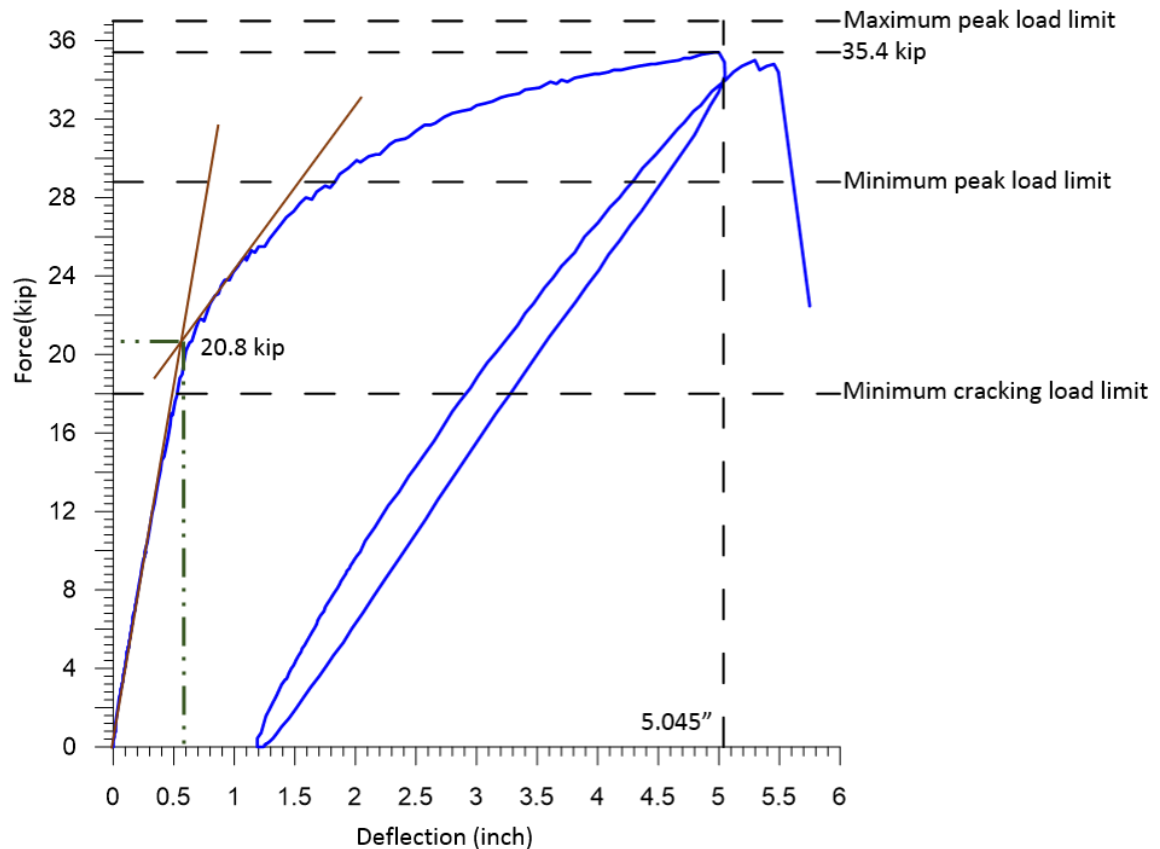


Figure 4: Force Vs Deflection at midspan

Observed midspan deflection corresponding to maximum applied load i.e 35.4 kips is 5.04". The cracking load is estimated as the intersection of the initial tangent up to elastic limit and tangent following the elastic limit. The cracking load was obtained as 20.8 kips.

The LED sensors installed in the beam continuously provided the changing coordinates at a frequency of 10 Hz. Based on the initial and final coordinates, strain at each location across the depth was calculated for every 1 kips force interval. The summation of top strain and bottom strain divided by the depth of the beam provided curvature for each applied force. The curvature was then plotted with moment which is named as experimental moment-curvature in this report. The experimental moment-curvature is compared with the moment-curvature calculated theoretically and moment-curvature obtained from Response 2000.

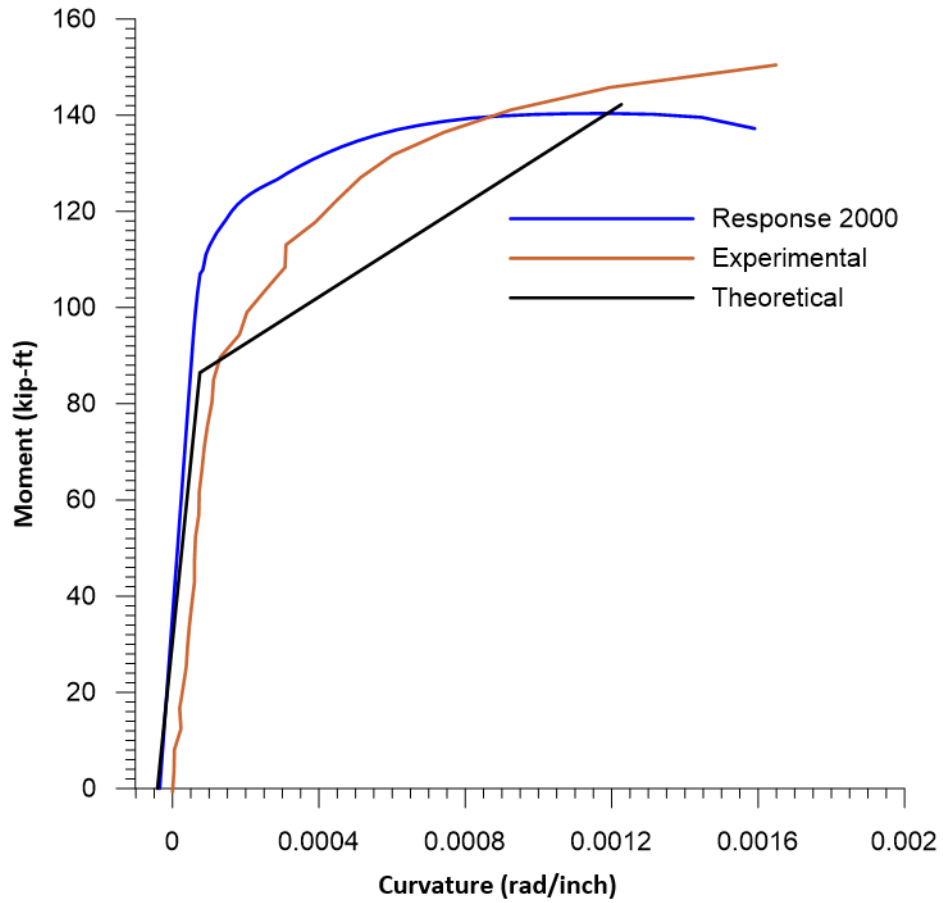


Figure 5: Comparison of Moment Vs Curvature

Lessons Learned

Monica Lages Do Amaral

PCI Big Beam Competition has given me a great opportunity to work with my colleagues as a team and to learn valuable lessons together with them. Some of my roles on the team were to help with the design, drawing and testing of our beam, and seeing the whole process from the design level to testing was very interesting. It was first time that I helped in instrumentation for testing. It was amazing knowing the functions of different type of instruments and their data collection process.

Overall, it was a great experience to participate in this competition and to work as a group. We had the opportunity to combine together different sets of skills from our group members to have a great output.

Bipul Poudel

Designing big beam was not straight forward task. The competition required beam to be as ductile as possible with optimized section and capable of resisting limited maximum load range. I was primarily involved in design process, hence, I got the opportunity to review the theoretical methods of prestress design. I compared my theoretical results with results from experiment. Even though our prediction of deflection deviated by around 15%, our prediction of maximum anticipated load and cracking load was within 10% and we could satisfy the requirements of loading range as set by competition. We got the expected failure mode that we anticipated. From this, I got the opportunity to realize how close our calculation could be if we could obtain the desired failure mode. Apart from that, I would have to thank GATE Precast Plant, for giving us the tour in their plant so that we could visualize how actually things work as per design in the industry. I got acquainted to different innovation and quality control challenges the industry faces.

Overall, the experience in participating the big beam was fruitful and I learnt how prestress beam is designed and constructed from the very beginning.

Revanth Naidu Vasireddy

Participating in the PCI Big Beam competition has allowed me to collaborate with team members, and I was so excited to see how the theoretical knowledge that I learned in the class applied when we worked in the project. The lessons that I learned in class helped me to work on the beam design and one of my responsibilities on the team was to manage the test setup. The precast plant tour given by our concrete plant partner showed me the step-by-step construction process of our beam. Moreover, testing of the beam made me understand how much preparation and organization are required for arranging all the test setup and various types of instrumentation. This preliminary preparation phase was crucial for us to be able to accurately analyze the experimental data and compare our results with our calculations. Regardless of our final ranking, the big beam competition experience has taught me many lessons.

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Appendix A: Bibliography

Concrete Design and Testing:

1. ASTM International. *C39/C39M-21 Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens*. West Conshohocken, PA, 2014. Web. 01 Mar 2021. <https://doi.org/10.1520/C0039_C0039M-21>
2. ASTM International. *C496/C496M-17 Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens*. West Conshohocken, PA, 2017. Web. 12 Jun 2018. <https://doi.org/10.1520/C0496_C0496M-17>

Structural Design:

1. American Concrete Institute. *Building Code Requirements for Structural Concrete (ACI 318-19)*. Farmington Hills, MI, 2019.
2. Precast/Prestressed Concrete Institute. *PCI Design Handbook (7th Edition) - 5.2.4 End Stresses at Transfer*. pp. 5-40. Chicago, IL, 2010.
3. American Association of State Highway and Transportation Officials (AASHTO). *AASHTO LRFD Bridge Design Specifications (8th Edition) - 5.9.4.4 Pretensioned Anchorage Zones*. Washington, D.C., 2017. Web. via Knovel.com. 12 Jun 2018. pp. 5-143.

Appendix B: Design Calculation

SUMMARY OF DESIGN CALCULATIONS

Properties

a. Cross Section Properties

A_g =	98	in ²	(Gross Area)
I_g =	2276.5	in ⁴	(Gross Moment of Inertia)
y_{bot} =	6.85	in.	(Distance to Centroid from top)
y_{top} =	7.14	in.	(Distance to Centroid from bottom)
W_g =	0.1021	k/ft	(Self weight of beam)
M_g =	61.25	Kip-inch	(Moment due to self weight)

b. Strands and Compression Reinforcement

n_s =	3		(Nos. of prestressing strands)
A_{ps} =	0.217	in ²	(Area of prestressing strands)
f_{pu} =	270	ksi	(Ultimate stress of prestressing strands)
E_{ps} =	28500	ksi	(Modulus of Elasticity of prestressing strands)
f_{pi} =	189	ksi	(Initial prestress in individual strands)
F_o =	123	kip	(Total prestress force without losses)
c_{gs} =	10.67	in.	(Distance to centroid of strands from top)
e =	3.52	in.	(Eccentricity of strands)
n_{cs} =	1		(Nos. of compression steel)
d_{cs} =	0.375	in ²	(Diameter of compression steel)
c_{cs} =	1.375	in.	(Clear cover for compression steel)
E_{cs} =	29000	ksi	(Modulus of Elasticity of compression steel)

c. Concrete Properties

f_{ci} =	5963	psi	(Strength of concrete at release of prestress)
E_{ci} =	4401	ksi	(Modulus of Elasticity of concrete at release of prestress)
f_c =	11418	psi	(Compressive strength of concrete)
f_r =	892	psi	(Modulus of rupture)
E_c =	6090.7	ksi	(Modulus of Elasticity of concrete)
density =	150.2	pcf	(Density of Concrete)

Loss Calculation

a. Elastic Shortening Losses

The stress at the centroid of the strands immediately after application of prestress:

$$s_{ci} = \frac{0.9*F_o}{A_g} + \frac{0.9*(F_o*e)*e}{I_g} - \frac{(M_g*e)}{I_g} = 1.64 \text{ ksi}$$

The corresponding elastic shortening loss is:

$$ES = \frac{E_{ps}*s_{ci}}{E_{ci}} = 10.62 \text{ ksi}$$

The effective prestress after accounting for elastic shortening losses is:

$$f_{se} = f_{pi} - ES = 178.38 \text{ ksi}$$

The effective prestress force after accounting for elastic shortening losses :

$$F_e = f_{se} * A_{ps} = 116.1 \text{ kip}$$

Check for Flexural Stresses Immediately after Transfer of Prestress

a. At mid-span

The stresses at extreme fibers in tension of the beam section:

$$\begin{aligned} s_{top} &= \frac{F_e}{A_g} - \frac{(F_e*e)*y_{top}}{I_g} + \frac{M_g*y_{top}}{I_g} \\ &= 0.093 \text{ ksi} > \left(-0.003 * \sqrt{f_{ci}} = -0.231 \text{ ksi} \right) \text{ (o.k.) } \mathbf{ACI-318 24.5.3.1} \end{aligned}$$

The stresses at extreme fibers in compression of the beam section:

$$\begin{aligned} s_{bot} &= \frac{F_e}{A_g} + \frac{(F_e*e)*y_{bot}}{I_g} - \frac{(M_g*e)*y_{bot}}{I_g} \\ &= 2.23 \text{ ksi} < (0.6 * f_{ci} = 3.57 \text{ ksi}) \text{ (o.k.) } \mathbf{ACI-318 24.5.3.1} \end{aligned}$$

b. At edge (2 ft. from the edge) of the beam

The stresses at extreme fibers in tension of the beam section:

$$\begin{aligned} s_{top} &= \frac{F_e}{A_g} - \frac{(F_e*e)*y_{top}}{I_g} + \frac{M_g*y_{top}}{I_g} \\ &= -0.029 \text{ ksi} < \left(-0.006 * \sqrt{f_{ci}} = -0.463 \text{ ksi} \right) \text{ (o.k.) } \mathbf{ACI-318 24.5.3.2} \end{aligned}$$

The stresses at extreme fibers in compression of the beam section:

$$s_{bot} = \frac{F_e}{A_g} + \frac{(F_e * e) * y_{bot}}{I_g} - \frac{(M_g * e) * y_{bot}}{I_g}$$

$$= 2.351 \text{ ksi} < (0.7 * f_{ci} = 4.17 \text{ ksi}) \text{ (o.k.) } \mathbf{ACI-318 24.5.3.1}$$

Cracking Moment Calculation

$$M_{cr} = \frac{I_g}{y_{bot}} * \left\{ f_r + \frac{F_e}{A_g} + \frac{F_e * e * y_{bot}}{I_g} - \frac{M_g * y_{bot}}{I_g} \right\}$$

$$= 1037.5 \text{ kip in}$$

$$\phi_{cr} = \frac{M_{cr}}{E_c * I_g} = \frac{987}{(5407.5 * 2234)} = 7.48 * 10^{-5} \text{ rad/in}$$

Ultimate Moment Calculation

From MATLAB iteration, neutral axis depth at ultimate 'c' = 2.45 in.

The compression force in concrete above the N.A.

$$C_c = 0.85 * f_c * (\beta * c) * b_f = 0.85 * 9 * (0.65 * 3.04) * 11 = 169.75 \text{ kip}$$

The compression force in compression steel

$$C_{cs} = E_{cs} * \epsilon_{cs} * A_{cs} = 29000 * 0.00201 * 0.11 = 3.42 \text{ kip}$$

The tension force from strands

$$T = f_{ps} * A_{ps} = 265.85 * 0.651 = 173.1 \text{ kips}$$

The ultimate moment including moment due to self weight

$$M_{ult} = C_c * \left(cgs - \frac{(\beta * c)}{2} \right) + C_{cs} * (cgs - d')$$

$$= 169.75 * \left(10.67 - \frac{(0.65 * 2.45)}{2} \right) + 3.42 * (10.67 - 1.562)$$

$$= 1706.8 \text{ kip in}$$

$$\text{Ultimate Curvature} = \phi_{ult} = \frac{\epsilon_{cu}}{c} = \frac{0.003}{2.45} = 0.00123$$

Shear Design

The beam section was subjected to unsymmetrical shear loading. Hence, the beam was analyzed across the span length at a distance of one feet and at some special point of interests. The shear demand (V_u) was calculated by taking account of self-weight of the beam as well. The minimum of the flexural shear strength (V_{ci}) and web shear strength (V_{cw}) was taken as shear capacity of the beam (V_c). Based on the demand and capacity, required stirrup requirement is calculated. Shear strength provided by stirrups is denoted as V_s .

Following equations from ACI 318-19 were used to carry out the shear check.

$$V_{ci} = 0.6 * \sqrt{f_c} * b_w * d_p + V_d + \frac{V_i * M_{cre}}{M_{max}} \text{ (ACI - 318 - 19 22.5.8.3.1a)}$$

$$V_{cw} = (3.5 * \sqrt{f_c} + 0.3 f_{pc}) * b_w * d_p + V_p \text{ (ACI - 318 - 19 22.5.8.3.2)}$$

$$M_{cre} = \frac{I}{y_{top}} (6 * \sqrt{f_c} + f_{se} - f_d) \text{ (ACI-318-19-22.5.8.3.1c)}$$

$$V_s = A_v * f_{yt} * d / \text{spacing} \text{ (ACI-318-19-22.5.10.5.3)}$$

Description	x	V_u	V_{cw}	V_{ci}	V_c	V_s	
	(ft)	(kip)	(kip)	(kip)	(kip)	(kip)	Stirrup spacing
0.5h	0.58	14.7	12.4	54.4	12.4	16.4	#3 bar @ 4.5" c/c
1.5h	1.5	14.6	20.4	58.1	20.4	16.4	
	3.00	14.4	20.4	29.8	20.4	14.8	# 3 bar @ 5" c/c
	4.00	14.3	20.4	22.7	20.4	14.8	
	5.00	14.2	20.4	18.4	18.4	14.8	
	6.00	14.1	20.4	15.5	15.5	14.8	
	7.00	14.0	20.4	13.4	13.4	14.8	
	8.00	13.9	20.4	11.9	11.9	14.8	
	9.00	13.8	20.4	10.7	10.7	14.8	
Beam C.L.	10.00	13.7	20.4	9.7	9.7	14.8	
	11.00	2.5	20.4	5.1	5.1	14.8	
	12.00	2.6	20.4	5.1	5.1	14.8	
	13.00	18.9	20.4	13.4	13.4	14.8	
	14.00	19.0	20.4	15.5	15.5	14.8	
	15.00	19.1	20.4	18.4	18.4	14.8	
	16.00	19.2	20.4	22.7	20.4	14.8	
	17.00	19.3	20.4	29.8	20.4	14.8	
L – 1.5h	18.5	19.4	20.4	58.1	20.4	16.4	#3 bar @ 4.5" c/c
L – 0.5h	19.42	19.5	12.4	54.4	12.4	16.4	

From the table, it can be observed that, except at the ends; shear capacity is greater than demand even if stirrups were not provided. But as per the minimum stirrup requirement of ACI; single legged #3bar-stirrup is provided at 5" spacing.

Check for Development Length

Development length was checked as per ACI 318-19 clause 25.4.8.1.

$$l_d = \frac{f_{se}}{3000} * d_b + \frac{f_{pu} - f_{se}}{1000} * d_b$$
$$= 91 \text{ inch}$$

Point of maximum moment from the support = 120 inch

Hence, development length was adequate.

Deflection Calculation

For deflection calculation, theoretical curvature was calculated for initial condition, cracking condition and ultimate condition using strain compatibility. The theoretical moment and curvature is summarized below:

Initial curvature at zero moment = $-4.084 * 10^{-5}$

Curvature at cracking moment @ 86.5 kip-ft = $7.482 * 10^{-5}$

Curvature at ultimate moment @ 142.2 kip-ft = 0.00123

Then the moment area theorem was used to calculate the mid-span deflection based on initial curvature and final curvature.

The mid-span deflection obtained from moment area theorem at ultimate load is 4.342 inch.

Bursting Force Calculation

Bursting Force Demand:		
f_{pu} Specified tensile strength of prestressing reinforcement	= 270 ksi	
f_i Initial prescribed prestress	= $0.70 * f_{pu} = 189$ ksi	
A_{ps} Area of prestressing steel	= $0.217 \text{ in}^2 * 3 \text{ strands} = 0.651 \text{ in}^2$	
P_i Initial prestressing force in the strands	$= f_i * A_{ps}$ $= 189 \text{ ksi} * 0.651 \text{ in}^2$ $= 123.04 \text{ kips}$ (Requested)	$= 41,020 \text{ lbs per strand}$ $= 41.020 \frac{\text{kips}}{\text{strand}} * 3 \text{ strands}$ $= 123.06 \text{ kips}$ (Actual Provided by Precaster)
Bursting Force to Resist: 4% of Prestressing Force - We learned that 4% of the Prestressing force is a standard value for this purpose	$= 0.04 * P_i$ $= 0.04 * 123.04 \text{ kips}$ = 4.92 kips	$= 0.04 * P_i$ $= 0.04 * 123.06 \text{ kips}$ = 4.92 kips
Bursting Force Resistance Capacity:		
AASHTO LRFD Bridge Design Specifications (8th Edition) Section 5.9.4.4. – Prestensioned Anchorage Zones Equation 5.9.4.4.1-1		
$P_r = f_s * A_s$ Factored splitting resistance of prestensioned anchorage zones provided by reinforcement in the ends of pretensioned beams	$= 20.0 \text{ ksi} * 0.66 \text{ in}^2$ = 13.2 kips	
f_s Stress in steel not to exceed 20.0 ksi	= 20.0 ksi	
A_s Total area of reinforcement located with $h / 4$ from the end of the beam (in ²) For pretensioned bulb tees, A_s shall be taken as the total area of the vertical reinforcement located within $h / 4$ from the end of the beam.	<i>Using #3 closed tie reinforcement</i> $= (0.11 \text{ in}^2 \text{ per leg}) * 2 \text{ legs}$ $= 0.22 \text{ in}^2 \text{ per tie}$ <i>Using 3 ties</i> $= 0.22 \text{ in}^2 \text{ per tie} * 3 \text{ ties}$ = 0.66 in²	
$h / 4$ (Overall dimension of precast member in the direction in which splitting resistance is being evaluated)/4	$= 14 \text{ in} / 4$ = 3.5 in	
Design Conclusion:		
Include 3 #3 ties within 3.5 in of each end of the beam.		

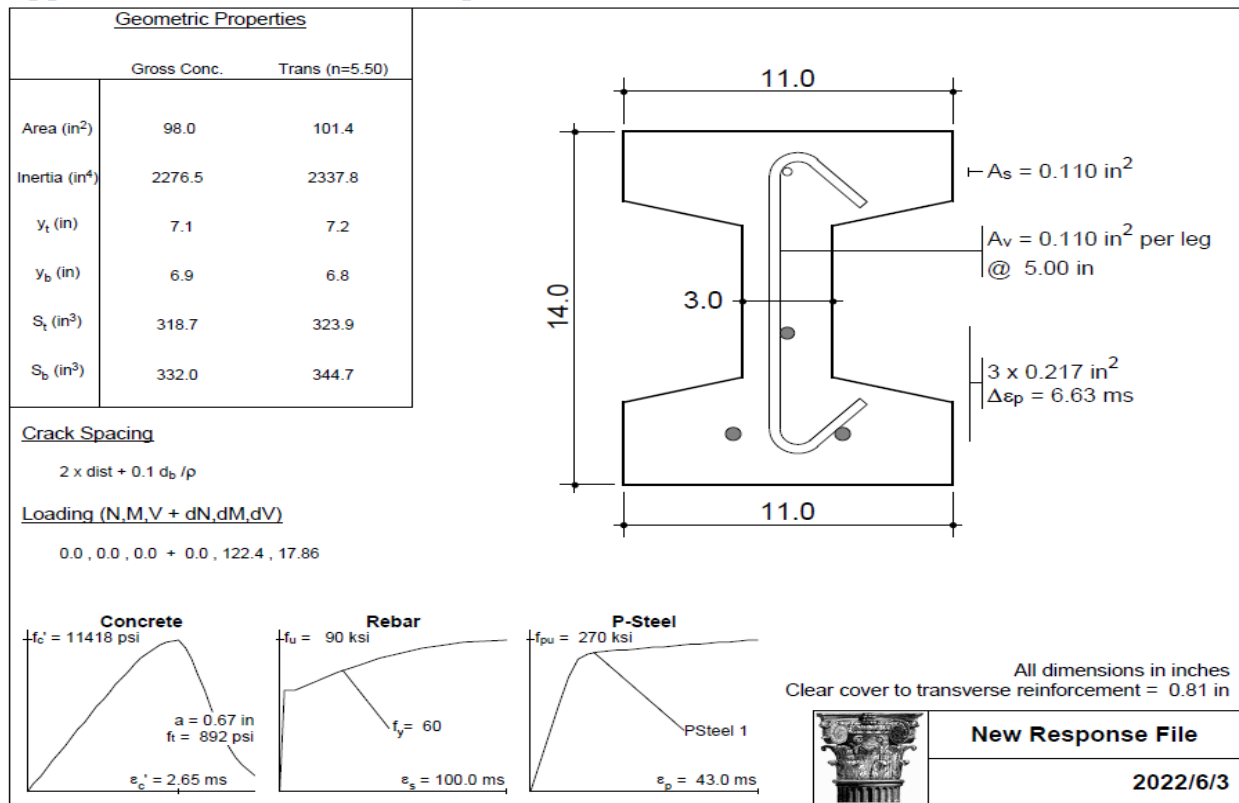
Appendix C: Cost Estimation

The cost required for constructing the Big Beam is calculated as per the competition rules.

Abstract of Cost					
S.N	Items	Quantity	Units	Rate	Amount(\$)
1	Concrete	0.54	Cubic Yard	130	69.98
2	Reinforcing Steel	42.14	lb	0.45	18.96
3	Prestressing Strands	61.5	ft	0.42	25.83
4	Formwork	86.40	Square feet	1.25	108.01
Sum					222.78

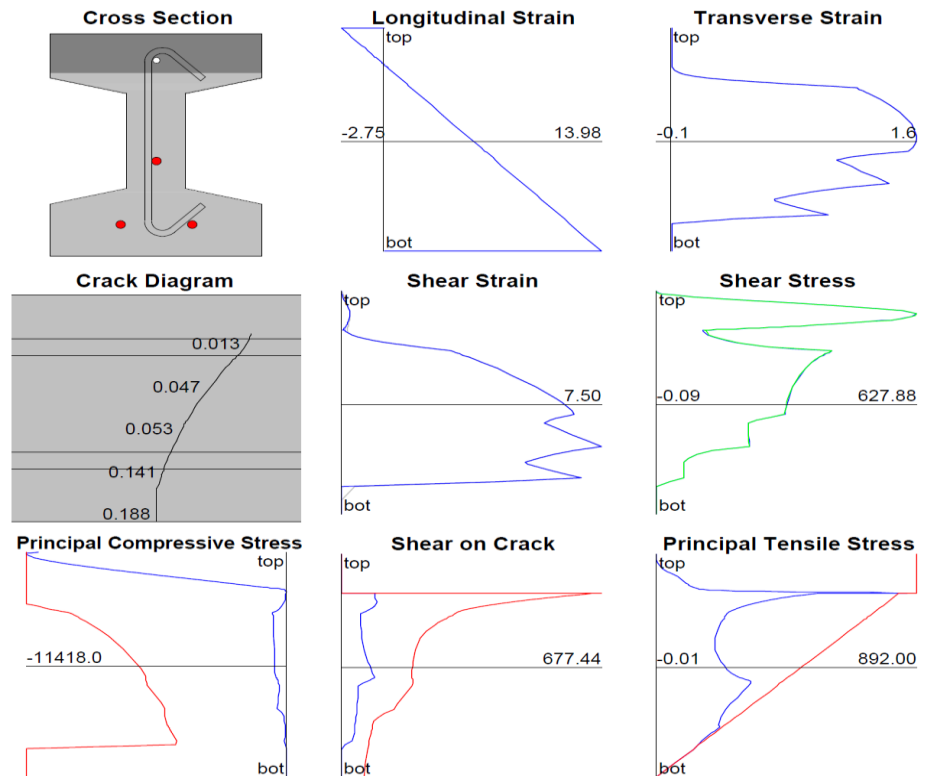
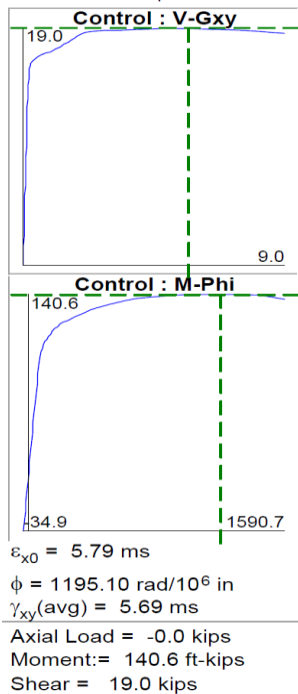
Quantity Estimation Sheet			
A. Concrete			
	Area(ft ²)	Length(ft)	Volume(ft ³)
I-section	0.681	18.5	12.590
Tapered Section	0.875	1	0.875
End Section	1.069	1	1.069
		Sum	14.535
		Sum in yd ³	0.54
B. Reinforcing Steel			
	Area(ft ²)	Length(ft)	Volume(ft ³)
Compression bar	0.0008	20.25	0.016
48 C-Strirups	0.0008	72	0.055
6-2-legged end Stirrups	0.0008	19.875	0.015
		Sum	0.086
Unit weight of Reinforcing steel		490	lb/ft ³
		Sum	42.14
C. Prestressing Strand			
	No. of strands	Length(ft)	Length(ft)
3-0.6 inch diameter strands	3.0	20.5	61.5000
		Sum	61.5000
D. Formwork			
	Perimeter(ft)	Length(ft)	Surface area(ft ²)
I-section	4.291	18.5	79.384
Tapered Section	3.771	1	3.771
End Section	3.250	1	3.250
		Sum	86.40

Appendix D: Results from Response 2000



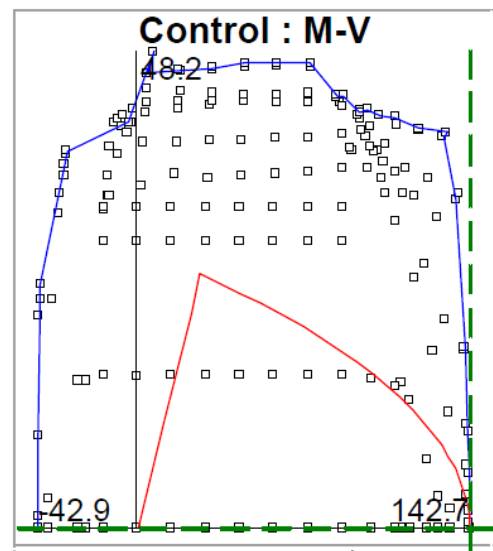
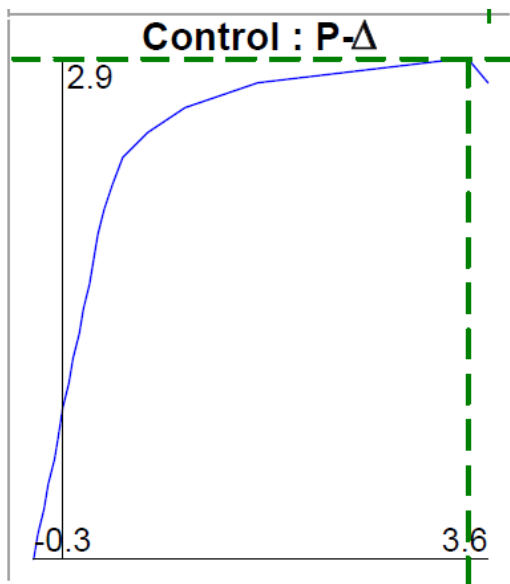
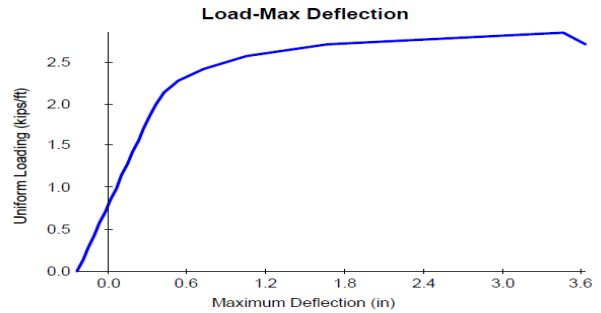
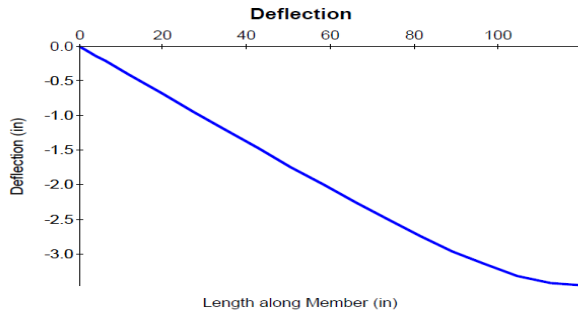
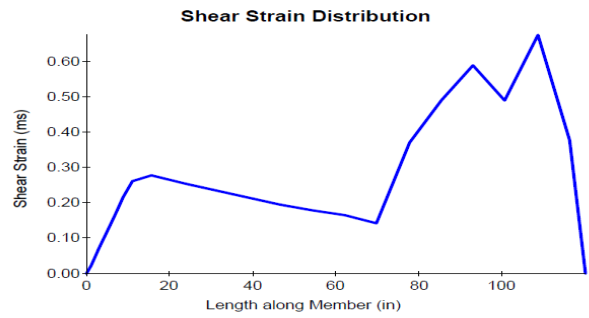
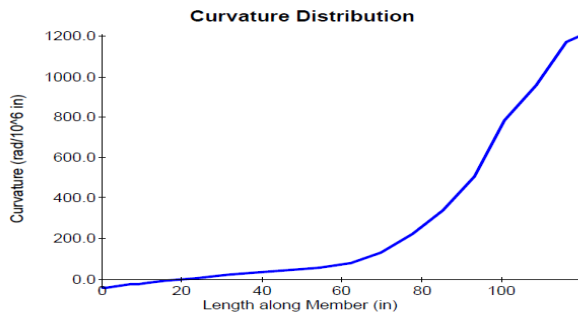
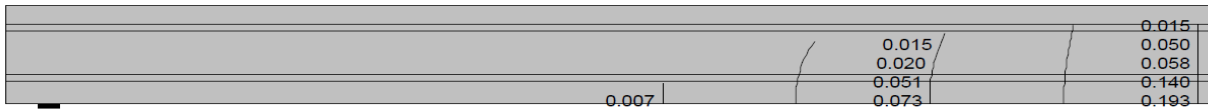
Response-2000 v 1.0.5

New Response File
 2022/6/29 - 3:49 pm



PCI Big Beam Competition 2021-22

Member Crack Diagram



Appendix E: MATLAB Code

```

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%For I-shaped Prestressed Beam Design %%%%%%%%%%
disp('XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX');

disp('UNIVERSITY OF ALABAMA PCI BIG BEAM DESIGN');

disp('XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX');

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% MAIN FILE
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
clc
clear
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%INPUT%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

bf=11; %breadth of top flange (in.)
hf=2.75; %height of top flange (in.)
bw=3.0; %breadth of web (in.)
hw=8; %height of the web (in.)
bf2=11; %breadth of flange (in.)
hf2=3.25; %height of flange (in.)
ch1=1; %chamfer slope (in.)
ch2=1; %chamfer slope (in.)
l=20; %span of beam (ft.)

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

Ag=98;
Ig=2276.5;
ybot=6.8571;
ytop=7.1429;
disp('The gross area of section ,in^2');
disp(Ag);
disp('The moment of inertia of gross section,in^4');
disp(Ig);
disp('The cg of section from bottom,in');
disp(ybot);
disp('The cg of section from top,in');
disp(ytop);

% %%%%%%%%% Strand & Compn reinforcement Location %%%%%%%%%%
% %%%%%%%%% This program envisions at maximum 3 layer of strands and strands of same
dimension%%%%%%%%%
%
% %%%%%%%%%INPUT%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%
ns= 3; % total no of strands
cc= 2; % distance from cg. of bottom layer of strand to bottom of the beam
ns1 = 2; %no of strands in layer 1 i.e bottom layer
ns2 = 1; %no of strands in layer 2

```

```

ns3 = 0; %no of strand in layer 3
grid1 =4;% distance between two layers of strands c/c
aps=0.217; % area of prestressing strand,0.6 in dia, in2
fpu = 270; %ultimate stress of strands ksi,
fpi1 = 0.70*fpu;%initial prestressing of strands layer 1,ksi
fpi2= 0.70*fpu;%initial prestressing of strands layer 2,ksi
fpi3= 0*fpu;%initial prestressing of strands layer 3,ksi
Eps = 28500; %ksi modulus of elasticity of prestressing strand
cccs=5/8; %in clear cover for the compression reinforcements
dcs=3/8; %in diameter of compression steel
ncs=1;% no of compression steel
Aps=ns1*aps+ns2*aps+ns3*aps; %total prestress area
Acs=3.1416*(dcs)^2/4*ncs; %Area of compression steel
Ecs=29000; %ksi modulus of Elasticity of compression steel
% %%%%%%%%%%%%%%% Concrete Properties%%%%%%%%%%%%%%
%
Fo=(ns1*aps*fpi1+ns2*aps*fpi2+ns3*aps*fpi3);
fpi=(ns1*fpi1+ns2*fpi2+ns3*fpi3)/(ns1+ns2+ns3);
cgsbot=(ns1*cc*fpi1+ns2*(cc+grid1)*fpi2+ns3*(cc+2*grid1)*fpi3)/(ns1*fpi1+ns2*fpi2+ns3*fpi3)
cgs=hf+hw+hf2-cgsbot
e=ybot-cgsbot
% %%%%%%%%%%%%%%% Concrete Properties%%%%%%%%%%%%%%
%
fci = 5963; %initial strength of concrete, psi
fc= 11418; %final strength of concrete, psi
if fc<4000
    beta1=0.85;
elseif fc>=8000;
    beta1=0.65;
elseif (4000<fc) && (fc<8000)
    beta1=0.85-0.05*(fc-4000)/1000;
end

Eci =57*sqrt(fci) %modulus of elasticity of concrete at initial condition, ksi
Ec= 57*sqrt(fc); % modulus of elasticity of concrete final condition, ksi
density = 0.150; %density of concrete in kcf;
wg=density*Ag*(1/144)
Mg=wg*l^2/8*12 %moment due to self weight at center, k-in
fr=0.892;% tensile capacity of concrete, ksi
ecu=0.003;
%
%
% %%%%%%%%%%%%%%% Time Independent Losses%%%%%%%%%%%%%%
%
% %%%%%%%%%%%%%%% Elastic Shortening%%%%%%%%%%%%%%
%
sci = 0.9*Fo/Ag+(0.9*Fo*e)*e/Ig-Mg*e/Ig
ES = Eps/Eci*sci;

```

```

disp('The elastic shortening loss at midspan is, ksi')
disp(ES)
%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%INPUT%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
fse= fpi-ES;
Fe=fse*Aps
disp('The effective stress after Elastic Shortening at midspan,ksi');
disp(fse)
%
% %%%%%%%%%%%%%Flexural Stresses at Mid Span immediately after transfer
% %%%%%%%%%%%%%of prestress %%%%%%%%%%%%%
%
% %%%%%%%%%%%%%stress on extreme fibers on top and bottom%%%%%%%%%%%%
%
sTop = Fe/Ag-(Fe*e)*ytop/Ig+Mg*ytop/Ig;
sBot = Fe/Ag+(Fe*e)*ybot/Ig-Mg*ybot/Ig;

if sTop>(-0.003*sqrt(fci))
    disp('Stress at Top fiber during prestress release is OK, ksi');
    disp(sTop);
else
    disp('Stress at Top fiber during prestress release is NOT OK,ksi');
    disp(sTop);
end
%
if sBot>(0.6*(fci)/1000)
    disp('Stress at Bottom fiber during prestress release is NOT OK,ksi');
    disp(sBot);
else
    disp('Stress at Bottom fiber during prestress release is OK,ksi');
    disp(sBot);
end
%
% %%%%%%%%%%%%%Flexural Stresses at 2 feet from the end immediately after transfer
% %%%%%%%%%%%%%of prestress %%%%%%%%%%%%%
%
% %%%%%%%%%%%%%stress on extreme fibers on top and bottom%%%%%%%%%%%%
%
lcheck= 2; %distance from the end of the beams to check stresses at transfer
Mg2 = (wg*l/2*lcheck-(wg*lcheck)*1)*12; % kip-in, self weight moment at lcheck' from the end of the
beam

sTop2=Fe/Ag-(Fe*e)*ytop/Ig+Mg2*ytop/Ig;
sBot2=Fe/Ag+(Fe*e)*ybot/Ig-Mg2*ybot/Ig;

if sTop2>(-0.006*sqrt(fci))
    disp('Stress at Top fiber 2 feet from the end during prestress release is OK, ksi');
    disp(sTop2);
else
    disp('Stress at Top fiber 2 feet from the end during prestress release is NOT OK,ksi');

```

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```

disp (sTop2);
end
%
if sBot2>(0.7*(fci)/1000)
    disp ('Stress at Bottom fiber 2 feet from the end during prestress release is NOT OK,ksi');
    disp (sBot2);
else
    disp('Stress at Bottom fiber 2 feet from the end during prestress release is OK,ksi');
    disp (sBot2);
end
%
% %%%%%%%%%%%Cracking Moment
Calculation%%%%%%%%%%
% %%%%%%%%%%%Mcr by gross section properties%%%%%%%%%%
% fr=0.85;
Fem=Aps*fse; %effective prestress at midspan
Mcr=Ig/ybot*(fr+Fem/Ag+Fem*e*ybot/Ig-Mg*ybot/Ig);

if Mcr>979.25
    disp('The beam design is ADEQUATE for service load, Mn,kip-in')
    disp (Mcr);
else
    disp('The beam design is INADEQUATE for service load, Mn,Kip-in')
    disp(Mcr);
end
Ec = 57*(fc)^0.5
curvcr=Mcr/(Ec*Ig)

%
% %%%%%%%%%%%Ultimate Capacity
Calculation%%%%%%%%%%
% %%%%%%%%%%%Mn using rectangular stress block %%%%%%%%%%%
%
for c=0:0.001:(hf+hw)*0.5
    Cw=0.85*fc/1000*beta1*c*bw;
    Cf=0.85*fc/1000*beta1*(bf-bw)*c;
    ecs=ecu/c*(c-1.063);
    if ecs<=0.00207
        fcs=ecs*Ecs;
    else
        fcs=60;
    end
    Ccs=fcs*Acs;

    C=Cw+Cf+Ccs;
    es=(cgs-c)/c*ecu;
    ese=fse/Eps;
    eps=es+ese;
    tol=0.05;
    if eps<=0.0086
        fps=Eps*eps;

```

```

else
    fps=fpu-(0.04/(eps-0.007));
end
T=Aps*fps;

if abs(C-T)<tol
    break
else
    continue
end

end
if c<hf
Mn=Cw*(cgs-beta1*c/2)+Cf*(cgs-beta1*c/2)-wg*l^2/8*12+Ccs*(cgs-1.063);
else
    Mn=Cw*(cgs-beta1*c/2)+Cf*(cgs-hf/2)-wg*l^2/8*12+Ccs*(cgs-1.063);
end

if Mn>1524    %corresponds to ultimate load
    disp('The beam design is ADEQUATE for maximum load, Mn,kip-in')
    disp (Mn);
else
    disp('The beam design is INADEQUATE for maximum load, Mn,Kip-in')
    disp(Mn);
end
%
%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%
% %%%%%%%%%%Calculation of
Curvature%%%%%%%%%
%
disp('The neutral axis at ultimate moment capacity')
disp(c);

curvult = ecu/c;

disp('The curvature at ultimate moment capacity');
disp (curvult);

```