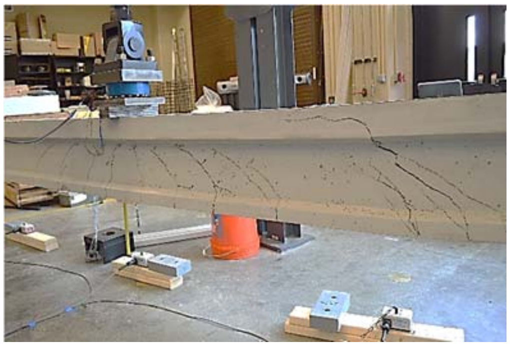
2016

THE UNIVERSITY OF ALABAMA®

PCI Big Beam Report



LARGE SCALE
STRUCTURES LAB
THE UNIVERSITY OF ALABAMA

Team Jelly Beam: Vidya Sagar Ronanki
Saeid Hayati
Md. Kobir Hossain

Faculty Advisor: Dr Sriram Aaleti
Precast Producer: Gate Precast, Monroeville, AL

Table of Contents

List of figures

List of tables

1. Introduction

Prestressed concrete offers various advantages over normal reinforced concrete. As a prestressed member remains uncracked at service loads, these members can span larger distances for a given depth. Also, being uncracked relatively minimizes water ingress and thus decreasing the chance of steel rebar corrosion and increasing the durability when compared to normal reinforced concrete members. Further, prestressed concrete members are produced in a controlled plant environment. This results in a higher quality control and also a safer production environment for the workers. These are a few among the many insights the student team was able gain by learning and working alongside the industry professionals at Gate Precast.

This report presents the processes adopted and details the experiences of the student team in designing, constructing and testing a 17 ft. long prestressed beam for the PCI Big Beam competition. The report starts by presenting the criteria for the mix design and discusses the material properties of concrete and prestressing strands. It then presents the evolution of the chosen section shape. The design and analysis methods adopted are also discussed in this section. Further sections explain the beam construction and test setup. The results from the test are analyzed and put in perspective with the predicted values. The report concludes by stating the lessons learnt from the competition.

2. Material Testing

2.1 Concrete Mix Design

Performing a concrete mix design involves the proportioning of various ingredients to achieve the desired level of performance. The student team realized that the desired level of performance relates not only to the hardened concrete, but also to the concrete in its initial flowable state.

The student team learning from the previous teams experience had a shape developed for an ultimate strength of around 15000 psi. This initial design factoring a high compressive strength had to be revised due to the feasibility considerations on part of the precast producer. We thus adopted a mix design that would have the maximum possible strength and the least disruption to the daily activities of the precast yard. Two mix designs were thus examined with a 28-day strength of 5000 psi and 8000 psi. The section shape resulting from a 5000 psi mix resulted in a very large section size. It was consequently decided to adopt an 8000 psi mix design. Table 1 presents the details of this mix design.

Table 1: Concrete Mix Design

Mix Quantities		
Type III Cement	846	lb
Gravel	1536	lb
Sand	1177	lb
Water	291	lb
Workability Retainer	50	fl.oz
Viscosity Modifier	76	fl.oz
Air Entrainer	4	fl.oz
High-Range Water Reducer	80	fl.oz

It should be noted that Type-III cement was used as part of the mix to achieve a high early strength gain. The small section and low web thickness of 3 in. mandated a concrete mix that can flow very well. Hence the mix adopted was an SCC mix with a spread of 25 in. The mix had a unit weight of 142 pcf and an air content of 6.2%

Concrete cylinders were tested periodically to monitor the strength gain of concrete as per the ASTM C 39 Standard [1]. The results of these tests are plotted alongside the mix design test data in Figure 1. The compression testing setup can be seen in Figure 2a.

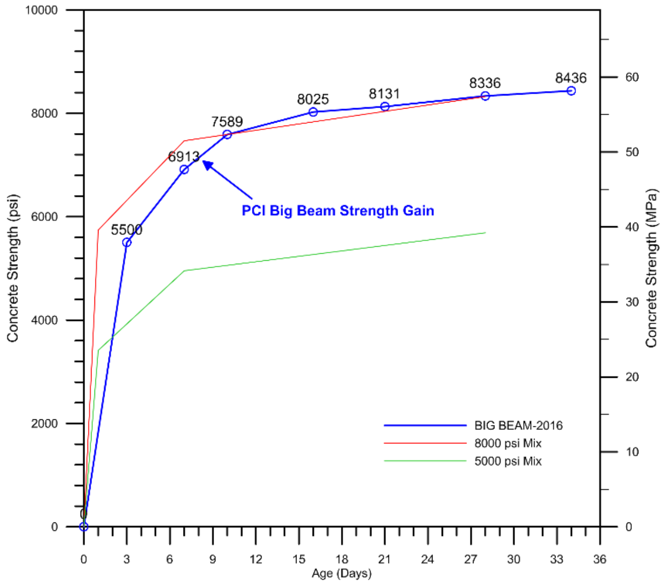
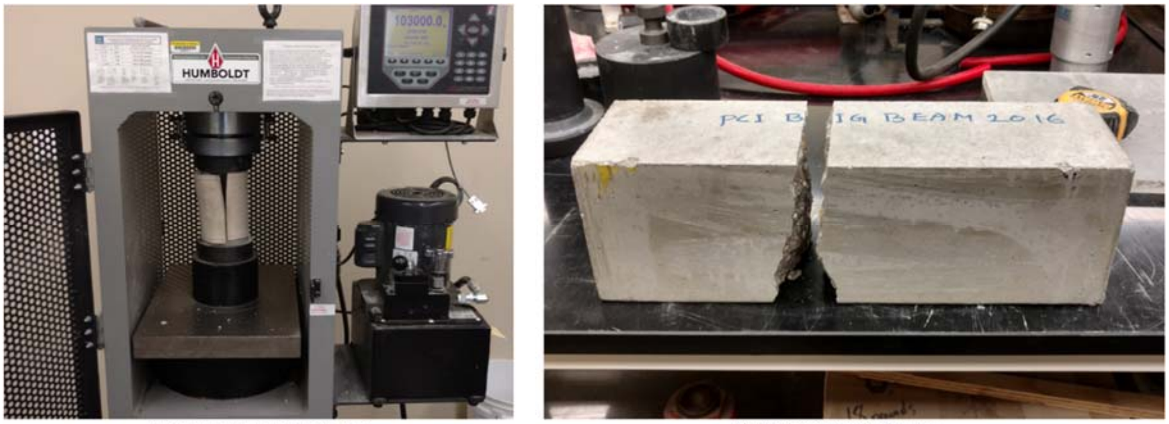


Figure 1: Concrete compressive strength vs age

To obtain the cracking strength of concrete, 3 MOR beam tests were conducted on the day of the test. It was decided not to adopt the split cylinder test as the MOR beam test more realistically simulates the stress state in a real beam under flexure. A cracking strength of 536 psi was obtained from these tests. A broken beam sample can be seen in Figure 2b.



a) Compression testing of cylinders

b) MOR beam sample after test

Figure 2: Material testing of concrete

2.2 Prestressing Strands

The team used 270 ksi low relaxation seven wire 0.6 in strands in the design. The material properties for the prestressing strand were adopted from the PCI Design handbook [2], Figure 3 gives the material stress-strain curve that has been used.

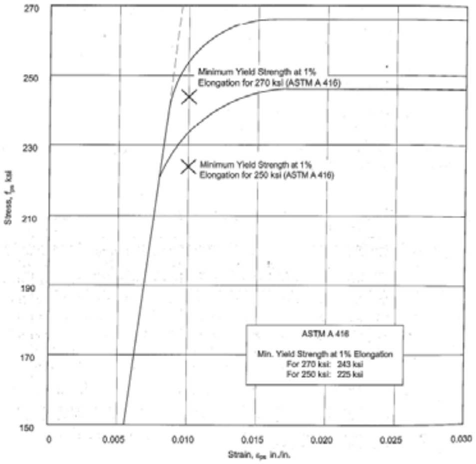
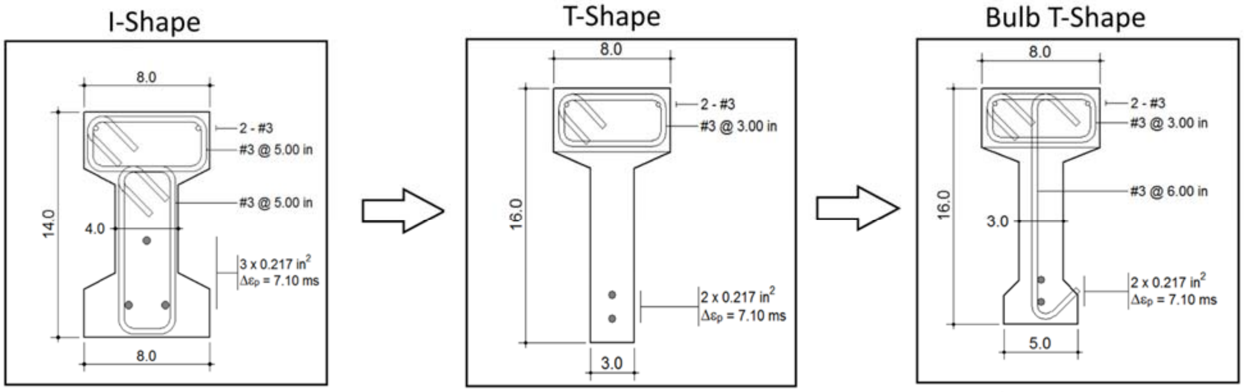


Figure 3: Stress-strain behavior of prestressing strands

3. Beam Design

The design was based on the Big Beam competition requirements. There were two main requirements. 1) The beam needed to behave linearly under a point load at midspan up to a value of 18.75 kips. 2) The ultimate capacity of the beam needed to be in range of 30 to 37 kips. It was also intended to design the beam with an efficient cross sectional area i.e. achieve a high load to weight ratio and allow for the beam to deflect sufficiently at ultimate load.

To full fill the aforementioned requirements and criteria, several cross section choices were examined (Refer Figure 4). The design was started by examining an I-shape (Refer Figure 4a), which places the maximum amount of mass farthest away from the centroidal axis. This is an efficient way of achieving high load carrying capacity with minimal amount of mass. While this is a largely accurate principle it is not true for concrete. This is due to the disparity in concrete behavior for tensile and compressive loads. The design team realized that the bottom flange has negligible effect on the ultimate load carrying capacity of the beam. It was thus decided to eliminate the bottom flange and adopt a T shaped cross section (Figure 4b). The T shaped section thus chosen was adequate to carry the required loads, but failed to be within the permissible stress levels at prestress release. At prestress release the bottom portion of the beam is under axial compression and the lack of a bottom flange resulted in a stress level beyond the code specified limits. To address this behavior a bottom flange which is considerably smaller than the top flange was added. The area of this newly added bottom flange was just adequate enough to keep the release stresses within permissible limits. Thus resulting in a Bulb Tee shape as shown in Figure 4c.



a) Preliminary design
A = 86 sq.in

b) Low weight design
A = 70 sq.in
Release stresses exceed permissible limits

c) Optimized shape
A = 75 sq.in

Figure 4: Evolution of design

For the purposes of this competition a spread sheet was developed. This spread sheet enabled us to investigate the mechanical properties of the concerned sections. It also allowed us to compute the cracking moment and ultimate capacity of these sections. An iterative design was performed by considering different number of strands with varying configurations.

The final cross section chosen includes two 0.6 in diameter strands located at the bottom of the section with a constant eccentricity along the whole beam length. There are also two #3 rebar located at the top flange of the section to provide a support for the stirrups. The effect of these two rebar, was also included in the calculation of the moment-curvature ($M - \Phi$) relationship of the section. A copy of the calculations are provided in the appendix.

Further, to improve the ductility of the section a confinement effect was introduced by providing closely spaced stirrups around the mid-span of the beam. Confinement of concrete improves the compression strength and the ultimate failure strain. While many different models exist for the confined concrete stress-strain relationship, Mander's model [3] was adopted for this competition. The calculation showed that the confined compressive strength improved from 8000 ksi to 12000 ksi. The strain at peak stress condition was 0.007 and at first hoop fracture (failure) was 0.012. These results were used to further extend the moment-curvature relationship beyond the traditional 0.003 strain failure condition for concrete.

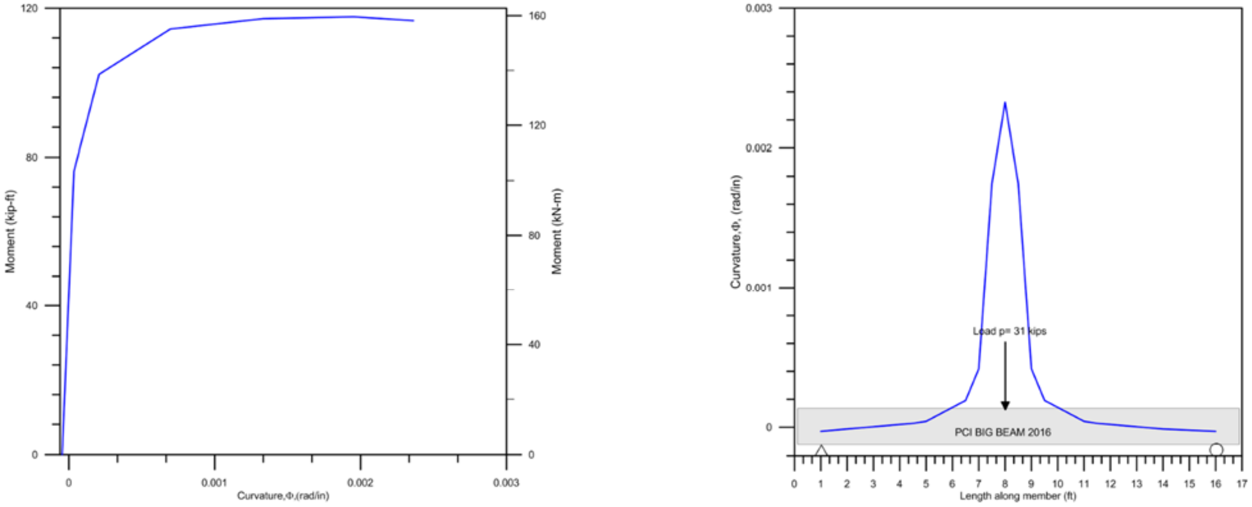
4. Beam Analysis

To predict the behavior of the designed beam under a concentrated load located at the midspan two different analysis approaches were used: 1) The spreadsheet made by the team members together with a code written in MATLAB and 2) Response-2000 software which was used to validate the results calculated based on the spreadsheet and written code.

Spreadsheet and MATLAB code

To understand the behavior of the designed beam under a static concentrated load, and to predict the possible failure load a spreadsheet was developed in Microsoft Excel. This spreadsheet is capable of performing a moment-curvature analysis for the given beam section. To model the compressive behavior of the concrete more accurately, the spreadsheet uses the Mander's model [3] stress-strain relationship instead of using the equivalent rectangular compressive stress block.

For the deflection calculations the moment diagram along the beam length under the concentrated load applied at the midspan is calculated. Consequently, the curvature distribution diagram is generated by using the moment-curvature relationship obtained from the spreadsheet. Based on this data the MATLAB code calculates the deflection using the moment area method. The Moment curvature response and curvature distribution from this analysis are shown in Figure 5



a) Moment curvature response from excel

b) Curvature distribution from excel

Figure 5: Beam response from analysis

Response-2000

Response-2000 is a free and user friendly software which calculates the strength of a reinforced concrete cross section based on the modified compression field theory. The team used this software to check the behavior of the designed cross section and to compare the results with those obtained based on the written spreadsheet and MATLAB code. Figure 6 illustrates the moment-curvature plot determined by Response-2000.

Summary

The results tabulated in Table 2 are in good agreement with each other. For the deflection calculations it was chosen to go with the values calculated by the spreadsheet and MATLAB code as it considers the confinement effect of the shear stirrups.

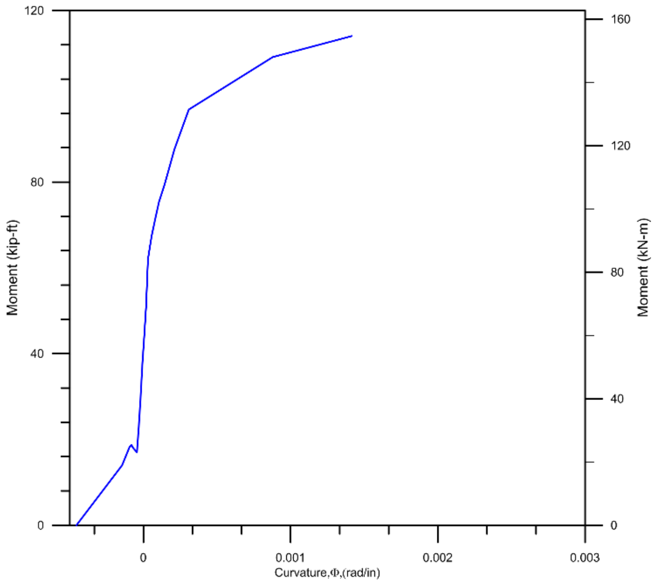


Figure 6: Moment Curvature from Response-2000

Table 2: Summary of predicted values

Procedure	Cracking Load (kips)	Peak Load (kips)	Max. Disp. (in)
Moment-Curvature	20.3	31.4	2.4
Response-2000	19.1	32.8	1.1
Final Prediction	**20.3**	**31.4**	**2.4**

5. Beam Fabrication

After completion of the design, a detailed drawing was sent to Gate Precast Concrete plant, Monroeville, AL. On the day of casting the beam, May 10, 2016, the team members checked the dimensions of mold, size and location of tendons, rebars and stirrups before pouring concrete into the mold to ensure that the design requirements are met. After that, concrete strain gauges were placed at top and bottom at mid-span of the beam to measure the concrete strains during testing. The concrete was mixed and poured into the mold with an overhanging crane supported hopper. The self-consolidating concrete required no external vibration for compaction except beating the mold lightly with hammer. After casting, the top surface of the beam was leveled by trowel. Along with the beam, twenty-five 4"x8" cylinders and three 6"x6"x18" rectangular beams were cast from the same batch to observe the compressive and tensile strength of concrete at different ages.

The strength gain of concrete was monitored by testing cylinders at the Gate Precast plant from the time of casting till they shifted the beam to UA. The beam was allowed to harden without any disturbance until the concrete gained the specified compressive strength of 5500 psi. At the age of 3 days, on May 13, 2016 the concrete compressive strength reached 5500 psi and then the beam was de-molded and the tendons were cut. After that the beam was left to cure in open air until it was shifted to UA campus on May 17, 2016. The beam, cylinders and prisms were placed in Large Scale Structures Lab to cure in air until the beam was tested on June 14, 2016.

The following figure shows some of the work carried out by students at the precast yard.

a) Formwork before casting

b) Students inspecting the formwork prepration

c) Students installing the concrete strain guages

d) Finished Beam

6. Beam Testing

6.1 Test Setup

The competition required the application of a point load at mid-span. The test setup (see Figure 7) consisted of a reaction frame supporting a load jack connected to a 100 kip load cell. The load was transferred onto the beam using 4 in. wide steel plates at mid-span. The deflection of the beam was measured at quarter points using string potentiometers (see Figure 7). At the time of casting two concrete strain gauges were embedded inside the beam at midspan. These strain gauges enabled the monitoring of concrete strains during loading. Further to this an NDI Optotrak system was also used to provide redundancy in the measurement of strains and displacement.

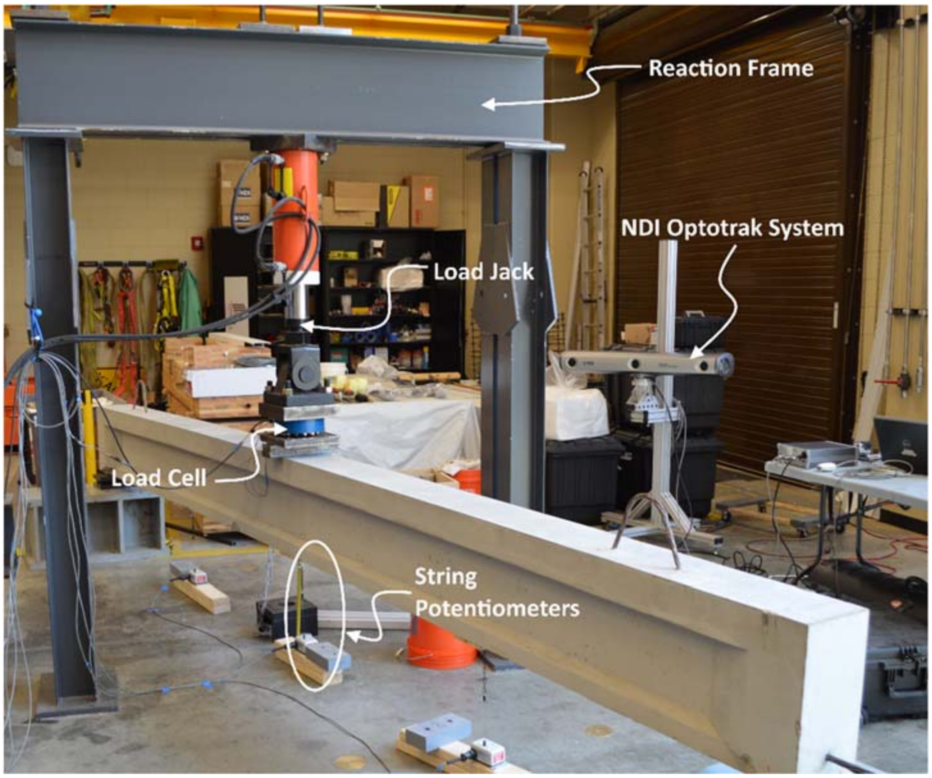


Figure 7: Test Setup

6.1 Test Results

A hand pump connected to the hydraulic jack was used to load the beam till failure. The loading rate was maintained at around 1-2 kips / minute. The beam was periodically examined for cracks. The first flexure cracks were observed at18 kips (see Figure 8a). As the load was increased to 25 kips these cracks became inclined shear cracks and propagated further up to the bottom of the top flange. This is typical of a flexure shear crack behavior.

At around the 27 kip mark an inclined shear crack developed at about 4 feet from the support point. There was no further increase in the load carrying capacity of the beam. This shear crack became horizontal as it reached the top flange (see Figure 8b). Figure 9 shows the load displacement response of the beam. The bend over point can be observed to be at 17 kips. A possible reason for the shear failure of the beam could be due to the material irregularities in the slender web section. The design calculations performed indicated sufficient shear capacity to resist the applied loading.

The deflection values at failure was 2.4 in. While this value is close to the predicted value, it should be noted that it includes the shear deflection contributed due to the unexpected shear failure. Following the Euler-Bernoulli beam equations the shear deformation values are not typically included as part of the deflection calculations.

a) Flexure shear cracks

b) Shear cracks observed at ultimate load

Figure 8: Cracking in the beam

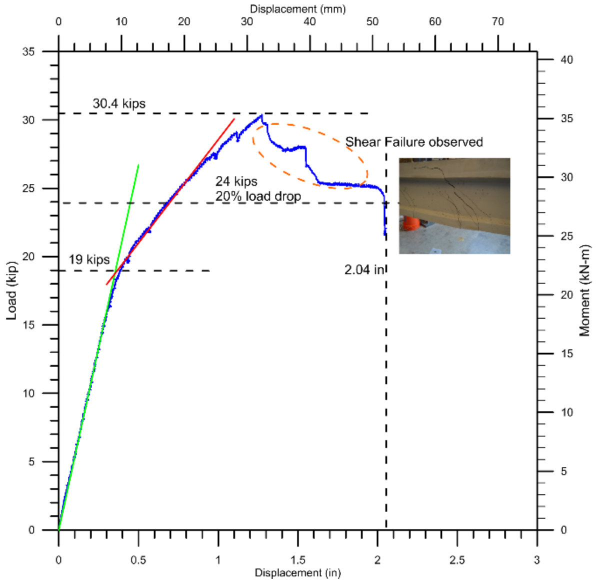


Figure 9: Load-Displacement response from testing

7. Conclusions

The performance of the beam was satisfactory. The values of ultimate load were off by around 1.4 kips. The shear failure of the beam limited the cross section in reaching its intended design load. The slender web thickness coupled with material irregularities may have caused the premature failure of the beam.

It has to be noted that the confinement effect calculations for the displacement predication proved to be more accurate than the values generated by Response-2000 software. Proving the robustness of our design.

8. Acknowledgements

The team would like to thank PCI for providing such a wonderful opportunity to design fabricate and test a prestressed beam. We are grateful to Gate precast Monroeville, Alabama for their help and support. We also would like to thank our faculty advisor Dr. Sriram Aaleti for his invaluable guidance.

9. References

[1] ASTM International, *ASTM C39 / C39M-15a, Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens,* West Conshohocken, PA: www.astm.org.

[2] Precast/Prestressed Concrete Institute (PCI), PCI Design Hand Book, 7th Edition (2010).

[3] J. B. Mander, M. J. N. Priestly and R. Park, "Theoretical Stress-Strain Model for Confined Concrete," *Journal of Structural Engineering,* pp. 1804-1825, 1988.

[4] ACI-318, Building Code Requirements for Structural Concrete, American Concrete Institute, 2011.

Lessons learned from the contest

A big part of designing and constructing the beam involved interacting with members from the Gate Precast facility. These interactions enabled us to get a real world perspective, on how things are handled. For example, in a classroom we might work on any given prestressed concrete problem without due consideration to the feasibility of the concrete compressive strength or the section sizes. Following a similar trend, we as students figured out that the best cost efficiency within the contest rules would be achieved at very high compressive strengths. This led us to initially designing a section which required a compressive strength of 15000 psi. Upon approaching Gate precast with this initial design we realized that it would not be practical to implement such a high strength and not so common place mix design. Further it would also cause considerable disruption to the daily activities of the precast facility. The student team with this experience realized that any good engineering design should also take due consideration of the feasibility in implementing the proposed scheme.

The visit to the precast yard for the casting of the beam was a very good learning experience in itself. We as students being from a structural engineering back ground never truly realize the intricacies of the architectural side of things. During our plant tour we were able to witness the amount of work and intricate detailing that goes on behind the building of beautiful and often stunning facades of buildings.

In performing the design engineering for this competition we learned that, as a structural designer one must be able to merge the concepts learned from the classroom with new techniques that we will be learning on the job. For example, we were able to combine the moment curvature analysis techniques that we learned in the classroom with the more sophisticated confinement effect calculations that enhance the compressive strength and failure strain of concrete. It should also be noted that this was an improvement over the design performed by the student team from UA last year.

During the test setup, team members learned how to install a load-cell and various sensors such as string potentiometers and NDI Optotrack. Correct installation and using right configuration is necessary to perform a successful test.

In summary, taking part in the Big Beam competition provided us an invaluable opportunity to utilize the knowledge obtained from the classroom in the real world. It made us realize that as a designer we can never work on a project without considering the limitations and capabilities of the company that is responsible for construction. The entire exercise also proved to be a very good team building experience.

Appendix A
Design Calculations

Material

Concrete			Strands			Compressive Steel					
f'c	8500	psi	#	2		#	2		n	6.741999	
f'ci	5500	psi	A	0.217	in2	A	0.11	in2			
rho	150	pcf	fpu	270	ksi	E	29000	ksi			
l	17	ft	E	28500	ksi	Fy	60	ksi			
fcr	0.56	ksi	Cover from	1.5	in	d	1.0625	in			
Ec	5255.14	ksi									
Eci	4227.233										

Section properties

Ag	78.9	in2	b	8
Ig	2064.2	in4	a	4
yt	6.9	in	web thickn	3
yb	9.1	in		
St	300.9	in3	dp	13
Sb	225.8	in3		
yb_strand	3	in		
wg	82.1875	plf		

Prestressing Steel

Aps	0.434	in2
e	6.1	in
fsi	202.5	ksi
Fi	87.885	kips

	start	midspan	end	
Mg	0	2.969023438	0	kip-ft
F0	79.0965			kips
fcir	2.428312	2.323025447	2.428312006	ksi
ES	16.37168	15.66183437	16.37167621	ksi
fse	186.1283	186.8381656	186.1283238	ksi
F	80.77969	81.08776388	80.77969253	kips
Mcr	852.023	854.7879733	852.0230419	kip-in
	71.00192	71.2323311	71.00192016	kip-ft

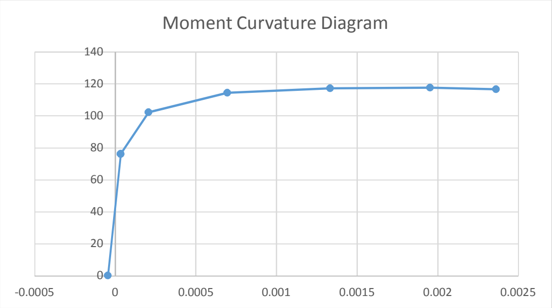
M app = 0

stress t	-0.62331	-0.625688983	-0.623311844	kips
stress b	3.196133	3.208322138	3.196132972	
strain t	-0.00012	-0.000119062	-0.00011861	
strain b	0.000608	0.000610511	0.000608192	
phi	-4.5E-05	-4.55983E-05	-4.54251E-05	rad/in
strain ce	0.00054	0.000542114	0.000540054	

zero concrete strain @centroid of steel

str se	0.006531	0.006555725	0.006530818	
str ps	0.007071	0.007097839	0.007070872	
fps	201.5199	202.2884062	201.5198653	
F	87.45962	87.79316829	87.45962153	
stress t	-0.67486	-0.67742919	-0.674855478	
stress b	3.460431	3.473628472	3.460431346	
stress c	2.685065	2.69530516	2.685065067	
M0	908.6084	912.0735922	908.6084115	kip-in
stress t	2.362349	2.371358615	2.36234927	

stress b	-0.54516	-0.547236603	-0.545157524
stress c	0	0	0
strain t	0.00045	0.000451246	0.000449531
strain b	-0.0001	-0.000104134	-0.000103738
phi0	3.46E-05	3.47112E-05	3.45793E-05
delta f b	0.014842	0.012763397	0.014842476
delta m	3.366796	2.895187164	3.366795549
Mcr	911.9752	914.9687793	911.9752071
	75.99793	76.24739828	75.99793392
stress t	2.373603	2.381036355	2.373603455
stress b	-0.56	-0.56	-0.56
strain t	0.000452	0.000453087	0.000451673
strain b	-0.00011	-0.000106562	-0.000106562
phi crack	3.49E-05	3.49781E-05	3.48897E-05

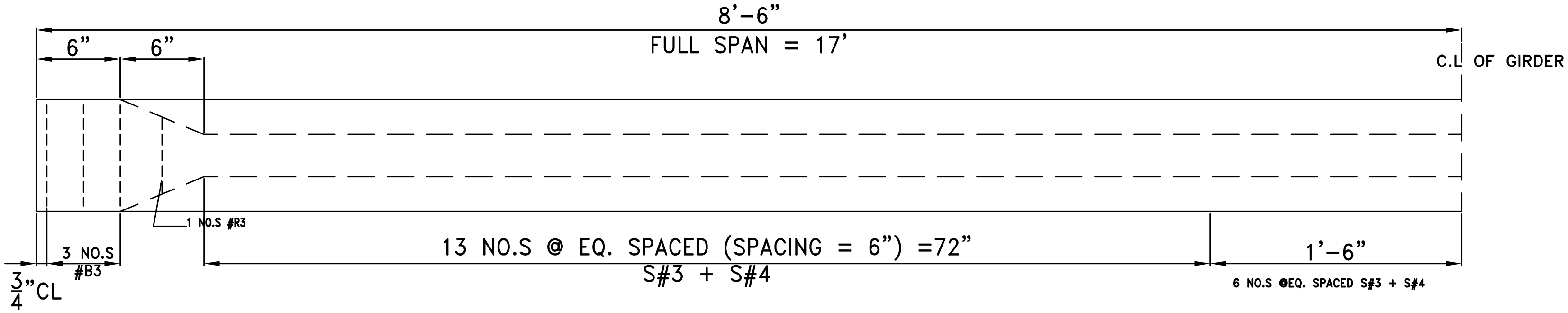


factor	0.5
strain c	0.000809
strain 0	0.002761

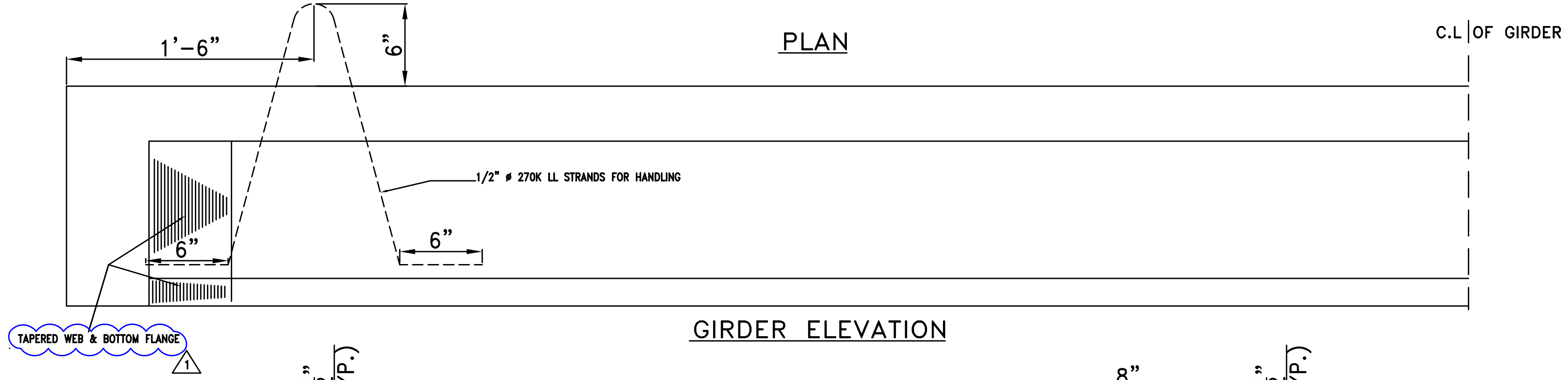
strain =0.001		strain =0.002		strain =0.003	
strain	0.005	strain	0.002	strain	0.003
c	2.116512782	c	2.97002	c	2.579137
phi	0.002362376	phi	0.000673	phi	0.001163
Cc1	103.3074715	Cc1	110.9664	Cc1	121.5398
Cc2	0	Cc2	0	Cc2	0
strain stl	0.002489975	strain stl	0.001285	strain stl	0.001764
Ct	13.2	Ct	8.053919	Ct	11.06104
strain s	0.025710894	strain s	0.006754	strain s	0.012121
strain ps	0.032808733	strain ps	0.013852	strain ps	0.019219
fps	268.450137	fps	264.1623	fps	266.7265
T	116.5073595	T	114.6464	T	115.7593
T-C	-0.000112025	T-C	-4.373916	T-C	-5.780538
y1	1.142433332	y1	1.901236	y1	1.597388
y2	-1.310506113	y2	-0.693285	y2	-0.966937
M	1399.942444	M	1323.964	M	1460.696
	116.6618704		110.3304		121.7247

Appendix B
Detail Drawings

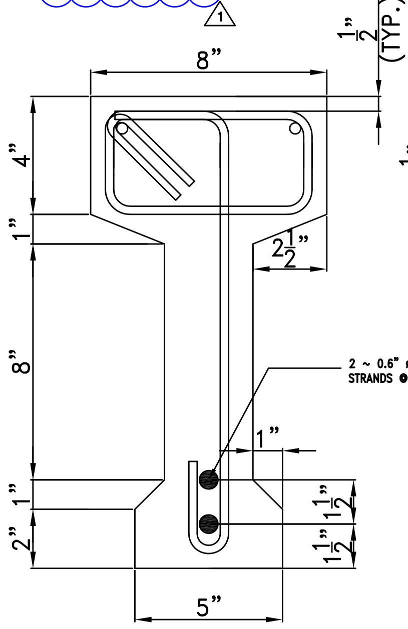
DWG.NO.— SHT_OF_ REV. NO. 0



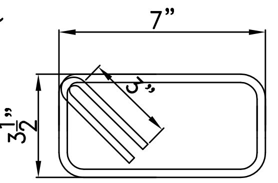
PLAN



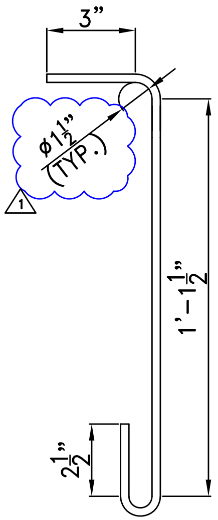
GIRDER ELEVATION



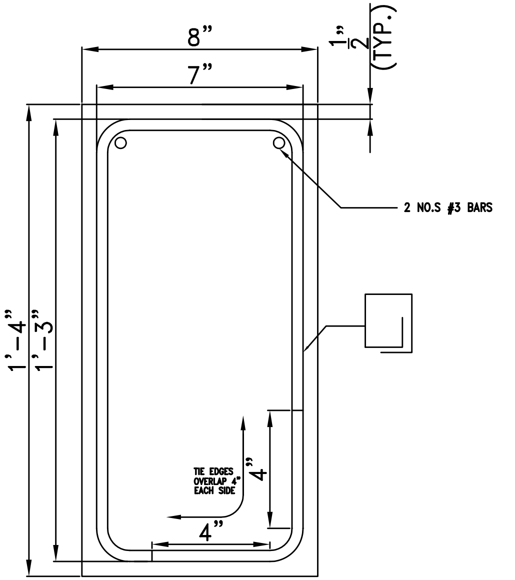
SECTIONAL DETAILS



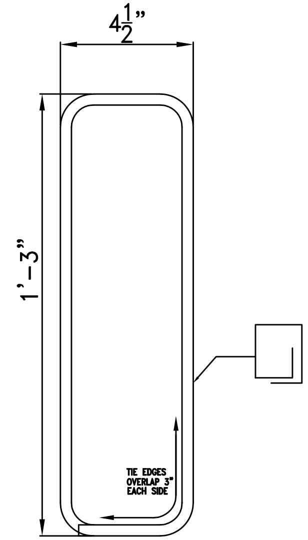
STIRRUP DETAILS (S#3)
#3 BARS



STIRRUP DETAILS (S#4)
#3 BARS



SECTIONAL DETAILS (#B3)
END ZONE #3 BARS



STIRRUP DETAILS (#R3)

LEGEND:–

TYP.	TYPICAL
No.s	NUMBERS
EQ.	EQUALLY
CL	CENTER LINE

PCI-BIG BEAM-2016

UNIVERSITY OF ALABAMA | JOB NO.

LSSL-DEPARTMENT OF CIVIL, CONSTRUCTION & ENVIRONMENTAL ENGINEERING

DRAWN : VIDYA SAGAR	CHECKED :	SCALE	N.T.S
REVIEWED : –		DATE	–
APPROVED : –		JOB NO.	–
DWG. NO. –		SHT_OF_	REV. NO. 1

Appendix C- Cost Calculations

Concrete:

Volume of concrete = 15259.2 in^3 = 0.33 yd^3
Per unit cost of concrete = 100$/$yd^3$ [actual strength =7.5 ksi <10 ksi]
Total cost of concrete = **33$**

Prestressing Strand:

Length of strands = 34ft.
Per unit cost of strands = 0.42$/ft. [0.6in strands]
Total cost of strands = **14$**

Reinforcing Steel:

Stirrup type S#3
Length of stirrup = 21 in.
No of stirrups = 38
Total Length of stirrups = 66.6 ft.

Stirrup type S#4
Length of stirrup = 19 in.
No of stirrups = 38
Total Length of stirrups = 60.2 ft.

Stirrup type B#3
Length of stirrup = 42 in.
No of stirrups = 6
Total Length of stirrups = 21 ft.

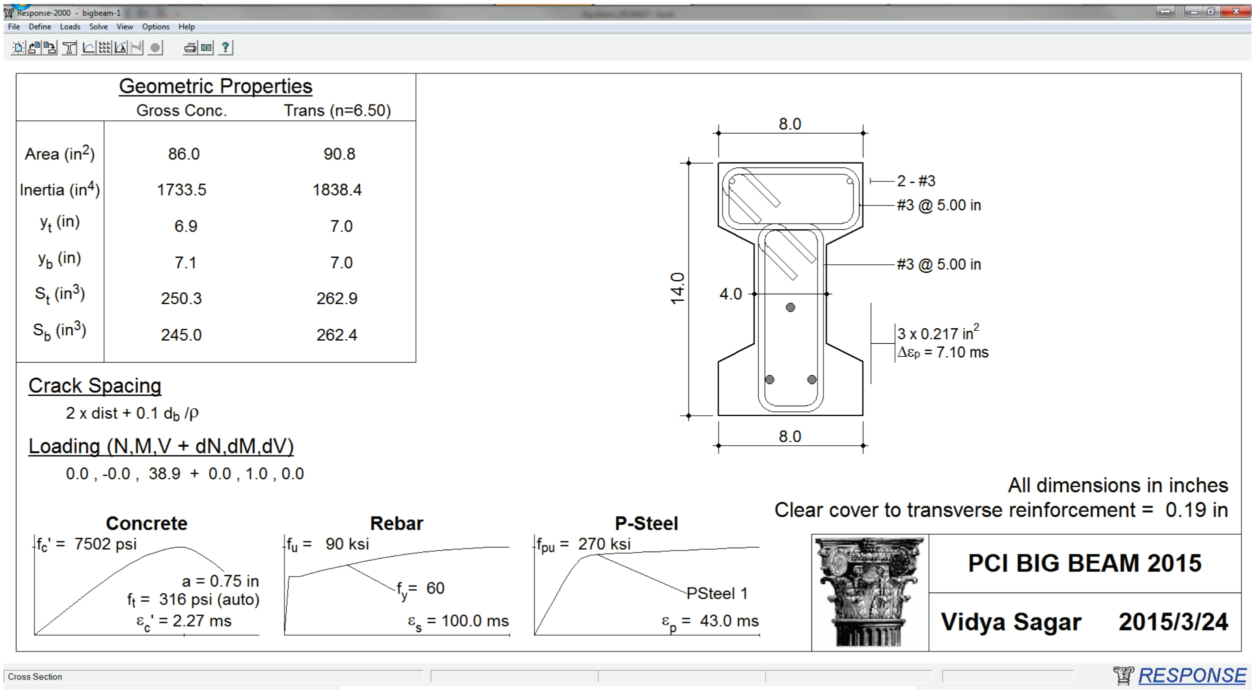
Total Length of #3 stirrups = 147.8 ft.
Unit weight of #3 Bars = 0.376 lb/ft [from PCI hand book[2]]
Total weight = 55.6 lbs.
Per unit cost of Steel = 0.45$/lb.
Total cost of steel = **25 $**

Formwork:

Surface area of formwork = 58 ft^2
Per unit cost of formwork = 1.25$/$ft^2$
Total cost of formwork = **70$**

TOTAL COST = 33$ + 14$ +25$ +70$
= 142$

Appendix –D: Response-2000 Analysis



Geometric Properties

	Gross Conc.	Trans (n=6.50)
Area (in^2)	86.0	90.8
Inertia (in^4)	1733.5	1838.4
y_t (in)	6.9	7.0
y_b (in)	7.1	7.0
S_t (in^3)	250.3	262.9
S_b (in^3)	245.0	262.4

Crack Spacing

2 x dist + 0.1 d_b /ρ

Loading (N,M,V + dN,dM,dV)

0.0 , -0.0 , 38.9 + 0.0 , 1.0 , 0.0

Concrete

f_c' = 7502 psi
a = 0.75 in
f_t = 316 psi (auto)
ε_c' = 2.27 ms

Rebar

f_u = 90 ksi
f_y = 60
ε_s = 100.0 ms

P-Steel

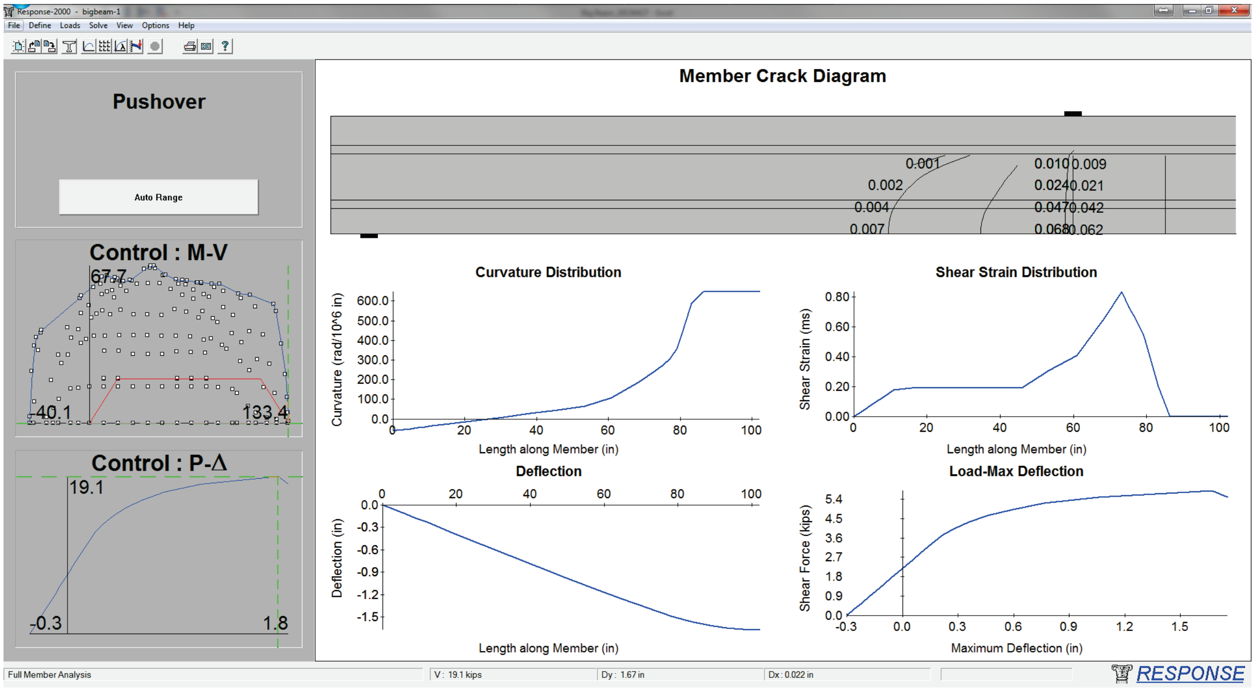
f_{pu} = 270 ksi
PSteel 1
ε_p = 43.0 ms

All dimensions in inches
Clear cover to transverse reinforcement = 0.19 in

PCI BIG BEAM 2015

Vidya Sagar 2015/3/24

Response-2000 Inputs



Response-2000 Analysis Results

PCI BIG BEAM COMPETITION 2016

13th June, 2016
Date

The University of Alabama
Student Team (school name)

#1
Team Number

10th May, 2016
Date of Casting

Basic information

1. Age of beam at testing (days) 34 days

2. Compressive cylinder tests*
Number tested: 3
Size of cylinders: 4" x 8"
Average: 8436 psi

3. Unit weight of concrete (pcf) 142
Slump (in.): 25" Spread (SCC mix)
Air content (%): 6.2%
Tensile strength (psi): 544
Circle one:
Split cylinder [✓ MOR beam]

4. Pretest Calculations
a. Applied point load at midspan to cause cracking (kip) 20.3
b. Maximum applied point load at midspan (kip) 31.4
c. Maximum anticipated deflection due to applied load only (in.)
2.4"

Pretest calculations MUST be completed before testing.

*International entries may substitute the appropriate compressive strength test for their country.

Test summary forms must be included with the final report, due June 17, 2016

Judging Criteria

Teams MUST fill in these values.

a. Actual maximum applied load (kip) 30
b. Measured cracking load (kip)‡ 19
c. Cost (dollars) 142
d. Weight (lb) 1328
e. Largest measured deflection (in.) 2.1
f. Most accurate calculations

(a) Absolute value of (maximum applied load – calculated applied load) / calculated applied load
0.046

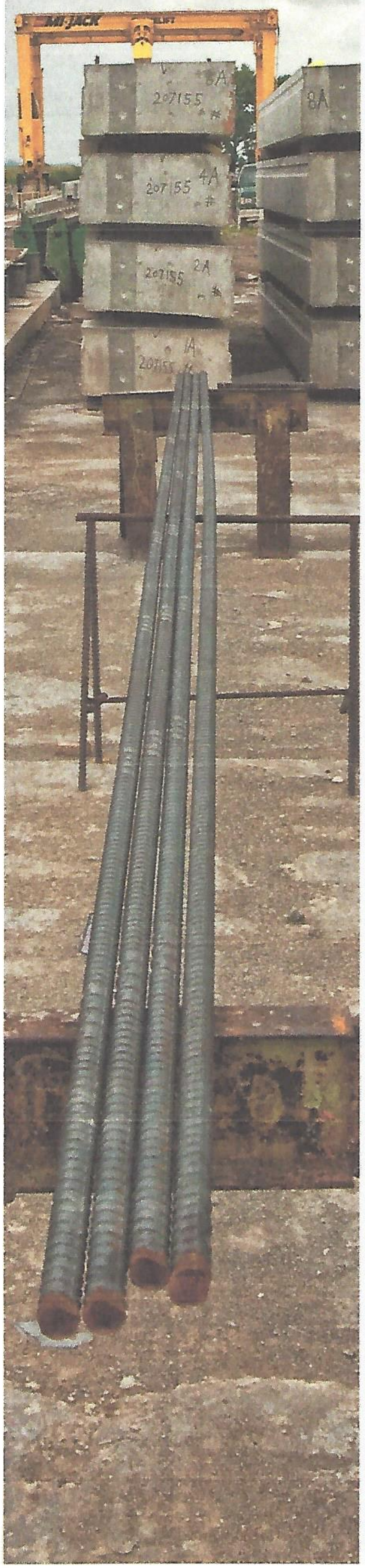
(b) Absolute value of (maximum measured deflection – calculated deflection) / calculated deflection
0.125

(c) Absolute value of (measured cracking load – calculated cracking load) / calculated cracking load
0.045

Total of three absolute values (a + b + c) = 0.216

‡Measured cracking load is found from the "bend-over" point in the load/deflection curve. Provide load/deflection curve in report.

PCI BIG BEAM COMPETITION 2016



CERTIFICATION

Gate Precast, Monroeville Alabama
As a representative of (name of Producer Member or sponsoring organization)

The University of Alabama
Sponsoring (name of school and team number)

I certify that:

- The big 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 B. Carter
Signature

Harris B. Carter
Name (please print)

6-13-16
Date

THIS CERTIFICATION MUST BE PART OF THE FINAL REPORT

Sponsored by **BUILDING TRUST**