Letter of Transmittal

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May 9, 2017
NAU PCI Big Beam Team
Northern Arizona University Department of Civil Engineering, Construction Mangement, and Environmental Engineering
Flagstaff, Arizona 86001

To Tpac,

Attached, you will find our team's final design report for the PCI Big Beam Competition. This report includes the project description, concrete mixture design, structural design, final design, final predictions, beam testing and analysis, project cost and project schedule. This project was completed within the 2016-2017 school year at Northern Arizona University.

If you have any questions or comments about this proposal, do not hesitate to contact us at raw256@nau.edu.

Sincerely,
Qusai Al Ghalbi
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Kacy Aoki
Rick Wilson

PCI BIG BEAM COMPETITION 2017
NORTHERN ARIZONA UNIVERSITY

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Sponsoring PCI Member:
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Acknowledgments
The team would like to thank Dr. Tuchscherer for his advice and support throughout this project, and Vince Rossi our contact at TPAC, for his time working with us, his advice for the final beam design, fabricating our beam, and providing mix materials. Finally we would like to thank Arizona Materials, CalPortland (Oro Grande Plant), and Fritz-Pac for the Type II and III cement, fly ash, and silica fume used to test our mix designs.

1.0 Project Description

1.1 Purpose of Project

The main purpose of the PCI Big Beam project is to design a concrete mix and design a prestressed concrete beam according to the rules provided by the PCI Student Education Committee. The length of the beam should be 18 feet center to center of bearing and no longer than 20 feet long. It must also be designed to be loaded for dead load and two applied service live loads and can not crack under the service live load of 20 kips. The judging criteria is based on seven different categories, the design accuracy, which the beam must also hold at least 32 kips but no more than 39 kips, the lowest cost, the lowest weight, the largest measured deflection, the prediction accuracy, the report quality, and the use of the ACI 318 code [1]. The second purpose of this project is to allow students to use the information that has been learned through the team's engineering education. For this competition, the team's knowledge of concrete design will help to design different mixes and cross-section designs to determine the most optimal beam.

1.2 Project Background

The PCI Big Beam Contest started in 2005. Since then, PCI Student Education Committee has invited students to participate in the engineering student design competition each year. Every year the PCI Student Education Committee changes the rules from the year before. This year our team will follow the rules for 2016-2017, which has changed a little bit from the previous year. Each year, the NAU PCI teams are sponsored by TPAC Kiewit Western Company who fabricates the beam for the teams and ships it up to NAU to be tested. Our beam will be tested in the NAU Engineering building (Figure 1.2.1) using "The Hulk" machine.

Figure 1.2.1 Engineering building [2]

2.0 Concrete Mixture Design

2.1 Preliminary Concrete Mixture Selection

Our team evaluated many different mixture designs with many different mixture possibilities, we created four mixtures based on Tpac's lightweight (LW) and normal weight (NW) mixtures and resulting in a total of six different mixtures. Table 2.1.1 shows the material variables for each of the mixes.

Table 2.1.1: Mix Design Materials*

Mix	Cement	Course Aggregate	Pozzolan**
TPAC - LW	Type II	½" Expanded Shale	Fly Ash
Mix #1	Type III	Cinders	Fly Ash
Mix #2	Type III	½" Expanded Shale	50% FA, 50% SF
TPAC - SCC	Type II	½" No. 7 River Rock	Fly Ash
Mix #3	Type III	Quartz	Fly Ash
Mix #4	Type III	½" No. 7 Rock	50% FA, 50% SF

*All mixtures contained "Maricopa" sand and water-reducing, air-entraining, retardant, and rheological admixtures

**FA = Fly Ash, SF = Silica Fume

For each mixture, we decided to change the cement type to Type III because its high early strength and allows for higher release stresses. Mixes #1 and #2 were adjusted based on Tpac's lightweight mix and Mixes #3 and #4 were adjusted based on Tpac's normal weight mix. For Mix #1 cinders were substituted for shale. For Mix #3 quartz was substituted for river rocks. The team decided to use cinders to experiment with the lightness of the material and to use materials local to Flagstaff, Arizona. For Mix #3, the team decided to use quartz to provide more compressive strength to the concrete. For Mixes #2 and #4, silica fume was substituted for half of the fly ash to provide more compressive strength as well. After designing each mix, a total of 118 cylinders were fabricated for testing.

2.2 Concrete Testing

After curing was completed, three different tests were done on each 4x8-in cylinders. The first test was the compression test according to ASTM C39[3]. A total of ten samples of Mixes, #1 through #4 were tested. Compression tests were not done for TPACs two mixes because sufficient data were available. The second test was the split cylinder test according to ASTM C496[4]. Since no tensile data was provided from TPAC, a total of 60 cylinders were tested (10 for each mix). Finally, the third test was the Modulus of Elasticity test according to ASTM C469[5]. No stress-strain data was provided from TPAC for their mixes as well, so a total of 18 cylinders were tested (3 for each mix). Figures 2.2.1 through 2.2.4 show the test set up for each test and Figure 6 shows the split cylinder testing results.

Figure 2.2.1 ASTM C39 Compression

Figure 2.2.2 ASTM C469 Modulus of Elasticity

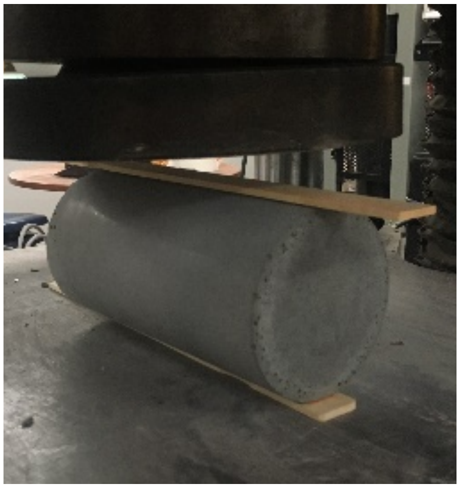


Figure 2.2.3 ASTM C496 Split Cylinder

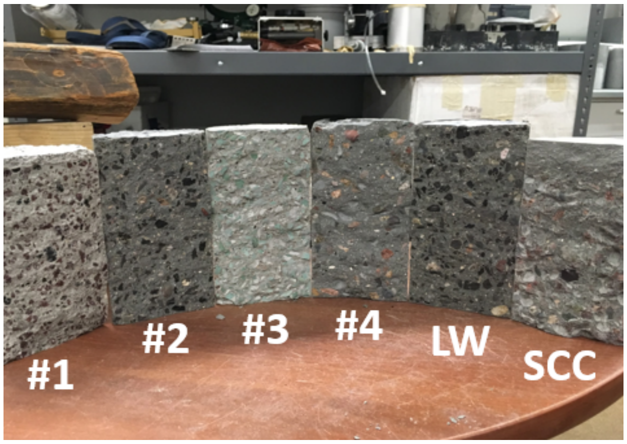


Figure 2.2.4 Split Cylinder Testing Results

2.3 Final Concrete Mixture Selection

The average test results were normalized and scored as shown in Table 2.3.1. Mixtures were compared based on the average values because there was a small difference in the standard deviations. In bold are the highest compressive and tensile strength for a high cracking and the highest peak strain and lowest Modulus of Elasticity for a high deflection. These values were used to maximize the amount of points our beam could receive by determining a mixture that would create the greatest deflection, meet the 20 kip cracking load minimum, and increase the overall strength of the beam. By increasing the overall strength of the beam with the mixture, it would allow us to create a smaller cross-section and therefore cheaper and lighter beam. From these results, we determined that substituting silica fume for half of the fly ash and using quartz as a course aggregate the total deflection will be decreased but the cracking load will increase.

Table 2.3.1: Test Results and Scoring

	Compression (PSI)	Score	Modulus of Elasticity (KSI)	Score	Peak Strain (in/in)	Score	Tension (PSI) ASTM C496	Score	Total Score
N =	10 or 30*		3		3		10		
Mix #1	5260	0.59	9730	0.36	0.00122	0.46	327	0.58	1.99
Mix #2	8410	0.87	5070	0.68	0.00235	0.89	482	0.86	3.30
Mix #3	8570	0.96	4660	0.74	0.00220	0.83	498	0.89	3.42
Mix #4	**8900**	1.00	4860	0.71	0.00202	0.76	**560**	1.00	3.48
LW	7610*	0.85	**3460**	1.00	**0.00265**	1.00	497	0.89	**3.74**
SCC	8360*	0.93	4630	0.75	0.00186	0.70	511	0.91	3.29

Finally, to determine the best mixture for our beam, we scored each mixture. To score each mixture, average test result was divided by the most optimal mixture result and the scores were summed. The team then decided that the mixture with the highest score would be the mixture for our beam. Based on the results of this analysis, the chosen mixture was Tpac's lightweight mixture.

2.4 Final Mixture Design

The mixture selected for our beam was Tpac's lightweight concrete mix. Table 2.4.1 shows the proportion details of the mixture. Table 2.4.2 lists the testing results of the six 4x8-in cylinders. In comparison to the team's test results when determining the most optimal mix and the final mix, the compression strength was greater, the tensile strength was lower, the Modulus of Elasticity and peak strain were greater.

Table 2.4.1: Mix Proportions

Material	Weight
Type II Arizona Portland Cement	730 lbs
Class F Fly Ash	185 lbs
WCS Maricopa	1328 lbs
½" Expanded Shale	867 lbs
Water	308 lbs
Estimated Air	1.00%
Admixtures*	

*Mix contained HRWR, rheology-modifying, and retardant admixtures

Table 2.4.2: Testing Results

32-day, N=3	
Compressive	8352 psi
Tensile	607 psi
Peak Strain	0.00290 in/in
Modulus of Elasticity	5210 ksi
Unit Weight	126.6 lb/ft^3
Spread	27"

3.0 Structural Design

3.1 MathCAD Analysis

In order to aid in the design of the beam, a MathCAD analytical worksheet was created. The worksheet calculates stresses at release, cracking capacity, and ultimate capacity for variable cross-sectional dimensions and reinforcement configurations. The model uses ACI 318-14 standard in order to determine what analysis to perform in accordance with the requirements of ACI 318-14. This was done for the three day loads and stresses as well as 28 day loads. Calculations included release stresses at 3 days using ACI 318-14[24.5.3.1], the cracking moment due to live load using ACI 318-14[22.5.8.3.1], and finally the nominal capacity of the beam derived from the nominal moment.

The MathCAD worksheet was also used to analyze the shear capacity and the required shear strength per requirements of ACI 318-14[22.5], and proportioned shear reinforcement accordingly. The shear envelope was graphed in MathCAD showing the shear capacity of the beam and the applied shear load.. In order to make sure that the beam did not fail in shear the team used W4xW4 (4"x4") WWF to provide shear reinforcement. The WWF was bent around the top compression steel in order to brace the #4 compression steel (Figure 4.1). The WWF mesh was used through the entire length of the beam. The reinforcement was not cut or reduced to ensure that the compression steel would not buckle in the middle, or any part of the beam. Once reinforcement was designed using the worksheet, the shear capacity fell within the design envelope; thus, we know that shear was not something that needed to be worried about in the design process. All calculation are found in **Appendix A.**

3.2 Initial Design Process

When designing the beam, the dimensions, compression steel, and the number of strands were changed in order to optimize the design. The process of finding the optimal beam consisted of, first, assessing three designs; 1) highest deflection, 2) lowest cost, 3) lowest weight. All designs met the requirements for cracking and ultimate capacity. As expected, the lowest cost and lowest weight designs would were very similar.

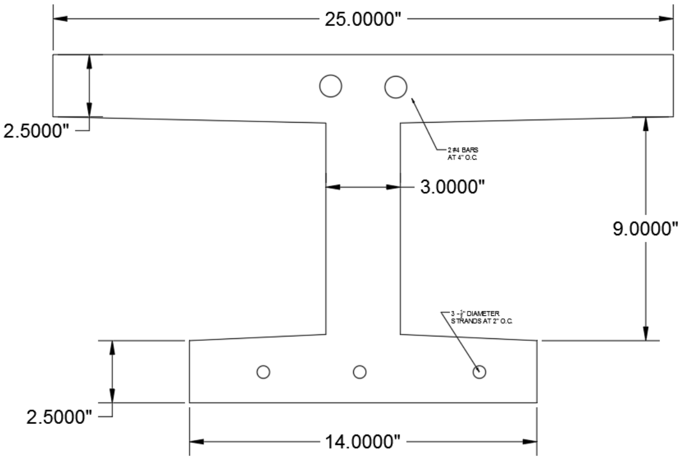


Figure 3.2.1 Highest Deflection

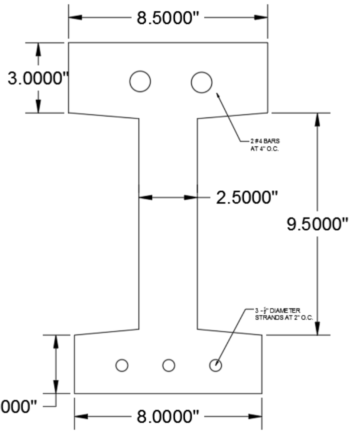


Figure 3.2.2 Lowest Cost

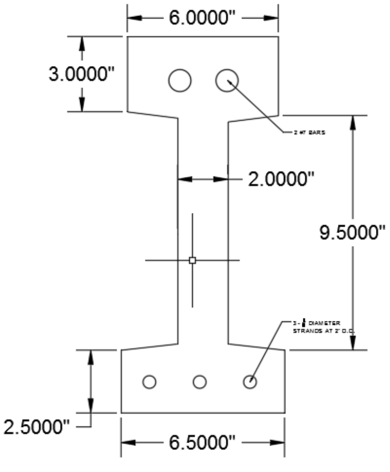


Figure 3.2.3 Lowest Weight

After the three designs, above, were created, the team also assessed intermediate designs that met the requirements, to see if a more optimal design could be created. Shown in **Appendix B**, the team selected the different designs that were analyzed using a normalized scoring technique and the design that scored the highest would be the design chosen. The final design, shown in Figure 4.1 and detailed in **Appendix C,** meets the strength, serviceability, and detailing requirements of ACI 318-14.

Materials used in the beam consisted of: prestressing strands, compression steel, and Welded Wire Fabric. The prestressing strand sizes used by our fabricator TPac were ASTM A416 grade 270, 0.5" diameter strands. During fabrication, the strands were pulled to 31kips and sat in the poured beam three days after fabrication before they were cut, allowing the concrete to cure enough so it would not crack. Strand information can be seen in **Appendix D.** Two pieces of #4 ASTM 615 grad 60 rebar was used. This amount of rebar was able to give us the correct compression steel area needed, and the team found that they were the optimal size to reduce weight and cost. ASTM 1064 W4xW4, 4"x4" grade 65 WWF was used as shear reinforcement throughout the entire beam. A detail of the design can been

4.0 Final Design

The final design that was chosen is shown in Figure 4.1 and 4.2 and the bill of materials is shown in Table 4.1.

Table 4.1: Bill of Materials

MATERIAL	QUANTITY	UNIT	COMMENTS/CRITERIA
1/2" DIAMETER STRAND	60	LF	ASTM A416 (270 KSI)
#4 BAR	40	LF	ASTM A615 (60 KSI)
W4XW4 – 4.0X4.0 WWF	72.2	SF	ASTM A1064 (65 KSI)
LW-5 CONCRETE	0.356	CY	f'_{ci}= 5000 PSI f'_{c} (28 DAY) = 8000 PSI
4X8 CYLINDERS	6	EA	ASTM C31

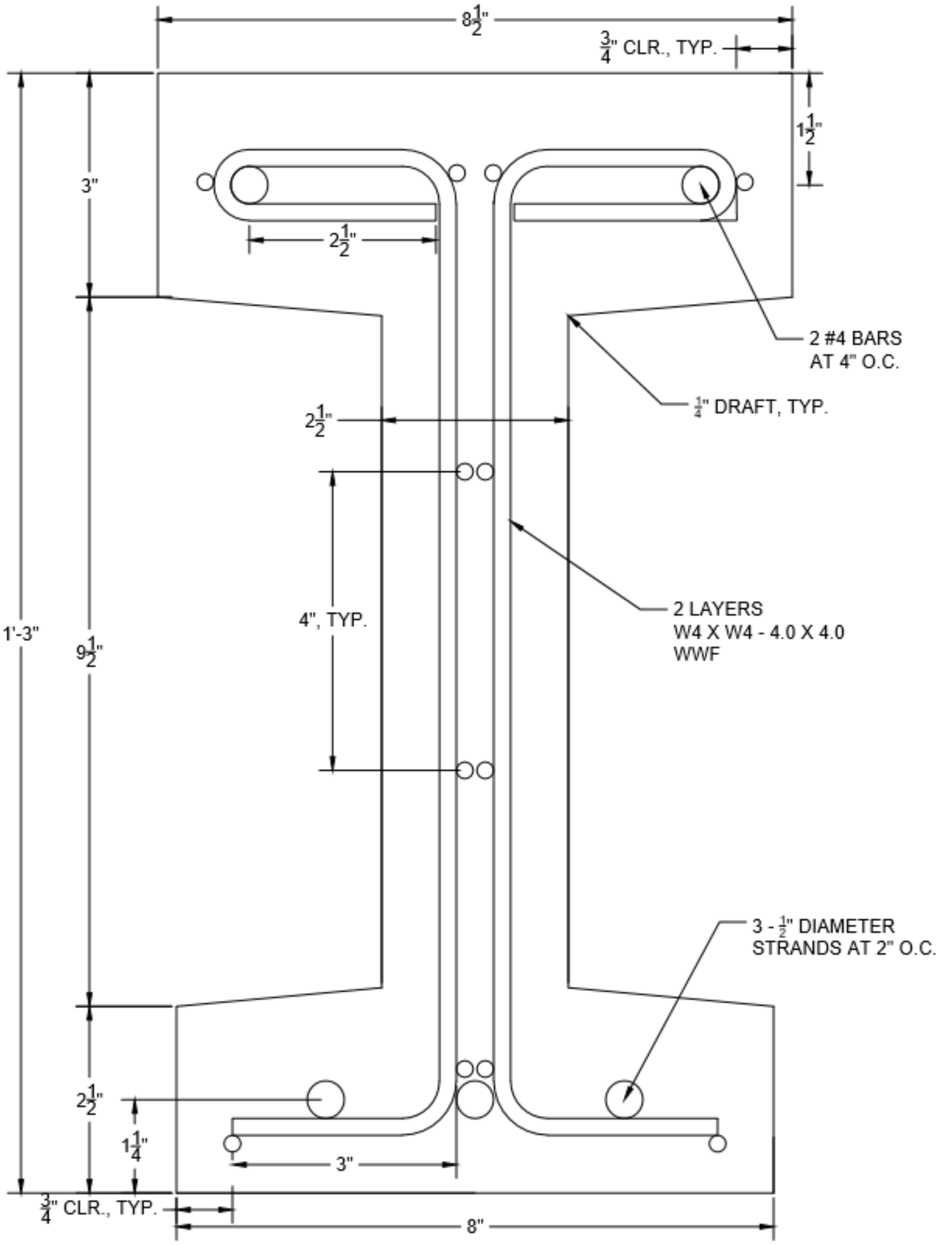


Figure 4.1 Beam Cross-Section

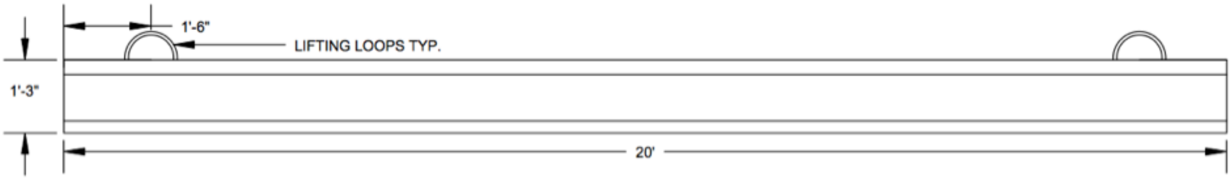


Figure 4.2 Beam Elevation

The top flange is 8 ½” x 3”, the bottom flange is 8” x 2 ½”, and the web is 2 ½” x 9 ½”. This final beam is the best optimization of lowest cost, lowest weight, and highest deflection. Based on competition scoring the final beam came out better than all of the other designs using TPACs lightweight concrete. This beam has two #4 compression steel pieces in the top flange and three ½” diameter prestressing strands in the bottom flange. The beam also has W4xW4 WWF mesh in it to replace the stirrups and lightest weight. According to the team’s MathCAD model, the beam will hold 33.0 kips and crack at 25.2 kips.

5.0 Beam Fabrication

5.1 Fabrication

After finalizing the mixture design and beam design, shop drawings were created and submitted to Tpac. Tpac is our sponsor for the contest and is located in Phoenix, Arizona. The shop drawings included a bill of materials and a cross-section and elevation view of the beam with the rebar, mesh and prestressing strands (refer to Figure 4.1). Tpac built a custom form for our beam based on the approved design using plywood and other lumber. After building the form, a thin steel mesh was provided for shear reinforcement to hold the compression steel in place (refer to Figure 4.1). Finally, before placing concrete, the prestressing strands on the bottom of the beam were pulled with an initial force of 31 kips before losses (Figure 5.1.1). The formwork, mesh, and rebar can be seen in Figure 5.1.2.

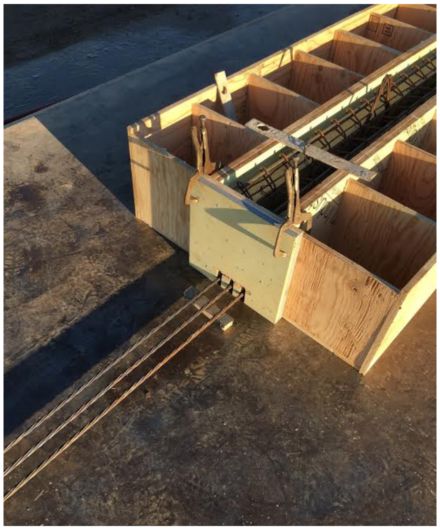


Figure 5.1.1 Prestressing Strands

Figure 5.1.2 Formwork

5.2 Site Visit and Inspection

Tpac scheduled the fabrication date for March 16th, 2017. On that day the team traveled to the facility in order to ensure the formwork and beam details met our design criteria. During our visit, we verified the dimensions of the formwork, the diameter and number of strands, and the size and placement of compression reinforcement and shear reinforcement. Figure 5.2.1 shows the lightweight concrete mix being placed into the formwork and Figure 5.2.2 shows our beam two weeks after its cutting date. The strands were released after three days.

Figure 5.2.1 Pour Day

Figure 5.2.2 Beam at Two Weeks

6.0 Final Predictions

To predict the behavior of the final designed beam the team chose to use a program called Response 2000. Response numerically integrates the strain compatibility of concrete, reinforcement, and prestressing strands, and considers the full stress-strain behavior of these materials. This allowed the team to find a more accurate final prediction of breaking loads and deflections. To use the program the preliminary dimensions per MathCAD, as well as the steel and concrete information were input into the program and then refined in Response. Along with that prestrain, or loss, calculations were done using Excel, refer to **Appendix E**, and placed into the program. The prestrain calculated took into account all of the losses that could occur after the beam is poured. These include losses due to shrinkage, bed and anchoring, reinforcements, and compression steel. The prestrain was determined to be 5.76 in. **Appendix F** shows the different information put into Response 2000 and **Appendix G** shows the output.

Before the test proceeded, the team tested six cylinders, made up of the same concrete as the beam, to determine the properties of the concrete used in the beam. These values, seen in **Appendix F**, were then inputted into Response. Using the moment-curvature graph created by Response, figure 6, the cracking moment came out to be 77.1 kip-ft and ultimate moment was determined to be 34.8 kip-ft. These moments were then used to determine the cracking load and ultimate load. To determine the predicted deflection, a numerical integration was used to use the virtual work method of analysis; this method was done in Excel and is shown in **Appendix H**.

Using virtual work the initial deflection found was then doubled to account for the entire length of the beam.

Based on the results of our analysis we predict the cracking load, ultimate load, and maximum deflection as listed in Table 6.1.

Table 6.1: Final Predictions

Final Predictions	
Cracking Load	20.0 kips
Ultimate Load	34.8 kips
Maximum Deflection	3.45 inches

7.0 Beam Testing and Analysis

7.1 Testing Frame

The beam was tested April 17, 2017 at Northern Arizona University using a steel testing frame (“The Hulk”). Figure 7.1.1 shows the “The Hulk”.

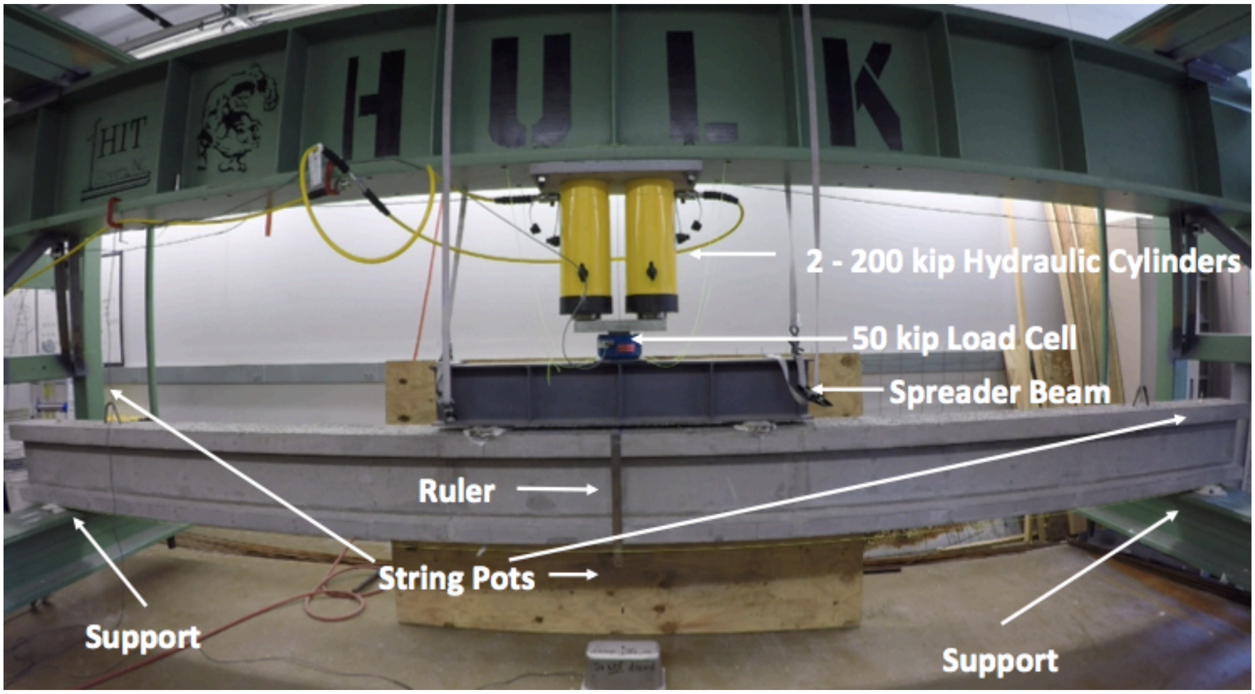


Figure 7.1.1 "The Hulk" Test Setup

“The Hulk” was set up before testing. Supports were positioned 18 feet from center to center. Load plates were placed 1.5 feet from the centerline in each direction for the two point loads. A spreader beam was used to distribute the load. Two hydraulic cylinders applied the load. A 50-

kip load cell was placed at the load location. The team placed a string potentiometer over each support and at the beam's centerline to collect the displacement of the supports, and the deflection of the beam. A ruler was glued to the middle of the beam and a mason string stretched from support to support to provide visual indication of deflection.   Load and deflection data was collected via a National Instruments SCXI Data Acquisition system and respective modules.

7.2 Results

The beam was tested by applying a single point load from two-200 kip hydraulics cylinders and was loaded monotonically with a rate between 100-200 pounds per second. As the load was applied, LabView was used to collect, display, and record the data at a rate of 5 Hz. Shown Figure 7.2.1 are the three locations of the string potentiometers where deflection was measured. To determine the beam deflection, the average deflection of the left and right potentiometers had to be subtracted from the deflection in the center as showing in equation below.

$$\Delta Beam = \Delta \text{℄} - \left(\frac{\Delta R - \Delta L}{2}\right)$$

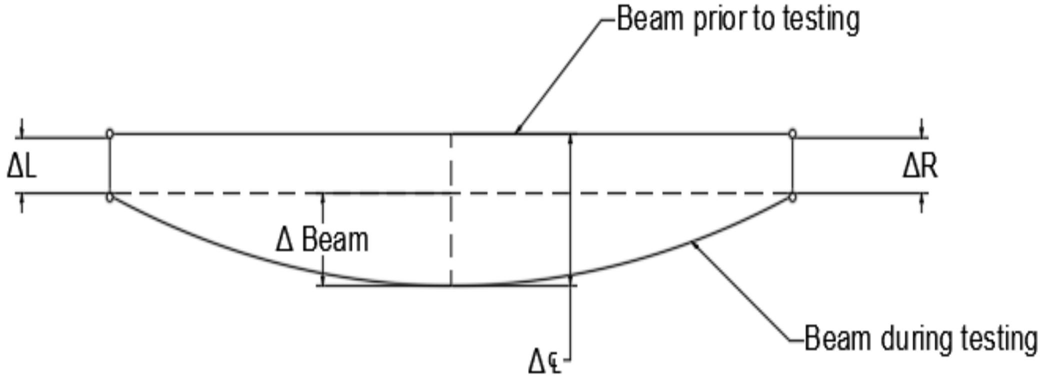


Figure 7.2.1 Determination of Beam Deflection

The Load vs Deflection data is shown in Figure 7.2.2.

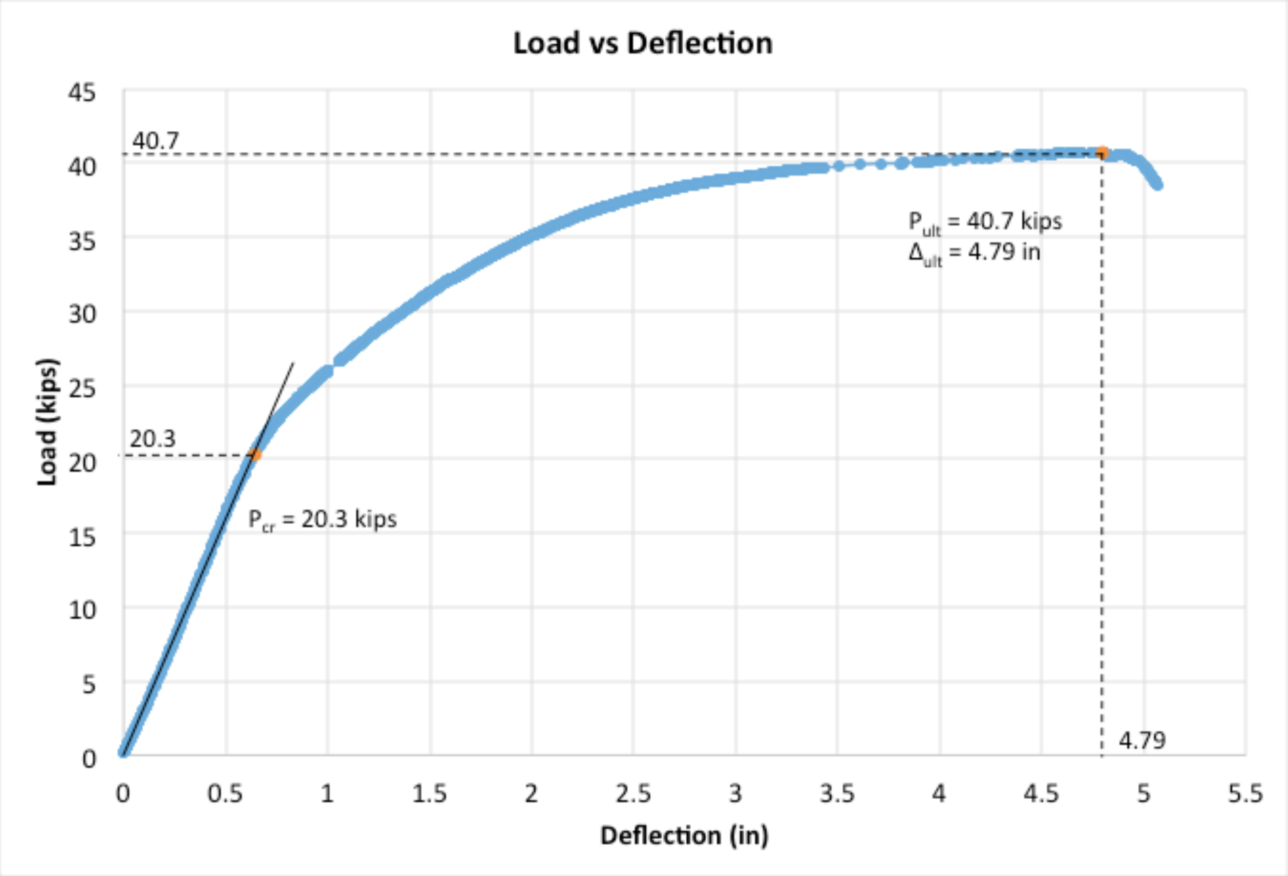


Figure 7.2.2 Load vs Deflection Graph

From the data the team documented, the cracking load, ultimate load, and maximum deflection of the beam. Predicted and actual results and the percent difference between them are shown in Table 7.2.1.

Table 7.2.1: Predicted Verse Actual Results

	Predicted	**Actual**	**%Difference**
Cracking Load	20.0 kips	20.3 kips	+2%
Ultimate Load	34.8 kips	40.7 kips	+17%
Maximum Deflection	3.45 inches	4.79 inches	+39%

7.3 Failure

Prior to failure, flexural cracked formed on the bottom flange and propagated towards the top flange. These cracks indicate the yielding of prestressing strands. As the concrete on the top of the beam began crushing the load-deflection curve started to descend. This can be seen in Figure 7.3.1.

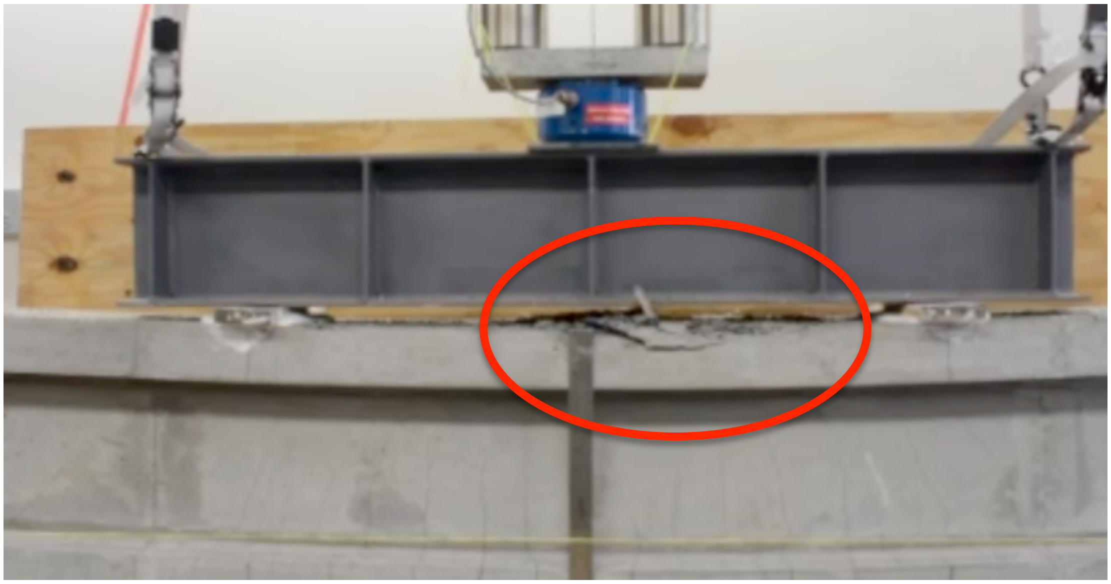


Figure 7.3.1 Initial Crushing of Beam

As this is happening the maximum compression strain is moving down the cross-section, increasing the strain in the compression steel. Finally, a secondary failure occurs when the compression steel at the top buckled, Figure 7.3.2. The secondary failure causes a loss of equilibrium and the test was stopped. The moment-curvature graph shoots quickly downwards and forces on the beam drop to zero.

After observing the failure, and the video, the beam failed a tension-controlled manner as predicted by the team. Load-deflection data and results can be seen in Figure 7.2.2.

Figure 7.3.2 Condition of Beam After Failure

7.4 Differences in Results

Our team believes that there are two main reasons why we had differences between our predicted results and our actual results. The first reason is due to the spacing of the mesh within the beam. Not knowing the exact spacing between each mesh, the team decided to enter the mesh as 4 inches apart in Response 2000. From the Response 2000 calculations the final predictions were then calculated. However, if we spaced the mesh closer together and added more mesh into Response 2000, we would have had a different moment-curvature graph with a higher ultimate moment. By including more mesh in the beam, there is more support for the compression steel and protects the steel from buckling, which therefore increases the flexural strength. With a higher ultimate moment, the ultimate load would have been greater and the maximum deflection would have had also been greater because the determined ultimate load was used in the virtual work calculations. The second reason is due to the different concrete properties entered into Response 2000. The concrete values entered caused a lower flexural strength of the beam and in turn decreased the ultimate moment. To determine the compressive and tensile strength and peak strain to be entered into the program, only three cylinders were tested for each property and the average values were used. According to the ASTM standards a minimum of 30 cylinders should be tested, but since we only had three each to test it was hard to determine whether the data collected was the most accurate. In reality, the "correct" value could have been the lowest, average, or highest values collected, but our team decided to use the average values to be conservative.

8.0 Project Costs

The projects costs are shown below in Table 9.1. Our predicted cost were slightly higher than our actual cost by about $1,500. The main differences between our predicted cost and our actual cost were the increase of hours for the Engineer and the Administrative Assistant and only traveling to Tpac twice instead of three times.

Table 8.1: Project Costs

	Classification	Hours (hr)	Rate/ Hour ($)	Cost ($)	Hours (hr)	Rate/ Hour ($)	Cost ($)
1.0 Personnel	SENG	138	140	$19,320	83	140	$11,620
	ENG	279	88	$24,552	328	88	$28,864
	LAB	320	61	$19,520	320	61	$19,520
	AA	79	28	$2,212	160	28	$4,480
	Total			$45,039			64,484
2.0 Travel	Tpac meetings @ 290 miles/meeting	$0.44/mile (3 Meetings)		$383	$0.44/mile (2 Meetings)		$255
3.0 Lab	Lab cost for equipment and facilities	50	100	$5,000	47	100	$4,700
4.0 Subcontract	Beam fabrication			$5,000			$5,000
5.0 Total				$75,987			$74,439
		Predicted			Actual		

9.0 Project Schedule

The project schedule is shown below in Table 10.1. The dates highlighted in red are the tasks that fell behind schedule and the task highlighted in green are the tasks that were ahead of schedule. The changes in the schedule were due to the stress-strain cylinder tests in the laboratory, Tpac's schedule, and the concrete mixture. The reason the stress-strain cylinder tests changed our schedule is because four magnets needed to be glued onto the cylinders for 24 hours before testing and the team also had some technical difficulties with the machines in the laboratory. Our schedule also changed due to the schedule of our sponsor Tpac. While working with a company it is hard to predict what their schedule will be, but working with Tpac our schedule was both pushed forward and a little back but overall everything finished in a timely manner. The last reason our schedule changed was due to our concrete mix. Our team wanted to make sure that the mixture reached 8000 psi before testing and to do so we waited until 32 days to test our beam instead of 28 days which pushed our final testing four days behind schedule.

Table 9.1: Project Schedule

Task Name	Scheduled Finish	Actual Finish
Task 1: Mix Design	**Sun 1/22/17**	**Mon 1/30/17**
1.1 Design Mix Experimental	Thu 10/20/16	
1.2 Mix Design	Thu 11/3/16	
1.3 Collect Materials	Fri 12/9/16	
1.4 Cylinder Creation	Sun 12/11/16	Sat 12/9/6
1.5 Curing Time	Tue 1/17/17	
1.6 Cylinder Testing	Sun 1/22/17	Mon 1/30/17
Task 2: Beam Cross-Section Design	**Fri 12/9/16**	**Wed 1/15/17**
2.1 Creating a MathCAD model	Fri 11/25/16	
2.2 Cross-Section Designs	Fri 12/9/16	Wed 2/22/17
Task 3: Final Design	Tue 2/28/17	Fri 2/24/17
Task 4: Beam Fabrication	**Thu 4/13/17**	**Fri 4/14/17**
4.1 Submit Shop Drawings	Thu 3/9/17	Fri 2/24/17
4.2 Beam Fabrication	Mon 3/13/17	Fri 3/17/17
4.3 Curing Time	Mon 4/13/17	Fri 4/14/17
Task 5: Beam Testing	**Fri 4/14/17**	**Mon 4/17/17**
5.1 Test Setup	Wed 4/12/17	Fri 4/14/17
5.2 Final Predictions	Thu 4/13/17	Mon 4/17/17
5.3 Beam Test	Fri 4/14/17	Mon 4/17/17
Task 6: Beam Analysis	Tue 4/25/17	Wed 4/19/17
Task 7: Project Management	**Thu 5/11/17**	**Tues 5/9/17**
7.1 Communications	Fri 5/5/17	
Team Meetings	**Fri 5/5/17**	
7.1.2 Client Meetings	**Fri 3/10/17**	**Thu 3/16/17**
7.1.2.1 TPAC Tour	Fri 9/2/16	
7.1.2.2 Beam Fabrication Day	Fri 3/17/17	Thu 3/16/17
7.2 Deliverables	Thu 5/11/17	
7.2.1 50% Design Report	Tue 3/14/17	Thu 3/2/17
7.2.2 Final Draft of report	Mon 5/1/17	
7.2.3 Website	Mon 4/24/17	Tue 5/9/17
7.2.4 Final Presentation	Fri 5/5/17	Fri 4/28/17
7.2.5 Final Report	Thu 5/11/17	Tue 5/9/17

10.0 References

[1]Official Rules for the PCI Engineering Design Competition Academic Year 2016-17. [Online]. Available: https://www.pci.org/uploadedFiles/Siteroot/Education/_Related_Content/EDU16-3271_Big%20Beam%20Brochure_Web.pdf. [Accessed: 02- Mar- 2017].

[2]"Engineering Building - Facility Services - Northern Arizona University", *Nau.edu*, 2016. [Online]. Available: http://nau.edu/facility-services/planning/building-green/engineering-building/. [Accessed: 18- Sep- 2016].

[3] ASTM C39/C39M-17. Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens, ASTM International, West Conshohocken, PA, 2017. www.astm.org.

[4] ASTM C469/C469M-14, Standard Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression, ASTM International, West Conshohocken, PA, 2014, www.astm.org.

[5] ASTM C496/C496M-11, Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens, ASTM International, West Conshohocken, PA, 2004, www.astm.org.

11.0 Appendix

11.1 Appendix A: MathCAD Model

Given Material Properties and Dimensions

Area of strand $A_p := 3 \cdot .153in^2 = 0.459 \cdot in^2$

Area of comp. steel $As' := 2 \cdot .2in^2 = 0.4 \cdot in^2$

Comp strength concrete @ 3 days $fci' := 5ksi$

Comp strength concrete @ 28 days $fc' := 7.6ksi$

Modulus of Elasticity @ 28 days $Ec28 := 57ksi \cdot \sqrt{\frac{fc'}{psi}} = 4969 \cdot ksi$

Modulus of Elasticity @ 3 days $Ec3 := 57ksi \cdot \sqrt{\frac{fci'}{psi}} = 4031 \cdot ksi$

Modulus of Steel $Es := 29000ksi$

Beam Dimmensions

$i := 1..5$

Width	Height
$b_1 := 8.5in$	$h_1 := 3in$
$b_2 := 2.5in$	$h_2 := 9.5in$
$b_3 := 8in$	$h_3 := 2.5in$

Length of Beam $L := 216in$

Length of development $l_d := 12in$ *assumed*

Total Height $H := h_1 + h_2 + h_3 = 15 \cdot in$

Stress in Strand

Release: $f_p := 174ksi$

Cracking: $f_{pc} := 180ksi$

Ultimate: $f_{pu} := 265ksi$

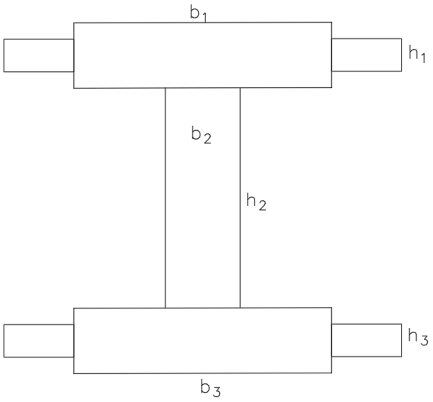
Force on Strand

Release $F_p := f_p \cdot A_p = 79.866kip$

Cracking: $F_{pc} := f_{pc} \cdot A_p = 82.62 \cdot kip$

Ultimate: $F_{pu} := f_{pu} \cdot A_p = 121.635kip$

Stress of compression reinforcement $fy := 60ksi$



Transformed Section Properties at 3 Days

$n3 := \frac{Es}{Ec3} = 7.195$

$A_1 := b_1 \cdot h_1 = 25.5 \cdot in^2$ $\quad I_1 := \frac{b_1 \cdot \left(h_1\right)^3}{12} = 19.125 \cdot in^4$ $\quad y_1 := \frac{h_1}{2} + h_2 + h_3 = 13.5 \cdot in$

$A_2 := b_2 \cdot h_2 = 23.75 \cdot in^2$ $\quad I_2 := \frac{b_2 \cdot \left(h_2\right)^3}{12} = 178.62 \cdot in^4$ $\quad y_2 := \frac{h_2}{2} + h_3 = 7.25 \cdot in$

$A_3 := b_3 \cdot h_3 = 20 \cdot in^2$ $\quad I_3 := \frac{b_3 \cdot \left(h_3\right)^3}{12} = 10.417 \cdot in^4$ $\quad y_3 := \frac{h_3}{2} = 1.25 \cdot in$

$A_4 := (n3 - 1) \cdot A_p$ $\quad I_4 := 0in^4$ $\quad y_4 := \frac{h_3}{2} = 1.25 \cdot in$

$A_5 := (n3 - 1) \cdot As'$ $\quad I_5 := 0in^4$ $\quad y_5 := \frac{h_1}{2} + h_2 + h_3 = 13.5 \cdot in$

$y_{bar} := \frac{\sum_i \left(A_i \cdot y_i\right)}{\left(\sum_i A_i\right)} = 7.757 \cdot in$ $\quad d_i := y_{bar} - y_i$

$Itr3 := \sum_i \left[I_i + A_i \cdot \left(d_i\right)^2\right] = 2104 \cdot in^4$

$Atr3 := \sum_i A_i = 74.572 \cdot in^2$

$e := (H) - y_{bar} + y_3 = 8.493 \cdot in$

uniform SW $\quad \omega_{sw} := 125 \frac{lbf}{ft^3} \cdot Atr3 = 64.732 \cdot plf$

Moment at ld due to SW $\quad M_{sw} := \frac{\omega_{sw} \cdot L}{2} \cdot \left(l_d\right) - \omega_{sw} \cdot l_d \cdot \left(\frac{l_d}{2}\right) = 0.55 \cdot kip \cdot ft$

Release Stress at 3 days

Axial Stress Strand $\sigma_{pa} := \frac{-F_p}{Atr3} = -1.071 \cdot ksi$

Flexural Stress Strand $\sigma_{pf} := \frac{-\left(F_p \cdot e\right) \cdot y_{bar}}{Itr3} = -2.5 \cdot ksi$

Flex Stress DW $\sigma_{sw} := \frac{M_{sw} \cdot y_{bar}}{Itr3} = 0.024 \cdot ksi$

$$f_{bot} := \sigma_{pa} + \sigma_{pf} + \sigma_{sw} = -3.5471 \cdot ksi$$

$$f_{top} := \sigma_{pa} - \sigma_{pf} - \sigma_{sw} = 1.405 \cdot ksi$$

Check: Based on ASTM 24.5.3.1

End of simply supported members

$0.7 \cdot fci' = 3.5 \cdot ksi$

Transformed Section Properties at 28 Days

$$n28 := \frac{Es}{Ec28} = 5.836$$

$A_1 := b_1 \cdot h_1 = 25.5 \cdot in^2$ $I_1 := \frac{b_1 \cdot \left(h_1\right)^3}{12} = 19.125 \cdot in^4$ $y_1 := \frac{h_1}{2} + h_2 + h_3 = 13.5 \cdot in$

$A_2 := b_2 \cdot h_2 = 23.75 \cdot in^2$ $I_2 := \frac{b_2 \cdot \left(h_2\right)^3}{12} = 178.62 \cdot in^4$ $y_2 := \frac{h_2}{2} + h_3 = 7.25 \cdot in$

$A_3 := b_3 \cdot h_3 = 20 \cdot in^2$ $I_3 := \frac{b_3 \cdot \left(h_3\right)^3}{12} = 10.417 \cdot in^4$ $y_3 := \frac{h_3}{2} = 1.25 \cdot in$

$A_4 := (n28 - 1) \cdot A_p$ $I_4 := 0 in^4$ $y_4 := y_3 = 1.25 \cdot in$

$A_5 := (n28 - 1) \cdot As'$ $I_5 := 0 in^4$ $y_5 := H - 1.5in - .25in = 13.25 \cdot in$

$Y_{bar} := \frac{\sum_i \left(A_i \cdot y_i\right)}{\left(\sum_i A_i\right)} = 7.763 \cdot in$ $d_i := y_{bar} - y_i$

$$Itr28 := \sum_{i} \left[I_i + A_i \cdot (d_i)^2 \right] = 2054 \cdot in^4$$

$$Atr28 := \sum_{i} A_i = 73.404 \cdot in^2$$

$$e := (H) - y_{bar} + y_3 = 8.487 \cdot in$$

Uniform SW $\omega_{sw} := 150 \frac{lbf}{ft^3} \cdot Atr28 = 76.463 \cdot plf$

Moment at L/2 due to SW $M_{sw} := \frac{\omega_{sw} \cdot L^2}{8} = 3.097 \cdot kip \cdot ft$

Cracking Load at 28 days

Axial Stress Strand $\sigma_{pa} := \frac{-F_{pc}}{Atr28} = -1.126 \cdot ksi$

Flexural Stress Strand $\sigma_{pf} := \frac{-(F_{pc} \cdot e) \cdot y_{bar}}{Itr28} = -2.65 \cdot ksi$

Flex Stress DW $\sigma_{sw} := \frac{M_{sw} \cdot y_{bar}}{Itr28} = 0.14 \cdot ksi$

Cracking Stress $\sigma_{cr} := 7.5psi \sqrt{\frac{fc'}{psi}} = 0.654 \cdot ksi$

Moment due to Live Load $M_{LL} := 1kip \cdot in$

Given

$$\left(\sigma_{pa} + \sigma_{pf} + \sigma_{sw} + \frac{M_{LL} \cdot y_{bar}}{Itr28} = \sigma_{cr} \right)$$

$$M_{LL} := Minerr(M_{LL})$$

$$Pcr := \frac{2(M_{LL})}{7.5ft} = 25.221 \cdot kip$$

Pcr: Needs to be greater than 20 kip

Ultimate Capacity at 28 days

$d := y_1 = 13.5 \cdot in$

$b_1 = 8.5 \cdot in$

$d' := y_4 = 1.25 \cdot in$

Strain of Concrete $\varepsilon c := 0.003$

$f_{pu} = 265 \cdot ksi$

$fc' = 7.6 \cdot ksi$

$$\beta_1 := \left| \begin{array}{l} 0.85 \ \text{ if } \ fc' \le 4000psi \\ 0.85 - 0.05 \dfrac{(fc' - 4000psi)}{1000psi} \ \text{ if } \ 4000psi < fc' < 8000psi \\ 0.65 \ \text{ if } \ fc' \ge 8000psi \end{array} \right. = 0.67$$

$c := 1in$

Given

$$\left(0.85 \cdot fc' \cdot \beta_1 \cdot c \cdot b_1\right) + \min\left[As' \cdot 0.003 \left(\frac{c - d'}{c}\right) \cdot Es, fy \cdot As'\right] - A_p \cdot f_{pu} = 0$$

$c := \text{Minerr}(c)$

$c = 2.785 \cdot in$

h1 has to be greater than or equal to c

$Cc := \left(0.85 \cdot fc' \cdot \beta_1 \cdot c \cdot b_1\right) = 102.455 \cdot kip$

$$Cs := \left[As' \cdot 0.003 \left[\frac{(c - d')}{c}\right] \cdot Es\right] = 19.18 \cdot kip$$

$T := A_p \cdot f_{pu} = 121.635 \cdot kip$

$$Mn := \left[f_{pu} \cdot A_p \cdot \left[d - \left(\beta_1 \cdot c \cdot 0.5\right)\right] + Cs \cdot \left(\beta_1 \cdot c \cdot 0.5 - d'\right)\right]$$

$Mn = 127 \cdot kip \cdot ft$

$Pu := 39kip$ $\quad$ $Pn := 1kip$

$$Pn := \frac{(Mn - M_{sw}) \cdot 2}{(7.5ft)} = 33.008 \cdot kip$$ between 32 and 39

Shear Capacity at 28 days

$x := 1in, 2in .. 90in$

Properties of Mesh

Spacing: $S := 4in$

W4 X 4 4"X 4" (0.04in^2) $Av := 0.04in^2$

Ultimate Shear: $$Vu(x) := \frac{Pn}{2} + \frac{\omega_{sw} \cdot L}{2} - \omega_{sw} \cdot (x)$$

Beam properties:

Web width: $bw := b_2 = 2.5 \cdot in$

ASTM Mod Factor: [19.2.4.2] $\lambda := 0.75$

Distance from extreme compression fiber to center of prestressing strands: $dp := \max(y_5, 0.8H) = 13.25 \cdot in$

Concrete Shear Capacity:

$$f_{pc}(x) := \frac{F_p}{Atr28}$$

$$f_d(x) := \frac{M_{sw}(x) \cdot y_{bar}}{Itr28}$$

$$f_{pe} := \frac{F_p}{Atr28} + \frac{(F_p \cdot e) \cdot y_{bar}}{Itr28}$$

$$Vd(x) := \frac{\omega_{sw} \cdot L}{2} - \omega_{sw} \cdot (x)$$

$$Vi(x) := Vu(x) - Vd(x)$$

$$M_{sw}(x) := \frac{\omega_{sw} \cdot L}{2}(x) - \frac{\left[\omega_{sw} \cdot (x^2)\right]}{2}$$

$$Mmax(x) := \frac{Pn}{2} \cdot (x)$$

$$Mcre(x) := \left(\frac{Itr28}{y_{bar}}\right)\left(6psi \cdot \lambda \cdot \sqrt{\frac{fc'}{psi}} + f_{pe} - f_d(x)\right)$$

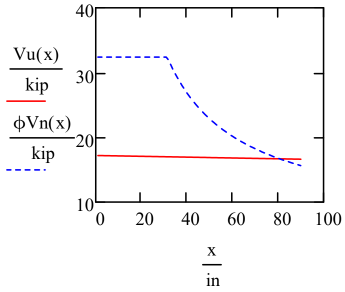
$$Vci(x) := \max\left(0.6psi \cdot \lambda \cdot \sqrt{\frac{fc'}{psi}} \cdot bw \cdot dp + Vd(x) + \frac{Vi(x) \cdot Mcre(x)}{Mmax(x)}, 1.7psi \cdot \lambda \cdot \sqrt{\frac{fc'}{psi}} \cdot bw \cdot d\right)$$

$$Vcw(x) := \left(3.5psi \cdot \lambda \cdot \sqrt{\frac{fc'}{psi}} + 0.3 \cdot f_{pc}(x)\right) \cdot bw \cdot d + Vi(x)$$

$$Vc(x) := \min(Vci(x), Vcw(x))$$

Steel Shear Capacity: $Vs(x) := \frac{Av \cdot fy \cdot dp}{S}$

$$\phi Vn(x) := 0.75(Vc(x) + Vs(x))$$



11.2 Appendix B: Decision Matrix

Design	Cost	Weight	Δ (in)*	Score- Cost	Score- Weight	Score - Δ	*Score*
1	$131.71	1174	13.5	10.0	8.5	8.9	**27.4**
2	$136.88	1454	13	9.0	7.0	9.6	**25.6**
3	$158.80	2111	12.75	4.7	3.3	10.0	**18.0**
4	$157.36	1374	19.5	5.0	7.4	0.0	**12.4**
5	$149.55	967	13.5	6.5	9.6	8.9	**25.0**
6	$158.69	903	13.5	4.7	10.0	8.9	**23.6**
7	$160.81	967	13.5	4.3	9.6	8.9	**22.8**
8	$155.80	1959	13	5.3	4.2	9.6	**19.1**
9	$183.06	2713	13	0.0	0.0	9.6	**9.6**
10	$150.39	992	13.5	6.4	9.5	8.9	**24.8**

*Not predicted deflection, Δ is a relative measure of deflection for comparison purposes only.

11.3 Appendix C: Beam Detail

Geometric Properties	
Beam Height	15 in
Top Flange Height	3 in
Top Flange Width	8.5 in
Web Width	2.5 in
Bottom Flange Height	2.5 in
Bottom Flange Width	8 in
Total Beam Length	20 ft
Prestressing Strands	½ in
Compression Steel	#4 bar
WWF	W4 X W4 - 4.0 X 4.0

Weight Calculations	
Volume	9.62 ft^3
Unit Weight	126.6 lb/ft^3
Total	**1217.65 lbs**

Cost Calculations	
Concrete:	
Volume	0.36 yd^3
Per unit	110 \$/yd^3
Total	$39.18
Prestressing strands:	
Amount	3 strands
Length	20 ft
Per unit	0.3 $/ft
Total	$18.00
Compression Steel:	
Amount	2 bars
Length	20 ft
Weight	0.668 lb/ft
Per unit	0.45 $/lb
Total	$12.02
WWF Mesh:	
Area	72.2 ft^2
Weight	0.85 lb/ft^2
Per unit	0.5 $/lb
Total	$30.69
Formwork:	
Surface area	63.6 ft2
Per unit	1.25 \$/ft^2
Total	$79.50
Total Cost	**$179.39**

11.4 Appendix D: Prestressing Strand Details

```
                              TPAC TENSIONING PROGRAM

                           Date: 3/14/2017  Time: 9:55:52 AM

     Job Number / Name: 30-8090.C  /  BIG BEAM
        Plant Location: Phoenix
                   Bed: 170
           Pump Number: TP20, TP22, TP23
   Default Strand Type: 1/2
Initial Pull in Pounds: 3000
     Number of Strands: 3
            Bed Number: 2
               Remarks: 3 - 1/2" 270K LOLAX

     Bed Data: Length = 2168 inches, Shortening = 0.375 inches.
    Pump Data: Zero load reading = 3.9304574431 pounds, Slope = 0.060737864
  Strand Data: Area = 0.153 inches^2, Modulus of elasticity = 28,700,000
    Pull Data: Default final pull = 31,000 pounds, Maximum pull = 33,000 pounds.
Slippage Data: Live end slippage = 0.5 inch, Dead end slippage = 0.125 inch.
 Splice Chuck: Splice chuck is not being used.

Beginning | Ending     | Elongation | Number of | Strand | Final  |
Strand #  | Strand # | Reduction  | Pieces    | Type   | Pull   |  Bed
    1     |     3    |            |           |  1/2   | 31,000 | 170
```

PHOENIX TENSIONING RECORD

DAY: Wed DATE: 3-15-17 TIME: 840

CAST: INSPECTOR: TENSIONED BY: J-Gonzalez

JOB ID: 30-8090.C / BIG BEAM

BED: 170 BED ID: 2

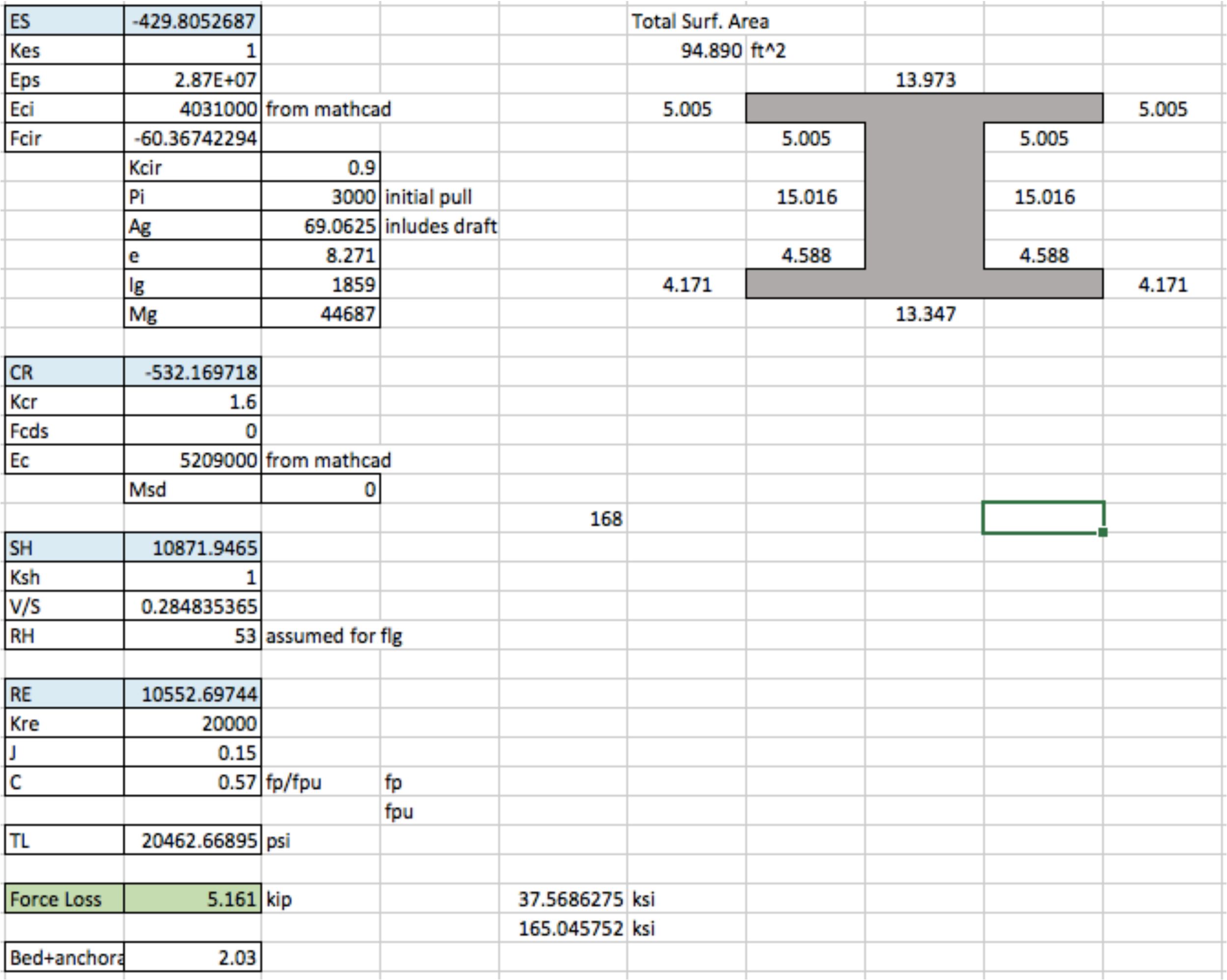
PUMP: TP20, [✓ TP22], TP23 JACK: 23 [✓ 22]

REMARKS: 3 - 1/2" 270K LOLAX

NOTE: ALL STRANDS TO RECEIVE INITAL 3000 POUNDS TENSION BEFORE MEASUREMENTS

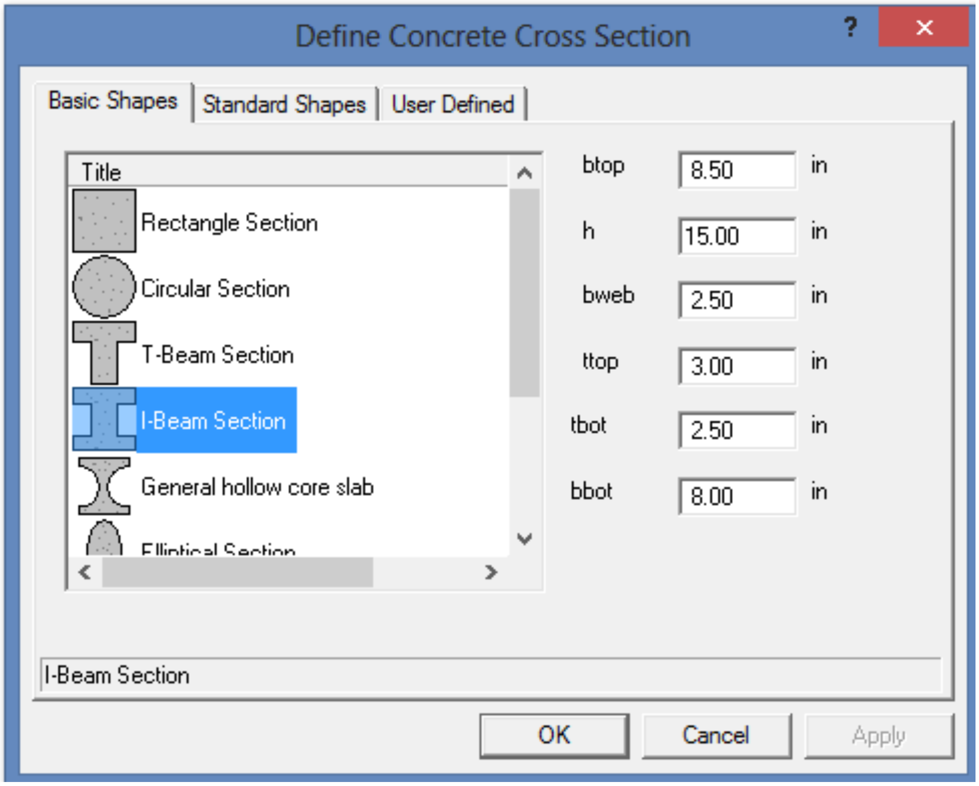
STRAND			ELONGATION				GAUGE			
STR NO.	STR SIZE	PACK NUMBER	FINAL ELONGATION MEASUREMENT	DESIRED ELONG	ELONGATION TOLERANCE (IN.)		FINAL GUAGE READ.	REQD GAUGE READ.	GAUGE TOLERANCE	
					LOW	HIGH			LOW	HIGH
1	1/2	630683	14 1/2	14 3/8	14 0/8	14 5/8	1950	1950	1900	2000
2	1/2	630690	14 1/2	14 3/8	14 0/8	14 5/8	1950	1950	1900	2000
3	1/2	731129	14 3/8	14 3/8	14 0/8	14 5/8	1950	1950	1900	2000

11.5 Appendix E: Prestrain Calculations (Loss Calculations)



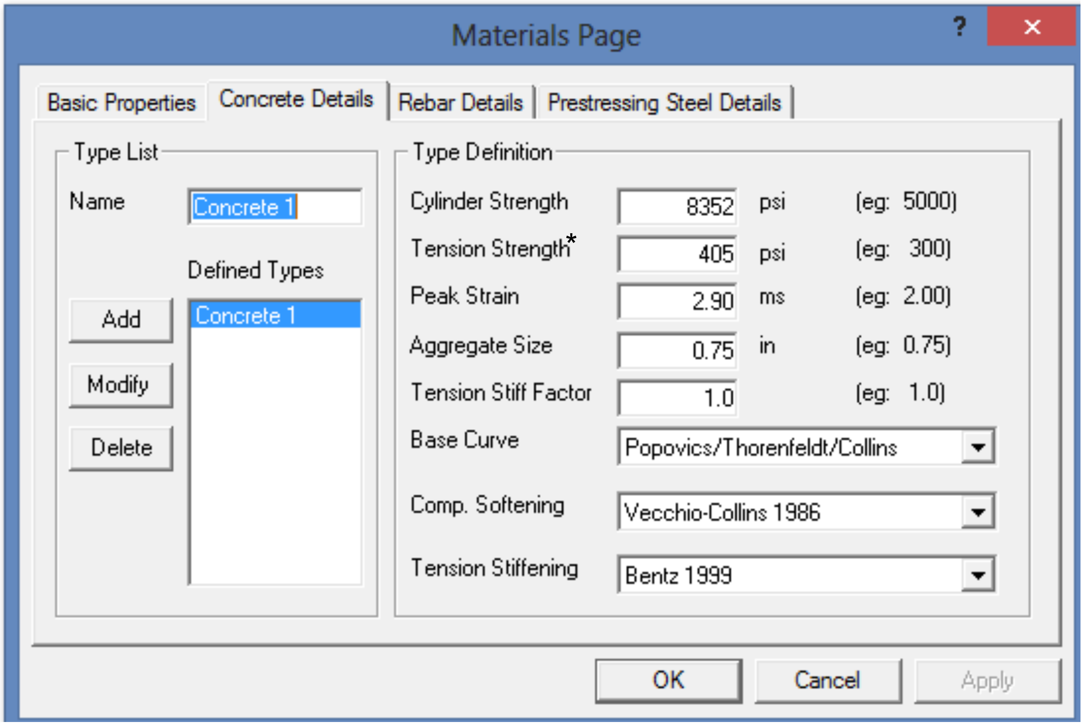
ES	-429.8052687				Total Surf. Area				
Kes	1				94.890	ft^2			
Eps	2.87E+07						13.973		
Eci	4031000	from mathcad			5.005				5.005
Fcir	-60.36742294					5.005		5.005	
	Kcir	0.9							
	Pi	3000	initial pull			15.016		15.016	
	Ag	69.0625	inludes draft						
	e	8.271				4.588		4.588	
	Ig	1859			4.171				4.171
	Mg	44687					13.347		
CR	-532.169718								
Kcr	1.6								
Fcds	0								
Ec	5209000	from mathcad							
	Msd	0							
				168					
SH	10871.9465								
Ksh	1								
V/S	0.284835365								
RH	53	assumed for flg							
RE	10552.69744								
Kre	20000								
J	0.15								
C	0.57	fp/fpu	fp						
			fpu						
TL	20462.66895	psi							
Force Loss	5.161	kip		37.5686275	ksi				
				165.045752	ksi				
Bed+anchora	2.03								

11.6 Appendix F: Response 2000 Inputs



btop 8.50 in
h 15.00 in
bweb 2.50 in
ttop 3.00 in
tbot 2.50 in
bbot 8.00 in

I-Beam Section

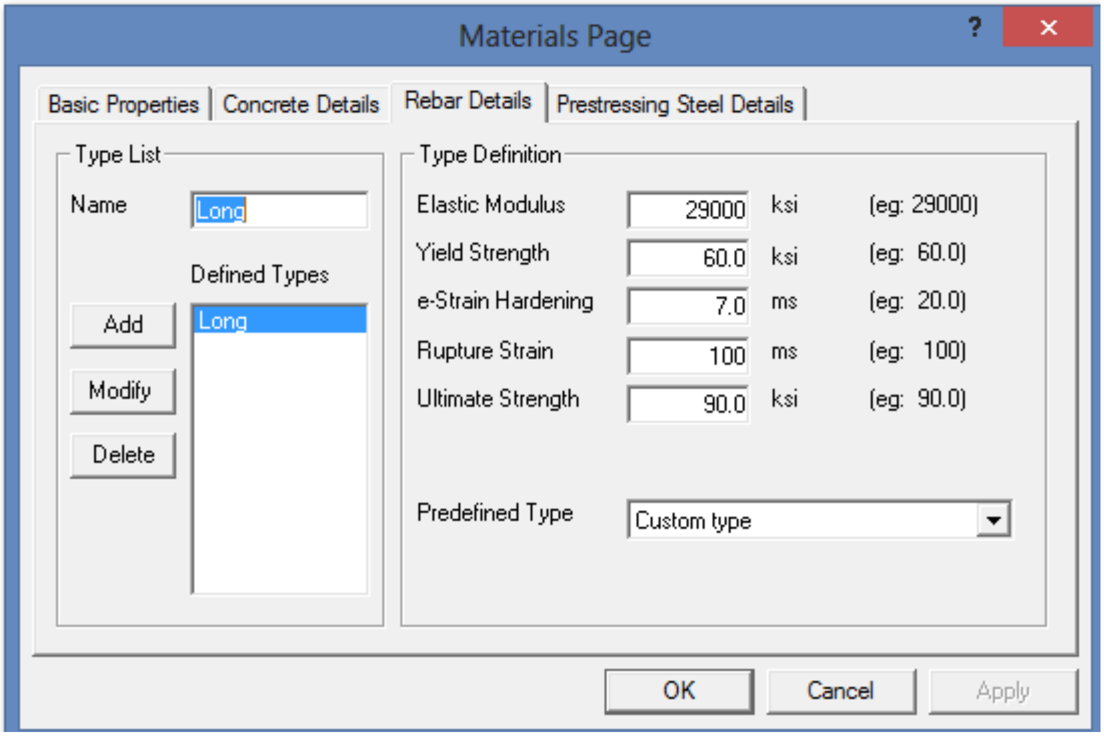


Name: Concrete 1

Defined Types: Concrete 1

Cylinder Strength	8352	psi	(eg: 5000)
Tension Strength*	405	psi	(eg: 300)
Peak Strain	2.90	ms	(eg: 2.00)
Aggregate Size	0.75	in	(eg: 0.75)
Tension Stiff Factor	1.0		(eg: 1.0)
Base Curve	Popovics/Thorenfeldt/Collins		
Comp. Softening	Vecchio-Collins 1986		
Tension Stiffening	Bentz 1999		

*Direct tensile strength

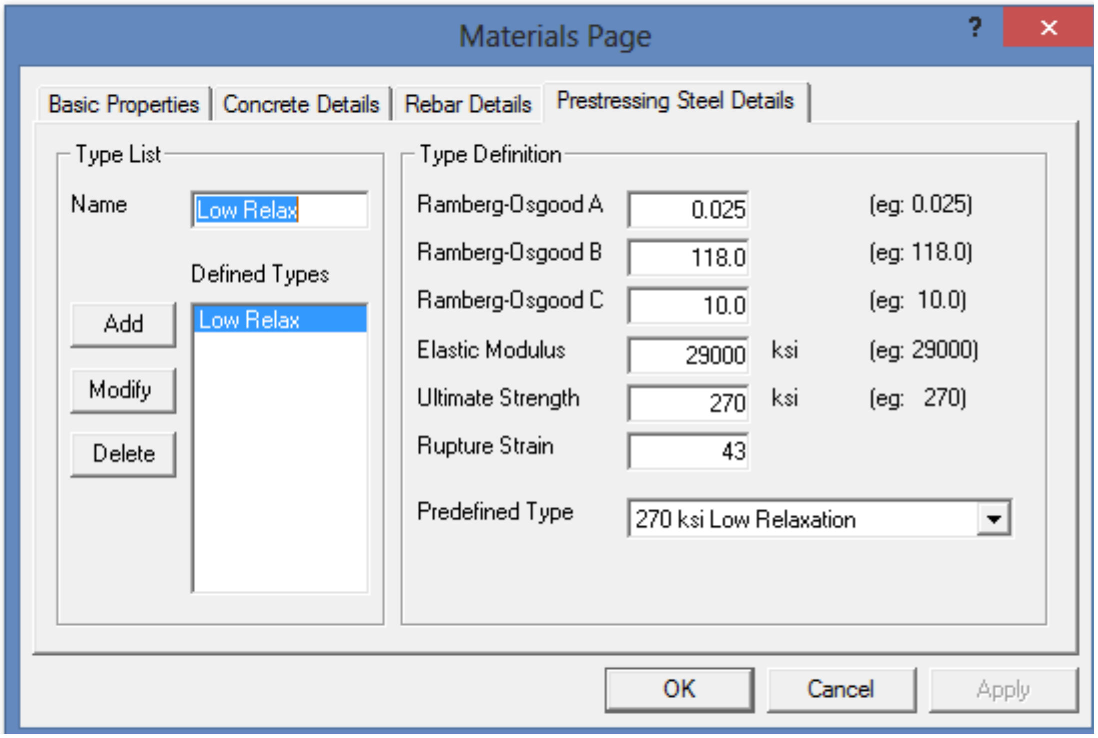


Name: Long

Defined Types: Long

Elastic Modulus	29000	ksi	(eg: 29000)
Yield Strength	60.0	ksi	(eg: 60.0)
e-Strain Hardening	7.0	ms	(eg: 20.0)
Rupture Strain	100	ms	(eg: 100)
Ultimate Strength	90.0	ksi	(eg: 90.0)

Predefined Type: Custom type

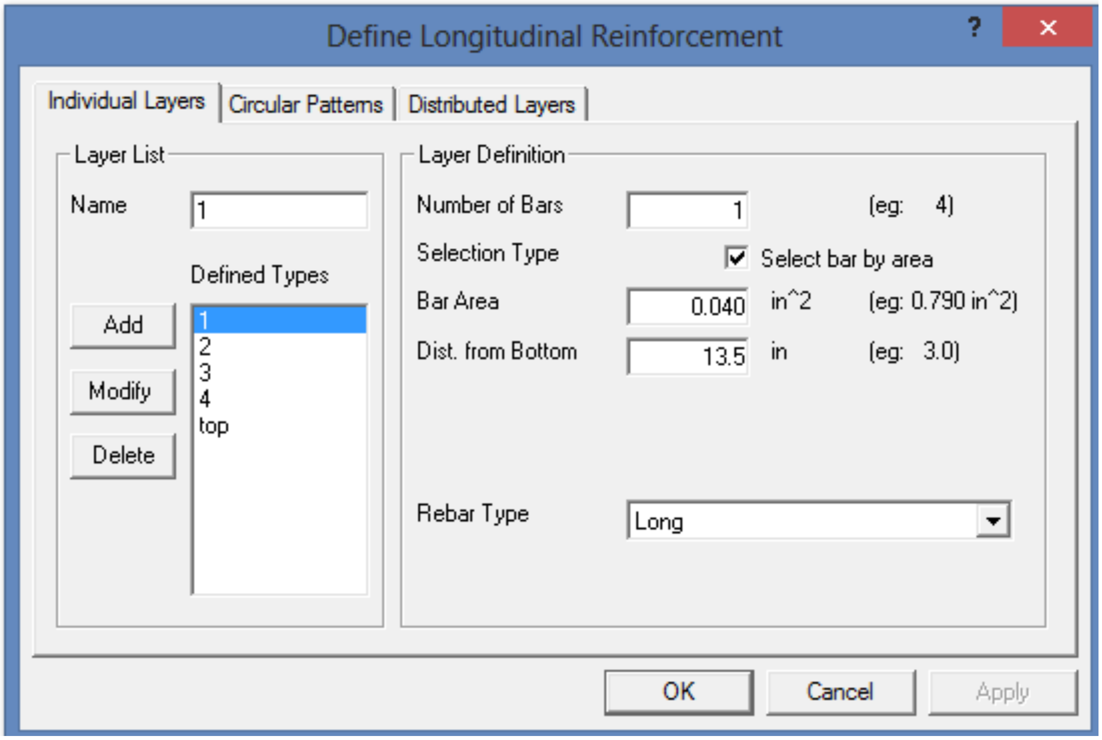


Name: Low Relax

Defined Types: Low Relax

Ramberg-Osgood A	0.025		(eg: 0.025)
Ramberg-Osgood B	118.0		(eg: 118.0)
Ramberg-Osgood C	10.0		(eg: 10.0)
Elastic Modulus	29000	ksi	(eg: 29000)
Ultimate Strength	270	ksi	(eg: 270)
Rupture Strain	43		

Predefined Type: 270 ksi Low Relaxation



Name: 1

Defined Types: 1, 2, 3, 4, top

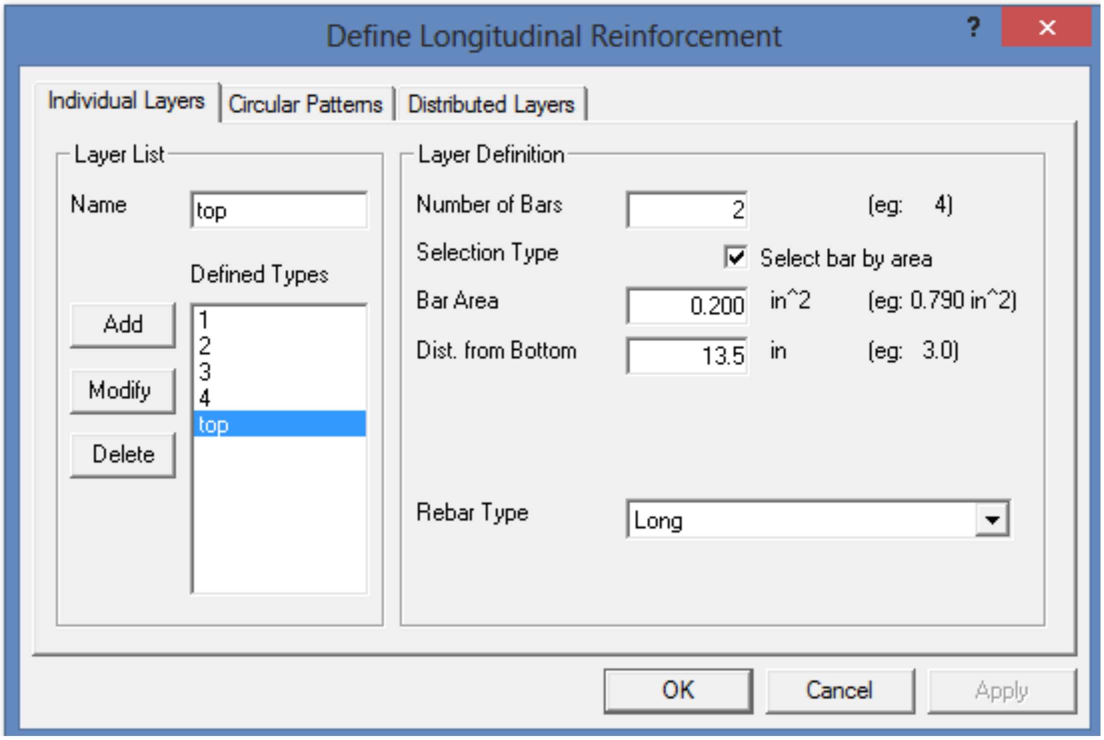
Number of Bars: 1 (eg: 4)

Selection Type: ☑ Select bar by area

Bar Area: 0.040 in^2 (eg: 0.790 in^2)

Dist. from Bottom: 13.5 in (eg: 3.0)

Rebar Type: Long



Name: top

Defined Types: 1, 2, 3, 4, top

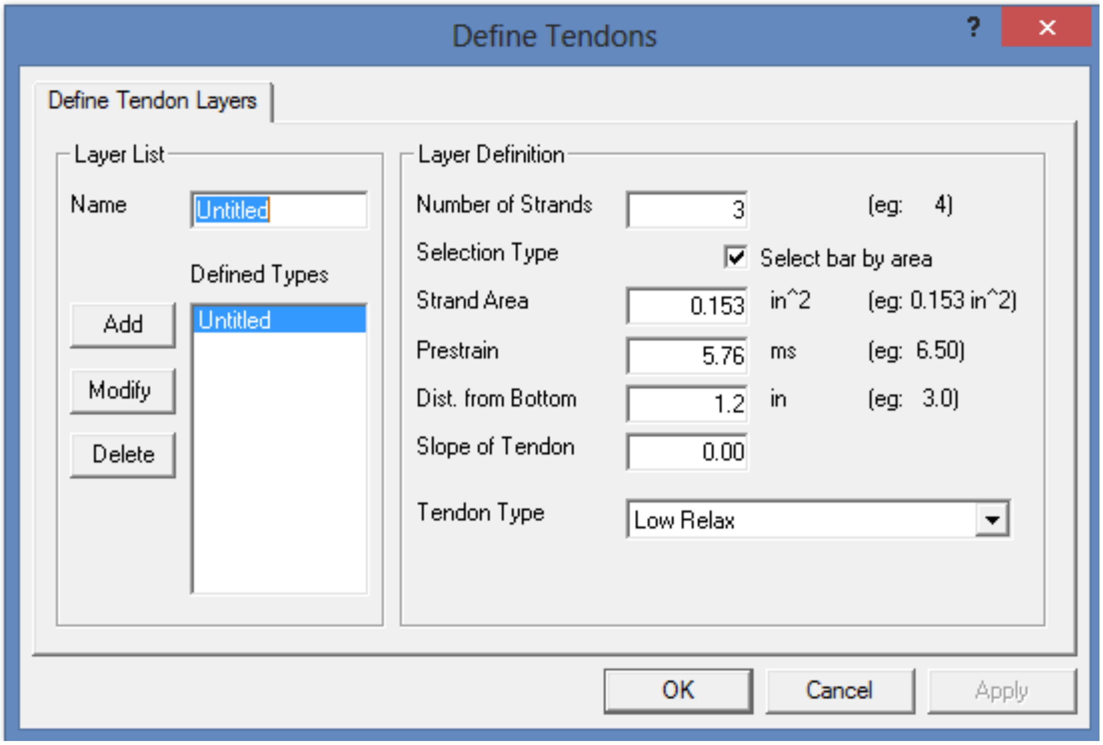
Number of Bars: 2 (eg: 4)

Selection Type: ☑ Select bar by area

Bar Area: 0.200 in^2 (eg: 0.790 in^2)

Dist. from Bottom: 13.5 in (eg: 3.0)

Rebar Type: Long



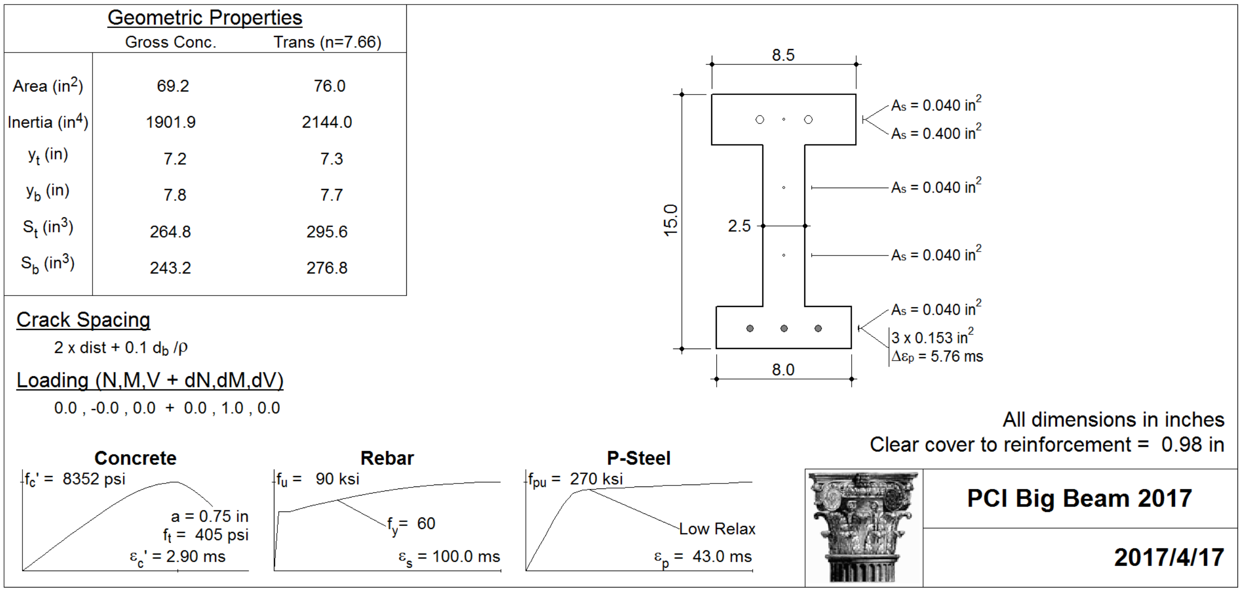
Layer List

Name: Untitled

Defined Types: Untitled

Layer Definition

Number of Strands	3		(eg: 4)
Selection Type	☑ Select bar by area		
Strand Area	0.153	in^2	(eg: 0.153 in^2)
Prestrain	5.76	ms	(eg: 6.50)
Dist. from Bottom	1.2	in	(eg: 3.0)
Slope of Tendon	0.00		
Tendon Type	Low Relax		



Geometric Properties

	Gross Conc.	Trans (n=7.66)
Area (in^2)	69.2	76.0
Inertia (in^4)	1901.9	2144.0
y_t (in)	7.2	7.3
y_b (in)	7.8	7.7
S_t (in^3)	264.8	295.6
S_b (in^3)	243.2	276.8

Crack Spacing

2 x dist + 0.1 d_b /ρ

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

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

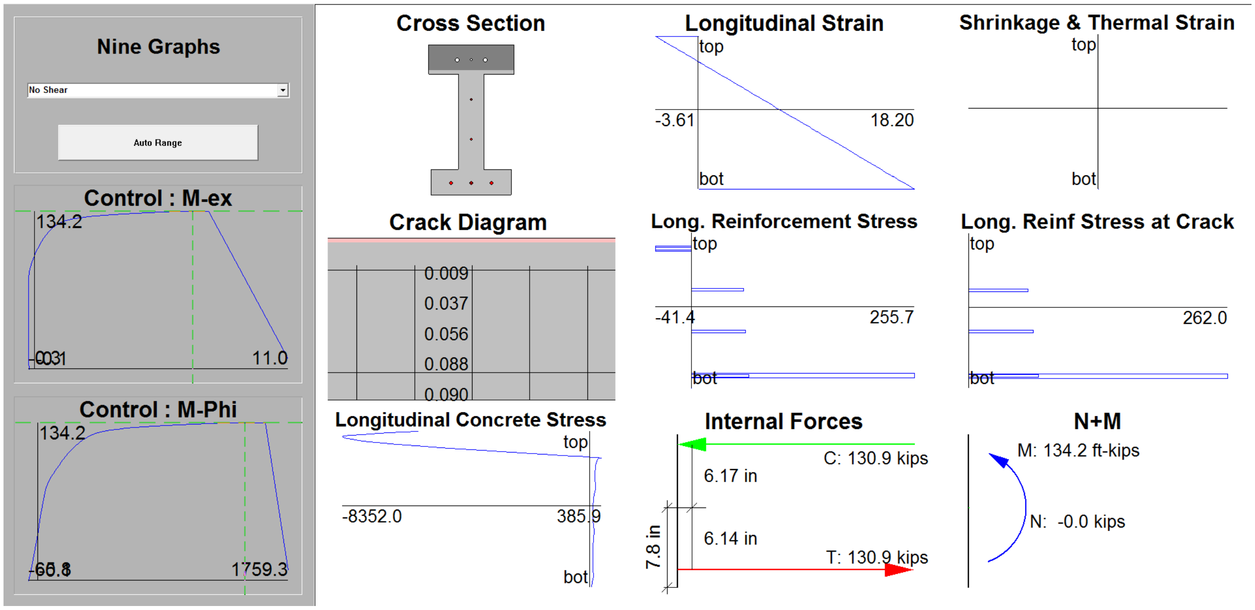
All dimensions in inches

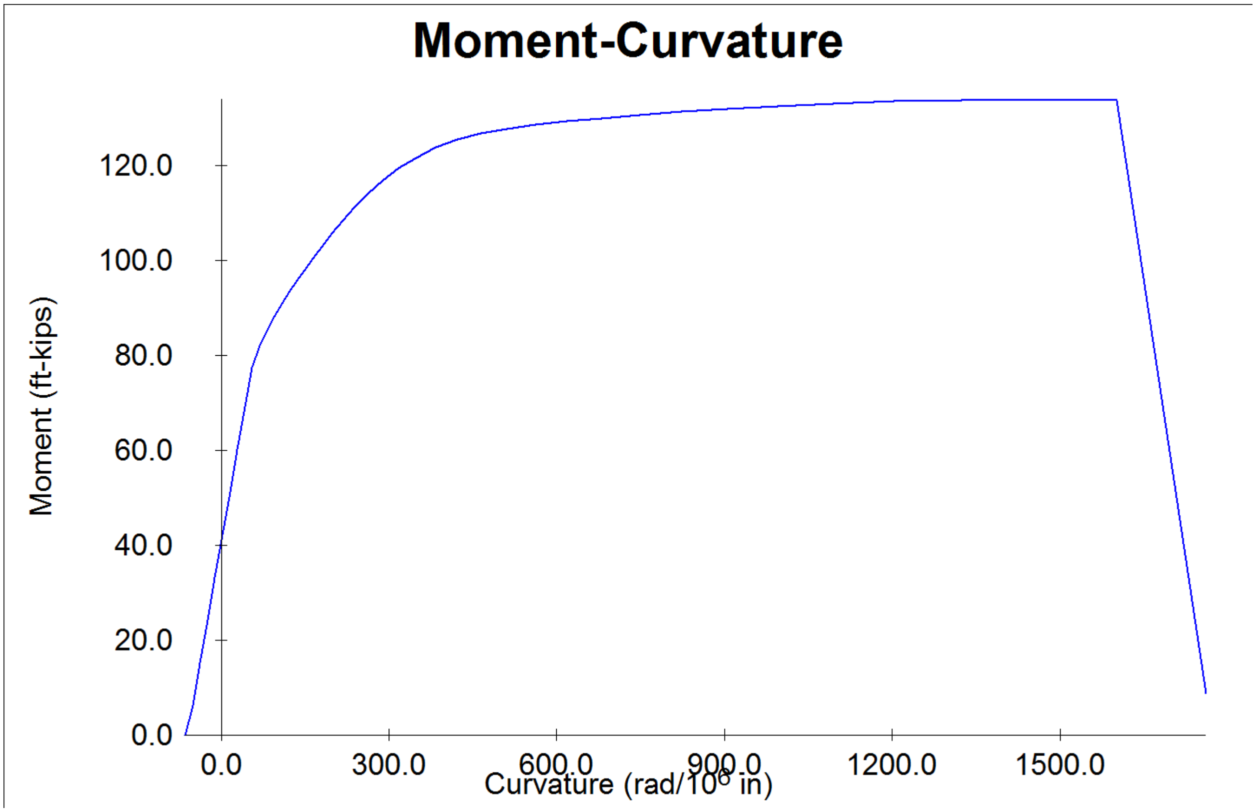
Clear cover to reinforcement = 0.98 in

PCI Big Beam 2017

2017/4/17

11.7 Appendix G: Response 2000 Outputs





11.8 Appendix H: Predicted Deflection

x (in)	m(x)	M(x)	m/EI(x)	$\Delta = \int \frac{mM}{EI} dx$
0	0	0.0	0.00E+00	0.00
6	3	105.5	-4.89E-05	0.00
12	6	211.0	-3.58E-05	0.00
18	9	316.4	-2.28E-05	0.00
24	12	421.9	-9.79E-06	0.00
30	15	527.4	3.22E-06	0.00
36	18	632.9	1.62E-05	0.00
42	21	738.3	2.93E-05	0.00
48	24	843.8	4.24E-05	0.01
54	27	949.3	5.83E-05	0.01
60	30	1054.8	9.09E-05	0.02
66	33	1160.3	1.37E-04	0.03
72	36	1265.7	1.93E-04	0.04
78	39	1371.2	2.58E-04	0.06
84	42	1476.7	3.62E-04	0.09
90	45	1582.2	8.25E-04	0.22
96	48	1583.8	8.44E-04	0.24
102	51	1587.2	8.81E-04	0.27
108	54	1590.5	9.21E-04	0.30
		Subtotal (integrating to midspan)		1.29
		Total		2.58
		Total + camber		3.45