PCI Big Beam Competition 2017-2018

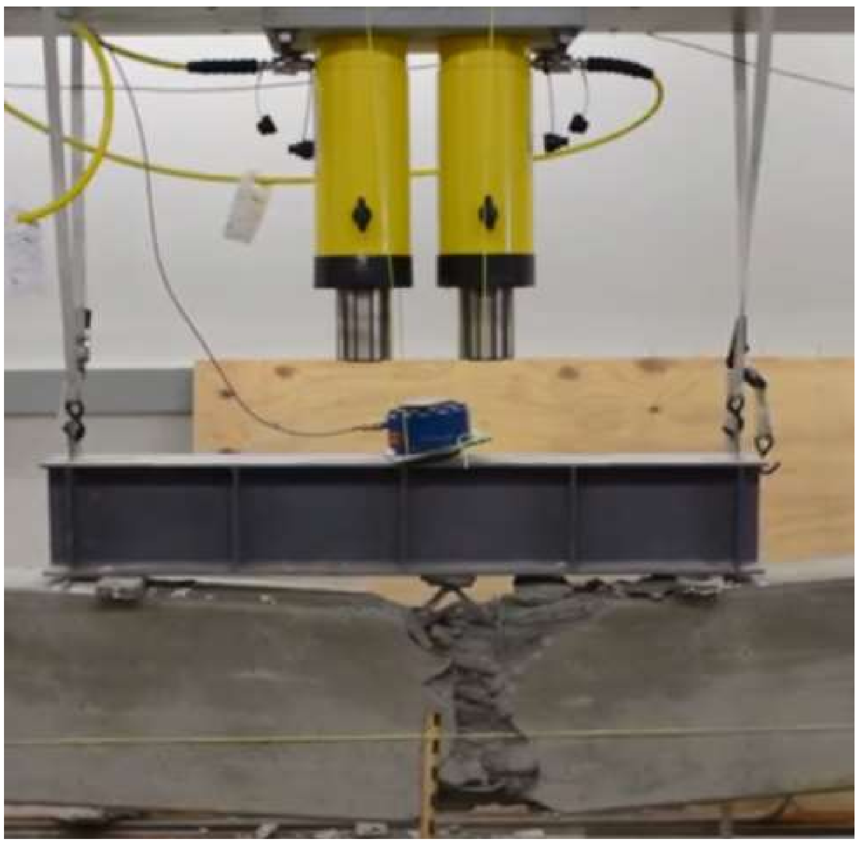

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Table of Contents

List of Figures

List of Tables

List of Abbreviations

PCI – Prestressed/Precast Concrete Institute
Kips – Kilo-Pound
ASTM – American Society for Testing and Materials
NAU – Northern Arizona University
Lb – Pound
CF – Cubic Foot
CY – Cubic Yard
W/C Ratio – Water-to-Cement Ratio
NW – Normal Weight
LW – Lightweight
PSI – Pounds per Square Inch
KSI – Kilo-Pounds per Square Inch
In – Inch
Fc – Compressive Strength at 28 days
S. Eng – Senior Engineer
Eng – Engineer
AA – Administrative Assistant
LF – Lineal Feet

Acknowledgements

The PCI Big Beam Competition Team representing Northern Arizona University would like to thank Dr. Robin Tuchscherer for his guidance and counsel throughout the course of this project, as well as Vince Rossi and Gabby Wilson, our contacts representing our sponsor, Tpac, for their time supporting this project with final design advice, material acquisition, and beam fabrication and transportation. Finally, we would also like to thank Cemex and Arrow Redi Mix for the cement, aggregate, and sand donated for concrete mix design.

1.0 Project Introduction

PCI, or the Precast/Prestressed Concrete Institute, is an industry trade association and technical institute for the precast/prestressed concrete structures industry [1]. The Big Beam Competition challenges student teams to design and build a precast/prestressed concrete beam per the requirements described in the competition brochure [2]. This year, teams must design a beam that is 22 feet long and subjected to two point loads. The concrete beam must not crack below a total load of 20 kips and must fail between a total load of 32 kips and 39 kips. To meet these design criteria, teams will design and select a concrete mix as well as a cross section for the beam, in order to carry the applied loads efficiently.

The competition has 7 different judging criteria, and they are as follows; design accuracy, lowest cost, lowest weight, largest measured deflection, most accurate prediction, report quality, and a final category which includes points for innovation, practicality, and conformance to code. Design accuracy is scored based on how accurately the beam is designed based on the competition values. The most accurate prediction category is scored based on predictions made prior to beam loading, based on how closely those predictions compare with the actual performance of the beam, as measured in the lab during testing.

2.0 Technical Considerations

This section provides information on the technical work that must be completed to finish this project.

2.1 Mix Design

The mix design is a crucial aspect of the overall weight and strength of the concrete member. The mix design selected also has a large impact on the overall cost of the beam per competition rules.

2.1.1 Concrete Mix

Concrete, traditionally, is a mixture of cement, fine and coarse aggregate, and water and is used to create structural elements. Various types of concrete exist such as light-weight and high-strength concrete which each offer an advantage in the competition but also penalizes the use of these materials in the cost portion. In the use of the concrete today, admixtures are introduced into the concrete mixture to produce effects such as increased workability, high early compressive strength, and hydration stabilization. All constituents of the concrete mix must adhere to their relevant ASTM standards.

2.1.2 Portland Cement

Portland Cement is a common type of cement used in the production of concrete. Portland Cement is offered in types I thru V and each type is useful in different applications of concrete. The Portland Cement used for the competition was selected by determining the most optimal type of cement as well as determining what was available locally in Northern Arizona.

2.1.3 Supplementary Cementitious Materials

Supplementary cementitious materials, often Fly Ash or Silica Fume, are byproducts of various production activities and are used to replace a percentage of the Portland Cement needed to produce the binding necessary for the concrete mix. The use of these replacement cementitious materials have other benefits, such as reducing the water demand of the concrete [1].

2.1.4 Mix Selection

The mix selection will be determined based upon the compressive and tensile strength, modulus of elasticity, and unit weight of the concrete mixtures evaluated. Four unique mix designs were created by the NAU team to be evaluated in regards to the characteristics noted above. The NAU concrete mixes are comprised of both light-weight and normal-weight coarse aggregates. Additionally, Tpac's standard normal-weight and lightweight concrete mixtures were also considered.

2.2 Structural Considerations

As the project members begin designing the concrete beam, the beam dimensions and the steel reinforcement must be considered for the intended loading. Additionally, characteristics of precast-prestressed concrete must be researched, as these differ from the structural characteristics of non-prestressed reinforced concrete.

2.2.1 Precast-Prestressed Concrete

Precast-Prestressed concrete is used in structures to reduce the effect of external forces by introducing internal forces prior to loading. These internal forces then help negate the tension forces experienced by the concrete beam, which is a characteristic weakness of concrete structural members. To do this, a high tensile force is introduced by pulling on the strands within the beam, creating an internal compressive force within the beam prior to loading. This compressive force can be visually witnessed because the beam will camber. Camber refers to the beam having an initial curvature prior to loading the beam. This is different than a traditional reinforced concrete member, which has no internal forces prior to loading. With this method, concrete beams can attain the structural capacity of high-strength concrete in compression while also possessing the ductility of steel in tension.

2.2.2 Cross-Section

Ten different cross sections were created that met the requirements for the competition. In order to choose one of the ten cross sections developed, a decision matrix was developed. The decision matrix weighed each cross section based on the criteria needed for the competition, the cross section with the highest score overall would be the cross section that would be used for this competition. The cross section with the best overall score was a box beam. The box beam has a height of sixteen inches and a width of eight inches.

2.2.3 Steel Reinforcement

Steel reinforcement is used to increase the tensile strength of concrete beams, or other concrete elements. As previously stated, concrete is very weak in tension and these steel reinforcing bars (rebar) allows the beam to carry a higher load. With the addition of steel reinforcement bars the beam will also have a larger moment capacity, this is because of the internal moment created by the variance of the compression in the concrete and tension in the steel. Additionally, steel reinforcement is implemented into the design so that the beam fails in tension rather than in compression. This is critical because a beam that ultimately fails in tension is actually slower to fail all together, and tension failure gives signs of failure well in advance so that there is time to address the issue before the failure actually occurs. A beam which fails in compression typically fails suddenly, with little to no warning of failure.

2.3 Potential Challenges

The potential challenges that have been identified for the big beam project consist of, concrete mix testing, beam manufacturing, and the transportation of the beam. The creation of the concrete mix designs and testing can be difficult to get accomplished in the timeline allotted for this project. Strength testing should take place 3 and 28 days after molding the concrete, meaning that the concrete molds will need to settle and cure in a 28 day period and broken at the conclusion of this period. This can be a challenge, not only because of the rigorous schedule of this project, but also because the molds must remain unhindered during that time. The testing follows ASTM standards and must be adhered to carefully, such as ASTM C39 for compressive strength testing, and ASTM C496 for tensile strength testing. Another potential challenge of the competition is coordinating the manufacture of the beam with Tpac, as specified Tpac is an actual company and therefore their jobs will be given priority. This can be a potential challenge because the manufacture of our beam may be continuously pushed back depending on the jobs Tpac is performing. Finally, the transportation of the fabricated beam from Phoenix, Arizona to Flagstaff, Arizona will be another potential challenge. Flagstaff, Arizona has iced over roads for most of the year and the accessibility to vehicles that are able to transport the beam are limited. However, Tpac will provide the transportation of the beam.

2.4 Stakeholders

There are several stakeholders for this project, as it involves multiple parties with varying interests these stakeholders are identified as Tpac, PCI, Dr. Tuchscherer, Northern Arizona University, and the project members.

Tpac is an architectural and structural precast concrete company, this company is the primary stakeholder, as they are sponsoring this project and will be responsible for fabricating and the transportation of the completed concrete beam. They will be impacted by this project because their name will be on the report that gets reviewed by PCI judges, and anyone who reviews this project. This can affect their relationship with PCI and potentially the other companies that review the report submissions. PCI will also be affected by this competition. The more people to hear and learn of precast/prestressed concrete beam competition, it will have an effect and impact on PCI socially and economically. Robin Tuchscherer plays a major role in this project because his knowledge and expertise provides substantial guidance for the project. This project has a social impact on Dr. Tuchscherer, as it has the potential to affect his relationship with Tpac, as well as other PCI members, positively or negatively. The biggest stakeholders for this project however, would be the members of this project as they are the ones who must agree with each other on each aspect and make sure everyone is on aboard with project decisions and that they are doing what they believe is best for the project. This project has a social impact for each team member, as their relationships with each other, their peers, Robin Tuchscherer, and the sponsor will be affected.

3.0 Summary of Engineering Work

The following subsections provide in depth information on the engineering work that is required for the completion of this project.

3.1 Developing Concrete Mixtures

Tpac's standard normal weight and lightweight mixtures were selected as two of the team's concrete mix designs considered. The team used these mixes, as well as a concrete textbook, to design four other unique mixes that were also considered by the team.

3.1.1 Lightweight Mix

Lightweight concrete mixes are created by using a lightweight coarse aggregate such as Expanded Shale or Pumice. A concrete mix that is more lightweight is advantageous per the judging criteria as it decreases the unit weight of the beam. Light-weight concrete mixes were created by the NAU team to be above the 115 pounds per cubic foot threshold in order to not be penalized as a lightweight mix in the cost portion of the judging criteria. A lightweight mix of the sponsor Tpac was also considered.

3.1.2 Normal Weight Mix

A normal weight concrete mix is created by mixing coarse aggregate of average to high unit weights. A normal weight mix is advantageous to examine as a potential concrete mix as they will not be penalized for being lightweight and can potentially be stronger than a comparable lightweight concrete mix. The NAU team created two concrete mixes considering the use of normal weight coarse aggregates. The team also considered Tpac's standard normal weight concrete mixture.

3.2 Creation of Concrete Cylinders

The project began with the concrete design process, through the development of several concrete mix designs for testing and analysis. Research was conducted in order to better understand standards for concrete mix design, including typical portions for aggregates and pozzolans in the overall materials used in the concrete mix. To assist with this, a spreadsheet was created using Microsoft Excel, to normalize concrete mix designs for comparison and analysis. Four unique designs were selected for testing and analysis. Two concrete designs from the sponsor, Tpac were also considered, totaling in six concrete designs that were used for testing and analysis in this project. The proportions of each concrete mixture, by weight and volume per cubic yard, as well as the water to cement, w/c, ratio, are shown in Table X: Concrete Mixture Proportions.

Table 3.2: Concrete Mix Design Proportions.

Mixtures	Type II Cement		Pozzolan (Fly Ash)		Course Agg.		Fine Agg.		W/C Ratio
	Weight (lb)	Volume (CF)	Weight (lb)	Volume (CF)	Weight (lb)	Volume (CF)	Weight (lb)	Volume (CF)	
Tpac NW	730	3.71	185	1.35	1,484	8.97	1,268	7.79	.310
NAU #1 NW	623	3.17	267	1.94	1,550	9.37	1,288	7.91	.303
NAU #3 NW	600	3.05	356	2.59	1,390	8.41	1,360	8.35	.282
Tpac LW	730	3.71	185	1.35	867	8.58	1328	8.15	.337
NAU #2 LW	610	3.10	261	1.90	150	3.70	1,200	7.37	.310
NAU #4 LW	400	2.04	478	3.48	940	9.30	1,070	6.57	.342

The cement used in each mixture was Type II Cement, and this was chosen for its ability to achieve a high, early compressive strength, which is crucial for the fabrication of a prestressed concrete structural member. The Pozzolan, or supplementary cementitious material, used in the design of each concrete mix was fly ash which beneficially reduces the permeability of the concrete and allows the concrete to become more dense (REFERENCE). A 30% replacement of cement with fly ash was used for each mixture except for NAU #4 LW mixture, where the team evaluated the effect of increasing the fly ash replacement. For each normal weight concrete mix design, ½" River Rock coarse aggregate was used as it was an easily attainable local aggregate. For Tpac's lightweight standard mixture and NAU #4 LW mixture, a ½" Expanded Shale was used as the coarse aggregate for its relatively low unit weight. The team used Pumice in the NAU #2 LW mixture as its unit weight is even lighter than the ½" Expanded Shale. The fine aggregate, or sand, used in each of the concrete mix designs was a Maricopa sand donated to the team by Tpac. The W/C ratios shown in Table X: Concrete Mix Design Proportions were determined based off of Tpac's standard concrete mixtures as well as established typical W/C ratios [3].

3.3 Testing of Concrete Cylinders

Once concrete mixes were developed, six designs were selected, the testing processes determined the compressive and tensile strengths and modulus the modulus of elasticity of each design. Before testing was able to be conducted, the team acquired the necessary materials from our sponsor Tpac and a local cement plant, as well as acquired concrete test cylinders.

3.3.1 Compressive Strength Test

The compressive strength of concrete is a critical point of information, as this value helps determine the cracking and ultimate capacities of the concrete. Compressive strength tests were only be performed for the four concrete mix designs developed by the team, as the compressive strength is already provided for the two other designs from the sponsor. Compressive strength tests were performed in accordance with ASTM C39 *Compressive Strength of Cylindrical Concrete Specimens* standards. It is important to note that, for compressive strength tests, two values were determined; the stress at release, which is measured 3 days after the release of the strands, and the compressive stress at 28 days used for cross-sectional design.

3.3.2 Tensile Strength Test

The tensile strength was determined in accordance with ASTM C496 *Splitting Tensile Strength of Cylindrical Concrete*. For this test, three cylinders were tested for each concrete design, including the sponsor's two concrete mixes, as their tensile strength data were not provided. This means that 18 concrete cylinders were required for conducting this test.

3.3.3 Strain Test

The determination of the modulus of elasticity for each concrete mix design was made using provision 8.5.1 of ACI code 318-14. The equation used relates the 28-day compressive strength of each concrete mix to the modulus of elasticity, shown as Equation 1.

Equation 3.3.3: Modulus of Elasticity.

$$(Modulus\ of\ Elasticity) = 57{,}000 * \sqrt{(28 - Day\ Compressive\ Strength)}$$

3.4 Final Beam Design

Before the final beam design could be created, a model had to be created to evaluate beam dimensions to ensure the design would be able to withstand the loading criteria set forth in the competition. MathCad is a computer software that allows for the validation, documentation and re-use of engineering calculations, because this software allows for live editing of the formulas it was used as the model to evaluate beam designs. Once the MathCad model was complete 10 different beam designs were created, that consist of different shapes and dimensions, to perform within the parameters set for the competition. The scoring of the beam was completed using a scoring technique similar to the actual competition. Using a normalized scoring, each beam is scored based on the highest performing beam in each category, the categories used were lowest weight, largest deflection, and lowest cost.

3.4.1 Beam Design

3.4.1.1 Develop MathCad Model

The MathCad analytical worksheet created provides the calculations for the stresses at release, cracking capacity, as well as the ultimate capacity. Additionally, the worksheet was used to calculate the shear capacity, required shear strength, and proportioned shear reinforcement for the beam. This software provides the re-use of the worksheet allowing for the analysis and design of various cross sections as well as reinforcement configurations. The model was designed to adhere to the Building Code Requirements for structural concrete standard ACI 318-14, this standard dictates which analysis to perform. Analysis was completed for both the three day and 28 day loads and stresses. Calculations include the release stresses at three 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 the nominal capacity of the beam.

When originally designing the beam using MathCad shear reinforcement of W4xW4 (4”x 4”), was used to ensure that the beam had sufficient shear strength. However, due to a shortage of this material at the time of fabrication, the team used shear reinforcement of D8 x D8 (8” x 8”). This reinforcement was ultimately designed to surround the entire box design and provide bracing for the top #4 bars, and was used throughout the entire length of the beam. The shear capacity of this change was checked using the shear envelope graph located within the MathCad worksheet. This shear envelope check confirmed that the compression steel would not buckle at any point on the length of the beam. The MathCad worksheet and all calculations can be found in Appendix J of this report.

3.4.1.2 Develop Beam Designs

In order for a beam design to be considered, the design first had to meet the competition requirements for cracking and ultimate capacity determined using the MathCad model. However to determine the optimal beam design, only three competition design categories were used which are as follows; highest deflection, lowest weight, and lowest cost. Each beam cross section design was created to optimize one of the previously mentioned categories.

3.4.1.3 Beam Scoring

The scoring of the beams was performed to be as close to the scoring used in the actual competition. This scoring technique is normalized scoring, which ranks the beams based on the best performing beam in each category. Therefore the final beam design would be the cross section design that scored the highest based on the three categories. The final cross section design, shown in Figure 3.4.1.3.3 and detailed in Appendix C, meets the strength, serviceability, as well as the detailing requirements of ACI 318-14.

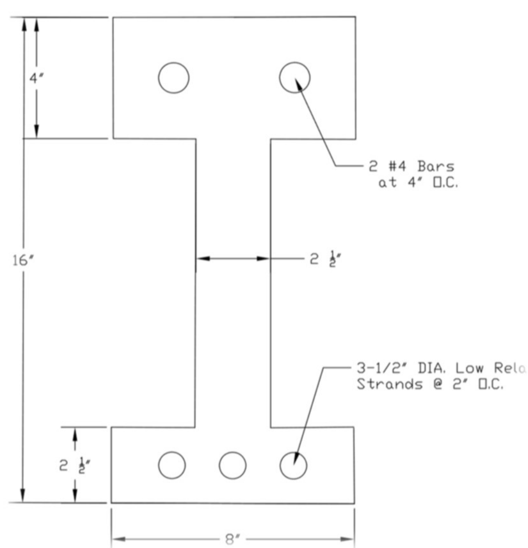


Figure 3.4.1.3.1: I Beam #3

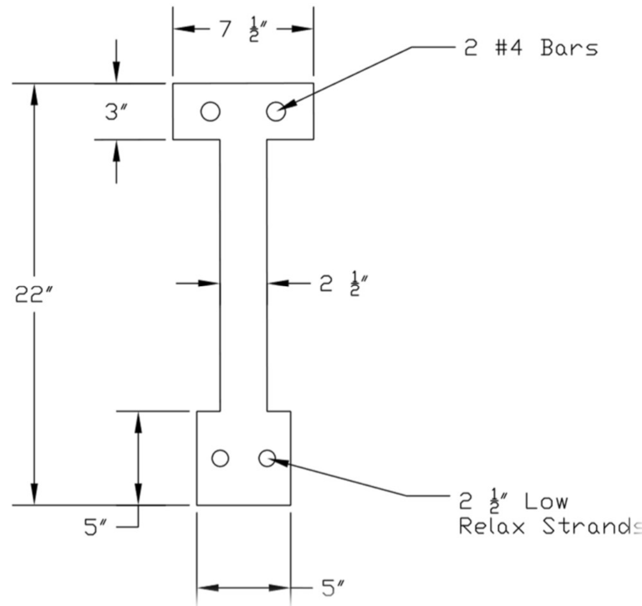


Figure 3.4.1.3.2: Bulb T

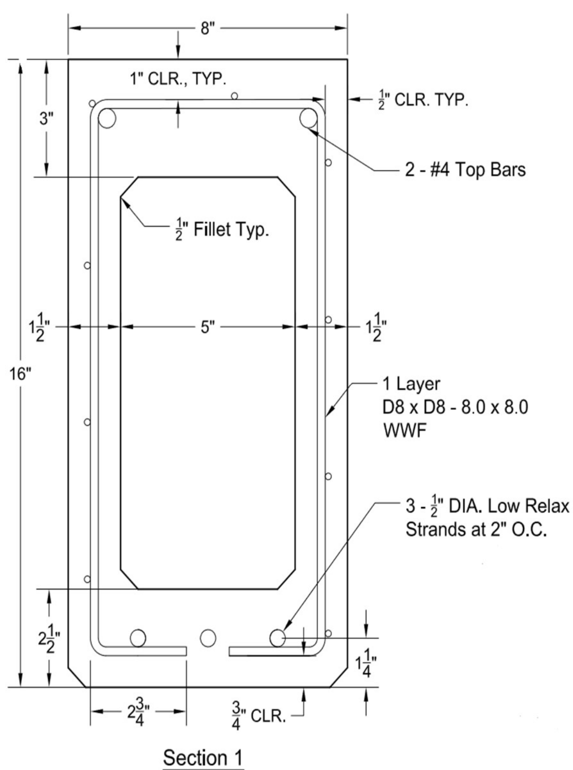


Figure 3.4.1.3.3: Box Beam #2

3.4.1.4 Final Beam Design Specifics

The materials used to fabricate the beam are: prestressing strands, compression reinforcement steel, and Welded Wire Fabric. Tpac, the beams fabricator, used ASTM A416 grade 270, 0.5" diameter, low relaxation prestressing strands. During the fabrication of the beam, a total of three prestressing strands were pulled to 31 kips and were left in the cast beam. Three days after fabrication, allowing the concrete adequate time to cure, the prestressing strands were cut. It was critical to wait three days before cutting the strands because if they were released earlier the beam would ultimately crack. Another detail was adding #4 compression steel to both ends of the beam within a 6" solid section. This detail was added to prevent a crack that could potentially form and run along the prestressing strands at the bottom of the section, indicating that the concrete had not bonded well enough to the prestressing strands. Two #4 ASTM 615 grade 60 rebar were placed at the top of the section.

Table 3.4.1.4: Bill of Materials.

Material	Quantity	Unit	Comments/ Criteria
#4 Bar	46	LF	ASTM A615 (60 KSI)
D8 XD8 - 8.0 X 8.0 WWF	83.52	SF	ASTM A1064 (65 KSI)
4 X 8 Cylinders	6	EA	ASTM A416 (270 KSI)
½" Dia. Low Relax Strands	66	LF	fc= 5000 PSI
Tpac LW Concrete	0.422	CY	fc (28 day)= 8000 PSI

3.5 Shop Drawings

The overall box girder dimensions are 8" x 16", the top section of the beam measures 3" from the top, the bottom section measures 2.5" from the bottom, and the sides of the beam are each 1.5" in width. The box beam design scored the best overall in each category, making it the optimized beam for lowest cost, largest deflection, and lowest weight. According to the developed MathCad model, the beam will begin cracking at 20.7 kips and will ultimately fail at 33.4 kips. The detailed shop drawing for this beam is included in Appendix C of this report.

3.6 Concrete Mix Volumes

The Concrete Mixture Decision Matrix included in Appendix I shows the results of the concrete cylinder testing, as well as the ranking system used to determine the most optimal concrete mixture to use in the design of the beam.

Table X: Tpac Lightweight Concrete Mixture Proportions shows a detailed breakdown of the weights and volumes of each concrete constituent per cubic yard of mixed concrete.

Table 3.6: Tpac Lightweight Concrete Mixture Proportions.

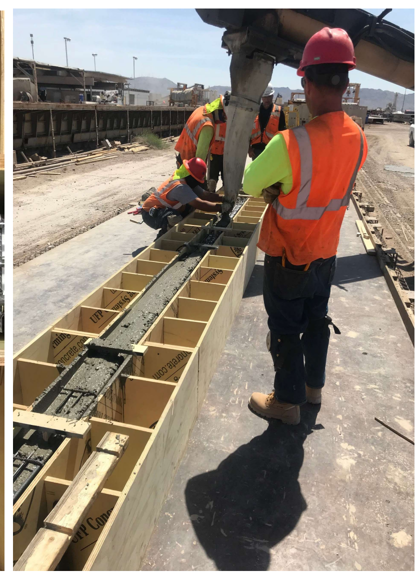
Material	Cement (Type II)	Fly Ash	½" Expanded Shale Agg (Coarse)	WCS Maricopa Sand Agg (Fine)	Water Content

Material Weight (lbs/CY)	730	185	867	1,328	308
Material Volume (CF/CY)	3.71	1.35	8.58	8.15	4.94

3.7 Beam Manufacturing

Once the mixture design and beam design were finalized, the created shop drawings were submitted to Tpac, the teams sponsor located in Phoenix, Arizona, for fabrication. Tpac constructed the custom form based on the final beam design using plywood and other lumber materials. After the form was constructed, styrofoam and the steel mesh reinforcement were placed in form. The steel mesh was used to hold the compression steel in place using small ties throughout the length of the beam. The prestressing strands were pulled to 31 kips and seated prior to casting the beam. Also throughout the length of the beam small wooden wedges were placed periodically, these wedges measured 3” in length and would stop the styrofoam from rising more than three inches once the pouring began. The formwork, mesh, rebar, and wedges can be seen in the figures below.





The beam was scheduled for fabrication on April 6th, 2018, and the team traveled to the sponsor’s facility in Phoenix, Arizona to perform quality control. This entailed verifying that the framework and beam details met the final specified beam design criteria. During this visit the dimensions of the framework, diameters of prestressing strands and compression steel, and placement of Styrofoam were all verified to meet the specified criteria. The prestressing strands were each pulled to 31 kips prior to casting. The concrete was self-consolidating concrete and did not need vibration treatment, at the same time the beam was cast, six 4” X 8” cylinders were also cast to observe the compressive and tensile strength of the concrete prior to testing the beam. The beam stayed on the bed for three days before the strands were cut, and the beam was allowed to cure for 28 days before testing the beam.

3.8 Predictions

In order to understand more clearly how the final designed beam will behave, a computer program known as Response 2000 was used to help predict the box beam behavior once the testing begins. Response 2000 is a computer program that was designed to predict the load-deflection response of reinforced concrete members that are subjected to bending moments, axial loads, and shear forces. This program allows for specific values to either be estimated by the system, or to be manually inputted. Because this system can numerically integrate the strain compatibility of concrete, reinforcement, prestressing strands, and considers the full stress-strain behavior of these materials, it is able to produce more precise predictions than the MatchCAD model alone. Calculations for the prestrain, or loss, were completed in Excel and can be found in Appendix E. The calculated prestrain value of 5.9 in was placed in the program along with additional inputs, included in Appendix F.

These inputs generated many useful results used for predictions, one of which being the moment vs curvature data used to predict deflections. The virtual work method was used to make predictions for deflections, using the equation below.

Equation 3.8: Deflection Equation.

$$\Delta = \int_0^{L/2} \frac{mM}{EI} dx$$

The Response 2000 data provided was given for moments at various lengths along the beam, however, since the deflection equation was solved using numerical methods, the team interpolated the moment-curvature data provided from Response for the values desired along the length of the beam, in 6-inch increments. With this data, and the moment data for the virtual load, placed at L/2 along the beam, where the maximum deflection happens, the deflection was calculated using the spreadsheet included in Appendix H. The table below includes all of the predicted values, per the competition rules named in the brochure [2].

Table 3.8: Predicted Values.

Category	Prediction
Cracking Capacity (kips)	20.3
Failure Capacity (kips)	38.3
Max Deflection (in)	5.12

3.9 Testing

3.9.1 Transportation

The finished beam was sent to Northern Arizona University on April 26, 2018 by Tpac, and arrived on a semi-truck. The beam was then carefully maneuvered until the team was able to set the concrete beam onto its supports and into its final location for testing.

3.9.2 Testing Preparation

Before testing, the beam had to be marked up to indicate the locations of where the potentiometers and the loading cell plates would be placed. Two potentiometers were placed above the location of the beam supports to measure this deflection at failure. Also, a potentiometer was placed beneath the center of the beam so that the maximum deflection at failure could also be determined precisely. Also, measures to ensure that, after failure, the loading cell would not make contact with the floor and potentially break an expensive piece of laboratory equipment were taken by securing the loading cell with straps onto the frame of the metal support system. Finally, a ruler was glued perpendicular to the span of the beam and a Mason's string was ran along the bottom of the beam to show a visual indication of deflection in the video recording of the beam testing.

3.9.3 Testing

Once all testing preparation was completed, the beam was loaded using a hydraulic loading system operated by Dr. Robin Tuchscherer, the technical advisor to the team. A computer software was used to display the load vs. deflection curve created by the loading of the beam and the potentiometer data. This load vs. deflection curve was then used to determine the cracking and ultimate failure load, as well as the maximum displacement at the failure load.

3.9.4 Video

A video of the beam during loading was taken in order to be submitted to the competition committee to show proof of testing. The video also was able to display the visual indication of deflection using the ruler and Mason's string. A computer software was also used to capture a screen recording of the load vs. deflection data and was overlaid with the video of the beam testing to show the load vs. deflection curve being created simultaneously.

3.9.5 Testing Results

With the load vs. deflection data recorded during testing, the graph in Appendix A was created, and the maximum load carried by the beam was determined to be 40.3 kips. The deflection measured at this loading was determined to be 4.98 inches. The cracking load for concrete is the point where the load vs. deflection graph becomes nonlinear. To determine the cracking load, a linear function was created to display how the measured load vs. deflection curve would behave before cracking occurred, which was named the "pre-cracking" equation, and is shown below.

Equation 3.9.5.1: Pre-Cracking Equation

$$y = 29.261x$$

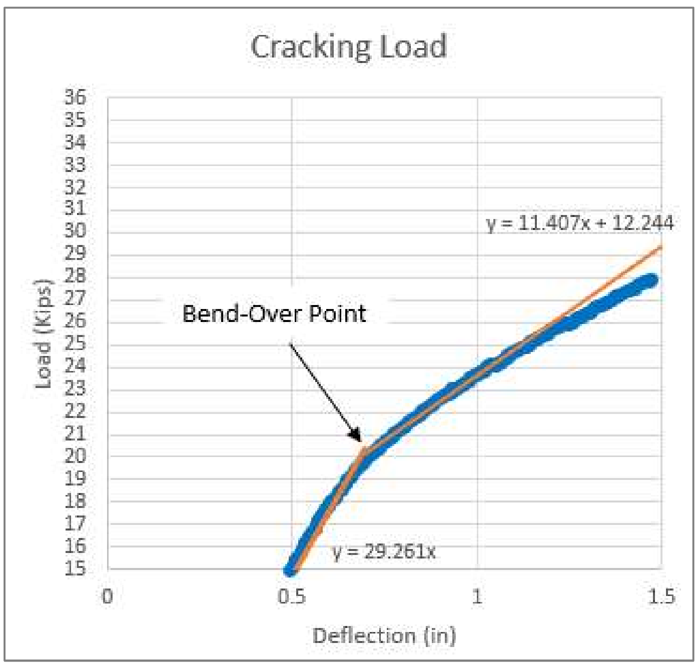
The pre-cracking equation was determined by creating a best-fit curve for the data measured up to where the load reached 21 kips, as this was estimated to be near the cracking load by inspection. A second linear function, called “post-cracking,” was also created for the range beyond where cracking occurred, and is defined below.

Equation 3.9.5.2: Post-Cracking Equation

$$y = 11.407x + 12.244$$

These two functions were set equal to one another to determine the point where they intersect, which would be the “bend-over point,” where cracking occurs. This was determined to have a y-value of 20.1, meaning the load where cracking occurred was 20.1 kips. These equations, as well as the bend-over point where cracking occurs can be seen in Figure 3.9.5 below.

Figure 3.9.5: Cracking Load.



The table below shows the predicted values as compared with the values measured during testing, including the percent difference for these values.

Table 3.9.5: Predictions Vs. Measured Values.

	Predictions	Actual	% Diff
Cracking Load (kips)	20.3	20.1	0.99 %
Ultimate Load (kips)	38.3	40.3	5.09%
Deflection (in)	5.12	4.96	3.17%
		Total	**9.25%**

4.0 Summary of Engineering Costs

This section provides details on how many professionals will be assisting throughout the project as well as explaining what their job titles/roles will be for this project. This section will also include each individuals pay, overhead calculations, and an overall total cost for the project.

4.1 Scheduling

Table X. below shows the schedule the team had development in the beginning of the project. The team did fall behind schedule around mid-February, the team however, when creating the project schedule they had the project being completed by April 6th, 2018 even though the deadline was May 10th, 2018. The team was had enough time in order to get back on schedule. The team fell a little behind due to having the beam casted later than anticipated, our sponsor Tpac was generous enough to cast the beam for us considering how busy they are during that time of year.

Table 4.1: Project Schedule

Task Number	Task Name	Duration	Start Date	End Date	Actual Finish Date
1	2.1.1 Concrete Mix Development	11 days	Wed 10/4/17	Wed 10/18/17	10/18/17
2	2.1.2 Mix Testing	22 days	Thu 10/19/17	Fri 11/17/17	11/17/17
3	2.1.3 Analysis of Mix Testing Results	5 days	Mon 1/15/18	Fri 1/19/18	1/19/18
4	2.1.4 Mix Selection	5 days	Mon 1/22/18	Fri 1/26/18	1/26/18
5	2.2.1 Develop Beam Designs	33 days	Wed 11/1/17	Fri 12/15/17	12/15/17
6	2.2.2 Develop MathCAD Model	50 days	Mon 11/20/17	Fri 1/26/18	01/26/18
7	2.2.3 Beam Scoring	1 day	Mon 1/29/18	Mon 1/29/18	02/17/18
8	2.2.4 Beam Selection	1 day	Wed 1/31/18	Wed 1/31/18	02/20/18
9	2.3.1 Shop Drawings	10 days	Thu 2/1/18	Wed 2/14/18	03/06/18

10	2.3.2 Concrete Mix Volumes	10 days	Thu 2/1/18	Wed 2/14/18	03/06/18
11	2.4.0 Beam Manufacturing	16 days	Thu 2/15/18	Thu 3/8/18	04/06/18
12	2.5.0 Predictions	10 days	Thu 2/1/18	Wed 2/14/18	02/14/18
13	2.6.1 Transportation	5 days	Mon 3/12/18	Fri 3/16/18	04/26/18
14	2.6.2 Testing Prep	5 days	Fri 3/9/18	Thu 3/15/18	05/01/18
15	2.6.3 Testing	1 day	Mon 3/19/18	Mon 3/19/18	05/04/18
16	2.6.4 Video	5 days	Fri 3/16/18	Thu 3/22/18	05/10/18
17	2.7.2 Final Report to PCI	5 days	Mon 4/2/18	Fri 4/6/18	05/10/18
18	2.7.3 Final Report to NAU	1 day	Mon 4/2/18	Mon 4/2/18	05/10/18

4.2 Staffing

This project was composed of four team members. There was a senior engineer, engineer in training, laboratory technician and an administrative assistant. The personal with the most amount of hours spent on this project was the lab technician. The lab technician was in charge of all the laboratory testing which included mix development and mix testing as well as acquiring the necessary data for the team. The engineer in training also had many hours accumulated throughout the project, the engineer in training was responsible for the development of the mixes that were created analyzed for this project, and the engineer in training was also responsible for the development of the MathCad sheet as well as the development of the shop drawings. The administrative assistant was responsible for compiling all the information/data the team collected and created tables, graphs, charts, etc. as well as compiling all the given data into reports and presentations. The senior engineer had the least amount of hours throughout the project, but that does not mean the senior engineer was not as involved in the project. The senior engineer was responsible for the accuracy in the mix design, mix testing, predictions, MathCad sheet and shop drawing. Between all the staff, this project took 708 hours to complete.

Below is table X which shows the staff that was part of this project and the amount of hours accumulated through the duration of the project.

Table 4.2: Staffing Hours Distribution

Task	S. ENG	ENG	Lab	AA	Total
Mix Design	15	50	45	20	130
Mix Testing	5	35	95	10	145
Beam Design	15	45	8	5	73
Beam Manufacturing	5	20	10	8	43
Predictions	20	40	5	5	70
Testing	10	40	90	10	150
Report	12	35	15	35	97
Total Hours	82	265	268	93	708

4.3 Budgeting

Table X displayed below shows the overall cost of the project. The largest part of the cost was the staffing since the team spent over 700 hours working on it which accounts for 75% of the total cost. Lab use made up about 15% of the total cost due to there being 90 hours of lab time to fabricate the beam down in Phoenix, Arizona and have it shipped to Northern Arizona in Flagstaff was $5,000. The travel costs are from when the team had to travel down to the sponsor location in Phoenix, Arizona in order to conduct a site visit as well as acquiring materials and beam casting. The total cost of the project was $57,585.

Table 4.3: Cost of Project.

Staffing	Personnel	Hours	Billing Rate ($/hr)	Cost ($)
	S. ENG	82	130	10,660
	ENG	265	70	18,550
	LAB	268	40	10,720
	AA	93	35	3,255

Lab Use	90	100	9,000
Beam Fabrication/Shipping			5,000
Travel Costs			400
Total cost of project			**$57,585**

5.0 Conclusion

The team performed well with respect to the judging criteria of the competition. This was evidenced by each of the three predictions, for cracking and ultimate failure load as well as maximum deflection, being within 6% of the actual values determined during testing. For reference, the NAU entry last year, which placed 6^{th} in the competition, had a percent difference in the predicted deflection of over 30%. This indicates that the team will likely place higher than 6^{th} in the competition if the other entries do not improve as much as the NAU team did this year. Also, since the team used a lightweight concrete mix, the beam will likely perform well in the judging category of lowest weight. The team is eager to find out how well we performed with respect to the other schools competing in the 2018 PCI Big Beam Competition.

6.0 References

[1] Precast/Prestressed Concrete Institute, "PCI," [Online]. Available: pci.org. [Accessed 30 11 2017].

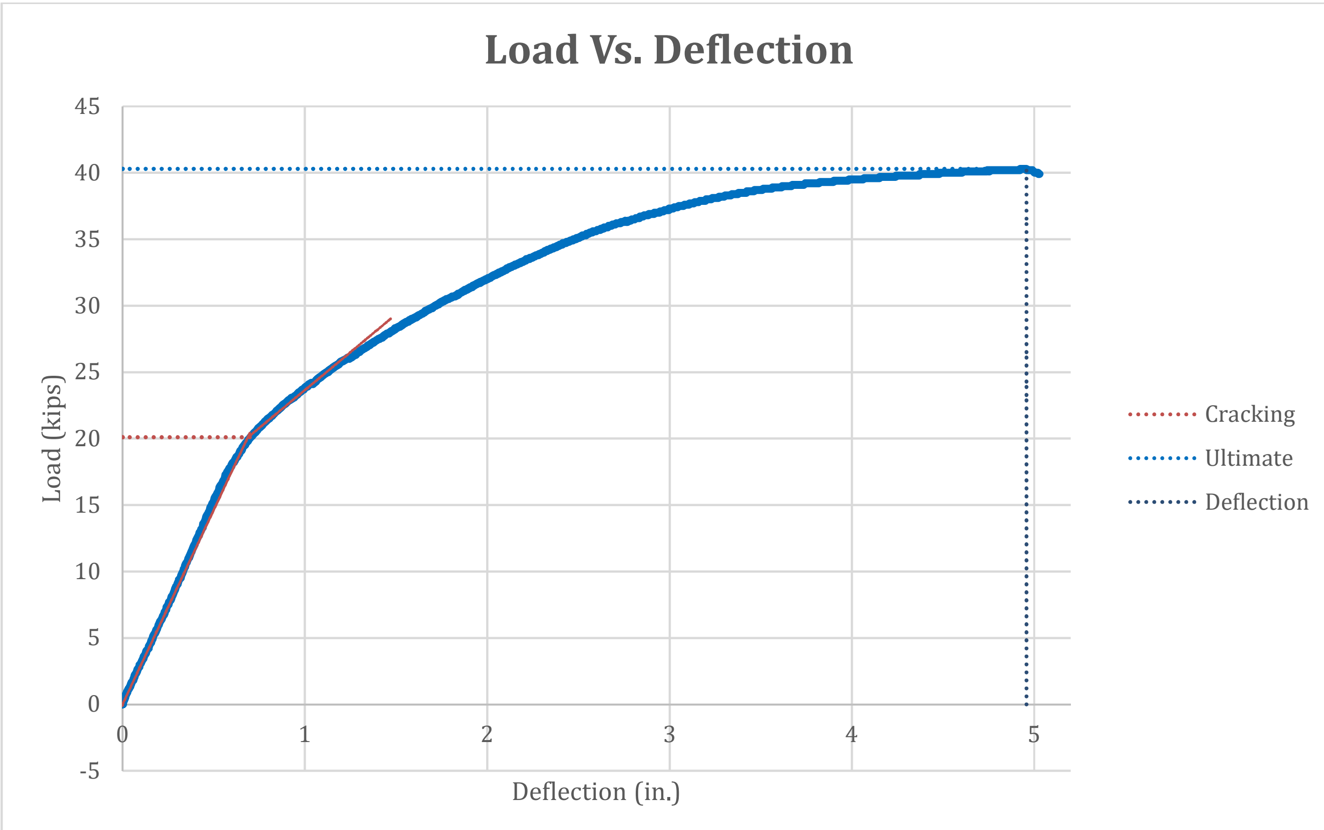
[2] PCI, "2018 PCI Big Beam Brochure," [Online]. [Accessed 30 11 2017].

[3] K. a. Panarese, Design and Control of Concrete Mixtures, Skokie, IL: Portland Cement Association, 1988.

[4] National Precast Concrete Association, "SCMs in Concrete," 2018.

6.1 Appendices

Appendix A – Load Vs. Deflection

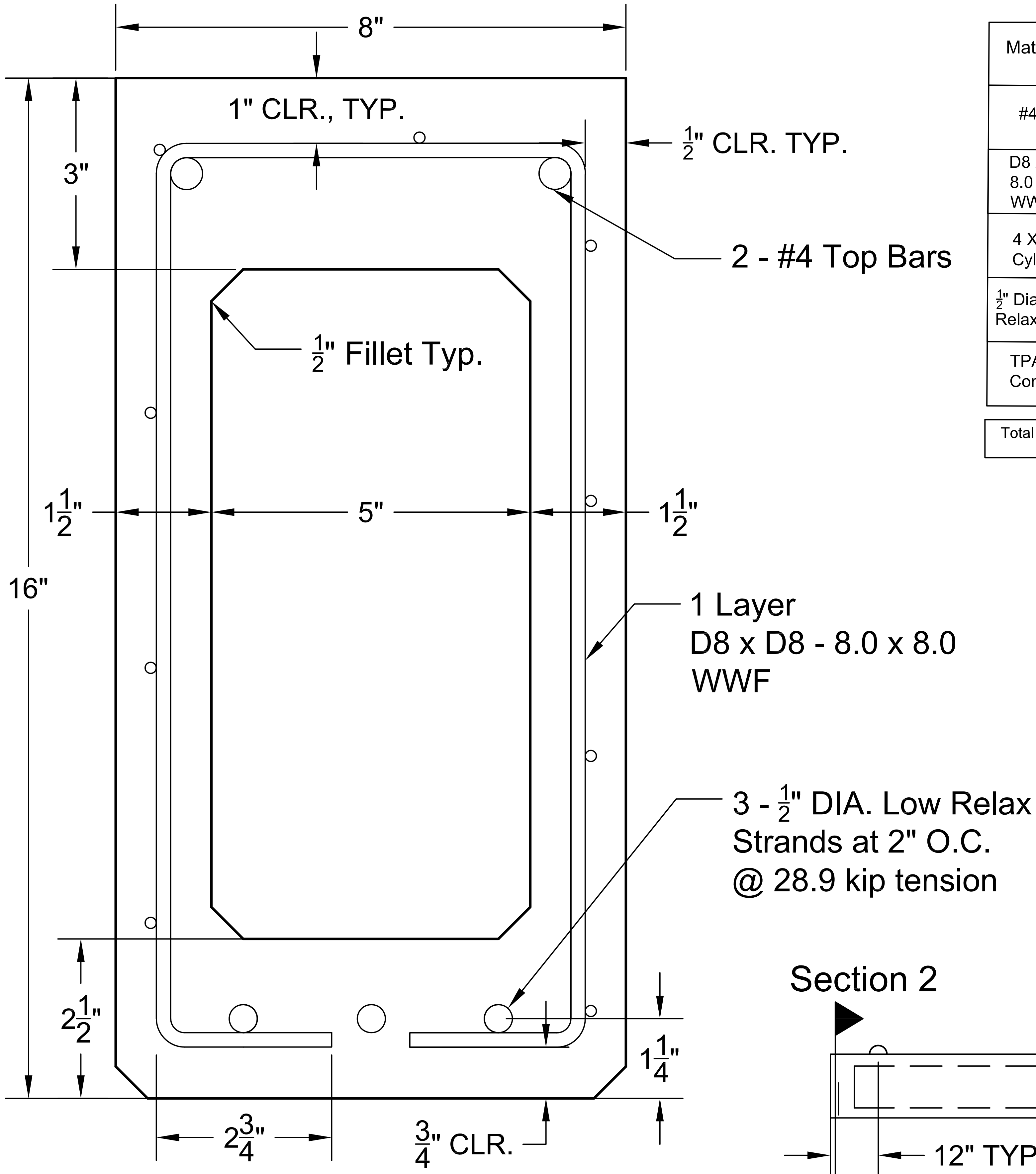


Appendix B – Beam Details & Cost Calculations

Beam Properties		
Beam Height	16	in
Beam Width	8	in
Web Width (ea.)	1.5	in
Top Flange Height	3	in
Bottom Flange Height	2.5	in
Beam Length	22	ft
Compression Steel	#4 Rebar	
Prestressing Strands	1/2 in DIA Low Relax	
Mesh	D8 x D8 - 8.0 x 8.0 WWF	

Costs Calculations		
Concrete:		
Unit Cost	100	$/yd^3
Ag	75.5	in^2
Volume	0.427212	yd^3
Total	**$42.72**	
Strands:		
Unit Cost	0.3	$/ft
Length	66	ft
Total Cost	**$19.80**	
Reinforcing Steel:		
Unit Cost	0.45	$/lb
Unit Weight	0.668	lbs/ft
Weight	29.392	lbs
Total Cost	**$13.23**	
D8 x D8 WWF:		
Unit Cost	0.5	$/lb
Unit Weight	85	lbs/100ft
Weight	70.992	lbs
Total Cost	**$35.50**	
Formwork:		
Unit Cost	1.25	$/ft^2
Surface Area	58.66667	ft^2
Total Cost	**$73.33**	
Total Beam Cost	**$184.58**	

Appendix C – Shop Drawings

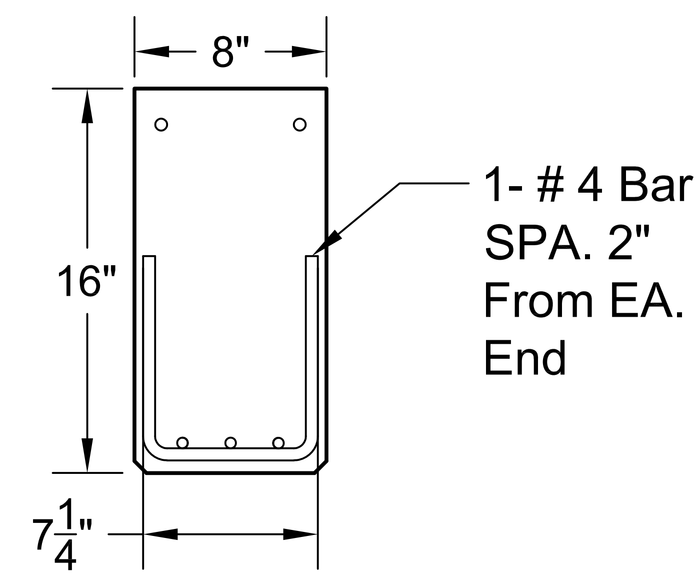


Section 1
Scale: 6" = 1' - 0"

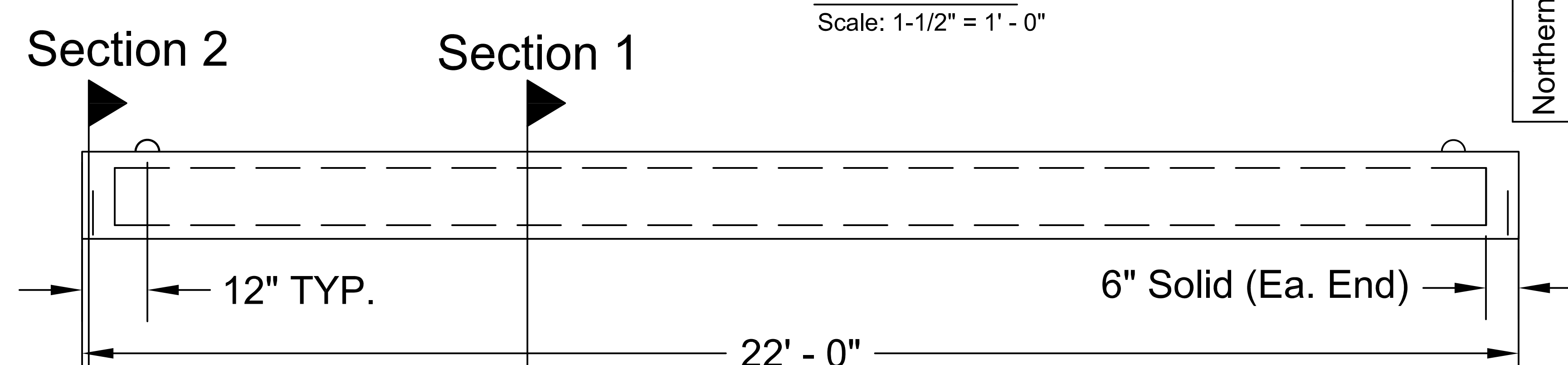
Bill of Materials

Material	Quantity	Unit	Comments/ Criteria
#4 Bar	46	LF	ASTM A615 (60 KSI)
D8 X D8 - 8.0 X 8.0 WWF	83.52	SF	ASTM A1064 (65 KSI)
4 X 8 Cylinders	6	EA	ASTM C31
½" Dia. Low Relax Strands	66	LF	ASTM A416 (270 KSI)
TPAC LW Concrete	0.422	CY	fci= 5000 PSI fc (28 DAY)= 8000 PSI

Total Beam Weight	1501 lbs



Section 2
Scale: 1-1/2" = 1' - 0"



Elevation
Scale: 3/8" = 1' - 0"

Northern Arizona University Big Beam Team 2018 Shop Drawing Flagstaff , Arizona	Designed By: BW, SG, FR, RC	Date: March 6, 2018
	Checked By: Dr. T	Scale: As Shown

Appendix D – Prestressing Report

PCI BIG BEAM

CHARGE # 30-8105.C

APPROVED DATE: 4-4-18

POUR	TOTAL	FORM #1	NOTES
1	X4 / X6		RELEASE : 5000 / 8000
LENGTH	22'-0"	22'-0"	NOTE: LIGHTWEIGHT CONCRETE
L.F	22.00	22.00	PLASTIC UNIT WEIGHT = 126.6 PCF
M.H.	0	0'-8" 0	NEED (6) 4" X 8" CYLINDERS FOR N.A.U
C.Y.	0.43	0.43	(3) 1/2" (270K) LO-LAX @ 31.0
W.T		1,501	MIX = LW-6-NAU
2			FORM COMPLETE
LENGTH			
S.F			
M.H.			
C.Y.			
3			
LENGTH			
S.F			
M.H.			
C.Y.			
4			
LENGTH			
S.F			
M.H.			
C.Y.			
5			
LENGTH			
S.F			
M.H.			
C.Y.			

TPAC TENSIONING PROGRAM

Job Number / Name: 30-8105.C / PCI BIG BEAM
Plant Location: Phoenix
Bed: 240
Pump Number: TP20, TP22, TP23
Default Strand Type: 1/2
Initial Pull in Pounds: 3000
Number of Strands: 3
Bed Number: North
Remarks: 3 - 1/2" 270K LOLAX

Bed Data: Length = 2976 inches, Shortening = 0.3125 inches.
Pump Data: Zero load reading = 3.9304574431 pounds, Slope = 0.060737864
Strand Data: Area = 0.153 inches^2, Modulus of elasticity = 28,900,000
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 Strand #	Ending Strand #	Elongation Reduction	Number of Pieces	Strand Type	Final Pull	Bed
1	3			1/2	31,000	240

PHOENIX TENSIONING RECORD

DAY: Friday DATE: 4-6-18 TIME: 10:15 AM

CAST: 1 INSPECTOR: Currie TENSIONED BY: Kramer

JOB ID: 30-8105.C / PCI BIG BEAM

BED: 240 BED ID: North

PUMP: TP20, TP22, TP23 JACK: 23

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.) LOW	HIGH	FINAL GUAGE READ.	REQD GAUGE READ.	GAUGE TOLERANCE LOW	HIGH
1	1/2	120137845l7	19 3/8	19 1/4	18 3/4	19 3/4	1930	1930	1880	1980
2	1/2	1201378415 23	19 1/2	19 1/4	18 3/4	19 3/4	1930	1930	1880	1980
3	1/2	12013784l516	19 1/4	19 1/4	18 3/4	19 3/4	1930	1930	1880	1980

TPAC

MULTIPLE STRAND STRESSING / ELONGATION REPORT

JOB ID: 30-8105.C / PCI BIG BEAM
BED: 240
PUMP: TP20, TP22, TP23
REMARKS: 3 - 1/2" 270K LOLAX
NOTES: All strands to receive initial 3000 pounds tension before mearsurements.

PLANT: PHOENIX
BED ID: North
JACK: 23

Stressed By: K. [signature]

Date: 4-6-18

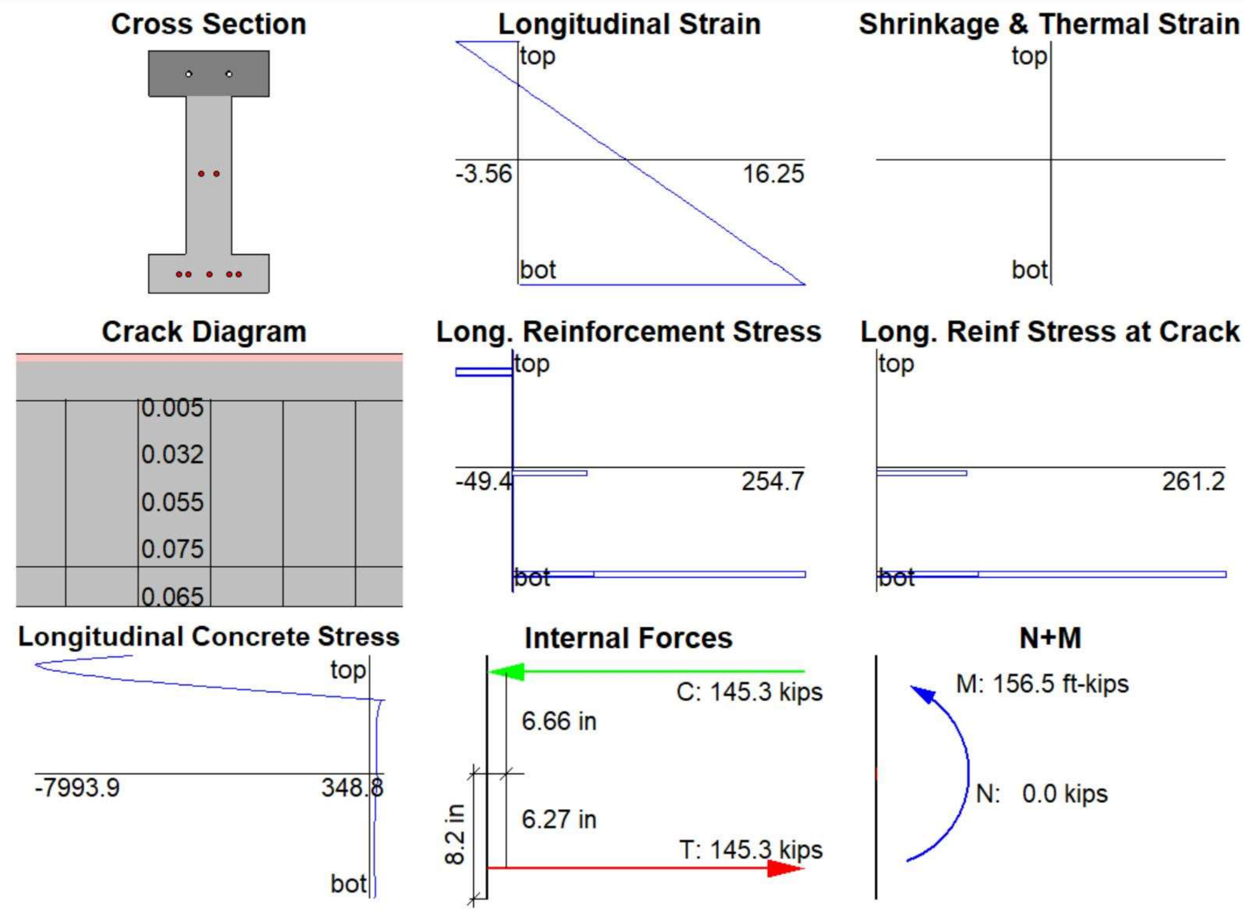
INITIAL		CHECKLIST
PK	1).	Check strand vises for proper seating and extension.
PK	2).	Strand extends at least 2" beyond the strand vise cap.
PK	3).	Hoses, rams, and pump oil level are in good condition and are ready for use.
PK	4).	Stress to initial tension as required.
PK	5).	Blow the all clear siren to clear the bed.
PK	6).	Line is cleared, final stressing may proceed.
PK	7).	Three people maximum in the stressing area.
PK	8).	Final pressure/elongation is reached.
PK	9).	Release the pump pressure.
PK	10).	Wait 30 seconds after pressure is released, sound the siren for crew return.
Doc. Control	11).	Record Elongation to the nearest 1/8".
MC	12).	Route Completed Checklist to QC Department by end of shift.
Log	13).	MC 4.9.18
File	14).	MC 4.9.18
X-File	15).	

Comments / Other:

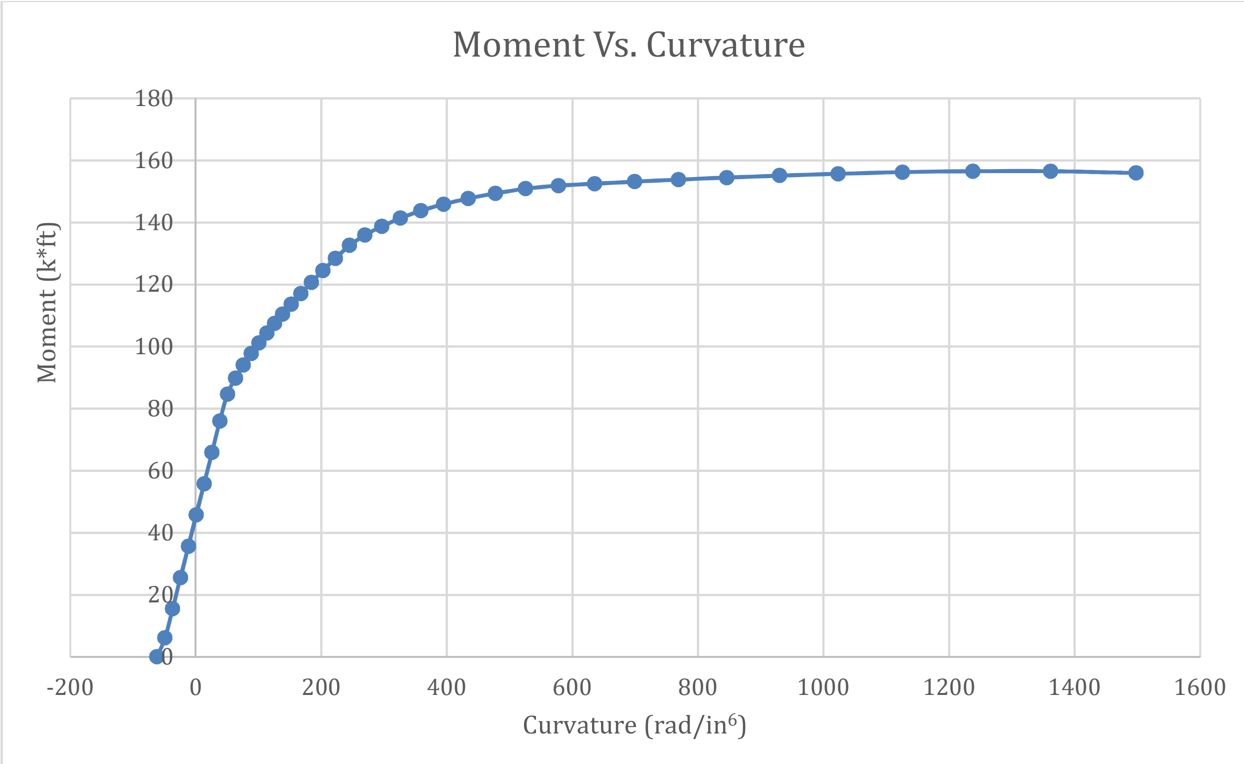
Appendix E – Prestrain Loss Calculations

Estimating Prestress Loss									
Elastic Shortening			Losses Due to Shrinkage				Losses Due to Relaxation		
			K_{sh}	1			K_{re}	5000	Table 5.7.
K_{es}	1		V/S	0.00589			*C*	0.53	Table 5.7.
E_{ps}	28500000	psi	RH	30	%	Design Aid	f_{pi}	198.2571	K/in^2
f_{cir}	2613.951	psi					J	0.04	Table 5.7.
E_{ci}	4030509	psi							
ES	18483.42	psi	**SH**	16353.22	psi		**RE**	1911.463	psi
To Calculate f_{cir}									
K_{cir}	0.9						Total Losses		
A_g	74.641	in^2				**TL**	36748.1	psi	
e	6.75	in				f_p	125.8835	ksi	
I_g	2248.3	in^3							
M_g	3970.071	lb-ft							
						Strain Calculation			
Anchorage losses						A	0.025		
A_{ps}	0.459	in^2				B	118		
f_{pu}	176.2745	ksi				C	10		
P_i	**91**	**kip**				E_p	28500	ksi	
						ϵ_p	0.005853	in/in	
						f_p	166.4144	ksi	
						f_{pu}	176.2745	ksi	
							166.414		

Appendix F – Response 2000



Appendix G – Moment Vs. Curvature



Appendix H – Deflection Predictions

x [in]	M(x) [k*in]	m(x) [rad/in]	M/EI (x) [rad/in]	Δ_i [in]
0	0	0	0	0
6	114.9123	3	-4.5E-05	-0.0008
12	230.0294	6	-3.2E-05	-0.00116
18	345.3511	9	-2E-05	-0.0011
24	460.8775	12	-8.4E-06	-0.0006
30	576.6086	15	3.6E-06	0.000324
36	692.5444	18	1.56E-05	0.001683
42	808.6849	21	2.76E-05	0.003476
48	925.0301	24	3.98E-05	0.005738
54	1041.58	27	5.58E-05	0.009047
60	1158.335	30	8.41E-05	0.015141
66	1275.294	33	0.000121	0.023938
72	1392.458	36	0.000163	0.035165
78	1509.826	39	0.000209	0.048977
84	1627.4	42	0.000267	0.067368
90	1745.178	45	0.000387	0.104503
96	1863.16	48	0.000958	0.275792
102	1866.538	51	0.001002	0.306471
108	1870.12	54	0.001054	0.341429
114	1873.907	57	0.001114	0.381078
120	1877.898	60	0.001228	0.442032
Deflection (without camber)				4.117003
Total Predicted Deflection (including camber)				**5.12 in.**

Appendix I – Decision Matrices

Mixes	Unit Weight (pcf)	Rank	Compressive Strength (psi)	Rank	Tensile Strength (psi)	Rank	Modulus of Elasticity (ksi)	Rank	Score
Tpac NW	148.3	1	10,000	6	349	4	5,700	1	3.5
NAU #1 NW	148.1	2	7,130	4	474	5	4,813	3	3.75
NAU #3 NW	147.3	3	2,360	3	239	3	2,769	4	3.3
Tpac LW	**126**	**5**	**8,000**	**5**	**505**	**6**	**5,098**	**2**	**4.35**
NAU #2 LW	126.8	4	1,312	1	230	2	2,064	6	3.05
NAU #4 LW	118.1	6	1,526	2	150	1	2,227	5	3.05
Weighted Factor		.10		.35		.25		.30	

X-Section	Cost ($)	Rank	Weighted Factor	Weight of Section (plf)	Rank	Weighted Factor	Defl. (in)	Rank	Weighted Factor	Total Score
I Beam #1	71	5	0.745	108.0	6	0.306	0.019	3	0.579	1.629
I Beam #2	62	4	0.929	78.00	4	0.833	0.010	8	0.078	1.839
I Beam #3	59	2	0.997	69.00	2	0.996	0.017	6	0.495	2.489
Box Beam #1	100	9	0.116	126.0	10	0.000	0.023	2	0.795	0.911
Bulb T	60	3	0.964	75.00	3	0.882	0.009	9	0.016	1.862

C Beam	79	6	0.560	108.0	5	0.318	0.011	7	0.085	0.963
Box Beam #2	59	1	1.000	68.00	1	1.000	0.018	5	0.520	2.520
I Beam #4	80	7	0.549	109.00	7	0.302	0.008	10	0.000	0.852
I Beam #5	106	10	0.000	125.00	9	0.006	0.027	1	1.000	1.003
T Beam	89	8	0.366	120.00	8	0.114	0.018	4	0.522	1.002

Appendix J – MathCAD

Given Properties

Area of Reinforcing Steel	$Asprime := 0.4in^2$
Area of Strand	$Ap := 3 \cdot 0.153in^2 = 0.459 \cdot in^2$
Compressive Strength of Concrete at 3 days	$fc_3 := 5 \cdot ksi$
Compressive Strength of Concrete at 28 days	$fc_{28} := 8ksi$
Modulus of Elasticity at 3 days	$Ec_3 := 57\,ksi \sqrt{\frac{fc_3}{psi}} = 4030.509 \cdot ksi$
Modulus of Elasticity at 28 days	$Ec_{28} := 57ksi \sqrt{\frac{fc_{28}}{psi}} = 5098.235 \cdot ksi$
Modulus of Elasticity of Steel	$Es := 29000ksi$
Unit Weight of Concrete	$\gamma c := 0.07 \frac{lbf}{in^3}$
Unit Weight of Steel	$\gamma s := 490 \frac{lbf}{ft^3}$

Section Properties

$i := 1..5$

Width: Height: Area: Moment of Inertia:

$b_1 := 8in$ $h_1 := 3in$ $A_1 := b_1 \cdot h_1 = 24 \cdot in^2$ $I_1 := b_1 \cdot \frac{(h_1)^3}{12} = 18 \cdot in^4$

$b_2 := 3in$ $h_2 := 10.5in$ $A_2 := b_2 h_2 = 31.5 \cdot in^2$ $I_2 := b_2 \cdot \frac{(h_2)^3}{12} = 289.406 \cdot in^4$

$b_3 := 8in$ $h_3 := 2.5in$ $A_3 := b_3 h_3 = 20 \cdot in^2$ $I_3 := b_3 \cdot \frac{(h_3)^3}{12} = 10.417 \cdot in^4$

$H := h_1 + h_2 + h_3 = 16 \cdot in$

$Agconcrete := (A_1 - Asprime) + A_2 + (A_3 - Ap) = 74.641 \cdot in^2$

Centroid:

$y_1 := h_3 + h_2 + \left(\frac{h_1}{2}\right) = 14.5 \cdot in$

$y_2 := h_3 + \frac{h_2}{2} = 7.75 \cdot in$

$y_3 := \frac{h_3}{2} = 1.25 \cdot in$

$y_4 := \frac{h_3}{2} = 1.25 \cdot in$

$y_5 := h_3 + h_2 + \frac{h_1}{2} = 14.5 \cdot in$

Transformed section at 3 days

$$n_3 := \frac{Es}{Ec_3} = 7.195$$

$$A_4 := \left(n_3 - 1\right) \cdot Asprime = 2.478 \cdot in^2$$

$$A_5 := \left(n_3 - 1\right) \cdot Ap = 2.844 \cdot in^2$$

$$Atr_3 := \sum_{i=1}^{5} A_i = 80.822 \cdot in^2$$

$$ybar3 := \frac{\left[\sum_{i=1}^{5} \left(A_i \cdot y_i\right)\right]}{\left(\sum_{i=1}^{5} A_i\right)} = 8.184 \cdot in$$

$$d_1 := ybar3 - y_1 = -6.316 \cdot in$$

$$I_4 := 0$$

$$I_5 := 0$$

$$d_2 := ybar3 - y_2 = 0.434 \cdot in$$

$$d_3 := ybar3 - y_3 = 6.934 \cdot in$$

$$d_4 := ybar3 - y_4 = 6.934 \cdot in$$

$$d_5 := ybar3 - y_5 = -6.316 \cdot in$$

$$Itr_3 := \sum_{i=1}^{5} \left[I_i + A_i \cdot \left(d_i\right)^2\right] = 2475 \cdot in^4$$

Transformed Section at 28 days

$$n_{28} := \frac{Es}{Ec_{28}} = 5.688$$

$$A_4 := \left(n_{28} - 1\right)\cdot Asprime = 1.875\cdot in^2$$

$$A_5 := \left(n_{28}\right)\cdot Ap = 2.611\cdot in^2$$

$$Atr_{28} := \sum_{i=1}^{5} A_i = 79.986\cdot in^2$$

$$ybar28 := \frac{\left[\sum_{i=1}^{5} \left(A_i\cdot y_i\right)\right]}{\left(\sum_{i=1}^{5} A_i\right)} = 8.218\cdot in$$

$$d_1 := ybar28 - y_1 = -6.282\cdot in$$

$$d_2 := ybar28 - y_2 = 0.468\cdot in$$

$$d_3 := ybar28 - y_3 = 6.968\cdot in$$

$$d_4 := ybar28 - y_4 = 6.968\cdot in$$

$$d_5 := ybar28 - y_5 = -6.282\cdot in$$

$$Itr_{28} := \sum_{i=1}^{5} \left[I_i + A_i\cdot\left(d_i\right)^2\right] = 2437\cdot in^4$$

Stresses at Release

Release: $fpi := 174ksi$ $Fpi := fpi \cdot Ap = 79.866 \cdot kip$

Cracking: $fcr := 180ksi$ $Fcr := fcr \cdot Ap = 82.62 \cdot kip$

Ultimate: $fu := 265ksi$ $Fu := fu \cdot Ap = 121.635 \cdot kip$

$$H := \sum_{i=1}^{3} h_i = 16 \cdot in$$

$$e := ybar3 - y_3 = 6.934 \cdot in$$

axial stress $$\sigma a := \frac{Fpi}{Atr_3} = 988.176 \cdot psi$$

flexural stress $$\sigma f := \frac{(Fpi \cdot e) \cdot ybar3}{Itr_3} = 1.831 \times 10^3 \cdot psi$$

$\sigma t := \sigma a - \sigma f = -842.829 \cdot psi$ stress at top

$\sigma b := \sigma a + \sigma f = 2.819 \times 10^3 \cdot psi$ stress at bottom

Cracking Capacity

$$\omega sw := (Agconcrete \cdot \gamma c) + (\gamma s \cdot Ap) + (\gamma s \cdot Asprime) = 65.621 \cdot \frac{lbf}{ft}$$

$$L := 20ft$$

$$Msw := \frac{\omega sw \cdot L^2}{8} = 3.281 \cdot ft \cdot kip$$

$$\sigma sw := Msw \cdot \frac{ybar28}{Itr_{28}} = 132.773 \cdot psi$$

$$MLL := 1kip \cdot in$$

Given

$$fcr := 7.5psi \sqrt{\frac{fc_{28}}{psi}} = 670.82 \cdot psi$$

$$-\sigma a + \sigma sw - \sigma f + \frac{MLL \cdot ybar28}{Itr_{28}} = fcr$$

$$MLL := Minerr(MLL)$$

$$Pcr := \frac{2 \cdot (MLL)}{8ft} = 20.741 \cdot kip$$

$$MLL = 82.964 \cdot kip \cdot ft$$

Ultimate Capacity

$d := y_1 = 14.5 \cdot in$

$dprime := y_4 = 1.25 \cdot in$

$\varepsilon := 0.003$

$fy := 60ksi$

$fp := 265ksi$

$$\beta := \begin{cases} 0.85 & \text{if } fc_{28} \le 4000psi \\ \left[0.85 - \left[0.05 \cdot \frac{(fc_{28} - 4000psi)}{1000psi}\right]\right] & \text{if } 4000psi < fc_{28} < 8000psi \\ 0.65 & \text{if } fc_{28} \ge 8000psi \end{cases}$$

$c := 1in$

Given

$$\left(0.85 \cdot fc_{28} \cdot \beta \cdot c \cdot b_1\right) + \min\left[Asprime \cdot \varepsilon \cdot \left(\frac{c - dprime}{c}\right) \cdot Es, fy \cdot Asprime\right] - Ap \cdot fp = 0$$

$c := Minerr(c)$

$c = 2.883 \cdot in$

$Cc := 0.85 \cdot fc_{28} \cdot \beta \cdot c \cdot b_1 = 101.926 \cdot kip$

$$Cs := Asprime \cdot Es \cdot \varepsilon \cdot \left[\frac{(c - y_4)}{c}\right] = 19.709 \cdot kip$$

$T := Ap \cdot fp = 121.635 \cdot kip$

$Mn := fp \cdot Ap \cdot [d - (\beta \cdot c \cdot 0.5)] + Cs \cdot (\beta \cdot c \cdot 0.5 - dprime) = 136.965 \cdot ft \cdot kip$

$$Pn := \frac{(Mn - Msw) \cdot 2}{8ft} = 33.421 \cdot kip$$

Shear Capacity

$x := 0.1in, 0.5in .. 90in$

Shear Properties

$Av := 0.04in^2$ $\quad bw := 3in$ $\quad \lambda := 0.75$ $\quad fym := 65ksi$

$H = 16 \cdot in$ $\quad ld := 4in$ $\quad S := 4in$

$dc := \max\left(y_5, 0.8H\right) = 14.5 \cdot in$

$$Vu(x) := \frac{Pn}{2} + \frac{\omega sw \cdot L}{2} - \omega sw \cdot (x) \qquad Vu(0) = 17.367 \cdot kip$$

<u>Concrete Shear Capacity</u>

$$fpc(x) := \begin{cases} \frac{fp}{ld} \cdot x & \text{if } 0 < x < ld \\ fp & \text{otherwise} \end{cases} \qquad Msw(x) := \frac{\omega sw \cdot L \cdot (x)}{2} - \frac{\omega sw \cdot \left(x^2\right)}{2}$$

$$fd(x) := \frac{(Msw(x) \cdot ybar28)}{Itr_{28}} \qquad Mmax(x) := \frac{Pn}{2} \cdot (x)$$

$$fpe := \frac{Fpi}{Atr_{28}} + \frac{(Fpi \cdot e \cdot ybar28)}{Itr_{28}} \qquad Mcre(x) := \left(\frac{Itr_{28}}{ybar28}\right) \cdot \left(6psi \cdot \lambda \cdot \sqrt{\frac{fc_{28}}{psi}} + fpe - fd(x)\right)$$

$$Vd(x) := \frac{\omega sw \cdot L}{2} - \omega sw \cdot (x) \qquad Vi(x) := Vu(x) - Vd(x)$$

$$Vci(x) := \max\left(0.6psi \cdot \lambda \cdot \sqrt{\frac{fc_{28}}{psi}} \cdot bw \cdot dc + Vd(x) + \frac{Vi(x) \cdot Mcre(x)}{Mmax(x)}, 1.7psi \cdot \lambda \cdot \sqrt{\frac{fc_{28}}{psi}} \cdot bw \cdot dc\right)$$

$$Vcw(x) := \left(3.5\lambda \cdot psi \cdot \sqrt{\frac{fc_{28}}{psi}} + 0.3 \cdot fpc(x)\right) \cdot bw \cdot d \qquad Vc(x) := Vci(x) + Vcw(x)$$

$$Vs(x) := \frac{2Av \cdot fym \cdot dc}{S} \qquad \phi Vn(x) := 0.75(Vc(x) + Vs(x))$$