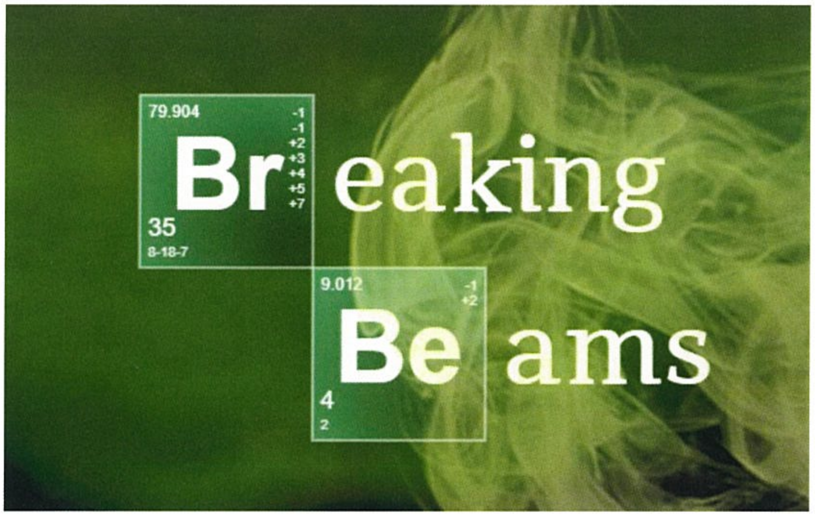
NORTHERN
ARIZONA
UNIVERSITY



Team Members:
Roy Crouch
Stephen Gergal
Fernando Rojo
Brandy Wagoner

Technical Advisor:
Dr. Robin Tuchscherer

PCI Producing Sponsor:
Tpac (Phoenix, AZ)

1.0 Testing Summary

PCI BIG BEAM COMPETITION 2017-18

Date 5/20/2018

Student Team (school name) Northern Arizona University
Team Number 1
Date of Casting 4/6/2018

Basic Information

1. Age of beam at testing (days) 28

2. Compressive cylinder tests*

Number tested 2
Size of cylinders 4 x 8
Average (psi) 8,000

3. Concrete properties

Unit weight of concrete (lb/ft^3) 122.5
Slump (in.) 27
Air content (%) 4
Tensile strength (psi) 358

Circle one: [✓ Split cylinder] MOR beam

4. Pretest calculations

a. Applied load (total) to cause cracking (kip) 20.3
b. Maximum applied point load at midspan (kip) 38.3
c. Maximum anticipated deflection due to applied load only (in.) 5.12

Pretest calculations MUST be completed before testing.

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

Judging Criteria

Teams MUST fill in these values.

1. Actual maximum applied load (kip) 40.3
2. Measured cracking load (kip)‡ 20.0
3. Cost (dollars) 184.58
4. Weight (lb) 1501
5. Largest measured deflection (in.) 4.96
6. Most accurate calculations
   a. Absolute value of (maximum applied load – calculated applied load)/calculated applied load) 5.22%
   b. Absolute value of (maximum measured deflection – calculated deflection)/calculated deflection) 3.13%
   c. Absolute value of (measured cracking load – calculated cracking load)/calculated cracking load) 1.48%

Total of three absolute values (a + b + c) = 9.83%

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

Test summary forms must be included with the final report, due June 15, 2018.

Sponsored by:

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GRACE CONSTRUCTION & PACKAGING

AUTODESK'S SOLUTION ASSOCIATE FOR PRECAST
EDGE^REVIT
PTAC Consulting Engineers, Inc.
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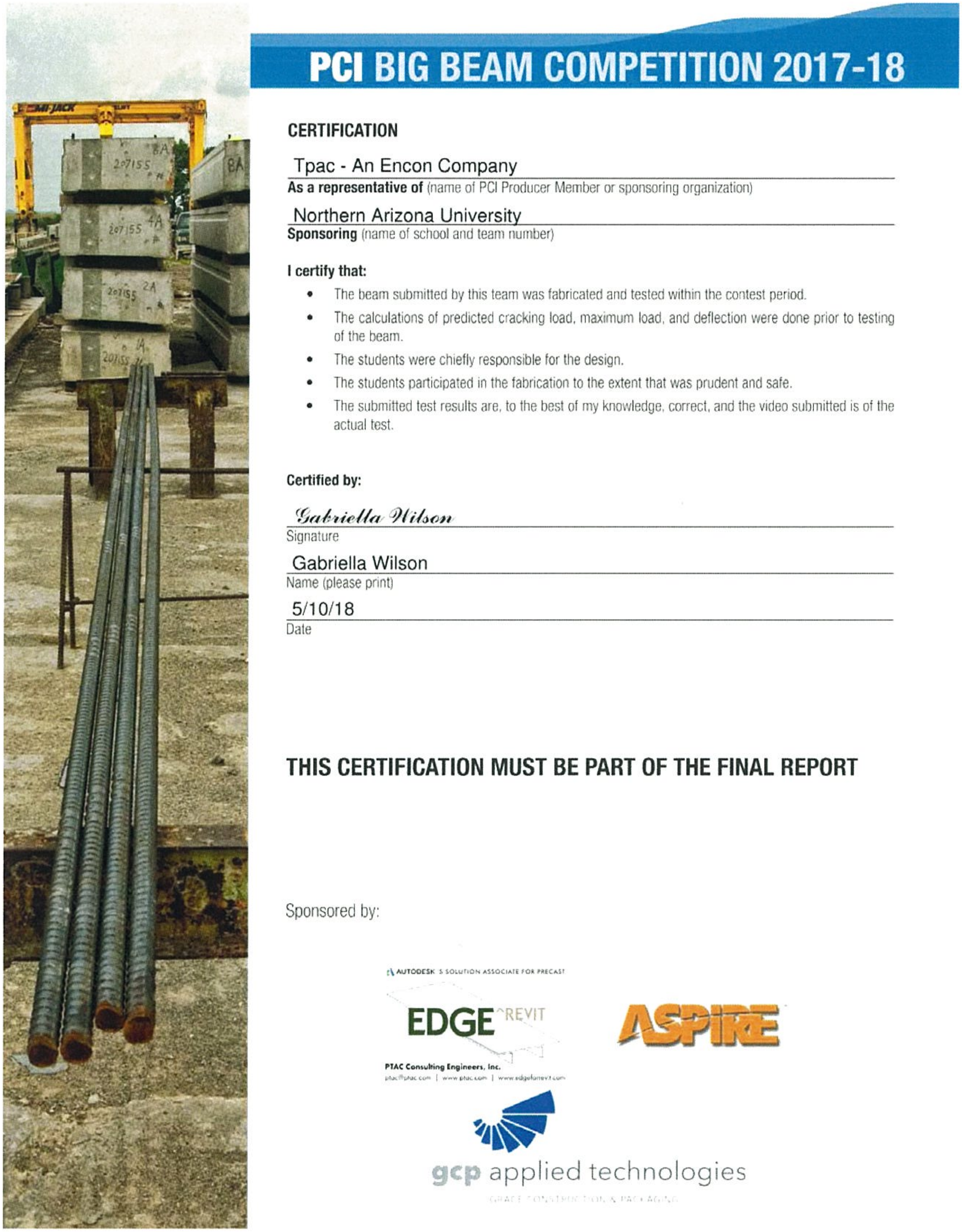
ASPIRE

2.0 Member Certification



PCI BIG BEAM COMPETITION 2017-18

CERTIFICATION

Tpac - An Encon Company

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

Northern Arizona University

Sponsoring (name of school and team number)

I certify that:

- The beam submitted by this team was fabricated and tested within the contest period.
- The calculations of predicted cracking load, maximum load, and deflection were done prior to testing of the beam.
- The students were chiefly responsible for the design.
- The students participated in the fabrication to the extent that was prudent and safe.
- The submitted test results are, to the best of my knowledge, correct, and the video submitted is of the actual test.

Certified by:

Gabriella Wilson

Signature

Gabriella Wilson

Name (please print)

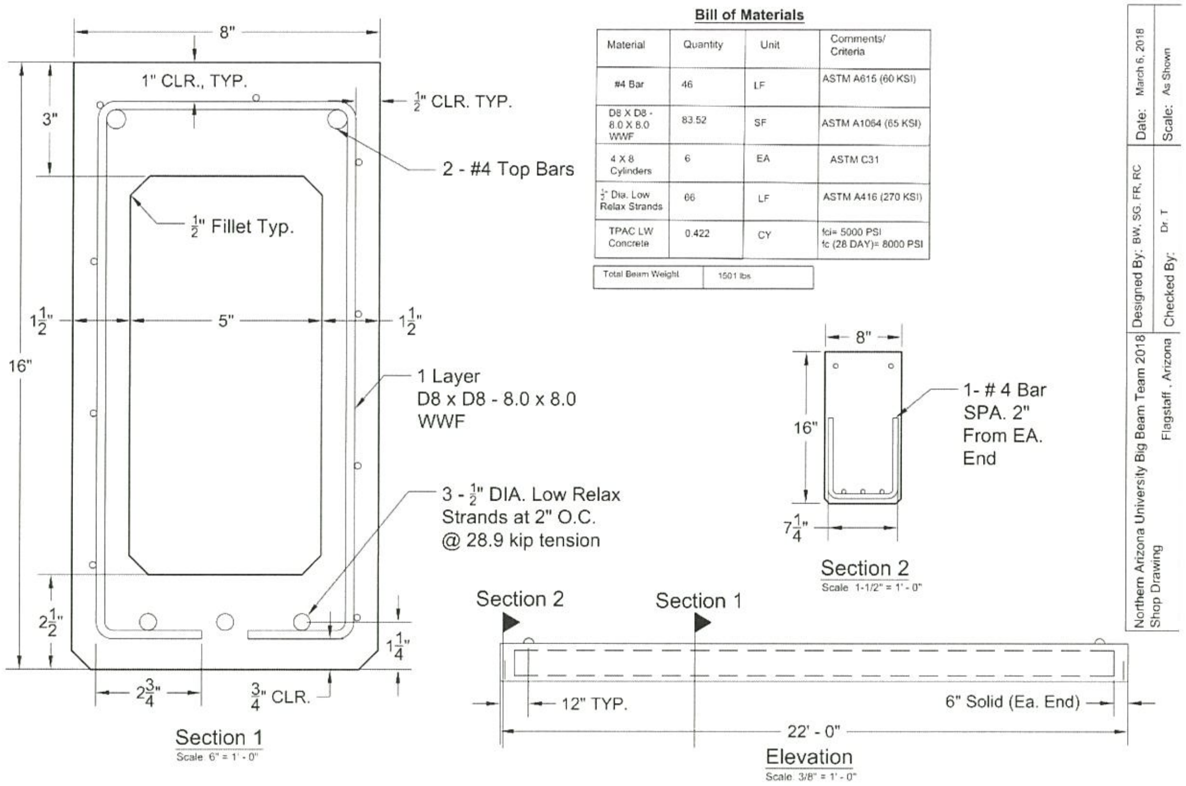
5/10/18

Date

THIS CERTIFICATION MUST BE PART OF THE FINAL REPORT

Sponsored by:

3.0 Shop Drawings



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
$\frac{1}{2}$" 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

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

4.0 Concrete Mixture

4.1 Concrete Mixture Design

The mix selected for use in the fabrication of the prestressed beam was determined by considering six different mix designs, including three mixtures using normal weight coarse aggregates and three mixtures using lightweight coarse aggregates. The team chose to evaluate both normal weight and lightweight mixtures as each type of mixture has advantages and disadvantages when considering the competition judging criteria. The team evaluated two standard concrete mixtures of our sponsor Tpac, including one normal weight concrete aggregate and one with lightweight aggregate. The team also designed four of our own concrete mixtures based off of the proportions of the concrete mixtures from Tpac and typical mix proportioning measurements. These individual mixtures were designed with the intention of highlighting specific components in each mixture, including higher flyash substitute, water to cement ratios, etc. These individual mixtures are described further in Table 1 below. The proportions for each component of the mix are for the full amount of concrete needed for the beam, equivalent to a volume of 27 cubic feet, and the values are in units of pounds.

Table 1: Concrete Mix Design Summary.

	Mix #1 (lbs)	Mix #2 (lbs)	Mix #3 (lbs)	Mix #4 (lbs)	Mix #5 (lbs)	Mix #6 (lbs)
Cement	623	610	600	400	730	730
Fly Ash	267	261	356	478	185	185
Course Aggregate	1550	710	1390	940	867	1484
Fine Aggregate	1288	1200	1360	1070	1328	1268
Water	270	270	270	300	308	283

The team then created a decision matrix, shown below and included in Appendix A: Concrete Mix Decision Matrix, to determine which concrete mixture would perform best in the competition. The weighted factor for each scoring criteria in the decision matrix is shown in the bottom row, and the selected mix is indicated in bold. The team did not make any modifications to our sponsor's lightweight mixture as it could negatively impact the predictability of the concrete mixtures' characteristics, as Tpac has their standard mix proportions well established.

Table 2: Concrete Mix Decision Matrix.

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

4.2 Concrete Mixture Selection

The mixture selected to be used by the team in the fabrication of the prestressed concrete beam was our sponsor Tpac's standard lightweight mix. This mix was selected due to its ability to achieve a high compressive strength while also reducing the weight of the concrete beam. The concrete mix ticket provided by Tpac lists each concrete constituent as well as the material weight, in pounds, and the volume, in cubic feet, of each material per cubic yard of mixed concrete. A breakdown of the concrete mix proportions of Tpac's standard lightweight mix is shown in Table 1, as mix number 2.

The unit weight of Tpac's standard lightweight concrete mixture was determined using Table 1: Tpac Lightweight Concrete Mix Proportions. The total wet unit weight of the concrete mixture is 126.6 pounds per cubic foot, and the dry unit weight of the concrete mixture is 117 pounds per cubic foot. These values both are above the 115 pounds per cubic foot delineation for lightweight concrete and therefore it will not cause our entry to be penalized in our cost analysis for using lightweight concrete.

The mix characteristics for the Tpac standard lightweight mix used for design were determined based on testing performed by the Tpac quality assurance team as well as testing performed by the team in the testing laboratory located in the NAU engineering building. In the design of the beam, the 3-day and 28-day compressive strength of the selected mix was provided by Tpac and their testing laboratories.

The actual slump and air content values of the concrete mixture was provided to the team by Tpac and their testing laboratories. The actual 28-day compressive and tensile strength of the concrete mixture was determined by the team using tests performed on concrete cylinders comprised of the same concrete mixture that was used to fabricate the beam. The modulus of elasticity was determined as a function of the 28-day compressive strength of the mixture per ACI 318-14, Section 19.2.2.1.b [1].

The mixture performed very similarly to what the team expected regarding its compressive strength and modulus of elasticity. The predictions the team made for cracking and ultimate failure loading, as well as the maximum deflection were all within approximately 5% of the actual values determined after testing. This indicates that the 28-day compressive strength of 8,000 psi and the modulus of elasticity value of 5,098 ksi used in design were very close to the actual values of the concrete beam.

5.0 Structural Design

5.1 Preliminary Design

The first step in the design process was to create an automated analytical procedure using MathCAD. MathCAD is a computer program capable of automating calculation for determining critical design parameters. Using MathCAD, the team developed a worksheet to calculate stresses at release, cracking capacity, and ultimate capacity of a prestressed beam. Additionally, MathCAD was used to calculate the shear capacity, required shear strength, and proportion the shear reinforcement for the beam. MathCAD calculations are provided in Appendix B.

A total of 10 cross-sections were analyzed using MathCAD. The team analyzed I shapes, box shapes, bulb T shapes, and C shaped cross-sections. Various shapes were considered, rather than just typical analyzing a typical I-shaped cross-section because innovation is also a scoring parameter in the competition. Cross Sections were proportioned to meet release stress requirements of ACI 318-14, Section 24.5.3.1, and service and ultimate load criteria of the competition.

5.2 Decision Matrix

The team selected the most optimal cross-section using a decision matrix based on three competition categories. These categories are; maximum deflection, minimum weight, and minimum cost. Each of the 10 cross sections were optimized to maximize their score in one or multiple of the previously mentioned categories. The Cross-Section Decision Matrix, shown in Table 3 below and included in Appendix C, illustrates the categories used to determine the best performing beam from our possible design considerations. Ultimately, the beam with the lowest weight, lowest cost, and largest deflection will score the highest. To determine the weighted factor for each beam, a normalized scoring technique was utilized. This technique allowed the team to assign each design consideration a factor based on the best and worst performing beam in each category. The highest-ranking beam cross-section was the Box Beam #2 design, because it provided the largest deflection at the lowest cost and weight.

Table 3: Cross-Section Decision Matrix.

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

In addition, the team preferred a box-shaped beam design because of its improved stability relative to I-shaped cross-sections. While a box and I-shaped section resist flexure similarly, a box section has its web at the outside of the beam cross-section. Moving the web to the outside increases the section's ability to resist any stability effects of lateral-torsional buckling of the flange.

5.3 Final Predictions

MathCAD was used to optimize the cross-section design, and the predicted values were reliable. However, the team employed Response 2000 to achieve a more precise set of prediction values. Response 2000 is a computer program that is used to numerically integrate the full stress strain compatibility behavior of the concrete, reinforcement, and prestressing strands. The preliminary information from MathCAD and the information for the concrete and prestressing strands provided by Tpac were input into the program. Prestrain after losses was calculated using excel (refer to Appendix D) and input into the program. The prestrain calculation included all losses that could occur after casting, except for creep. Creep was disregarded because the beam was tested at 28 days rather than long term, there was also no superimposed dead load. Appendix E: Response Calculations displays the different information put into Response 2000 and shows the beam cross-section as an I-beam, which for the calculations performed in Response 2000 is structurally similar to an I-Beam. Deflection at ultimate load was calculated using the method of virtual work and the moment-curvature behavior provided by Response 2000. Deflection calculations are provided in Appendix F. The final predictions of the team, shown in Table 4: Final Predictions for Beam Performance, shows the cracking, ultimate failure, and maximum deflection of the beam design.

Table 4: Final predictions for final beam performance.

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

6.0 Beam Fabrication and Testing

6.1 Fabrication

As shown, the final beam consists of two mild reinforcement #4 grade compression steel bars, ½" diameter grade 270, low relaxation prestressing strands, and D8 x D8- 8.0 X 8.0 welded wire fabric (WWF). Originally however, the beam was designed using a W4.0 X W4.0 WWF cage but due to availability the D8.0 x D8.0 WWF was used instead.

The beam was cast the morning of April 6, 2018 at the Tpac's plant in Phoenix, AZ. The team performed quality control measurements of the beam such as height and width. Styrofoam was used to form the box's void, and small wooden wedges measuring exactly 3" were placed periodically along the top of the form to prevent the Styrofoam from rising above acceptable tolrances. Quality control also including verifying the grade of the mild reinforcement, prestressing strands, and welded wire fabric. The prestressing strands were each pulled to 31 kips prior to casting. The concrete was self-consolidating and did not need to be vibrated. At the same time the beam was cast, six 4 X 8 in. cylinders were also cast for later determination of concrete compressive and tensile strengths. The beam cured for three days before the strands were cut. The beam was allowed to cure for an additional 28 days before it was shipped from Phoenix to Flagstaff.

Figure 1: Formwork – Side View.

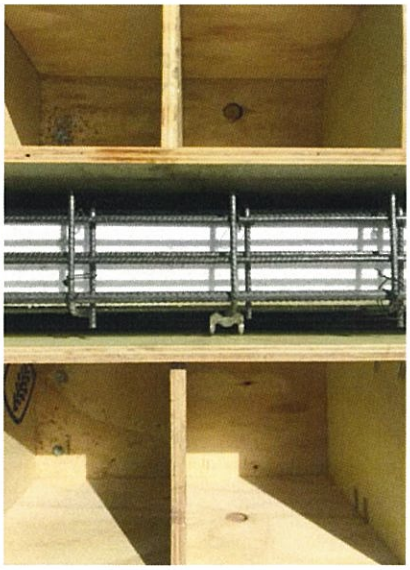


Figure 2: Formwork – Top View.

Figure 3: Beam Casting.

The beam and cylinders were shipped to the concrete lab at Northern Arizona University (NAU) on April 26, 2018.

6.2 Test Setup

The steel testing frame located at the NAU concrete lab known as "The Hulk", had to be adjusted to load the beam per the competition requirements of the 2017-2018 competition year. The supports were placed 20 feet from center to center. Load plates were placed two feet from the centerline of the testing frame in each direction to act as the two point loads. A total of two hydraulic cylinders applied the load, and a 50-kip capacity load cell was placed at the load location. String potentiometers were placed at the support locations and at the centerline of the beam to collect the displacements of the supports and the overall deflection of the beam. The deflection measured at the beam centerline was reduced by the average deflection measured at the support. Finally, a ruler was glued to the centerline of the beam, and neon yellow mason string stretched between supports. Combined, the ruler and string provide visual verification of the member deflection of the beam. The load and deflection data was collected and conditioned using a National Instruments SCXI Data Acquisition system and respective modules.

6.3 Results

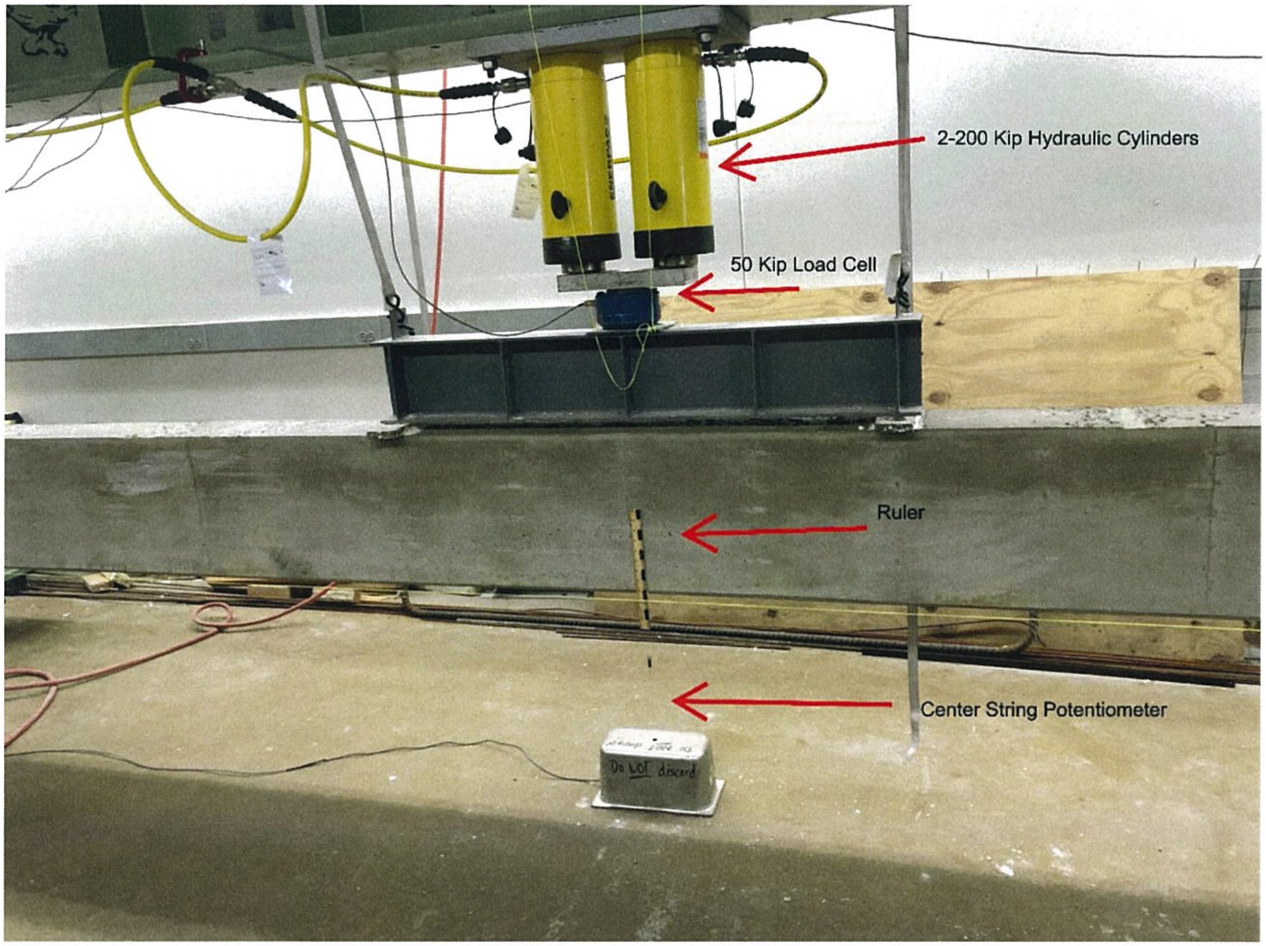


Figure 4: Testing Set-Up.

The beam was loaded at a rate of 100-200 pounds per second by applying a single point load from two-200 kip hydraulic cylinders to the load cell. As the test was performed, LabView was used to collect and display the test data. The team uploaded Labview data into excel to determine the cracking load, failure load, and maximum deflections. The Labview data is shown as Figure 5: Load Vs. Deflection Plot.

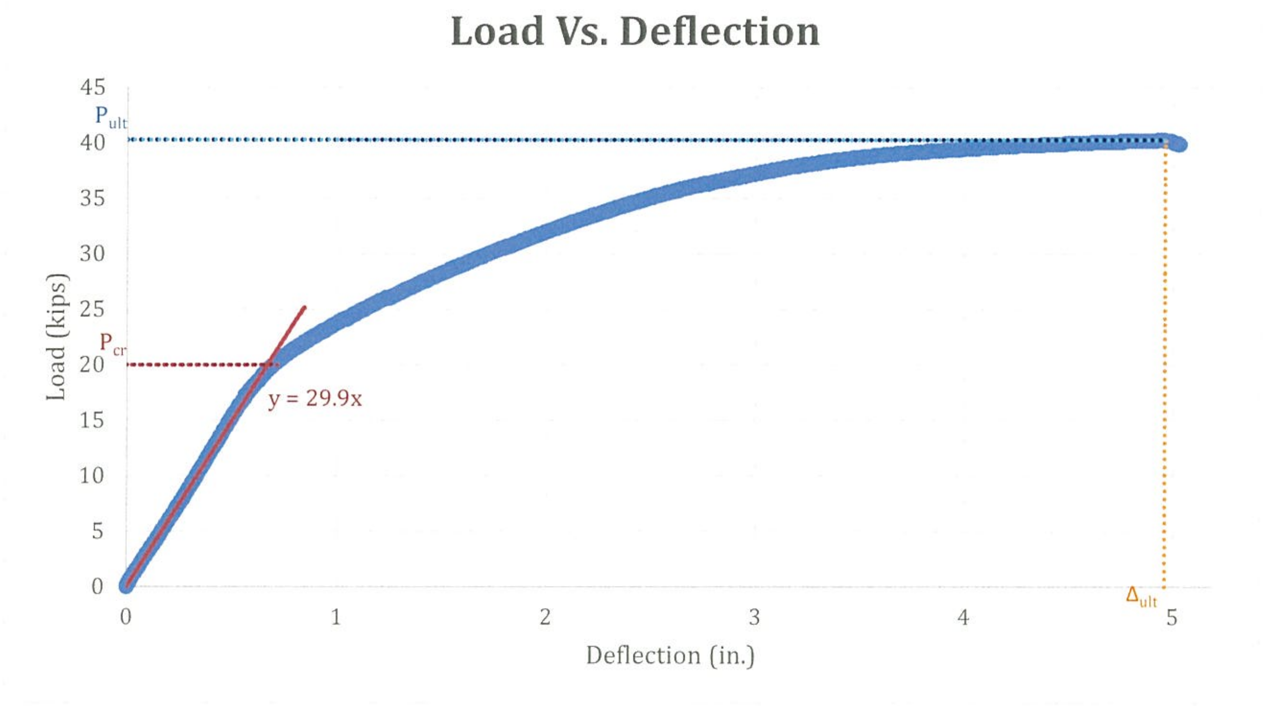


Figure 5: Load Vs. Deflection Plot.

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. The pre-cracking equation was determined by creating a best-fit curve for the data measured up to where the load reached 10 kips, as this was an area of the load vs displacement curve that was known to be linear. Then, a second linear function was defined as "crack deviation," which was simply a function with the same slope as the pre-cracking equation (29.9), offset by a predetermined deviation value, which was assumed to be 0.01 in. This deviation represents a significant departure from the linear response to ensure a cracking has occurred, while also being small enough to measure when the "first" crack occurs. This line intersects with the measured Load Vs. Deflection curve at 20.0 kips, which is the measured cracking load, as shown in Figure 6 below.

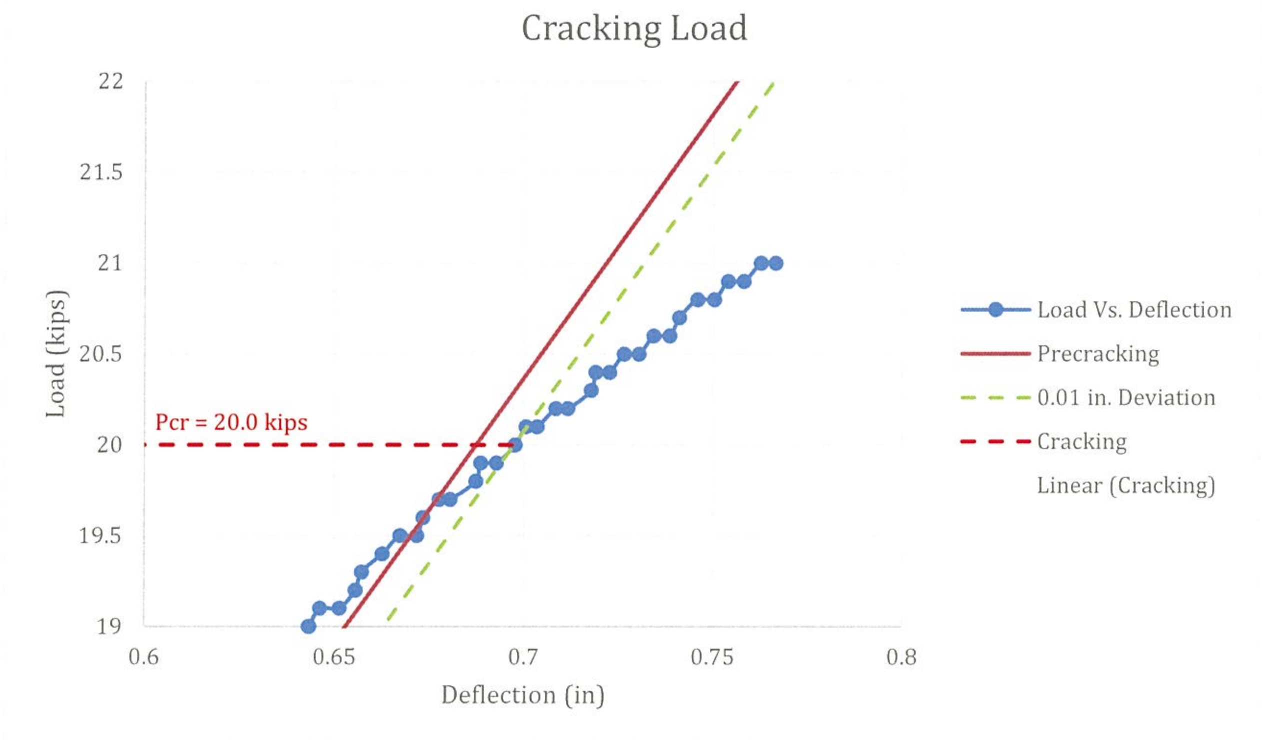


Figure 6: Cracking Load.

Table 5: Predictions Vs. Measured Values below, shows the predicted values as compared with the values measured during testing, including the percent difference for these values.

Table 5: Predictions Vs. Measured Values.

	Predictions	**Actual**	**% Diff**
Cracking Load (kips)	20.3	20.0	1.48%
Ultimate Load (kips)	38.3	40.3	5.22%
Deflection (in)	5.12	4.96	3.13%
	Total		**9.83%**

6.4 Autopsy

At the bottom of the beam, many small cracks began to form and propagate to the top of the beam. This indicated a flexural failure of the beam as well as yielding of the prestressing strands. The concrete was not crushed at all, and this is shown in the load deflection diagram where the curve drops immediately at the ultimate cracking load. This is because immediately after the flexural failure, the beam experienced a secondary failure as the compression steel buckled. It is due to the secondary failure that the beam lost equilibrium and the test was stopped.

7.0 Personal statements

This competition was fun to work on because in school we learn a lot of equations and methods to use in structural analysis, but we never actually create and load anything until we begin an engineering career. This project gave us an opportunity to put our education to the test in several different areas including designing a beam for fabrication, where it must live up to industry engineering drawing standards. It also required a high degree of engineering and structural analysis, performing calculations on everything from deflection predictions to various loading considerations during transportation. Finally, this competition gave the team an opportunity to learn more about a specific type of structural engineering, compared to the course we take on mildly-reinforced concrete members in our undergraduate studies.

Roy Crouch
1816 W Tombstone Trail
Phoenix, AZ 85085

The most challenging aspect of this competition for me was determining the mix proportions that would perform best in the competition. With this competition being the first time any of the team members had created a concrete mix, it took research of typical concrete mixture proportions as well as considering the standard mixes of our sponsor to determine mixes that would perform adequately. Also, the materials available to us as far as aggregates were limited to local supplies of aggregate that the team could have donated to us, and if our school was located somewhere else, different aggregates would have been considered for use in the concrete mixtures. The fact that our predictions were so close to the actual values that were determined upon testing gives me a feeling that the methods learned in school and used in the analysis of our beam are viable methods to predict how prestressed concrete beams perform under loading.

Stephen Gergal
1103 N Montrose Way
Scottsdale, AZ 85254

This competition has helped me gain a lot of information, for starters, I have never mixed concrete before. When it came to developing the concrete mixes and then having to make concrete cylinders in order to test them in order to determine their strengths. It was a nice learning experience figuring out how to test our concrete cylinders for compressive strength and tensile strength using different machines. When testing day finally came, I was so excited to see a whole year's worth of work be worth it when our predicted values were really close with the actual values.

Fernando Rojo
6358 W Mohave St
Phoenix, AZ 85043

This competition allowed me to expand my knowledge in the concrete industry. Through this competition I gained the abilities to not only analyze, but also design a prestressed concrete beam without ever taking a course in prestress design. This competition was very rewarding to me personally by giving me the opportunity to explore a new engineering discipline, and giving me unforgettable experiences with my teammates, professors, and sponsors.

Brandy Wagoner
PO Box 948
St. Johns, AZ 85936

References

[1] American Concrete Institute, "ACI 318-14".

APPENDICES

Table of Appendices:

Appendix A: Concrete Mix Decision Matrix

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	

Appendix B: MathCAD Calculations

Given Properties

Area of Reinforcing Steel	$\mathrm{Asprime} := 0.4\mathrm{in}^2$
Area of Strand	$\mathrm{Ap} := 3\cdot 0.153\mathrm{in}^2 = 0.459\cdot\mathrm{in}^2$
Compressive Strength of Concrete at 3 days	$\mathrm{fc}_3 := 5\cdot\mathrm{ksi}$
Compressive Strength of Concrete at 28 days	$\mathrm{fc}_{28} := 8\mathrm{ksi}$
Modulus of Elasticity at 3 days	$\mathrm{Ec}_3 := 57\,\mathrm{ksi}\sqrt{\dfrac{\mathrm{fc}_3}{\mathrm{psi}}} = 4030.509\cdot\mathrm{ksi}$
Modulus of Elasticity at 28 days	$\mathrm{Ec}_{28} := 57\mathrm{ksi}\sqrt{\dfrac{\mathrm{fc}_{28}}{\mathrm{psi}}} = 5098.235\cdot\mathrm{ksi}$
Modulus of Elasticity of Steel	$\mathrm{Es} := 29000\mathrm{ksi}$
Unit Weight of Concrete	$\gamma\mathrm{c} := 0.07\,\dfrac{\mathrm{lbf}}{\mathrm{in}^3}$
Unit Weight of Steel	$\gamma\mathrm{s} := 490\,\dfrac{\mathrm{lbf}}{\mathrm{ft}^3}$

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

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

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

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

$$Atr_3 := \sum_{i=1}^{5} A_i = 80.822\cdot in^2 \qquad ybar3 := \frac{\left[\sum_{i=1}^{5} (A_i\cdot y_i)\right]}{\left(\sum_{i=1}^{5} A_i\right)} = 8.184\cdot in$$

$$d_1 := ybar3 - y_1 = -6.316\cdot in \qquad I_4 := 0 \qquad I_5 := 0$$

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

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

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

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

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

Transformed Section at 28 days

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

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

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

$$Atr_{28} := \sum_{i=1}^{5} A_i = 79.986 \cdot in^2 \qquad ybar28 := \frac{\left[\sum_{i=1}^{5} \left(A_i \cdot y_i\right)\right]}{\left(\sum_{i=1}^{5} A_i\right)} = 8.218 \cdot in$$

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

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

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

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

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

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

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

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

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

$d := y_1 = 14.5 \cdot in$

$dprime := y_4 = 1.25 \cdot in$

$\varepsilon := 0.003$

$fy := 60ksi$

$fp := 265ksi$

$$\beta := \begin{array}{|l} 0.85 \;\; \text{if} \;\; fc_{28} \le 4000psi \\ \left[0.85 - \left[0.05 \cdot \dfrac{\left(fc_{28} - 4000psi\right)}{1000psi}\right]\right] \;\; \text{if} \;\; 4000psi < fc_{28} < 8000psi \\ 0.65 \;\; \text{if} \;\; fc_{28} \ge 8000psi \end{array}$$

$c := 1in$

Given

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

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

$c = 2.883 \cdot in$

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

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

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

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

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

Shear Capacity

$x := 0.1\text{in}, 0.5\text{in} .. 90\text{in}$

Shear Properties

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

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

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

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

Concrete Shear Capacity

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

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

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

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

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

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

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

Appendix C: Cross-Section Decision Matrix

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 D: Prestrain Calculations

Estimating Prestress Loss

Elastic Shortening

K_{es}	1	
E_{ps}	28500000	psi
f_{cir}	2613.951	psi
E_{ci}	4030509	psi
ES	18483.42	psi

Losses Due to Shrinkage

K_{sh}	1	
V/S	0.00589	
RH	30	%
SH	16353.22	psi

Losses Due to Relaxation

	K_{re}	5000	Table 5.7.
	C	0.53	Table 5.7.
Design Aid	f_{pi}	198.2571	K/in^2
	J	0.04	Table 5.7.
	RE	1911.463	psi

To Calculate ⍰f_{cir}

K_{cir}	0.9	
A_g	74.641	in^2
e	6.75	in
I_g	2248.3	in^3
M_g	3970.071	lb-ft

Total Losses

TL	36748.1	psi
f_p	125.8835	ksi

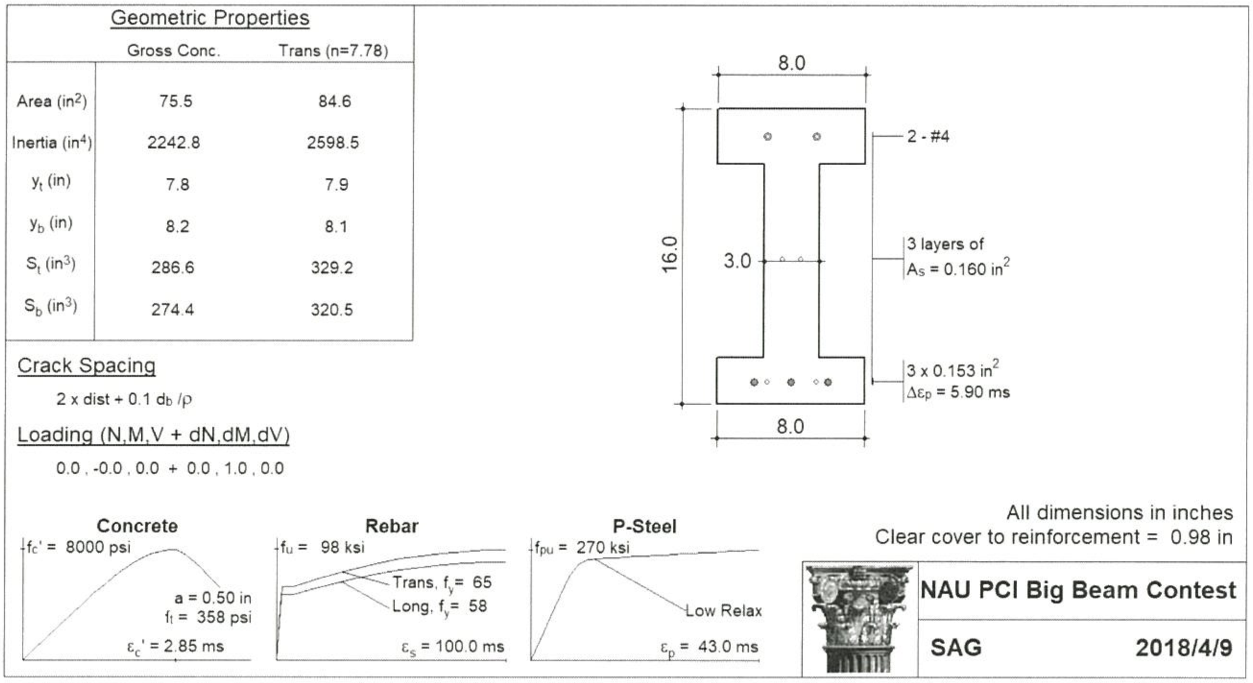
Anchorage losses

A_{ps}	0.459	in^2
f_{pu}	176.2745	ksi
$\mathbf{P_i}$	**91**	**kip**

Strain Calculation

A	0.025	
B	118	
C	10	
E_p	28500	ksi
ϵ_p	0.005853	in/in
f_p	166.4144	ksi
f_{pu}	176.2745	ksi
	166.414	

Appendix E: Response Calculations



Geometric Properties

	Gross Conc.	Trans (n=7.78)
Area (in^2)	75.5	84.6
Inertia (in^4)	2242.8	2598.5
y_t (in)	7.8	7.9
y_b (in)	8.2	8.1
S_t (in^3)	286.6	329.2
S_b (in^3)	274.4	320.5

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

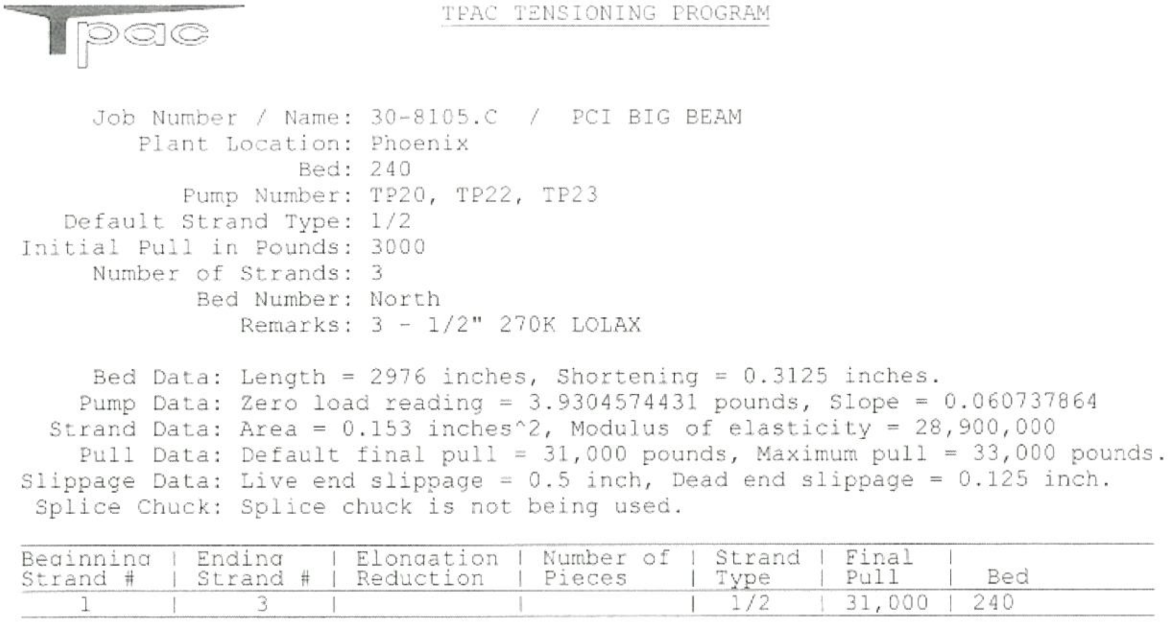
NAU PCI Big Beam Contest

SAG **2018/4/9**

Appendix F: Deflection Calculations

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
	Deflection with camber			**5.117003**

Appendix G: Tpac Tensioning Report



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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 | Ending    | Elongation | Number of | Strand | Final  |
Strand #  | Strand #  | Reduction  | Pieces    | Type   | Pull   |  Bed
    1     |     3     |            |           |  1/2   | 31,000 | 240
```

Tpac

PHOENIX TENSIONING RECORD

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

CAST: / INSPECTOR: Currie TENSIONED BY: K

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			
					ELONGATION TOLERANCE (IN.)				GAUGE TOLERANCE	
STR NO.	STR SIZE	PACK NUMBER	FINAL ELONGATION MEASUREMENT	DESIRED ELONG	LOW	HIGH	FINAL GUAGE READ.	REQD GAUGE READ.	LOW	HIGH
1	1/2	2013784517	19 3/8	19 1/4	18 3/4	19 3/4	1930	1930	1880	1980
2	1/2	120137841523	19 1/2	19 1/4	18 3/4	19 3/4	1930	1930	1880	1980
3	1/2	120137841516	19 1/4	19 1/4	18 3/4	19 3/4	1930	1930	1880	1980

MULTIPLE STRAND STRESSING / ELONGATION REPORT

JOB ID: 30-8105.C / PCI BIG BEAM
PLANT: PHOENIX
BED: 240
BED ID: North
PUMP: TP20, TP22, TP23
JACK: 23
REMARKS: 3 - 1/2" 270K LOLAX
NOTES: All strands to receive initial 3000 pounds tension before mearsurements.

Stressed By: ____________ 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 H: Beam Photos

Figure A-1: Split-Cylinder Test.

Figure A-2: Compression Test.

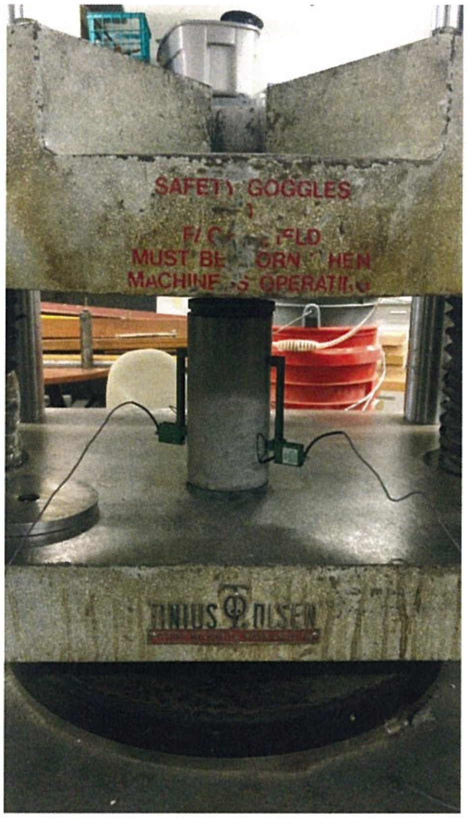

Figure A-3: Tinius Olsen Machine.

Figure A-4: Formwork – Side View.

Figure A-5: Concrete Casting.

Figure A-6: Beam 28 days after Casting.

Figure A-7: Beam at Failure.

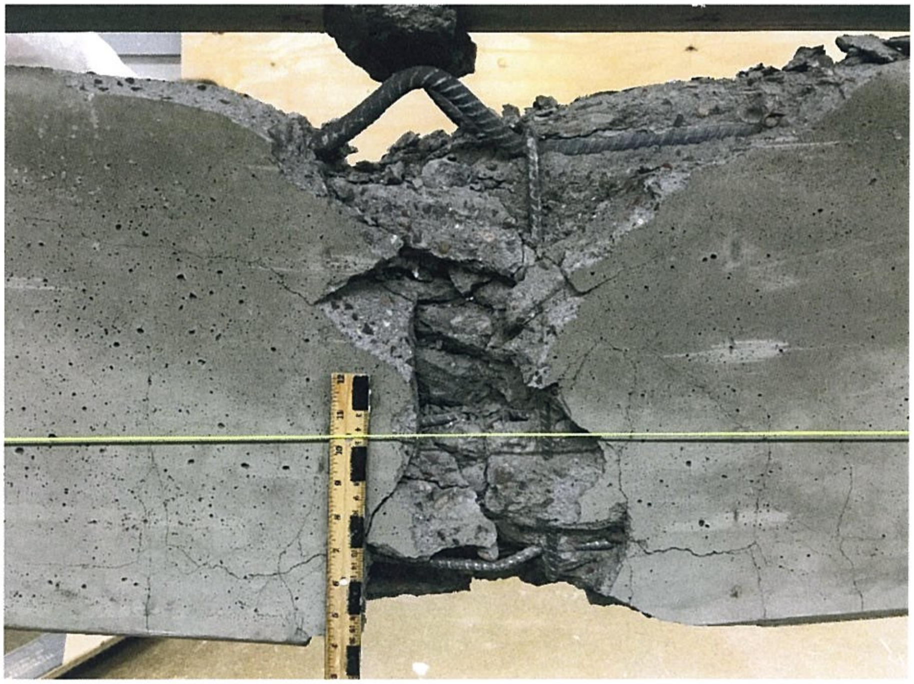

Figure A-8: Compression Steel Buckling.