Oregon State UNIVERSITY OSU

PCI Big Beam Contest 2016-2017

Oregon State University

Advisor: Dr. Keith Kaufman

Madhav Parikh, Thomas Fruin, Kolton Mahr, Spenser Maunu, Makenzie Ellett, Andy Truong

Table of Contents

List of Figures

List of Tables

Executive Summary

The Oregon State University's 2016-2017 Big Beam Team greatly appreciated the opportunity to participate in this competition. This year's team was comprised of six students: Thomas Fruin, Kolton Mahr, Spenser Maunu, Madhav Parikh, Andy Truong, and team lead Makenzie Ellett. The team was advised by Dr. Keith Kaufman, an instructor at Oregon State University and a professional design engineer for Knife River, the PCI Producer Member.

The Big Beam Team designed, fabricated, and tested a prestressed beam over a span of nine weeks. This year's team began designing the beam at the start of April, the beam was cast at the beginning of May, and testing was completed exactly 28 days later on June 2nd. The chosen design was a bulb-shaped member composed of three straight prestressing strands, and incorporating a varying top flange width to reduce cost and weight. The final weight and cost of the beam were 928 lbf and $133.77, respectively. After constructing the beam, the team predicted the cracking load, failure load, and ultimate deflection of the beam using a moment-curvature analysis. These predictions were compared to actual values obtained during testing. See Table 1, below, for a summary of these results. The team felt that the expected values were reasonably close to the actual results, and were satisfied with the beam's performance.

Table 1: Summary of Results

	Predicted Values	Actual Values	Percent Difference
Cracking Load	23.48 kip	23.50 kip	0.09%
Failure Load	38.41 kip	40.71 kip	5.99%
Ultimate Deflection	5.37 in	4.53 in	15.6%

Design

Concepts and Considerations

To begin the design process, the team familiarized themselves with the rules and loading scenario for this year's competition. Based on this information, and past designs from Oregon State Big Beam teams, the team chose to focus on an I-shape cross-section. Beam theory shows that the I-shaped section is efficient for carrying both bending and shear loads in the plane of the web, and it produces a higher moment of inertia by moving material as far away as possible from the centroid.

Flexure

The first design component considered for the beam was flexure. Three main criteria dictated the flexural design of the beam: cracking load, failure load, and ultimate deflection. After initial discussions with Knife River, the prestressing plant, it was decided that only straight strands would be used, both for ease of construction and safety. Additionally, Knife River recommended using f'ci = 9,000 psi (at transfer) and f'c = 12,000 psi (28-day strength) for design parameters, based on expected performance of the concrete mixture. Based on past designs, an initial cross-section and prestressing strand layout was selected. From this starting point, the team used an iterative process to determine the most efficient flexural design. The team used strain-compatibility analysis to determine flexural capacity of the initial beam designs.

The height was the most critical parameter controlling the nominal moment capacity of the beam. For maximum competition points, the beam was required to fail within the 32 – 39 kip range, and a height was selected such that the failure load was within that range. As part of the flexural design, the team also checked the development length of the prestressing strand to ensure they would develop prior to the loading points. The second design requirement controlling the beam was the no cracking under service load conditions constraint. This criteria controlled the extreme fiber stresses, and thus the amount of prestressing strand in the beam. The number and size of the prestressing strands had to be selected so that the tension fiber stresses were kept below the modulus of rupture. The modulus of rupture that limited the tension fiber stresses was dependent on the team's initial concrete strength assumptions, which were conservative. The hardest part was resisting cracking under service loading while also staying below the upper bound failure range of 39 kips. Whenever the service stresses were satisfied the beam would become too strong. Eventually, after many iterations, the cross-section and strand layout were finalized. See Figure 1 for rendering of the beam cross section.

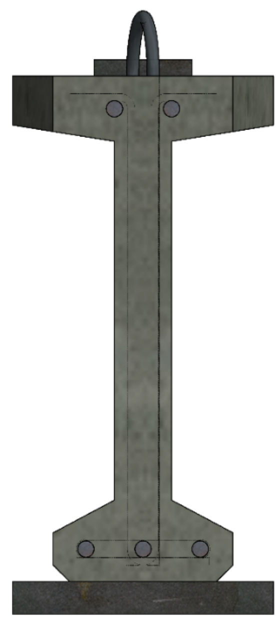

Figure 1: Cross Section

Losses

To make accurate predictions about the beam for the competition, the team needed an accurate prediction for the effective prestressing force at the time of testing, 28 days after casting. Unlike typical prestressed concrete beam design, this beam will never see the total losses found using the traditional PCI method. The NCHRP method for predicting prestressing losses at a given time was implemented to determine the losses that would occur during the 28-day curing window (Tadros, Al-Omaishi, Seguirant, & Gallt, 2003). The effective prestressing force was then determined from the actual jacking forces and these 28-day losses. This calculation was especially critical in determining the cracking load for the beam.

Shear

To ensure the beam had adequate shear capacity, and to prevent excessive use of steel, the team performed a comprehensive shear analysis to take advantage of the high strength concrete contribution of the web. V_{ci}, the nominal shear strength provided by concrete when diagonal cracking results from combined shear and moment, was higher at the supports, while the contribution from V_{cw}, the nominal shear strength when diagonal cracking results from excessive principal tensile stress in web, was higher near midspan. The stirrup spacing design between these two regions of the beam was aggressive to ensure the shear capacity of the beam barely exceeded shear demands.

D4 steel stirrups donated by Davis Wire, which have significantly smaller area and higher yield strength, 65 ksi, were chosen for use in this beam. Additionally, the team opted to utilize an alternating single leg stirrup configuration to reduce congestion in the web for constructability purposes. A strong understanding of concrete shear behavior allowed the team to reduce web width by nearly 50%, from 3.25” to 1.75”, leading to significant cost and weight savings.

Optimization

To develop an optimal structural design, the team opted to use minimum allowable dimensions for concrete cover on both the top and bottom flanges, as well as the web. Additionally, as chamfers are required on the level surfaces of the designed cross section for form removal, the team maximized these chamfers while still maintaining required cover to cut on concrete costs.

Understanding the top flange width was limited by the flexural demands in the 3 ft. between loading points, the team sought a way to further economize the design by considering a non-prismatic shape of the top flange. After verifying that the modification conformed to code and rule requirements, the team moved forward with the idea of reducing the top flange width where the flexural demands were low. The required top flange width was tapered at a slope of 1:6 starting 6 in. from the point of load, decreasing from 8.0 in. at midspan to 5.5 in. at the ends. This change shaved off roughly 55 lbs. of concrete, allowed the mild steel reinforcement to be reduced from #5 bars to #4 bars, and reduced formwork area by 4.77%. Total costs reduction from the top flange reduction can be seen in Table 2.

Table 2: Optimization Summary

Material	**Prismatic Section**	**Non-prismatic Section**	**Difference**	**% Difference**	**Cost Savings**
Concrete	0.214 yd^3	0.20 yd^3	0.014 yd^3	6.54	\$1.63
Mild Steel	2-#5 bar (0.62in^2)	2-#4 bar (0.40in^2)	14.0 lbs	35.5	\$6.30
Formwork	61.286 ft^2	58.365 ft^2	2.921 ft^2	4.77	\$3.65

See Figure 2 below for a plan view of the tapered flange. For further detail, see Appendices A and B for shop drawings and design calculations.

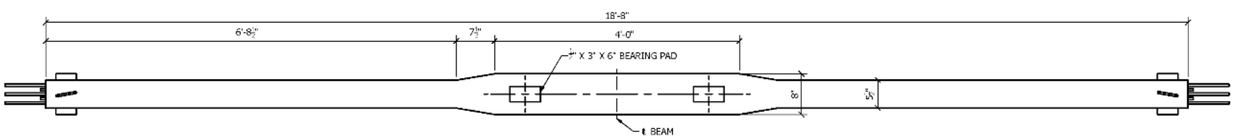

Figure 2: Plan View of Tapered Flange

Materials

Concrete

The concrete mix used to construct the beam was provided by Knife River. This concrete mixture was composed of Type III cement, ½" coarse aggregates, sand, and included 3% entrapped air. The provided batch tickets of the day of casting indicated a water-to-cement ratio of 0.281, unit weight of 151 pcf, and an expected 28-day compressive strength of 11,560 psi. Additional admixtures were added to the mix prior to casting to improve its fluidity for pouring. See Appendix C for the concrete mix design and batch tickets. The concrete mix performed better than expected, reaching a 28 day strength of over 15,000 psi.

Prestressing Strand

Three uncoated, seven wire, ½" diameter, Grade 270, low relaxation prestressing strands following ASTM A416 were used in the fabrication of this beam. These prestressing strands were provided by Sumiden Wire. The mill certificate provided with the prestressing strand, which can be found in Appendix C, listed the properties of the strand, as shown in Table 3.

Table 3: Prestressing Strand Properties

Material Property	Value
Elastic Modulus	28,700 ksi
Area of Prestressing Strand	0.1512 in^2
Yield Strength	40.3 kip
Breaking Strength	43.2 kip
Ultimate Stress	286 ksi
Yield Stress	266 ksi

Shear Reinforcement

D4 welded wire shear reinforcement was used throughout the beam. The 75 stirrups were cut and bent by Knife River prior to fabrication of the beam. The shear reinforcement was assumed to have a yield strength of 65 ksi.

Mild Reinforcement

Mild reinforcement was added to the top flange of the beam to control cracking at transfer of prestressing. Two #4 grade 60 bars, a total area of 0.4 in^2, were provided by Knife River. The mild reinforcement extended past the formwork of the beam, and were cut after the beam's release.

Cost

Using the cost specifications provided by PCI, and the volume of materials used in fabrication, the cost of the beam was calculated to be $133.77. The concrete quantity determined for the cost analysis used the total volume of the cross-section, and subtracted out the volume of prestressing strand, shear reinforcement, and mild steel. The formwork was the most significant component of cost, followed by the concrete quantity. Table 4 below shows the itemized summary, and a detailed breakdown of the quantities and costs associated with each component of the beam can be found in Appendix 3.

Table 4: Cost Summary

ITEM	UNIT	QUANTITY	$/UNIT	COST
Concrete	CY	0.196	$ 120	$ 23.54
Prestressing Strand	FT	56.0	$ 0.30	$ 16.80
Mild Steel	LB	27.5	$ 0.45	$ 12.39
Shear Reinforcement	LB	16.2	$ 0.50	$ 8.07
Formwork	SF	58.4	$ 1.25	$ 72.96
			TOTAL =	**$ 133.77**

Fabrication

Strand Jacking

Prior to jacking, 12 banding strips were placed around the prestressing strands; six strips were positioned at each end spaced roughly 2 in. apart. Three ½ in. diameter strands were used in the beam and they were specified to be jacked to 31 kips. The actual jacking force per strand was 31.7 kips, 31.2 kips, and 31.6 kips for the three strands. The strand was jacked with a hydraulic ram and strand anchor grips. One strand was jacked at a time.

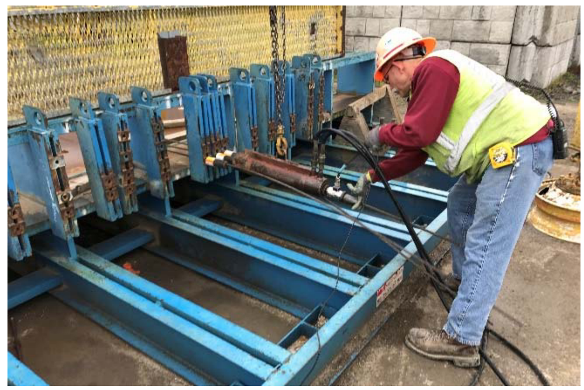

Figure 3: Strand Jacking

Cage Construction

The cage was assembled following the strand jacking. The cage was composed of 75 WWR D4 stirrups, and two #4 reinforcing bars that spanned the entire length of the beam. The stirrups were tied to the prestressing strand and the mild reinforcing bars using zip-ties and wire ties. According to the design, the stirrup legs alternated directions. After the cage was assembled, the formwork was pulled into place.

Figure 4: Stirrup Installation

Casting

The beam was cast with the concrete mix described in the materials section. The mix was made at the batch plant on site and delivered to the casting bed with a pump truck. The mix was poured and vibrated starting at one end of the cage and slowly moving to the other end. After the pour was completed, the top was finished with a finishing trowel. Test cylinders and flexure beams were also cast in order to verify and adjust the assumed material properties of the concrete used in the beam analysis.

Figure 5: Concrete Pour

Curing

Immediately after casting the beam a concrete curing compound was added and wet burlap was laid over the top. The beam remained on the casting bed for three days with burlap and heaters. Following these three days, the formwork was removed and the prestressing strand was cut. The beam cured for a full 28 days before testing.

Analysis

The initial calculations performed to design the cross-section and reinforcement detailing of the beam were done using the strain-compatibility method. For this analysis, the ultimate concrete compression strain was conservatively assumed to be 0.003 in/in. This spreadsheet also tracked the top and bottom stresses along the beam due to prestressing, self-weight, and the test load. For the final prediction calculations using the as-built beam parameters, the team sought to develop a more advanced model to predict beam behavior. This was achieved through research into material behavior of the concrete and prestressing steel, and by using a more accurate analysis method to predict total deflection.

First, a better stress-strain relationship of the strands was found using the "power formula" developed at the University of Nebraska-Lincoln for 270 ksi low-relaxation strand (Devalapura & Tadros, 1992). The power formula utilized the material specifications provided by the manufacturer, and ultimately provided the steel stress at ultimate flexure, f_{ps}. The power formula calculations for prestressing strand stress-strain behavior can be found in Appendix B.

For total deflection, the team studied the moment-curvature approach. A moment-curvature analysis uses the true non-linear stress-strain concrete relationships rather than the Whitney stress block that is typically assumed for design and analysis. As the name implies, this approach uses the mechanical relationship between bending moment and curvature to get an accurate deflection. Curvature was determined from the strain diagram and the extreme fiber strain. Bending moment was calculated using equilibrium between the non-linear concrete compression stress and the axial tension in the reinforcement. A range of moment and curvature values were obtained for each typical section by iterating on the extreme compression fiber strain, taking it all the way to failure. Due to the optimized flange design, moment-curvature was done for 3 typical sections: the 5.5 in. flange at the ends, the tapered region using an average flange width of 6.75 in., and the 8 in. flange at midspan. The ultimate concrete compression strain was assumed to be 0.0035 in/in for the moment curvature analysis. The team decided to use this strain based on the high-strength concrete used, and analysis of previous Oregon State final reports for the competition showed that the beams failed closer to this higher strain.

With the moment-curvature data for each typical section, total deflection at failure could be calculated. The bending moment along the beam at the expected failure load of 38.4 kips was correlated with the curvature for each section along the beam. This curvature was then plotted against the beam span, and integrated to find total deflection. Because of the iterative nature of the moment-curvature method, a Microsoft Visual Basic for Applications (VBA) script was used to perform this analysis. See Appendix B for the output from the moment-curvature and load deflection analyses. The total deflection prediction was taken as a difference in the load-deflection from ultimate loading, 4.91 in., and the initial camber that was also estimated using moment-curvature analysis with only the self-weight of the beam applied, 0.88 in.

Testing

The beam was transported to the Hinsdale Wave Research Lab at Oregon State University on May 26th. The surface of the top flange was made smooth with a grinder at the load point locations and strain gauge location. The center of the beam was marked on the top flange and bearing locations were marked that either end of the 18 ft. span.

The beam exhibited approximately 1/8” of out-of-plane sweep as a result of error in the formwork and the resulting asymmetry of the prestressing strands, along with the slightly unbalanced jacking forces. To ensure that the application of point loads did not impart any external moment (due to eccentricity caused by the sweep), the points of application for the loads were adjusted to lie in the same line as the bearing points. Two points, 1.5 ft. away from the centerline of beam were marked. One side of the beam was painted according Oregon State's colors, while the other side was whitewashed to better see the propagation of cracks. The day before testing, the beam was placed on the supports 18 ft. apart at marked end bearing locations in the test setup and 6 in. bearing pads were placed at the marked locations of the point loads. Two strain gauges were applied to the flange, on either side of the centerline. Two displacement measuring devices were attached to either side of the top flange of the beam at midspan.

Flexure tests were performed by the team on three 6"x6"x18" beams according to ASTM C78, the results of which can be seen in Table 5. The flexure tests were used to determine the modulus of rupture of the concrete, for use in predicting the failure load and deflection through the moment-curvature analysis. The results of the second flexure test were thrown out in the analysis because the team determined that the rate of loading was too high, which caused the failure load of that sample to read too high.

Table 5: Flexure Test Results

Sample	Failure Load	MOR
1	10,310 lbf	877 psi
2	12,890 lbf	~~1,097 psi~~
3	11,390 lbf	959 psi
Average		918 psi

Concrete cylinder tests were performed by Knife River on 4"x8" cylinders on the day of the test, six cylinders were broken: three that were field-cured, and three that were moist-cured. The average strength of the field-cured tests was 15,527 psi, while the average strength of the moist-cured tests was 14,570 psi. The team chose to average the strengths from the field-cure and moist-cure tests, for an overall strength of 15,050 psi. The team took the overall average because it matched well with the modulus of rupture calculated from the flexure tests.

Figure 6: Beam Test Setup – Go Beavs!

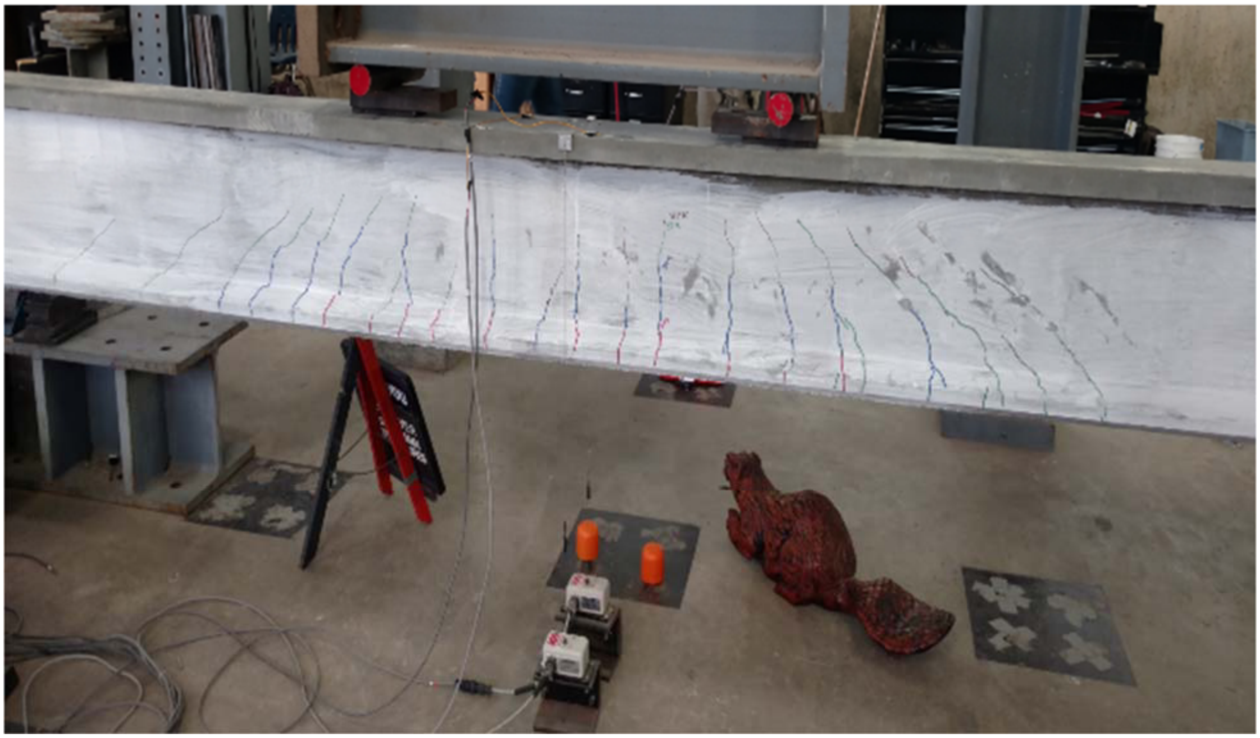

Figure 7: Crack Propagation at 37 kips

After testing the flexure beams and compressive cylinders, the material properties were updated, and the team calculated their predictions for cracking load, failure load, and ultimate deflection. These predictions were submitted to a PCI representative prior to the start of testing.

Testing of the beam began by monotonically applying load up to 11 kips, and then unloading the beam in order to calibrate the test setup, which can be seen in Figure 6. After this initial calibration, the beam was loaded up to 20 kips, the lower bound limit for cracking. There were no cracks observed at this point. The loading was then increased until cracking was observed, through a jump in deflection, by the test administrator at approximately 23.5 kips. The cracks were marked on the beam at this loading point, and were observed to start at the bottom flange near midspan. No shear cracks were observed at this point. The beam was again loaded and the loading was stopped at 25 kips, 30 kips, 35kips, and 37kips to mark the cracks. Figure 7 shows cracks at 37 kips. The cracks propagated upwards from bottom flange to the web. It should be noted that the beam was again unloaded at 35 kips because the loading apparatus was not level. After removing the bearing pads and adjusting the actuator, the load was reapplied back up to 35 kips, where the test continued. This loading and reloading sequence is not believed to have impacted the final results of the beam in any way. The loading was again stopped at 39 kips, the upper bound for failure in this competition, for visual inspection of cracks. Then the loading was continued until the beam failed at 40.7 kips. The failed beam is shown in Figure 8.

Figure 8: Beam Failure

Results

Once the test had concluded, the data was analyzed and compared to the team's predictions. The actual cracking load was shown to be 0.09% greater than the predicted load of 23.48 kips. At the predicted failure strain of 0.0035, the failure load was estimated to be 38.41 kips, with an estimated midspan deflection of 5.37 inches. The observed load from testing was 40.71 kips, and the midspan deflection was 4.53 inches. The actual failure load was 5.96% higher than the prediction, and the actual deflection was 15.6% lower than what was predicted.

After review of the beam's failure, it was determined that a local failure of the top flange occurred prior to a global flexural failure. Strain-gauge data supported this conclusion as the extreme compression fiber strain at failure was 0.0020, significantly lower than the estimated value of 0.0035. The initial sweep and point load offset most likely induced secondary effects into the member, which reduced the ultimate strain. The team feels that had the compression fiber reached a strain of 0.0035, the deflection prediction would have been much closer, while the ultimate load would not have changed much.

The use of the moment-curvature analysis method was satisfactory to predict the behavior of the beam due to the non-linear nature of the problem. Despite not reaching the predicted deflection, the team felt that they predicted the beam's behavior with a high degree of precision and were satisfied with the results, considering the challenges of testing and predicting an imperfect beam with sweep.

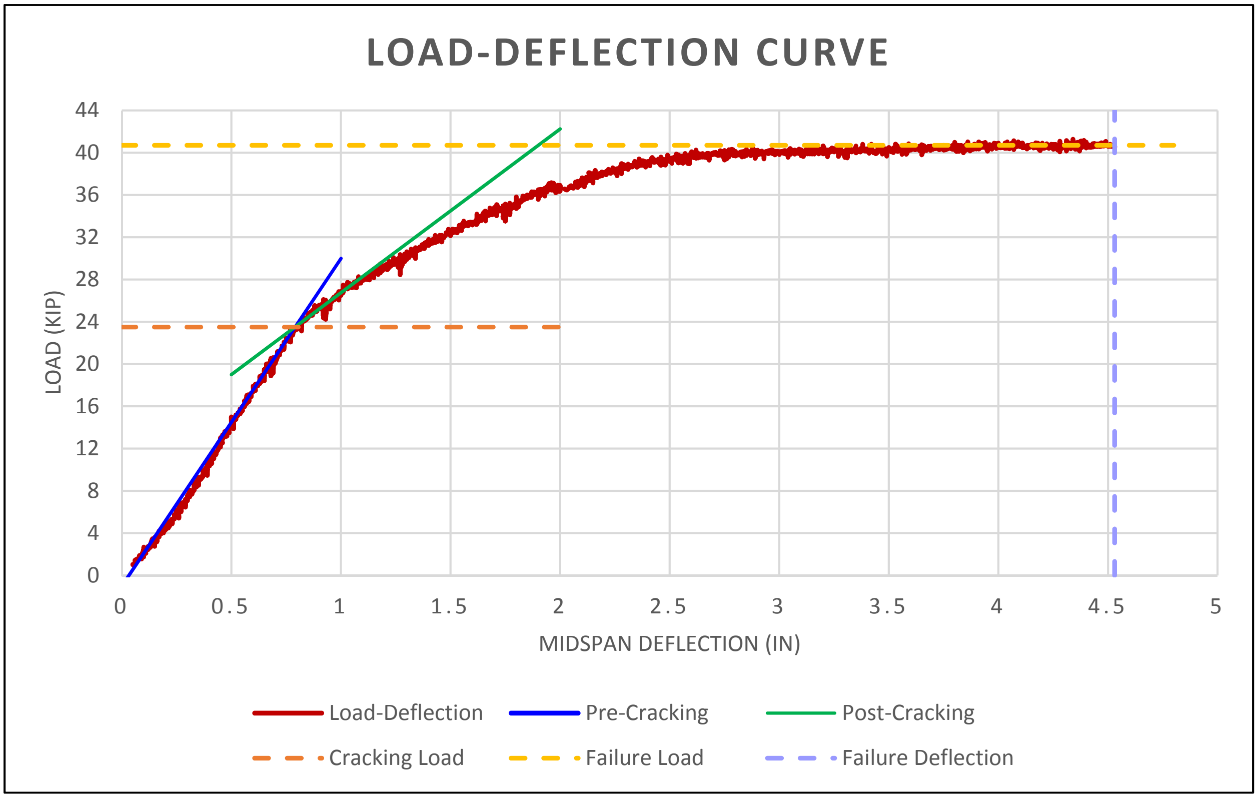

Figure 9: Load-Deflection Test Results

Discussion and Takeaways

Regardless of the testing results and whether or not the Oregon State beam will be amongst the best in the field for the competition, the Big Beam Contest provided a unique learning opportunity for the team members. The group of six students who participated on this year's Oregon State Big Beam Team gained applicable knowledge, skills, and experience through each step of the project, which could not have been learned in a classroom environment.

During the design stage, the group learned how important initial assumptions are, and how each design variable changed the strength, ductility, and cost of the beam. What would have been taught in a qualitative manner in the classroom became a quantitative exercise that was a highly optimized, iterative process of changing the cross-section and reinforcement properties, performing the calculations, and tabulating and analyzing the results to understand the beam's behavioral trends. The team realizes that had more accurate assumptions been used initially (i.e. a higher concrete strength), and moment-curvature analysis been utilized from the beginning, a more efficient beam cross-section may have been determined which failed within the specified loading limits. Using the simpler strain-compatibility analysis, the cross-section was consistently limited by the 20 kip cracking load, which was sensitive to concrete strength and beam height. Using a higher concrete strength than the assumed 12,000 psi may have allowed for a smaller beam that would have still met the cracking load requirements.

During the fabrication stage, the team learned that the design process is idealized and dependent on many assumptions, many of which do not hold true when the beam is actually built. From the formwork accuracy to the reinforcement installation, the beam will only perform as predictably as the precision with which it is built. The team learned that for this reason, it is safer to be more conservative with details such as reinforcement cover, despite what ACI might provide as the minimum.

Related to the construction of the beam, the team learned that testing can be difficult if imperfections are present, such as the sweep this year's beam had. The assumptions made during the design process about the ideal testing conditions are difficult to replicate come testing day, no matter how experienced the technicians are.

Despite the difficulties encountered throughout this project, the Oregon State Big Beam Team members have all had a great experience and learned lessons that will be immensely valuable as they each begin their respective careers in the civil engineering and construction industry.

Acknowledgements

The Oregon State University team would like to acknowledge the following people for their help and support, which were invaluable throughout this competition:

Dr. Keith Kaufman, chief design engineer at Knife River in Harrisburg, Oregon and the instructor for the Prestressed Concrete Design course at OSU. Dr. Kaufman served as the advisor for the Big Beam team, and his advice, help, and encouragement throughout the design, fabrication, analysis, and testing of the beam was indispensable. The dedication of Dr. Kaufman to the team and this program is greatly appreciated.

The employees of Knife River in Harrisburg, Oregon who assisted in the fabrication of the beam, providing expertise which greatly assisted the construction process. The team would like to especially thank Tom Walker, the foreman assigned to help construct the beam; Dan Serra a design engineer who observed the fabrication; Russell Alldridge, who was responsible for quality control of the jacking and concrete mixture; and Anders Lovendahl who helped cut and bend the shear reinforcement prior to casting and drafted the shop drawings for the beam.

The Hinsdale Wave Research Lab for allowing us to test our beam in their facilities. The team would like to especially thank Dr. Chris Higgins, who set up the testing equipment, helped the team prepare the beam, and operated the testing equipment, thereby providing the necessary expertise for a dependable test.

The Prestressed Concrete Institute (PCI) and the Sika Corporation for sponsoring this competition. By participating in the Big Beam Competition, each team member was able to gain valuable experience that can be used in their future careers.

Thank you!

References

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Tadros, M. K., Al-Omaishi, N., Seguirant, S. J., & Gallt, J. G. (2003). *NCHRP Report 496: Prestress Losses in Pretensioned High-Strength Concrete Bridge Girders.* National Cooperative Highway Research Program.

Team Members

Makenzie Ellett
3815 Brown Creek Rd.
The Dalles, OR 97058

Thomas Fruin
210 Oakway Rd.
Eugene, OR 97401

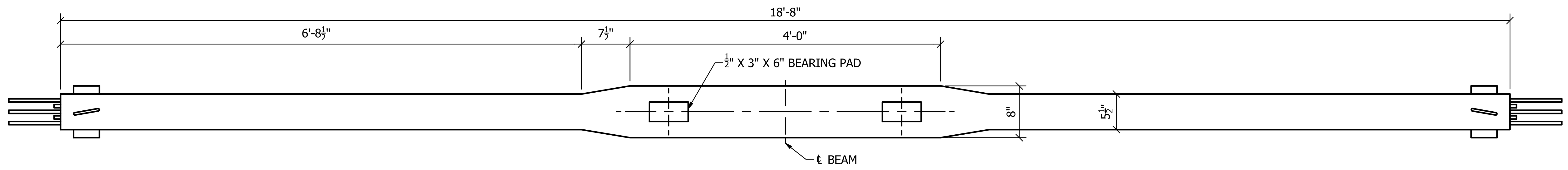
Kolton Mahr
3020 NW Orchard Avenue
Corvallis, OR 97330

Spenser Maunu
225 SE Lilly Ave.
Corvallis, OR 97333

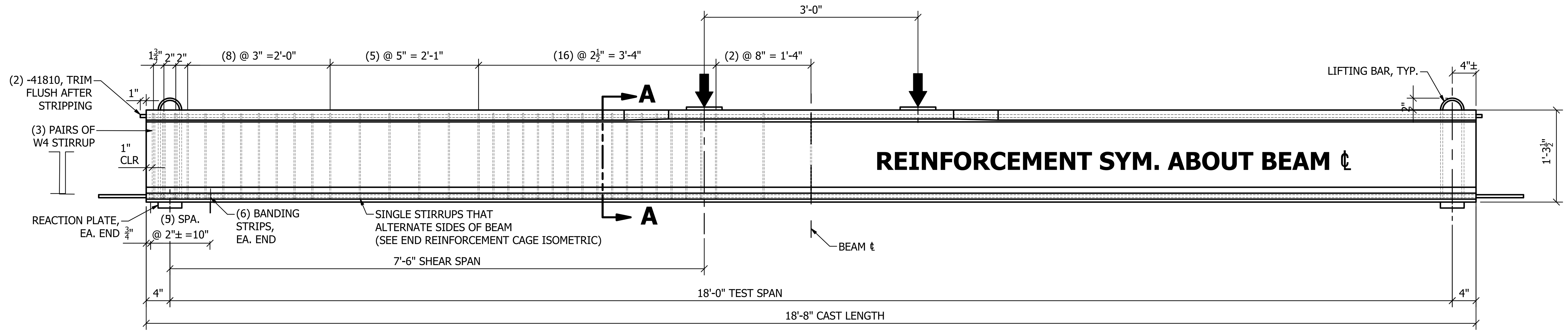
Madhav Parikh
825 NW 23rd St. Apt #49
Corvallis, OR 97330

Andy Truong
3054 Ala Poha Pl. Apt #903
Honolulu HI, 96818

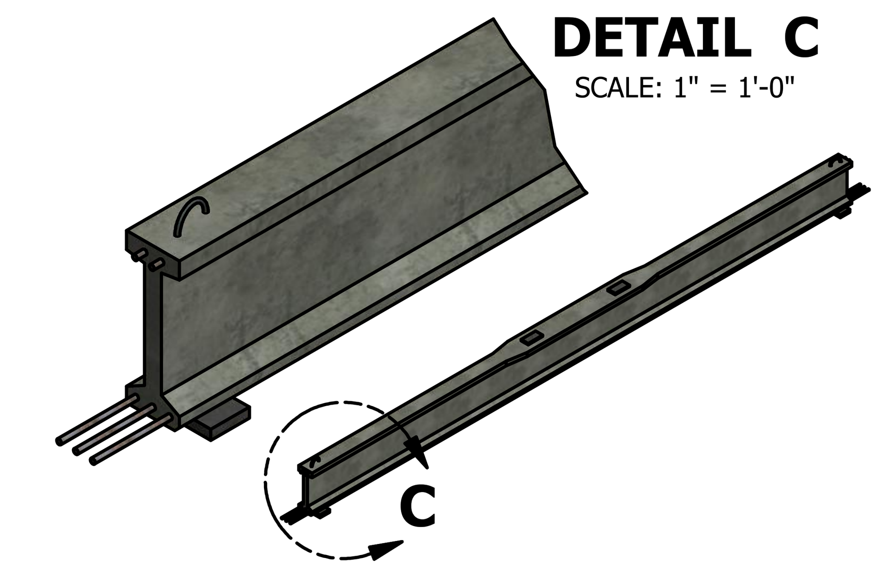
Appendix A – Shop Drawings



PLAN
SCALE: 1" = 1'-0"

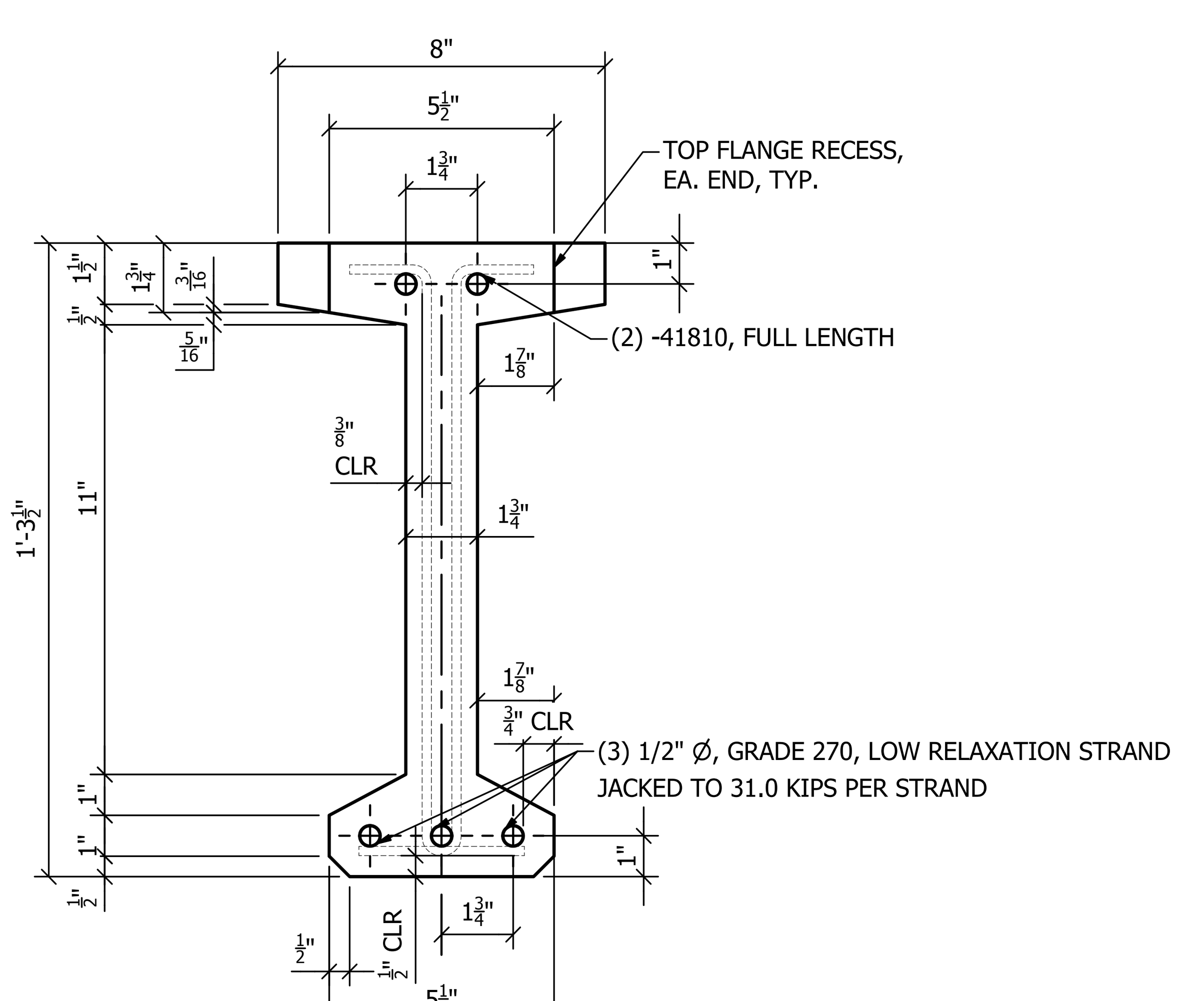


ELEVATION
SCALE: 1" = 1'-0"

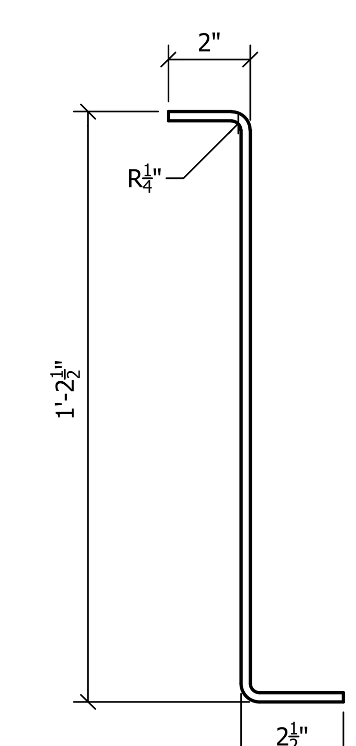


DETAIL C
SCALE: 1" = 1'-0"

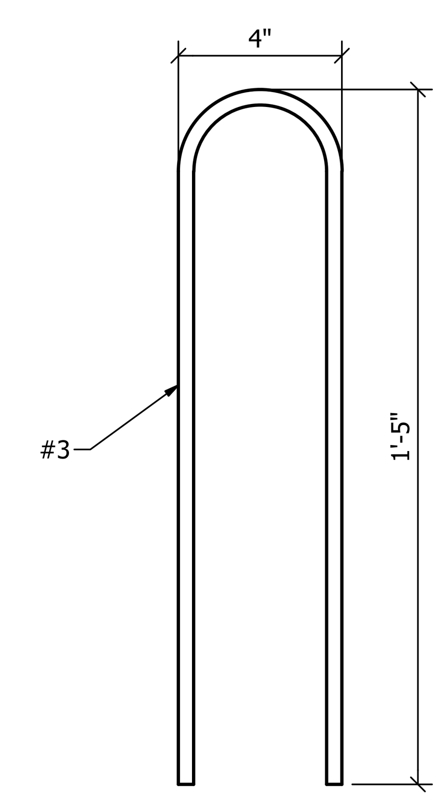
ISOMETRIC
SCALE: 1/4" = 1'-0"



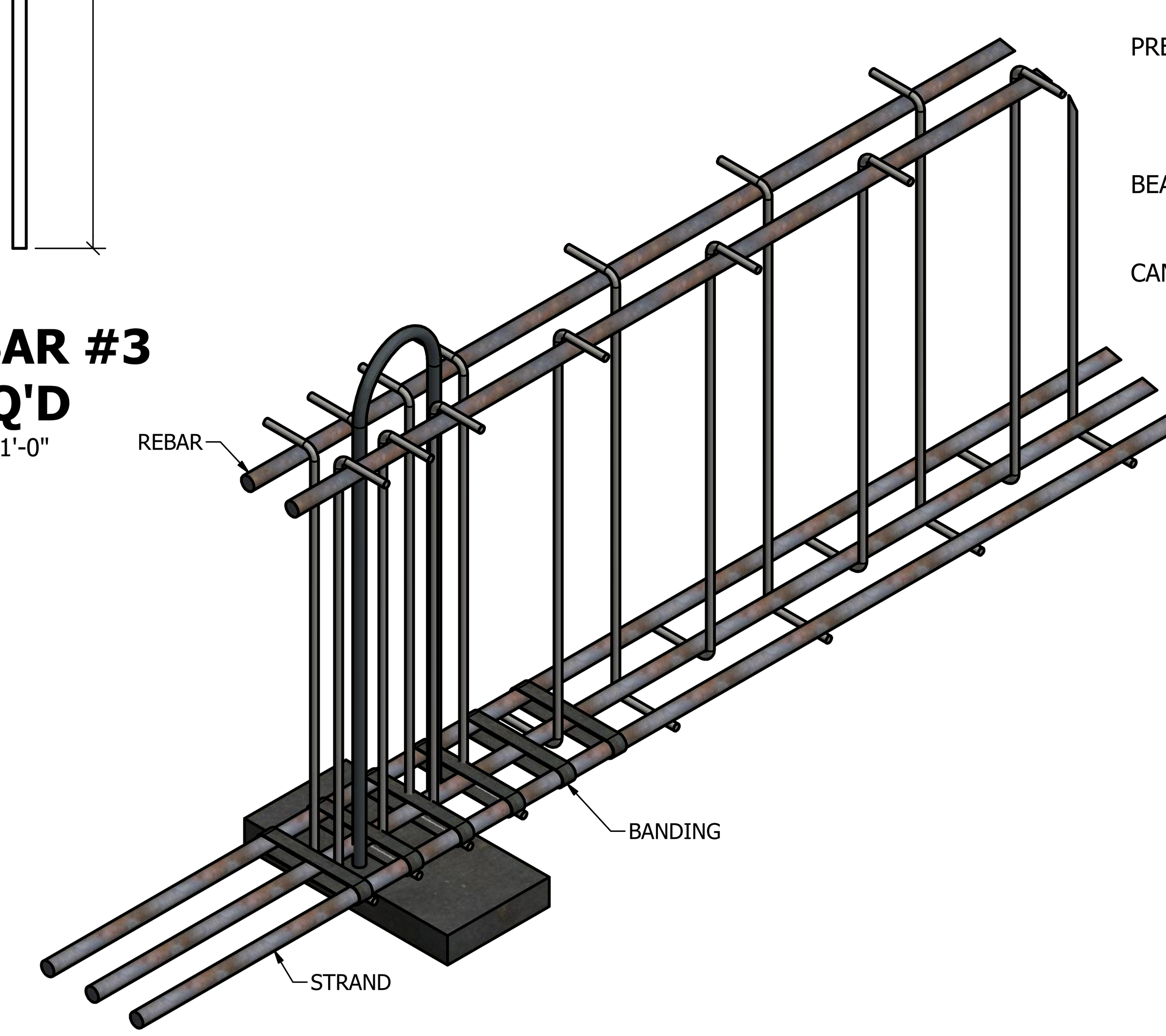
TYPICAL SECTION A-A
SCALE: 3" = 1'-0"



STIRRUP - D4 WWR
(75) REQ'D
SCALE: 3" = 1'-0"



LIFTING BAR #3
(2) REQ'D
SCALE: 3" = 1'-0"



END REINFORCEMENT CAGE

MATERIALS

CONCRETE:
MIX: H80N2G
f`ci: 9000 psi (AS-BUILT 11050 psi)
f'c: 12000 psi (AS-BUILT 15050 psi FIELD & MOIST CURE)
VOLUME: 5.32 CU FT = 0.20 CY PRECAST
2.40 CU FT = 0.09 CY TEST SPECIMEN
(3) 6 X 12 AND (12) 4 x 8 CYLINDERS, AND (3) FLEXURE BEAMS

TOTAL VOLUME: 0.29 CY

REINFORCEMENT
(2) #4 X 18'-10" - 41810 - A615, GRADE 60
(2) #3 - A615, GRADE 60, SEE DETAIL

BANDING
(12) BANDING STRIPS

WWR
(75) D4 STIRRUPS, GRADE 65, SEE DETAIL.
PROVIDED BY DAVIS WIRE.

PRESTRESSING
(56) LF 1/2"Ø, GRADE 270, LOW RELAXATION STRAND
STRAND CERT HEAT NO. S0290086, PACK NO. S529985-6

BEAM WEIGHT
830 LBS (AS-BUILT 928 LBS)

CAMBER
TRANSFER: 0.45"
TESTING: 0.86" (AS-BUILT 1.125")

PROJECT DATES

CAST:	MAY 5, 2017
TRANSFER OF PRESTRESS:	MAY 8, 2017
BEAM DELIVERY:	MAY 19, 2017
TEST:	JUNE 2, 2017

PROJECT NAME
PCI BIG BEAM CONTEST 2017
OREGON STATE UNIVERSITY
ELLETT, PARIKH, TRUONG,
FRUIN, MAHR, MAUNU

CONTRACTOR
PH:
FAX:
EMAIL:

INSPECTION
PH:
FAX:
EMAIL:

ENGINEER
OSU BIG BEAM TEAM
PH:
FAX:
EMAIL:

ENGINEER STAMP

KNIFE RIVER
AN MDU RESOURCES COMPANY

P.O. BOX 181
23505 PEORIA RD.
HARRISBURG, OREGON 97446
PH: (541) 995-4100
FAX: (541) 995-9447

DRAWING STATUS
APPROVED
FOR CONSTRUCTION
4/26/2017

KNIFE RIVER PRESTRESS
HARRISBURG, OREGON

DRAWN KK, AL	DATE 4/26/2017
HANDLING	DATE
CHECKED OSU BIG BEAM	DATE 4/26/2017
APPROVED BY OSU BIG BEAM	DATE 4/26/2017
PROJECT NO. SEE LEFT	
PRODUCT TYPE OSU BIG BEAM	
SHEET 1	OF 2

Appendix B – Design Calculations

Section Properties

$A_g := 45.3125\ in^2$ cross sectional area

$SA := 51.4937\ in$ cross sectional perimeter (surface area)

$I := 1374.5196\ in^4$ second moment of area (moment of inertia)

$y_b := 8.2726\ in$ centroid location

$h := 15.5\ in$ depth

$VS := \frac{A_g}{SA} = 0.88\ in$ volume to surface ratio

$\gamma_{rc} := 155\ pcf$ unit weight of concrete (reinforced)

$w_D := A_g \cdot \gamma_{rc} = 48.8\ \frac{lbf}{ft}$ dead load per foot length

$b_f := 8\ in$ top flange width

$b_w := 1.75\ in$ web width

Mild Reinforcement

$f_y := 60\ ksi$ yield strength

$f_{s.allow} := 30\ ksi$ allowable mild steel stress

$N'_s := 2$ number bars

$A_{bar} := 0.2\ in^2$ area per bar (#4)

$d' := 1.0\ in$ steel centroid (from top)

$A_s := A_{bar} \cdot N'_s$

$A_s = 0.4\ in^2$ Area of Steel

$E'_s := 29000\ ksi$

Shear Reinforcement

see page 14

Prestressing

$d_b := 0.5\ in$ strand diameter

$N_{ps} := 3$ number of prestressing strands

$y_c := 1\ in$ strand centroid

$f_{pu} := 270\ ksi$ strand stress at ultimate

$f_{py} := f_{pu} \cdot 0.9 = 243\ ksi$ strand stress at yield

$f_{pj} := f_{pu} \cdot 0.75 = 202.5\ ksi$ strand jacking stress

$E_{ps} := 28500\ ksi$ strand elastic modulus

$A_{strand} := 0.153\ in^2$ area per strand

$A_{ps} := N_{ps} \cdot A_{strand} = 0.5\ in^2$ total strand area

Span Geometry

$L_{span} := 18\ ft$ span length

$L_{bearing} := 6\ in$ bearing pad size

$L_{beam} := 18\ ft + 8\ in$ beam length

Time Analysis

$t_{transfer} := 24\ hr$ time at transfer

$t_{final} := 28\ day$ final time

Loss Coefficients

$\chi := 0.70$ aging coefficient

$K_1 := 1.0$

$RH := 70$ relative humidity

$K_2 := 1.0$

Concrete Properties

$f'_{ci} := 10000\ psi$ concrete strength at transfer

$f'_c := 14500\ psi$ concrete strength at 28 days

$$w_c := min\left(140\ pcf + \frac{f'_c}{1000\ psi}\ pcf, 155\ pcf\right)$$

$w_c = 154.5\ pcf$ weight of unreinforced concrete

$$E_{concrete}(f_c) := 33 \cdot K_1 \cdot K_2 \cdot \left(\frac{w_c}{pcf}\right)^{1.5} \cdot \sqrt{f_c \cdot psi}$$

$E_{ci} := E_{concrete}(f'_{ci}) = 6337\ ksi$ concrete elastic modulus at transfer

$E_c := E_{concrete}(f'_c) = 7631\ ksi$ concrete elastic modulus at 28 days

$$n_i := \frac{E_{ps}}{E_{ci}} = 4.5$$

modular ratios

$$n := \frac{E_{ps}}{E_c} = 3.73$$

Losses

Prior to transfer

$$LR(t_1, t_2) := \frac{f_{pj}}{45} \cdot \left(\frac{f_{pj}}{f_{py}} - 0.55\right) \log\left(\frac{24 \cdot \frac{t_2}{day} + 1}{24 \cdot \frac{t_1}{day} + 1}\right)$$

$LR(0\ day, t_{transfer}) = 1.78\ ksi$ relaxation losses prior to transfer

$$f_{pi} := f_{pj} - LR(0\ day, t_{transfer})$$

$f_{pi} = 200.7\ ksi$ strand stress just before transfer

Shrinkage

$k_f := \dfrac{5}{1 + \dfrac{f'_{ci}}{ksi}} = 0.5$ concrete strength factor for shrinkage

$VS = 0.1\ ft$

$k_s := \dfrac{1064 - 94 \cdot \dfrac{VS}{in}}{735} = 1.3$ size factor

$k_{hs} := 2 - 0.0143 \cdot RH = 1$ humidity factor for shrinkage

$$k_{td}(t) := \frac{\left(\frac{t}{day}\right)}{61 - 4 \cdot \frac{f'_{ci}}{ksi} + \frac{t}{day}}$$

$k_{td}(t_{final}) = 0.6$ time development factor

$$\gamma_{sh}(t) := k_{td}(t) \cdot k_s \cdot k_{hs} \cdot k_f$$

$$\gamma_{sh}(t_{final}) = 0.35$$

$$\varepsilon_{sh}(t) := 480 \cdot 10^{-6} \cdot \gamma_{sh}(t)$$

$\varepsilon_{sh.final} := \varepsilon_{sh}(t_{final}) = 166 \cdot 10^{-6}$ strain due to shrinkage

Creep

$t_i := t_{transfer}$ $\quad t_i = 24\ hr$

$$k_{td}(t) := \frac{\left(\frac{t}{day}\right)}{61 - 4 \cdot \frac{f'_{ci}}{ksi} + \frac{t}{day}}$$

$k_{td}(t_{final}) = 0.6$ time development factor

$k_{la} := \left(\frac{t_i}{day}\right)^{-0.118} = 1$ loading factor

$k_{hc} := 1.56 - 0.008 \cdot RH = 1$ humidity creep factor

$k_f := \frac{5}{1 + \frac{f'_{ci}}{ksi}} = 0.5$ concrete strength factor

$k_s := \frac{\left(1064 - 94 \cdot \frac{VS}{in}\right)}{735} = 1.3$ size factor

$\gamma_{cr}(t) := k_{td}(t) \cdot k_{la} \cdot k_s \cdot k_{hc} \cdot k_f$ $\quad \gamma_{cr}(t_{final}) = 0.3$

$\psi(t) := 1.9 \cdot \gamma_{cr}(t)$ $\quad \psi(t_{final}) = 0.7$

$\psi_{creep.final} := \psi(t_{final} - t_{transfer})$ $\quad \psi_{creep.final} = 0.65$

Transformed Section Properties (at transfer of prestress)

$A_{ti} := A_g + (n_i - 1) \cdot A_{ps}$ $\quad A_{ti} = 46.9\ in^2$ $\quad \dfrac{A_{ti}}{A_g} = 1.04$

$y_{bti} := \dfrac{A_g \cdot y_b + (n_i - 1) \cdot A_{ps} \cdot y_c}{A_{ti}}$ $\quad y_{bti} = 8.02\ in$ $\quad \dfrac{y_{bti}}{y_b} = 0.97$

$I_{ti} := I + A_g \cdot (y_{bti} - y_b)^2 + (n_i - 1) \cdot A_{ps} \cdot (y_{bti} - y_c)^2$

$I_{ti} = 1457\ in^4$ $\quad \dfrac{I_{ti}}{I} = 1.1$

$e_{pti} := y_{bti} - y_c$ $\quad y_c = 1\ in$ $\quad e_{pti} = 7\ in$

$e_p := y_b - y_c$ $\quad e_p = 7.3\ in$

$\alpha := 1 + \dfrac{A_g \cdot {e_p}^2}{I}$ $\quad \alpha = 2.7$

$K_r := \dfrac{1}{1 + (n_i - 1)\ \alpha \cdot \dfrac{A_{ps}}{A_g}}$ $\quad K_r = 0.9$

$K_{rd} := \dfrac{1}{1 + \left((n_i - 1) \cdot \alpha \cdot \dfrac{A_{ps}}{A_g} \cdot (1 + \chi \cdot \psi_{creep.final})\right)}$ $\quad K_{rd} = 0.9$

Total Prestress Loss Calculations

$f_{pi} = 200.7\ ksi$ Stress in strand just before transfer

1) Elastic Shortening (Prestressing)

$P_i := f_{pi} \cdot A_{ps}$ $P_i = 92.1\ kip$

$\Delta_{ESp} := \dfrac{P_i \cdot \alpha \cdot K_r \cdot n_i}{A_g}$ $\Delta_{ESp} = 22.9\ ksi$ ES losses (prestressing)

$f_{p.net1} := f_{pi} - \Delta_{ESp}$ $f_{p.net1} = 177.9\ ksi$

2) Elastic Shortening (Self Weight)

$M := \dfrac{w_D \cdot L_{beam}^{\ 2}}{8}$ $M = 2.12\ kip \cdot ft$ moment at midspan due to self weight

$\Delta_{ESg} := -M \cdot \dfrac{e_p}{I} \cdot K_r \cdot n_i$ $\Delta_{ESg} = -0.55\ ksi$ ES losses (self weight)

$f_{p.net2} := f_{p.net1} - \Delta_{ESg}$ $f_{p.net2} = 178.4\ ksi$

3) Shrinkage

$\varepsilon_{sh.final} = 166 \cdot 10^{-6}$

$\Delta_{SHbd} := \varepsilon_{sh.final} \cdot E_{ps} \cdot K_{rd}$ $\Delta_{SHbd} = 4.2\ ksi$

$f_{p.net3} := f_{p.net2} - \Delta_{SHbd}$ $f_{p.net3} = 174.3\ ksi$

4) Creep

$f_{cir} := \dfrac{\left(\Delta_{ESp} + \Delta_{ESg}\right)}{n_i}$ $f_{cir} = 5\ ksi$

$\Delta_{CRbd} := n_i \cdot f_{cir} \cdot \psi_{creep.final} \cdot K_{rd}$ $\Delta_{CRbd} = 12.7\ ksi$

$f_{p.net4} := f_{p.net3} - \Delta_{CRbd}$ $f_{p.net4} = 161.6\ ksi$

5) Relaxation Between Transfer and Final

$LR_i := LR\left(t_{transfer}, t_{final}\right)$ $LR_i = 1.8\ ksi$

$\phi_i := 1 - \dfrac{3\ \left(\Delta_{SHbd} + \Delta_{CRbd}\right)}{f_{p.net2}}$ $\phi_i = 0.72$

$\Delta_{LRbd} := LR_i \cdot \phi_i \cdot K_{rd}$ $\Delta_{LRbd} = 1.1\ ksi$

$f_{p.net5} := f_{p.net4} - \Delta_{LRbd}$ $f_{p.net5} = 160.4\ ksi$

Loss Results

$LT := LR\left(0\ day, t_{transfer}\right)$

$LT = 1.8\ ksi$ relaxaton losses before transfer

$ES := \Delta_{ESp} + \Delta_{ESg}$

$ES = 22.3\ ksi$ elastic shortening losses

$IL := ES + LT$

$IL = 24.1\ ksi$ Inital Losses

$TL := f_{pj} - f_{p.net5}$

$TL = 42.1\ ksi$ Total 28 Day Losses

Stresses at Transfer

Prestressing

$f_i := f_{pj} - IL$ | $f_i = 178.4\ ksi$ | strand stress (at transfer)

$f_{se} := f_{pj} - TL$ | $f_{se} = 160.4\ ksi$ | strand tress (after total loss)

$L_{transfer} := \frac{f_i}{3000\ psi} \cdot d_b$ | $L_{transfer} = 2.5\ ft$ | transfer Length

$x := 0\ in, 1\ in .. \frac{L_{beam}}{2}$ | length along beam

$$P_i(x) := \begin{cases} f_i \cdot A_{ps} \cdot \frac{x}{L_{transfer}} & \text{if } x \le L_{transfer} \\ f_i \cdot A_{ps} & \text{else} \end{cases}$$

prestressing force along length of beam at transfer

$P_i(9\ ft) = 81.9\ kip$

Beam Properties

$d_p := h - y_c$ | $d_p = 14.5\ in$ | structural depth

$y_t := h - y_b$ | $y_t = 7.2\ in$ | neutral axis to top fiber

$e := e_p$ | $e = 7.3\ in$ | strand eccentricity

$S_b := \frac{I}{y_b}$ | $S_b = 166.2\ in^3$ | Section Modulus (Bottom)

$S_t := \frac{I}{y_t}$ | $S_t = 190.2\ in^3$ | Section Modulus (Top)

$f_{ri} := -7.5 \cdot \sqrt{f'_{ci} \cdot psi}$ | $f_{ri} = -750\ psi$ | Modulus of Rupture at transfer

$f_r := -7.5 \cdot \sqrt{f'_c \cdot psi}$ | $f_r = -903.1\ psi$ | 28-day Modulus of Rupture

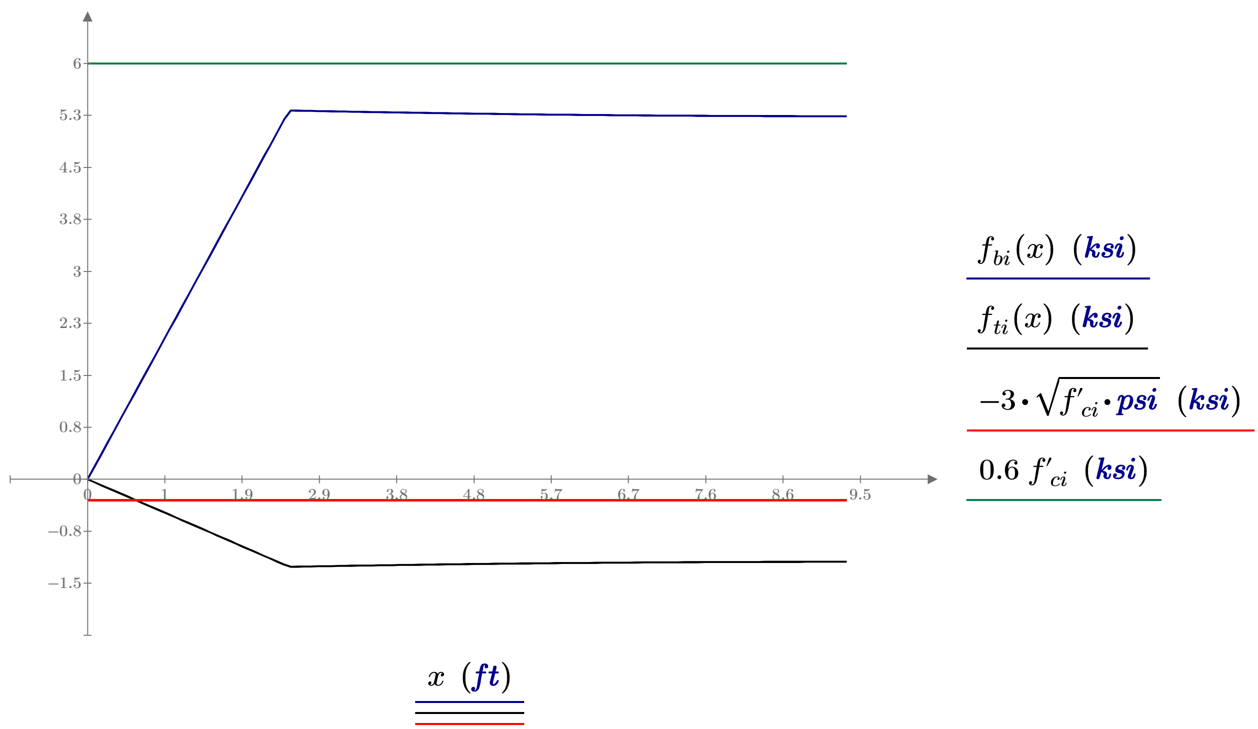
Moment due to self weight and extreme fiber stresses at transfer

$M_d(x) := w_D \cdot \frac{x}{2} \left(L_{beam} - x\right)$ moment due to self weight

$f_{bi}(x) := P_i(x) \cdot \left(\frac{1}{A_g} + \frac{e}{S_b}\right) - \frac{M_d(x)}{S_b}$ bottom fiber stress at transfer

$f_{ti}(x) := P_i(x) \cdot \left(\frac{1}{A_g} - \frac{e}{S_t}\right) + \frac{M_d(x)}{S_t}$ top fiber stress

$M_d\left(\frac{L_{beam}}{2}\right) = 2.1\ kip \cdot ft$ moment at midspan



Mild Steel Requirements

$f_{ti.max} := -f_{ti}\left(L_{transfer}\right)$ | $f_{ti.max} = 1.3\ \textit{ksi}$ | max top fiber stress at transfer (in tension)

$f_{bi.max} := f_{bi}\left(L_{transfer}\right)$ | $f_{bi.max} = 5.3\ \textit{ksi}$ | max bottom fiber stress at transfer

$NA_i := \dfrac{h \cdot f_{ti.max}}{f_{ti.max} + f_{bi.max}}$ | $NA_i = 3\ \textit{in}$ | neutral axis at transfer

$T' := \dfrac{f_{ti.max}}{2} \cdot NA_i \cdot b_f$ | $T' = 15\ \textit{kip}$ | tension force to be supported by mild steel

$A_{s.required} := \dfrac{T'}{f_{s.allow}}$ | $A_{s.required} = 0.5\ \textit{in}^2$ | required area of mild steel

$A_s - A_{s.required} = -0.1\ \textit{in}^2$ | difference of provided and required mild steel, positive means requirements met

Service Loading

$LL_{service} := 10\ \textit{kip}$ | service load (half)

$$M_L(x) := \begin{array}{l} \text{if } x < 94\ \textit{in} \\ \quad LL_{service} \cdot (x - 4\ \textit{in}) \\ \text{else if } x \geq 94\ \textit{in} \\ \quad LL_{service} \cdot 7.5\ \textit{ft} \end{array}$$

Moment due to live load along length of beam

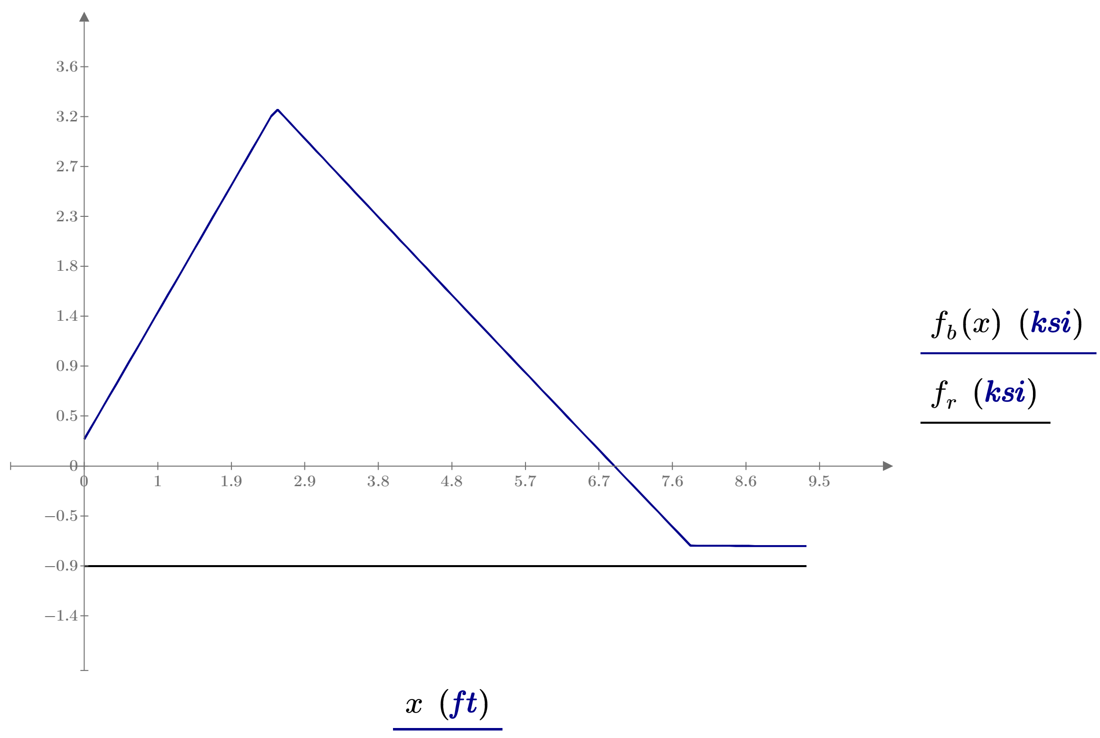
Service Stress

$$P_e(x) := \begin{Vmatrix} \text{if } x < L_{transfer} \\ \quad \begin{Vmatrix} f_{se} \cdot A_{ps} \cdot \dfrac{x}{L_{transfer}} \end{Vmatrix} \\ \text{else} \\ \quad \begin{Vmatrix} f_{se} \cdot A_{ps} \end{Vmatrix} \end{Vmatrix}$$

Effective prestressing force along length of beam

$$f_b(x) := P_e(x) \cdot \left(\frac{1}{A_g} + \frac{e}{S_b}\right) - \frac{M_d(x)}{S_b} - \frac{M_L(x)}{S_b}$$

service level bottom fiber stress



$f_b(9\ ft) = -721.7\ psi$ $\qquad f_r = -903.1\ psi$

Strain Compatability

$LL_{ultimate} := 19.5\ kip$ — factored live load

$$M_{LU}(x) := \begin{Vmatrix} \text{if } 4\ in < x < 94\ in \\ \quad \| LL_{ultimate} \cdot (x - 4\ in) \\ \text{else if } x \geq 94\ in \\ \quad \| LL_{ultimate} \cdot 7.5\ ft \end{Vmatrix}$$

moment due to live load along length of beam

$$f_{dc} := P_e\left(\frac{L_{beam}}{2}\right) \cdot \left(\frac{e^2}{I} + \frac{1}{A_g}\right) - \frac{M_d\left(\frac{L_{beam}}{2}\right) \cdot e}{I}$$

stress in conc. at centroid of prestressing strand

$f_{dc} = 4324\ psi$

$c := 1.6975\ in$ — neutral axis depth

$$\varepsilon_{dc} := \frac{f_{dc}}{E_c} = 0.000567$$

Decompression strain

$$\varepsilon_{pe} := \frac{f_{se}}{E_{ps}} = 0.00563$$

Strain from prestressing effects

$$\varepsilon_s := \frac{0.003 \cdot (d_p - c)}{c} = 0.0226$$

Strain from loading (after decompression)

$$\varepsilon_{ps} := \varepsilon_{dc} + \varepsilon_{pe} + \varepsilon_s = 0.0288$$

Strain in prestressing strand at ultimate

$$f_{ps} := f_{pu} - \frac{0.04\ ksi}{\varepsilon_{ps} - 0.007} = 268.17\ ksi$$

Design stress in prestressing strand

$$\varepsilon'_s := \frac{(c - 1\ in)}{c} \cdot .003 \qquad \varepsilon'_s = 0.00123$$

Strain in Compression Steel

$$f'_s := \text{if } \varepsilon'_s \le 0.002 \left\| \varepsilon'_s \cdot E'_s \right. \text{ else } \left\| f_y \right.$$ $f'_s = 35.75$ ***ksi***

Force in compression steel

$C' := A_s \cdot f'_s$ $C' = 14.3$ ***kip***

$\beta := 0.65$ $a := c \cdot \beta$

$C_c := 0.85 \cdot f'_c \cdot a \cdot b_f = 108.8$ ***kip*** whitney compression stress block

$C := C_c + C' = 123.1$ ***kip***

$T := A_{ps} \cdot f_{ps} = 123.1$ ***kip*** tension force in prestressing strands

$T - C = 0$ ***kip*** tension minus compression

$M_n := C_c \cdot \left(d_p - \frac{a}{2}\right) + C' \cdot \left(d_p - d'\right) = 142.5$ ***kip·ft*** Nominal moment capacity

$P_{live} := \frac{M_n}{7.5\ ft} = 19.01$ ***kip*** point load capacity

$M_u(x) := M_d(x) + M_{LU}(x)$ moment demand along length of beam

$M_u(9\ ft) = 148.4$ ***kip·ft*** moment demand at midspan

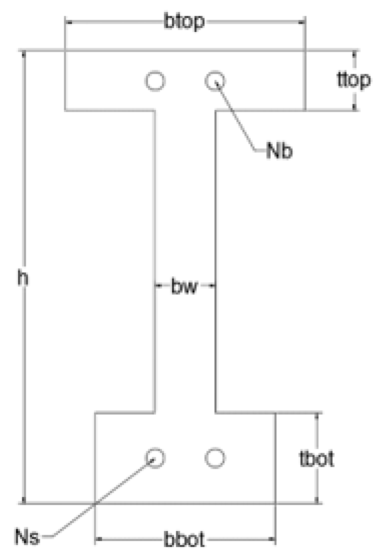
$L_{development} := \frac{f_{se}}{3000\ psi} \cdot d_b + \frac{\left(f_{ps} - f_{se}\right)}{1000\ psi} \cdot d_b = 6.7$ ***ft*** development Length

Shear Design

$L_{beam} = 18.7\ ft$	The beam is 19 ft long
$L_{effective} := 18\ ft$	Effective length, tested on a 18 foot span, center to center of bearing
$b_{plate} := 6\ in$	The bearing plate is 4 inches wide
$f_{pu} = 270\ ksi$	Grade 270 low relaxation strand
$TL = 42.1\ ksi$	Total prestress losses
$f'_c = 14500\ psi$	28 day concrete compressive strength
	[ACI 22.5.3.1] limiting material strength, but we have web steel present

Gross Section Properties (recall)

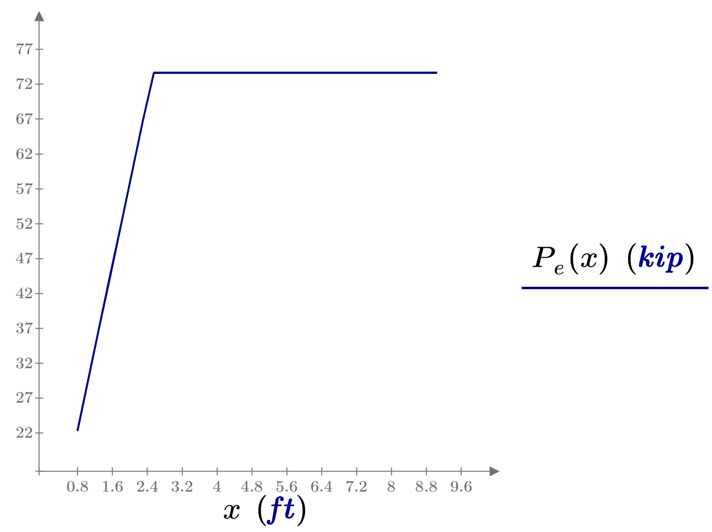
$h = 15.5\ in$	height
$b_w = 1.75\ in$	width of web
$b_f = 8\ in$	width of top flange
$N_{ps} = 3$	No. Strands
$I = 1375\ in^4$	moment of inertia
$A_g = 45.3\ in^2$	area of section
$SA = 51.5\ in$	cross sectional perimeter (surface area)
$\gamma_{rc} = 155\ pcf$	Normal weight concrete
$w_D = 48.8\ plf$	self weight per ft
$d_b = 0.5\ in$	Strand Diameter
$A_{strand} = 0.2\ in^2$	Area per Strand
$A_{ps} = 0.5\ in^2$	Total area of straight strand



Calculate V_{cw} using ACI Code Equation (22.5.8.3.2)

$x := 9\ in, 12\ in .. \frac{L_{effective}}{2}$ range variable of half the beam

$\lambda := 1.0$ light-weight concrete factor, does not apply



$P_e(7\ ft) = 73.6\ kip$

$f_{pc}(x) := \frac{P_e(x)}{A_g}$ stress along beam $f_{pc}(7\ ft) = 1625.1\ psi$

$V_p(x) := 0$ vertical component of effective prestress force at section, lbs

$d := h - 1.0\ in = 14.5\ in$ [ACI 22.5.2.1]

$d_p := \max(d, 0.8 \cdot h) = 14.5\ in$ distance from extreme compression fiber to centroid of prestressing reinforcement

$y_b = 8.273\ in$

$V_{cw.ACI}(x) := \left(3.5 \cdot \lambda \cdot \sqrt{f'_c \cdot psi} + 0.3 \cdot f_{pc}(x)\right) \cdot b_w \cdot d_p + V_p(x)$ [ACI eq. 22.5.8.3.2] web-shear strength

$f'_c = 14.5\ ksi$

$V_{cw.ACI}(9\ in) = 14.4\ kip$

$V_{cw.ACI}(12\ in) = 15.7\ kip$

$V_{cw.ACI}(24\ in) = 20.7\ kip$

$V_{cw.ACI}(36\ in) = 23.1\ kip$

$V_{cw.ACI}(48\ in) = 23.1\ kip$

$V_{cw.ACI}(60\ in) = 23.1\ kip$

$V_{cw.ACI}(72\ in) = 23.1\ kip$

$V_{cw.ACI}(84\ in) = 23.1\ kip$

$V_{cw.ACI}(96\ in) = 23.1\ kip$

$V_{cw.ACI}(108\ in) = 23.1\ kip$

Calculate V_{ci} using ACI Code Equation (22.5.8.3.1a)

$I=1374.5\ in^4$

$y_t := y_b = 8.27\ in$ distance from c.g. to tension fiber

$\lambda = 1$

$S_b := \dfrac{I}{y_b} = 166.2\ in^3$ section modulus

$$f_{pe}(x) := P_e(x) \cdot \left(\frac{1}{A_g} + \frac{e}{S_b}\right)$$

$w_D = 48.8\ plf$ self weight of beam

$M_d(x) := \dfrac{w_D \cdot x}{2} \cdot (L_{effective} - x)$ moment due to self weight

$f_d(x) := \dfrac{M_d(x)}{S_b}$ stress due to unfactored dead load, at extreme fiber of section where tensile stress is caused by externally applied loads, psi

$M_{cre}(x) := \left(\dfrac{I}{y_t}\right) \cdot \left(6 \cdot \lambda \cdot \sqrt{f'_c \cdot psi} + f_{pe}(x) - f_d(x)\right)$ [ACI eq. 22.5.8.3.1c]

$V_d(x) := w_D \cdot \left(\dfrac{L_{effective}}{2} - x\right)$ [ACI eq. 22.5.8.3.1a] flexure-shear strength

$$V_{ci}(x) := \max\left(0.6 \cdot \lambda \cdot \sqrt{f'_c \cdot psi} \cdot b_w \cdot d_p + V_d(x) + \left(\frac{1}{x}\right) \cdot M_{cre}(x), 1.7 \cdot \sqrt{f'_c \cdot psi} \cdot b_w \cdot d_p\right)$$

$V_{ci}(9\ in) = 42.2\ kip$ $V_{ci}(36\ in) = 27.5\ kip$ $V_{ci}(72\ in) = 14.5\ kip$

$V_{ci}(12\ in) = 38.9\ kip$ $V_{ci}(48\ in) = 21\ kip$ $V_{ci}(84\ in) = 12.7\ kip$

$V_{ci}(24\ in) = 33.9\ kip$ $V_{ci}(60\ in) = 17.1\ kip$ $V_{ci}(96\ in) = 11.3\ kip$

$V_{ci}(108\ in) = 10.2\ kip$

The design team supplied web reinforcement consisting of (1) W4 wires at 2 inch constant spacing the full length of the beam. Calculate the nominal shear strength, V_n. Use the results of Part #3 to represent V_{cw}. The Grade of web reinforcement is $65\ ksi$.

$f_{yt} := 65\ \textbf{ksi}$ grade of web reinforcement

$A_v := 1 \cdot 0.040\ \textbf{in}^2$ $A_v = 0.04\ in^2$ [ACI App. A]

$s := 2.5\ \textbf{in}$ spacing of wires $d_p = 14.5\ \textbf{in}$

$V_s(x) := A_v \cdot f_{yt} \cdot \dfrac{d_p}{s}$ steel shear strength

$V_c(x) := min\left(V_{cw.ACI}(x), V_{ci}(x)\right)$ concrete shear strength [ACI 22.5.8.3]

$V_n(x) := V_c(x) + V_s(x)$ nominal shear strength [ACI 22.5.1.1]

$V_n(9\ \textbf{in}) = 30\ \textbf{kip}$

$V_n(12\ \textbf{in}) = 31\ \textbf{kip}$

$V_n(24\ \textbf{in}) = 36\ \textbf{kip}$

$V_n(36\ \textbf{in}) = 38\ \textbf{kip}$

$V_n(48\ \textbf{in}) = 36\ \textbf{kip}$

$V_n(60\ \textbf{in}) = 32\ \textbf{kip}$

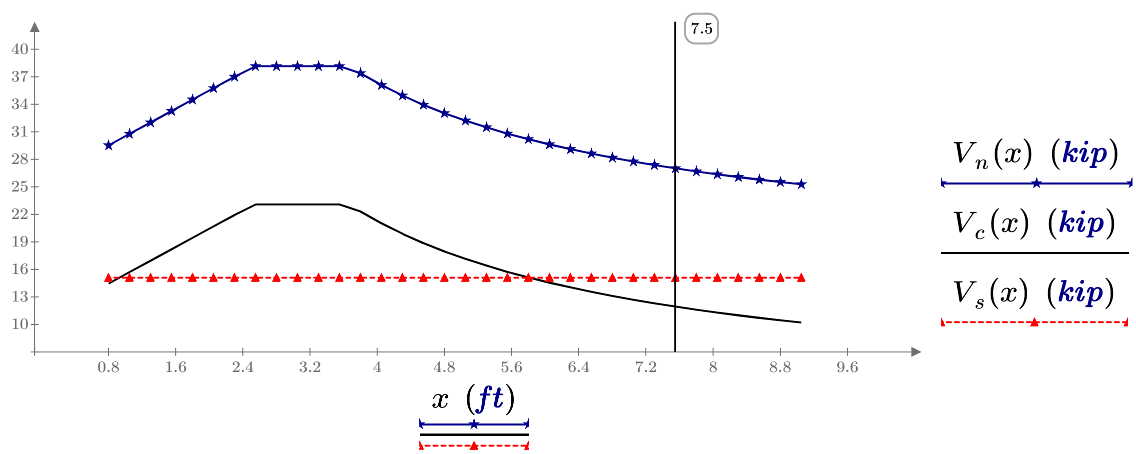
$V_n(72\ \textbf{in}) = 30\ \textbf{kip}$

$V_n(84\ \textbf{in}) = 28\ \textbf{kip}$

$V_n(96\ \textbf{in}) = 26\ \textbf{kip}$

$V_n(108\ \textbf{in}) = 25\ \textbf{kip}$

$V_n(3\ \textbf{ft}) = 38.1\ \textbf{kip}$



Evaluate the limits (maximum, spacing, and minimum) of the web reinforcement to ensure the code provisions are satisfied.

$\frac{A_v}{s} = 0.192\ \frac{in^2}{ft}$ actual web reinforcement

$a := 7.5\ ft$ shear span

$V_s(a) = 15.1\ kip$ max web reinforcement at critical section (shear span)

$V_{s.max}(x) := 8 \cdot \sqrt{f'_c \cdot psi} \cdot b_w \cdot d_p$ $V_{s.max}(a) = 24.4\ kip$

$V_{s.spacing}(x) := 4 \cdot \sqrt{f'_c \cdot psi} \cdot b_w \cdot d_p$ $V_{s.spacing}(a) = 12.2\ kip$

$s_{max} := min\left(12\ in, \frac{3 \cdot h}{8}\right) = 5.8\ in$ [ACI Table 9.7.6.2.2] maximum spacing of shear reinforcement

$\textbf{if}\left(s < s_{max}, \text{"OK"}, \text{"NG"}\right) = \text{"OK"}$

Check min steel

$A_s = 0.4\ in^2$

$f_y := 60\ ksi$

$\textbf{if}\left(A_{ps} \cdot f_{pu} \geq 0.4 \cdot \left(A_{ps} \cdot f_{pu} + A_s \cdot f_y\right), \text{"OK"}, \text{"NG"}\right) = \text{"OK"}$

$$A_{v.min} := \max\left(0.75 \cdot \sqrt{f'_c \cdot psi} \cdot \frac{b_w}{f_{yt}}, 50\ psi \cdot \frac{b_w}{f_{yt}}\right)$$

$$A_{v.min} = 0.029\ \frac{in^2}{ft}$$

$$A_{v.min}(x) := min\left(A_{v.min}, \frac{A_{ps} \cdot f_{pu}}{80 \cdot f_{yt} \cdot d_p}\left(\sqrt{\frac{d_p}{b_w}}\right)\right)$$

$$A_{v.min}(a) = 0.029\ \frac{in^2}{ft}$$

$$\text{if}\left(\frac{A_v}{s} > A_{v.min}(a), \text{“OK”}, \text{“NG”}\right) = \text{“OK”}$$

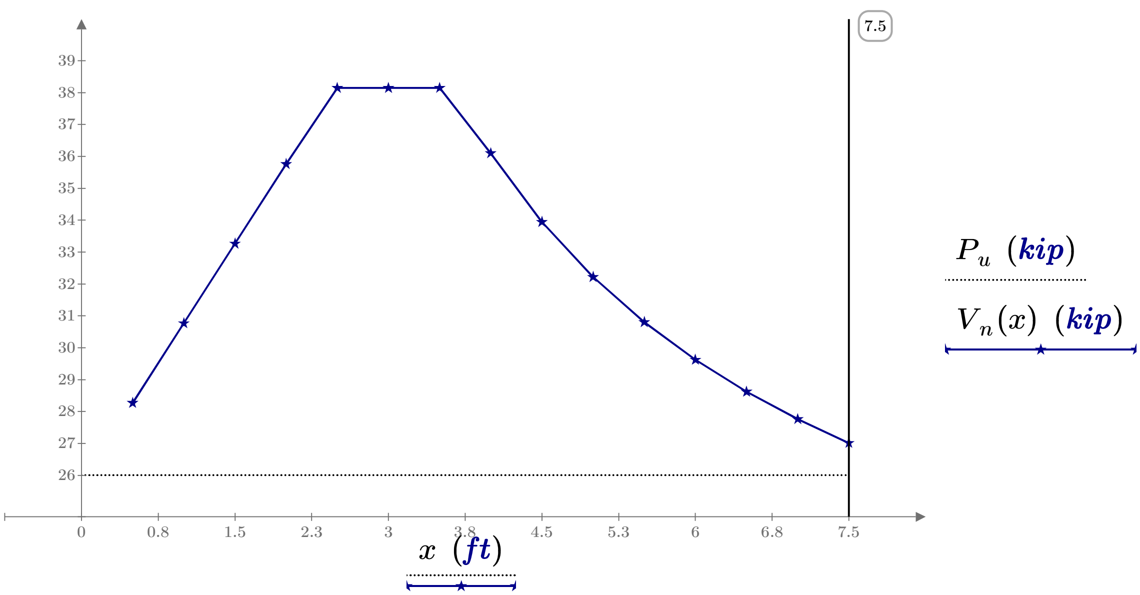
$$\phi_v := 0.75$$

$V_n(a) = 27\ kip$ shear capacity at critical secton (shear span)

$x := 0\ ft, 0.5\ ft..a$ shear span

$P_u := \dfrac{19.5\ kip}{\phi_v} = 26\ kip$ maximum applied load

$$\text{if}\left(V_n(a) \geq P_u, \text{“OK”}, \text{“NG”}\right) = \text{“OK”}$$



INPUT

(yellow)	Input
(grey)	Calculation

Note: For each trial, only change the yellow cells that are **bold**

Section:	Custom

Geometry

L (ft) =	18.67
L_{span} (ft) =	18
L_{brg} (in) =	6
L_{OH} (in) =	4

Section Properties

h (in) =	15.5
b_{top} (in) =	8
b_{web} (in) =	1.75
t_{top} (in) =	2
t_{bot} (in) =	2.5
A (in^2) =	45.3
I (in^4) =	1,375
Q (in^3) =	
y_b (in) =	8.34
y_t (in) =	7.16
S_b (in^3) =	165
S_t (in^3) =	192
Perim (in) =	51

Concrete Properties

f'_{ci} (psi) =	9,000
f'_c (psi) =	14,000
f'_{c_v} (psi) =	10,000
w_c (pcf) =	155
E_c (ksi) =	7,534.866
f_r (ksi) =	0.89

Loading

w_{pc} (plf) =	48.77
LL (k) =	10
LL_{fact} (k) =	16
X_{LL} (ft) =	7.5

Prestressing

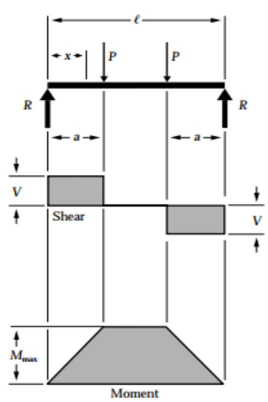
Pattern:	Straight
f_{pu} (ksi) =	270
N_s =	3
d_s (in) =	0.5
A_s (in^2) =	0.1512
y_e (in) =	1
y_c (in) =	1
ES (ksi) =	24.1
TL (ksi) =	44.9
A_{ps} (in^2) =	0.4536
f_{pj} (ksi) =	202.5
f_{pi} (ksi) =	178.4
f_{pe} (ksi) =	157.6
P_j (k) =	92
P_i (k) =	80.92
P_e (k) =	71.5
L_{tr} (in) =	26

Mild Reinforcement

F_y (ksi) =	60
F_{y_allow} (ksi) =	30
d' (in) =	1.0
N_b =	2
$Size_b$ =	4
d_b (in) =	0.5
A_b (in^2) =	0.20
wt (plf) =	0.668

Shear Reinforcement

Type:	D4
F_{yv} (ksi) =	65
N_v =	1
A_v (in^2) =	0.04
s (in) =	2.5
0.8h (in) =	12.4



$R = V$ . . . . $= P$

M_{max} (between loads) . . . . $= Pa$

M_x (when $x < a$) . . . . $= Px$

Δ_{max} (at center) . . . . $= \frac{Pa}{24EI}(3\ell^2 - 4a^2)$

Δ_x (when $x < a$) . . . . $= \frac{Px}{6EI}(3\ell a - 3a^2 - x^2)$

Δ_x $\left(\text{when } x > a \text{ and } < (\ell - a)\right)$ . . . $= \frac{Pa}{6EI}(3\ell x - 3x^2 - a^2)$

STRESS ANALYSIS

STRAND PATTERN

Location:	0	0.1L	L_{tr}	0.2L	0.25L	0.3L	0.4L	LL	0.5L
X (in) =	0	22	26	45	56	67	90	90	112
X (ft) =	0.0	1.9	2.2	3.7	4.7	5.6	7.5	7.5	9.3
y_s (in) =	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
e (in) =	7.34	7.34	7.34	7.34	7.34	7.34	7.34	7.34	7.34

LOADING

Location:	0	0.1L	L_{tr}	0.2L	0.25L	0.3L	0.4L	LL	0.5L
M_{pc} (k-in) =	0.0	9.2	10.6	16.3	19.1	21.4	24.5	24.5	25.5
M_{LL} (k-in) =	0	224	263	448	560	672	896	900	900
M_{tot} (k-in) =	0.0	233.2	273.2	464.3	579.1	693.4	920.5	924.5	925.5

TRANSFER STRESS LIMITS

	Location:	0	0.1L	L_{tr}	0.2L	0.25L	0.3L	0.4L	LL	0.5L
(ACI Tbl. 24.5.3.2)	T (top) =	-569	-569	-285	-285	-285	-285	-285	-285	-285
(ACI Tbl. 24.5.3.1)	C (bot) =	6,300	6,300	6,300	5,400	5,400	5,400	5,400	5,400	5,400

SERVICE LOAD STRESS LIMITS

	Location:	0	0.1L	L_{tr}	0.2L	0.25L	0.3L	0.4L	LL	0.5L
(ACI Tbl. 24.5.2.1)	T (bot) =	-887	-887	-887	-887	-887	-887	-887	-887	-887
(ACI Tbl. 24.5.4.1)	C_{sust} (top) =	6,300	6,300	6,300	6,300	6,300	6,300	6,300	6,300	6,300
(ACI Tbl. 24.5.4.1)	C_{tot} (top) =	8,400	8,400	8,400	8,400	8,400	8,400	8,400	8,400	8,400

TRANSFER STRESSES

Location:	0	0.1L	L_{tr}	0.2L	0.25L	0.3L	0.4L	LL	0.5L
P_i (k) =	0	69	80.92	81	81	81	81	81	81
P_i/A (psi) =	0	1,523	1,786	1,786	1,786	1,786	1,786	1,786	1,786
P_ie/S_b (psi) =	0	3,070	3,600	3,600	3,600	3,600	3,600	3,600	3,600
M_{pc}/S_b (psi) =	0	56	64	99	116	130	148	149	155
f_{bot} (psi) =	**0**	**4,538**	**5,322**	**5,287**	**5,270**	**5,256**	**5,238**	**5,238**	**5,232**
Check:	OK	OK	OK	OK	OK	OK	OK	OK	OK
P_ie/S_t (psi) =	0	2,639	3,094	3,094	3,094	3,094	3,094	3,094	3,094
M_{pc}/S_t (psi) =	0	48	55	85	100	112	128	128	133
f_{top} (psi) =	**0**	**-1,068**	**-1,253**	**-1,223**	**-1,209**	**-1,197**	**-1,181**	**-1,180**	**-1,175**
Check:	OK	No Good	No Good	No Good	No Good	No Good	No Good	No Good	No Good
Δf =	0	5,605	6,575	6,510	6,479	6,453	6,418	6,418	6,407

MILD STEEL

Needed to prevent cracking if limit of 12*SQRT(f'c) is used

Needed?	Need
Neutral Axis (in) =	2.95
Mild Tension Force (k) =	10.18
A_{s_req} (in^2) =	0.339
A_{s_act} (in^2) =	0.4
Check:	OK

SERVICE STRESSES

Location:	0	0.1L	L_{tr}	0.2L	0.25L	0.3L	0.4L	LL	0.5L
P_e (k) =	0	61	71	71	71	71	71	71	71
P_e/A (psi) =	0	1,345	1,578	1,578	1,578	1,578	1,578	1,578	1,578
P_ee/S_b (psi) =	0	2,712	3,181	3,181	3,181	3,181	3,181	3,181	3,181
M_{pc}/S_b (psi) =	0	56	64	99	116	130	148	149	155
M_{SILL}/S_b (psi) =	0	1,359	1,593	2,717	3,396	4,076	5,434	5,458	5,458
f_{bot} (psi) =	**0**	**2,644**	**3,101**	**1,942**	**1,246**	**553**	**-824**	**-849**	**-855**
Check:	OK	OK	OK	OK	OK	OK	OK	OK	OK
P_ee/S_t (psi) =	0	2,331	2,733	2,733	2,733	2,733	2,733	2,733	2,733
M_{pc}/S_t (psi) =	0	48	55	85	100	112	128	128	133
M_{SILL}/S_t (psi) =	0	1,167	1,369	2,335	2,919	3,502	4,670	4,691	4,691
f_{PC_sust} (psi) =	**0**	**-938**	**-1,101**	**-1,071**	**-1,056**	**-1,044**	**-1,028**	**-1,028**	**-1,023**
Check:	OK	OK	OK	OK	OK	OK	OK	OK	OK
f_{PC_full} (psi) =	**0**	**230**	**268**	**1,264**	**1,863**	**2,458**	**3,642**	**3,663**	**3,668**
Check:	OK	OK	OK	OK	OK	OK	OK	OK	OK

CRACKING MOMENT

Location:	0	0.1L	L_{tr}	0.2L	0.25L	0.3L	0.4L	LL	0.5L
M_{cr} (k-in) =	0	669	785	785	785	785	785	785	785

STRESS ANALYSIS

STRAND PATTERN

Location:	0	0.1L	L_{tr}	0.2L	0.25L	0.3L	0.4L	LL	0.5L
X (in) =	0	22	26	45	56	67	90	90	112
X (ft) =	0.0	1.9	2.2	3.7	4.7	5.6	7.5	7.5	9.3
y_s (in) =	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
e (in) =	7.34	7.34	7.34	7.34	7.34	7.34	7.34	7.34	7.34

LOADING

Location:	0	0.1L	L_{tr}	0.2L	0.25L	0.3L	0.4L	LL	0.5L
M_{pc} (k-in) =	0.0	9.2	10.6	16.3	19.1	21.4	24.5	24.5	25.5
M_{LL} (k-in) =	0	224	263	448	560	672	896	900	900
M_{tot} (k-in) =	0.0	233.2	273.2	464.3	579.1	693.4	920.5	924.5	925.5

TRANSFER STRESS LIMITS

	Location:	0	0.1L	L_{tr}	0.2L	0.25L	0.3L	0.4L	LL	0.5L
(ACI Tbl. 24.5.3.2)	T (top) =	-569	-569	-285	-285	-285	-285	-285	-285	-285
(ACI Tbl. 24.5.3.1)	C (bot) =	6,300	6,300	6,300	5,400	5,400	5,400	5,400	5,400	5,400

SERVICE LOAD STRESS LIMITS

	Location:	0	0.1L	L_{tr}	0.2L	0.25L	0.3L	0.4L	LL	0.5L
(ACI Tbl. 24.5.2.1)	T (bot) =	-887	-887	-887	-887	-887	-887	-887	-887	-887
(ACI Tbl. 24.5.4.1)	C_{sust} (top) =	6,300	6,300	6,300	6,300	6,300	6,300	6,300	6,300	6,300
(ACI Tbl. 24.5.4.1)	C_{tot} (top) =	8,400	8,400	8,400	8,400	8,400	8,400	8,400	8,400	8,400

TRANSFER STRESSES

Location:	0	0.1L	L_{tr}	0.2L	0.25L	0.3L	0.4L	LL	0.5L
P_i (k) =	0	69	80.92	81	81	81	81	81	81
P_i/A (psi) =	0	1,523	1,786	1,786	1,786	1,786	1,786	1,786	1,786
P_ie/S_b (psi) =	0	3,070	3,600	3,600	3,600	3,600	3,600	3,600	3,600
M_{pc}/S_b (psi) =	0	56	64	99	116	130	148	149	155
f_{bot} (psi) =	**0**	**4,538**	**5,322**	**5,287**	**5,270**	**5,256**	**5,238**	**5,238**	**5,232**
Check:	OK	OK	OK	OK	OK	OK	OK	OK	OK
P_ie/S_t (psi) =	0	2,639	3,094	3,094	3,094	3,094	3,094	3,094	3,094
M_{pc}/S_t (psi) =	0	48	55	85	100	112	128	128	133
f_{top} (psi) =	**0**	**-1,068**	**-1,253**	**-1,223**	**-1,209**	**-1,197**	**-1,181**	**-1,180**	**-1,175**
Check:	OK	No Good	No Good	No Good	No Good	No Good	No Good	No Good	No Good
Δf =	0	5,605	6,575	6,510	6,479	6,453	6,418	6,418	6,407

MILD STEEL

Needed to prevent cracking if limit of 12*SQRT(f'c) is used

Needed?	Need
Neutral Axis (in) =	2.95
Mild Tension Force (k) =	10.18
A_{s_req} (in^2) =	0.339
A_{s_act} (in^2) =	0.4
Check:	OK

SERVICE STRESSES

Location:	0	0.1L	L_{tr}	0.2L	0.25L	0.3L	0.4L	LL	0.5L
P_e (k) =	0	61	71	71	71	71	71	71	71
P_e/A (psi) =	0	1,345	1,578	1,578	1,578	1,578	1,578	1,578	1,578
P_ee/S_b (psi) =	0	2,712	3,181	3,181	3,181	3,181	3,181	3,181	3,181
M_{pc}/S_b (psi) =	0	56	64	99	116	130	148	149	155
M_{SILL}/S_b (psi) =	0	1,359	1,593	2,717	3,396	4,076	5,434	5,458	5,458
f_{bot} (psi) =	**0**	**2,644**	**3,101**	**1,942**	**1,246**	**553**	**-824**	**-849**	**-855**
Check:	OK	OK	OK	OK	OK	OK	OK	OK	OK
P_ee/S_t (psi) =	0	2,331	2,733	2,733	2,733	2,733	2,733	2,733	2,733
M_{pc}/S_t (psi) =	0	48	55	85	100	112	128	128	133
M_{SILL}/S_t (psi) =	0	1,167	1,369	2,335	2,919	3,502	4,670	4,691	4,691
f_{PC_sust} (psi) =	**0**	**-938**	**-1,101**	**-1,071**	**-1,056**	**-1,044**	**-1,028**	**-1,028**	**-1,023**
Check:	OK	OK	OK	OK	OK	OK	OK	OK	OK
f_{PC_full} (psi) =	**0**	**230**	**268**	**1,264**	**1,863**	**2,458**	**3,642**	**3,663**	**3,668**
Check:	OK	OK	OK	OK	OK	OK	OK	OK	OK

CRACKING MOMENT

Location:	0	0.1L	L_{tr}	0.2L	0.25L	0.3L	0.4L	LL	0.5L
M_{cr} (k-in) =	0	669	785	785	785	785	785	785	785

STRESS ANALYSIS

STRAND PATTERN

Location:	0	0.1L	L_{tr}	0.2L	0.25L	0.3L	0.4L	LL	0.5L
X (in) =	0	22	26	45	56	67	90	90	112
X (ft) =	0.0	1.9	2.2	3.7	4.7	5.6	7.5	7.5	9.3
y_s (in) =	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
e (in) =	7.34	7.34	7.34	7.34	7.34	7.34	7.34	7.34	7.34

LOADING

Location:	0	0.1L	L_{tr}	0.2L	0.25L	0.3L	0.4L	LL	0.5L
M_{pc} (k-in) =	0.0	9.2	10.6	16.3	19.1	21.4	24.5	24.5	25.5
M_{LL} (k-in) =	0	224	263	448	560	672	896	900	900
M_{tot} (k-in) =	0.0	233.2	273.2	464.3	579.1	693.4	920.5	924.5	925.5

TRANSFER STRESS LIMITS

	Location:	0	0.1L	L_{tr}	0.2L	0.25L	0.3L	0.4L	LL	0.5L
(ACI Tbl. 24.5.3.2)	T (top) =	-569	-569	-285	-285	-285	-285	-285	-285	-285
(ACI Tbl. 24.5.3.1)	C (bot) =	6,300	6,300	6,300	5,400	5,400	5,400	5,400	5,400	5,400

SERVICE LOAD STRESS LIMITS

	Location:	0	0.1L	L_{tr}	0.2L	0.25L	0.3L	0.4L	LL	0.5L
(ACI Tbl. 24.5.2.1)	T (bot) =	-887	-887	-887	-887	-887	-887	-887	-887	-887
(ACI Tbl. 24.5.4.1)	C_{sust} (top) =	6,300	6,300	6,300	6,300	6,300	6,300	6,300	6,300	6,300
(ACI Tbl. 24.5.4.1)	C_{tot} (top) =	8,400	8,400	8,400	8,400	8,400	8,400	8,400	8,400	8,400

TRANSFER STRESSES

Location:	0	0.1L	L_{tr}	0.2L	0.25L	0.3L	0.4L	LL	0.5L
P_i (k) =	0	69	80.92	81	81	81	81	81	81
P_i/A (psi) =	0	1,523	1,786	1,786	1,786	1,786	1,786	1,786	1,786
P_ie/S_b (psi) =	0	3,070	3,600	3,600	3,600	3,600	3,600	3,600	3,600
M_{pc}/S_b (psi) =	0	56	64	99	116	130	148	149	155
f_{bot} (psi) =	**0**	**4,538**	**5,322**	**5,287**	**5,270**	**5,256**	**5,238**	**5,238**	**5,232**
Check:	OK	OK	OK	OK	OK	OK	OK	OK	OK
P_ie/S_t (psi) =	0	2,639	3,094	3,094	3,094	3,094	3,094	3,094	3,094
M_{pc}/S_t (psi) =	0	48	55	85	100	112	128	128	133
f_{top} (psi) =	**0**	**-1,068**	**-1,253**	**-1,223**	**-1,209**	**-1,197**	**-1,181**	**-1,180**	**-1,175**
Check:	OK	No Good	No Good	No Good	No Good	No Good	No Good	No Good	No Good
Δf =	0	5,605	6,575	6,510	6,479	6,453	6,418	6,418	6,407

MILD STEEL

Needed to prevent cracking if limit of 12*SQRT(f'c) is used

Needed?	Need
Neutral Axis (in) =	2.95
Mild Tension Force (k) =	10.18
A_{s_req} (in^2) =	0.339
A_{s_act} (in^2) =	0.4
Check:	OK

SERVICE STRESSES

Location:	0	0.1L	L_{tr}	0.2L	0.25L	0.3L	0.4L	LL	0.5L
P_e (k) =	0	61	71	71	71	71	71	71	71
P_e/A (psi) =	0	1,345	1,578	1,578	1,578	1,578	1,578	1,578	1,578
P_ee/S_b (psi) =	0	2,712	3,181	3,181	3,181	3,181	3,181	3,181	3,181
M_{pc}/S_b (psi) =	0	56	64	99	116	130	148	149	155
M_{SILL}/S_b (psi) =	0	1,359	1,593	2,717	3,396	4,076	5,434	5,458	5,458
f_{bot} (psi) =	**0**	**2,644**	**3,101**	**1,942**	**1,246**	**553**	**-824**	**-849**	**-855**
Check:	OK	OK	OK	OK	OK	OK	OK	OK	OK
P_ee/S_t (psi) =	0	2,331	2,733	2,733	2,733	2,733	2,733	2,733	2,733
M_{pc}/S_t (psi) =	0	48	55	85	100	112	128	128	133
M_{SILL}/S_t (psi) =	0	1,167	1,369	2,335	2,919	3,502	4,670	4,691	4,691
f_{PC_sust} (psi) =	**0**	**-938**	**-1,101**	**-1,071**	**-1,056**	**-1,044**	**-1,028**	**-1,028**	**-1,023**
Check:	OK	OK	OK	OK	OK	OK	OK	OK	OK
f_{PC_full} (psi) =	**0**	**230**	**268**	**1,264**	**1,863**	**2,458**	**3,642**	**3,663**	**3,668**
Check:	OK	OK	OK	OK	OK	OK	OK	OK	OK

CRACKING MOMENT

Location:	0	0.1L	L_{tr}	0.2L	0.25L	0.3L	0.4L	LL	0.5L
M_{cr} (k-in) =	0	669	785	785	785	785	785	785	785

STRAIN COMPATIBILITY ANALYSIS

Set: ε_c = 0.003
Modify: **c (in) = 1.73**

CONCRETE

Assuming: 1. Normalweight concrete
2. f'c ≤ 8000 psi
3. Compression block in top flange

f'_c (psi) = 14,000	
h = 15.5	
b_{cf} = 8	
f_r (psi) = 887	(ACI 19.2.3.1)
E_c (ksi) = 7,535	(ACI 19.2.2.1)
β_1 = 0.65	(ACI 22.2.2.4.3)
a (in) = 1.12	
C_c (k) = 107	

BOTTOM PRESTRESSING STEEL

Assuming: 1. Low-Relax Strand
2. Grade 270
3. 1/2" Strand

- E_{ps} (ksi) = 28,700
- f_{pe} (ksi) = 158
- N_b = 3
- d_p (in) = 14.5
- TL (ksi) = 45
- A_{ps} (in^2) = 0.45
- f_{dc} (ksi)= -0.56
- ε_{dc} = -0.000075
- ε_{pe} = 0.005491
- ε_s = 0.022173
- ε_{ps} = 0.027590
- f_{ps} (ksi) = 268.06
- T_{ps} (k) = 122

TOP PRESTRESSING STEEL

Assuming: 1. Low-Relax Strand
2. Grade 270
3. 1/2" Strand

- E'_{ps} (ksi) = 28,500
- f_{pe} (ksi) = 158
- N'_b =
- d'_p (in) =
- TL (ksi) = 45
- A'_{ps} (in^2) =
- f_{dc} (ksi)= -0.56
- ε_{dc} = -0.000075
- ε_{pe} = 0.005491
- ε_s = -0.003
- ε_{ps} = 0.002417
- f_{ps} (ksi) = 268
- T_{ps} (k) = 0

COMPRESSION STEEL

Assuming: 1. Grade 60

- E'_s (ksi) = 29,000
- F_y (ksi) = 60
- N_b = 2
- $Size_b$ = 4
- d' (in) = 1
- A'_s (in^2) = 0.40
- ε'_y = 0.002069
- ε'_s = 0.001264
- f'_s (ksi) = 37
- C'_s (k) = 15

TENSION STEEL

Assuming: 1. Grade 60

- E_s (ksi) = 29,000
- F_y (ksi) = 60
- N_b =
- $Size_b$ =
- d (in) =
- A_s (in^2) = 0.00
- ε_y = 0.002069
- ε_s = 0.003000
- f_s (ksi) = 60
- T_s (k) = 0

EQUILIBRIUM

- ΣF_x (k) = 0
- Φ = 0.90 (ACI Tbl. 21.2.2)
- Mn (k-ft) = 141
- (ΣM about bottom prestressing)
- **ΦMn (k-ft) = 127**
- Mu (k-ft) = 122
- Check: OK

FAILURE LOAD

P_u (k) = 37.0

DEVELOPMENT LENGTH

L_d (ft) = 6.79

SHEAR ANALYSIS

PRESTRESSING

Location:	0	0.1L	L_{tr}	0.2L	0.25L	0.3L	0.4L	LL	0.5L
X_{brg} (in) =	0	22	26	43	54	65	86	90	108
X_{end} (in) =	4	26	30	47	58	69	90	94	112
y_s (in) =	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
e (in) =	7.34	7.34	7.34	7.34	7.34	7.34	7.34	7.34	7.34
d (in) =	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5
d_{act} (in) =	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5
P_e (k) =	10.9	69.7	71.5	71.5	71.5	71.5	71.5	71.5	71.5

CONCRETE CONTRIBUTION, V_{cw}

	Location:	0	0.1L	L_{tr}	0.2L	0.25L	0.3L	0.4L	LL	0.5L
	f_{pc} (psi) =	240	1,538	1,578	1,578	1,578	1,578	1,578	1,578	1,578
	f_{sp} (psi) =	473	473	473	473	473	473	473	473	473
	V_p (k) =	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
(ACI 22.5.8.3.2)	V_{cw} (k) =	12.3	22.2	22.5	22.5	22.5	22.5	22.5	22.5	22.5

CONCRETE CONTRIBUTION, V_{ci}

	Location:	0	0.1L	L_{tr}	0.2L	0.25L	0.3L	0.4L	LL	0.5L
	f_{pe} (psi) =	725	4,637	4,758	4,758	4,758	4,758	4,758	4,758	4,758
	M_{pc} (lb-in) =	0	8,533	10,128	15,171	17,778	19,911	22,756	23,046	23,704
	V_d (k) =	0.44	0.35	0.33	0.26	0.22	0.18	0.09	0.07	0.00
	V_i (k) =	16	16	16	16	16	16	16	16	0
	f_d (psi) =	0.0	51.8	61.4	92.0	107.8	120.8	138.0	139.8	143.8
	M_{cre} (k-in) =	218	855	873	868	866	864	861	860	860
	M_{max} (k-in) =	0	346	420	691	864	1,037	1,382	1,440	1,440
(ACI 22.5.8.3.1a)	V_{ci} (k) =	N/A	41.5	35.1	21.9	17.8	15.0	11.6	11.2	1.5
(ACI 22.5.8.3.1b)	V_{ci_min} (k) =	4.31	4.31	4.31	4.31	4.31	4.31	4.31	4.31	4.31
	V_{ci} (k) =	N/A	41.5	35.1	21.9	17.8	15.0	11.6	11.2	4.3

SHEAR CAPACITY

Location:	0	0.1L	L_{tr}	0.2L	0.25L	0.3L	0.4L	LL	0.5L
V_s (k) =	15.1	15.1	15.1	15.1	15.1	15.1	15.1	15.1	15.1
V_c (k) =	12.3	22.2	22.5	21.9	17.8	15.0	11.6	11.2	4.3
ϕV_n (k) =	20.6	28.0	28.2	27.7	24.6	22.6	20.0	19.7	14.5
V_u (k) =	20.0	19.9	19.8	19.8	19.7	19.7	19.6	19.6	0.0
Check V =	OK	OK	OK	OK	OK	OK	OK	OK	OK

WEB REINFORCEMENT

Location:	0	0.1L	L_{tr}	0.2L	0.25L	0.3L	0.4L	LL	0.5L
Max Spacing (ACI Tbl. 9.7.6.2.2):									
$4\sqrt{f'c}b_w d$ =	10.2	10.2	10.2	10.2	10.2	10.2	10.2	10.2	10.2
s_{max} (in) =	5.8125	5.8125	5.8125	5.8125	5.8125	5.8125	5.8125	5.8125	5.8125
Check s_{max} =	OK	OK	OK	OK	OK	OK	OK	OK	OK
Max Reinforcement (ACI Eq. 22.5.1.2):									
V_{s_max} (k) =	20.3	20.3	20.3	20.3	20.3	20.3	20.3	20.3	20.3
Check V_{s_max} =	OK	OK	OK	OK	OK	OK	OK	OK	OK
Min Reinforcement (ACI Tbl. 9.6.3.3):									
Equations to Use:	C,D,E	C,D,E	C,D,E	C,D,E	C,D,E	C,D,E	C,D,E	C,D,E	C,D,E
A_{v,min_c} (in^2/ft) =	0.024	0.024	0.024	0.024	0.024	0.024	0.024	0.024	0.024
A_{v,min_d} (in^2/ft) =	0.016	0.016	0.016	0.016	0.016	0.016	0.016	0.016	0.016
A_{v,min_e} (in^2/ft) =	0.056	0.056	0.056	0.056	0.056	0.056	0.056	0.056	0.056
A_{v_min} (in^2/ft) =	0.024	0.024	0.024	0.024	0.024	0.024	0.024	0.024	0.024
A_{v_prov} (in^2/ft) =	0.192	0.192	0.192	0.192	0.192	0.192	0.192	0.192	0.192
Check A_{v_min} =	OK	OK	OK	OK	OK	OK	OK	OK	OK

SHEAR ANALYSIS

PRESTRESSING

Location:	0	0.1L	L_{tr}	0.2L	0.25L	0.3L	0.4L	LL	0.5L
X_{brg} (in) =	0	22	26	43	54	65	86	90	108
X_{end} (in) =	4	26	30	47	58	69	90	94	112
y_s (in) =	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
e (in) =	7.34	7.34	7.34	7.34	7.34	7.34	7.34	7.34	7.34
d (in) =	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5
d_{act} (in) =	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5
P_e (k) =	10.9	69.7	71.5	71.5	71.5	71.5	71.5	71.5	71.5

CONCRETE CONTRIBUTION, V_{cw}

	Location:	0	0.1L	L_{tr}	0.2L	0.25L	0.3L	0.4L	LL	0.5L
	f_{pc} (psi) =	240	1,538	1,578	1,578	1,578	1,578	1,578	1,578	1,578
	f_{sp} (psi) =	473	473	473	473	473	473	473	473	473
	V_p (k) =	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
(ACI 22.5.8.3.2)	V_{cw} (k) =	12.3	22.2	22.5	22.5	22.5	22.5	22.5	22.5	22.5

CONCRETE CONTRIBUTION, V_{ci}

	Location:	0	0.1L	L_{tr}	0.2L	0.25L	0.3L	0.4L	LL	0.5L
	f_{pe} (psi) =	725	4,637	4,758	4,758	4,758	4,758	4,758	4,758	4,758
	M_{pc} (lb-in) =	0	8,533	10,128	15,171	17,778	19,911	22,756	23,046	23,704
	V_d (k) =	0.44	0.35	0.33	0.26	0.22	0.18	0.09	0.07	0.00
	V_i (k) =	16	16	16	16	16	16	16	16	0
	f_d (psi) =	0.0	51.8	61.4	92.0	107.8	120.8	138.0	139.8	143.8
	M_{cre} (k-in) =	218	855	873	868	866	864	861	860	860
	M_{max} (k-in) =	0	346	420	691	864	1,037	1,382	1,440	1,440
(ACI 22.5.8.3.1a)	V_{ci} (k) =	N/A	41.5	35.1	21.9	17.8	15.0	11.6	11.2	1.5
(ACI 22.5.8.3.1b)	V_{ci_min} (k) =	4.31	4.31	4.31	4.31	4.31	4.31	4.31	4.31	4.31
	V_{ci} (k) =	N/A	41.5	35.1	21.9	17.8	15.0	11.6	11.2	4.3

SHEAR CAPACITY

Location:	0	0.1L	L_{tr}	0.2L	0.25L	0.3L	0.4L	LL	0.5L
V_s (k) =	15.1	15.1	15.1	15.1	15.1	15.1	15.1	15.1	15.1
V_c (k) =	12.3	22.2	22.5	21.9	17.8	15.0	11.6	11.2	4.3
ϕV_n (k) =	20.6	28.0	28.2	27.7	24.6	22.6	20.0	19.7	14.5
V_u (k) =	20.0	19.9	19.8	19.8	19.7	19.7	19.6	19.6	0.0
Check V =	OK	OK	OK	OK	OK	OK	OK	OK	OK

WEB REINFORCEMENT

Location:	0	0.1L	L_{tr}	0.2L	0.25L	0.3L	0.4L	LL	0.5L
Max Spacing (ACI Tbl. 9.7.6.2.2):									
$4\sqrt{f'c}b_w d$ =	10.2	10.2	10.2	10.2	10.2	10.2	10.2	10.2	10.2
s_{max} (in) =	5.8125	5.8125	5.8125	5.8125	5.8125	5.8125	5.8125	5.8125	5.8125
Check s_{max} =	OK	OK	OK	OK	OK	OK	OK	OK	OK
Max Reinforcement (ACI Eq. 22.5.1.2):									
V_{s_max} (k) =	20.3	20.3	20.3	20.3	20.3	20.3	20.3	20.3	20.3
Check V_{s_max} =	OK	OK	OK	OK	OK	OK	OK	OK	OK
Min Reinforcement (ACI Tbl. 9.6.3.3):									
Equations to Use:	C,D,E	C,D,E	C,D,E	C,D,E	C,D,E	C,D,E	C,D,E	C,D,E	C,D,E
A_{v,min_c} (in^2/ft) =	0.024	0.024	0.024	0.024	0.024	0.024	0.024	0.024	0.024
A_{v,min_d} (in^2/ft) =	0.016	0.016	0.016	0.016	0.016	0.016	0.016	0.016	0.016
A_{v,min_e} (in^2/ft) =	0.056	0.056	0.056	0.056	0.056	0.056	0.056	0.056	0.056
A_{v_min} (in^2/ft) =	0.024	0.024	0.024	0.024	0.024	0.024	0.024	0.024	0.024
A_{v_prov} (in^2/ft) =	0.192	0.192	0.192	0.192	0.192	0.192	0.192	0.192	0.192
Check A_{v_min} =	OK	OK	OK	OK	OK	OK	OK	OK	OK

SHEAR ANALYSIS

PRESTRESSING

Location:	0	0.1L	L_{tr}	0.2L	0.25L	0.3L	0.4L	LL	0.5L
X_{brg} (in) =	0	22	26	43	54	65	86	90	108
X_{end} (in) =	4	26	30	47	58	69	90	94	112
y_s (in) =	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
e (in) =	7.34	7.34	7.34	7.34	7.34	7.34	7.34	7.34	7.34
d (in) =	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5
d_{act} (in) =	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5
P_e (k) =	10.9	69.7	71.5	71.5	71.5	71.5	71.5	71.5	71.5

CONCRETE CONTRIBUTION, V_{cw}

	Location:	0	0.1L	L_{tr}	0.2L	0.25L	0.3L	0.4L	LL	0.5L
	f_{pc} (psi) =	240	1,538	1,578	1,578	1,578	1,578	1,578	1,578	1,578
	f_{sp} (psi) =	473	473	473	473	473	473	473	473	473
	V_p (k) =	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
(ACI 22.5.8.3.2)	V_{cw} (k) =	12.3	22.2	22.5	22.5	22.5	22.5	22.5	22.5	22.5

CONCRETE CONTRIBUTION, V_{ci}

	Location:	0	0.1L	L_{tr}	0.2L	0.25L	0.3L	0.4L	LL	0.5L
	f_{pe} (psi) =	725	4,637	4,758	4,758	4,758	4,758	4,758	4,758	4,758
	M_{pc} (lb-in) =	0	8,533	10,128	15,171	17,778	19,911	22,756	23,046	23,704
	V_d (k) =	0.44	0.35	0.33	0.26	0.22	0.18	0.09	0.07	0.00
	V_i (k) =	16	16	16	16	16	16	16	16	0
	f_d (psi) =	0.0	51.8	61.4	92.0	107.8	120.8	138.0	139.8	143.8
	M_{cre} (k-in) =	218	855	873	868	866	864	861	860	860
	M_{max} (k-in) =	0	346	420	691	864	1,037	1,382	1,440	1,440
(ACI 22.5.8.3.1a)	V_{ci} (k) =	N/A	41.5	35.1	21.9	17.8	15.0	11.6	11.2	1.5
(ACI 22.5.8.3.1b)	V_{ci_min} (k) =	4.31	4.31	4.31	4.31	4.31	4.31	4.31	4.31	4.31
	V_{ci} (k) =	N/A	41.5	35.1	21.9	17.8	15.0	11.6	11.2	4.3

SHEAR CAPACITY

Location:	0	0.1L	L_{tr}	0.2L	0.25L	0.3L	0.4L	LL	0.5L
V_s (k) =	15.1	15.1	15.1	15.1	15.1	15.1	15.1	15.1	15.1
V_c (k) =	12.3	22.2	22.5	21.9	17.8	15.0	11.6	11.2	4.3
ϕV_n (k) =	20.6	28.0	28.2	27.7	24.6	22.6	20.0	19.7	14.5
V_u (k) =	20.0	19.9	19.8	19.8	19.7	19.7	19.6	19.6	0.0
Check V =	OK	OK	OK	OK	OK	OK	OK	OK	OK

WEB REINFORCEMENT

Location:	0	0.1L	L_{tr}	0.2L	0.25L	0.3L	0.4L	LL	0.5L
Max Spacing (ACI Tbl. 9.7.6.2.2):									
$4\sqrt{f'c}b_w d$ =	10.2	10.2	10.2	10.2	10.2	10.2	10.2	10.2	10.2
s_{max} (in) =	5.8125	5.8125	5.8125	5.8125	5.8125	5.8125	5.8125	5.8125	5.8125
Check s_{max} =	OK	OK	OK	OK	OK	OK	OK	OK	OK
Max Reinforcement (ACI Eq. 22.5.1.2):									
V_{s_max} (k) =	20.3	20.3	20.3	20.3	20.3	20.3	20.3	20.3	20.3
Check V_{s_max} =	OK	OK	OK	OK	OK	OK	OK	OK	OK
Min Reinforcement (ACI Tbl. 9.6.3.3):									
Equations to Use:	C,D,E	C,D,E	C,D,E	C,D,E	C,D,E	C,D,E	C,D,E	C,D,E	C,D,E
A_{v,min_c} (in^2/ft) =	0.024	0.024	0.024	0.024	0.024	0.024	0.024	0.024	0.024
A_{v,min_d} (in^2/ft) =	0.016	0.016	0.016	0.016	0.016	0.016	0.016	0.016	0.016
A_{v,min_e} (in^2/ft) =	0.056	0.056	0.056	0.056	0.056	0.056	0.056	0.056	0.056
A_{v_min} (in^2/ft) =	0.024	0.024	0.024	0.024	0.024	0.024	0.024	0.024	0.024
A_{v_prov} (in^2/ft) =	0.192	0.192	0.192	0.192	0.192	0.192	0.192	0.192	0.192
Check A_{v_min} =	OK	OK	OK	OK	OK	OK	OK	OK	OK

QUANTITIES AND UNIT COSTS

Prestressing Strand		
Number of Strands =	3	EA
Length of Each Strand =	18.67	FT
Area of Each Strand =	0.001	SF
Unit Weight of Each Strand =	0.520	PLF
Total Volume of Strand =	**0.059**	**CF**
Total Weight of Strand =	**29**	**LB**
Total Length of Strand =	**56**	**FT**

Mild Steel		
Number of Long. Bars =	2	EA
Unit Weight of Each Long. Bar =	0.668	PLF
Length of Each Long. Bar =	18.83	FT
Area of Each Long. Bar =	0.001	SF
Number of Lifting Bars =	2	EA
Unit Weight of Each Lifting Bar =	0.376	PLF
Length of Each Lifting Bar =	3.17	FT
Area of Each Lifting Bar =	0.001	SF
Total Volume of Mild Steel =	**0.06**	**CF**
Total Weight of Mild Steel =	**27.54**	**LB**

Shear		
Number of Bars =	75	EA
Unit Weight of Each Bar =	0.136	PLF
Length of Each Bar =	1.58	FT
Area of Each Bar =	0.0003	SF
Total Volume of Stirrups =	**0.03**	**CF**
Total Weight of Stirrups =	**16.2**	**LB**

Concrete		
Area of Midspan =	0.31	SF
Length of Midspan Section =	4.00	FT
Area of Taper (Average) =	0.30	SF
Length of Taper Section =	1.25	FT
Area of End =	0.28	SF
Length of End Section =	13.4	FT
Unit Weight of Concrete =	161	PCF
Volume of Concrete =	5.30	CF
Volume of Concrete =	**0.20**	**CY**
Weight of Concrete =	**855**	**LB**

Forming		
Midspan Side Formwork =	3.2	FT
Taper Side Formwork =	3.1	FT
End Side Formwork =	3.0	FT
Face Area =	0.29	SF
Forming Area =	**58.4**	**SF**

COST SUMMARY				
ITEM	**UNIT**	**QUANTITY**	**$/UNIT**	**COST**
Concrete	CY	0.20	$120	$24
Prestressing Strand	FT	56	$0.30	$17
Mild Steel	LB	28	$0.45	$12
Shear Reinforcement	LB	16	$0.50	$8
Forming	SF	58	$1.25	$73
Weight	LB	928	--	--
			TOTAL =	**$133.77**

PCI BIG BEAM CONTEST
Load Deflection Response

Latest Revision: April 17, 2014

Moment Curvature Data …..

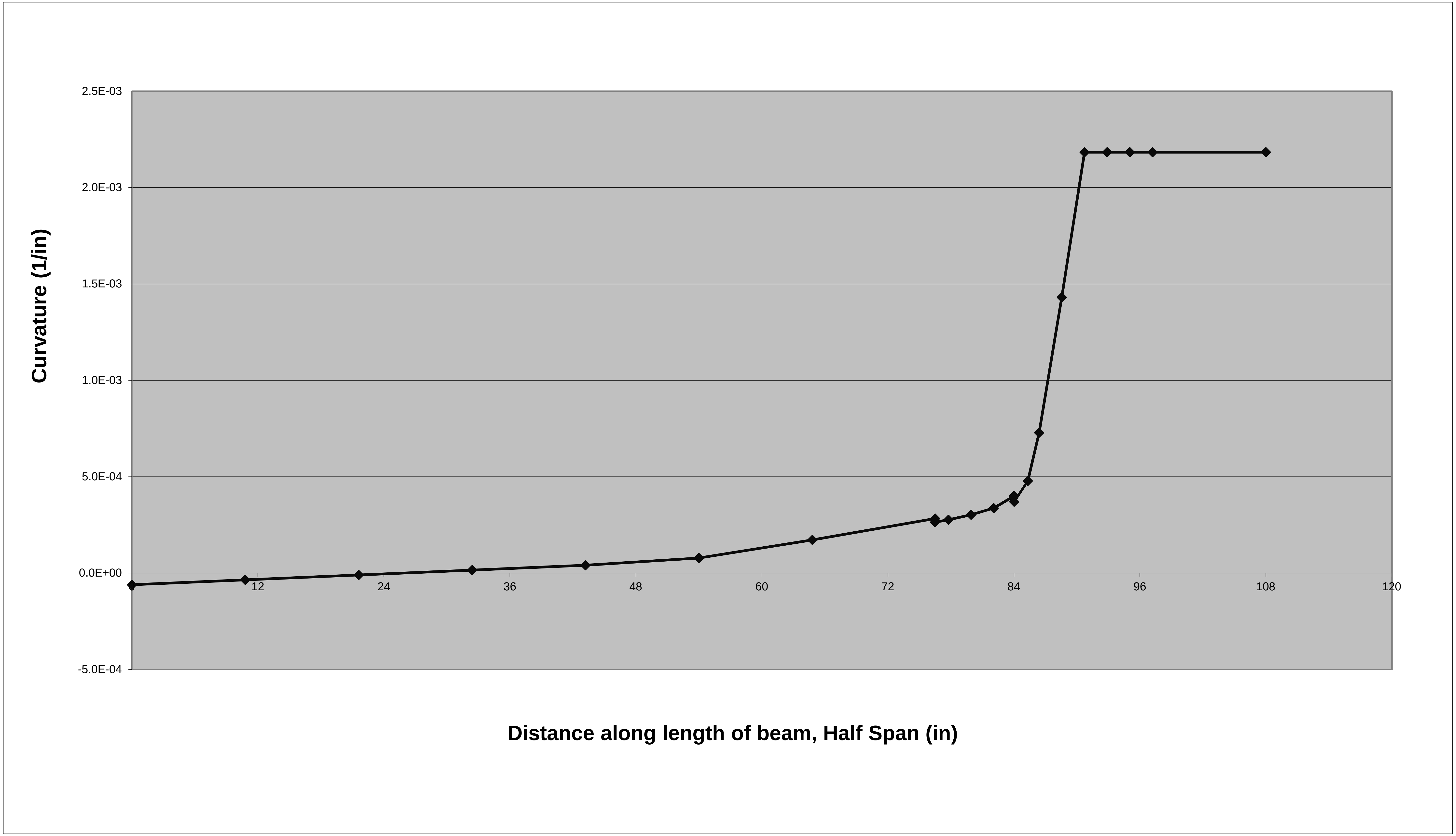
Section …	**1 MS**		**2 Taper**		**3 End**		**4**		**5**		**6**		**7**		**8**		**9**		**10**	
Data Pt.	Curvature (1/in.)	Moment (in-kip)	Curvature (1/in.)	Moment (in-kip)	Curvature (1/in.)	Moment (in-kip)	Curvature (1/in.)	Moment (in-kip)	Curvature (1/in.)	Moment (in-kip)	Curvature (1/in.)	Moment (in-kip)	Curvature (1/in.)	Moment (in-kip)	Curvature (1/in.)	Moment (in-kip)	Curvature (1/in.)	Moment (in-kip)	Curvature (1/in.)	Moment (in-kip)
1	-5.70E-05	0	-5.85E-05	0	-6.03E-05	0														
2	5.38E-05	1067	5.79E-05	1039	6.24E-05	1014														
3	1.49E-04	1269	1.27E-04	1192	1.08E-04	1113														
4	1.82E-04	1343	2.50E-04	1459	1.32E-04	1170														
5	2.17E-04	1418	2.84E-04	1524	1.58E-04	1229														
6	2.52E-04	1492	3.22E-04	1583	1.85E-04	1288														
7	2.92E-04	1563	3.73E-04	1624	2.13E-04	1347														
8	3.39E-04	1619	4.38E-04	1643	2.42E-04	1407														
9	4.05E-04	1647	5.10E-04	1654	2.72E-04	1467														
10	4.85E-04	1658	5.90E-04	1662	3.04E-04	1524														
11	7.58E-04	1681	6.74E-04	1669	4.39E-04	1630														
12	1.27E-03	1712	1.05E-03	1694	8.05E-04	1671														
13	1.79E-03	1739	1.53E-03	1719	1.23E-03	1695														
14	2.18E-03	1748	1.88E-03	1726	1.51E-03	1699														

Deflection Analysis …..

%L	X (in)	MC Data	Moment (in*kip)	Curvature (1/in)	Φ∗dx*xi (in)	Φ∗dx*xj (in)
0.00L	0.000	3	0	-6.03E-05		
0.05L	10.800	3	210	-3.49E-05	-0.00136	-0.00117
0.10L	21.600	3	420	-9.49E-06	-0.00092	-0.00271
0.15L	32.400	3	629	1.59E-05	0.00247	-0.00129
0.20L	43.200	3	839	4.13E-05	0.00883	0.00309
0.25L	54.000	3	1049	7.85E-05	0.02137	0.01043
0.3000L	64.800	3	1259	1.72E-04	0.05683	0.02442
0.3542L	76.500	3	1486	2.83E-04	0.12013	0.06911
0.3542L	76.501	2	1486	2.64E-04	0.00001	0.00001
0.3600L	77.760	2	1511	2.77E-04	0.01349	0.01279
0.3700L	79.920	2	1553	3.03E-04	0.02589	0.02347
0.3800L	82.080	2	1595	3.37E-04	0.02961	0.02636
0.3889L	84.000	2	1632	4.00E-04	0.03198	0.02676
0.3890L	84.024	1	1632	3.71E-04	0.00037	0.00040
0.3950L	85.320	1	1657	4.78E-04	0.02628	0.02029
0.4000L	86.400	1	1678	7.28E-04	0.03383	0.02210
0.4100L	88.560	1	1720	1.43E-03	0.13573	0.06851
0.4200L	90.720	1	1748	2.18E-03	0.21225	0.13795
0.4300L	92.880	1	1748	2.18E-03	0.21735	0.21565
0.4400L	95.040	1	1748	2.18E-03	0.22244	0.22074
0.4500L	97.200	1	1748	2.18E-03	0.22754	0.22584
0.5000L	108.000	1	1748	2.18E-03	1.23107	1.18862

Span Geometry & Point Load …..

Span (in)	216		
Shear Span (in)	90	0.42L	
Applied Shear (kip)	19.43	19.43	Max Load Available
Active Midspan Def. (in)	4.91		
Camber Est. at Zero Load	-0.88	This value will not match the camber estimated at test time using the PCI Multiplier Method.	
Camber Est. at Max Load	4.91		
Total Deflection	5.78		



2.5E-03
2.0E-03
1.5E-03
1.0E-03
5.0E-04
0.0E+00
-5.0E-04
Curvature (1/in)
12
24
36
48
60
72
84
96
108
120
Distance along length of beam, Half Span (in)

PCI BIG BEAM CONTEST

Latest Version: Apr 11, 2017

Concrete Properties …..

f'c (psi)	15,050
Ec (ksi)	5,910
MOR (psi)	920

Cross Section Geometry …..

Ag (in2)	40.94	I (in4)	1,182
yt (in)	6.46	w (plf)	48.5
yb (in)	7.66	h (in)	15.5

Prestress Information …..

Jacking Stress (ksi)	208.5	Aps (in2)	0.4536
Total Losses (ksi)	47.2	Pe (kips)	73.17
Effective Prestress, fpe (ksi)	161.3	e (in)	6.665
Eps (ksi)	28,700	L (ft)	18.00
ε_{pe} (in/in)	0.00562	M DL (ft*lb)	1962
$\varepsilon_{pe} + \varepsilon_{ce}$ (in/in)	0.006365	$\varepsilon_{ce\ top\ fiber}$ (in/in)	0.000127
		ε_{ce} (in/in)	-0.000745
		$\varepsilon_{ce\ bot\ fiber}$ (in/in)	-0.000812

Stress vs. Strain Parameters

A	406	C	107
B	28,294	D	25.3

Strain Profile …..

ec @ extreme fiber (in/in) -0.00081 negative for compression

c (in) 12.92

Equilbruim …..

Concrete (kips)	77.2
Reinforcement (kips)	-6.9
Prestressing Strand (kips)	84.2
Equilibrium (C-T)	0.0

Internal Moment & Curvature …..

Moment (in-kip)	1046.5
Curvature (1/in)	6.299E-05

Select Concrete Stress vs. Strain Profile

○ Parabola ◉ Mitchell & Collins

Moment Curvature Data …..

Data Pt.	Strain (in/in)	Curvature (1/in.)	External Moment (in-kip)	
1	0.000127	-6.05E-05	0.0	Strain Profile w/o loading, see above for strain profile.
2	-0.000814	6.30E-05	1046	Strain Profile at MOR, see notes below.
3	-0.001000	1.07E-04	1131	
4	-0.001100	1.31E-04	1189	
5	-0.001200	1.57E-04	1248	
6	-0.001300	1.85E-04	1308	
7	-0.001400	2.12E-04	1367	
8	-0.001500	2.42E-04	1428	
9	-0.001600	2.72E-04	1486	
10	-0.001700	3.05E-04	1542	
11	-0.002000	4.48E-04	1634	
12	-0.002500	8.26E-04	1673	
13	-0.003000	1.26E-03	1699	
14	-0.003500	1.58E-03	1705	

Active Bottom Fiber

Existing Bot Fiber Strain (in/in)	0.000153
MOR Strain (from above) (in/in)	0.000156
Difference (in/in)	0.000003

Cracking Load

22.731

Failure Load

37.366

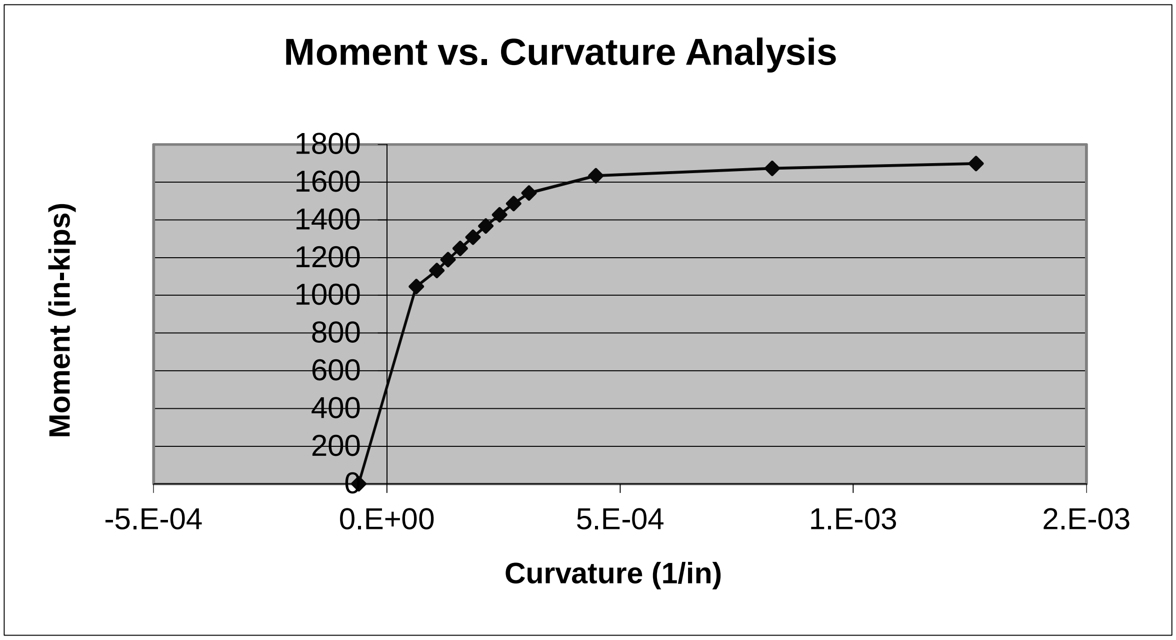
Strain Profile …..

y (in)	Strain (in/in)
15.50	-0.000814
2.58	0

Notes:

Data Pt #1 is the strain profile in the beam before any loading is applied.

Data Pt #2 is the strain profile prior to flexure cracking.
Adjust the concrete strain until the extreme fiber strain is slightly
less than the MOR strain. Make sure you have equilibrium.
Copy the strain, curvature and moment values into the appropriate columns.



PCI BIG BEAM CONTEST

Latest Version: Apr 11, 2017

Concrete Properties …..

f'c (psi)	15,050
Ec (ksi)	5,910
MOR (psi)	920

Cross Section Geometry …..

Ag (in2)	43.13	I (in4)	1,283
yt (in)	6.11	w (plf)	51.04
yb (in)	8.02	h (in)	15.5

Prestress Information …..

Jacking Stress (ksi)	208.5	Aps (in2)	0.4536
Total Losses (ksi)	47.2	Pe (kips)	73.17
Effective Prestress, fpe (ksi)	161.3	e (in)	7.017
Eps (ksi)	28,700	L (ft)	18.00
ε_{pe} (in/in)	0.00562	M DL (ft*lb)	2,067
$\varepsilon_{pe} + \varepsilon_{ce}$ (in/in)	0.006359	$\varepsilon_{ce\ top\ fiber}$ (in/in)	0.000106
		ε_{ce} (in/in)	-0.000739
		$\varepsilon_{ce\ bot\ fiber}$ (in/in)	-0.000804

Stress vs. Strain Parameters

A	406	C	107
B	28,294	D	25.3

Strain Profile …..

ec @ extreme fiber (in/in)	-0.00074	negative for compression
c (in)	12.63	

Equilbruim …..

Concrete (kips)	77.9
Reinforcement (kips)	-6.3
Prestressing Strand (kips)	84.2
Equilibrium (C-T)	0.0

Internal Moment & Curvature …..

Moment (in-kip)	1062.9
Curvature (1/in)	5.858E-05

Select Concrete Stress vs. Strain Profile

○ Parabola ◉ Mitchell & Collins

Moment Curvature Data …..

Data Pt.	Strain (in/in)	Curvature (1/in.)	External Moment (in-kip)	
1	0.000106	-5.87E-05	0.0	Strain Profile w/o loading, see above for strain profile.
2	-0.000740	5.86E-05	1039	Strain Profile at MOR, see notes below.
3	-0.001000	1.26E-04	1211	
4	-0.001400	2.50E-04	1479	
5	-0.001500	2.85E-04	1543	
6	-0.001600	3.27E-04	1598	
7	-0.001700	3.80E-04	1631	
8	-0.001800	4.48E-04	1647	
9	-0.001900	5.22E-04	1656	
10	-0.002000	6.06E-04	1664	
11	-0.002100	6.88E-04	1671	
12	-0.002500	1.07E-03	1696	
13	-0.003000	1.57E-03	1722	
14	-0.003500	1.94E-03	1732	

Active Bottom Fiber

Existing Bot Fiber Strain (in/in)	0.000159
MOR Strain (from above) (in/in)	0.000156
Difference (in/in)	0.000003

Strain Profile …..

Cracking Load

22.536

Failure Load

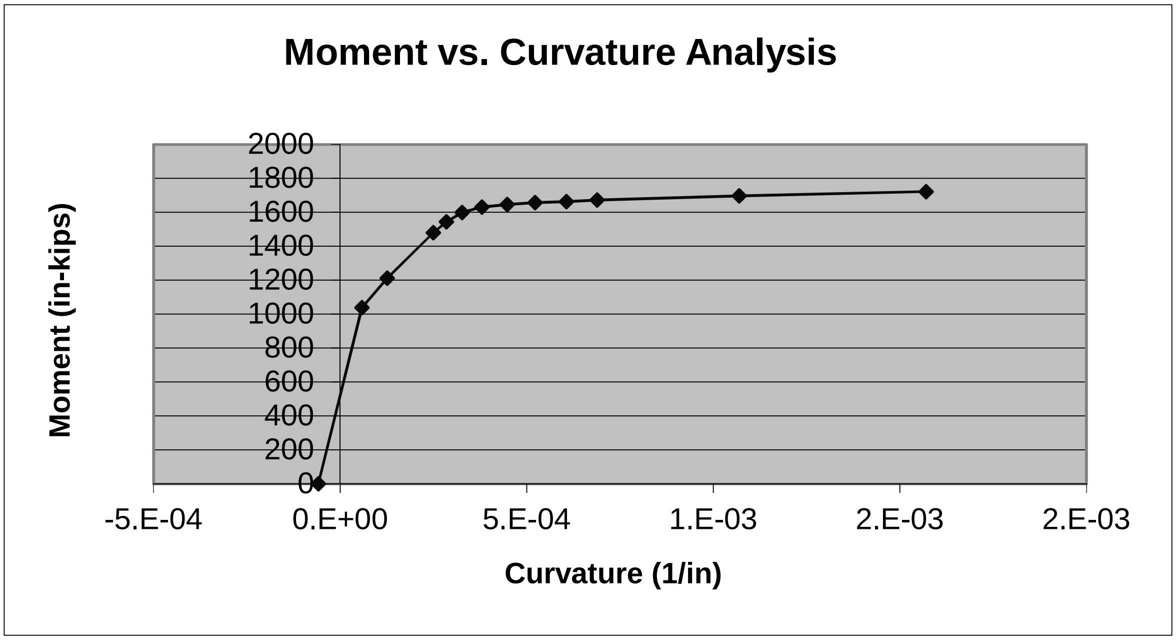
37.935

y (in)	Strain (in/in)
15.50	-0.00074
2.87	0

Notes:

Data Pt #1 is the strain profile in the beam before any loading is applied.

Data Pt #2 is the strain profile prior to flexure cracking.
Adjust the concrete strain until the extreme fiber strain is slightly less than the MOR strain. Make sure you have equilibrium.
Copy the strain, curvature and moment values into the appropriate columns.



PCI BIG BEAM CONTEST

Latest Version: Apr 11, 2017

Concrete Properties …..

f'c (psi)	15,050
Ec (ksi)	5,910
MOR (psi)	920

Cross Section Geometry …..

Ag (in2)	45.31	I (in4)	1,375
yt (in)	5.79	w (plf)	48.77
yb (in)	8.34	h (in)	15.5

Prestress Information …..

Jacking Stress (ksi)	208.5	Aps (in2)	0.4536
Total Losses (ksi)	47.2	Pe (kips)	73.17
Effective Prestress, fpe (ksi)	161.3	e (in)	7.336
Eps (ksi)	28,700	L (ft)	18.00
ε_{pe} (in/in)	0.00562	M DL (ft*lb)	1975
$\varepsilon_{pe} + \varepsilon_{ce}$ (in/in)	0.006357	$\varepsilon_{ce\ top\ fiber}$ (in/in)	0.000092
		ε_{ce} (in/in)	-0.000737
		$\varepsilon_{ce\ bot\ fiber}$ (in/in)	-0.000800

Stress vs. Strain Parameters

A	406	C	107
B	28,294	D	25.3

Strain Profile …..

ec @ extreme fiber (in/in)	-0.00068	negative for compression
c (in)	12.45	

Equilbruim …..

Concrete (kips)	78.4
Reinforcement (kips)	-5.8
Prestressing Strand (kips)	84.2
Equilibrium (C-T)	0.0

Internal Moment & Curvature …..

Moment (in-kip)	1084.0
Curvature (1/in)	5.469E-05

Select Concrete Stress vs. Strain Profile

○ Parabola ◉ Mitchell & Collins

Moment Curvature Data …..

Data Pt.	Strain (in/in)	Curvature (1/in.)	External Moment (in-kip)
1	0.000092	-5.76E-05	0.0
2	-0.000681	5.47E-05	1084
3	-0.001000	1.48E-04	1289
4	-0.001100	1.81E-04	1364
5	-0.001200	2.16E-04	1439
6	-0.001300	2.52E-04	1513
7	-0.001400	2.94E-04	1581
8	-0.001500	3.47E-04	1629
9	-0.001600	4.14E-04	1651
10	-0.001700	4.97E-04	1661
11	-0.002000	7.73E-04	1683
12	-0.002500	1.29E-03	1714
13	-0.003000	1.81E-03	1742
14	-0.003500	2.25E-03	1755

Strain Profile w/o loading, see above for strain profile.

Strain Profile at MOR, see notes below.

Active Bottom Fiber

Existing Bot Fiber Strain (in/in)	0.000158
MOR Strain (from above) (in/in)	0.000156
Difference (in/in)	0.000003

Strain Profile …..

Cracking Load

23.562

Failure Load

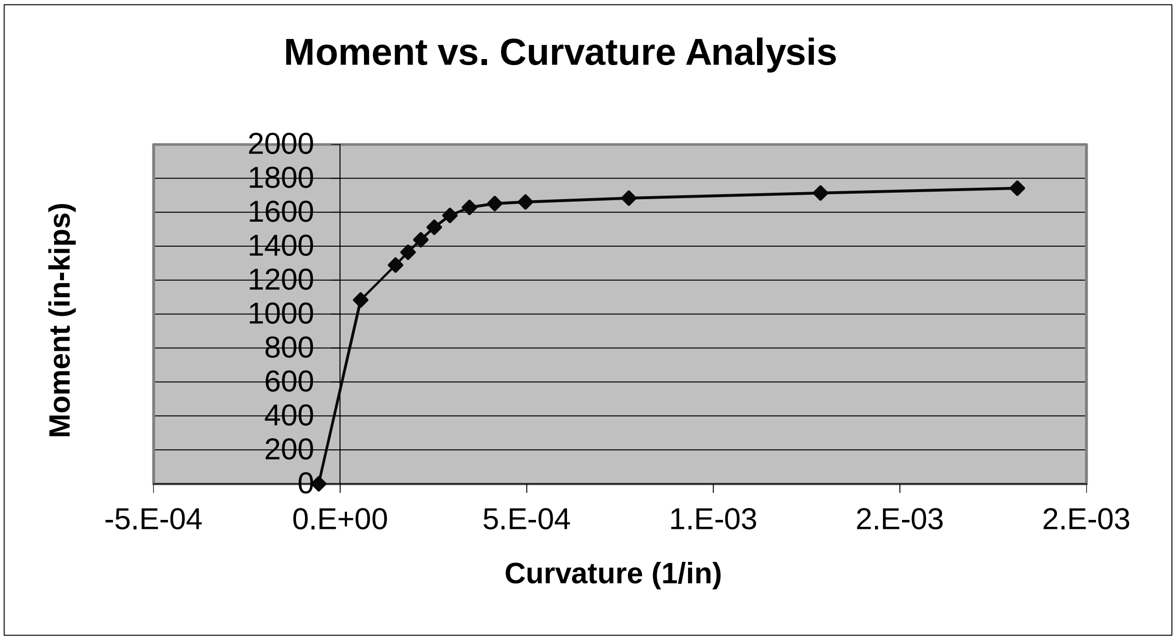
38.465

y (in)	Strain (in/in)
15.50	-0.000681
3.05	0

Notes:

Data Pt #1 is the strain profile in the beam before any loading is applied.

Data Pt #2 is the strain profile prior to flexure cracking.
Adjust the concrete strain until the extreme fiber strain is slightly
less than the MOR strain. Make sure you have equilibrium.
Copy the strain, curvature and moment values into the appropriate columns.



Appendix C – Material Specifications

SUMIDEN WIRE
PRODUCTS CORPORATION

Prestressed Concrete Strand Division
East: 710 Marshall Stuart Drive, Dickson, TN 37055 • 866-491-5020
West: 1412 El Pinal Drive, Stockton, CA 95205 • 866-246-3758

MILL CERTIFICATE OF INSPECTION

Order Number: SLPC170260-1 | Page No : 1 OF 1
B/L No: SIPC170628 | Issue Date : 03/14/2017

Commodity: Steel Strand, Uncoated Seven Wire for Prestressed Concrete
Size & Grade: 1/2" x 270 KSI
Specification: ASTM A416-Latest 1/2"-Low Relaxation
Customer Name: KNIFE RIVER CORPORATION NORTHWEST
Customer P.O.: 389354H
Destination: KNIFE-OR
State Job No:
Packing: Cal Wrap - "The California Transporation Agency's Standard Specification, Section 50 for Prestressing Concrete."

No	Pack #	Heat #	B.S.	Elong.	Y.P.	Area	-REPRESENTATIVE- E-Modulus	-REPRESENTATIVE- CURVE#
			Min:41,300	3.5	37,170			
			(LB)	(%)	(LB)	(IN2)	(MPSI)	
1	S129584-3	S0290086	43,498	5.3	40,291	0.1513	28.7	100001R
2	S529980-3	S0290653	42,936	5.6	39,997	0.1510	28.7	100001R
3	S529981-3	S0290653	43,507	6.6	40,407	0.1511	28.7	100001R
4	S529983-4	S0290666	43,079	5.1	40,414	0.1510	28.7	100001R
5	S529983-5	S0290666	43,079	5.1	40,414	0.1510	28.7	100001R
6	S529984-1	S0290666	43,093	4.8	40,453	0.1514	28.7	100001R
7	S529985-6	S0290086	43,241	5.4	40,289	0.1512	28.7	100001R

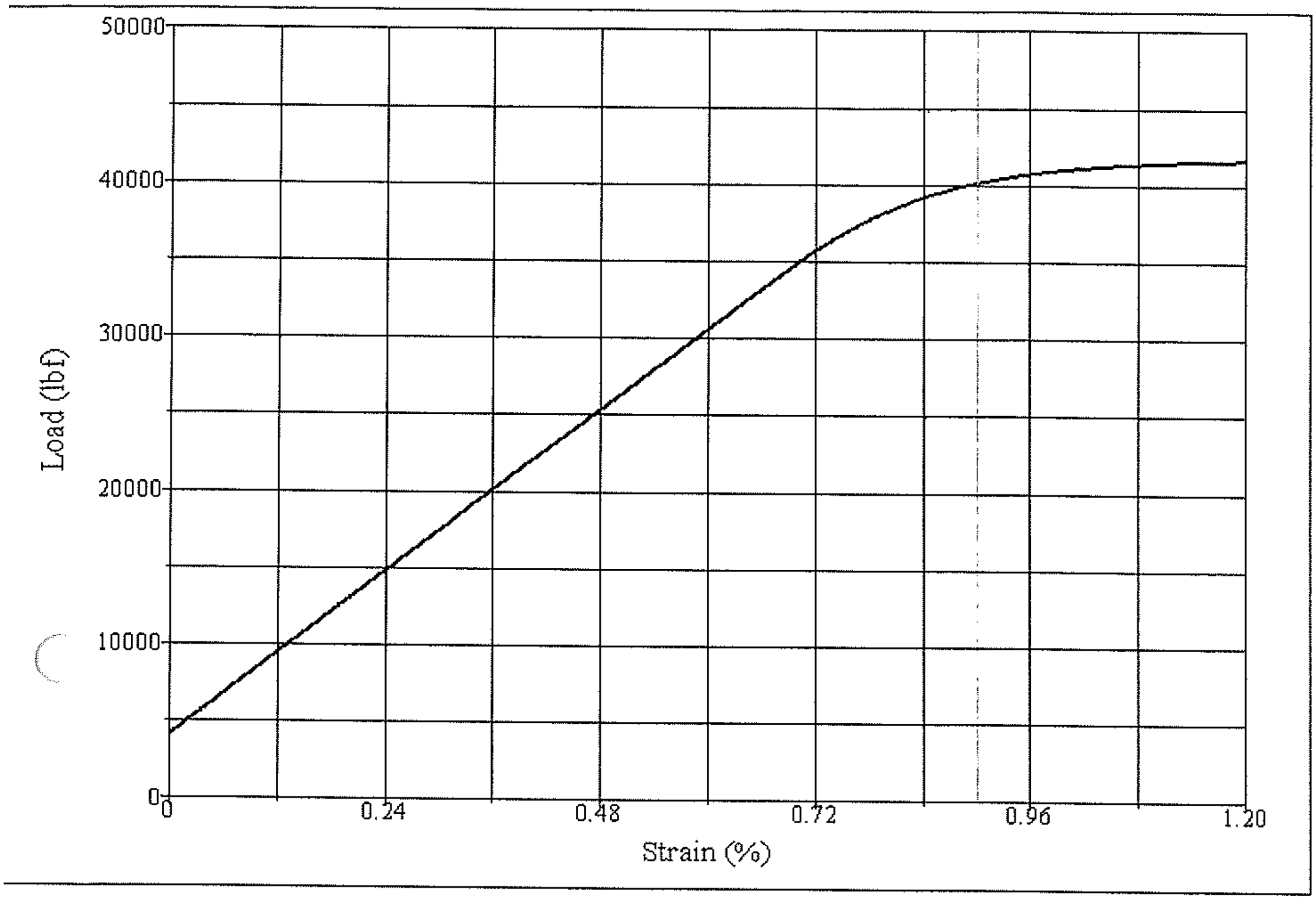
We hereby certify that:

* We have accurately carried out the inspection of COMMODITY and met the requirements in accordance with the applicable SPECIFICATION, both listed above.
* The raw material, and all manufacturing processes used in the production of the COMMODITY described above occurred in the USA, in compliance with the Buy America requirements of 23 CFR 635.410.
* The material described above will bond to concrete of a normal strength and consistency in conformance with the prediction equations for transfer and development length given in the ACI/AASHTO specifications.
* The individual below has the authority to make this certificate legally binding for SWPC.

Quality Assurance Section

SUMIDEN WIRE
PRODUCTS CORPORATION

Prestressed Concrete Strand Division
East: 710 Marshall Stuart Drive, Dickson, TN 37055 • 866-491-5020
West: 1412 El Pinal Drive, Stockton, CA 95205 • 866-246-3758



***Vertical Line is drawn at 1% Extension Under Load**

Curve#	S100001R	
Size	0.5"	
Nominal Area[1]	0.153	in²
Modulus	28.7	Msi

[1] See SWPC Mill Certificate of Inspection for actual area

SUMIDEN WIRE
PRODUCTS CORPORATION

Prestressed Concrete Strand Division
East: 710 Marshall Stuart Drive, Dickson, TN 37055 • 866-491-5020
West: 1412 El Pinal Drive, Stockton, CA 95205 • 866-246-3758

Bill of Lading

B/L NO. : SIPC170628
CONSIGNEE/NAME : KNIFE RIVER CORPORATION NORTHWEST

PAGE : 1 of 1
SHIP DATE : 03/15/2017

SHIP TO : KNIFE RIVER CORPORATION NORTHWEST
HIGHWAY 99 & PEORIA ROAD
HARRISBURG, OR 97446

CONTACT PERSON :
SAM JEWELL
TEL :
(541)995-6327

NO	ITEM NAME / SIZE(in) / SPECIFICATION	CUST P.O NO.	SO NO.	COIL NO. / HEAT NO. / PACKAGE	LENGTH(ft) / FOR DELIVERY	NET WT(lb) / GROSS WT(lb)
1	1/2" x 270 KSI 1/2 ASTM A416-Latest 1/2"-Low Relaxation	389354H	SLPC170260	S129584-3 S0290086 CAL WRAP	12,150.00 03/16/2017	6,236.00 6,269.00
2				S529980-3 S0290653	12,150.00	6,247.00 6,280.00
3				S529981-3 S0290653	12,150.00	6,242.00 6,275.00
4				S529983-4 S0290666	12,150.00	6,252.01 6,285.01
5				S529983-5 S0290666	12,150.00	6,257.01 6,289.99
6				S529984-1 S0290666	12,150.00	6,277.01 6,310.01
7				S529985-6 S0290086	12,150.00	6,261.99 6,295.00
				TOTAL	85,050.00	43,773.02 44,004.01

***** TRUCK MUST TARP *****

CARRIER NAME : PAUL TRANSPORTATION, INC.
DRIVER/SIGNATURE :
SHIPPER/SIGNATURE : Victor C. Trejo
FREIGHT CHARGES : PREPAID
REMARK : RECEIVING HOURS: 7AM-12:30PM

KNIFE RIVER — AN MDU RESOURCES COMPANY

	KNIFE RIVER CORP.	
PROJECT TITLE	OSU	
PROJECT NO.		
PRODUCT TYPE	Big Beam	
BED NO.	18	
MARK NO.	1	
INSPECTION	OSU	
DATE	Fri.	05/05/17
CONCRETE MIX NO.	H80N2G	
CEMENT TYPE	Ashgrove Type III	
CEMENT CONTENT	800 lbs. cement / CY	

TESTS	VALUES
SLUMP/SPREAD/VSI	9.00
CON. TEMP.	66.00
AMB. TEMP.	60.00
POT WT.	44.27
AIR	0.8

RELEASE STRENGTH		ACTUAL
DESIGN :	9000	10880
28 DAY:	12000	11560
		11220
HEAT START		16:10
RELATIVE YIELD		0.983
W/C RATIO		0.281

Control #	4477				
Batch Size	1.50	CY	Test Meter	922	
Batch Weights (lbs.)			Add Water Quantities (gals.)		
Cement I			Water at Plant	27	(WP)
Cement III	1188	(CW)	Water at Jobsite	0	(WA)
Slag	0	(FA)	Total Water	27	(TG)
S. Fume	0	(SF)	Weight of Water	225	(WW)
CA #1 ½	2530	(CA1)			
CA #2 ¾	0	(CA2)	Admixtures (ozs.)		
Sand	2060	(SND)	Air Entrainment	0	(AEA)
Water	225	(WW)	Polyheed	0	(PH)
Admixture	9.94	(AW)	VMA	0	(XR)
			Glenium	128	(GL)
TOTAL	6013	(TW)	Pozzolith	0	(POZ)
			RT Z60	31	(DEL)
			Total Admixtures	159	(TA)
			Admixture Weight	9.94	(AW)

Unit Weight, Yield, and Cement Content

Concrete + Pot:	44.27				
Pot Weight (tare):	7.17		Cement Content	805.47	lbs./cy.
Calibration:	4.070		S.K.	8.57	
UNIT WEIGHT:	151.00	lbs./cu. ft.			
			Yield	1.47	

Available Water		333.51		
	Batch Weight	Absorption	Free Moisture	Water lbs
CA1	2530	2.40	1.1	26.89
CA2	0	2.30	0	0.00
Sand	2060	2.90	3.7	71.50

Available Water (lbs.)				
CA1	26.889	Water Added:	225.18	(WW)
CA2	0.000	Admixtures:	9.94	(TA)
Sand	71.501	*Total Available Water:*	333.51	(TAW)
Total	98.390			

SUMMARY PRINT 05/05/17 15:48:43 PAGE 2 PLANT A: MIXER A B: MIXER B

CUSTOMER ID KNIFE RIVER PRESTRESS JOB ID BEAM
103 23505 PEORIA ROAD 3142 HSBG. PRESTRESS
HARRISBURG OR 97446

OSU BIG BEAM CONTEST

PRODUCT ID	DESCRIPTION
H8ON2G	800 # TYPE III CEM

TICKET #	QUANTITY
B 209	1.500
TOTAL:	1.500

HEREBY CERTIFY THAT THE AGGREGATES USED IN THE CONCRETE IDENTIFIED BELOW HAVE BEEN TESTED, FOUND SUITABLE FOR USE AND ARE IN PROPORTIONS INDICATED BY THE OREGON HIGHWAY MATERIAL DIV. FURTHER, THE CEMENT CONTENT IS 800 LbS
~~SKS~~ PER CU. YD. TYPE III
AND THE CERTIFICATION CONCERNING QUALITY FROM ASH GROVE CEMENT CO. ACCOMPANIED DELIVERY OF CEMENT AS SHOWN BELOW:

MILL ANALYSIS NUMBER 17-9

(CONTINUED)

Sold to Customer: 103
KNIFE RIVER PRESTRESS
23505 PEORIA ROAD
HARRISBURG OR 97446
MIX: H8ON2G
800 # TYPE III CEM

Deliver to job: 3142
BEAM
HSBG. PRESTRESS

Nbr Batches: 1

05/05/17 12:29:30
Form # B 209
Ctrl # 004477
Plant: MIXER B

Water Adj: 0.00 Gal/CuYd

Batch 1 of 1 1.50 CuYds

Admix %: 66 100

Scale Zeros: AGGB 10 CMTB -2

DESCRIPTION	MTRL	BIN	AMOUNT	TARGET	DESCRIPTION	MTRL	BIN	AMOUNT	TARGET	DESCRIPTION	MTRL	BIN	AMOUNT	TARGET
1/2-#4	3	AGB4	2530 Lb	2531	SAND	2	AGB2	2060 Lb	2092	CEM III ASHG	23	CMB3	1188 Lb	1200
WATER A	31	WTB1	27 Gal	27	RHEOTEC 760	42	ADB2	31 Oz	32	GLEN. 3400NV	46	ADB5	108 Oz	108

+20 OZ

% Moist: AGB4 1.1 % AGB2 3.7 %

OSU BIG BEAM CONTEST

Water Cement Ratio 0.279

Truck	Driver	Load Quanity:	Delivered:	
755	KELLY	1.50 CuYds	1.50 CuYds	Temper Water Amount= 0.00 Gal Maximum Add Water= 0.00 Gal

CONCRETE MIX DESIGN SUBMITTAL

Project: BIG BEAM CONTEST 2017 Contract No.: ______

Contractor: ______ Concrete Supplier: Knife River Prestress

Concrete Class: ______ Agg. Size 1/2" Contractor Design No.: H80N2G
O.D.O.T. Lab. No. :

Intended Use: ______

Date

MIX PROPORTIONS - QUANTITIES PER CUBIC YARD

		Weight (lbs.)		Absolute Volume		Brand	Type
Cement:		800 #		4.070 ft3	=>	Ash Grove	III
Agg. Size		# (SSD)		ft3			
Agg. Size	1/2"-#4	1669 # (SSD)		10.191 ft3			
Agg. Size	Sand	1345 # (SSD)		8.339 ft3			
Mix Water		224 #		3.590 ft3			
Entrained / entrapped Air		3.0 %		0.810 ft3			
				27.000			

Admixtures - Brand/Type/Dosage
AEA:

WR: BASF - RheoTEC Z60
(4 +/- 2 oz. per 100 lbs. Cement)

WR: BASF-Glenium 3400NV
(9 +/- 3 oz. Per 100 lbs Cement)

Other: BASF NC534 (optional)

TOTAL WEIGHT 4038 lbs/cu. yd.

UNIT WEIGHT 149.56 lbs/cu. ft.

Design W/C Ratio: 0.280
Design Slump Range: 7" - 10"

AGGREGATE DATA (Used in calculating the mix design)

Course Agg. Source Knife River (Harrisburg) State Source # 22-018-2

Fine Agg. Source Knife River (Harrisburg) State Source # 22-018-2

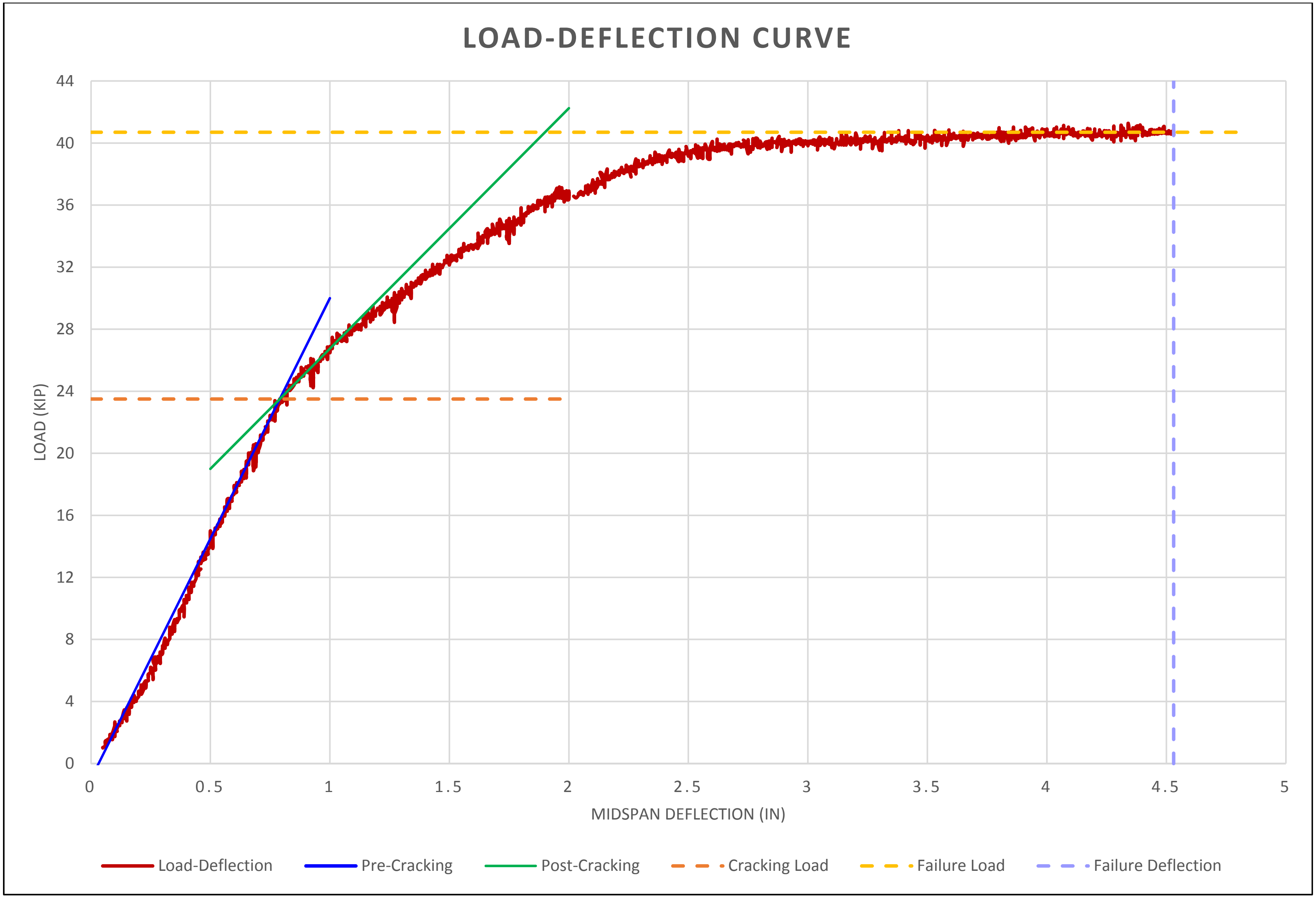
Size	Specific Gravity (SSD)	Absorption
3/4"-1/2"		
1/2"-#4	2.624	2.40
Sand	2.584	2.90

Coarse Agg. Unit Wt. 101.10 lbs/cu. ft.
(Combined wt. if 2 or more sizes)

Avg. Sand F. M. 3.00

Prepared By: Mark Duberowski
CCT 41858

Appendix D – Testing Results


LOAD-DEFLECTION CURVE
LOAD (KIP)
44
40
36
32
28
24
20
16
12
8
4
0
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
MIDSPAN DEFLECTION (IN)
Load-Deflection
Pre-Cracking
Post-Cracking
Cracking Load
Failure Load
Failure Deflection

PCI BIG BEAM COMPETITION 2016-17

6/2/17
Date

Oregon State University — Student Team (school name)
1 — Team Number
5/5/17 — Date of Casting

Basic information

1. Age of beam at testing (days) 28

2. Compressive cylinder tests*

Number tested: 6

Size of cylinders: 4" × 8"

Average: 15,050 psi psi

3. Unit weight of concrete (pcf) 151 pcf

Slump (in.): 9 in

Air content (%): 0.8%

Tensile strength (psi): 918 psi

Circle one: Split cylinder MOR beam

4. Pretest Calculations

a. Applied point load at midspan to cause cracking (kip) 23.48 k

b. Maximum applied point load at midspan (kip) 38.41 k

c. Maximum anticipated deflection due to applied load only (in.) 5.37 in

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) 40.71 k
2. Measured cracking load (kip)‡ 23.50 k
3. Cost (dollars) $133.77
4. Weight (lb) 928 lb
5. Largest measured deflection (in.) 4.53 in
6. Most accurate calculations ________

   a. Absolute value of (maximum applied load – calculated applied load)/calculated applied load 5.99%

   b. Absolute value of (maximum measured deflection – calculated deflection)/calculated deflection 15.6%

   c. Absolute value of (measured cracking load – calculated cracking load)/calculated cracking load 0.09%

Total of three absolute values (a + b + c) = 21.68%

‡ 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 16, 2017

PCI BIG BEAM COMPETITION 2016-17

CERTIFICATION

Knife River Prestress

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

Oregon State 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:

Signature

Dusty Andrews

Name (please print)

6/13/17

Date

THIS CERTIFICATION MUST BE PART OF THE FINAL REPORT

Sponsored by:

AUTODESK 'S SOLUTION ASSOCIATE FOR PRECAST

EDGE REVIT

PTAC Consulting Engineers, Inc.

ptac@ptac.com | www.ptac.com | www.edgeforrevit.com

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