Author:

Farshad Haddadi

Final Report

Design of Prestressed Concrete Beams for Specific Performance

Contents

List of Tables:

List of Figures

1. EXECUTIVE SUMMARY

The Florida International University's 2020 Big Beam Team greatly appreciated the opportunity to participate in this competition. The presented report is a step by step design procedure for designing prestressed concrete beams which is expected to perform and fail in a predefined load.

The chosen design was a I-shaped member composed of four straight prestressing strands, and incorporating two compression longitudinal bars. The beam was designed supported span of 18 ft., center-to-center of bearing, and a total length of 19 ft. The loading consists of two point loads as live load and the beam self-weight as dead load. The beam is designed to remain uncracked under the unfactored live load of 20 kips (10 kips at each point) and have capacity of more than factored live load of 32 kips. The final capacity should be less than 40 kips.

The team predicted the cracking load, failure load, and ultimate deflection of the beam using a moment-curvature analysis. Later, these predictions will compare to actual values during testing. A summary of these results are presented in Table 1.

Table 1: Summary of results

	Predicted/ calculated Values
Cracking Load	25.6 kips
Failure Load	38.4 kips
Ultimate Deflection	3.78
Final weight	1679 lb
Total cost	$ 181

2. CONCRETE MIX DESIGNS

The Coreslab Structure(FLA) has limited the mix designs based on past experiences into three self-consolidating concrete (SCC) mix designs which could be used for fabrication in local plant in Medley, Florida. Their properties are summarized in Appendix A.

However, three other mix designs were developed to show a comparison between all mixes and choose the most suitable one for the team's best fit design requirements. Preliminarily, team had developed three concrete mix designs: Ultra-High Performance Concrete, High-Strength Concrete, and Concrete/Conventional Concrete. After comparing all the mixes with the those required by our sponsor plant (Coreslab Structure), further analysis will be made to narrow it down to choose the front runner for the competition.

The team did a brief literature review to develop three mix designs for this competition [1]–[8]. The important parameters for evaluation of all mix designs are summarized in Table 2.

Table 2: Concrete mix designs summary

	Coreslab Structures			***Designed by Team***		
	775 S.C.	***800 S.C.***	***838 S.C.***	***Mix #1***	***Mix #1***	***Mix #1***
Type of Concrete[1]	***SCC[2]***	***SCC***	***SCC***	***CC[3]***	***HPC[4]***	***UHPC[5]***
Cement (lbs/cy)	775	838	838	800	750	1215
Fine aggregate (lbs/cy)	1392	1389	1367	1389	1720	2063
Coarse aggregate (lbs/cy)	1272	1293	1281	1282	1326	0
Water/Cement ratio (lbs/lb)	0.40	0.40	0.39	0.45	0.3	0.18
Slump/Spread (in+-in)	26±4	26±4	26±4	4±1	8±1	22±1
Unit Weight (lbs/cf)	139	141	141	140	145	156
f'_c (psi)	6000	6000	6000	6000	11600	23000
Price($/cy)- Based on PCI rules	100	100	100	100	120	400

[1]Mix proportions are saturated dry surface
[2]SCC: Self Consolidating Concrete
[3]CC: Conventional Concrete
[4]HPC: High Performance Concrete
[5]UHPS: Ultra-High Performance Concrete

UHPC has great tensile and compressive strength and can bear more deflection before cracking, but due to steel fiber, the average cost of UHPC is four times more expensive than normal mix design. On the other hand, HPC concrete, is also more expensive than normal concrete and make it an uneconomical option. On the other hand, conventional mix design is an economic choice but due to its low workability is not recommended. An outstanding merit of Coreslab Structures mix designs, is their slump flow which was about 26 inches and made them self-consolidating concrete which is completely appropriate for casting precast members without any vibration operation.

The optimal mix design for this competition, is a mix design that the compressive strength is under 10 ksi in order to have lowest price and concrete must have high slump to can flow easily between tiny spaces without vibration. These characteristics define self-consolidating concrete

(SCC) which had recommended by Coreslab Structures. High slump flow (26 inches), low water to cement ratio and enough compressive strength, make SCC mix designs better than other developed mixes.

Looking at water to cement ratio, compressive strength, concrete weight and also their propositions, revealed that all those three mix designs were very similar to each other but based on actual test results, the mix number "838 S.C." had shown higher actual compressive strength than two others. Therefore, the team decided to choose mix "838 S.C." for design purpose with average actual compressive strength of 8941 psi.

3. ASSUMPTIONS

The force in tendon approach was used in design process of this beam and the following assumptions were made:

- Using strength concrete of f'_c = 8.9 ksi
- Early concrete strength of f'_{ci} = 0.75 f'_c =6.7 ksi at 7 days for release of prestressing bars
- ½ 7-wire low relaxation strands with f_{pu} = 270 ksi
- Total length of 19 ft.
- Load configuration (Figure 1)

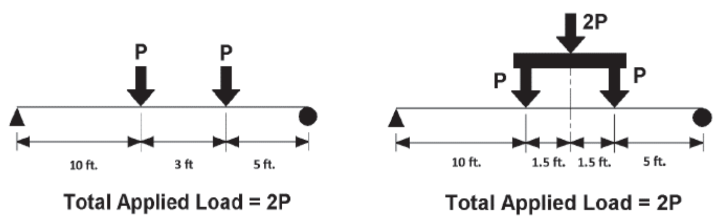

Figure 1: Permitted load configuration (PCI 2019)

4. DESIGN

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. So the primary focus of team was I-shaped section for this competition. Team tried to design more sections for this competition but due to time limitation only one design was conducted.

Design procedure includes flexure design, shear design, cost analysis and maximum deflection. An excel spreadsheet was developed which calculates all the section properties based on various parameters such as cross-section sizes, number of prestressing strands, and position of strands. Then the section properties were used in another sheet for design calculations and stress checks. The design was optimized by changing these variables so that the cracking moment and ultimate capacity are in desired range. All the design calculations are based on provision provided in ACI detailed procedure [9].

The final design layout and shop drawing have been shown in Appendix B and Appendix C-Shop Drawing respectively.

4.1. Prestress Losses

For accurate design, team needed to calculate the effective prestresing force at the time of testing, 28 days after casting. The PCI design handbook method for predicting prestressing losses was implemented to determine the losses due to elastic shortening, creep, shrinkage and relaxation[10]. The effective prestressing force was then determined from the actual jacking forces and all calculated losses. This calculation was especially critical in determining the cracking load for the beam.

Detail calculation is presented in Appendix D- Prestress Losses.

4.2. Flexure

The first step of design procedure is flexure design. Cracking load, failure load, and ultimate deflection are three main criteria dictated the flexural design of beam. Based on past designs, I-shaped cross-section and prestressing strand layout was selected. In this regard, the team used an iterative process to determine the most efficient flexural design.

For maximum competition points, the beam was required to fail within the 32 – 39 kip range, and dimensions were selected such that the failure load was within that range. To ensure critical locations are not overstressed, stresses at release and service in top, bottom and mid-span, according AASHTO and PCI standards have been checked. Controlling the amount of stress in top fiber and bottom fiber was dependent on the team's initial concrete strength assumptions, which considered 0.75 percent of actual strength of concrete.

The next criteria for competition was the no cracking under service live loads. Resisting cracking under service loading was so challenging and usually resulted over design section. Eventually, after many iterations, the cross-section and strand layout were finalized.

Moreover, the team considered compression steel bars in top flange and included in all calculation such as net section and short term transformed section properties.

Moreover, for accuracy of design, team developed a finite element model with ABAQUS for verifying the cracking load of beam. The results of this have shown good agreement with the team design calculation.

All the calculations have been shown in Appendix E- Flexure Design.

4.3. Shear Design

The shear design in this project is based on ACI Detailed Procedure Method. This method provides equations to determine the nominal shear strength for both flexure-shear cracking and web-shear cracking. The nominal shear strength, V_c, is taken as the lesser shear causing these two types of cracking. Minimum shear reinforcement should be provided for the sections where ϕV_c is greater than V_u. An important consideration that the team paid attention to it, was shear calculation based on failure mode which was equal to 20 kips. It was because that the beam was not supposed to fail due to shear before reaching the 20 kips. load, so designing for failure load would guarantee that beam won't experience shear failure before desire applied load (two 20 kips).

Based on AASHTO LRFD 2016, it is required to provide confinement reinforcement for the distance of 1.5d from the end of the beams other than box beams. Reinforcement shall be placed to confine the prestressing steel in the bottom flange. The reinforcement shall not be less than No.3 deformed bars, with spacing not exceeding 6.0 in. and shaped to enclose the strands [11].

Therefore, the team considered the minimum amount defined by AASHTO LRFD 2016 for 24 in. from both ends of beam.

Detail calculation is presented in Appendix F- Shear Design.

4.4. DEFLECTION

Response 2000 software was used for analysis of Moment-curvature of the beam. Total deflection which is calculated is equal to 3.57 in. including final camber of beam.

Detail calculation is presented in Appendix G- Deflections

4.5. COST ANALYSIS

The cost for the fabrication of the beam was calculated by using PCI material rates. Formwork has high amount of cost than the others and the mild steel and prestressing have low amount in overall cost. Total cost is summarized in

Table 3:Cost Analysis

Costs		
Material	Cost $	%
Concrete	44.10	24.4
Prestressing	22.80	12.6
Formwork	92.2	50.9
Stirrups	6.52	3.6
Confining reinforcement	1.13	0.6
Compression steel	14.30	7.9

This implies that the amount of prestressing will not change the overall cost by remarkable margin, because it is contributing only 12.6% of the total. However, the change in the surface area would lead to greatest impact on overall cost.

The total cost of the section is $181 and the weight is 1679lb. The cost of labor and equipment is not included here.

Detail calculation is presented in Appendix H- Cost Analysis.

5. REFERENCES

[1] B. Graybeal, “Ultra-high performance concrete,” 2011.

[2] B. A. Graybeal, “Development of Non-Proprietary Ultra-High Performance Concrete for Use in the Highway Bridge Sector: TechBrief,” United States. Federal Highway Administration, 2013.

[3] A. ACI, “211.1-Standard Practice for Selecting Proportions for Normal,” *Heavyweight Mass Concr.*, 2009.

[4] D. Garber and E. Shahrokhinasab, “Performance Comparison of In-Service, Full-Depth Precast Concrete Deck Panels to Cast-in-Place Decks,” Accelerated Bridge Construction University Transportation Center (ABC-UTC), 2019.

[5] E. Shahrokhinasab, N. Hosseinzadeh, A. Monirabbasi, and S. Torkaman, “Performance of Image-Based Crack Detection Systems in Concrete Structures,” *J. Soft Comput. Civ. Eng.*, vol. 4, no. 1, pp. 127–139, 2020.

[6] E. Shahrokhinasab, “ABC-UTC Guide for: Full-Depth Precast Concrete (FDPC) Deck Panels,” 2019.

[7] M. Abedin, N. Kiani, E. Shahrokhinasab, and S. Mokhtari, “Net Section Fracture Assessment of Welded Rectangular Hollow Structural Sections,” *Civ. Eng. J.*, vol. 6, no. 7, pp. 1243–1254, 2020.

[8] M. Abedin, S. Maleki, N. Kiani, and E. Shahrokhinasab, “Shear Lag Effects in Angles Welded at Both Legs,” *Adv. Civ. Eng.*, vol. 2019, 2019.

[9] American Concrete Institute (ACI) Committee 318, “Building Code Requirements for Structural Concrete (ACI 318-14) and Commentary,” Farmington Hills, MI, 2014.

[10] Precast/Prestressed Concrete Institute (PCI), “PCI Design Handbook, 7th Edition,” Precast and Prestressed Concrete Institute (PCI), Chicago, 2010.

[11] American Association of State Highway and Transportation Officials (AASHTO), “AASHTO LRFD Bridge Design Specification, Customary U.S. Units, 7th Edition,” Washington, D. C., 2015.

6. APPENDIX A- MIX DESIGNS DETAIL

Mix designs proportions and properties summarized in Table 4 and Table 5.

Table 4: Statistical data for three Coreslab Structures Mix designs

Mix Name	**775 S.C.**	**800 S.C.**	**838 S.C.**
f'_c	6000 psi	6000 psi	6000 psi
f'_{cr}	6133 psi	6180 psi	6270 psi
s	99	135	201
n	30	30	30
smf	1.00	1.00	1.00
CV	1.3%	1.6%	2.3%
Xi_{max}	7953 psi	8820 psi	9366 psi
Xi_{min}	7630 psi	8314 psi	8510 psi
Xa	7813 psi	8621 psi	8941 psi

Table 5: Coreslab Structure mix designs properties (Selected mix for design)

	775 S.C.		***800 S.C.***		***838 S.C.***	
Mix Proportions (Sat., Surface-Dry)	***Amou nt***	***Identification of Materials***	***Amount***	***Identification of Materials***	***Amount***	***Identification of Materials***
Cement (lbs/cy)	775	Titan Portland T-I/II	838	Titan Portland T-I/II	838	Titan Portland T-I/II
Fine aggregate (lbs/cy)	1392	Titan CML. SCR.	1389	Titan CML. SCR.	1367	Titan CML. SCR.
Coarse aggregate (lbs/cy)	1272	Titan 3/8 Stone	1293	Titan 3/8 Stone	1281	Titan 3/8 Stone
Mineral admixture (lbs/cy)	0		0		0	
Water(gls/cy)	37±0		38±0		40±0	
Superplasticizer (oz/cy)	34.0	Grave ADVA Cast 575	36.0	Grave ADVA Cast 575	38.5	Grave ADVA Cast 575
Water reducer (oz/cy)	13.0	Grace WRDA 64	12.0	Grace WRDA 64	12.5	Grace WRDA 64
Air entrainer (oz/cy)	11.6	Grace Darex AEA	4.2	Grace Darex AEA	4.2	Grace Darex AEA
Pigment (oz/cy)	0.0		0.0		0.0	
Water/Cement ratio (lbs/lb)	0.40		0.40		0.39	
Slump/Spread (in+-in)	26±4		26±4		26±4	
Unit Weight (lbs/cf)	139		141		141	

7. APPENDIX B- CROSS SECTION

Cross section properties and related calculation:

Table 6:Section properties calculations

No. Strands	A_p	e_g	A_p(total)
4	0.153	3.60676	0.612

Compression steel	A'_s	y_s	A'_s(total)
2	0.11	14.125	0.22

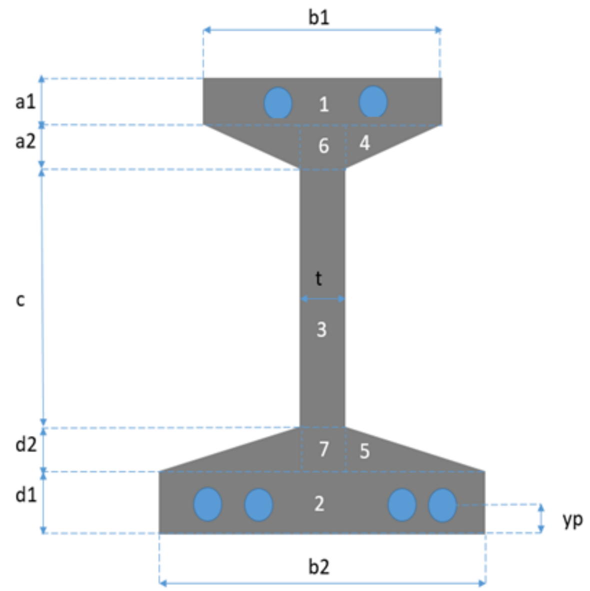

Figure 2: Schematic of cross section

a_1	a_2	d_1	d_2	c	b_1	b_2	t	y_p
2.25	1.5	4	2	5.5	9	9.75	2	3.25

	Gross Section				
A_g	h	$y_b=y_g$	y_t	I_g	P
90.25	15.25	6.86	8.39	2426. 8	55.59

S_b	S_t
353.928	289.137

	Net Section				
A_{net}	h	y_{net}	y_t	I_{net}	enet
89.42	15.25	6.86	8.39	2407.21	3.61

Sb	St
350.72	287.04

	Short-term transformed section			
$A_{tr,st}$	h	ytr,st	yt	$I_{tr,st}$
92.71	15.25	6.83	8.42	2760.77

n_{ST}
5.380592

8. APPENDIX C- SHOP DRAWING

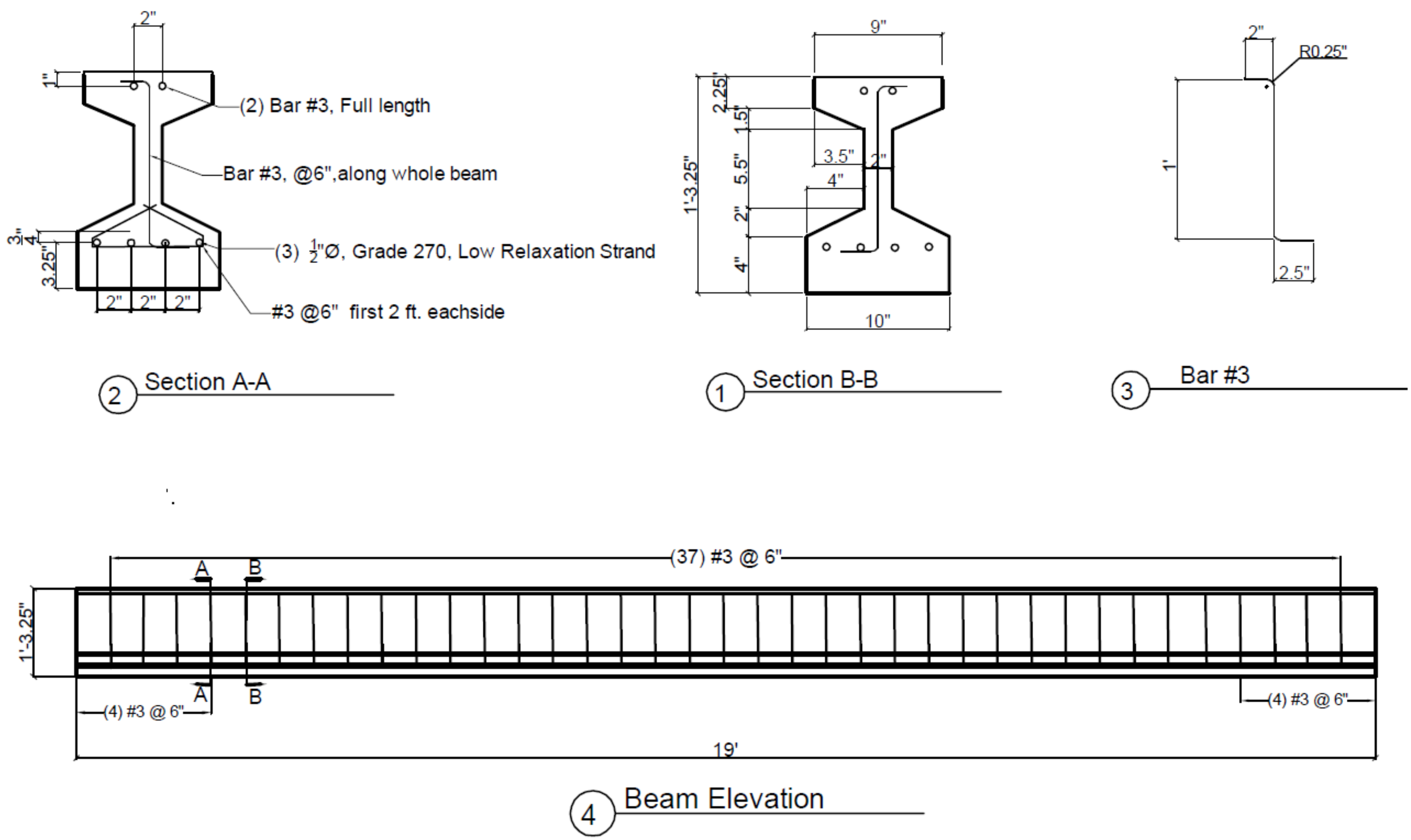

Figure 3: Shop drawing

9. APPENDIX D- PRESTRESS LOSSES

Table 7: Prestress losses

Prestress Losses											
Elastic Shortening			Creep			Shrinkage			Relaxation		
K_{cir}	0.9		K_{cr}	2		K_{sh}	1		K_{re}	5	ksi
P_j	123.93	kips				RH	75	%	J	0.04	
f_{cir}	1.770	ksi	f_{cds}	0.064	ksi	e_{sh}	0.00019		C	1	
Δf_{pES}	11.00	ksi	Δf_{pCR}	18.36	ksi	Δf_{pSH}	5.37	ksi	Δf_{pRE}	3.61	ksi

f_{pj}	205.5	ksi	f_{pi}	191.50	ksi	f_{pf}	164.17	ksi
P_j	123.9	kips	P_i	117.2	kips	P_f	100.5	kips

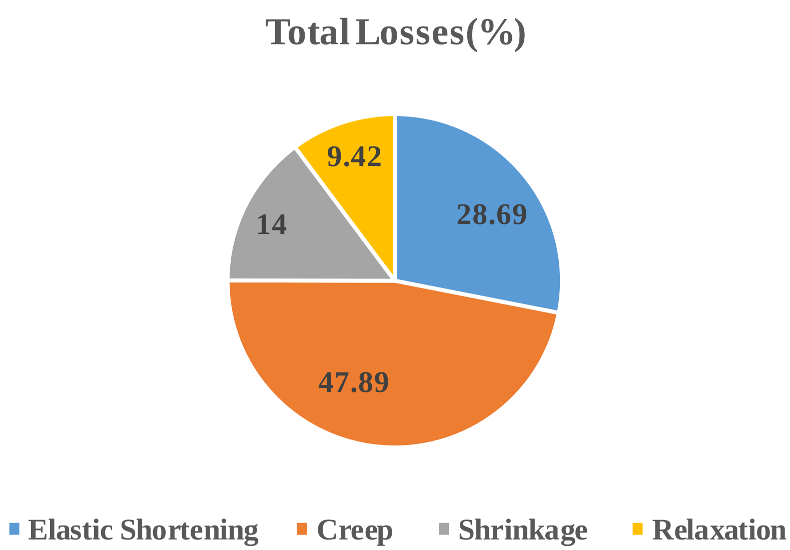

Figure 4: Prestress Loss Distribution

10.APPENDIX E- FLEXURE DESIGN

Table 8: Required data for flexure design

Geometry imported from Section Calculator								
I_g	2426.80	in^4	$I_{tr,ST}$	2760.77	in^4	I_{net}	2407.21	in^4
A_g	90.25	in^2	$A_{tr,ST}$	92.71	in^2	A_{net}	89.42	in^2
y_b	6.86	in	$y_{tr,ST}$	6.83	in	y_{net}	6.86	in
y_t	8.39	in	-		-	e_{net}	3.61	in
h	15.25	in	b	9	in			
s_b	353.93	in^3	d_p	12	in			
s_t	289.14	in^3	$t_{f,top}$	2.25	in			
P	55.59	in	-		-			
V/S ~A/P	1.62	in	A'_s	0.22	in^2			

Table 9: length, prestressing, concrete and loads information

Beam Length					
L_{span}	18	ft	L_{tr}	2.083	ft
L_{total}	19	ft			
Prestressing					
A_p	0.612	in^2	E_p	29000	ksi
e_p	3.61	in	f_{pu}	270	ksi
no of p/s	4		f_{pj}	202.5	ksi
$A_{p/s}$	0.153	in	y_p	3.25	in
Concrete					
f'_{ci}	6.70	ksi	E_{ci}	4667.65	ksi
f'_c	8.941	ksi	E_c	5389.74	ksi
w_c	141	lbs/ft^3			
Loads					
SW	88.4	lb/ft	$M_{sw,mid}$	42.9	k-in
LL	20	k	M_L	867	k-in
$L_{u,min}$	32	k	$M_{u,min}$	1387	k-in
$L_{u,max}$	39	k	$M_{u,max}$	1690	k-in

Table 10:Stress check limits

Stress Limits	Initial			Final		
Compression	End=0.7f'_{ci}	-4.694	ksi	Sustained= 0.45*f_c	-4.023	ksi
	Other=0.6f'_{ci}	-4.023	ksi	Total= 0.6*f_c	-5.365	ksi
Tension	End=6*$\sqrt{f'_{ci}}$	0.491	ksi	7.5*$\sqrt{fc}$	0.709	ksi
	Other=3*$\sqrt{f'_{ci}}$	0.246	ksi			

Table 11: Stresses at release

Distance from end	M_{sw}	f_{top}	f_{bot}	Limit C	Limit T	check
ft	k-in	ksi	ksi	ksi	ksi	
1.583	13.8	0.221	-4.075	-4.694	0.491	OK
7	40.8	0.127	-3.998	-4.023	0.246	OK
9	42.9	0.120	-3.992	-4.023	0.246	OK
10	42.4	0.121	-3.994	-4.023	0.246	OK

Table 12: Stresses due to sustained load

Distance from end	M_{sw}	f_{top}	f_{bot}	Limit C	Limit T	check
ft	k-in	ksi	ksi	ksi	ksi	
1.583	13.8	0.093	-2.119	-4.023	0.709	OK
7	40.8	-0.001	-2.042	-4.023	0.709	OK
9	42.9	-0.008	-2.036	-4.023	0.709	OK
10	42.4	-0.007	-2.038	-4.023	0.709	OK

Table 13: ***Stresses due to service loads***

Distance from end	M_{sw}	M_L	f_{top}	f_{bot}	Limit C	Limit T	check
ft	k-in	k-in	ksi	ksi	ksi	ksi	
1.583	13.8	137	-0.325	-1.780	-5.365	0.709	OK
7	40.8	607	-1.852	-0.542	-5.365	0.709	OK
9	42.9	780	-2.388	-0.107	-5.365	0.709	OK
10	42.4	867	-2.650	0.106	-5.365	0.709	OK
11	40.8	833	-2.543	0.019	-5.365	0.709	OK
12	38.2	800	-2.432	-0.071	-5.365	0.709	OK

20.3.2.3.1 As an alternative to a more accurate calculation of f_{ps} based on strain compatibility, values of f_{ps} calculated in accordance with Eq. (20.3.2.3.1) shall be permitted for members with bonded prestressed reinforcement if all prestressed reinforcement is in the tension zone and $f_{se} \geq 0.5f_{pu}$.

$$f_{ps} = f_{pu}\left\{1-\frac{\gamma_p}{\beta_1}\left[\rho_p\frac{f_{pu}}{f'_c}+\frac{d}{d_p}\frac{f_y}{f'_c}(\rho-\rho')\right]\right\} \qquad (20.3.2.3.1)$$

where γ_p is in accordance with Table 20.3.2.3.1.

If compression reinforcement is considered for the calculation of f_{ps} by Eq. (20.3.2.3.1), (a) and (b) shall be satisfied.

(a) If d' exceeds $0.15d_p$, the compression reinforcement shall be neglected in Eq. (20.3.2.3.1).

(b) If compression reinforcement is included in Eq. (20.3.2.3.1), the term

$$\left[\rho_p\frac{f_{pu}}{f'_c}+\frac{d}{d_p}\frac{f_y}{f'_c}(\rho-\rho')\right]$$

shall not be taken less than 0.17.

Table 14: Flexural capacity and cracking moment

Flexural Capacity					
			ρ'	0.021728395	
α_1	0.85		ρ_p	0.0056	
β_1	0.65		f_{ps}	250.10	ksi
γ_p	0.28		a	2.24	in
M_n	1666.5	k-in	**→ $2P_{equal,cr}$= 38.43 kips < 40 kips**		

Cracking moment			
f_b	-2.038	ksi	
f'_t	0.709	ksi	
f_{add}	2.747	ksi	
M_{add}	972.239	k-in	
M_{cr}	1110.6	k-in	**→$2P_{equal,n}$=25.63 kips > 20 kips**

Finite Element Modeling:

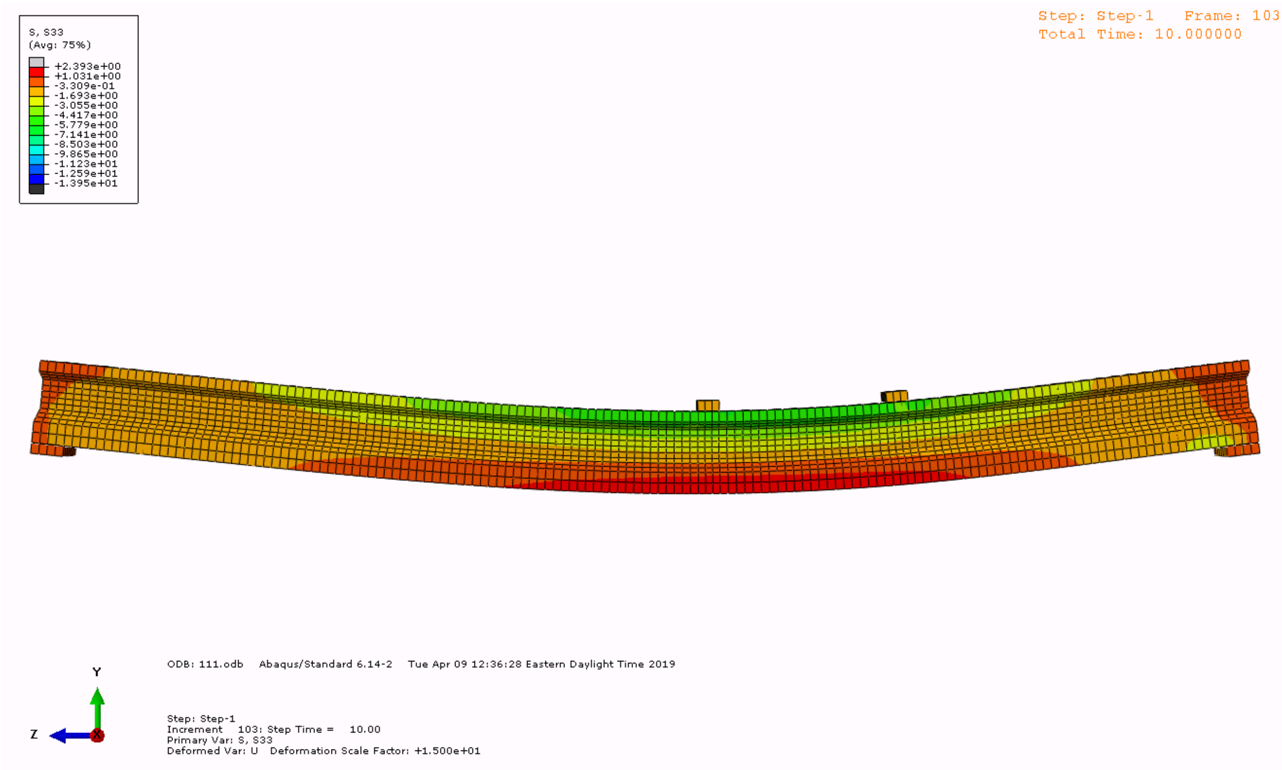

Figure 5: Finite Element Modelling Using ABAQUS- Cracking Load:26kips

11.APPENDIX F- SHEAR DESIGN

Table 15: Input data for shear design

Input Data for Shear Design						
f'_c =	8.941	ksi		A_g =	90.25	in^2
f_{pu} =	270	ksi		I_g =	2426.799	in^4
A_{ps} =	0.612	in^2		y_b =	6.86	in
f_{pe} =	164.17	ksi		h =	15.25	in
$d_{p,end}$ =	12	in		P_e =	100.4701	kips
$d_{p,mid}$ =	12	in		E_c =	5389.741	ksi
L_{span}=	18	ft		E_p =	29000	ksi
L_{beam} =	19	ft		n=	5.4	
				sb	353.9278	in^3
w_{sw} =	88.4	lb/ft		ep =	3.61	in
LL	**44**	k		t=	2	in
$L_{u,min}$	32	k		fpc=	1.113243	ksi

Table 16: ACI 318-14 Detailed Method for shear design

Distance	V_u	V_d	V_i	M_u	M_d	M_{max}	M_{cre}	V_{ci}	V_{cw}	V_c	fV_c	V_u<fV_c	$A_{v,req}$
ft	k	k	k	k-in	k-in	k-in	k-in	k	k	k	k		in^2/ft
1	16.7	0.7	16.0	201.5	9.0	192.5	948.2	81.0	16.0	16.0	12.0	no	0.106
2	16.6	0.6	16.0	401.7	17.0	384.7	940.2	41.1	16.0	16.0	12.0	no	0.104
3	16.5	0.5	16.0	600.6	23.9	576.8	933.3	27.8	16.0	16.0	12.0	no	0.101
4	16.4	0.4	16.0	798.3	29.7	768.6	927.5	21.1	16.0	16.0	12.0	no	0.099
5	16.3	0.4	16.0	994.7	34.5	960.2	922.7	17.1	16.0	16.0	12.0	no	0.097
6	16.2	0.3	15.9	1189.8	38.2	1151.6	919.0	14.3	16.0	14.3	10.8	no	0.121
7	16.1	0.2	15.9	1383.7	40.8	1342.8	916.4	12.4	16.0	12.4	9.3	no	0.151
8	16.0	0.1	15.9	1576.2	42.4	1533.8	914.8	10.9	16.0	10.9	8.2	no	0.173
9	15.9	0.0	15.9	1767.5	42.9	1724.6	914.2	9.8	16.0	9.8	7.3	no	0.190
10	15.8	-0.1	15.9	1957.6	42.4	1915.2	914.8	8.9	16.0	8.9	6.6	no	**0.203**

Using 1 #3 bars A_v=0.11 in^2 @ 6in

As the price of stirrups are a small proportion of total cost, the team decided to use them uniformly along the beam.

Burst reinforcement: Assigned the minimum requirement

Using 1 #3 bar A_v=0.11 in^2 @ 6in (1.5d+6=24 in. from ends)

12. APPENDIX G- DEFLECTIONS

Table 17:Moment Curvature results from Response 2000

Curvature(/rad)	Moment(k-in)
-0.000032251	0.012
-0.000019136	156.204
-0.000006021	312.396
0.000007094	468.588
0.000020208	624.744
0.000033323	780.828
0.000046438	936.78
0.000059553	1076.76
0.000072667	1179.528
0.000085782	1255.512
0.000098897	1310.4
0.000112012	1347.996
0.000125126	1375.908
0.000138241	1399.656
0.000152065	1422.588
0.000167272	1445.976
0.000183999	1469.82
0.000202399	1493.976
0.000222639	1518.252
0.000244902	1542.348
0.000269393	1565.832
0.000296332	1588.2
0.000325965	1608.9
0.000358562	1627.524
0.000394418	1643.748
0.000433859	1657.5
0.000477245	1668.972
0.00052497	1678.476
0.000577467	1686.348
0.000635214	1692.984
0.000698735	1698.936
0.000768608	1703.88
0.000845469	1707.54
0.000930016	1708.8
0.001023018	1705.344
0.00112532	1684.704
0.001237852	300.288
0.001217553	140.112

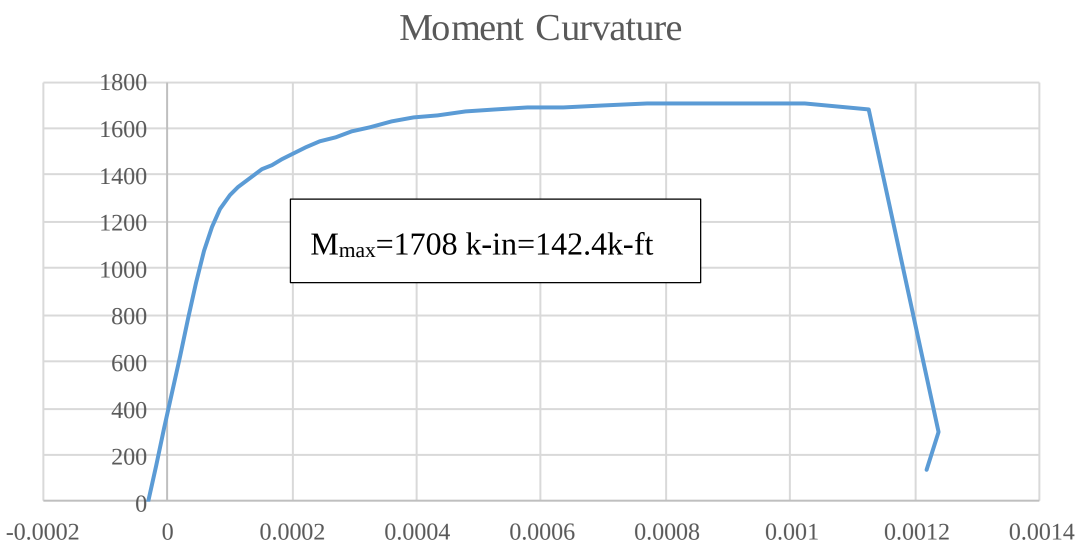

Figure 6:Moment-Curvature diagram

Table 18: Final camber

Final camber		
e=	3.61	in
P_f =	100.4701	kips
$E_{c,eff}$ =	1796.6	ksi
L_{span}	18	ft
I_g	2426.80	in^4
SW	88.4	lb/ft
Δ_{mid} =	**-0.44**	in

Table 19: Maximum deflection estimation

Max moment	**142.4**	k-ft	Max load	P=19.22 kips	2P=38.44956 kips			
x	M_{sw}	M	ϕ	ϕ'_i	Δxi	dxi		
ft	k-ft	k-ft						
0	0.000	0.00	-0.000035687		0.5ft=6in			
0.5	0.389	10.00	-2.21748E-05	-2.89309E-05	6	3	-0.00052	
1	0.755	19.98	-1.212E-05	-1.71474E-05	6	9	-0.00093	
1.5	1.100	29.94	-2.0875E-06	-7.10373E-06	6	15	-0.00064	
2	1.422	39.87	7.92269E-06	2.91759E-06	6	21	0.000368	
2.5	1.722	49.78	1.79119E-05	1.29173E-05	6	27	0.002093	
3	1.999	59.67	2.78829E-05	2.28974E-05	6	33	0.004534	
3.5	2.255	69.54	3.78365E-05	3.28597E-05	6	39	0.007689	
4	2.488	79.39	4.79245E-05	4.28805E-05	6	45	0.011578	
4.5	2.699	89.21	5.8969E-05	5.34468E-05	6	51	0.016355	
5	2.888	99.01	7.41538E-05	6.65614E-05	6	57	0.022764	
5.5	3.055	108.79	9.77238E-05	8.59388E-05	6	63	0.032485	
6	3.199	118.55	0.000152055	0.000124889	6	69	0.051704	
6.5	3.321	128.28	0.000242165	0.00019711	6	75	0.0887	
7	3.421	137.99	0.000429369	0.000335767	6	81	0.163183	
7.5	3.499	147.68	0.000635458	0.000532413	6	87	0.27792	
8	3.554	157.35	0.000745625	0.000690542	6	93	0.385322	
8.5	3.588	167.00	0.000956481	0.000851053	6	99	0.505526	
9	3.599	176.62	0.001050004	0.001003242	6	105	0.632043	
9.5	3.588	186.22	0.001240054	0.001145029	6	111	0.762589	
10	3.554	195.80	0.001604588	0.001422321	6	117	0.998469	
						Δ	**3.961234**	in

13.APPENDIX H- COST ANALYSIS

Table 20: Costs detail for Big Beam competition

Item	***Price***	***Explanation***
Concrete	$100/cy	Using gross section geometry
High-Strength Concrete	$120/cy	Defined as ≥ 10 ksi
Fiber-Reinforced Concrete	$110/cy	
Ultra-High-Performance Concrete	$400/cy	
Lightweight Concrete	Add $10/cy to the concrete cost	
Prestressing Strand: ***3⁄8 in. diameter*** ***1⁄2 in. diameter*** ***1⁄2 in. special*** ***0.6 in. diameter*** ***0.7 in. diameter***	 $0.17/ft $0.30/ft $0.32/ft $0.42/ft $0.55/ft	Use estimated lengths used in the beam
Steel: ***A615/A706*** ***Welded Wire (deformed or smooth; for shear)*** ***Epoxy Coated*** ***A1035*** ***Plate Steel***	 $0.45/lb $0.50/lb $0.50/lb $0.70/lb $0.55/lb	Use estimated lengths and nominal unit weights in this calculation as provided in the PCI Design Handbook
Forming	$1.25/ft2 of formwork (include all contact surfaces)	
• There is no need to include cost of steel fabrication, concrete fabrication, curing, inserts, etc. Concrete cost is based on actual strength. • The beam weight shall be estimated by using the measured unit weight of the concrete or by actually weighing the beam. If the beam weight is estimated, it is estimated based on the gross concrete cross section only, ignoring reinforcement, bearing plates, etc. * Special circumstances or special materials not addressed in these rules must be reviewed by the chairman of the committee and/or PCI staff.		

Table 21: Cost Analysis

Concrete			Prestressing			Formwork			Stirrup			Bursting reinforcement			compression steel		
									A615/A706			A615/A706			A615/A706		
A_g	90.75	in^2	No.	4		P	46.79	in	l	12.5	in	l	10	in	No.	2	
L_{total}	19	ft	L_{total}	19	ft	L_{total}	19	ft	No.	37		No.	8		L_{total}	19	ft
V	11.97	ft^3	Length	76	ft	Area	74.09	ft^2	Length	38.54	ft	Length	6.67	ft	Length	38	ft
Cost	$100	$/yd^3$	Cost	$0.30	/ft	Cost	$1.25	$/ft^2$	W	0.376	lb/ft	W	0.376	lb/ft	W	0.376	lb/ft
									Cost	0.45	lb	Cost	0.45	lb			
Total	$44.35		Total	$22.80		Total	$92.61		Total	6.52125		Total	1.128		Total	$14.29	
	24.4			12.5			51			3.6			0.6			$7.9	
Total Cost		$181.70															
Total weight		1688.33 lb															