PCI Big Beam Contest Report

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Introduction

The University of Illinois' entry into 2006 Big Beam Contest was designed, constructed and tested according to the rules prescribed by the Precast/Prestressed Concrete Institute. The stages of the project are outlined in this report.

Design and Materials Cost

The objective of the design was to specify and proportion the concrete, mild reinforcing and prestress strands to create a beam that supports a large load, is ductile and has a low cost of materials based on the unit costs provided in the contest rules. Design calculations are attached to this report. The total cost of materials, using the unit costs provided in the contest rules, is $55.97. The material properties assumed in the design are summarized in Table 1.

Table 1. Material Strengths Assumed in Design

Concrete Compressive Strength, fc'	13,800 psi
Mild Reinforcing Yield Strength, fy	60,000 psi
Welded Wire Reinforcing Yield Strength, fy	75,000 psi
Prestress Strand Tensile Strength, fpu	270,000 psi

Prestressing

Two representatives of Prestress Engineering Corporation in Blacktone, Illinois, the Sponsoring Producer/Member for this project, came to the University of Illinois campus and provided the ½"-diameter prestress strands. They applied tension to the strands using a hydraulic jack as shown in Figure 1.

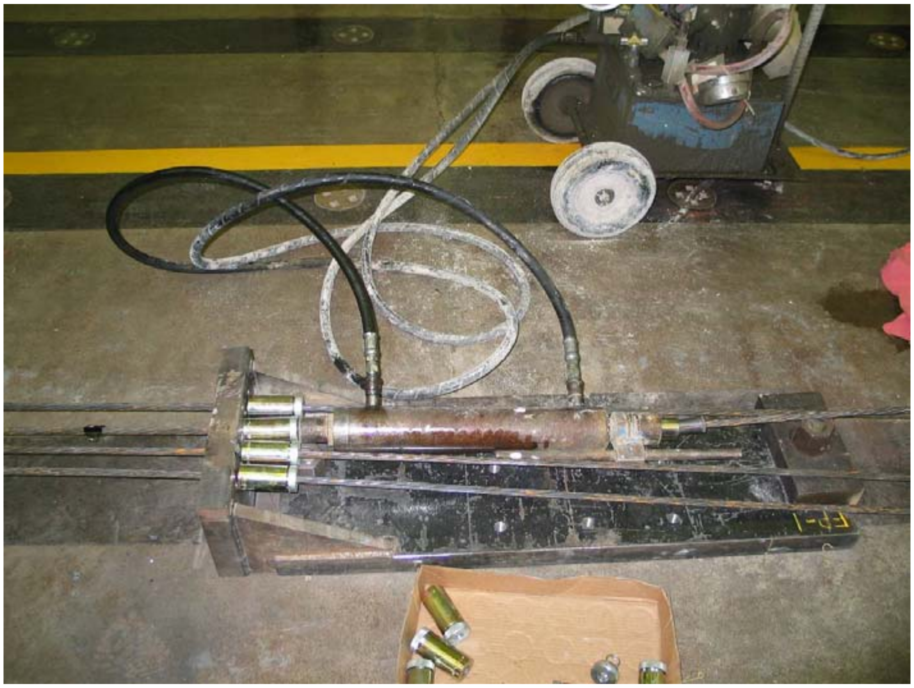

Figure 1. Stressing of reinforcing strands with a hydraulic jack

Casting and Curing
The beam was cast by placing the fresh concrete into the formwork by hand as shown in Figure 3. As the concrete was placed, vibration was used to consolidate the concrete. After finishing the top of the beam to create a flat surface, the beam was covered with moist burlap in order to inhibit shrinkage cracking. The burlap was moistened daily for one week, and a plastic tarp was placed over the burlap and beam to retain moisture.

Figure 2. Beam formwork and reinforcement prior to concrete placement

Figure 3. Placement of concrete

Analysis and Prediction of Behavior

This section describes the analysis procedure used to predict the beam's load-deformation response. During the design phase, the load-deformation response was used to make slight revisions to the beam shape, location and number of prestress strands, quantity and location of shear and confining reinforcement, and to gauge the overall ductility of the beam.

Nonlinear finite element analysis was selected as the most suitable tool for generating the load-deformation response of the beam. The software package *Vector2* was used for the nonlinear analysis; it is based on the modified compression field theory analytical model to describe the behavior of a two-dimensional reinforced concrete element. Preprocessing and postprocessing of the data were accomplished with the software packages *Formwork* and *Augustus*, respectively.

A finite element model of the final design of the beam, illustrated in Figure 4, was generated using *Formwork*. The mesh detail of one-half of the beam span is shown in Figure 4. The beam was modeled as a simply-supported member, and a single concentrated load was applied at midspan.

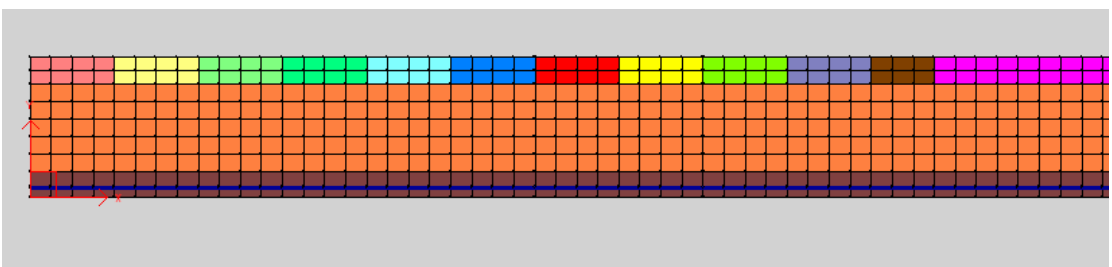

Figure 4. Mesh detail of one-half of the beam span

900 Q4 plane stress elements and 214 truss elements were used in the model. The tapered top flange was modeled using discrete blocks of Q4 elements. The tapered length of the top flange was divided into ten elements with varied thicknesses. A plan view of these elements is displayed below in Figure 5. In this figure, the taper is exaggerated to show the concept clearly.

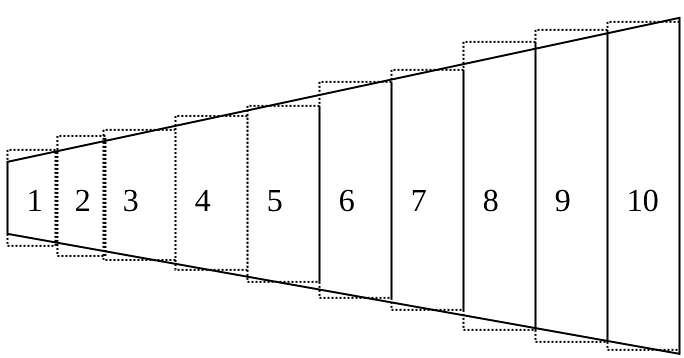

Figure 5. Plan view of tapered portion of beam finite element analysis model

Each element of the tapered flange portion of the finite analysis model was defined with unique reinforcement ratios and thicknesses (flange widths). These element properties are summarized in Table 2.

Table 2. Element details for beam top flange model

Element #	ρx (%)	ρy (%)	t (in)
1	0	0.144	3.25
2	0	0.124	3.75
3	0	0.110	4.25
4	0	0.0982	4.75
5	0	0.0889	5.25
6	0	0.0812	5.75
7	0	0.0746	6.25
8	0	0.0691	6.75
9	0	0.0644	7.25
10	0	0.0602	7.75

The compressive strength of concrete used in the analysis is 13.8 ksi, and the yield strength of the welded wire mesh reinforcement is 75 ksi in both directions of the mesh. The welded wire mesh was used only as confining reinforcement in the top flange of the beam at midspan as illustrated in the drawing of the beam attached to this report.

The concrete constitutive model used in the analysis is the Hognestad (Parabola) model for compression pre-peak response. For post-peak response, the Modified Park-Kent model was used. The compression softening model proposed by Vecchio (1992-A(e1/e2-Form)) was incorporated into the analysis using the *Vector2* software. The model also included the tension stiffening effect proposed by Bentz (2003). Finally, in areas of small amounts of distributed reinforcement, the linear tension softening model with no residual was included in the analysis.

The vertical shear reinforcement used in the beam was a #3 single leg stirrup (Grade 60), and the stirrups were spaced at 5-inch intervals along the length of the beam. The regular element reinforcement density was modeled only in the vertical direction as shown in Table 2 above. In the top flange of the beam at midspan, 2 x 2 – W1.4 x W1.4 x 2'-0" confining reinforcement was provided to maintain structural integrity around the area loaded by the actuator. This confining reinforcement was modeled using out-of-plane reinforcement in this zone. The constitutive model for the strength enhancement of confined concrete was adopted from the model proposed by Kupfer and Richart. In this model, the Poisson's ratio value is variable. The out-of-plane reinforcement increases the capacity of the beam because it provides a passive confining effect. The transverse reinforcement effect of the stirrup hook at the bottom of the beam was neglected.

Strands were modeled using truss elements with an area of 0.7854 in^2 and a yield strength of 270 ksi. The initial prestress applied to the strand element was 200 ksi. The loss of stress was assumed to be 20%, resulting in an effective prestress of 160 ksi. The effect of prestress was modeled as a pre-strain effect in the truss elements with a Young's

Modulus value of 29,000 ksi, and the initial pre-strain in the truss elements was 5.516 millistrain.

The #5 continuous top reinforcing bar was modeled using truss elements. In order to prevent a progressive crack pattern at the end of the beam due to bursting stresses from the prestress forces, #3 single-leg stirrups were provided at each end of the beam. Truss elements were used to model this bursting-resistant reinforcement.

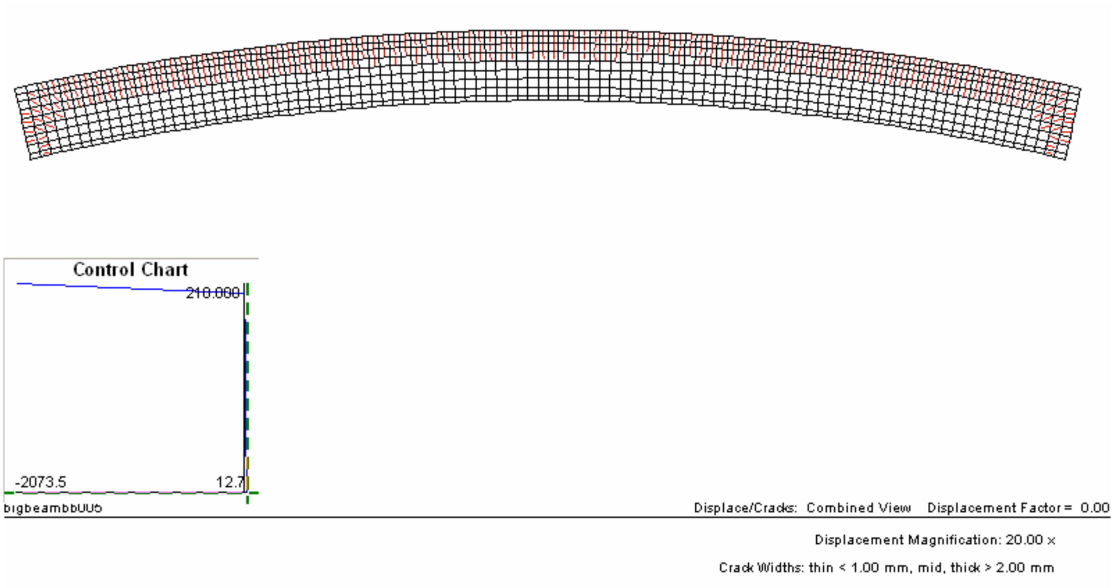

Figure 6. Initial camber of the beam with no applied concentrated load

The maximum crack width at the ends of the beam was predicted to be only 0.004 in. The small size of the crack is due to the presence of the #3 single-leg stirrups at each end of the beam that were included to resist bursting stresses. The initial camber, based on the effective prestress, was predicted to be 0.403 in.

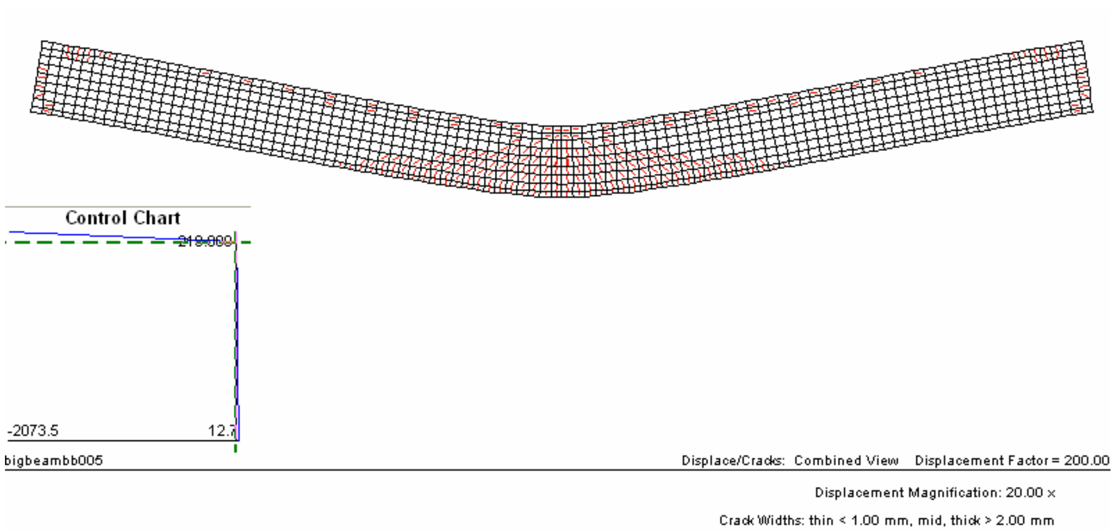

Figure 7. Beam deflected shape at predicted failure. (Applied load = 47.1 kips)

Materials Testing and Beam Load Test Results
In addition to casting the beam, 4" x 8"cylinders and Modulus of Rupture (MOR) beams were cast in accordance with ASTM standards. One day before the beam was tested to failure, three cylinders were tested to measure compressive strength. The information obtained from these tests was used to perform a final analysis of the beam as described in the analysis section of this report. The average measured compressive strength was 14.0 ksi. Two cylinders were used for split tension tests in order to provide additional refinement to the analysis related to the prediction of cracking. Test results are summarized in Table 3. The average tensile strength was 800 psi. Five 4" x 8" cylinders remain to measure the 28-day compressive and tensile strengths. Two additional MOR beams will be tested at 28 days. The largest MOR or split-tension strength will be reported.

Table 3. Concrete Compression and Tension Strength Results

	Ultimate Load (lbs)	Average Strength
Compression	174900	14.0 ksi
	173400	
	178800	
Split-tension	40000	800 psi
	40200	

The simple span beam load test configuration is shown in Figure 8. A 100-kips actuator was used to apply load at midspan. In addition to measuring applied load, the actuator is equipped with an LVDT to measure displacement. Midspan load and deflection was recorded using National Instruments' *Labview* software, and the results are plotted in Figure 10. A representative of Prestress Engineering Corporation was present for the test and certified the prediction and results.

Figure 8. Test configuration just prior to loading

Figure 9. Beam after failure in shear

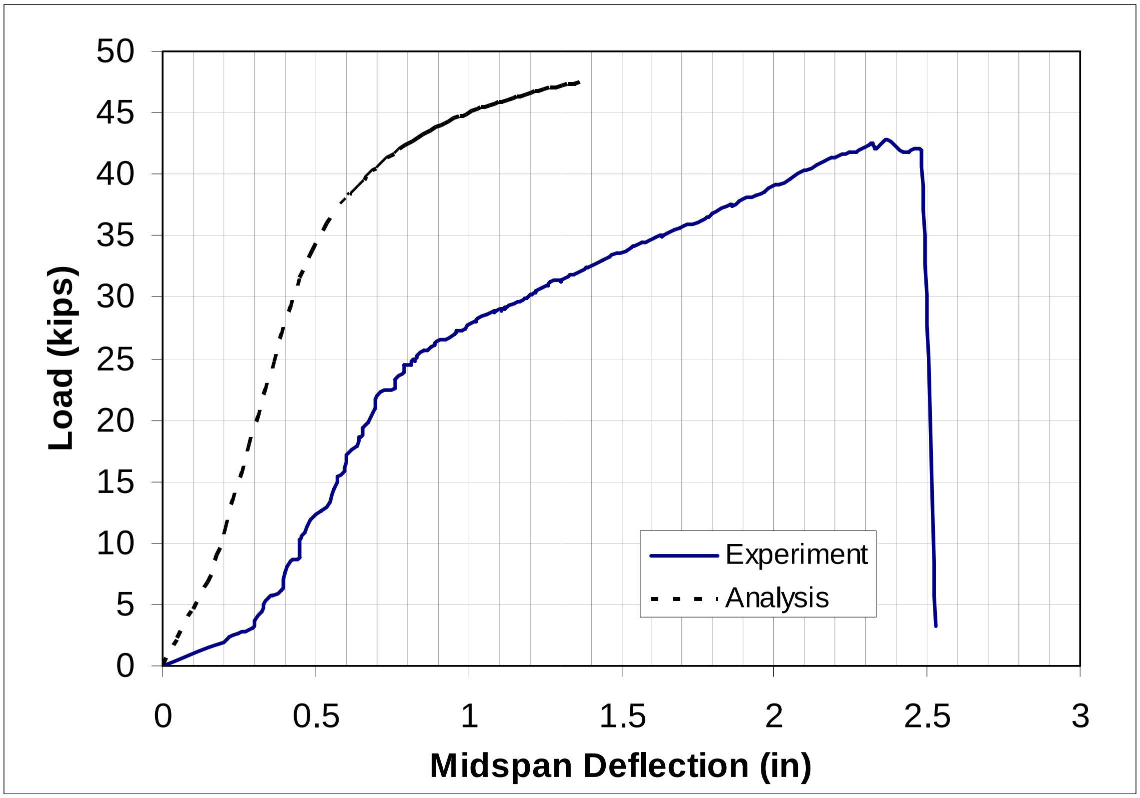

Figure 10. Actual and Predicted load-deflection response at beam midspan

What was Learned

The sharp corners at the beam bottom flange made consolidating the concrete difficult when the beam was cast. After the formwork was removed, there were a few locations at the ends of the beam where strands were exposed because the concrete was unconsolidated. Making modifications to the mix design in order to improve workability would be an improvement to the project. In addition, the minimum cover allowed by code was used for the beam. The benefits and drawbacks of using the minimum cover would be reevaluated if the beam were redesigned. Improved consolidation around the strands may be worth the reduction in effective depth.

In a future design, welded wire mesh will be preferred instead of stirrups. After failure, a top leg of the stirrup was observed outside the cross section of the beam. While it is not clear that the movement of this stirrup was a contributing factor to the failure, using welded wire mesh should lead to better performance than discrete, relatively large bars.

Recommendations for Future Contests

An interesting change to the contest rules would be to require the structural member to support a specified load over a certain span with fewer restrictions on the cross section. Another idea is to have teams work with a cost estimator to weigh labor and constructability issues in addition to the weight of materials. Centralizing the cost estimation will be challenging so that results from different entries will be comparable, but the design process will be more realistic.

References

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