Design, Construction, and Test of a Postensioned Segmental Beam

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ABSTRACT

This paper describes the construction of a 21'4" postensioned segmental beam and its respective loading test. The segments were two solid end blocks and nine hollow blocks, all of them were cast using high strength lightweight concrete, poured on a metal form. The postensioning was performed according to the design plan so as to control the deflections produced by the postensioning of each strand. Two strands were located along the bottom of the beam, another strand was located along the center, and a fourth half-loaded strand ran along the top of the beam. The segmental beam was tested to failure by applying a load at the center of the beam. The strains, deflections, and the ultimate load obtained during the tests match well with the theoretical predictions.

Keywords: Postension, concrete, segmental, lightweight

1. INTRODUCTION

This paper describes the construction of a postensioned segmental beam which was tested using a load applied at the center comparing the experimental structural behavior with the theoretical calculations. The segmental beam was 21'4" long with trapezoidal cross section, consisting of nine hollow segments and two solid end blocks joined by postensioned cables. The segments were cast using high strength lightweight concrete.

The laboratory tests of the lightweight aggregates allowed the design of trial mixes from which one mix was selected to construct the beam. The tests of the lightweight concrete showed that the desired strength of 8,000 psi was obtained at 14 days, and the tension strength and the modulus of elasticity compared well with the values indicated by ACI-318 for this type of concrete (Tito et al, 2010).

The beam was postensioned after the concrete obtained the required strength. All the strands were type ASTM A-416, with ½" nominal diameter and 7 wires grade 270. An epoxy paste applied to the joints provided smooth surfaces and sufficient shear strength. The segmental beam was tested to failure by applying a central load, aligned with the transversal diaphragm. The deflections and strains at selected points were recorded and compared with the calculations.

2. DESCRIPTION OF THE SEGMENTAL BEAM

Figure 1 shows the drawings for the segmental beam, consisting of two solid end blocks 20" long, eight hollow blocks 24" long, and one hollow block with a transversal diaphragm, resulting in a total length of 21'4". The beam had a trapezoidal cross section 2'0" height, and widths of 13" at top and 7" at bottom. The hollow sections had 1.75" uniform wall thickness, which were obtained using a styrofoam block properly spaced from the form.

TXI Industries provided the lightweight aggregates and the correspondent technical support (TXI-ES&C, 2010). Their most important advice was to maintain the aggregate saturated in order to provide internal curing avoiding cracks due to shrinkage.

The segments were cast in a two week time frame since only one steel form was available. The concrete had a uniform quality presenting the desired compression strength (f'c) of 8 ksi at 14 days. The mix design was done using a spreadsheet that follows the recommendation of ACI 211-98 and the UHD's laboratory experience. The engineering properties of the aggregates were obtained from corresponding laboratory tests (Tito et al, 2010).

Figure 2 shows the #3 stirrups used to resist the bursting forces from the postensioning, and the pouring of the end solid blocks. A steel plate of 7"x24"x1.5" was used to receive the anchors. Figure 3 shows the reinforcement of the hollow segments consisting of wire mesh of 2"x2"x0.12". The styrofoam block was removed after curing.

Figure 4 shows the process for making the beam using the segments, strands, and epoxy. The segments were aligned over the testing beam maintaining a space between segments of 1" to permit the application of the epoxy. The epoxy paste PC-7 had a working time of 1 hour and setting time of 24 hours. The main use of the epoxy paste was to provide a uniform contact surface avoiding stress concentrations during posttensioning. The epoxy was applied over dirty surfaces, and then it cannot resist tension stresses. The segments were joined stressing the central strand P1 until 28 kips.

After the epoxy cured, the beam was positioned on its end supports, proceeding to the jacking of the other strands according to a planned sequence. Figure 5 shows the jacking sequence and the resulting postensioned beam, which showed a horizontal misalignment of 0.75" at center, or 1/340 respect to the beam length.

3. INSTRUMENTATION

Figure 6 shows a sketch with the location of the instrumentation. The dial gauges DG1 to DG4 were used to measure the vertical deformation. The central movement was measured with redundancy using the dial gauges DG2, DG3 and the surveying level. The dial gauge DG5 was used to measure the lateral movement of the beam, and the dial gauges DG6 and DG7 were used to measure the shortening of the beam during the postensioning. The elongation of the cables was measured with a ruler.

The strain gage SG1 was located on the top surface and at 6" from the center, avoiding interference with the loading system. The strain gage SG2 was located at 1" from the bottom. Both strain gages, SG1 and SG2, measured the longitudinal strains at the center of the beam. The strain gage SG3 was located at 2'6" from the support, was inclined 135 degrees to the horizontal, and was used to measure the diagonal strain.

The hollow jack used had a 20 ton capacity; it was used to stretch the cables and to load the beam.

4. BEHAVIOR OF THE SEGMENTAL BEAM DURING POSTENSIONING

The theoretical calculations of deformations and stresses followed the construction sequence to obtain a segmental beam, verifying that the compression stresses were lower than the concrete capacity, and that the beam was not in tension stress. The deformations and strains at selected points were computed to compare with the measurements, which was useful for the quality control of the beam construction.

The postensioning sequence to obtain a segmental beam was:

a) Jacking of the central strand, P1, until it reached 28 kips. This strand was located at the centroid of the hollow section inducing a uniform compression stress at the whole cross area, permitting the alignment and joining of the segments without bending.

b) Installation of the definitive supports at 5" from the ends, making a simple supported beam of 20'6" span and loaded with its self-weight.

c) Full stressing until 28 kips of the bottom strand P2.

d) Jacking at 15 kips of the upper strand, P3, which is used to avoid tension stress at top of the beam.

e) Fully stressing until 28 kips of the second bottom strand, P4.

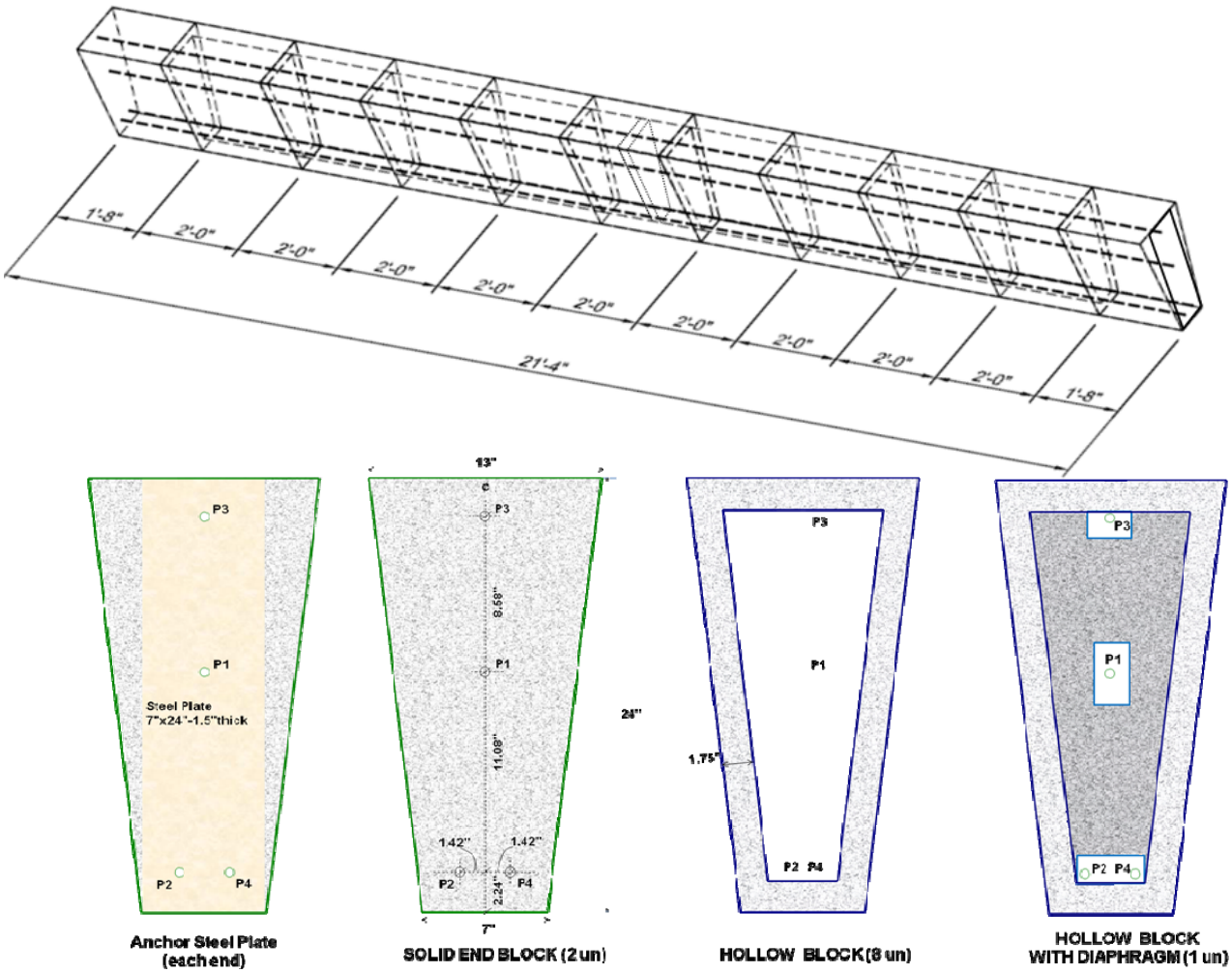


Figure 1. Segmental beam dimensions

a) Anchor steel plate, pipes to install the strands, and rebar inside the form (2.2 in^2 vert., 3.3 in^2 hor., and 1.32 in^2 long.)

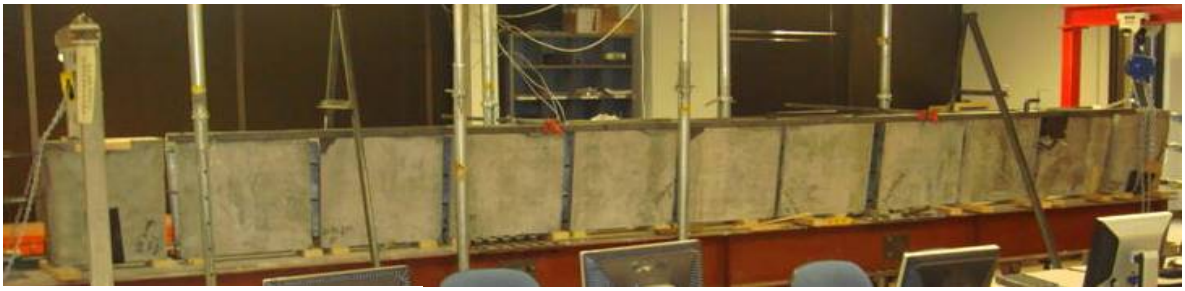
b) Concrete pouring verifying that the pipes are in the correct position.

Figure 2. Construction of the solid end blocks

a) Styrofoam block, welded wire mesh and spacers

b) Concrete pouring and segment after form removal

Figure 3. Construction of the hollow segments



a) Alignment of the segments

b) Application of epoxy paste c) Jacking of central strand P1 and joint closing

Figure 4. Construction of the segmental beam: alignment, epoxy and jacking of central strand.

Figure 7 shows the response of the segmental beam during postensioning. The elongation of the strand 1 shows the maximum difference with the estimated value because the joints were closing. The elongation of the last strand is closer to the estimated value, with an error of about 12%. The elongation of the strands (Δ) was estimated using the following equation:

$$\Delta = Pj \cdot Lc / (Es \cdot As) \quad (1)$$

Where:

Pj: Force applied by the jack

Lc: Length of the cable, between end of chucks = 21'4" + 2x3" = 21'10"
Es: Modulus of elasticity of the steel used by the strand = 27,000 ksi
As: Cross sectional area of one strand = 0.153 in^2

a) Sequence of postensioning after the beam was positioned on its supports: Strand P2 until 28 kips, Strand P3 until 15 kips, and Strand P4 until 28 kips

b) Full postensioned segmental beam and final alignment error of 3/4" (Length/340)

Figure 5. Postensioning of the segmental beam

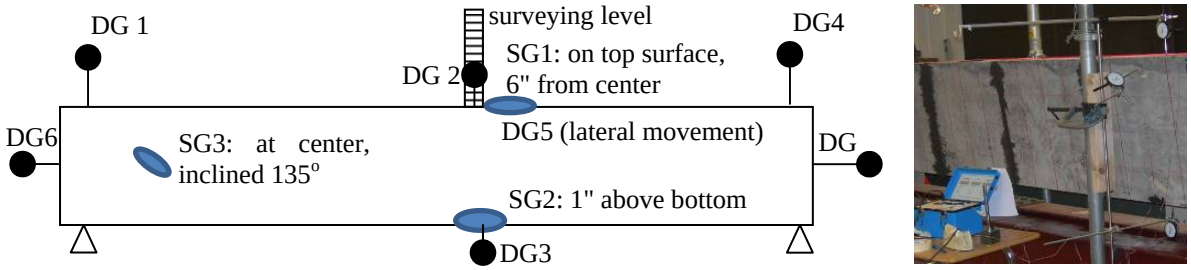


Figure 6. Sketch showing the dial gauges (DG) and strain gages (SG)

The strand P1 did not produced vertical deflection because it had no eccentricity. When the strand P2 was stretched the deflection of the beam was upward, which was reduced after jacking the strand P3, and again went upward after the strand P4 was jacked. Finally, the beam had an upward deflection like a camber of 0.17". The theoretical deflections had errors of 6% to 9%. The equation used to estimate the deflections (Δ_v) was:

$$\Delta_v = 8\ Pj\ .\ L^2\ .\ e\ /\ (8.Ec.I) \qquad (2)$$

Where:

L: Span = 20'6"
e: Eccentricity between the strand and the centroid
e = 0.00" for strand P1; e = -11.17 for strands P2 and P4; and e = +8.49" for strand P3
Ec: Modulus of elasticity of concrete obtained experimentally = 3200 ksi.
I: Moment of inertia respect to the centroid of the hollow section and strands = 7196 in^4

The strains at the top surface (SG1) and at 1" from the bottom (SG2) of the beam center were measured during the postensioning. The strand P1 produced a uniform compression stress. The eccentricity of the strand P2 reduced the compression stress at top (SG1) and increased the compression stress at bottom (SG2). The strand P3 was needed to avoid excessive tension stress at top when the bottom strand P4 was fully loaded. The self-weight produced a bending moment that compressed the top and stretched the bottom.

The calculations showed that the top surface of the beam had a compression stress of 146 psi at center and 68 psi near the end block, which becomes the critical point. The tension stresses were not expected during the postensioning, which was corroborated by observing the absence of cracks or joint opening along the beam.

Figure 7 shows the stresses measured by SG1 and SG2 for each jacking, which had an error between 6% and 33% respect to the calculations for the strains produced by the jacking of each strand. The joint movement, the beam misalignment, and internal interference protuberances of the epoxy paste may have influenced the errors. The calculations were done using the following equation:

$$\sigma_{pt} = -\Sigma(Pj / A) - \Sigma(Pj \,.\, e \,.\, Y / Ix) - Mx \,.\, Y / Ix \qquad (3)$$

$$\varepsilon_{pt} = \sigma_{pt} / Ec \qquad (4)$$

Where:

- σ_{pt}: Stress due postensioning.
- ε_{pt} : Strain due postensioning. Tension is positive, and compression is negative.
- A: Cross sectional area of the hollow segment = 107.9 in^2
- Y: Yt = +10.6" Distance from centroid to the top
  Yb = -13.4" Distance from centroid to the bottom
- Mx: Moment due self-weight
  Mxt = +77 psi at top and center of the beam
  Mxb = -98 psi at bottom and center of the beam
  Mx = 0 psi at end of the beam

The initial loss of 17% of postensioning was estimated using the differential of deformations at fully jacking load and totally unload.

5. BEHAVIOR OF THE SEGMENTAL BEAM DURING POSTENSIONING

The beam was tested by applying a punctual load at the center of the beam using the hollow jack of 20 ton capacity. The diaphragm located at the center of the beam helped to avoid local failures due to the concentrated loading. The deformations and strains were measured using the instrumentation indicated in Figure 6. The theoretical deformations and strains were computed using the elastic properties of the concrete and considering the postensioning after the estimated losses. The deflections were computed using the following equation:

$$\Delta_L = P_L \,.\, L^3 / (48.Ec.I'x) \qquad (5)$$

Where:

- Δ_L: Vertical deflection due to the testing load applied at center of the span
- L: Span = 20'6"
- P_L: Testing load applied at center of the span.
- I'x: Moment of inertia respect to the centroid. This value changes after the first crack.

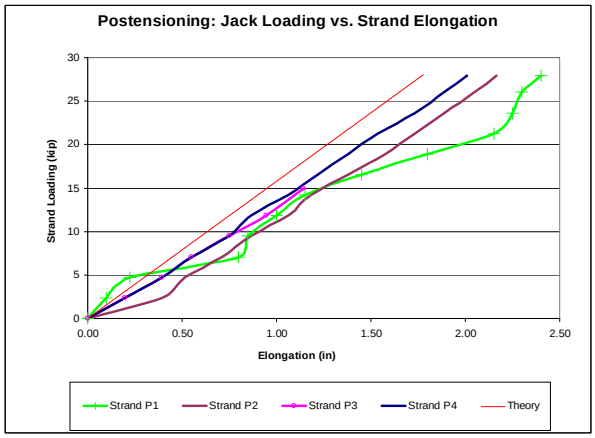
The bending stresses were computed using the previously calculated stresses due to postensioning and adding the stresses due to the testing load, as shown in the following equation:

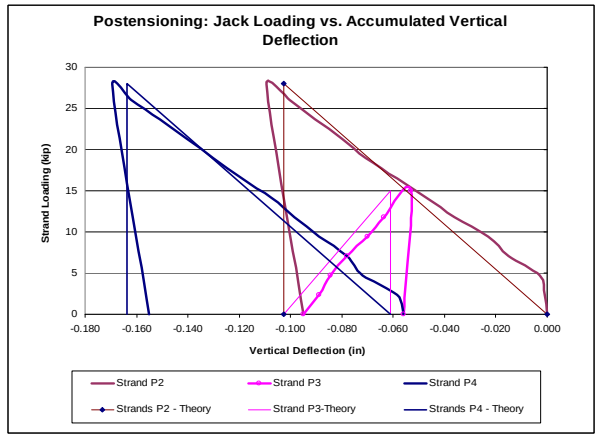
$$\sigma_L = \sigma_{pt} + M_L \,.\, Y / Ix \qquad (6)$$

$$\varepsilon_L = \sigma_L / Ec \qquad (7)$$

Where:

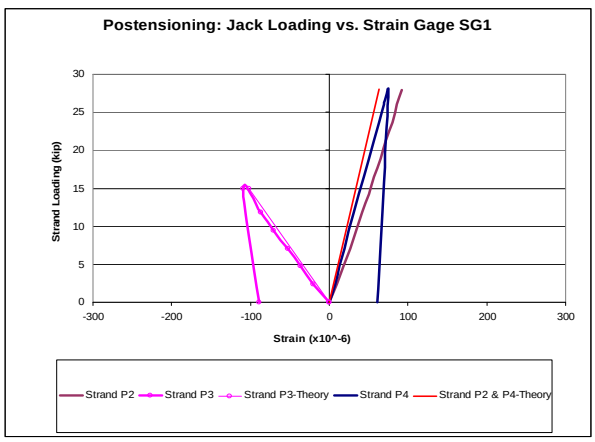
σ_L: Stress due to the testing load.
ε_L: Strain due to the testing load.
M_L: Bending moment due testing load, which changes along the beam. $M_L = P_L \cdot L / 4$





Strain sign: Positive is stretching
Negative is compression

Deflections: Positive is downward
Negative is upward



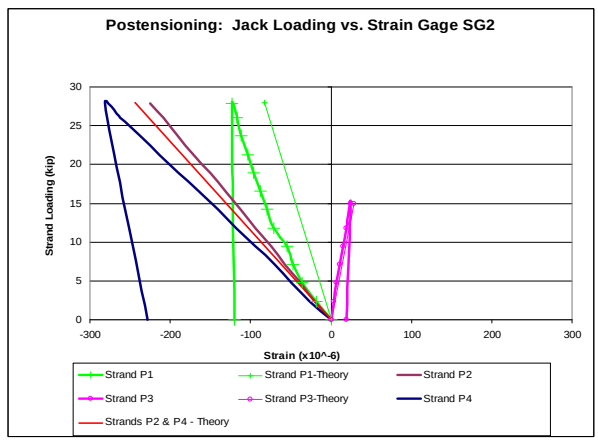


Figure 7. Segmental beam response during postensioning: cable elongation, accumulated vertical deflection, and strains at top (SG1) and bottom (SG2) of the central segment.

The shear stress and strain during the testing were calculated using the following equation:

$$\tau_L = 1.2\ V / (2\ th \cdot h) \quad (8)$$

$$\varepsilon_t = \tau_L / E \quad (9)$$

Where:

τ_L: Diagonal Stress due to the shear force.
V: Shear force due to the testing load, $V = P_L / 2$
ε_t: Diagonal strain due to the testing load.
th: Thickness of the hollow section = 1.75”
h: Height of the hollow section = 24”

The critical stresses due to flexure were verified using the strain gages, SG1 and SG2, which were installed at the middle of the beam, and at top and 1" from bottom, respectively. The diagonal strain produced by the shear force was verified using the inclined strain gage SG3.

Table 1 shows the concrete and beam properties used to compute the loads for the first cracking and for ultimate conditions with the correspondent deflections. The concrete properties were obtained from the cylinder samples tested in compression and tension. Despite the concrete was able to resist 400 psi in tension, the tension capacity was neglected because during the construction the epoxy paste was applied without caring about cleaning the surfaces. The shear transfer from segments was achieved by friction. The maximum capacity was obtained using the recommendations of ACI 318, the stress-strain properties of the strand, and verifying the internal equilibrium.

The load application was planned in order to observe the beam behavior prior to the first cracking, after cracking and at ultimate instance, defining 4 cycles of loading-unloading. Figure 8 shows the deflections and strains for the different cycles. The starting points for these curves don't consider the deflection and strains produced by the postensioning, which were zeroed before starting the test.

The first loading was from 0 to 5 kips and then it was unloaded. The deflections and strains were very close to the elastic theory and returning to zeroes after unloading. The maximum deflection was 0.10”.

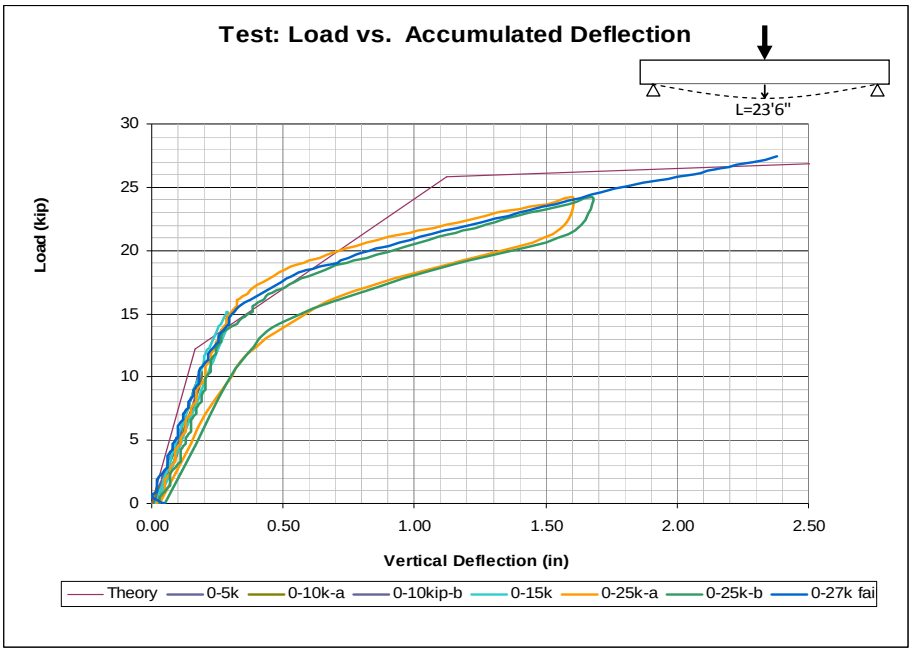
The second load was from 0 to 10 kips, which was done twice with similar results. The maximum deflection for the load of 10.41 kips was 0.19” and after unloading the remaining deformation was 0.01”. The maximum strain read by SG2 was 264 $\mu\varepsilon$; by SG1, -375 $\mu\varepsilon$; and by SG3, 33$\mu\varepsilon$. The strain gage SG2 did not increase its reading after a load of 7 kips. All the strain gages returned to zeroes after unloading.

Table 1. Theoretical deflection and strains due to the testing load

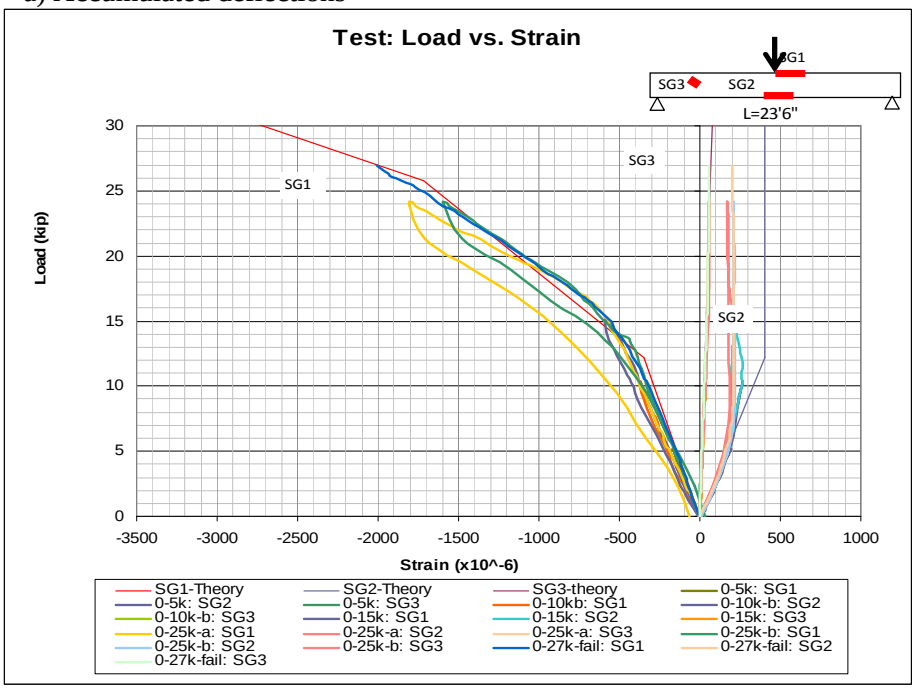
Description		**Load**	**Deflection** **+: down**	**Strains (x10^{-6})** **+: elongation**
Self-weight + Postensioning (after losses)			-0.125" (up)	SG1 = -47 SG2 = -404 SG3 = 0
Cracking load, Pcr	ft = 0 psi Ix = Ig = 7196 in^4 d = 21.76"	12 kip	From zero: 0.16"	From zeroes: SG1 = -344 SG2 = 404 SG3 = 39
Yielding of bottom strands, Py	f'c = 9 ksi fs = 243 ksi (yielding)	26 kip	0.164” + 0.957” = 1.12”	SG1 = -1714 SG2 = 404 SG3 = 62
Nominal Ultimate load, bottom strand is yielding: Pn	ε_{cu} = 0.003; a = 1.14"; c = 1.75" Ix = Ie = 1379 in^4 d = 20.76" (strand touches the diaphragm)	31 kip	0.164" + 1.957" + 6.881 = 8.0"	SG1 = -2953 SG2 = 404 SG3 = 76

The third loading was from 0 to 15 kips. The deflections were very close to the theoretical obtained from the elastic equation; however, the theoretical cracking load of 12 kips was not observed, being linear during all this loading. The deflection for a load of 15.14 kips was 0.291", and it was negligible at unloading. The strain gage SG2 followed the curve obtained in the previous loading cycle, and started to reduce after 11.35 kips, which corresponds to the aperture observed of the central segment joint. After the theoretical cracking load it was observed that the strain gage SG2 remained constant. The maximum reading of SG2 was 268 $\mu\varepsilon$, going to zero after unloading. The maximum reading of SG1 is -586 $\mu\varepsilon$; and -12 $\mu\varepsilon$ after unloading. The strain gage SG3 registered a maximum of 48 $\mu\varepsilon$ and zero for unloading, matching well with the theoretical results.

The fourth loading cycle was from 0 to 25 kips, which was done twice. Initially, the curves were similar to the previous load cycles, observing a strong change after the bottom of the segments started to crack. The cracks started to be visible after 15 kips, which corresponded to the load that produced cracks assuming a concrete tension capacity of 400 psi. The joint opening started to be visible at 13.7 kips, reaching a maximum aperture of 9 mm for 24.1 kips. Small concrete cracks in the anchor blocks were observed. Theoretically, the strands are taking forces close to their yielding increasing the bursting forces in the anchor blocks and therefore in the internal reinforcement, which worked properly.



a) Accumulated deflections



b) Strain gage reading

Figure 8. Deflections and strains during the segmental beam test

The deflections followed the curves obtained in the previous loading cycles with a notorious change of stiffness at 15 kips. The maximum deflection was 1.65" for 24.1 kips and it returned to 0.02" after unloading.

During the fourth loading cycles the strain gages followed the curves obtained in previous cycles. The maximum strain read by SG2 was 218 με for a load of 9.93 kips. The reading remained constant during the loading and returned to 12 με at zero-load. The strain gage SG1 had a maximum reading of -1599 με for 24.1 kips and -68 με for zero-load. The strain gage SG3 provided linear reading from 0 to 20.3 kips, with a maximum strain of 56 με and remaining constant for greater loads. The SG3 returned to zero after unloading.

Finally, the beam was loaded from 0 to 27.43 kips, whereby the failure of the top concrete layer became present. The deflection curve followed the previous curves. The maximum deflection was 2.38". The strain curves also followed the previous curves. The strain gage SG2 had a maximum reading of 213 με, remaining almost constant from 8 kips. The strain gage SG1 had a maximum reading of -2011 με at failure. The strain gage SG3 is very linear and the maximum reading was 55 με for 23.65 kips, remaining constant after this load.

Figure 9 shows the joint opening and failure of the central hollow segment. It is observed that the epoxy paste does not resist tension, there are several diagonal cracks starting from the loading plate and having a 45° path, and the final failure is due compression crunch of the top layer of concrete. The nominal ultimate load was 31 kips, obtained using the ultimate strain of 3000 με, given by ACI 318-08, and assuming the strands were parallel to the bottom of the beam. However, the maximum strain read was 2011 με, which was added to the strain due postensioning of 45 με, having a total strain of 2056 με, at failure. Additionally, during the maximum loading the bottom strands were not parallel to the beam and they must be touching the central diaphragm; therefore, the effective depth "d" should be reduced by approximate 1". Using these values, the theoretical maximum load was closer to the load producing failure.

a) Joint aperture

b) Central segment after failure

Figure 9. Failure during test

6. CONCLUSIONS

A postensioning segmental beam was constructed and tested in order to study its structural behavior. The beam consisted of two solid end blocks and nine hollow segments, all of them were postensioned using two strands at the bottom, one at center and one at top with half-tension. The tension capacity is neglected because the epoxy was applied only to provide a smooth surface. The beam was tested applying a concentrated central load. The strains, deflections, and the ultimate load obtained during the tests match well with the theoretical predictions.

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