# STATIC AND FATIGUE STRENGTHS OF BEAMS CONTAINING PRESTRESSED CONCRETE TENSION ELEMENTS

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This study concerns the static and fatigue behavior of composite beams containing a 2-in. square precast tension element, concentrically prestressed with a single  $\frac{7}{16}$ -in. diameter 7-wire strand. The element was positioned in the 6 in. wide, 9 in. deep, and 120 in. long beam such that its centroid was 2 in, from the tension face. Two static tests were conducted to obtain the elastic and inelastic load-deflection behavior of the composite member and to determine  $P_{cr}$ , the load corresponding to initial cracking in the tension element, and  $P_{u}$ , the ultimate load. Repeated load tests were conducted on 17 beams. The principal objective was to determine the behavior of the tension element under conditions that simulated those at a continuity connection in a highway bridge and, in particular, to ascertain the fatigue strength of the tension element. The scope of this investigation was limited to the application of repeated loads over a range of 0.5 to 2 Pcr. Test results clearly indicate that the magnitude of the peak load determines the mode of failure. Results revealed that use of the tension element for continuity connection creates a section that is superior to one using conventional reinforcement because it increases the cracking load of the section by 58.0 percent and, thus, provides better protection of the reinforcement against corrosion.

•THE USE of precast, prestressed concrete prisms (or rods) as tension elements has been discussed earlier by a number of investigators  $(\underline{1}, \underline{2})$  and more recently by Burns  $(\underline{3})$ , Hanson  $(\underline{4})$ , Bishara and Almeida  $(\underline{5})$ . The earlier investigations have been summarized by Hanson.

The principal advantage of using precast, prestressed concrete tension elements as reinforcement is crack control. The precompressed concrete tension element exerts a restraining effect on the surrounding cast-in-place concrete so that the cracking moment of a section can be increased. In addition, cracks also tend to close after the load is removed because of the high tensile force in the pretensioned strands.

In prestressed concrete bridge construction, it is sometimes advantageous to establish continuity between precast, prestressed girders by placing reinforcement in the cast-in-place deck across the interior support. Control of flexural cracking in the composite T-beam flanges is then a problem in the negative moment regions of the continuous bridge. Both Burns and Hanson have suggested that precast, prestressed concrete prisms can be used to advantage as reinforcement in this type of continuous bridge. Their studies, however, have been limited to static tests only.

In order for this technique for developing continuity to be usable and acceptable for highway bridge construction, the fatigue behavior of the composite section consisting of the tension rods requires evaluation. The purpose of this investigation is to determine the effects of repeated load on the behavior of the composite member reinforced with the prestressed concrete tension element.

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#### Scope of Test Program

Nineteen beams were tested under 3 different loading conditions. These tests may be categorized as follows:

1. Two beams were tested under static load to failure to observe their static behavior and to determine the cracking and ultimate load.

2. Nine beams were subjected to different magnitudes of repeated loading, not more than the cracking load, that was discontinued after 1 million cycles and followed by a static test to failure. At several intermediate stages, static load tests were conducted after a predetermined number of cycles of loading. The load for these intermediate static tests never exceeded the magnitude of the repeated load. From these static tests, the variation of the beam stiffness was determined from the load-deflection curve.

3. Eight beams were subjected to repeated loading, in excess of the cracking load, that was continued until failure occurred. Intermediate static tests were also conducted to determine change of the beam stiffness.

## Precast, Prestressed Concrete Tension Element

Each element was a concrete prism of 2 in. by 2 in. by 10 ft axially prestressed by a  $\frac{7}{16}$ -in. diameter 7-wire strand. The elements were fabricated on a prestressing bed in a continuous wooden form with end blocks at 10-ft intervals. The initial tension in the prestressing strand was 18,900 lb. The strand had a yield strength of 249 ksi corresponding to 1 percent extension, an ultimate strength of 270 ksi, and a modulus of elasticity of 28,000 ksi.

The concrete used in the elements was made with type III portland cement. The fine aggregate was well-graded sand with a fineness modulus of approximately 3.0, and the coarse aggregate was gravel with a maximum size of  $\frac{3}{8}$  in. The concrete mix per cubic yard consisted of 708 lb cement, 1,280 lb sand, 1,650 lb gravel, 36 gal water, and  $17\frac{1}{2}$  oz admixture.

The ingredients were mixed thoroughly in a power-driven mixer and carefully scooped into the form. The concrete was vibrated by external application to the form. The element was rough-finished by wooden float in order to have a good bonding surface. After the concrete had been cured under wet burlap for 7 days, the strands were released. The concrete cylinder strength at the time of prestress transfer was 5,328 psi.

Twenty elements were cast, one of which was used as a control specimen to measure the loss of prestress periodically during the period of investigation.

# **Test Beams**

Concrete test beams reinforced with the prestressed element were cast in 4 groups of 4 beams each and 1 group of 3 beams. The groups are labeled A, B, C, D, and E according to the order of casting. The beams were cast in plywood forms. Before concrete was placed, the tension element was secured by steel wires and aligned in position. All the test beams were of rectangular cross sections, 6 in. wide, 9 in. deep, and 10 ft long. The tension element was positioned such that its centroid was 2 in. from the top as shown in Figure 1. There was no other reinforcement.

Ready-mixed concrete was used in the test beam. The concrete mix per batch was made up of 615 lb cement, 1,213 lb sand, 1,800 lb gravel, 283 lb water, and 13 oz Placewell and 2.16 oz Aircon as admixtures. After being placed, the concrete was internally vibrated with needle vibrators and trowel-finished at the surface. The average cylinder strength at 28 days was 3,250 psi.

Twenty-four hours after casting, the concrete was covered with wet burlap. The forms were removed 2 days later, and the specimens were further cured for 15 days under wet burlap. Following this, the beams were allowed to be air-cured in the laboratory for at least 21 days before testing.

9"



LOADING CONDITION

Figure 1. Tension element and composite

beam.



Figure 2. Static test arrangement.

# **Test Procedure**

Static Tests—The typical arrangement of the test setup is shown in Figure 2. The beam was supported on roller bearings over a 10-ft span with a single point load applied at midspan by a 5-ton capacity hydraulic jack. The applied load was monitored by a Bourdon hydraulic gage. Midspan deflection was measured by a 0.001-in. dial gage at the centerline on the tension face of the beam. Following the application and removal of a small load to ensure

proper seating of the test specimen, the load was applied in increments of 504 lb until failure. Load and deflection readings were recorded.

TENSION

ELEMENT

Intermediate Static Tests—The test setup was only slightly different from that of the static tests in that the load was applied by means of a smaller hydraulic jack and measured by a load cell. Static loads were applied in small increments until they were equal to the magnitude of the repeated load. Load cell and deflection gage readings were recorded.

<u>Repeated Load Test</u>—The arrangement of the test setup is shown in Figure 3. The repeated load machine consists of 2 systems: the hydraulic system for applying the



Figure 3. Repeated load test arrangement.

load and the electronic system for controlling the frequency and magnitude of the maximum and minimum load. The frequency of the repeated load was maintained at 1.5 cps for all tests. The electronic system includes a counter for recording the number of cycles of load application. In each load application, the minimum load was kept as 10 percent of the maximum. Load was monitored by a load cell and required periodic adjustment as the stiffness of the test specimen changed. After the predetermined number of loadings, the machine was stopped and intermediate static tests were conducted before the repeated loading was resumed. The machine was equipped with a limit switch that would turn off all systems if

the deflection of the test beam became excessive because of either fracture or excessive loss of stiffness.

### TEST RESULTS

## Static Tests

The initial cracking load P applied at midspan of a simply supported beam of span L is

$$P = (4f_{t}S)/L$$

where S is the section modulus and  $f_t$  is the tensile strength of the concrete. For a split cylinder strength of 385 psi and for S = 81 in.<sup>3</sup> and L = 120 in., the predicted initial cracking load for the composite test beam was 1,039 lb. The transformed section of the steel was neglected.

To determine the load at which cracks would initiate in the tension element, consider the force  $F_{tc}$  in the tendon when the element is on the verge of cracking.

$$F_{tc} = F_i(1 - L) + nF_i(1 - L) (A_s/A_c) + f_{tt}nA_s$$

where

 $E_{s}$  = modulus of elasticity of steel;

 $E_{c}$  = modulus of elasticity of tension element concrete;

 $n = E_S/E_C = modular ratio taken as 6;$ A<sub>S</sub> = area of steel strand = 0.116 in.<sup>2</sup>;

 $\mathbf{F_i}$  = initial tendon force = 18,900 lb;

L = total measured loss of prestressing force = 45.8 percent for 53 days or 57.3 percent for 62 days;

 $A_c$  = net area of tension element; and

 $f_{tt}$  = tensile strength of concrete used in tension element = 500 psi.

Thus,

$$F_{tc} = 12,428$$
 lb for 53 days and 12,093 lb for 62 days



Figure 4. Load-deflection characteristics of specimen B-4 and A-3 subjected to static loading.

TABLE 1 RESULTS OF REPEATED LOAD TESTS RL-1

Beam	Magnitude of Repeated Loads (lb)	Frequency of Loading (cps)	Intervals for Intermediate Static Test (cycles)	Ultimate Load (lb) in Final Static Load Test <sup>a</sup>
A-4	1,500	1.5	1 million	8,315
B-3	1,500	1.5	1 million	8,120
C-1	1,500	1.5	1 million	8,038
A-1	2,250	1.5	<sup>1</sup> / <sub>4</sub> million	6,666
B-2	2,250	1.5	<sup>1</sup> / <sub>4</sub> million	7,778
B-1	2,250	1.5	$\frac{i}{2}$ million	7,206
A-2	3,000	1.5	1 million	6,652
C-3	3,000	1.5	<sup>1</sup> / <sub>4</sub> million	7,037
C-4	3,000	1.5	$\frac{1}{4}$ million	7,037

Note: Repeated load test discontinued after a total of 10<sup>6</sup> cycles of load applications.

<sup>a</sup>Yielding of steel was mode of failure for all beams in final static load test.

The total tensile force causing cracking in the tension element is, therefore,

$$\Gamma = F_{tc} + f_{tt}A_c = 14,035$$
 lb for 62 days

The neutral axis of the cracked section (tension element on verge of cracking) is 2.81 in. from the extreme compression fiber, and the resultant compressive force is located at 0.94 in. from the compression face. The internal moment arm is, therefore, 6.06 in. Thus, the cracking moment  $M_{cr}$  is 85,053 in.-lb, which corresponds to an applied load  $P_{cr} = 2,835$  lb for the 62-day test. For the 53-day test, the corresponding cracking load is 2,903 lb.

Consider a similar beam with conventional reinforcing steel placed at the same location as the prestressed tension element.

The moment corresponding to a tensile stress of 385 psi in concrete at the level of the steel is 56,000 in.-lb. This indicates that the use of the tension element increases the cracking moment capacity by approximately 52 percent (85,053/56,000 = 1.52).

The theoretical ultimate moment of the composite section computed at the 1 percent yield strength of the prestressing strand and a concrete cylinder strength of 3,250 psi is 177,000 in.-lb. This corresponds to an applied load of 5,940 lb, which is a conservative estimate as shown by Figure 4.

The load-deflection curves of the 2 static tests are shown in Figure 4. Almost no change in beam stiffness is noted at the load corresponding to initial cracking of beam which is 1,039 lb. However, a decrease in beam stiffness is noted at approximately 3,000 lb corresponding to the calculated cracking load of the tension element.

### **Repeated Load Tests**

TABLE 2

The magnitude of the repeated loads, the interval for intermediate static tests, the number of load applications at which tests were discontinued, and the mode of failure are all given in Tables 1 and 2 for tests RL-1 and RL-2 respectively. A typical set of

Beam	Magnitude of Repeated Load (lb)	Frequency of Loading (cps)	Intervals for Intermediate Static Text (cycles)	Number of Cycles at Which Failure Occurred	Mode of Failure
E-3	2,750	1.5	_a	1,903,362	Rupture of steel due to fatigue
D-1	3,000	1.5	_a	1,787,961	Rupture of steel due to fatigue
D-3	3,500	1.5	20,000	288,000	Rupture of steel due to fatigue
D-4	4,000	1.5	20,000	105,651	Rupture of steel due to fatigue
C-2	4,500	1.5	20,000	90,720	Rupture of steel due to fatigue
D-2	5,000	1.5	10,000	59,572	Rupture of steel due to fatigue
E-1	5,500	1.5	10,000	20,700	Fatigue failure of concrete
E-2	6,000	1.5	_a	250	Fatigue failure of concrete

RESULTS OF REPEATED LOAD TESTS RL-2

Note: Repeated load tests continued to failure.

<sup>a</sup>No static test conducted.











load deflection curves from intermediate static tests is shown in Figure 5. It is quite clear that there was a gradual reduction in beam stiffness as the number of load applications increased.

Figure 6 shows the results of the repeated load tests in which the peak magnitude of the repeated load is plotted as a function of the number of cycles of loading at which failure occurred. The L-N curve is characteristically Z-shaped with the up-

per end approaching asymptotically the static ultimate load and the lower end approaching asymptotically the load level of 2,500 lb, which corresponds to approximately 80 percent of the calculated cracking load for the tension element.

# CONCLUSIONS

The following conclusions may be drawn on the basis of this investigation.

1. Over the upper range of loads from 1.7 to 2.0  $P_{cr}$ , failure resulted from fatigue of concrete well before 1 million cycles, indicating a low fatigue life.

2. A typical curve of repeated load versus number of cycles of loading corresponding to fatigue failure (on semilog scale) consists of a central segment from P<sub>cr</sub> to 1.7  $P_{cr}$  that has a steep slope and represents the loading range over which failures resulted from fatigue of prestressing steel after a load application of less than 1 million cycles.

3. Over the range of load less than 0.7  $P_{cr}$  (or approximately 0.3  $P_u$ ), the composite beam sustained repeated load application of well over 1 million cycles without fatigue failure.

4. The tests substantiated previous investigations that failure by fatigue before 1 million cycles of load is unlikely when the magnitude of the repeated load does not exceed the cracking load of the prestressed element.

5. The use of such a tension element for continuity reinforcement creates a section that is superior to mild steel reinforcement because it increases the cracking load of the section by 52 percent and, thus, provides better protection of the reinforcement against corrosion.

6. The loss of stiffness of the composite member, as measured by the deflections, was dependent on the magnitude of the repeated load. In general, the higher the magnitude of the repeated load is, the greater the rate of progressive loss of stiffness will be. When the magnitude of the repeated load is less than the cracking load, stiffness loss is negligible.

7. A gradual loss in stiffness was definitely detected with the application of repeated loads of magnitude in excess of the cracking load. This is probably due to the progression of cracks deeper and deeper into the section and also due to some deterioration in concrete strength.

8. Because the progressive loss of stiffness is usually a signal that cracking is gradually advancing into the section, it is also a positive signal that failure due to fatigue before 1 million cycles of load is highly probable.

9. The loss of stiffness after initial cracking of the composite section was much smaller than expected. This further reinforces the belief that cracks may be prevented from advancing deeper into the section by the restraining effect of the tension element.

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