FATIGUE TESTS OF PRESTRESSED GIRDERS WITH BLANKETED AND DRAPED STRANDS

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In pretensioned girders, draping of strands can be avoided by using straight tendons having unbonded "blanketed" lengths at the ends of girders. An experimental investigation was carried out to determine the effect of repetitive loading on the behavior and strength of girders with draped and blanketed strands. Six full-size Type II AASHTO-PCI girders were tested. Two girders contained draped strands. The other girders had straight strands with four tendons blanketed at each end. The effects of load level, development length, and confining ties were investigated. The test program called for 5-million cycles of loading followed by a static test to destruction. The paper presents results of the investigation and shows that blanketed strands can be used successfully if adequate strand development length is provided. Fatigue fracture of strands was observed in pre-cracked beams where load level produced tensile stress in the precompressed concrete.

Highlights

Use of draped strands in pretensioned girders presents problems for designers, fabricators and inspectors. The tensioning procedure is time consuming, costly, and may leave doubt as to the actual prestress level obtained throughout the length of the strand. Draping of strands can be avoided by using straight tendons having unbonded "blanketed" lengths at the ends of girders.

Test Program

An experimental investigation was carried out at the Portland Cement Association Laboratories to determine the effect of repetitive loading on the behavior and strength of girders with blanketed strands.

Six full-size Type II AASHTO-PCI girders, each 15.24-m (50-ft) long, were tested. Two girders contained draped strands. The other four had straight strands with four tendons blanketed at each end.

Controlled variables in the test program were load level, development length, and use of ties to confine the concrete in the stress transfer region of the blanketed strands. All specimens were cracked prior to fatigue loading.

The test program called for 5-million cycles of loading between dead load and dead load plus live load. Static tests to full dead load plus live load were performed before cyclic loading and after 1, 2-1/2 and 5-million cycles. At the completion of 5-million cycles, the girders were tested to destruction under static load.

This paper summarizes the experimental investigation (1) and presents the results of the tests.

Conclusions

The results of the fatigue tests of this investigation indicate the following:

1. In prestressed bridge girders, concrete stresses may be controlled by either draping strands or, alternatively, using straight strands having unbonded "blanketed" lengths at the ends of girders.
2. For similar loading conditions, the behavior and strength were the same for girders having either blanketed or draped strands.
3. The fatigue life of specimens designed for a tensile stress of $0.5\sqrt{f'_c}$ MPa ($6\sqrt{f'_c}$ psi) under full service load was significantly less than that of specimens designed for zero tension.
4. In specimens designed for zero tension in the concrete under service load condition, and having blanketed strands designed for one development length, ℓ_d, as defined in ACI 318-71, Clause 12.11.1, the behavior and strength of the specimens with blanketed strands were similar to those of conventional girders with draped strands.
5. In the specimen designed for a tensile stress of $0.5\sqrt{f'_c}$ MPa ($6\sqrt{f'_c}$ psi) in the uncracked concrete under full service load and having blanketed strands designed for twice the development length, $2\ \ell_d$, only small slip of the strands occurred. This indicated adequate bond of the blanketed strands for about 3-million cycles of repetitive loading.
6. In the specimen designed for a tensile stress of $0.5\sqrt{f'_c}$ MPa ($6\sqrt{f'_c}$ psi) in the uncracked

concrete under full service load and having blanketed strands designed for one development length, ℓ_d, the blanketed strands slipped indicating bond fatigue.

7. In the three specimens where cyclic loading produced a tension of $0.5\sqrt{f'_c}$ MPa ($6\sqrt{f'_c}$ psi) in the concrete, fatigue fracture of the strands occurred at about 3-million cycles of repetitive loading. These specimens included a control girder with draped strands. The calculated minimum and maximum stresses in the strands were between 980 and 1040 MPa (142 and 151 ksi), respectively.

8. Use of ties to confine the concrete in the stress transfer region of blanketed strands in one specimen did not cause any substantial improvement in the behavior of that specimen.

Recommendations

Based on the test results and the conclusions outlined above, it is recommended that:

1. In bridge girders, blanketed strands may be used as an alternative for draped strands.
2. In bridge girders designed for no allowable tension in the concrete under service load conditions, the blanketed length of strands should be calculated allowing for at least one development length, ℓ_d, as defined by ACI 318-71, Clause 12.11.1. In most girders, the development length can be greater than ℓ_d without exceeding the allowable concrete stress at the end of the girders. A length greater than ℓ_d will result in less strand lengths to be blanketed and, therefore, would be more economical to manufacture.
3. In bridge girders designed for an allowable tensile stress of $0.5\sqrt{f'_c}$ MPa ($6\sqrt{f'_c}$ psi) in the uncracked concrete under service load condition, the blanketed length of strands should be calculated allowing for at least two development lengths, $2\ \ell_d$. In most girders, the development length can be greater than $2\ \ell_d$ without exceeding the allowable concrete stress at the end of the girders. A length greater than $2\ \ell_d$ will result in less strand lengths to be blanketed and, therefore, would be more economical to manufacture.
4. Use of ties to confine the concrete in the stress transfer region of blanketed strands is not necessary.
5. When tension is allowed in the concrete under service load conditions, design of the girders to prevent strand fatigue should be a consideration.
6. Further research is needed to determine the fatigue properties of prestressing strands. The results can then be incorporated into specifications and codes. Currently the designer is not provided with any guidance regarding design of strands for fatigue.
7. Research is needed to determine the level of tension in the concrete at which pretensioned girders would be able to withstand traffic loading without strand fatigue during their design service life.
8. Research is needed to determine how far strands should be extended beyond the point where they are not needed. In reinforced concrete members, the cut-off point of a reinforcing bar is governed by either a development length measured from the critical section, or a minimum distance (e.g., 15 bar diameters) (2) measured from the theoretical point where the bars are not needed. Presently, specifications do not provide the designer with a minimum distance criterion for prestressing steel.

Introduction

Strands are draped at the ends of prestressed girders to control concrete stresses. Draping of strands can be avoided by using straight tendons as long as the concrete stresses at the ends of the beams remain within the allowable limits. This can be achieved by using the "blanketing" concept. The effect of prestressing is eliminated in a given strand by preventing bond with the concrete. This can be achieved by greasing the strand, coating it with retarder, or covering it with plastic tubing. Greasing or using a retarder is risky because of the possibility of affecting other than the specified strands. Plastic tubing is preferred because it also provides an easy means of inspection.

The blanketing technique has been tested previously (3,4). However, further tests were needed since recent Codes (5) and Specifications (2) permit tension in the precompressed fibers under service loads.

Therefore, the aims of this investigation were to:

1. Determine whether tension in the concrete under service load condition affects the development length.
2. Determine whether one or two development lengths, ℓ_d, (as defined by ACI 318-71, Clause 12.11.1) are required.
3. Determine whether ties to confine the concrete in the stress transfer region of blanketed strands are beneficial.

Design of Specimens

Six full-size Type II AASHTO-PCI specimens were tested in this investigation. Table 1 summarizes the test variables. Cross sections, reinforcing details and the loading pattern are shown in Fig. 1.

Test specimens were designed according to the 1973 AASHO Specifications (2) and the 1974 and 1975 AASHTO Interim Specifications (6,7).

Concrete strength at transfer of prestress, was assumed to be at least 27.6 MPa (4,000 psi). The concrete design strength at 28 days was taken as 34.5 MPa (5,000 psi).

The strands used were 11.1-mm (7/16-in.) diameter with a nominal strength of 1724 MPa (250 ksi). Prestress losses at service condition were assumed to be 20%.

A minimum number of strands were blanketed to ensure that the top and bottom concrete stresses of the end regions remained within the allowable values. At each end, four strands were blanketed in all girders having straight tendons only.

The blanketing location was determined from the concept of development length. The procedure is similar to that for stopping rebars in reinforced concrete members.

One development length was calculated (2) to be 1.68-m (5 ft - 6 in.). Location of blanketing tubing relative to the position of the applied loads is shown in Fig. 2. Strands were blanketed in pairs to maintain symmetry. Only strands in the bottom layer were blanketed.

Development length was measured from the locations where the strands were required to exhibit their full strength. To force the cracks to occur at these critical locations, crack forming devices were placed in the test girders at the locations shown in Fig. 2. The crack formers consisted of 55x454-mm (2-3/16x17-7/8-in.) pieces of 1.6-mm (1/16-in.) thick sheet metal.

Ties to confine the concrete in the end transfer region of all girders conformed with the Louisiana "typical details for prestressed concrete girder construction". The same confining tie details were used at the stress transfer regions of the blanketed strands of Specimen G14.

The choice of the range of loads for the fatigue testing of Specimens G11, G13 and G10 was governed by the following criteria:

1. Under full service load, tensile stress in the precompressed concrete fiber was $0.5\sqrt{f'_c}$ MPa ($6\sqrt{f'_c}$ psi). Therefore, the dead load moment, M_D, plus the live load moment, M_L, caused a tensile stress of $0.5\sqrt{f'_c}$ MPa ($6\sqrt{f'_c}$ psi) in the bottom concrete fibers at midspan.

2. Calculated flexural capacity, M_u, of the girder at midspan was:

$$M_U = 1.3\ M_D + 2.167\ M_L$$

These two conditions yielded the fatigue loads P_{min} and P_{max} for Specimens G11, G13 and G10. Load P_{min} corresponds to dead load moment in addition to the selfweight moment. Load P_{max} corresponds to total dead load plus live load moments.

For Specimens G14, G12 and G10-A, the maximum service load, P_{max}, was chosen to correspond to a midspan bottom concrete fiber stress of zero tension. The minimum load, P_{min}, was chosen to be a nominal 2.7 kN (600 lbs.) required to keep the rams in contact with the top of the girders. Table 2 summarizes calculated values for range of fatigue loads, the corresponding midspan moments, stresses in the bottom layer of strands and stress range in these strands. Note that the loads P_{min} and P_{max} are the inner point loads of Fig. 2. The outer point loads are 2.5 times the magnitude of the listed loads.

Present Codes (5) and Specifications (2) do not provide the designer with any guidance concerning allowable stress range to prevent fatigue failure in prestressing strands. The calculated stress levels listed in Table 2 are much smaller than the allowable stresses recommended by ACI Committees 215 (8) and 443 (9).

Test Program

Two loading systems were used to test each specimen. The first was basically for dynamic loading, and the second for static tests to destruction. The second system is shown in Fig. 3.

Dynamic loading was applied through four rams. Each ram was secured to a concrete frame prestressed to the laboratory floor. In Fig. 3, the stems of two rams are in the retracted position.

To accommodate the large deflections required to test the specimens to destruction, the test setup was modified. The second loading system consisted of cross heads and tie rods. Loads were applied by hydraulic rams reacting against the underside of the test floor (10).

Instrumentation was first installed during manufacture of the girders in the plant. Quantities measured included prestressing force, strand strains, confining tie strains, and camber.

In the laboratory, measurements of applied loads, deflections, strand strains, confining tie strains and strand slip were recorded during the static tests.

During the dynamic tests, measurements recorded were strand slip and number of cycles of repetitive loading.

Ends of the specimens were supported on a 127-mm (5-in.) diameter roller located between two steel plates. A jig was erected at each support to prevent the girder from rolling longitudinally during the dynamic testing.

Testing started with 3 cycles of static loading between P_{min} and P_{max}. These predetermined loads are listed in Table 2. To ensure that Specimens G14, G12 and G10-A would crack, they were loaded up to P_{max} = 65 kN (14.6 kips) during the static tests only.

Repetitive loading was applied at the testing machine rate of 265 cycles/min. The large mass of the girder necessitated a dynamic correction. This correction was accounted for by controlling the loads such that the deflections produced due to cyclic loading corresponded with the measured minimum and maximum static deflections.

To determine the effect of the cyclic loading on the girder's response, dynamic loading was interrupted at 1-million and 2.5-million cycles and a static test was conducted between P_{min} and P_{max}. After 5-million cycles, the repetitive loading was stopped. The loading system was then modified and the specimen loaded statically in increments to destruction.

The concrete compressive strength was determined from 152x305-mm (6x12-in.) concrete cylinders. At test time, the concrete strength of the girders ranged between 40.7 and 52.4 MPa (5900 and 7600 psi). Strength of the deck concrete was between 34.5 and 41.4 MPa (5000 and 6000 psi).

All strands were stress-relieved. They were manufactured in Japan. Coupons from the same strands used in the girders were tested in the laboratory. These coupons were instrumented with strain gages similar to those used in instrumenting strands in the girders. The modulus of elasticity was found to be 230,600 MPa (33,440 ksi). It was used to convert the measured strand strains into strand stresses. The measured modulus was high because the strain gages were placed along a wire, i.e., along a spiral.

When unrolled from their coils, the strand had a shiny surface. For about ten days the strands were exposed to high humidity due to rain and curing steam from adjacent prestressing beds. This resulted in brown surface rusting of the strands.

Behavior of Specimens

The following is a description of the behavior of each specimen. Specimens are discussed in the sequence of testing.

Specimen G11

For Specimen G11, increasing slip of the blanketed strands was measured as the dynamic test progressed. After 3.78-million cycles, fatigue loading was stopped because of the formation of a large crack at the outer east crack former. The stiffness of specimen had decreased considerably. The specimen was then unloaded and the loading system modified in preparation for the final static test to destruction.

During the test to destruction, sudden fracture of the specimen occurred at a load very close to the specified service load level. All distress occurred at the section where the large crack had formed. No other cracks appeared. Only two of the

22 strands did not fracture. These were blanketed over a longer length and slipped inside the end portion of the girder. A plot of the applied load versus midspan deflection is shown in Fig. 4.

Specimen G13

After 3.2-million cycles of repetitive loading, a large crack had extended high into the web at the inner east crack former of Specimen G13. Slip of the blanketed strands was negligible. The stiffness of the girder had decreased.

Specimen G13 was cut open at the critical section to inspect the strands. Six strands were found to be fully fractured in fatigue. Six strands had one to five of the seven wires fractured in fatigue. Only 10 of the 22 strands had no visible evidence of fatigue.

While removing the concrete cover at the critical section, the position of the crack former with respect to the bottom layer of strands was carefully observed. The outside strands of the bottom layer were bearing against the crack former while the intermediate strands were clear. Of the two strands, one was intact, and the other had fatigue fracture about 38-mm (1.5-in.) away from the crack former.

To determine whether the fatigue had affected the properties of the intact strands that crossed the critical section, coupons were extracted from the girder. These were tested statically in tension. The breaking strength of these strands corresponded to the manufacturers strand strength.

To obtain further information from Specimen G13, the strands at the inner west crack former were exposed. A crack of limited height had formed at this section. There were no external visible signs of damage. After exposing the tendons, it was found that one strand of the second layer and one wire from a bottom layer strand were fractured in fatigue.

Specimen G10

Behavior of Specimen G10 was very similar to that of the two previous specimens. After 3.63-million cycles, the dynamic loading was intentionally stopped after observing the formation of a large crack at the inner west crack former. This was the location of a hold-down device.

Specimen G10 was then loaded statically to destruction. It fractured prematurely and suddenly as illustrated by the applied load versus midspan deflection curve of Fig. 4. The failure was concentrated at the critical section. No new cracks appeared along the beam.

After separating the two segments of the girder, the fractured surface of all strands was inspected. It was possible to identify the strands that failed due to fatigue and the ones that failed due to tension. The two modes of fracture are very distinct as illustrated by Fig. 5. Six strands were found to be fully fractured in fatigue. Eight strands had one to four of the seven wires fractured in fatigue.

As observed earlier in Specimen G13, it was noticed that the two outer strands of the bottom layer were touching the crack former while all the intermediate ones were clear. The outer strands had fractured in tension. It is interesting to note that the hold-down device did not seem to be the cause of fatigue of strands. The distribution of fatigued wires and strands was random.

Specimen G14

Specimen G14 survived 5-million cycles. Only small cracks had formed at the four crack formers. Strand strains and confining tie strains remained stable during the test. Slip of the blanketed strands did not exceed 0.11-mm (0.0045-in.).

Specimen G14 was then loaded statically to destruction. Figure 4 illustrates the applied load versus midspan deflection curve. The specimen exhibited ductile behavior. Uniformly spaced cracks formed over the center 8.5-m (28-ft) of the specimen. After reaching a midspan deflection of 0.7-m (28-in.), the specimen fractured. The measured strength exceeded that calculated by 4%.

During the initial and intermediate static tests, the gages attached to the confining ties did not record any significant strains. It was only during the final static test, after closely spaced cracks were opening that some gages recorded strains.

Specimen G12

Specimen G12 was similar to Specimen G14 in every respect except that it did not contain confining ties in the stress transfer regions of the blanketed strands. Specimen G12 was tested in a similar manner and the response was similar. The measured strand slips were a little larger.

During the static test to destruction, Specimen G12 exhibited very ductile behavior as illustrated by the applied load versus midspan deflection curve of Fig. 4. The test was stopped after a midspan deflection of 0.8-m (31-in.) was reached. Measured strength exceeded that calculated by about 2%.

Specimen G10-A

Specimen G10-A had draped strands and was similar to Specimen G10. The only difference was the stress level during cyclic loading. Under cyclic loading, no tension was allowed in the bottom fibers at midspan.

Applied load versus midspan deflection curve during the final static test is shown in Fig. 4. The strength of Specimen G10-A exceeded that calculated by about 4%.

Analysis of Test Results

Based on the data collected from each test, comparisons of performance of the specimens is given in this section. Significant test observations are also discussed.

Level of Fatigue Loading

In Specimens G11, G13 and G10, the higher limit of repetitive loading corresponded to a tensile stress of $0.5\sqrt{f'_c}$ MPa ($6\sqrt{f'_c}$ psi) in the bottom concrete fibers at midspan. The specimens were cracked prior to fatigue loading. In these three specimens, strands fractured due to fatigue after 3.2 to 3.7-million cycles.

In Specimens G14, G12 and G10-A, the repetitive loading did not cause tension in the concrete. All three specimens survived 5-million-cycles of repetitive loading. In subsequent static tests to destruction, all three specimens exhibited ductile behavior as illustrated by Fig. 4. Strength of

Specimens G14, G12 and G10-A exceeded that calculated by 2% to 4%.

Strand Stress Range

Stress range is defined as the difference between maximum and minimum strand stresses corresponding to the respective maximum and minimum loads. Stress range was calculated through strain compatibility, equilibrium of internal forces and a knowledge of the actual material properties. The stress range was also measured by means of strain gages applied to the strands. To eliminate the time-dependent effects of creep and shrinkage, and any possible temperature effects, the stress range of each static test is used for comparison purposes.

Table 3 lists the highest measured range of strand strain corresponding to maximum and minimum inner loads of 65 kN (14.6 kips) and 18.2 kN (4.1 kips), respectively. Measured strand strains were converted to stresses using the experimentally determined modulus of elasticity. Specimen G10-A was not instrumented for strand strains.

Calculations for internal stresses indicate that stress range is a function of the effective prestress. For example at a 21% loss of prestress, the calculated stress range corresponding to maximum and minimum inner loads of 65 kN (14.6 kips) and 18.2 kN (4.1 kips) is 58 MPa (8.4 ksi). At 27% loss, the calculated stress range corresponding to the same loads is 82.7 MPa (12 ksi). The stress range as affected by prestress is shown in Fig. 6.

For all specimens, the measured stress range increased with increase of the cycles of repetitive loading as shown in Table 3. However, in Specimens G11, G13 and G10, the rate of increase in stress range was much higher. These three specimens were subjected to higher load levels. Strands of the above three specimens fractured due to fatigue between 3.2 and 3.7-million cycles of repetitive loading.

Figure 7 is a plot of the calculated stress range in the strands at 20% loss of prestress versus the fatigue life of Specimens G11, G13, and G10. The S-N curve was adapted from Fig. 12 of a report prepared by ACI Committee 215, Fatigue of Concrete (8). Their curve was obtained through a regression analysis of fatigue test results (11). It can be seen that the fatigue strength of Specimens G11, G13, and G10 was lower than previous fatigue test results.

Slip of Blanketed Strand

Strand slip measured with a dial gage provided a good indication of the effectiveness of the development length. Figure 8 illustrates the load versus slip recorded during the static tests. For each girder, the blanketed strand that had the largest slip is plotted. As shown in Fig. 8a for Specimen G11, slip increased with repeated load. This denoted bond fatigue (12,13). When Specimen G11 was loaded to destruction, two strands slipped inside the end portion of the girder.

Figure 8b is for Specimen G13. Slip stabilized after the initial elastic slip. Even after 3.2-million cycles, the increase in slip was negligible denoting good anchorage of the blanketed strands. Specimen G13 had double the development length specified in ACI 318-71, Clause 12.11.1.

Figures 8c and 8d are for Specimens G14 and G12, respectively. Slip of Specimen G14 was smaller than strand slip of Specimen G12. This suggests some beneficial effect of the extra confining ties. However the effect was not significant enough to justify the use of the ties. Slip in Specimen G14 also remained smaller during the static test to destruction as shown in Fig. 9. The maximum strand movements of Specimens G14 and G12 were small up to 5-million cycles. The small slip did not affect the strength and behavior of the two beams.

The effect of the number of cycles of repetitive loading on strand slip is illustrated in Fig. 10. For each specimen, the strand with the largest slip is plotted. This plot denotes rapid bond deterioration of Specimen G11.

It can be seen that for Specimens G12 and G14, magnitudes of slip plotted in Fig. 8 are different from those of Fig. 10. During the repetitive loading of Specimens G14 and G12, the maximum applied inner load, P_{max}, was 48.5 kN (10.9 kips). During the static tests, the maximum applied inner load was 65 kN (14.6 kips). Thus the slip measured during the static tests was larger.

Development Length

Specimen G13 was designed for two development lengths, $2\ \ell_d$. Specimen G11 was designed for one development length. Both specimens were cycled at the higher load level corresponding to a tensile stress of $0.5\sqrt{f'_c}$ MPa ($6\sqrt{f'_c}$ psi) in the concrete. Both specimens had fatigue fracture of the strands. The main difference in behavior was that, in Specimen G11, slip of the strands kept increasing with cyclic loading as shown in Fig. 10.

A bond fatigue failure of the blanketed strands of Specimen G11 was observed. On the other hand, in Specimen G13, slip of strands remained virtually unchanged after the initial elastic slip up to 3.2-million cycles of repetitive loading as shown in Fig. 8b. Therefore, twice the development length, $2\ \ell_d$, used in Specimen G13 provided good anchorage of the blanketed strands.

Specimens G14 and G12 were designed for one development length. They were tested at a load level corresponding to zero tension in the concrete. Both specimens survived 5-million cycles of repetitive loading. In the subsequent static test to destruction, both specimens reached their calculated strength. No bond fatigue of the strands was observed. Therefore, when the cyclic load corresponded to zero tension in the concrete, one development length was adequate.

Surface Condition of Strands

In the present investigation, strands used in the test specimens had brown surface rust. It is well known that the surface condition affects the required development length. However, the surface condition of the strands was not one of the control variables of this investigation. It is possible that the surface condition of the strands may have affected both development length and fatigue properties.

Confining Ties

Strains measured on the confining ties at service load levels were negligible. Significant strains were measured only at very high loads following the formation of large cracks, during the static test to destruction.

Smaller slip of the blanketed strands was measured in Specimen G14, with confining ties than in

Specimen G12. However, the behavior and strength of Specimen G14 do not indicate any significant beneficial effect of the confining ties.

Concluding Remarks

The tests of this investigation have confirmed that blanketing of strands is a feasible technique that could lead to safer and more economic manufacturing of pretensioned bridge girders.

The tests have also indicated that fatigue of strands may be an important consideration in prestressed girders designed according to recent Codes where a concrete tensile stress of $0.5\sqrt{f'_c}$ MPa ($6\sqrt{f'_c}$ psi) is permitted under service loads. Present Codes do not provide the designer with guidance regarding fatigue of strands.

Conclusions and Recommendations based on this investigation are listed in the section entitled HIGHLIGHTS at the beginning of the paper.

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Disclaimer

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Table 1. Test specimens.

Specimen	Stress Level	Development Length	Confinement Reinforcement
G11	Tension in	d	No
G13	Bottom Fiber	2 d	No
G10	$0.5\sqrt{f'_c}$ MPa	Draped	No
G14	No Tension	d	Yes
G12	under Service	d	No
G10-A	Load	Draped	No

$0.5\sqrt{f'_c}$ MPa = $6\sqrt{f'_c}$ psi

Table 2. Fatigue loads and stress levels.

Remarks	Specimen No.	
	G11,G13,G10	G14,G12,G10A
Applied Load, kN, P_{min} P_{max}	18.2 65.0	2.7 48.5
Moment (Constant Moment Zone), kN.m, Min. Max.	549 1275	303 1024
Strand Stress (Bottom Layer), MPa, Min. Max.	983 1041	968 1010
Strand Stress Range, MPa	58	42
Midspan Bottom Fiber Concrete Stress at P_{max}	$0.5\sqrt{f'_c}$ MPa	0

Note: Strand Stresses are calculated assuming 20% loss of prestress

1 kN = 0.225 kip 1 kN.m = 0.738 ft kip 1 MPa = 0.145 ksi

Table 3. Measured strains and corresponding stress ranges.

P_{min} = 18.2 kN P_{max} = 65.0 kN

Number of Cycles	Strain, millionths				
	G11	G13	G10	G14	G12
1	318	369	255	352	379
2	314	380	223	-	-
3	320	383	237	-	-
1.0×10^6	424	412	583	386	426
2.5×10^6	544	602	569	382	462
5.0×10^6	-	-	-	400	464

Corresponding stress range based on E = 230,603 MPa

Number of Cycles	Stress, MPa				
	G11	G13	G10	G14	G12
1	73	85	59	81	87
2	72	88	51	-	-
3	74	88	55	-	-
1.0×10^6	98	95	134	89	98
2.5×10^6	125	139	131	88	107
5.0×10^6	-	-	-	92	107

1 kN = 0.225 kip
1 MPa = 0.145 ksi

Figure 1. Cross section and reinforcing details of test specimens.

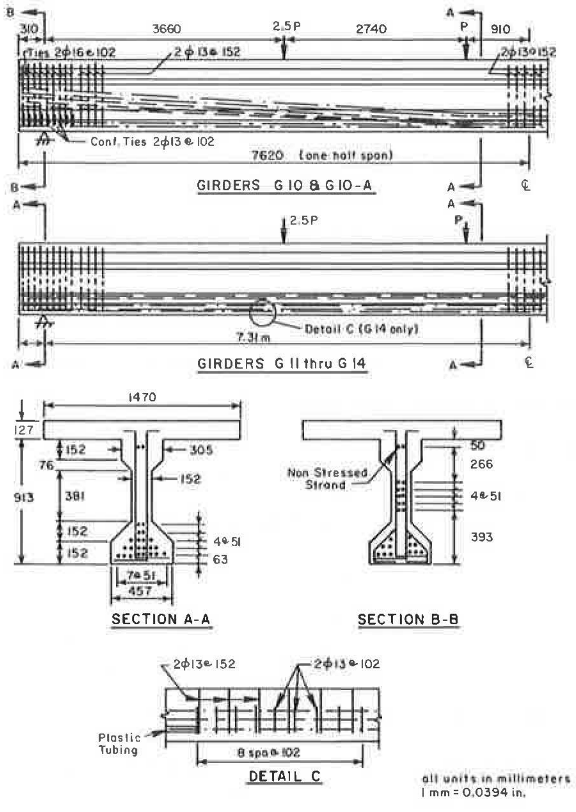


Figure 2. Location of blanketing tubing and crack formers relative to position of loading points.

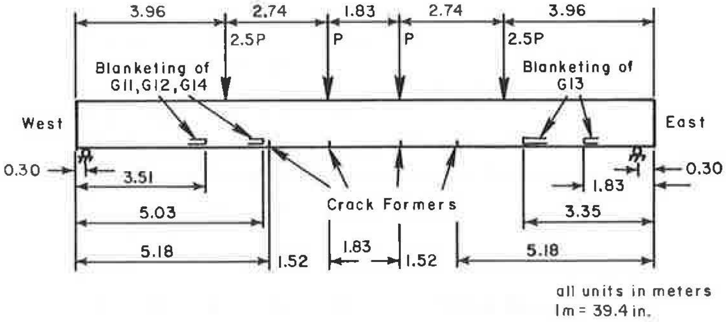


Figure 3. Test setup.

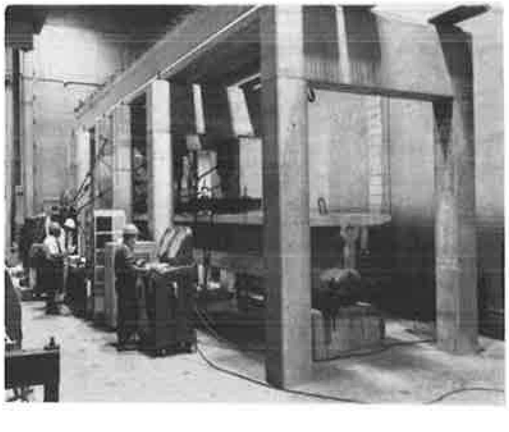


Figure 4. Load versus midspan deflection envelopes for static tests to destruction.

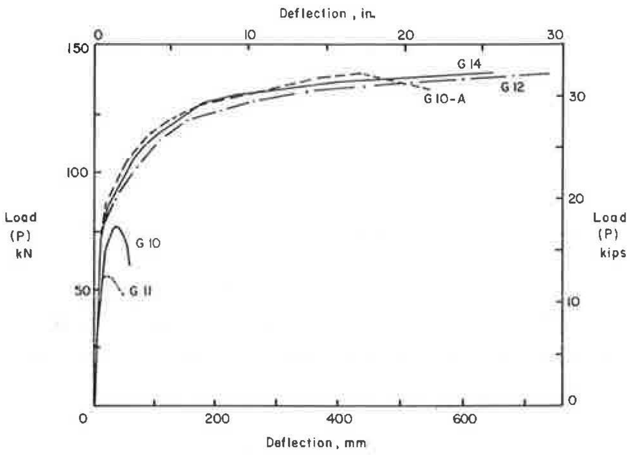
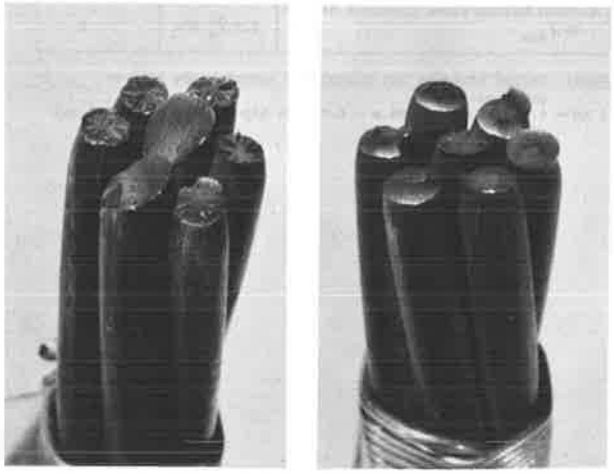


Figure 5. Fatigue and tension fracture surfaces of strands.

a. Fatigue fracture.



b. Combined fatigue and tension fracture.

c. Cup and cone tension fracture.

Figure 6. Calculated stress range versus percentage loss of prestress.

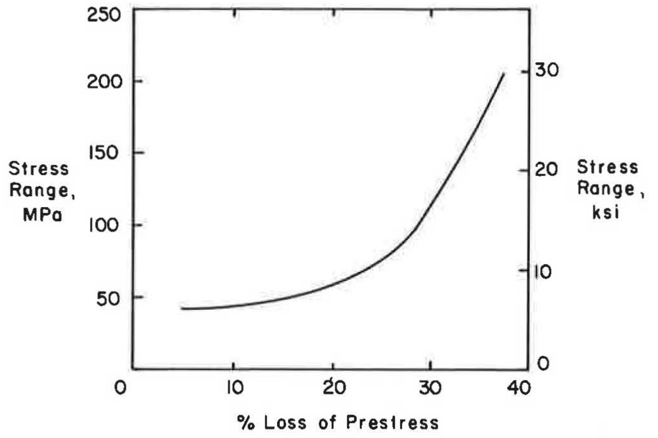


Figure 7. S-N curve for 7/16 in. diameter strands.

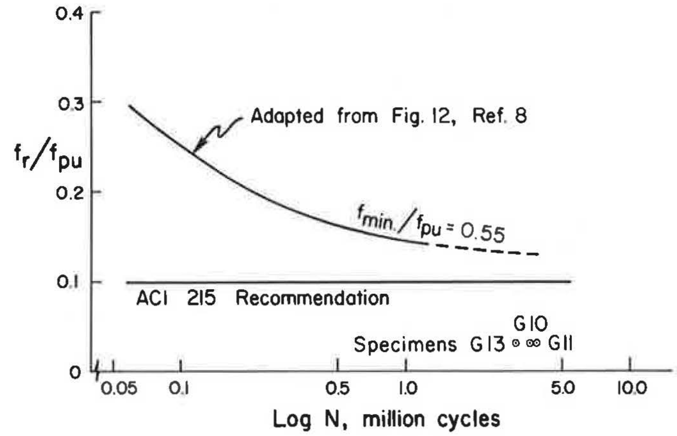


Figure 8. Measured load versus slip at different cycles.

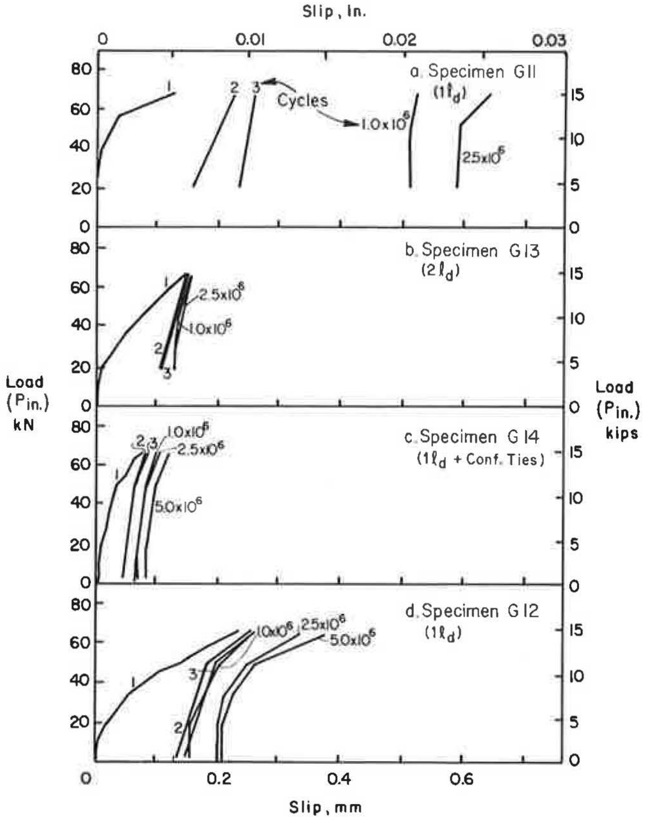


Figure 9. Load versus slip during static test to destruction.

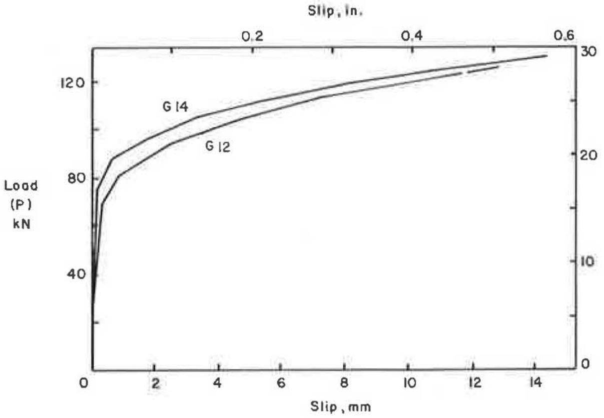


Figure 10. Variation of slip with applied cycles of repetitive loading.