Fatigue Tests of Bridge Materials Of the AASHO Road Test

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Analyses of the behavior under repeated applications of overstress of the test bridges at the AASHO Road Test required knowledge of the fatigue properties of reinforcing bars, prestressing wire and strand, and of steel beams with partial-length cover plates. Studies aimed to develop such knowledge are reported in this paper.

Included are fatigue tests of 20 specimens of No. 11 reinforcing bars, 18 specimens of prestressing strand, and 50 specimens of prestressing wire. In addition, tests of 10 beams with partial-length cover plates reported by other investigators are utilized in the study. The test data are described by mathematical equations which express the fatigue life as a function of the stress range and minimum stress. Numerical coefficients in the equations were evaluated by regression analyses.

● STUDIES of fatigue characteristics of structural metals were carried out at the AASHO Road Test, Ottawa, Ill., in connection with research on one-lane, simple-span bridges (1). One of the principal objectives of the bridge research was to study the behavior of the bridges under repeated applications of overstress. To correlate the observed behavior with simpler experimental laboratory studies, three fatigue experiments were carried out on samples of steel used in the beams of the reinforced and prestressed concrete bridges. Studies also were made of the fatigue strength of steel beams with partial-length cover plates utilizing data from experiments on materials similar to those used at the Road Test.

Fatigue tests of reinforcing bars were made on 20 specimens cut from No. 11 bars used as tension reinforcement in the reinforced concrete bridges. The bars were cast into short concrete beams and the beams were tested in bending at the Research and Development Laboratories, Portland Cement Association.

Fatigue tests of prestressing strand were made on 18 specimens of 7-wire strands of 3/8-in. diameter cut from excess lengths after stressing of beams for two prestressed concrete bridges. Tension specimens were prepared and tested at the Fritz Engineering Laboratory, Lehigh University.

Fatigue tests of prestressing wire were made on 50 specimens of 0.192-in. diameter wire cut from excess lengths of cables after tensioning of beams for two prestressed concrete bridges. Tension specimens were also prepared and tested at the Fritz Engineering Laboratory.

The study of the fatigue strength of steel beams with partial-length cover plates utilized the results of tests reported by Hall and Stallmeyer (2, 3). Bending tests were made on ten small built-up beams with partial-length cover plates having the same details as those used in seven steel bridges.

This report is a general discussion of the experiments and a presentation of the results of the analyses of the test data. The test data may be obtained in tabular form as data system 2145 from the Highway Research Board at the cost of reproduction. The details of the tests of beams with partial-length cover plates can be found elsewhere (2, 3).

EXPERIMENTAL STUDY OF REINFORCING BARS

The fatigue characteristics of intermediate-grade reinforcing bars were evaluated by tests on 20 No. 11 bars. (Altogether, 21 bars were tested. One failed in the weld and was omitted from this report.) Each bar was embedded near the top of a 12 by 14 by 80-in. concrete beam and the beam was tested in bending as shown in Figure 1.

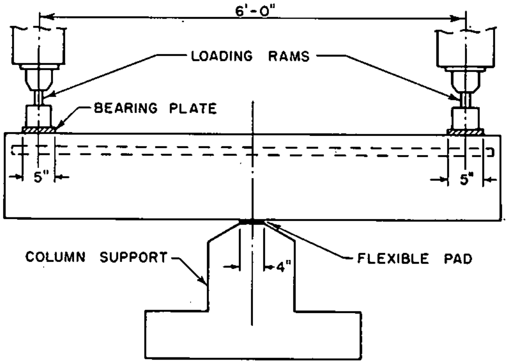

Figure 1. Arrangement for testing reinforcing bars.

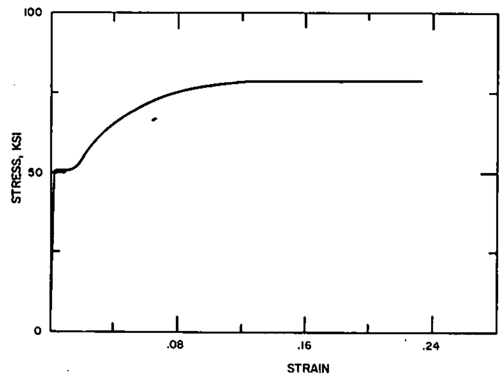

Figure 2. Typical stress-strain curve for reinforcing bars.

The bars were rolled from one heat and had diamond-shaped deformations conforming to ASTM designation A 305-56T. Fifteen additional coupons were tested in static tension. A typical stress-strain diagram of the bars in shown in Figure 2. The control tests (Table 1) indicated that all bars had essentially the same mechanical properties. The mean modulus of elasticity was 28.8×10^3 ksi and the mean cross-sectional area was 1.524 sq in. The chemical composition is given in Table 2.

TABLE 1

MECHANICAL PROPERTIES OF STEEL

Material	Yield Point or Yield Strength[a]			Ultimate Strength		
	No. Tests	Mean (ksi)	Std. Dev. (ksi)	No. Tests	Mean (ksi)	Std. Dev. (ksi)
No. 11 bars	15	49.5	0.77	15	81.0	1.72
3/8-in. strand	33	234.3	8.52	33	270.4	7.53
0.192-in. wire	90	227.2	1.93	90	257.5	2.29
3/16-in. plate	-	44.6	-	-	64.7	-
1/2-in. plate	-	36.1	-	-	61.0	-
3/4-in. plate	-	35.6	-	-	59.5	-

[a]The yield strength at 1% strain is applicable to the 3/8-in. strand and 0.192-in. diameter wire.

The details of the test beams are shown in Figure 3. The actual test coupon, obtained from the material used in the bridges, was 2 ft long; extensions were butt-welded to both ends making the overall bar length 78 in. Two No. 4 splice bars were placed adjacent to the welds to prevent failure at those points.

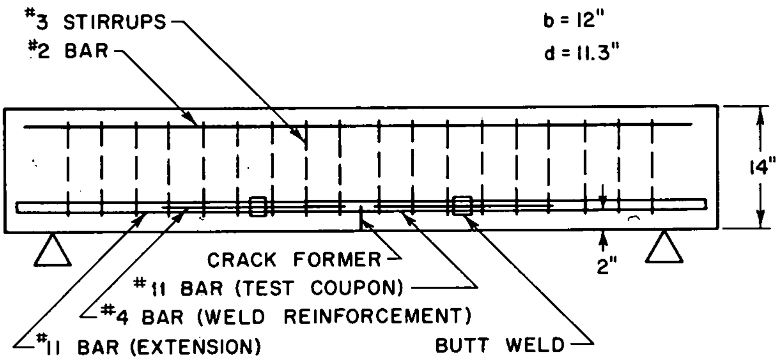

Figure 3. Details of beams for testing of reinforcing bars.

(The splice bars were not included in the first three specimens tested. One of the three specimens (Test No. 2) failed in the weld. No weld failures occurred in specimens with splice bars.) Stirrups were provided to prevent shear failure and longitudinal splitting. A metal strip was inserted in the beam at midspan to initiate a crack in the tension zone at the section of maximum moment.

TABLE 2

CHEMICAL COMPOSITION OF STEEL

Material	Chemical Content (%)				
	C	Mn	P	S	Si
No. 11 bars	0.37	0.60	0.023	0.03	0.07
3/8-in. strand	0.725	0.745	0.016	0.037	0.235
0.192-in. wire	0.800	0.670	0.016	0.040	0.250
3/16-in. plate	0.21	0.50	0.011	0.026	-
1-in. plate	0.25	0.46	0.010	0.024	-

The test beams were cast in groups of three. Four batches of concrete were distributed evenly through the three specimens. Nine cylinders were taken from the fourth batch representing concrete in the compression zone. Three cylinders were tested at the conclusion of the fatigue test of each beam. The mean compressive strength of all cylinders was 5,250 psi, with individual strengths varying between 4,200 to 5,890 psi.

The tests were made with an Amsler hydraulic pulsator, which induced sinusoidal stress cycles at the rate of 500 cycles per minute. The test beams were balanced on a center support and vertical downward loads were applied at each end (Fig. 1).

The tension caused in the bar by the load was computed on the basis of the cracked-section straight-line theory, assuming f'_c = 5,000 psi and E_c = 4,100,000 psi. In earlier studies, these procedures were found to result in close agreement between measured and computed stresses in similar specimens.

The hydraulically applied loads were read directly from an oil pressure gage calibrated to the ram area. In early stages of each test, periodic adjustments of the oil pressure had to be made to compensate for decreasing stiffness of the test beam and increasing temperature of the hydraulic fluid. The maximum variation observed was less than 1 percent and occurred only within the first 100,000 cycles. The repeated loads were applied continuously between the specified levels until failure occurred or 3,000,000 cycles of stress was exceeded.

The experiment included two controlled variables — the maximum stress level and the minimum stress level. An outline of these two variables and of specimens is given in Table 3.

TABLE 3

OUTLINE OF REINFORCING BAR EXPERIMENT

Specimen Designation for Test Block			Minimum Stress (ksi)	Maximum Stress (ksi)
1	2	3		
3111	3112	3113	5.0	34.0
3121	3122	3123	5.0	39.0
3131	3132	3133	5.0	44.0
3221	3222	3223	15.0	39.0
3231	3232	3233	15.0	44.0
3241	3242	3243	15.0	49.0

Four maximum stress levels and two minimum stress levels were selected on the basis of the stresses observed in the test bridges and of the expected endurance limit. Each minimum stress level was combined with three maximum stress levels in such a manner that two 2 by 2 factorial experiments were included: one to obtain data on the effect of the maximum and minimum stress (specimens 312, 313, 322 and 323) and the other to obtain data on the effect of stress range (specimens 311, 312, 323 and 324).

Stress levels were assigned to the test beams at random. One specimen from each maximum-minimum stress combination was assigned to a test block. There were three such test blocks, as indicated in Table 3.

Within each test block a random order of testing was followed to prevent variations caused by controlled variables from being confused with systematic variations due to uncontrolled variables.

The applied stresses and the numbers of cycles to the end of tests are given in Table 4 for each specimen, listed in order of testing. All bars tested to failure were ruptured completely; without exception the rupture occurred at the intersection of two diagonal ribs with a longitudinal rib. Figure 4 shows the rupture surfaces of two bars tested at different stress levels. All failures occurred within 2 in. of the beam center adjacent to a crack in the concrete.

EXPERIMENTAL STUDY OF PRESTRESSING STRAND

The fatigue characteristics of prestressing strand were evaluated by tension tests on 18 specimens of seven-wire, 3/8-in. diameter strand. The specimens were approximately 72 in. long and were tested in axial tension as shown in Figure 5.

The prestressing strand, made of seven cold-drawn bright wires, was stress relieved. The 18 specimens used in this study were selected from 24 pieces of strand, 6 to 15 ft long, taken from two spools used in construction of test bridges. Static tension

TABLE 4

TEST RESULTS OF REINFORCING BARS

Order of Testing	Specimen Designation	Stress (ksi)		No. of Cycles
		Min.	Max.	
1	3221	15.0	39.0	3,702,400[a]*
3	3121	5.0	39.0	515,300
4	3250	15.0	40.0	3,496,500[a]
5	3260	15.0	41.0	2,214,500
6	3241	15.0	49.0	441,000
7	3131	5.0	44.0	288,100
8	3111	5.0	34.0	864,500
9	3231	15.0	44.0	1,232,300
10	3242	15.0	49.0	406,600
11	3132	5.0	44.0	216,400
12	3112	5.0	34.0	626,000
13	3222	15.0	39.0	3,187,500[a]
14	3232	15.0	44.0	746,000
15	3122	5.0	39.0	356,800
16	3113	5.0	34.0	920,200
17	3233	15.0	44.0	971,900
18	3223	15.0	39.0	8,164,000[a]
19	3123	5.0	39.0	506,100
20	3133	5.0	44.0	315,600
21	3243	15.0	49.0	645,300

*[a]Specimen did not fail; all other specimens failed by fracture of the No. 11 bar.

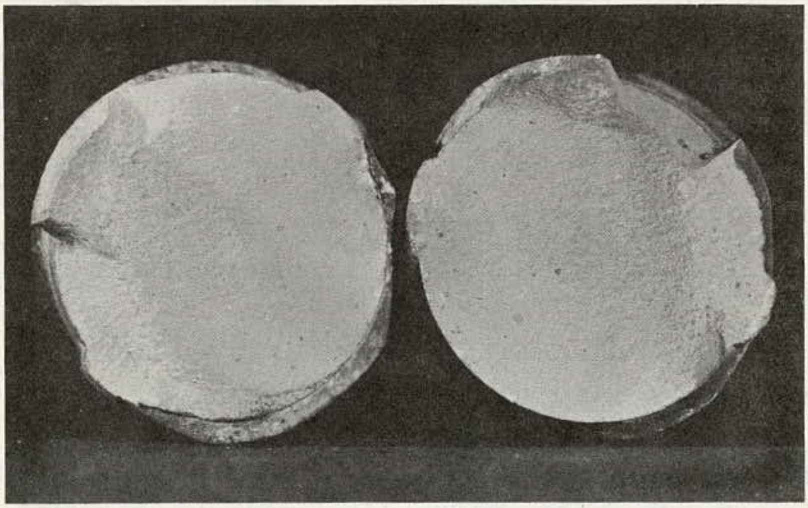

Figure 4. Fracture surface of reinforcing bar (specimen 3112).

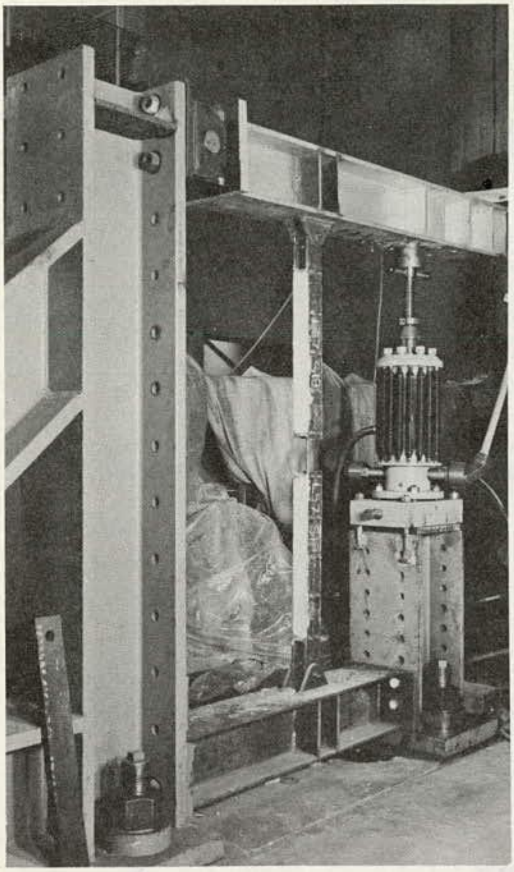

Figure 5. Strand fatigue test equipment.

tests on 33 coupons indicated that the two spools had only slightly different mechanical properties. A typical stress-strain diagram is shown in Figure 6; the mean yield and ultimate strengths are given in Table 1. The mean modulus of elasticity of the strand was 27.6×10^3 ksi and the mean cross-sectional area was 0.08065 sq in. Both spools had essentially the same chemical composition as given in Table 2.

The tests were performed in a steel frame (Fig. 5). The strand was connected to the frame through special end grips, shown schematically in Figure 7. Prior to placement in the testing frame, the strand was pretensioned to approximately 188 ksi and the end grips were attached to it with cement grout. After the grout had hardened, a spacer block was placed between the grips, the strand was released from the stressing bed and the specimen was transferred to the testing frame. A static load was then applied to the specimen, the spacer block removed and the load decreased to the minimum level for the fatigue tests.

The load was applied to the testing frame with a hydraulic jack (Fig. 5) operated from an Amsler pulsator. In the fatigue test the load fluctuated between the minimum and maximum levels at 500 cycles per minute. The test was discontinued when the strand failed or after 2,000,000 cycles of load were exceeded.

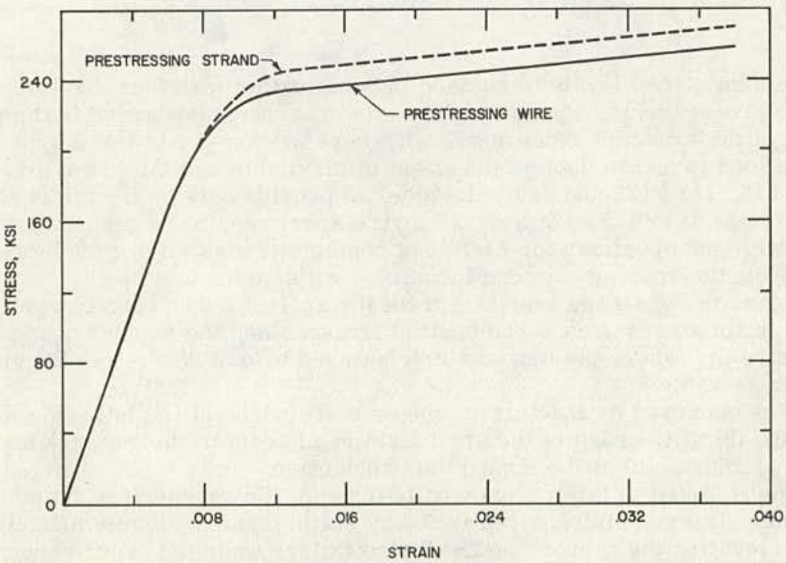

Figure 6. Typical stress-strain curve for prestressing steel.

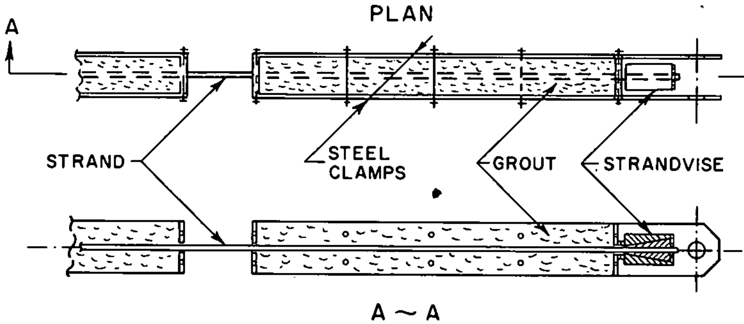

Figure 7. Gripping device for strand.

The experiment included two controlled variables — the maximum and minimum stress levels. The detailed outline of the strand experiment is given in Table 5.

TABLE 5

OUTLINE OF PRESTRESSING STRAND EXPERIMENT

Specimen Designation for Test Block			Minimum Stress (ksi)	Maximum Stress (ksi)
1	2	3		
1111	1112	1113	135.2	183.9
1121	1122	1123	135.2	197.4
1131	1132	1133	135.2	210.9
1221	1222	1223	162.5	197.4
1231	1232	1233	162.5	210.9
1241	1242	1243	162.5	224.4

Two minimum stress levels were used in combination with four maximum stress levels. The stress levels, chosen on the basis of stresses observed in the test bridges and of the expected endurance limit, were arranged into two 2 by 2 factorial experiments; one to obtain data on the effect of maximum and minimum stress levels (specimens 112, 113, 122 and 123), the other to provide data on the effect of stress range (specimens 111, 112, 123 and 124). The specimens were grouped into three test blocks with one specimen for each load combination tested in each block. The order of testing the specimens was randomized within each test block.

The stresses in the strand resulting from the applied loads were computed on the basis of the mean strand area. The applied stresses and the number of cycles to failure of one wire or, where the test was discontinued before failure, to the end of testing are given in Table 6.

All failures occurred by fracture of one or more wires at the following locations: (a) in the gap, (b) at the edge of the steel clamps adjacent to the gap, (c) inside the grout of the grip, and (d) at the strand vise anchorage.

In specimens tested to failure, generally three of the seven wires failed by fracture due to fatigue. The remaining wires failed by static tension. Some difficulty was encountered in locating the area of the first wire failure when the failure occurred inside the grout. Typical fractured surfaces are shown in Figure 8.

TABLE 6

TEST RESULTS OF PRESTRESSING STRAND

Order of Testing	Specimen Designation	Stress (ksi)		No. of Cycles	Location of Failure
		Min.	Max.		
1	1221	162.5	197.3	1,351,400	In grout
2	1131	135.2	210.9	68,100	In gap
3	1111	135.2	183.6	1,236,000	In grout
4	1241	162.5	224.6	213,400	Edge of clamp
5	1121	135.2	197.3	560,700	At strand vise
6	1231	162.5	210.9	512,800	In grout
7	1112	135.2	183.6	909,200	In grout
8	1222	162.5	197.3	2,190,000	Did not fail
9	1232	162.5	210.9	422,000	Edge of clamp
10	1132	135.2	210.9	48,700	Edge of clamp
11	1122	135.2	197.3	152,700	In gap
12	1242	162.5	224.6	90,600	At strand vise
13	1113	135.2	183.6	579,000	In grout
14	1123	135.2	197.3	174,000	In grout
15	1243	162.5	224.6	159,000	In grout
16	1223	162.5	197.3	2,489,300	Did not fail
17	1233	162.5	210.9	199,100	In grout and gap
18	1133	135.2	210.9	38,200	In gap and edge of clamp

EXPERIMENTAL STUDY OF PRESTRESSING WIRE

The fatigue characteristics of the prestressing wire were evaluated by tension tests of 50 short specimens of 0.192-in. diameter wire. The specimens were 12 in. long and were tested in axial tension as shown in Figure 9. (Altogether, 82 specimens were tested. Thirty-one failed where the specimen entered the grips. One other failed with the fracture following a crack existing in the specimen before testing. As these tests were repeated until failure occurred outside the grips, results for 32 specimens are not reported here.)

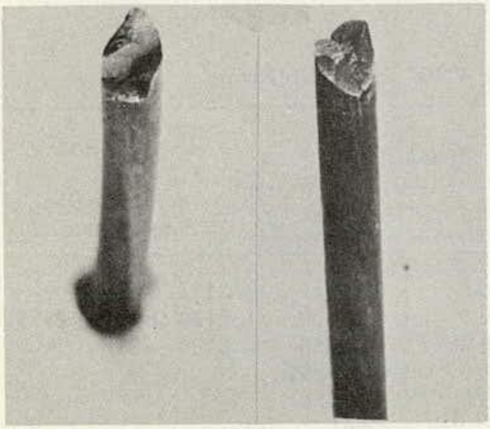

Figure 8. Typical fatigue failure of strand wire (specimen 1233).

The prestressing wire was cold-drawn and stress-relieved with bright, smooth surface. All specimens were taken from one shipment of wire. Static tensile tests on 90 coupons indicated that the material had uniform mechanical properties. Means of the yield and ultimate strengths are given in Table 1. The mean modulus of elasticity of the wire was 28.6×10^3 ksi and the mean cross-sectional area was 0.0293 in. The chemical composition of the wire was determined by analyses of three samples. The mean composition is given in Table 2.

The tests were performed in an Amsler high-frequency vibrophore shown in Figure 9. The wire was connected to the vibrophore through wedge jaws. To prevent failure in the grips, the surface of the wire in contact with the grips was treated by cold rolling. The rolled surface extended a small distance beyond the grips. (The set of grips and the procedure for preparation of specimens was changed during the conduct of the tests in the second test block.)

At the beginning of a test, a static load equal to the mean of the desired minimum and maximum loads was applied to the wire. The dynamic load was then superimposed at the frequency of 5,000 cycles per minute. The test was continued until failure of the wire or until 2,000,000 cycles were exceeded.

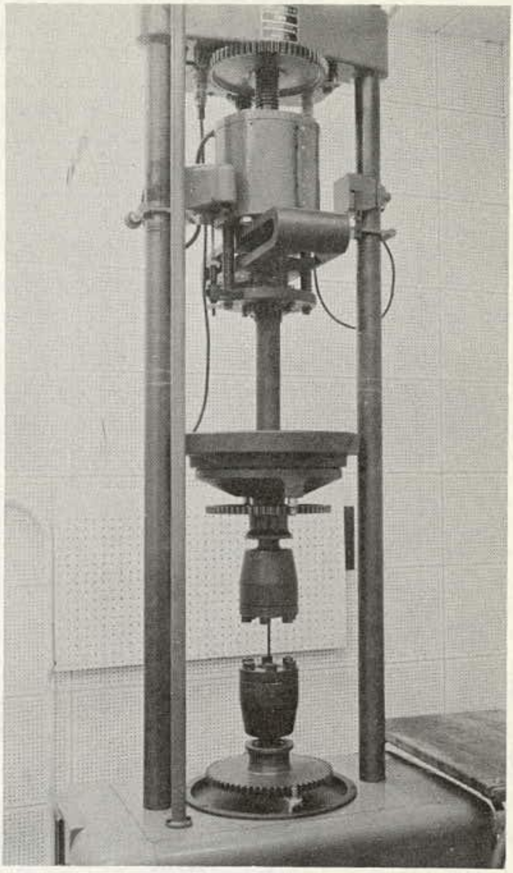

Figure 9. Wire fatigue test equipment.

The wire experiment included two controlled variables — the maximum and minimum stress levels. The outline of the wire experiment is given in Table 7.

Two minimum stress levels were used in combination with five maximum stress levels. The stress levels, chosen on the basis of the stresses observed in the test bridges and of the expected endurance limit, were arranged into a 2 by 4 factorial experiment to obtain data on the effect of the maximum and minimum stress levels (specimens 212, 213, 214, 215, 222, 223, 224 and 225), and into a 2 by 3 factorial experiment to obtain information on the effect of the stress range (specimens 211, 212, 213, 223, 224 and 225). The original experiment was arranged in an order that permitted the tests to be conducted in three test blocks, with each block containing a complete combination of minimum and maximum stress levels.

TABLE 7

OUTLINE OF PRESTRESSING WIRE EXPERIMENT

Designation of Original Specimens Test Block			Stress (ksi)		Designation of Additional Specimens
1	2	3	Min.	Max.	
2111	2112	2113	128.8	175.1	2114, 2115
2121	2122	2123	128.8	188.0	2124 through 21212
2131	2132	2133	128.8	200.9	2134, 2315
2141	2142	2143	128.8	213.7	
2151	2152	2153	128.8	226.6	
2221	2222	2223	154.5	188.0	
2231	2232	2233	154.5	200.9	2234
2241	2242	2243	154.5	213.7	2244, 2245
2251	2252	2253	154.5	226.6	

TABLE 8

TEST RESULTS OF PRESTRESSING WIRE

Order of Testing	Specimen Designation	Stress (ksi)		No. of Cycles	Location of Failure
		Min.	Max.		
1	2221	154.5	188.0	7,539,000	Did not fail
2	2241	154.5	213.7	949,000	At center
3	2111	128.8	175.1	1,603,000	At center
6	2121	128.8	188.0	980,000	At center
7	2131-B	128.8	200.9	4,968,000	Did not fail
8	2231-B	154.5	200.9	3,358,000	Did not fail
10	2121-C	128.8	188.0	7,348,000	Did not fail
14	2251-C	154.5	226.6	285,000	In rolled surface
15	2141-B	128.8	213.7	324,000	In rolled surface
17	2141-C	128.8	213.7	378,000	In rolled surface
20	2251-G	154.5	226.6	360,000	At center
21	2141-D	128.8	213.7	207,000	At center
23	2151-B	128.8	226.6	140,000	At center
24	2232	154.5	200.9	2,505,000	Did not fail
29	2222	154.5	188.0	2,771,000	Did not fail
32	2112	128.8	175.1	5,617,000	Did not fail
33	2122	128.8	188.0	2,080,000	Did not fail
39	2252-L	154.5	226.6	502,000	At center
42	2152	128.8	226.6	146,000	In rolled surface
44	2142-B	128.8	213.7	241,000	At center
45	2132	128.8	200.9	578,000	In rolled surface
46	2132-B	128.8	200.9	1,034,000	At center
47	2242	154.5	213.7	5,310,000	Did not fail
48	2233	154.4	200.9	5,300,000	Did not fail
49	2123	128.8	188.0	3,098,000	Did not fail
51	2143-B	128.8	213.7	253,000	In rolled surface
52	2143-C	128.8	213.7	440,000	At center
54	2253-B	154.5	226.6	521,000	In rolled surface
57	2113	128.8	175.1	3,429,000	Did not fail
58	2223	154.5	188.0	5,646,000	Did not fail
59	2133	128.8	200.9	626,000	In rolled surface
60	2133-B	128.8	200.9	681,000	At center
61	2243	154.5	213.7	1,515,000	At center
63	2153-B	128.8	226.6	104,000	At center
64	2114	128.8	175.1	3,300,000	Did not fail
65	2244	154.5	213.7	778,000	At center
67	2124-B	128.8	188.0	444,000	At center
68	2234	154.5	200.9	6,800,000	Did not fail
69	2134	128.8	200.9	206,000	At center
70	2125	128.8	188.0	4,781,000	Did not fail
73	2245-C	154.5	213.7	404,000	At center
74	2135	128.8	200.9	272,000	At center
75	2115	128.8	175.1	3,029,000	Did not fail
76	2126	128.8	188.0	4,670,000	Did not fail
77	2127	128.8	188.0	3,522,000	Did not fail
78	2128	128.8	188.0	292,000	At center
79	2129	128.8	188.0	106,000	At center
80	21210	128.8	188.0	3,566,000	Did not fail
81	21211	128.8	188.0	370,000	At center
82	21212	128.8	188.0	250,000	At center

The original experiment design specified testing of three specimens at each maximum-minimum stress combination. However, because of the trends of test results, it was considered necessary to test additional specimens to establish median values for several maximum-minimum stress combinations. The additional specimens are also listed in Table 7.

The stresses in the wire specimens were computed on the basis of the mean area and the applied loads. The applied stresses, number of cycles to the end of test, and the location of failure, are given in Table 8, which lists the specimens in the order of testing.

Specimens failed by fracture in the center untreated portion between the grips or in the rolled surface near the grips. (When failure occurred in the grips the test was repeated within the same test block until failure occurred outside the grips. The additional specimens were identified by letters; e.g. 2131-B. A few tests with failure in the rolled surface were also repeated.) A typical wire failure is shown in Figure 10.

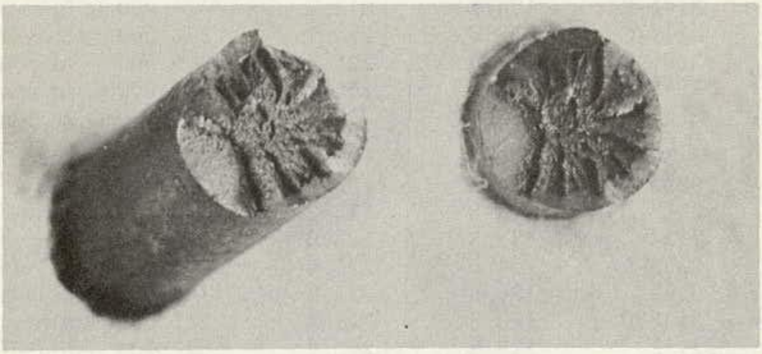

Figure 10. Typical fatigue failure of wire (specimen 2134).

Temperature measured on two specimens during the test indicated that the high frequency of loading had little, if any, effect on the temperature of the specimen.

STUDY OF BEAMS WITH PARTIAL-LENGTH COVER PLATES

The fatigue characteristics of steel beams with partial-length cover plates with no welds across the end were evaluated by studies of the results of flexural fatigue tests of ten small welded beams. Details of the experiments are given elsewhere (2, 3).

The beams were fabricated from A-373-54T plate steel. The mechanical properties, obtained by tests of coupons, are given in Table 1. The chemical compositions, given by mill reports, are given in Table 2. The beams of the Test Road bridges were rolled from steel of similar composition.

Six I-beam specimens were built up of two 3/4-in. thick flanges welded to a 3/16-in. web; 1/2-in. thick cover plates were attached to both the tension and the compression flanges. Four I-beam specimens were built up of two 3/8-in. thick flanges welded to a 1/4-in. web and a 1/4-in. thick cover plate attached to the tension flange. All welding was done manually with electrodes conforming to AWS Specification E-7016. The welds were continuous along the longtitudinal edges. The ends of the cover plates were cut off at right angle and there were no welds along the ends. All beams were 12 in. deep and 11 ft long.

The specimens were tested in flexure on a span of 8 ft 6 in. in a Wilson fatigue testing machine. The load was applied at a rate of 180 cycles per minute.

The experiment included two principal variables — the minimum and maximum stress levels. The stress level combinations were approximately as follows:

3 specimens, 0.4 to 13.6 ksi
3 specimens, 0.4 to 24.9 ksi
2 specimens, 15.5 to 27.9 ksi
2 specimens, 15.4 to 36.4 ksi

The results of the fatigue tests are given elsewhere (2, 3) and are reproduced in Figure 14. (Figure 14 includes specimens CPDF-1, CPDG-1, CPCD-1, CPDF-2, CPAD-1 and CPCD-2 from Ref. 2; and specimens 1, 2, 3 and 4 from Ref. 3. Two symbols pertain to each specimen: a dot representing the number of cycles to failure and a triangle representing the number of cycles to last inspection prior to failure.) The number of cycles at which the crack became visible is not known; however, at the last inspection prior to failure three beams had small cracks 1/4 to 1 1/2 in. long.

Failure was defined as the number of cycles at which the deflection of the fractured beam exceeded the static deflection by 0.05 in. When this deflection occurred the beam activated a microswitch that shut off the testing machine. All failures were similar in nature. The cracks started at the tip of one of the longitudinal welds and propagated transversely and vertically through the flange cross-section. Generally, at the time of failure about one-quarter of the cross-sectional area of the tension flange was fractured.

ANALYSIS OF DATA

The objective of this study was to develop a reliable basis for estimating the fatigue life of the test bridges at the AASHO Road Test. To this end, statistical correlations were made of the stress levels with the number of cycles to failure observed in the tests described in the preceding sections.

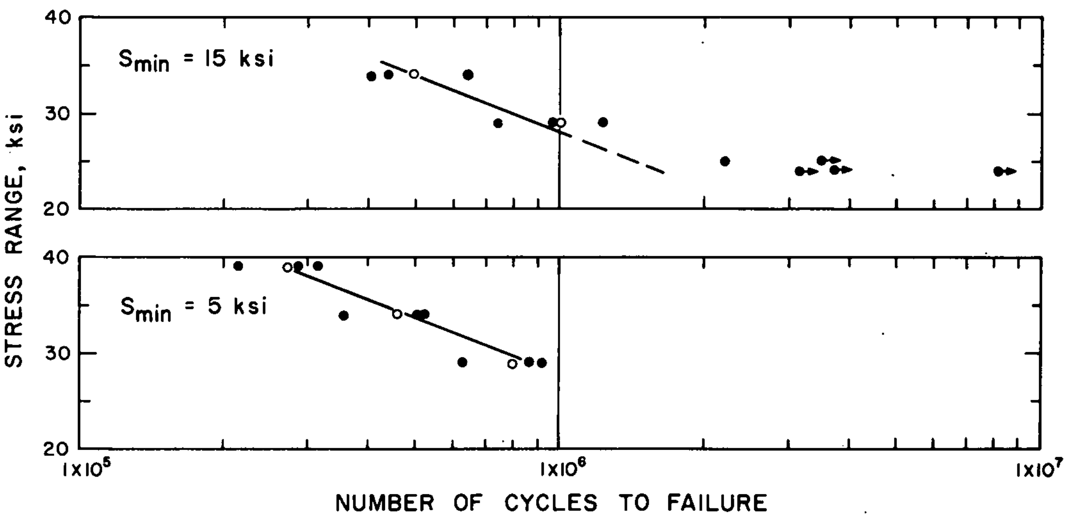

Figure 11. Test results for reinforcing bars.

The experimental data from Tables 4, 6 and 8 are plotted in Figures 11, 12 and 13, in which the stress range is given as a function of the logarithm of the number of cycles to failure. The experimental of Hall and Stallmeyer (2, 3) are plotted in Figure 14. A separate plot is included for each minimum stress level. The test data are shown dots; an arrow attached to a dot indicates that the test was discontinued before failure. Where all specimens tested at the same maximum-minimum stress combination failed, the mean log N is shown as a circle. Where more than 50 percent of the specimens tested at the same maximum-minimum stress combination failed, the median log N is shown as a circle.

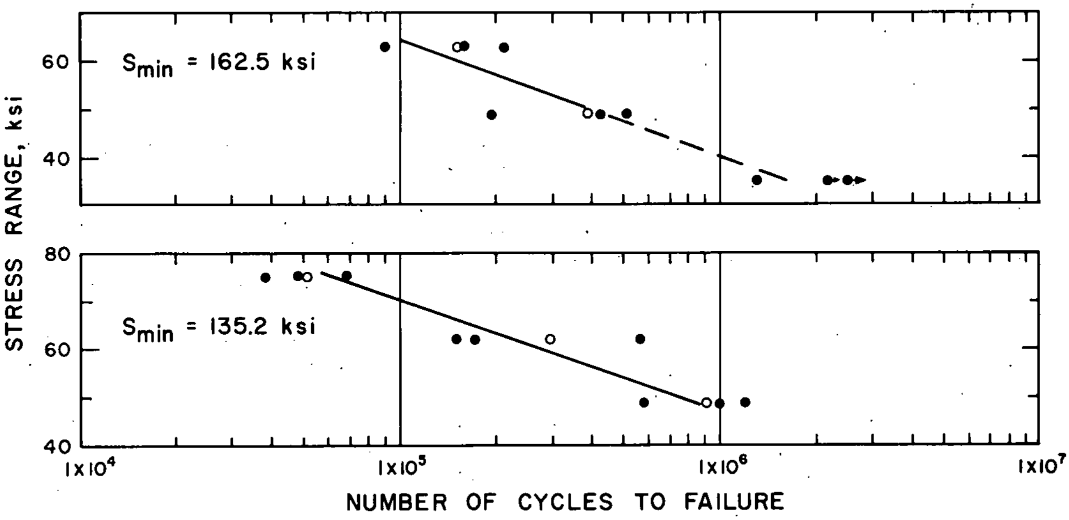

Figure 12. Test results for prestressing strand.

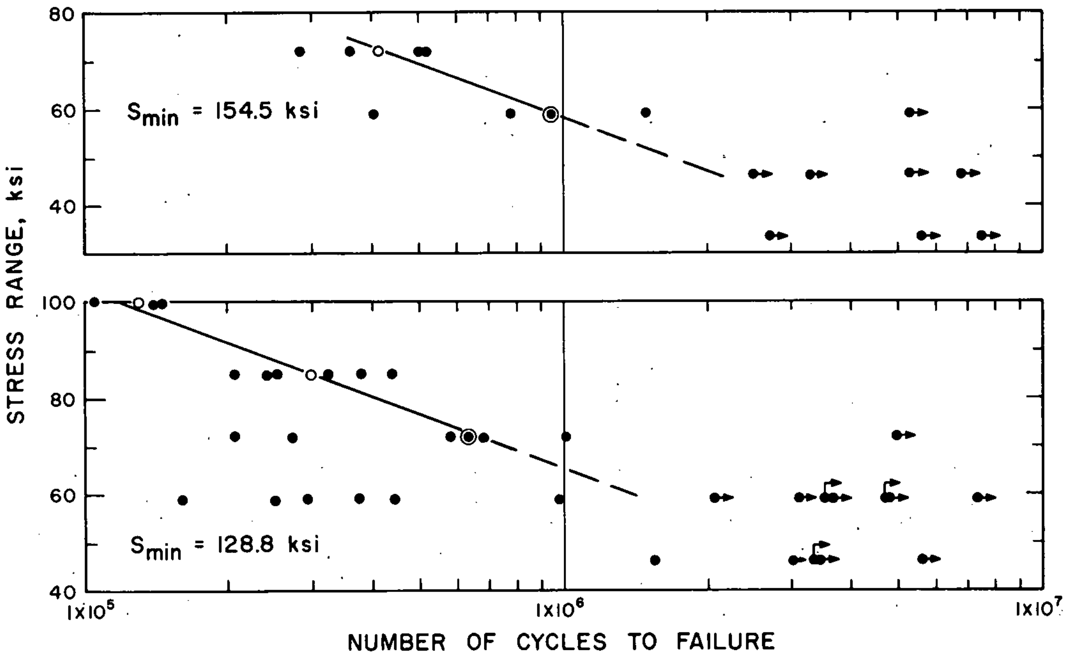

Figure 13. Test results for prestressing wire.

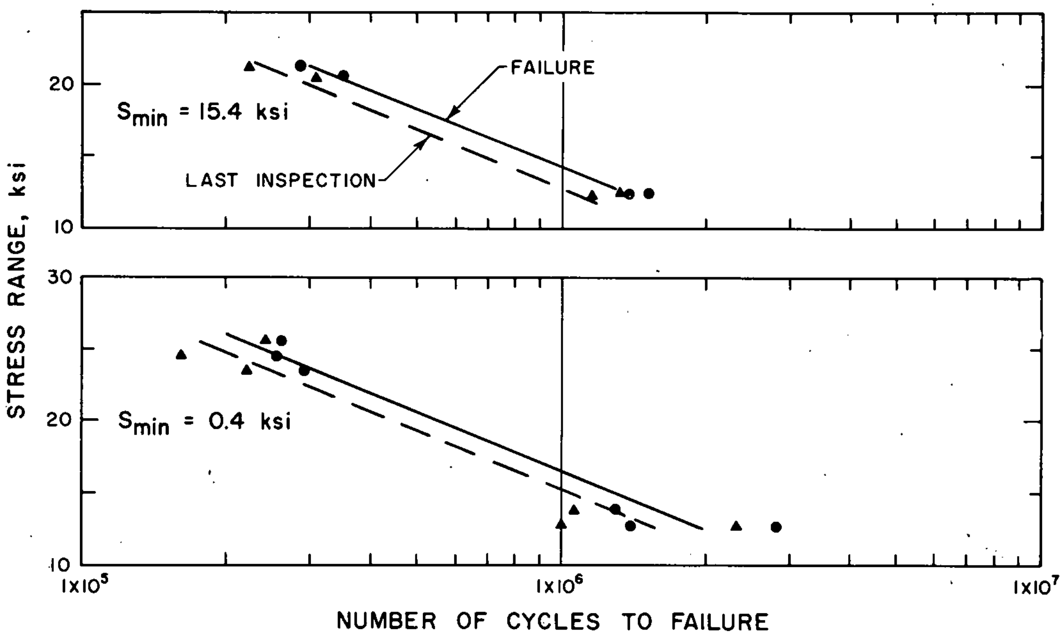

Figure 14. Test results for beams with partial-length cover plates and no end welds.

Examination of the means and medians in Figures 11, 12 and 13 shows that they follow essentially a straight line. Therefore, the following mathematical model was selected to represent the test data:

$$\log N = A + BS_r + CS_{min} \tag{1}$$

in which

S_r = range of stress, $S_{max} - S_{min}$;

S_{min} = minimum stress;

S_{max} = maximum stress;

N = number of cycles to failure; and

A, B, C = empirical constants.

Coefficients A, B and C of Eq. 1 were evaluated by a separate regression analysis for each material. For the reinforcing bars, prestressing strand, and prestressing wire the analyses were based on means or medians shown in Figures 11, 12 and 13 as circles. The following equations were obtained for the fatigue life:

Reinforcing bars:

$$\log N = 7.432 - 0.0515\, S_r \tag{2}$$

Prestressing strand:

$$\log N = 9.354 - 0.0423\, S_r - 0.0102\, S_{min} \tag{3}$$

Prestressing wire:

$$\log N = 8.722 - 0.0272\, S_r - 0.0074\, S_{min} \tag{4}$$

Two analyses were made for the beams with partial-length cover plates — one for the number of cycles to failure and the other for the number of cycles to the last inspection before failure. The individual data were the basis for the analyses because of the absence of replication of maximum stress levels (Fig. 14). The following equations were obtained:

Failure:

$$\log N = 7.216 - 0.0729\, S_r - 0.0129\, S_{min} \quad (5)$$

Last inspection:

$$\log N = 7.136 - 0.0724\, S_r - 0.0102\, S_{min} \quad (6)$$

The coefficients of correlation and the standard errors of estimate for Eqs. 2 through 6 are given in Table 9. The goodness of fit may be judged also from Figures 11, 12, 13 and 14, where the relevant equations are shown as straight lines.

The factorial nature of the experiments with reinforcing bars, prestressing strands and prestressing wires made possible independent determinations of the relative significance of the effect of stress range and minimum stress level upon the fatigue life. Analyses of variance indicated that stress range alone accounted for most of the variation in the reinforcing bar experiment (the effect of S_{min} was not significant at the 10 percent level), whereas the minimum stress level accounted for a small, barely significant portion of the variation in the experiments with prestressing strands and wires (the effect of S_{min} was significant at the 10 percent level but not at the 5 percent level).

Eq. 1 applies only to the finite life portion of the S-N diagram. In tests reported herein, testing was discontinued when the material sustained between 2 and 8 million cycles of loading. The endurance limit was then presumed to be reached. The limited data available indicated the limits of endurance shown in the last column of Table 9. It is noteworthy that the endurance limit for wire was found to be a function of the minimum stress level. The endurance limit was encountered at both minimum stress levels only in tests of wire.

No endurance limit was found in the tests of beams with partial-length cover plates.

TABLE 9

ANALYSIS OF FATIGUE TEST DATA

Material	Eq.	Coeff. of Correl.	Standard Error of Estimate	Endurance Limit (ksi)
Bars	1	0.85	0.091	24
Strands	3	0.82	0.209	35
Wires	4	0.74	0.230	-[1]
Beams	5	0.96	0.094	-
Beams	6	0.94	0.128	-

[1] 24 ksi - 0.5 S_{min}.

SUMMARY

1. Tests of 20 reinforcing bars cast in concrete beams, and of 18 prestressing strands and 50 prestressing wires, were made to determine the fatigue characteristics of these materials. Also studied were the results of tests of 10 beams with partial-length cover plates having no end welds. The results of the fatigue tests of each of the four materials were correlated by regression analyses utilizing one basic mathematical model.

2. A mathematical model expressing the logarithm of the fatigue life as a linear function of stress range and minimum stress level was found to fit the test data. An analysis of variance indicated clearly that the stress range was by far the most important independent variable.

3. Within the limits of the experiments, the results of the fatigue tests of reinforcing bars, prestressing strand, prestressing wire and beams with partial-length cover plates are represented by Eqs. 2 through 6, correlating the number of cycles to failure or inspection prior to failure with the minimum stress level and the stress range. However, the equations are applicable only to the finite life portion of the S-N diagram.

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Tests of prestressing strand and wire were conducted at Fritz Engineering Laboratory, Lehigh University. The tests were carried out and reported by F. S. Ople and C. P. Pitts under the direction of C. L. Hulsbos.

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