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FLEXURAL FATIGUE STRENGTH OF STEEL BEAMS

BY

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BULLETIN SERIES No. 377

FLEXURAL FATIGUE STRENGTH OF STEEL BEAMS

A REPORT OF AN INVESTIGATION

CONDUCTED BY

THE ENGINEERING EXPERIMENT STATION
UNIVERSITY OF ILLINOIS

IN COOPERATION WITH

THE PUBLIC ROADS ADMINISTRATION, FEDERAL WORKS AGENCY
THE CHICAGO BRIDGE AND IRON COMPANY
ASSOCIATION OF AMERICAN RAILROADS

AND

THE BUREAU OF SHIPS, NAVY DEPARTMENT

BY

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under the supervision of the

COMMITTEE ON FATIGUE TESTING (STRUCTURAL)

of the

WELDING RESEARCH COUNCIL, THE ENGINEERING FOUNDATION

sponsored by the

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FLEXURAL FATIGUE STRENGTH OF STEEL BEAMS

I. Introduction

1. *Object and Scope of Investigation.*—The stringers of through bridges and the beams of short beam-spans are subjected to a large number of stress cycles, and the dead load stress is very small. Moreover, stringers and beams often have plates for laterals riveted or welded to the bottom flange, and many short beam-spans have partial-length cover plates. These introduce stress-raisers in the flanges. Furthermore, stringers and, to a less extent, short beam-spans are subjected to several stress cycles during the passage of a single train or fleet of trucks. That is, stringers and short beam-spans have, to a considerable degree, all three conditions that enhance the possibility of fatigue failure — a large ratio of maximum to minimum stress, a large number of stress cycles during the life of the structure, and severe geometrical stress-raisers in the tension flange. For these reasons the fatigue strength of the flanges of stringers and short girders is of particular interest to bridge engineers.

The dead load stress is greater for long girders than for short girders and stringers. Moreover, in general, the longer the span the fewer the cycles of near-maximum stress resulting from a given density of traffic. As a result long girder spans are not so liable to failure by fatigue as stringers. However, the possibility of a girder's failing by fatigue should not be overlooked, particularly if the flanges of the girder contain severe stress-raisers.

The principal purpose of the investigation described in this bulletin was to determine the relative fatigue strengths of various kinds of flexural members, which are named below. The fatigue tests were supplemented by static tests of similar specimens.

Specimens tested include:

Rolled beams without reinforcement and without lateral plates.

Rolled beams without reinforcement and with lateral plates, some attached with rivets and others attached with welds.

Rolled beams reinforced with full-length cover plates, some attached with rivets and others attached with welds.

Rolled beams reinforced with partial-length cover plates attached with welds.

Fabricated beams made of web and flange plates attached with welds.

Beams with intermediate stiffeners, some welded to the web and both flanges, others welded to the compression flange and to the compression portion of the web, but not welded to the tension flange.

Some reinforcing cover plates were attached with continuous fillet welds; others were attached with intermittent fillet welds.

2. *Acknowledgments.*—The tests described in this bulletin were a part of the investigation resulting from a cooperative agreement entered into by the Engineering Experiment Station of the University of Illinois, of which DEAN M. L. ENGER is the Director, and the Public Roads Administration, of which THOMAS H. MACDONALD is the Commissioner. The tests were planned in cooperation with the Committee on Fatigue Testing (Structural), Welding Research Council of the Engineering Foundation, of which F. H. FRANKLAND is Chairman, and were financed by the Chicago Bridge and Iron Company; the Public Roads Administration, Federal Works Agency; the Bureau of Ships, Navy Department; and the Association of American Railroads. They were made in the Arthur Newell Talbot Laboratory by three Research Assistants in Civil Engineering—W. H. MUNSE, A. M. OZELSEL, and I. S. SNYDER— working successively under the direction of the author.

The tests were planned by a Sub-Committee (of which G. M. MAGEE was Chairman) on Flexural Fatigue Tests of the Committee on Fatigue Testing (Structural) named above.

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II. Results of Tests

3. *Description of Tests.*—The specimens included both rolled and fabricated beams. The dimensions of the specimens are given on the sketches at the head of Tables 3–17. The chemical composition and the mechanical properties of the steel from which the specimens were fabricated are given in Table 1. Specimens of series 44A, 44Ba, 44Bb, 44Ca, 44Cc and 44Cd, and specimens 3 and 4 of series 44Cb, were welded with 3⁄16-in. A.W.S. 6012 electrodes with normal polarity at 24 volts and 200 amperes. Specimens of series 44Ce, 44Ja, 44Jb and 44Jc, and specimens 1 and 2 of series 44Cb, were welded with 5⁄32-in. A.W.S. 6010 electrodes with normal polarity at 25 volts and 150 amperes.

The essential features of the machine used in making the fatigue tests are shown in Fig. 1. The load was derived from an adjustable-throw cam that raised and lowered the outer end of the overhead I-beam, thereby subjecting the flanges of the specimen to cycles of flexural stress. The load was measured with the open-loop dynamometer. The machines were cranked by hand while the cam was being adjusted to give the desired load. From time to time they were stopped and the load was adjusted as needed in order to keep it constant during the test. The stresses were computed from the load indicated by the dynamometer, using the flexural formula commonly used in structural design.

The loading and supporting rollers rested in cylindrical grooves in the loading and supporting blocks. The grooves were somewhat larger in diameter than the rollers, to prevent the rollers from introducing a horizontal restraint. All tests were made on a cycle in which

Table 1

Chemical Composition and Mechanical Properties of Steel in Flexural Fatigue Specimens (from Mill Tests)

Series No.	Section	Chemical Composition				Mechanical Properties		
		C	Mn	P	S	Yield Point p.s.i.	Ultimate Strength p.s.i.	Elongation in 8 in. per cent
All 12-in. I-Beams	12-in., 31.8-lb. I-Beams	0.25	0.64	0.015	0.030	43 350	70 530	26.25
44G	7″ x 5⁄8″ and 12″ x 7⁄16″ plates	0.24	0.49	0.011	0.027	39 070	63 080	25.75
44B	6″ x 3⁄8″ plates	0.22	0.48	0.016	0.030	40 800	68 870	25.00

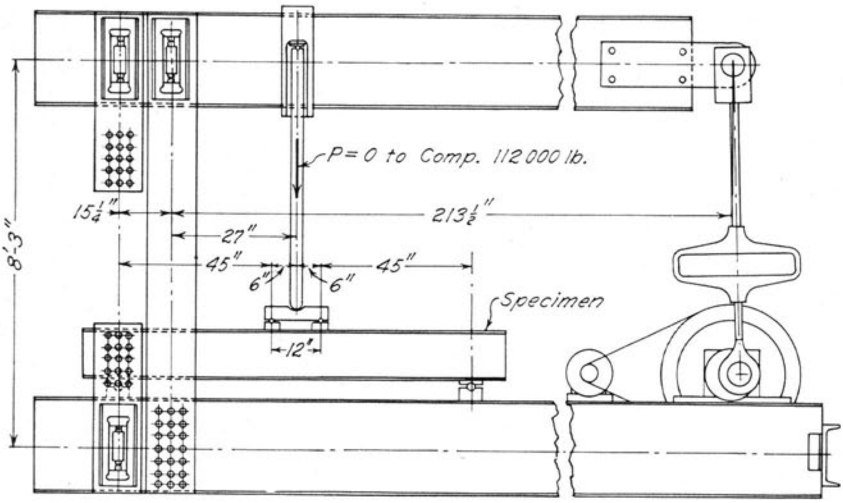


FIG. 1. 200,000-LB. FATIGUE MACHINE ADAPTED TO TEST FLEXURAL SPECIMENS

the stress in the bottom flange varied from a very small tension to a maximum tension. Some tests were designed to give the fatigue strength corresponding to failure at 100,000 cycles, designated as $F_{100,000}$; others to give the fatigue strength corresponding to failure at 2,000,000 cycles, designated as $F_{2,000,000}$. The machine was operated at a speed of approximately 150 rev. per min.

The values of $F_{100,000}$ and $F_{2,000,000}$ were computed from the results of the tests by means of the empirical equation* $F_n = S(N/n)^K$, in which S, numerically, is the maximum stress in the stress cycle, N the number of cycles for failure, K an experimental constant whose value depends upon the geometrical characteristics of the specimen and the mechanical properties of the metal, and F_n the fatigue strength corresponding to failure at n number of cycles. The value of K for each series was determined from the slope of the S–N diagram for the series in question, and had different values for different types of specimens. The error in F_n resulting from the use of an inaccurate value of K depends upon the amount by which the ratio N/n differs from unity. The following arbitrary rule was followed in deciding whether the results of a particular test were to be used to determine $F_{100,000}$ or $F_{2,000,000}$. Values of $F_{100,000}$ were determined from tests for which n was less than 600,000. Values of $F_{2,000,000}$ were determined from tests for which n was greater than 300,000, and values of both

* See Univ. of Ill. Eng. Exp. Sta. Bul. 302, p. 111. 1938.

$F_{100,000}$ and $F_{2,000,000}$ were determined from tests for which n was more than 300,000 and less than 600,000. If the number of cycles for failure exceeded 2,000,000, the value of the maximum stress in the stress cycle was taken as the value of $F_{2,000,000}$. A plus-sign (+) was placed after this value to indicate that the value of $F_{2,000,000}$ was somewhat greater than that reported.

Because of the small number of tests available and the extrapolation necessary to obtain the values of $F_{100,000}$ and $F_{2,000,000}$ reported, these values must be considered as more or less approximate. It is believed, however, that they are sufficiently accurate to indicate the relative fatigue strengths of the various beams tested, which was the primary purpose of the investigation.

A static test was made on each of most types of specimens, which were identical with the fatigue specimens of the corresponding series. The specimen was loaded and supported in the same manner for the static tests as for the fatigue tests. The compression flange had no lateral support except that afforded by the loading head of the testing machine. The ultimate strength and, where evident, the yield point are reported with the fatigue strength in Tables 3–17. The stresses reported are those at the load points computed from the maximum load which the specimen would carry, using the flexural formula commonly used in engineering design.* Plastic flow was limited to a relatively short length of flange, and the yield point was not so apparent as for the same steel under a static tension test. For some specimens there was a definite drop in the beam; for others there was none, but there was a definite slowing down in the rate of loading with the testing machine running at a uniform speed. The corresponding loads have been reported as the yield point. For other specimens, no yield point was detected with the method of testing used.

4. *Results of Tests.*—The results of the static tests are summarized in Table 2; the results of the fatigue tests, set forth in Tables 3–17, are summarized in Table 18. The details of the specimen and the location of the fracture are given in the sketch at the top of the table for each series. Only the maximum stress in the stress cycle is reported. The minimum load was just sufficient to keep the specimen and the parts of the machine in place, the minimum stress in the flange being of the order of 1000 to 1500 p.s.i. The values of $F_{100,000}$ and $F_{2,000,000}$ reported are based upon the maximum stress, on the assumption that the minimum stress was zero. For this reason the

* It is realized that this is not the true stress, inasmuch as the stress-strain relation changes at the proportional limit.

TABLE 2

STATIC FLEXURAL STRENGTH OF FATIGUE TYPE SPECIMENS

For all specimens: Compression flange supported at load points only.

Specimen Number	Description of Specimen	Strength, p.s.i.	
		Yield Point	Ultimate*
44 A4	Plain rolled beam†	35 900	43 800
44 Ba-4	Rolled beam with full-length cover plates attached with continuous fillet welds	42 200	59 300
44 Bb-4	Rolled beam with full-length cover plates attached with intermittent fillet welds	37 500	49 200
44 Ca-4	Rolled beam with partial-length cover plates attached with continuous fillet welds	37 500	45 800
44 Cb-4	Rolled beam with partial-length cover plates attached with intermittent fillet welds	Not apparent	39 300
44 Cc-4	Rolled beam with partial-length cover plates attached with intermittent fillet welds	32 900	44 800
44 Cd-5	Rolled beam with partial-length cover plates attached with intermittent fillet welds	Not apparent	38 900
44 E-4	Rolled beam with partial-length cover plates attached with rivets‡	38 500	46 500
44 Ga-4	Fabricated beam. Flange plates attached with continuous ⅛-in. fillet welds	Not apparent	55 000
44 Gb-5	Fabricated beam. Flange plates attached with continuous 3/16-in. fillet welds	Not apparent	54 800
44 Ha-4	16-in., 36-lb., wide-flange rolled beam. Stiffeners attached with welds	42 300	47 200
44 Mc-4	Rolled beam with lateral plates attached with rivets.‡	Not apparent	48 700

* See footnote, page 11.
† All beams are 12-in., 31.8-lb. I-beams unless otherwise noted.
‡ Stress based on gross section.

true zero-to-maximum fatigue values would be of the order of from 500 to 750 p.s.i. less than the values listed.*

For specimens which were designed to fail in tension but actually failed in the compression flange, the stress reported is designated as a tension, on the basis that the tension flange had been subjected to the same number of cycles as the compression flange. Actually, for these tests, the fatigue strength in tension was somewhat greater than the values reported. Likewise, for specimens which were designed to fail in compression but which actually failed in tension, the stress reported is designated as a compression, on the basis that the compression flange had been subjected to the same number of cycles as the tension flange. This policy was followed because the averaging

* A cycle, S_{max} to S_{min}, is approximately equivalent to a cycle $\left(S_{max} - \frac{S_{min}}{2}\right)$ to 0.

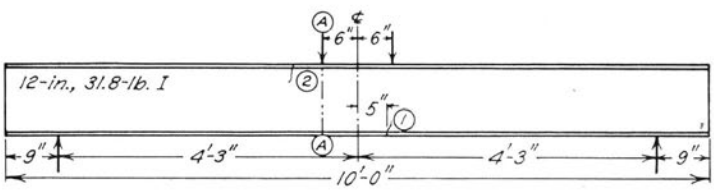
of tension stresses with compression stresses seemed incongruous. Actually the true average stresses would be slightly greater than the values reported.

The failure in the compression flange of specimen 44A-3, Table 3, is attributed to the influence of the loading block at A. This block was machined on all surfaces, and the friction resulting from the pressure of the block on the flange of the beam may have caused the two to act as a unit to a certain extent, thereby having the effect of a geometrical stress-raiser. After this test the bottom surface of each loading block was eased off a few thousandths of an inch near the outer end. No subsequent tests resulted in failure at the edge of the loading block.

The results of the individual tests are given in Tables 3–17, and the average values of $F_{100,000}$ and $F_{2,000,000}$ for the various series are given in Table 18.

TABLE 3

12-IN., 31.8-LB. I-BEAMS WITHOUT REINFORCEMENT: SERIES 44A



Specimen Number	Max. Stress in Cycle at A, 1000's of lb. per sq. in.	Number of Cycles for Failure, in 1000's	Fatigue Strength in 1000's of lb. per sq. in.* $F_{2,000,000}$	Section at Which Fracture Occurred
44A–1	+30.5	2 001.0	30.5	Did not fail
44A–2	+35.0	719.2	29.1	1
44A–3	+34.0	3 255.5	34.0+	2
Ave.	......	....	31.2	...

* Based on a value of K of 0.18.

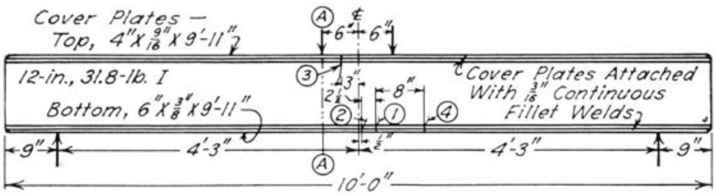
RESULTS OF STATIC TESTS

Stresses at A-A

44A–4	Yield Point = 35 900 lb. per sq. in. Ultimate = 43 800 lb. per sq. in. Top flange supported at load points only.

TABLE 4

12-IN., 31.8-LB. I-BEAMS WITH FULL-LENGTH COVER PLATES ATTACHED WITH CONTINUOUS FILLET WELDS: SERIES 44Ba



Specimen Number	Max. Stress in Cycle at A, 1000's of lb. per sq. in.	Number of Cycles for Failure, in 1000's	Fatigue Strength in 1000's of lb. per sq. in.*		Section at Which Fracture Occurred
			$F_{100,000}$	$F_{2,000,000}$	
44Ba-1	+35.0	237.5	41.2	....	1
44Ba-2	+26.0	734.7	....	21.5	2
44Ba-3	+25.0	1 246.4	....	22.9	3
44Ba-5	+34.3	225.7	40.0	....	2
44Ba-6	+34.2	301.7	42.2	23.9	1
44Ba-7	+27.0	854.8	....	23.0	4
Ave.	......	.....	41.1	22.8	...

* Based on a value of K of 0.19.

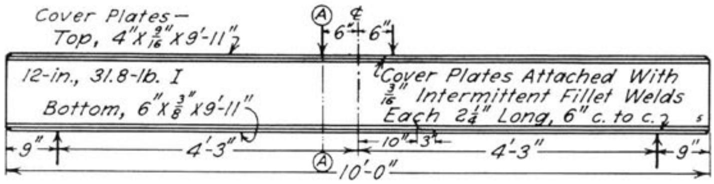
RESULTS OF STATIC TESTS

Stresses at A-A

44Ba-4	Yield Point = 42 200 lb. per sq. in. Ultimate = 59 300 lb. per sq. in. Top flange supported at load points only.

TABLE 5

12-IN., 31.8-LB. I-BEAMS WITH FULL-LENGTH COVER PLATES ATTACHED WITH INTERMITTENT FILLET WELDS: SERIES 44Bb



Specimen Number	Max. Stress in Cycle at A, 1000's of lb. per sq. in.	Number of Cycles for Failure, in 1000's	Fatigue Strength in 1000's of lb. per sq. in.*		Section at Which Fracture Occurred
			$F_{100,000}$	$F_{2,000,000}$	
44Bb-1	+20.0	1 051.9	....	16.5	Except for 44b-7, failure was at end of a weld bead and near mid-length of bottom flange.
44Bb-2	+19.0	1 270.1	....	16.6	
44Bb-3	+18.0	1 494.9	....	16.5	
44Bb-5	+30.0	278.7	40.8	....	
44Bb-6	+32.0	278.0	43.5	....	
44Bb-7	+31.0	293.6	42.8	....	
Ave.	......	....	42.4	16.5	....

* Based upon a value of K of 0.30.

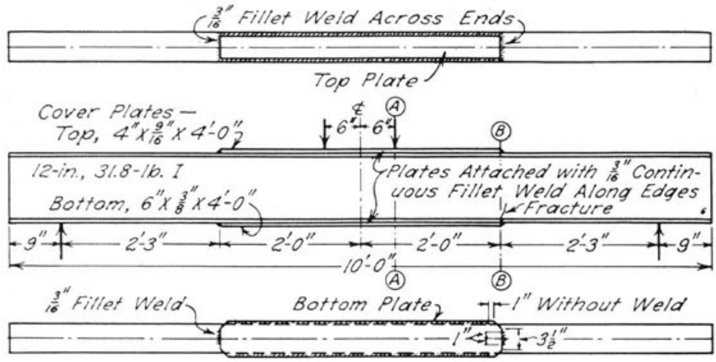
RESULTS OF STATIC TESTS

Stresses at A-A

44Bb-4	Yield Point = 37 500 lb. per sq. in. Ultimate = 49 200 lb. per sq. in. Top flange supported at load points only.

TABLE 6

12-IN., 31.8-LB. I-BEAMS WITH PARTIAL-LENGTH COVER PLATES ATTACHED WITH CONTINUOUS FILLET WELDS; SPECIAL ENDS: SERIES 44Bd



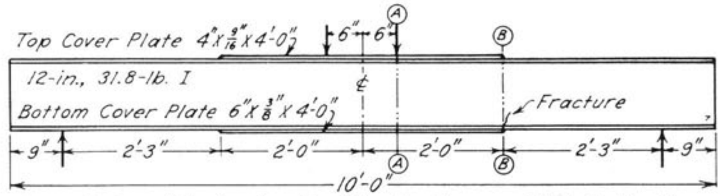
Specimen Number	Max. Stress in Cycle at B, 1000's of lb. per sq. in.	Number of Cycles for Failure, in 1000's	Fatigue Strength in 1000's of lb. per sq. in.*	
			$F_{100,000}$	$F_{2,000,000}$
44Bd-1	+12.0	1 159.3	....	10.4
44Bd-2	+10.0	1 923.2	....	9.6
44Bd-3	+14.0	543.3	22.1	9.9
Ave.	......	....	22.1	10.0

* Based on a value of K of 0.27

The stress computed by the simple theory of flexure was the same between the load points as at the ends of the cover plate.

TABLE 7

12-IN., 31.8-LB. I-BEAMS WITH PARTIAL-LENGTH COVER PLATES ATTACHED WITH CONTINUOUS FILLET WELDS: SERIES 44Ca



Cover Plates Attached with 3/16-in. Continuous Fillet Welds Along Edges, Around Corners, and Across Ends, Except for Specimens 44Ca-8, -9 and -10 which had no Welds Across Ends.

Specimen Number	Max. Stress in Cycle at B, 1000's of lb. per sq. in.	Number of Cycles for Failure, in 1000's	Fatigue Strength in 1000's of lb. per sq. in.*	
			$F_{100,000}$	$F_{2,000,000}$
44Ca-1	+21.5	67.0	19.6	...
44Ca-2	+18.4	118.0	19.1	...
44Ca-3	+11.3	806.3	....	9.2
44Ca-5	+ 8.9	2 326.8	....	8.9+
44Ca-6	+9.2	2 380.9	....	9.2+
44Ca-7	+9.8	2 293.6	....	9.8+
44Ca-8	+9.2	1 968.6	....	9.2
44Ca-9	+10.3	889.4	....	8.5
44Ca-10	+9.2	1 825.7	....	9.0
Ave.	......	....	19.4	9.1+

* Based on a value of K of 0.23.
All failures were at end of cover plate.

RESULTS OF STATIC TESTS

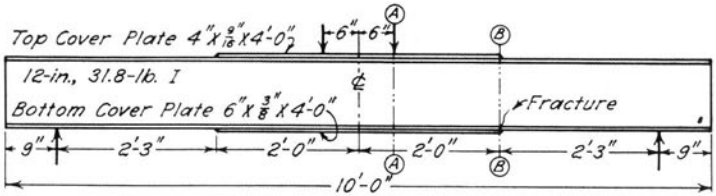
Stresses at A-A

44Ca-4	Yield Point = 37 500 lb. per sq. in. Ultimate = 45 800 lb. per sq. in. Top flange supported at load points only.

The stress computed by the simple theory of flexure was the same between the load points as at the ends of the cover plate.

TABLE 8

12-IN., 31.8-LB. I-BEAMS WITH PARTIAL-LENGTH COVER PLATES ATTACHED WITH INTERMITTENT FILLET WELDS: SERIES 44Cb



Cover Plates Attached with 5/16-in. Intermittent Fillet Welds Along Edges and 5/16-in. Continuous Fillet Welds Across Ends.

Specimen Number	Max. Stress in Cycle at *B*, 1000's of lb. per sq. in.	Number of Cycles for Failure, in 1000's	Fatigue Strength in 1000's of lb. per sq. in.*	
			$F_{100,000}$	$F_{2,000,000}$
44Cb-1	+14.3	295.6	19.0	...
44Cb-2	+11.2	741.7	....	8.7
44Cb-3	+9.2	1 210.5	....	8.1
Ave.	......	....	19.0	8.4

* Based upon a value of *K* of 0.26.
All specimens failed at the end of the cover plate of the tension flange.

RESULTS OF STATIC TESTS

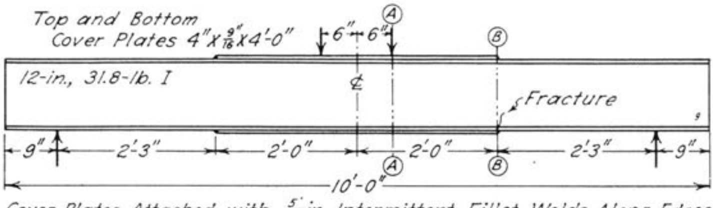
Stresses at *A-A*

44Cb-4	Yield Point = Not detected by drop of beam. Ultimate = 39 300 lb. per sq. in. Top flange supported at load points only.

The stress computed by the simple theory of flexure was the same between the load points as at the ends of the cover plate.

TABLE 9

12-IN., 31.8-LB. I-BEAMS WITH PARTIAL-LENGTH COVER PLATES ATTACHED WITH INTERMITTENT FILLET WELDS; BOTH COVER PLATES 4 IN. BY 9/16 IN. AND ALL WELDS LAID IN FLAT POSITION: SERIES 44Cc



Cover Plates Attached with 5/16-in. Intermittent Fillet Welds Along Edges and 5/16-in. Continuous Fillet Welds Across Ends.

Specimen Number	Max. Stress in Cycle at *B*, 1000's of lb. per sq. in.	Number of Cycles for Failure, in 1000's	Fatigue Strength in 1000's of lb. per sq. in.*	
			$F_{100,000}$	$F_{2,000,000}$
44Cc-1	+14.3	450.0	21.8	9.4
44Cc-2	+11.3	1 141.2	....	9.6
44Cc-3	+9.2	3 261.0†	....	9.2+
Ave.	......	....	21.8	9.4+

* Based upon a value of *K* of 0.28.
† Did not fail.
All failures were at the end of cover plates.

RESULTS OF STATIC TESTS

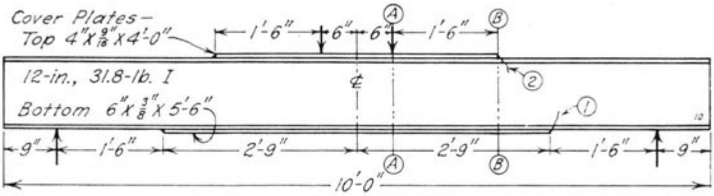
Stresses at *A-A*

44Cc-4	Yield Point = 32 900 lb. per sq. in. Ultimate = 44 800 lb. per sq. in. Top flange supported at load points only.

The stress computed by the simple theory of flexure was the same between the load points as at the ends of the cover plate.

Table 10

12-In., 31.8-Lb. I-Beams with Partial-Length Cover Plates Attached with ¼-In. Intermittent Fillet Welds; Bottom Plate Longer Than Top Plate; Failure in Compression Flange: Series 44Cd



Cover Plates Attached with ¼-in. Intermittent Fillet Welds Along Edges and ¼-in. Continuous Fillet Welds Across Ends.

Specimen Number	Max. Stress in Cycles at B, 1000's of lb. per sq. in.	Number of Cycles for Failure, in 1000's	Fatigue Strength in 1000's of lb. per sq. in.*		Section at Which Fracture Occurred
			$F_{100,000}$	$F_{2,000,000}$	
44Cd-1	−14.8	716.2	......	−12.9†	1
44Cd-2	−13.0	665.2	......	−11.1	2
44Cd-3	−11.1	1 295.9	......	−10.4	2
44Cd-4	−14.8	215.1	−16.5	......	2
Ave.	......	.....	−16.5	−11.5	...

* Based on a value of K of 0.14.
† Did not fail in compression flange.

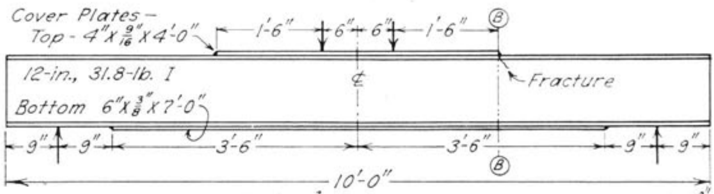
Results of Static Tests

Stresses at A-A

44Cd-5	Yield Point—Not detected by drop of beam. Ultimate = 38 900 lb. per sq. in. Top flange supported at load points only.

TABLE 11

12-IN., 31.8-LB. I-BEAMS WITH PARTIAL-LENGTH COVER PLATES ATTACHED WITH INTERMITTENT FILLET WELDS; FAILURE IN COMPRESSION FLANGE: SERIES 44Ce



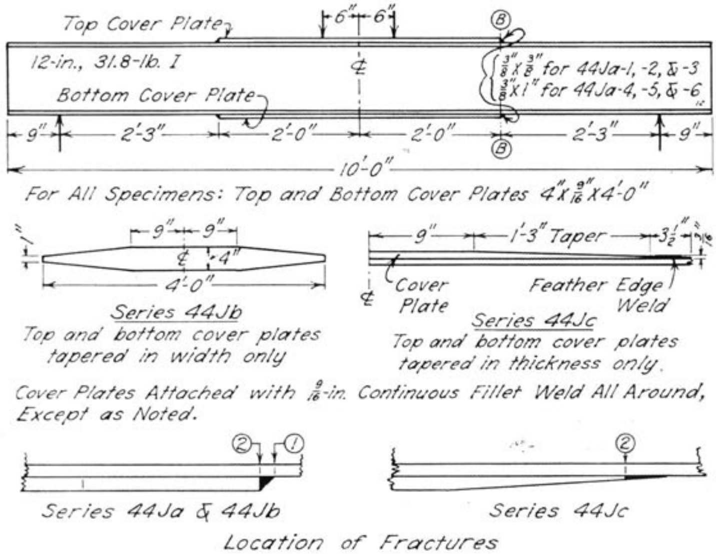
Cover Plates Attached with 3/16-in. Intermittent Fillet Welds, Each 2 3/4" Long, 6" c. to c., Along Edges and with 3/16-in. Continuous Fillet Welds Across Ends.

Specimen Number	Max. Stress in Cycle at *B*, 1000's of lb. per sq. in.	Number of Cycles for Failure, in 1000's	Fatigue Strength in 1000's of lb. per sq. in.*	
			$F_{100,000}$	$F_{2,000,000}$
44Ce 1	−16.8	233.5	−22.0	.....
44Ce-2	−11.1	672.6	......	−7.8
44Ce-3	−8.4	2 285.8	......	−8.4+
Ave.	......	....	−22.0	−8.2+

* Based upon a value of *K* of 0.32.
All specimens failed in the compression flange on section *B-B*.

TABLE 12

12-IN., 31.8-LB. I-BEAMS WITH PARTIAL-LENGTH COVER PLATES ATTACHED WITH CONTINUOUS FILLET WELDS; VARIOUS END CONDITIONS: SERIES 44Ja, 44Jb, AND 44Jc

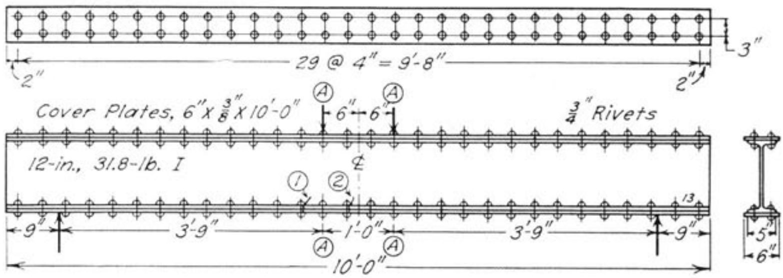


Specimen Number	Max. Stress in Cycle at B, 1000's of lb. per sq. in.	Number of Cycles for Failure in 1000's	Fatigue Strength in 1000's of lb. per sq. in.*		Section at Which Fracture Occurred†
			$F_{100,000}$	$F_{2,000,000}$	
44Ja-1‡	+18.0	281.2	22.8	....	2
44Ja-2	+14.0	796.6	....	11.3	1
44Ja-3	+12.0	1 303.4	....	10.9	2
44Ja-5‡	+14.0	1 173.8	....	12.4	1
44Ja-6	+14.0	1 444.4	....	13.0	1
44Ja-7	+13.0	1 575.6	....	12.3	2
Ave.	......	....	22.8	12.0	...
44Jb-1	+18.0	235.7	20.0	....	1
44Jb-2	+11.0	878.5	....	10.0	2
44Jb-3	+ 9.0	3 178.8	....	9.0+	1
Ave.	......	....	20.0	9.5+	...
44Jc-1	+18.0	997.8	....	14.3	2
44Jc-2	+16.0	1 386.5	....	14.2	2
44Jc-3	+14.0	2 189.1	....	14.0+	2
Ave.	......	....	....	14.2+	...

* $K_{Ja} = 0.23$, $K_{Jb} = 0.12$, $K_{Jc} = 0.33$.
† Section 1—outer edge of weld; section 2—at end of plate.
‡ End fillet welds 3/8 in. by 3/8 in. for specimens 44Ja-1, 2, 3; and 3/8 in. by 1 in. for specimens 44Ja-5, 6, 7.

TABLE 13

12-IN., 31.8-LB. I-BEAMS WITH FULL-LENGTH COVER PLATES ATTACHED WITH ¾-IN. RIVETS: SERIES 44EA

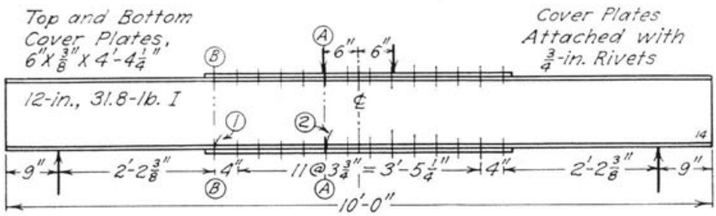


Specimen Number	Max. Stress in Cycle at A, 1000's of lb. per sq. in.	Number of Cycles for Failure, in 1000's	Fatigue Strength in 1000's of lb. per sq. in.*		Section at Which Fracture Occurred
			$F_{100,000}$	$F_{2,000,000}$	
44EA-1	+18.0	953.4	....	16.0	1
44EA-2	+16.0	1 715.4	....	15.6	2
44EA-3	+17.0	1 327.1	....	15.9	2
Ave.	......	....	....	15.8†	...

* Based on a value of K of 0.16.
† Based on gross section. Corresponding value based on net section is 21.6.

TABLE 14

12-IN., 31.8-LB. I-BEAMS WITH PARTIAL-LENGTH COVER PLATES ATTACHED WITH ¾-IN. RIVETS: SERIES 43E AND 44E



Specimen Number	Max. Stress in Cycle at B, 1000's of lb. per sq. in.	Number of Cycles for Failure, in 1000's	Fatigue Strength in 1000's of lb. per sq. in.*		Section at Which Fracture Occurred
			$F_{100,000}$	$F_{2,000,000}$	
44E-1	+11.1	3 620.3	....	11.1+	Did not fail
44E-2	+14.9	998.5	....	12.4	1
44E-3	+15.8	992.7	....	13.1	2
43E-1	+23.5	218.6	29.1	....	1
43E-2	+32.3	23.9	21.9	....	1
43E-3	+17.6	666.1	29.5	13.1	1
Ave.	......	.....	26.8†	12.4+†	...

* Based upon a value of K of 0.27. Also based upon the gross section of the beam.
† Based on gross section. The corresponding values based on the net sections are 36.5 and 16.9, respectively.

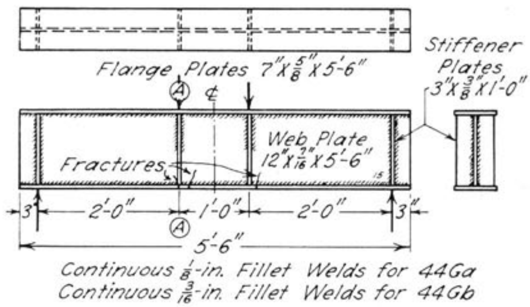
RESULTS OF STATIC TESTS

Stresses at A-A

44E-4	Yield Point = 38 500 lb. per sq. in. Ultimate = 46 500 lb. per sq. in. Top flange supported at load points only.

TABLE 15

FABRICATED BEAMS WITH FLANGE PLATES ATTACHED TO WEB PLATE WITH CONTINUOUS FILLET WELDS: SERIES 44Ga AND 44Gb



Specimen Number	Max. Stress in Cycle, 1000's of lb. per sq. in.	Number of Cycles for Failure, in 1000's	Fatigue strength in 1000's of lb. per sq. in.*	
			$F_{100,000}$	$F_{2,000,000}$
44Ga-1	+20.0	946.2	....	15.6
44Ga-2	+18.0	1 783.1	....	17.3
44Ga-3	+28.0	563.9	49.8	18.6
Ave.	......	....	49.8	17.2
44Gb-1	+26.0	586.1	46.9	17.3
44Gb-2	+24.0	594.7	43.5	16.0
44Gb-3	+19.0	1 335.0	....	16.6
Ave.	......	....	45.2	16.6

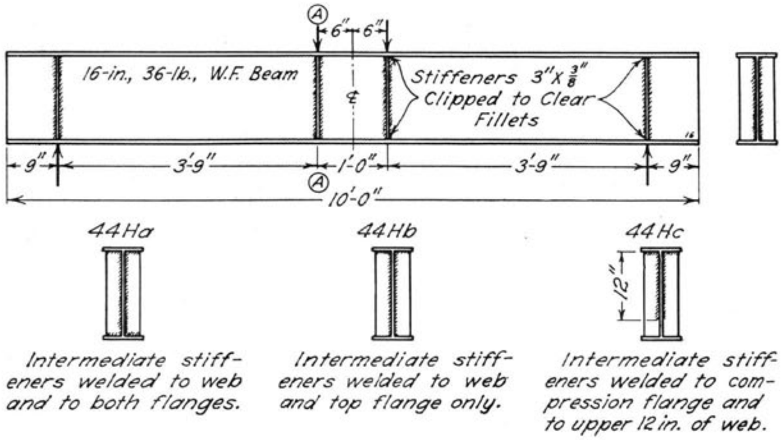
* Based upon a value of K of 0.33.
All specimens failed in the bottom flange at or near an intermediate stiffener.

RESULTS OF STATIC TESTS

44Ga-4	Ultimate = 55 000 lb. per sq. in.
44Gb-4	Ultimate = 54 800 lb. per sq. in.
	Top flange supported at load points only.

TABLE 16

16-IN., 36-LB. WIDE FLANGE BEAMS; STIFFENERS ATTACHED WITH WELDS: SERIES 44Ha, 44Hb, AND 44Hc



Specimen Number	Max. Stress in Cycle at *A*, 1000's of lb. per sq. in.	Number of Cycles for Failure, in 1000's	Fatigue Strength in 1000's of lb. per sq. in.*	
			$F_{100,000}$	$F_{2,000,000}$
Series 44Ha. Stiffeners Welded to Web and Both Flanges				
44Ha-1	+20.0	1 287.7	....	19.1
44Ha-2	+19.0	1 285.0	....	18.1
44Ha-3	+18.0	3 244.3†	....	18.0+
44Ha-3‡	+20.0	2 339.2	....	....
Ave.	......	....	....	18.4+
Series 44Hb. Stiffeners Welded to Web and Compression Flange				
44Hb-1	+26.0	2 444.0	....	26.0+
44Hb-2	+30.0	956.5	....	27.9
44Hb-3	+28.0	886.9	....	25.8
Ave.	......	....	....	26.6+
Series 44Hc. Stiffeners Welded to Compression Flange and to Top 12 In. of Web				
44Hc-1	+32.0	2 364.0†	....	32.0+
44Hc-2	+34.0	1 146.4	....	32.1
44Hc-3	+34.0	2 294.7	....	34.0+
Ave.	......	....	....	32.7+

* Based on a value of *K* of 0.10. All failures were at intermediate stiffeners.
† Specimen did not fail.
‡ Specimen 44Ha-3 was subjected to 3,244,300 cycles at 1,000 to 18,000 lb. per sq. in. and then tested on a cycle 1,000 to 20,000 lb. per sq. in., and failed at 2,339,200 additional cycles.

RESULTS OF STATIC TESTS

44Ha-4	Yield Point = 42 300 lb. per sq. in. Ultimate Strength = 47 200 lb. per sq. in.

TABLE 17

12-IN., 31.8-LB. I-BEAMS WITH LATERAL PLATES ATTACHED TO TENSION FLANGE: SERIES 44Ma, 44Mb, AND 44Mc

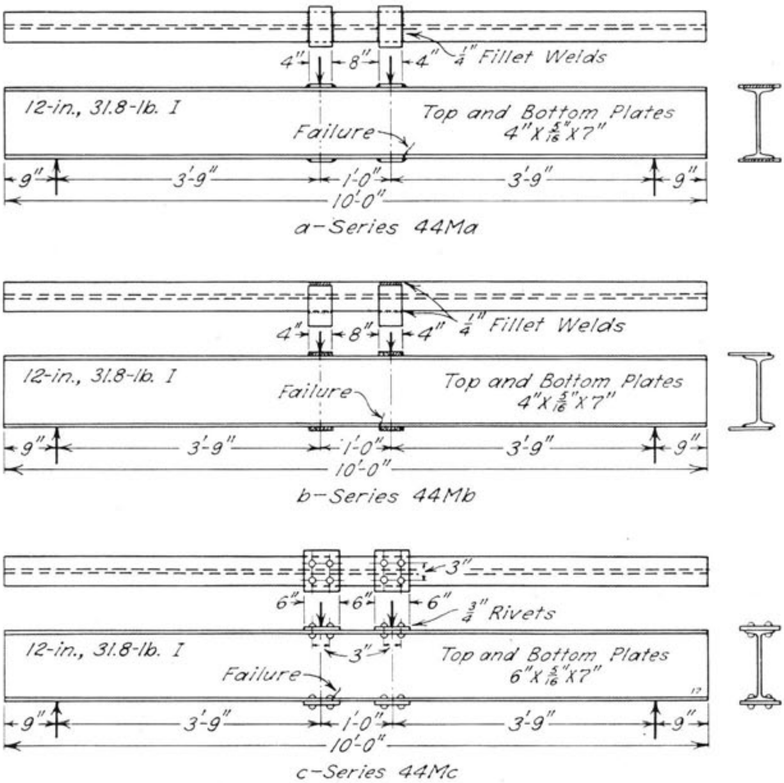
Specimen Number	Max. Stress in Cycle, 1000's of lb. per sq. in.	Number of Cycles for Failure, in 1000's	Fatigue Strength in 1000's of lb. per sq. in.*	
			$F_{100,000}$	$F_{2,000,000}$
Series 44Ma. Plates Attached with Transverse Fillet Welds				
44Ma-1	+20.0	82.1	19.2	....
44Ma-2	+16.0	928.8	....	13.4
44Ma-3	+11.0	3 442.9	....	11.0+
Ave.	......	....	19.2	12.2+
Series 44Mb. Plates Attached with Longitudinal Fillet Welds				
44Mb-1	+20.0	272.5	24.4	....
44Mb-2	+16.0	1 039.7	....	14.0
44Mb-3	+14.0	1 471.1	....	13.2
Ave.	......	....	24.4	13.6
Series 44Mc. Plates Attached with Rivets†				
44Mc-1	+20.0	400.0	26.4	14.5
44Mc-2	+18.0	745.0	....	14.8
44Mc-3	+16.0	1 224.1	....	14.5
Ave.	......	....	26.4	14.6

* Based upon a value of K of 0.20. Welded specimens failed at or in the weld; riveted specimens failed through the rivet hole.
† Stress based on gross section.

RESULTS OF STATIC TESTS

44Mc-4	Yield Point—Not detected. Ultimate Strength = 48 700 lb. per sq. in. Based on gross section.

The figure accompanying this table is on page 28.



12-In., 31.8-Lb. I-Beams with Lateral Plates Attached to Tension Flange: Series 44Ma, 44Mb, and 44Mc

TABLE 18

FLEXURAL FATIGUE STRENGTH OF VARIOUS TYPES OF BEAMS: SUMMARY OF RESULTS

Series Number	Table Containing Details of Tests		Description of Specimen	Average Value of Fatigue Strength, 1000's of lb. per sq. in.	
	Table No.	Page No.		$F_{100,000}$	$F_{2,000,000}$
44A	3	13	12-in., 31.8 Lb. I-Beams Without Reinforcement	....	31.2
44Ba	4	14	12-In., 31.8-Lb. I-Beams with Full-Length Cover Plates Attached with Continuous Fillet Welds	41.1	22.8
44Bb	5	15	12-In., 31.8-Lb. I-Beams with Full-Length Cover Plates Attached with Intermittent Fillet Welds	42.4	16.5
44Bd	6	16	12-In., 31.8-Lb. I-Beams with Partial-Length Cover Plates Attached with Continuous Fillet Welds; Special Ends	22.1	10.0
44Ca	7	17	12-In., 31.8-Lb. I-Beams with Partial-Length Cover Plates Attached with Continuous Fillet Welds	19.4	9.1
44Cb	8	18	12-In., 31.8-Lb. I-Beams with Partial-Length Cover Plates Attached with Intermittent Fillet Welds	19.0	8.4
44Cc	9	19	12-In., 31.8-Lb. I-Beams with Partial-Length Cover Plates Attached with Intermittent Fillet Welds; Both Cover Plates 4 In. by 9/16 In. and All Welds Laid in Flat Position	21.8	9.4
44Cd	10	20	12-In., 31.8-Lb. I-Beams with Partial-Length Cover Plates Attached with 1/4-In. Intermittent Fillet Welds; Bottom Plate Longer than Top Plate; Failure in Compression Flange	−16.5	−11.5
44Ce	11	21	12-In., 31.8-Lb. I-Beams with Partial-Length Cover Plates Attached with 3/16-In. Intermittent Fillet Welds; Failure in Compression Flange	−22.0	−8.2
44Ja 44Jb 44Jc	12	22	12-In., 31.8-Lb. I-Beams with Partial-Length Cover Plates Attached with Continuous Fillet Welds; Various End Conditions	22.8* 20.0	11.1*, 12.6† 9.5 14.2
44EA	13	23	12-In., 31.8-Lb. I-Beams with Full-Length Cover Plates Attached with 3/4-In. Rivets	....	15.8‡ 21.6¶
43E 44E	14	24	12-In., 31.8-Lb. I-Beams with Partial-Length Cover Plates Attached with 3/4-In. Rivets	26.8‡ 36.5¶	12.4‡ 16.9¶
44Ga 44Gb	15	25	Fabricated Beams with Flange Plates Attached to Web Plate with Continuous Fillet Welds	49.8 45.2	17.2 16.6
44Ha 44Hb 44Hc	16	26	16-In., 36-Lb. Wide Flange Beams; Stiffeners Attached with Welds	....	18.8 26.6 32.7
44Ma 44Mb 44Mc	17	27	12-In., 31.8-Lb. I-Beams with Lateral Plates Attached to Tension Flange	19.2 24.4 26.4	12.2 13.6 14.6

* For 44Ja-1, 2, and 3.
† For 44Ja-5, 6, and 7 (see Table 12).
‡ Based on gross area.
¶ Based on net area.

III. Summary

The average values of the fatigue strength are given in Table 18. For all specimens the fatigue strength is for a cycle in which the flexural stress in the flanges varies from near zero* to a maximum. The results may be summarized as follows.

(1) The outstanding feature of the results is the very large reduction in the fatigue strength due to abrupt changes in section at the ends of partial-length cover plates. Whereas the fatigue strength corresponding to failure at 2,000,000 repetitions of a cycle in which the flexural stress varied from near zero to a maximum tension was of the order of 31,000 p.s.i. for 12-in., 31.8-lb. I-beams without holes or attachments (Series 44A), the corresponding fatigue strength for similar beams with partial-length cover plates attached with longitudinal fillet welds (Series 44Bd, 44Ca, 44Cb, 44Cc, and 44Ja) was of the order of 8,000 to 11,000 p.s.i. Moreover, for beams reinforced with full-length cover plates attached with continuous fillet welds (Series 44Ba) and for beams fabricated by connecting flange plates to cover plates with continuous fillet welds (Series 44Ga and 44Gb), the fatigue strength was much less than for beams as rolled. Likewise, for rolled beams reinforced with full-length cover plates attached with fillet welds, the fatigue strength was less for those with intermittent welds (Series 44Bb) than for those with continuous fillet welds (Series 44Ba).

(2) The average value of $F_{2,000,000}$ for 12-in., 31.8-lb. I-beams in the as-rolled condition was 31,200 p.s.i. For 16-in., 36-lb. wide-flange beams the corresponding value was 32,700 p.s.i. For both sizes of rolled beams the fatigue strength corresponding to failure at 100,000 cycles evidently exceeded the yield point of the steel.†

(3) Beams fabricated by attaching flange plates to a web plate with continuous fillet welds had a much lower fatigue strength than rolled beams, the average value of $F_{2,000,000}$ being 16,900 p.s.i. for fabricated beams; whereas for the rolled beams $F_{2,000,000}$ had values of 31,200 p.s.i. and 32,700 p.s.i. for 12-in.–31.8-lb. and 16-in.–36-lb. beams, respectively. The rolled 12-in. beams used in this comparison had no intermediate stiffeners, whereas the 16-in. rolled beams and the fabricated beams had intermediate stiffeners welded to the compression portion only.

* 1000 to 1500 p.s.i.

† The value of K for Series 44A is given in the footnote to Table 3 as 0.18, and for Series 44Hc it is given in the footnote to Table 16 as 0.10. Moreover, $F_{100,000} = F_{2,000,000} \times \left(\frac{2,000,000}{100,000}\right)^K$. That is, $F_{100,000} = 31,200 \times (20)^{0.18} = 53,500$ p.s.i. for Series 44A. Similarly, $F_{100,000} = 32,700 \times (20)^{0.10} = 44,200$ p.s.i. for Series 44Hc.

(4) The reduction in the fatigue strength due to intermediate stiffeners welded to beams depended upon the portion of the beam to which the stiffeners were welded. For 16-in., 36-lb. wide-flange beams, the value of $F_{2,000,000}$ was 18,800 p.s.i. for beams with intermediate stiffeners welded to the web and both flanges (Series 44Ha); 26,600 p.s.i. for beams with intermediate stiffeners welded to the compression flange and the full depth of the web (Series 44Hb); and 32,700 p.s.i. for beams with intermediate stiffeners welded to the compression flange and to the compression portion of the web only.

(5) Rolled beams reinforced with full-length cover plates attached with continuous fillet welds had values for $F_{100,000}$ and $F_{2,000,000}$ of 41,100 p.s.i. and 22,800 p.s.i., respectively. The value for $F_{100,000}$ is somewhat less, and for $F_{2,000,000}$ somewhat greater, than the corresponding values for beams fabricated by welding flange plates to a web plate, and they are considerably less than the corresponding values for I-beams in the as-rolled condition.

(6) The values of $F_{100,000}$ were very nearly the same for I-beams reinforced with full-length cover plates attached with intermittent fillet welds as for similar beams and similar plates attached with continuous fillet welds. The value of $F_{2,000,000}$, however, was very much less for beams with reinforcing plates attached with intermittent welds than for similar beams and similar plates attached with continuous welds.

(7) The fatigue strength was very much less for rolled beams with partial-length fillet-welded cover plates than for similar rolled beams with full-length fillet-welded cover plates. Average values of $F_{100,000}$ for beams with full-length cover plates were 41,100 p.s.i. and 42,400 p.s.i. for continuous and intermittent welds, respectively. The corresponding values for beams reinforced with partial-length cover plates were 22,100 p.s.i. and 19,400 p.s.i., respectively. Average values of $F_{2,000,000}$ for beams with full-length cover plates were 22,800 p.s.i. and 16,500 p.s.i. for continuous and intermittent welds, respectively. The corresponding values for beams reinforced with partial-length cover plates were 10,000 and 9,100 p.s.i. for continuous fillet welds; and 8,400 and 9,400 p.s.i. for intermittent fillet welds. Of the rolled beams reinforced with partial-length cover plates attached with intermittent fillet welds, those with tension plates 4 in. by 9/16 in. were somewhat stronger than those with tension plates 6 in. by 3/8 in.

(8) Beams with welded partial-length cover plates with ends tapered by reducing the thickness had a somewhat greater fatigue strength than beams with partial-length cover plates with ends not tapered at all or tapered by reducing the width.

(9) The fatigue strength of beams reinforced with full-length cover plates attached with rivets was less than the fatigue strength of beams reinforced with similar plates attached with continuous fillet welds, the unit strength being based on the gross section for both types of beams. However, for beams with partial-length cover plates, those having cover plates attached with rivets had a fatigue strength as great as similar beams and plates attached with welds, or possibly a little greater, the unit stress being based on the gross section for both types of beams.

(10) Lateral plates attached to the tension flange of beams reduced greatly the fatigue strength of the beam. This was true whether the attachment was by longitudinal fillet welds, transverse fillet welds, or rivets. The reduction was not greater, however, than is occasioned by any of the tested methods of applying cover plates of partial length.

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