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FATIGUE STRENGTH OF FILLET-WELD AND PLUG-WELD CONNECTIONS IN STEEL STRUCTURAL MEMBERS

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
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
AMERICAN WELDING SOCIETY
and the
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FATIGUE STRENGTH OF FILLET-WELD AND PLUG-WELD CONNECTIONS IN STEEL STRUCTURAL MEMBERS

I. Introduction

1. *Object and Scope of Investigation.*—As sufficient information relative to the best types of fillet-weld and plug-weld joints to withstand fatigue upon which to base a comprehensive investigation was not available, most of the work described in this bulletin was exploratory, preparatory to a more extensive investigation to follow.

The first tests were planned to determine the unit fatigue strength in shear of fillet welds connecting structural plates, and to determine the fatigue strength in tension of plates and channels connected by fillet welds. These indicated that the fatigue strength in tension of the plates and channels thus connected was so low as compared with the fatigue strength of the welds in shear that the fatigue strength in tension of the plates or channels might govern the design of the connections for members to be subjected to pulsating or reversed loads. For this reason, most of the tests of fillet-weld connections were planned to develop the type of connection that would result in the greatest fatigue strength of the members connected.

Tests were also made to determine the fatigue strength in shear of plug welds, and to determine the fatigue strength in tension of plates connected with plug welds. A few composite joints were tested. For one type of joint, plates were connected by a combination of rivets and transverse fillet welds; for another type of joint, plates were connected by a combination of rivets and plug welds.

A large number of miscellaneous tests of riveted and welded butt joints in carbon-steel and low-alloy steel plates have also been made that are believed to be of interest to the profession. Reports of these tests have been included in this bulletin.

Unless otherwise specified the material in the plates and channels was carbon steel of structural grade having the general characteristics of A.S.T.M., A-7 steel.

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, Federal Works Agency, 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 JONATHAN JONES is Chairman. The tests 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. The fatigue tests were made in the Arthur Newell Talbot Laboratory and the metallurgical studies were made in the Metallurgical Laboratory, both of the University of Illinois.

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II. Fillet Welds

3. *Exploratory Tests; Fillet-Weld Joints Connecting Plates.*—The first tests to determine the fatigue strength of fillet-weld joints connecting plates were planned to determine the unit fatigue strength of the weld in shear, and the unit fatigue strength of the plates in tension. The details of the specimens are shown in Fig. 1. There were two types of specimens, W and Z. The fillet welds for the W specimens were 4 in. long, and the nominal ratio of the weld area in shear to the plate area in tension was 1/1.58, making the unit shear† on the throat of the weld 1.58 times the unit tension† on the plate, a stress-ratio which, it was believed, would result in a shear failure of the weld.

Specimens W1, W2, W5, and W6 were tested on a cycle in which the stress on a transverse section of outside plates varied from 0 to 10 000 lb. per sq. in. tension. The results of the tests are given in Table 1. Specimens W1 and W2 were tested as welded, and failure

*Deceased.

†The expressions, "unit shear" and "unit tension," here and elsewhere, mean "average unit shear" and "average unit tension," even though it is known that the maximum stress is considerably more than the average in most instances.

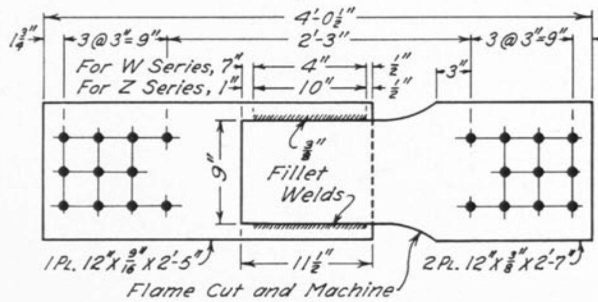


FIG. 1. SPECIMENS WITH TWO PARALLEL LONGITUDINAL FILLET WELDS CONNECTING PLATES

occurred in the outside plates at the end of the fillet weld despite the fact that the shear on the throat of the weld was 15 800 lb. per sq. in., whereas the tension on the transverse section of the plate was only 10 000 lb. per sq. in.

The change in section at the end of the fillet weld is a bad stress raiser which accounts, at least in part, for the low fatigue strength of the plate. The ends of the fillet welds of specimens W5 and W6 were ground to a feather edge with the idea of thus reducing their stress-raising effect. The specimens were tested on a cycle in which the stress range for the plate, 0 to 10 000 lb. per sq. in. tension, was the same as for specimens W1 and W2. The corresponding stress range for the throat of the weld was 0 to 20 800 and 20 500 lb. per sq. in. shear for W5 and W6, respectively. Failure occurred at 519 500 and 627 300 cycles, values slightly higher than for W1 and W2, but failure was in the outside plates at the ends of the fillets even though the unit shear in the weld was a little more than twice as great as the unit tension in the plate. Grinding the end of the fillet to a feather edge did not increase the fatigue strength of the plate by a significant amount.

The next expedient used to cause failure in the weld was to test specimens W3, W4, W7, and W8 on a cycle in which the stress in the outside plates varied from 0 to compression. Specimens W3 and W4 were tested on a cycle in which the shear on the throat of the weld varied from 0 to 30 000 lb. per sq. in. Failure occurred in the weld at 191 300 and 84 000 cycles, respectively, for the two specimens. The stress cycles for specimens W7 and W8 were 0 to 24 000 and 0 to 16 000 lb. per sq. in. shear, respectively. Specimen W7 cracked in both the plate and the weld at 158 200 cycles. Specimen W8 cracked in the plate at 1 375 000 cycles, but the test was continued. At 1 816 000 cycles the weld also cracked, but, since the load was maintained, the

TABLE 1
FATIGUE STRENGTH OF LONGITUDINAL FILLET-WELD JOINTS CONNECTING PLATES

Specimen No.	Cycle	Unit Stress in 1000's of lb. per sq. in.		Number of Cycles for Failure in 1000's	Part That Failed
		Shear on Throat of Weld	Tension or Compression in Plate		
W1	0 to tension	0 to 15.8	0 to +10.0	530.2	Plate
W2		0 to 15.8	0 to +10.0	340.1	Plate
W5*		0 to 20.8	0 to +10.0	519.5	Plate
W6*		0 to 20.5	0 to +10.0	627.3	Plate
W3	0 to compression	0 to 30.0	0 to −19.4	191.3	Weld
W4		0 to 30.0	0 to −19.6	84.0	Weld
W7		0 to 24.0	0 to −16.3	158.2	Weld and plate
W8		0 to 16.0	0 to −10.3	1 375.0 1 816.0 3 158.0	Plate; test continued Plate and weld; test continued Plate and weld; test discontinued
Z1	0 to tension	0 to 6.3	0 to +10.0	760.5	Plate
Z2		0 to 6.3	0 to +10.0	646.7	Plate
Z6*		0 to 7.3	0 to +10.0	1 514.6	Plate
Z5	Tension to equal compression	+10.0 to −10.0	+16.2 to −16.2	18.7	Plate
Z3	0 to compression	0 to 18.5	0 to −29.8	108.0 495.8	Plate; test continued Plate and weld
Z4		0 to 18.5	0 to −29.8	40.7 1 467.0	Plate; test continued Plate and weld
Z7		0 to 16.0	0 to −25.2	195.0 1 610.0	Plate; test continued Plate only; test discontinued
Z8		0 to 16.0	0 to −25.3	190.5 1 351.3	Plate; test continued Plate only; test discontinued

*Ends of fillets ground to a feather edge.

test was continued until 3 158 000 cycles; at this point the test was discontinued, although the weld was still able to carry the load.

The plates of specimens W1, W2, W5, and W6, connected with longitudinal fillet welds and tested on a cycle in which the stress varied from 0 to tension, had a fatigue strength corresponding to failure at 500 000 cycles of the order of 10 000 lb. per sq. in.

The results of the tests of the Z specimens, similar to the W specimens except that the fillets were 10 in. long, are reported in the lower part of Table 1. Specimens Z1 and Z2, which were tested in the as-welded condition and on a cycle in which the tension in the plate varied from 0 to 10 000 lb. per sq. in., failed in the plate at the end of the weld at approximately 700 000 cycles. The ends of the fillet welds of specimen Z6 were ground to a feather edge, and the specimen, which failed in the plate, had a life approximately twice the life of Z1 and Z2 when tested on the same cycle. Specimen Z5, tested in the as-welded

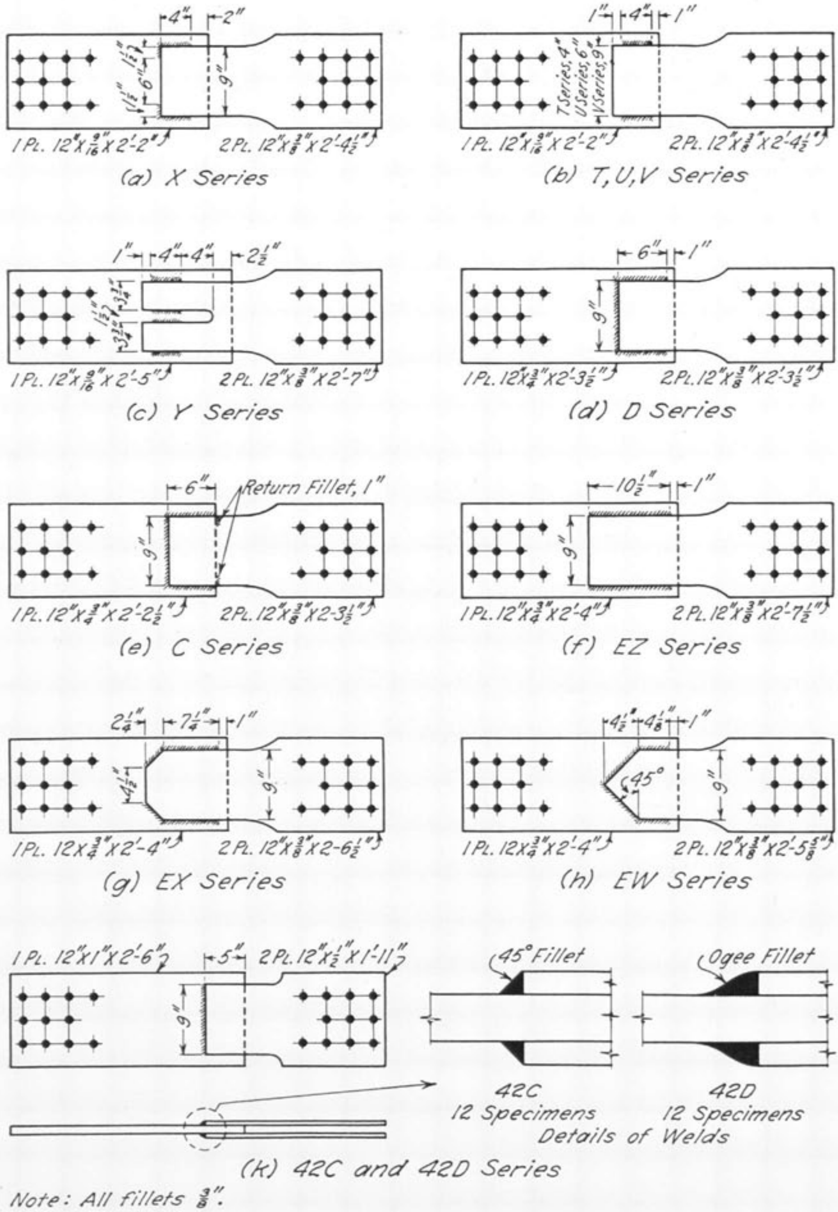


FIG. 2. VARIOUS TYPES OF FILLET-WELD JOINTS CONNECTING PLATES

condition on a cycle in which the stress in the plate varied from 16 200 lb. per sq. in. tension to an equal compression, failed in the plate at 18 700 cycles. Specimens Z3, Z4, Z7, and Z8 were tested in the as-welded condition on a cycle in which the stress in the plate varied from 0 to compression. The specimens failed first in the plates and, except for Z7 and Z8, later in the weld.

The tests reported in Table 1 were exploratory, and involve several variables so that they have not resulted in satisfactory quantitative values. They did show, however, that, for the type of specimen tested the unit fatigue strength of the longitudinal fillet weld in shear was considerably higher than the unit fatigue strength in tension of the plates connected. They also indicated that the fatigue strength of plates connected with longitudinal fillet welds, as shown in Fig. 1, was low, being of the order of 10 000 lb. per sq. in. for failure at 500 000 repetitions of a cycle in which the stress varied from 0 to tension.

4. *Various Types of Fillet-Weld Joints Connecting Plates.*—The exploratory tests of Section 3 indicated that the fatigue strength of plates connected with longitudinal fillet welds is low.

The next problem that presented itself was to determine the types of fillet-weld connections that had the greatest fatigue strength. Tests were therefore made to determine the fatigue strength of structural plates when connected by the various types of fillet welds shown in Fig. 2. All specimens were designed to fail in the plates rather than in the weld. To facilitate a comparison of the results, all specimens were tested on a cycle in which the stress in the outside plates, the ones that were to fail, varied from 0 to 18 000 lb. per sq. in. tension. The various specimens and tests are described in the following paragraphs.

T, U, and V Series

The tests of the T, U, and V series were planned to determine the effect of the width of the plate upon its fatigue strength when connected only by longitudinal fillet welds along the edges.

The specimens of the V series, shown in Fig. 2b, were the same as the specimens of the W series of Fig. 1. The T and U specimens were the same as the V specimens except for the width of the plate, which was 9 in. for V, 6 in. for U and 4 in. for T. The results of the tests are given in lines 1, 2, and 3 of Table 2.

The number of cycles for failure was somewhat greater for the narrow than for the wide specimens. This was probably due to the fact that the variation in stress along a transverse section was less for the narrow specimens than for the wide ones. The difference in the average

TABLE 2
FATIGUE STRENGTH OF VARIOUS TYPES OF FILLET-WELD JOINTS CONNECTING PLATES

Stress cycle for all tests: 0 to 18 000 lb. per sq. in. tension on outside plates. All specimens broke in outside plate at end of fillet weld.

Line	Specimen No.	Number of Cycles for Failure in 1000's	Line	Specimen No.	Number of Cycles for Failure in 1000's
1	V1 V2 V3	47.4 34.0 49.0 Av. 43.5	6	C1 C2 C3	363.1 313.6 352.8 Av. 343.2
2	U1 U2 U3	137.8 228.4 101.7 Av. 155.9	7	D1 D2 D3	296.5 223.9 330.2 Av. 283.5
3	T1 T2 T3	191.1 221.7 120.0 Av. 177.6	8	EW1 EW2 EW3	269.3 192.7 230.0 Av. 230.7
4	Y1 Y2 Y3	324.5 318.0 375.0 Av. 339.2	9	EX1 EX2 EX3	201.5 162.3 208.7 Av. 190.8
5	X1 X2 X3	36.2 71.8 47.2 Av. 51.7	10	EZ1 EZ2 EZ3	221.3 174.5 189.4 Av. 195.1

number of cycles for failure, which ranged from 43 500 for the V series to 177 600 for the T series, corresponds to a difference in the fatigue strength of the order of 20 per cent, a difference which is significant.

Y Series

The specimens of the Y series, shown in Fig. 2c, were very much like the specimens of the T series except that, for the former, each outside plate had two strips each 3¾ in. wide, whereas, for the latter, each outside plate consisted of a single strip 4 in. wide. The results of the tests are shown in line 4 of Table 2. The average number of cycles for failure was 339 200 for the Y series, almost double the number for the T series. It should be noted, however, that the stress is based upon the transverse section of the two 3¾-in. strips the combined width of which is considerably less than the width of the main plates, which are 9 in. wide.

X Series

The X specimens, shown in Fig. 2a, differed from the V specimens in having a transverse return fillet 1½ in. long at each corner. The number of cycles for failure, given in line 5 of Table 2, was very nearly the same for the X as for the V series, indicating that the return fillet had no appreciable effect upon the fatigue strength.

C and D Series

The C and D specimens, shown in Figs. 2e and 2d, had longitudinal fillet welds along both sides and a transverse fillet weld across the end of each outside plate. Specimen C differed from D in that it had a short transverse fillet weld on the inside of each outside plate. The average number of cycles for failure, given in lines 6 and 7 of Table 2, was 343 200 for C and 283 500 for D. These values are comparable with the 43 500 cycles for the V specimens, which did not have the transverse fillet welds across the ends of the outside plate.

EW, EX, and EZ Series

The details of the specimens are shown in Figs. 2f, 2g, and 2h. Specimens EW and EX differed from EZ in having the corners of the outside plates cut off and welded. The EZ specimens were similar to the Z specimens of Fig. 1. The average numbers of cycles for failure, given in lines 8, 9 and 10 of Table 2, were nearly the same for the three series and were all less than for the D specimens of Fig. 2d.

42C and 42D Series

Specimens 42C and 42D, shown in Fig. 2k, each had a single transverse fillet weld at the end of each outside plate. The two differed in that 42C had a 45-degree fillet whereas 42D had an ogee fillet, as shown in the figure. Specimens of these series were tested on the following cycles: 0 to 18 000 tension, 0 to 18 000 compression, and 12 000 tension to 12 000 compression, the stress being in lb. per sq. in. on the transverse section of the outside plates in all instances. The results of the tests are given in Table 3.

The 42D specimens, the ones with the ogee fillets, when tested on a cycle in which the stress in the outside plates varied from 0 to 18 000 lb. per sq. in. tension, and also when tested on a cycle in which the stress varied from 12 000 lb. per sq. in. tension to an equal compression, were slightly stronger in fatigue than the 42C specimens, the ones with 45-degree fillets; when tested on a cycle in which the stress varied from 0 to 18 000 lb. per sq. in. compression, the 42D specimens were very much stronger than the 42C specimens. Specimens 42D and 42C, when tested on a cycle in which the stress varied from 0 to tension, had approximately the same fatigue strength as specimens C and D of Table 2. Two specimens, 42D2 and 42D4,

TABLE 3
FATIGUE STRENGTH OF SINGLE TRANSVERSE FILLET WELDS CONNECTING PLATES

Specimen No.	Cycle	Unit Stress in 1000's of lb. per sq. in. Tension in Plate	Number of Cycles for Failure in 1000's	Location of Fatigue Cracks
42 D1	0 to tension	0 to +18.0	186.8*	Throat of weld
42 D2		0 to +18.0	651.5	Inside plate
42 D3		0 to +18.0	175.2	Edge of weld A
42 D4		0 to +18.0	408.0	Inside plate
			Av. 411.6	
42 D5	Tension to equal compression	+12.0 to −12.0	117.4	Edge of weld A
42 D6		+12.0 to −12.0	141.1	Edge of weld A
42 D7		+12.0 to −12.0	111.7	Edge of weld A
			Av. 123.4	
42 D8	0 to compression	0 to −18.0	1 006.6	Edge of weld B
42 D9		0 to −18.0	1 979.2	Edge of weld B
42 D10		0 to −18.0	857.6	Edge of weld A
			Av. 1 281.1	
42 C2	0 to tension	0 to +18.0	149.4	Edge of weld B
42 C3		0 to +18.0	175.0	Edge of weld B
42 C4		0 to +18.0	331.0	Throat of weld
			Av. 218.5	
42 C5	Tension to equal compression	+12.0 to −12.0	82.3	Throat of weld
42 C6		+12.0 to −12.0	47.5	Throat of weld
42 C7		+12.0 to −12.0	44.9	Throat of weld
			Av. 58.2	
42 C8	0 to compression	0 to −18.0	42.3	Edge of weld B
42 C9		0 to −18.0	32.4	Edge of weld B
42 C11		0 to −18.0	439.4	Edge of weld B
			Av. 171.4	

*Fillet was concave; this value was not included in the average.
A—Crack started at root and proceeded along edge in ½-in. plate.
B—Crack started at root and proceeded along edge in 1-in. plate.

broke in the inside plate, where the section was 12 sq. in., instead of in the outside plates, where the combined section of the two plates was 9 sq. in. These inside plates were slightly undercut at the ends of the welds.

The tests reported in this and the previous section indicate that, of the types of joints that were tested, there were none that had a significantly greater fatigue strength than the simple joint with longitudinal fillet welds along the sides and a transverse fillet weld across the ends of the plates, specimen D, Fig. 2d. Three joints of this type withstood an average of 283 500 repetitions of a cycle in which the tension in the outside plates varied from 0 to 18 000 lb. per sq. in.

The ratio of the static design strength of the plates to the static design strength of the welds,* was 1.07 for the Y series. The fatigue strength of the plates for the specimens of this series was as great as that for any specimens tested, and all specimens failed in the plates,

*1941 A.W.S. Specifications for Welded Highway and Railway Bridges, Formula 5, p. 16, and Formula 9, p. 18.

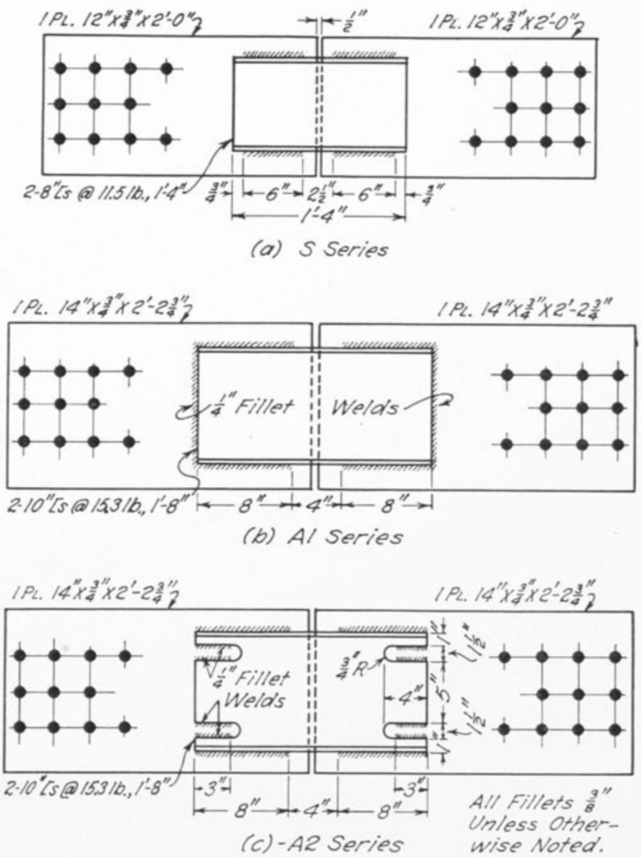


Fig. 3. Various Types of Fillet-Weld Joints Connecting Channels to Gusset Plates

indicating that, for a specimen of this type of balanced design under static loading, the fatigue strength is as great for the weld as for the plate when tested under pulsating loads.

5. *Various Types of Fillet-Weld Joints Connecting Channels to Plates.*—The specimens, shown in Fig. 3, consisted of channels connected to plates with fillet welds. The S specimens had longitudinal fillet welds along the edges of the channel only; the A1 specimens had longitudinal fillet welds along the edges and a transverse fillet weld across the ends of the channels; the webs of the A2 specimens were slotted, and there were longitudinal fillet welds along both edges of the slots as well as along the edges of the channels, but there were no transverse welds.

TABLE 4
FATIGUE STRENGTH OF VARIOUS TYPES OF FILLET-WELD JOINTS CONNECTING CHANNELS TO PLATES

All specimens were tested on a cycle in which the stress varied from 0 to 18 000 lb. per sq. in. tension on the channels. All specimens failed in a channel at the inner end of the longitudinal fillet weld.

Specimen No.	Number of Cycles for Failure in 1000's	Specimen No.	Number of Cycles for Failure in 1000's	Specimen No.	Number of Cycles for Failure in 1000's
S1	553.3	A1-1	870.7	A2-1	631.5
S2	407.6	A1-2	636.2	A2-2	506.1
S3	284.0	A1-3	1 040.7	A2-3	551.7
	Av. 415.0		Av. 849.2		Av. 563.1

The results of the tests are given in Table 4. The simple specimen A1 had the greatest fatigue strength, and the average number of cycles for failure was three times as great for it as for the D specimen of Fig. 2, one of the best of the specimens with fillet welds connecting plates described in Section 3. The arrangement of the welds was the same for the A1 as for the D type of joint, longitudinal fillet welds along the sides and transverse fillet welds across the end. The greater fatigue strength of the channel connection was attributed to the fact that the longitudinal fillet welds were adjacent to the flanges, which constitute a considerable portion of the total section of the channels.

6. *Channel Box Section With Fillet-Weld Connections.*—Truss members of light bridges sometimes consist of rolled channels fabricated so as to form a box section. The specimens of Fig. 4 were designed to represent the ends of such members where they are attached to the gusset plates. There were two types of welded connections and one type of riveted connection. The connections for the GB specimens were the same as for the A1 specimens of Fig. 3, except that there was a ⅛-in. transverse fillet weld at the edge of the gusset plate. The GA specimens had longitudinal fillet welds along the edges and a circular fillet weld across the ends of the channel. The GC specimens had riveted connections such as are used on a riveted truss. The two channels of a specimen were connected by a pair of batten plates at the center for all types of specimens. The gusset plates at each end of a specimen were bolted to the head of the testing machine, which was solid metal for the full thickness and which fitted snugly between the two gussets, thus holding the gussets rigidly to a plane. There were seven specimens of each type, some of which were tested on a cycle in which the stress varied from 0 to 18 000 lb. per sq. in.

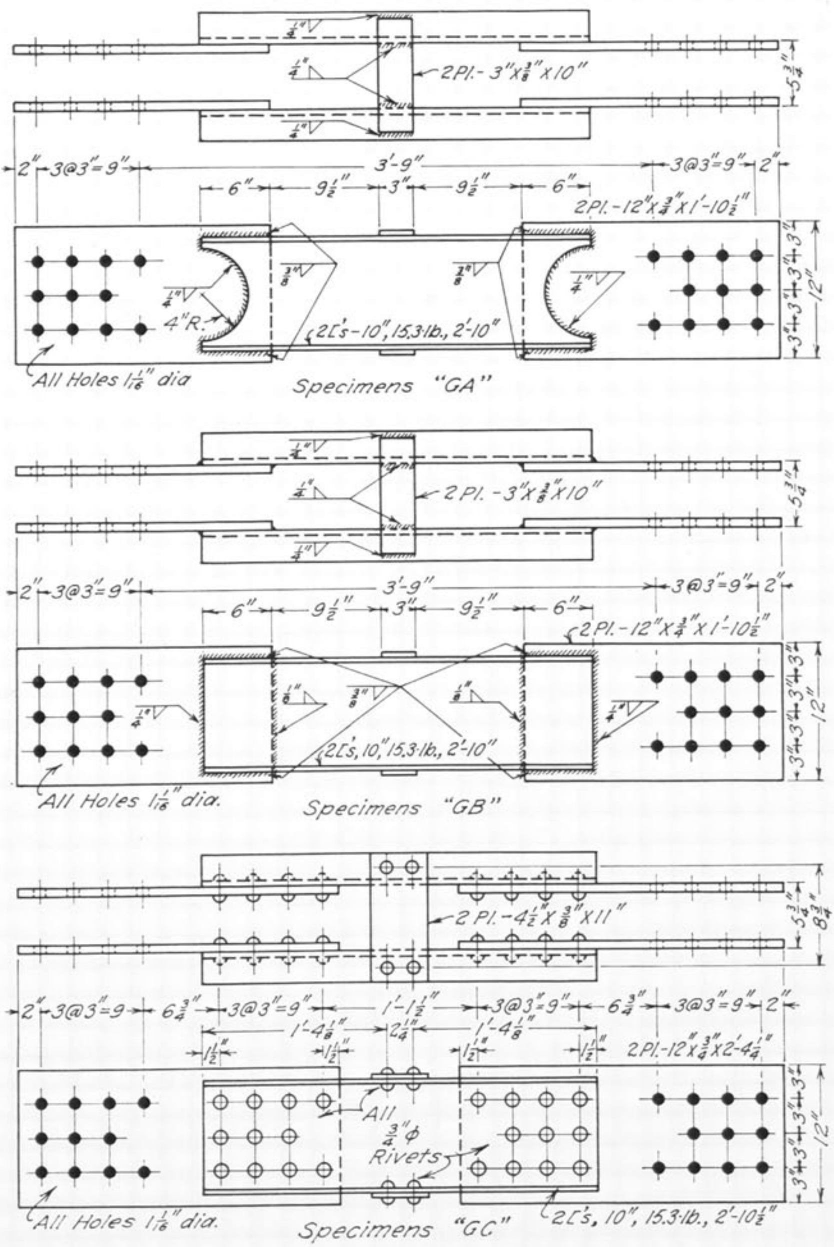


Fig. 4. Channel Box Sections With Fillet-Weld Connections

Table 5

Fatigue Strength of Channel Box Section

All GC specimens failed through the inner transverse row of rivet holes. Except as noted, all other specimens failed in the channel at the inner end of a longitudinal fillet weld.

Specimen No.	Stress Cycle in 1000's of lb. per sq. in. of Gross Section of Channel	Condition of Specimen When Tested	Number of Cycles for Failure in 1000's
GA-1	0 to 18.0	As fabricated	179.7
GA-2	0 to 18.0	As fabricated	140.6
GA-3	0 to 18.0	As fabricated	131.4
			Av. 150.6
GA-4	+12.0 to −12.0	As fabricated	82.1*
GA-5	+12.0 to −12.0	Outside fillet weld of batten plate removed	133.2
GA-6	+12.0 to −12.0	Outside fillet weld of batten plate removed	102.3
			Av. 105.9
GA-7	+12.0 to −12.0	Batten plates off	86.8
GB-1	0 to 18.0	As fabricated	294.4
GB-2	0 to 18.0	As fabricated	227.4*
GB-3	0 to 18.0	As fabricated	199.3*
			Av. 240.4
GB-4	+12.0 to −12.0	Outside fillet weld of batten plate removed	165.5
GB-5	+12.0 to −12.0	Outside fillet weld of batten plate removed	192.8†
GB-6	+12.0 to −12.0	Outside fillet weld of batten plate removed	207.5†
			Av. 188.6
GB-7	+12.0 to −12.0	Diaphragm welded on between gusset plates	125.5
GC-1	0 to 18.0	As fabricated	207.6
GC-2	0 to 18.0	As fabricated	257.5
GC-3	0 to 18.0	As fabricated	202.5
GC-4	0 to 18.0	As fabricated	248.9
			Av. 229.1
GC-5	+12.0 to −12.0	As fabricated	228.6
GC-6	+12.0 to −12.0	As fabricated	169.0
GC-7	+12.0 to −12.0	As fabricated	143.7
			Av. 180.4

*Failed in channel at batten plate, which was welded on.
†Failed in gusset plate at end of channel.

tension on the gross section of the channels; the others were tested on a cycle in which the stress varied from 12 000 lb. per sq. in. tension to an equal compression. The results of the tests are given in Table 5.

The batten plates of the welded specimens were attached to the flanges of the channels with fillet welds at the edge of the web and at the outer edge of the flanges. The latter were such severe stress raisers that they caused the channels to fail at the ends of the fillet welds connecting the batten plates to the flanges for specimens GA-4, GB-2 and GB-3. For this reason the fillet welds connecting the batten plates to the edges of the flanges were ground off for the remaining welded specimens. The welds connecting the battens to the webs of the channels proved to be sufficient to connect the battens to the channels, and they were not effective enough as stress raisers to cause fracture. Specimens GB-5 and GB-6 failed in the gusset plates rather than in the channel. All other welded specimens failed in the channels at the inner end of the longitudinal fillet welds connecting the channels to the gusset plates.

The batten plates were removed from GA-7, which was tested on a cycle in which the stress varied from 12 000 lb. per sq. in. tension to an equal compression, but the eccentricity of the channels relative to the gusset plates was so great that the channels deflected laterally under the reversed-load cycle. The low value of the fatigue strength for GA-7 may have been due to this excessive lateral deflection. Even with the battens on, there was considerable lateral deflection in the specimens tested on a reversed-load cycle. Diaphragms were welded between the gusset plates at their outer edges for GB-7. This prevented the channels from weaving in and out under the action of the reversed load, but apparently reduced the fatigue strength slightly. Reducing the flexibility of the channels may have increased the flexural stress near their ends where fatigue failure occurred.

Strain readings were taken with a Berry 2-in. strain gage at various sections of some specimens, the fatigue machine being cranked by hand while the readings were taken.

The stress diagrams for two of the GC specimens are shown on Fig. 5. One set of readings was taken on a section near the top and one on a section near the bottom, as shown on the sketch at the left of the figure. The location of the gage lines around the section is shown at the bottom of the sketch at the right. The stress distribution is shown by the diagrams with the developed section of the channel as a base line. The diagrams at the top are for specimen GC-5, and those at the bottom are for specimen GC-6, both specimens having been tested as originally fabricated. Each set of diagrams represents the average of the readings on four similarly-located sections, one at the top and one at the bottom of both the near and the far channels. For each set of diagrams, the line above the base line represents the stress when the specimen was in tension, and the line below the base line represents the stress when the specimen was in compression.

These diagrams are of interest only in that they show the variation in the simultaneous stress on the particular section at which the strain was measured. They do not necessarily show the relative uniformity of stress distribution for different types of members, because readings were not taken on enough sections to insure that they were

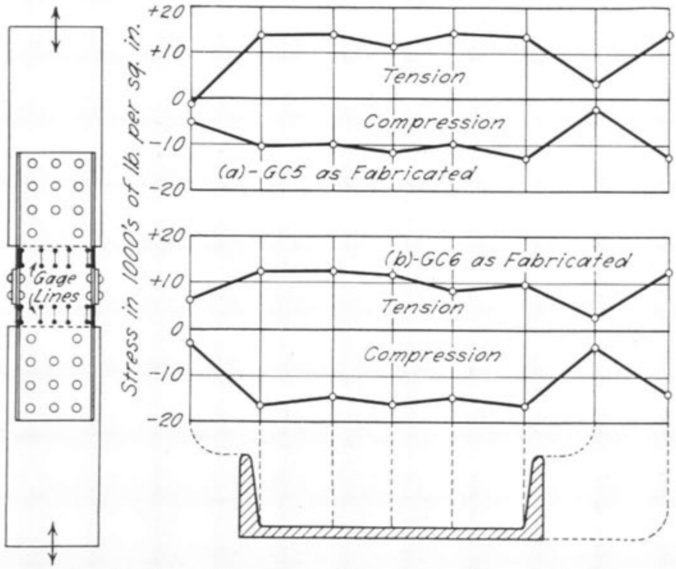


Fig. 5. Stress Diagrams; Specimens GC5 and GC6

taken on the section for which the stress distribution was the most uneven for the particular specimen being considered.

The diagrams of Fig. 5 indicate that, in loading the member GC-5 to an average tension of 12 000 lb. per sq. in., there were some points in the web where the stress was as high as 14 000 lb. per sq. in. tension, and some points in the flange where the simultaneous stress was as low as 1000 lb. per sq. in. compression. The fatigue crack developed in the web of the channel through the inner transverse row of rivet holes where the stress, taking into account the stress-raising effect of the holes, probably exceeded the yield point of the steel at the edge of the hole. This being true, the fatigue strength was probably only slightly affected, if at all, by the flexural stress due to the eccentricity of the channel relative to the web, but was determined largely by the stress-raising effect of the rivet holes. The similarity of the stress patterns for the two specimens is of interest.

The stress diagrams for some of the GA specimens are shown on Fig. 6. The upper diagrams are for GA-4 as fabricated, the middle diagrams are for GA-5 with the fillet welds connecting the batten plates to the outside edges of the flanges ground off, and the lower diagrams are for GA-7 with the batten plates removed. The upper diagrams show that for GA-4 as originally fabricated, when the average stress on the specimens was 12 000 lb. per sq. in. tension, the

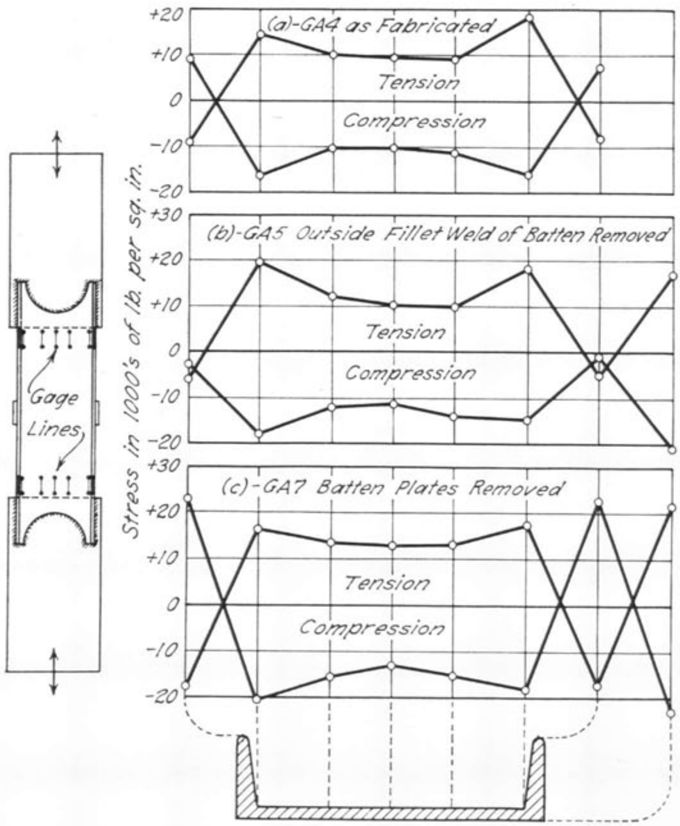


FIG. 6. STRESS DIAGRAMS; SPECIMENS GA4, GA5, AND GA7

maximum stress in the web on the sections near the ends was as great as 18 000 lb. per sq. in. tension, whereas the minimum simultaneous stress at the edge of the flange was as small as 8000 lb. per sq. in. compression. The middle diagrams show that, for GA-5 with the welds connecting the batten to the edges of the channel flanges ground off, when the average stress was 12 000 lb. per sq. in. tension, the maximum stress in the web on sections near the ends was as great as 19 000 lb. per sq. in. tension and the minimum simultaneous stress at the edge of the flange was as small as 6000 lb. per sq. in. compression. Similarly the lower diagrams show that for GA-7, with both battens removed, an average stress on the section of 12 000 lb. per sq. in. produced a stress in the web on sections near the ends as high as 21 000 lb. per sq. in. tension and a simultaneous stress in the flange as low as 17 000 lb. per sq. in. compression.

The strain in the web increased toward the edge of the channel where the longitudinal fillet weld transmitted the load to the gusset plate. The center of the gage length was out about 1½ in. from the end of the weld. It is reasonable to suppose that strain readings, if taken closer to the end of the fillet, would have shown an even more marked increase in the stress at the edge of the web than is given by the diagrams of Fig. 6. The fatigue fracture of all welded specimens (except GB-5 and GB-6, which failed through the bolt holes in the gusset plates, and GA-4, GB-2, and GB-3, which failed where the batten plates were attached), occurred at the inner end of the longitudinal fillet weld. It would seem, therefore, that the higher-than-average stress at the edge of the web, together with the abrupt change in section at the end of the weld, weakened the channel in fatigue.

The stress diagrams for specimens GB-6 and GB-7 are shown in Fig. 7. The diagrams at the top of the figure are for the stress near the top and bottom of the members, the same as has already been explained in connection with Figs. 5 and 6. The diagrams at the bottom of the figure are for the stress at the two sections near the middle, one just above and the other just below the middle, as shown in the sketch at the left. It is of interest to note that the stress was quite uniform over the sections near the center for both specimens. However, failure started at the ends where the stress pattern for the GB specimens was very similar to the stress pattern for the GA specimens of Fig. 6.

There is no reason to suppose that the stress was any more unevenly distributed over the sections of the fatigue specimens tested than it would be over the sections of similar members of a bridge truss.

The fatigue strength of specimens GA-4, GB-2, and GB-3, which failed at the end of the fillet welds connecting the battens to the edges of the channels, was probably reduced somewhat by this detail. Moreover, specimens GB-5 and GB-6, which failed through the holes in the gusset plates connecting the channels to the heads of the testing machine, would, with proper connecting plates, have a fatigue strength at least slightly greater than the values reported. Taking into account these irregularities, the tests reported in Table 5 appear to justify the following statements relative to the fatigue strength based upon the gross area of the channels.

The values of the fatigue strength of the three types of connections for members with channel box sections, were very nearly equal, the values for the GB welded connections and of the GC riveted connections being slightly greater than the values for the GA welded connections. The fatigue strength was somewhat lower for the two-channel members with a box section than it was for the two-channel

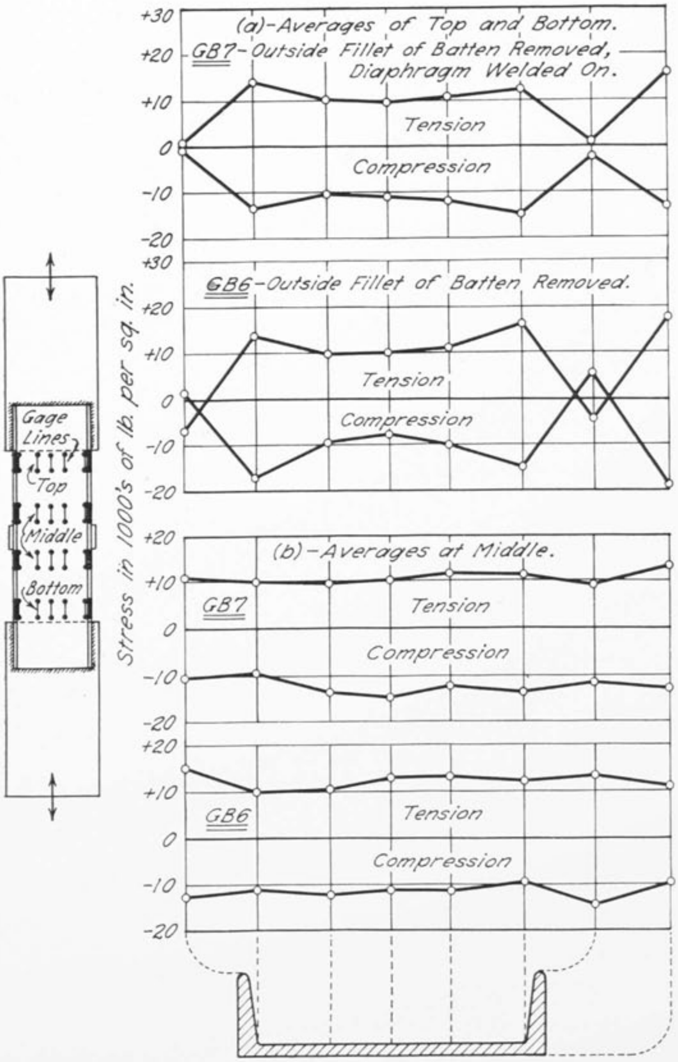


FIG. 7. STRESS DIAGRAMS; SPECIMENS GB6 AND GB7

members with the channels back-to-back with a gusset plate between, described in Section 5.

For all three types of specimens, the fatigue strength was approximately ⅔ as great for a cycle in which the stress varied from tension to an equal compression as it was for a cycle in which the stress varied from 0 to tension.

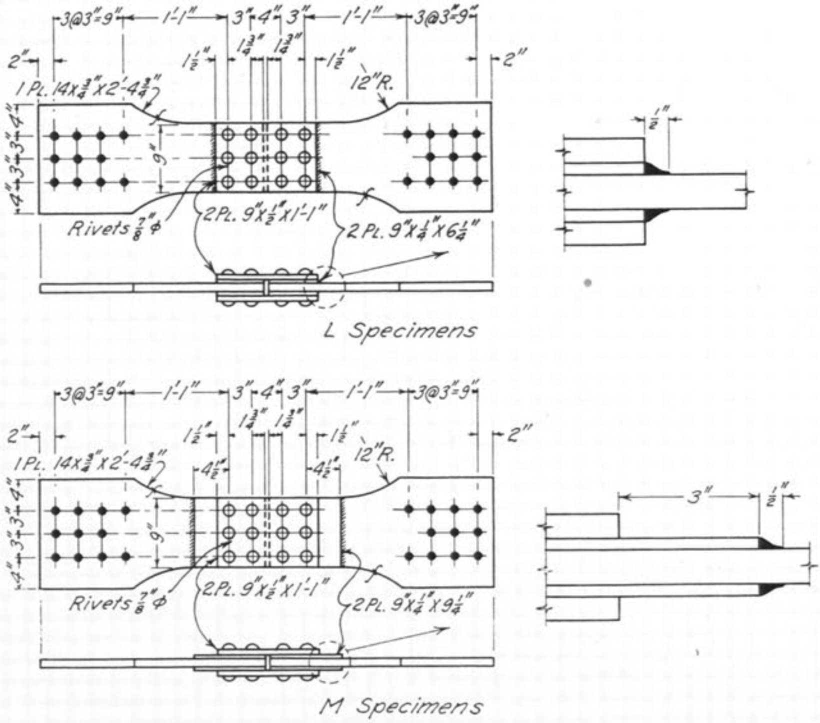


FIG. 8. COMPOSITE RIVETED AND FILLET-WELD JOINTS CONNECTING PLATES

7. *Composite Riveted and Fillet-Weld Joints Connecting Plates.*—The details of two types of composite riveted and fillet-weld connections that were tested statically and in fatigue are shown in Fig. 8. The basic idea of the design was to reinforce the section weakened by the rivet holes with a thin plate connected to the main plate with a transverse fillet weld. The two types of specimens, L and M, differed in the detail that, for L, the end of the reinforcing plate was flush with the end of the butt strap, whereas, for M, the reinforcing plate extended 3 in. beyond the butt strap. Simple riveted specimens, J, identical with the K specimens of Fig. 20, page 54, were used as controls with which to compare the strength of the composite specimens. There were four specimens of each type, one was tested statically, and the other three were tested in fatigue. The plates for all specimens were from the same heat. The results of the tests are given in Table 6.

The first riveted control specimen, J1, was tested on a cycle in which the stress varied from 0 to 30 000 lb. per sq. in. tension on the

TABLE 6
FATIGUE STRENGTH OF COMPOSITE RIVETED AND FILLET-WELD JOINTS CONNECTING PLATES

Specimen No.	Stress in 1000's of lb. per sq. in. Tension on Gross Section of ¾-in. Plate	Number of Cycles for Failure in 1000's
J1	0 to 30.0	37.6*
J2	0 to 27.0	234.6
J3	0 to 27.0	226.6
		Av. 230.6
Static strength—45 400 lb. per sq. in. tension on gross area of plate.		
L1	0 to 27.0	336.0
L2	0 to 27.0	245.6
L3	0 to 27.0	429.8
		Av. 337.1
Static strength—61 600 lb. per sq. in. tension on gross area of plate.		
M2	0 to 27.0	213.2
M3	0 to 27.0	286.3
M4	0 to 27.0	244.9†
		Av. 248.1
Static strength—60 900 lb. per sq. in. tension on gross area of plate.		

*Not included in average.
†Broke in first line of bolt holes in the head of the main plate, all other composite specimens broke at the outside edge of the transverse fillet welds. All J riveted specimens broke through the outside row of rivet holes in the ¾-in. plate.

gross section of the main plate. The number of cycles for failure was undesirably small, so the remaining specimens were tested on a cycle in which the stress varied from 0 to 27 000 lb. per sq. in. of the gross section of the main plate.

All composite specimens except M4 broke in the ¾-in. main plate at the outside edge of the transverse fillet weld where the change in section, possibly augmented by metallurgical damage, acted as a stress raiser that proved to be practically as injurious as the rivet holes in the plate of the simple riveted specimens. The drawing called for an elongated concave fillet weld and the contour of the actual welds was excellent in every way. Specimen M4 broke in the first line of bolt holes in the head of the main plate.

The average fatigue strength was not significantly greater for the composite riveted and fillet-weld joints than for the simple riveted joints.

The static strength of the control specimen, the simple riveted joint, J, was 45 400 lb. per sq. in. on the gross section of the main plate, and failure was in the main plate on a section through the outer transverse row of rivet holes. The static strength of the composite specimens was 61 600 and 60 900 lb. per sq. in. on the gross section of the main plate for the L and M specimens, respectively. Failure was

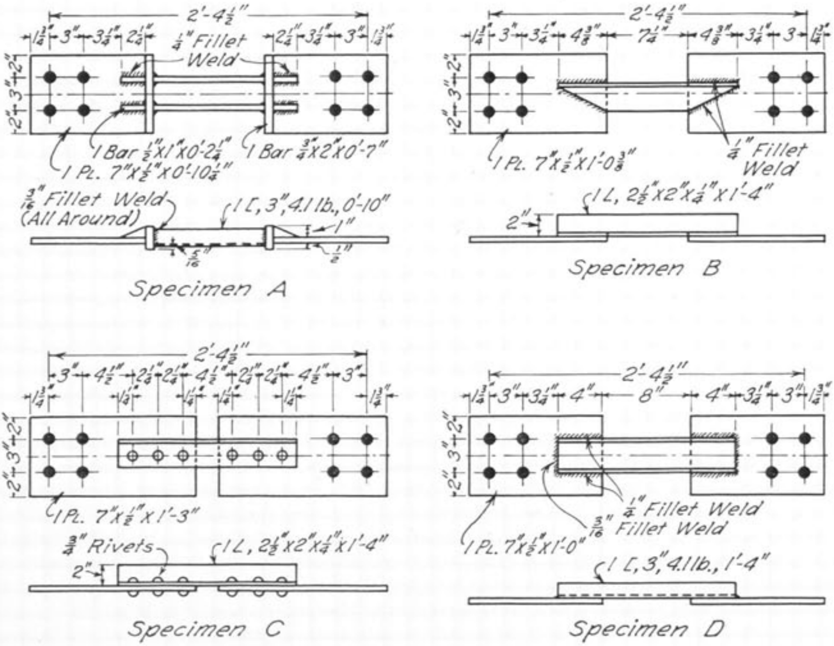


FIG. 9. DETAILS OF LATERAL CONNECTIONS

by rivet shear, and there was no evidence of impending failure in either the weld or the adjacent plate. Although the fatigue strength was not significantly greater for the composite specimens than for the simple riveted specimens, the tests indicated that it is possible to make a composite riveted and fillet-weld joint that will develop the full static strength of the gross section of the main plate. Moreover, for the composite joints shown in Fig. 8, all welding for a field connection can be done in the shop prior to other fabricating processes. Furthermore, the arrangement of the details is such that slip in the riveted joint does not affect the distribution of the load between the rivets and the welds.

8. *Fatigue Strength of Connections for Laterals.*—Fatigue tests were made on four types of end connections for laterals to determine their relative fatigue strength.* The details of the specimens are shown in Fig. 9.

Specimens A and D were welded connections for channels. They differed from each other in that A had a butt weld (really a transverse fillet weld that completely circumscribed the channel at its

*The specimens and the funds with which to pay the cost of the tests were contributed by the Aetna Iron and Steel Company, Jacksonville, Florida.

ends), and the gravity plane of the channel coincided with the gravity plane of the gusset plates, thus eliminating flexure; whereas, for D, the channel was connected to the gusset plates with longitudinal and transverse fillet welds. Moreover, for the latter, the gravity plane of the gusset plates was 0.69 in. from the parallel gravity plane of the channel and, as a result, the channel was subjected to considerable flexure.

Specimens B and C were connections for angles, B being a welded and C a riveted connection. The angles for the two types of specimens had the same section and the same eccentricity with respect to the gusset plates. This eccentricity, 0.79 in., was somewhat greater than the eccentricity for the channel specimens of the D type.

Although the flexural stress was considerable for all except the A specimens, the stress reported for the tests was the quantity, P/A, in which P is the total axial load on the specimen in pounds, and A is the area of the gross section of the angle or channel in square inches. Because of the eccentricity, the combined axial and flexural stress greatly exceeded P/A, the average stress. All specimens were tested on a cycle in which the axial load varied from 0 to tension.

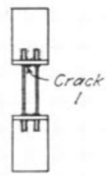
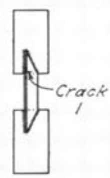
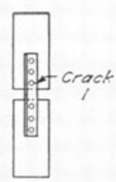
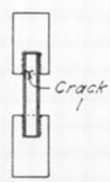
The results of the individual tests are given in Table 7. The S–N diagrams are shown in Figs. 10 and 11. The tests of the channel specimens, series A and D, were fairly consistent, and the two S–N diagrams of Fig. 10 are parallel. The tests of the welded angles, series B, were fairly consistent, and the position and direction of the S–N diagram, shown in Fig. 11, was fairly well established. The tests of the riveted angles, series C, were so inconsistent that the S–N diagram could not be determined from them. Instead, the results of the tests are represented by the small solid circles of Fig. 11, as distinguished from the small open circles which represent the results of the tests of the welded angles. It is of interest to note that the results of the tests are much more inconsistent, and, in general, the values of the fatigue strength based upon the gross section were less, for the riveted than for the welded angles.

Static tests of control specimens cut from the angles and channels gave the following results, each value being the average for four tests.

	Strength in lb. per sq. in.	
	Yield Point	Ultimate
Angles	49 450	66 650
Channels	46 100	63 400

TABLE 7

FATIGUE STRENGTH OF LATERAL CONNECTIONS

Specimen No.	Stress, S, in 1000's of lb. per sq. in.	Number of Cycles* for Failure, N, in 1000's	Fatigue Strength, F, in 1000's of lb. per sq. in.		Location of Failure
			n = 100 000	n = 2 000 000	
Channels Butt-welded Centrically to Gusset Plates					
A1	0 to 30.0	50.2	26.0		1
A2	0 to 25.0	88.4	24.6		1 
A3	0 to 20.0	126.6	21.0		1
A4	0 to 20.0	204.0	23.2		1
			Av. 23.7		
A5	0 to 10.0	2 370.8		10.0+	1
A6	0 to 10.0	3 935.3		10.0+	1
A7	0 to 12.0	4456.7		12.0+	No Failure
A8	0 to 12.0	3 568.7		12.0+	No Failure
				Av. 11.0+	
Angles Fillet-welded Eccentrically to Gusset Plates					
B1	0 to 10.0	2 572.0		10.0+	1
B2	0 to 10.1	5 177.0		10.1+	No Failure 
B4	0 to 12.8	511.8		9.88	1
B5	0 to 12.8	555.0		10.03	1
				Av. 10.0+	
B3	0 to 16.0	507.8	21.79		1
B6	0 to 16.0	494.0	21.68		1
B7	0 to 19.3	56.4	17.31		1
B8	0 to 19.3	34.3	15.76		1
			Av. 19.14		
Angles Riveted Eccentrically to Gusset Plates					
C1	0 to 10.0† 0 to 12.62	296.0			1
C2	0 to 10.0 0 to 12.62	5910.7			No Failure 
C4	0 to 15.0 0 to 18.93	1092.4			1
C5	0 to 12.8 0 to 16.15	209.3			1
C6	0 to 12.8 0 to 16.15	1909.3			1
C7	0 to 16.0 0 to 20.2	206.9			1
C8	0 to 12.8 0 to 16.15	205.7			1
Channels Fillet-welded Eccentrically to Gusset Plates					
D1	0 to 25.0	55.9	21.9		1
D2	0 to 25.0	41.8	20.2		1 
D3	0 to 20.0	47.5	16.6		1
D4	0 to 20.0	68.6	18.1		1
D7	0 to 18.0	108.4	18.1		1
			Av. 18.98		
D5	0 to 10.0	1137.1		8.8	1
D6	0 to 10.0	1688.1		9.7	1
D8	0 to 12.8	1011.4		11.2	1
				Av. 9.9	

* - Cycle was 0 to tension for all specimens.

† - Values in upper line based on gross section, those in lower line on net section.

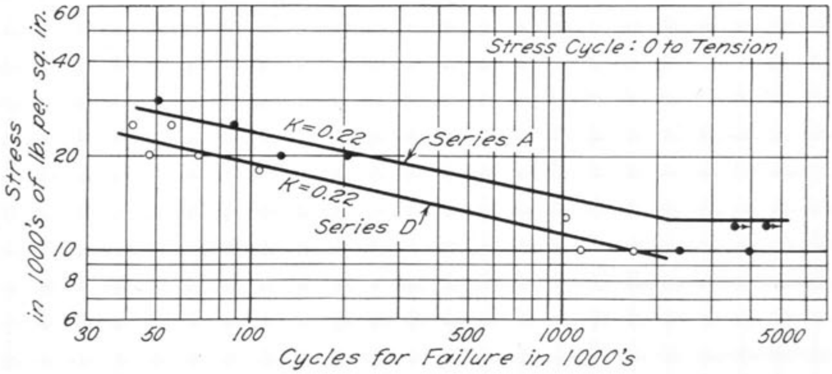


Fig. 10. S–N Diagrams for Series A and D; Lateral Connections

A summary of the results is given in Table 8. The average and minimum values of the fatigue strength for each type of specimen are given in adjacent columns. The values given are expressed in terms of the quotient obtained by dividing the axial load by the area of the gross section.

The following comparisons are of interest.

(a) The values of the fatigue strength of the individual specimens were much more erratic for the riveted angles than they were for either the welded angles or the welded channels, and minimum values based upon the gross section were, in general, less for the riveted than for the welded angles.

(b) There was no significant difference in the fatigue strengths of the angles and channels when they were both eccentrically connected with fillet welds.

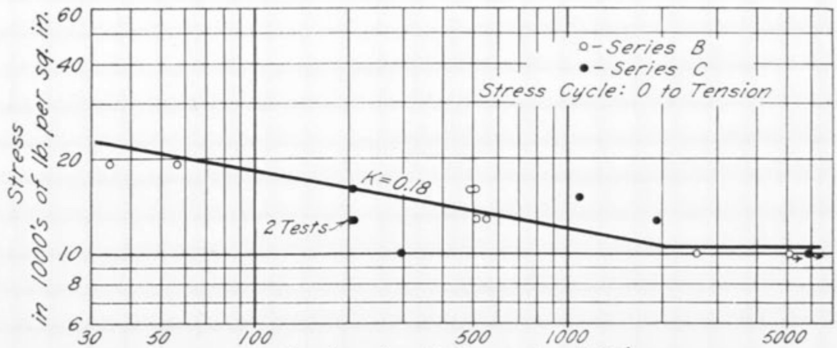


Fig. 11. S–N Diagrams for Series B and C; Lateral Connections

TABLE 8

FATIGUE STRENGTH OF LATERAL CONNECTIONS; SUMMARY OF RESULTS

Stress range: 0 to tension.
Series A—Butt-welded channels.
Series B—Fillet-welded angles.
Series D—Fillet-welded channels.

Series	Fatigue Strength in 1000's of lb. per sq. in.			
	$n = 100\ 000$		$n = 2\ 000\ 000$	
	Average	Minimum	Average	Minimum
A	23.7	21.0	11.0+	10.0+
B	19.1	15.8	10.0+	9.9
D	19.0	16.6	9.9	8.8

(c) The fatigue strength was 20 per cent less for the channels with longitudinal and transverse fillet welds and a relatively large eccentricity than for the channels with butt welds and no eccentricity.

(d) Failure of all specimens with longitudinal fillet welds occurred in the main member and at the end of the weld toward the center of the specimen. No welds failed.

(e) Failure of the specimens with butt welds occurred in the channel at the junction with the weld where the abrupt change in section caused a large stress concentration.

(f) Failure of the riveted angles occurred at the inner rivet hole and on the side away from the outstanding leg, as shown by the sketch in Table 7. The fatigue strength was probably reduced by the eccentricity of the rivet hole as well as by the hole itself. No rivets either failed or loosened.

9. *Fatigue Strength of Fillet Welds.*—The specimens for the exploratory tests of Section 3 that were tested in tension all failed in the plate, and the only specimens that gave any indication of the fatigue strength of a fillet weld in shear were those tested in compression. There were so few of these that additional tests seemed necessary. The specimens of Fig. 12, channels connected to plates, were designed to fail in the welds. There were four series of tests; series E* and G had transverse fillet welds across the ends and series F* and H had longitudinal fillet welds along the edges. The difference between the E and G specimens was that the welds were peened for the G specimens but were not peened for the E specimens. Likewise, the welds were peened

*The specimens of series 2E were identical with those of series E; likewise, the specimens of series 2F were identical with those of series F.

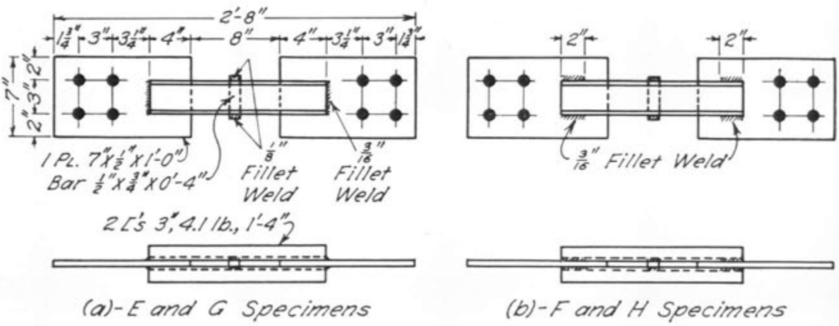


FIG. 12. FILLET-WELD JOINTS DESIGNED TO FAIL IN WELD

for the H specimens but were not peened for the F specimens. The welding procedures for the various specimens are given in Table 9. Some of the specimens were tested on a cycle in which the stress in the body of the specimen varied from 0 to tension, others were tested on a cycle in which this stress varied from tension to an equal compression.

The results of the individual tests are given in Table 10, and the results are summarized in Table 11.

The unpeened 3/16-in. transverse fillet welds of series E withstood an average of 454 300 repetitions of a cycle in which the stress* at the throat of the weld varied from 0 to 20 000 lb. per sq. in., and the unpeened welds of series 2E withstood an average of 189 200 repetitions of a cycle in which the stress at the throat of the weld varied

*This stress was taken equal to the total load divided by the total area of a section longitudinal with the weld and through its throat.

TABLE 9

WELDING PROCEDURE FOR FILLET-WELD SPECIMENS DESIGNED TO FAIL IN WELDS

All specimens were welded in the flat position with a 5/32-in. electrode. One welder, who had been qualified by a commercial inspection bureau, welded all specimens. All welds were made with a single pass.

Specimen No.	Direction of Fillet	Polarity	Electrode	Volts	Amperes	Peening
E1 to E9 and 2E1 to 2E9	Transverse	Reversed	E6010	30	125	None
G1 to G8						Peened while still hot with a round-nosed pneumatic tool
F1 to F9 and 2F1 to 2F9	Longitudinal	Straight	E6012	28	190	None
H1 to H8						Peened while still hot with a round-nosed pneumatic tool

TABLE 10
FATIGUE STRENGTH OF FILLET-WELD CONNECTIONS DESIGNED TO FAIL IN WELDS

Specimen No.	Direction of Fillet	Peened	Unit Stress in 1000's of lb. per sq. in. on Throat of Fillet	Number of Cycles for Failure in 1000's
E1	Transverse	No	0 to 25.0	245.7
E2			0 to 25.0	263.8
E3			0 to 25.0	218.0
				Av. 242.5
G6		Yes	0 to 25.0	480.2
G7			0 to 25.0	211.9
G8			0 to 25.0	271.7
				Av. 321.3
E7		No	0 to 20.0	312.0
E8			0 to 20.0	591.6
E9			0 to 20.0	459.2
				Av. 454.3
G1		Yes	0 to 20.0	803.3
G2			0 to 20.0	1 395.5
G3			0 to 20.0	1 612.7
				Av. 1 270.5
F1	Longitudinal	No	0 to 25.0	81.5
F2			0 to 25.0	237.0
F3			0 to 26.0	62.5†
F4			0 to 25.0	313.6
F5			0 to 25.0	397.9*
				Av. 257.5
H2		Yes	0 to 25.0	19.2
H3			0 to 25.0	17.2
H4			0 to 25.0	36.4
				Av. 24.3
F6		No	0 to 20.0	1 033.1*
F7			0 to 20.0	429.9
F8			0 to 20.0	248.6
F9			0 to 18.0	2 072.7†
				Av. 570.5
H6		Yes	0 to 20.0	68.0
H7			0 to 20.0	81.5
H8			0 to 20.0	5.5
				Av. 51.7
2E1	Transverse	No	+16.0 to −16.0	322.0
2E2			+16.0 to −16.0	245.8
2E3			+16.0 to −16.0	89.7
2E4			+16.0 to −16.0	149.4
2E5			+16.0 to −16.0	139.0
				Av. 189.2
2E7		No	+13.0 to −13.0	559.0
2E8			+13.0 to −13.0	1 885.2
2E9			+13.0 to −13.0	622.0
				Av. 1 022.1
2F1	Longitudinal	No	+16.0 to −16.0	123.3
2F2			+16.0 to −16.0	69.4
2F3			+16.0 to −16.0	53.2
2F4			+16.0 to −16.0	83.7
				Av. 82.4
2F7		No	+13.0 to −13.0	716.8
2F8			+13.0 to −13.0	369.6
2F9			+13.0 to −13.0	330.8
				Av. 472.4

*Failed in channel; all others failed in the weld.
†Not included in average because unit stress was different from that for other tests of the group.

TABLE 11

FATIGUE STRENGTH OF FILLET-WELD CONNECTIONS DESIGNED TO FAIL IN WELDS; SUMMARY OF RESULTS

Each value is the average of three or more tests. Specimens G and H were peened, the others were not.

Series	Peened	Unit Stress in 1000's of lb. per sq. in. on Throat of Fillet	Number of Cycles for Failure in 1000's	
			Average	Minimum
Specimens With Transverse Fillet Welds				
E	No	0 to 25.0	242.5	218.0
G	Yes	0 to 25.0	321.3	211.9
E	No	0 to 20.0	454.3	312.0
G	Yes	0 to 20.0	1 270.5	803.3
2E	No	+16.0 to −16.0	189.2	89.7
2E	No	+13.0 to −13.0	1 022.1	559.0
Specimens With Longitudinal Fillet Welds				
F	No	0 to 25.0	257.5	81.5
H	Yes	0 to 25.0	24.3	17.2
F	No	0 to 20.0	570.5	248.6
H	Yes	0 to 20.0	51.7	5.5
2F	No	+16.0 to −16.0	82.4	53.2
2F	No	+13.0 to −13.0	472.4	330.8

from 16 000 lb. per sq. in. in one direction to an equal stress in the opposite direction.

The unpeened $\frac{3}{16}$-in. longitudinal fillet welds of series F withstood an average of 570 500 repetitions of a cycle in which the shear at the root of the weld varied from 0 to 20 000 lb. per sq. in. and the unpeened welds of series 2F withstood an average of 82 400 repetitions of a cycle in which the shear at the root of the weld varied from 16 000 lb. per sq. in. in one direction to an equal shear in the opposite direction.

For the specimens with longitudinal fillet welds, the number of cycles for failure was less for the welds that were peened than it was for the welds that were not peened. The reverse was true for specimens with transverse fillet welds.

Unfortunately, the details of the peening procedure were not reported, and it is not definitely known whether the difference in fatigue strength was really due to peening or due to some variation in the welding procedure. The fact, however, that, for specimens with longitudinal fillet welds, the average number of cycles for failure was 5 to 10 times as great for unpeened welds as it was for peened welds, indicates that additional parallel tests should be made on peened and unpeened welds for which the welding and peening procedures are carefully controlled.

III. Plug Welds

10. *Fatigue Strength of Plug Welds.*—Tests were made to determine the fatigue strength of plug welds connecting carbon-steel plates. The specimens for the first series, shown in Fig. 13, each had two plug welds which completely filled the holes in the outside plates.

All the tests were made on a cycle in which the load on the specimen varied from 0 to tension. The maximum unit shear on the plugs during a cycle had values, based on the nominal diameter of the plug, of 45 000, 25 000, and 20 000 lb. per sq. in. for specimens G1, G2, and G3, respectively. All of the other specimens were tested on a cycle in which the stress varied from 0 to 25 000 lb. per sq. in. shear on the plugs.

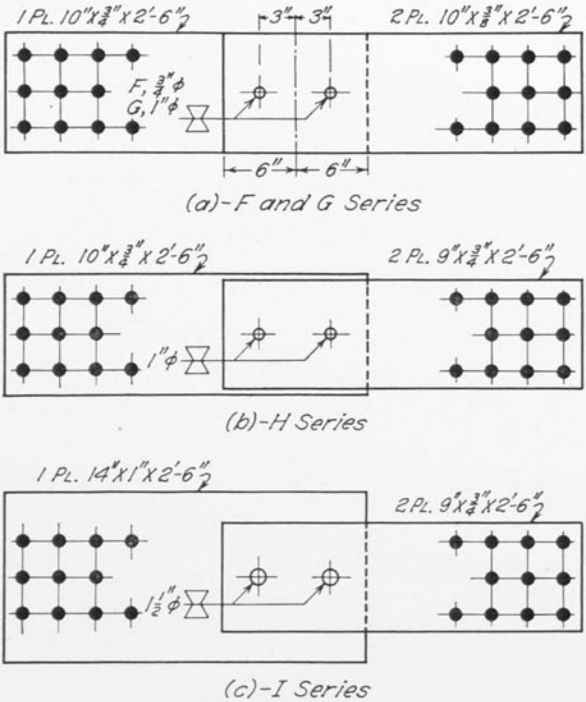


Fig. 13. Details of Plug-Weld Specimens Designed to Fail in Plugs; First Series

TABLE 12

FATIGUE STRENGTH OF PLUG-WELD JOINTS DESIGNED TO FAIL IN PLUGS; FIRST SERIES

Specimens detailed on Fig. 13.

Specimen No.	Stress Cycle in 1000's of lb. per sq. in. Shear on Plug*	Number of Cycles for Failure in 1000's	Specimen No.	Stress Cycle in 1000's of lb. per sq. in. Shear on Plug*	Number of Cycles for Failure in 1000's
¾-in. Plug—⅜-in. Outside Plates			1-in. Plug—¾-in. Outside Plates		
F1	0 to 25.0	521.7	H1	0 to 25.0	112.3
F2	0 to 25.0	268.3	H2	0 to 25.0	144.9
F3	0 to 25.0	351.9	H3	0 to 25.0	246.3
		Av. 380.6			Av. 167.8
1-in. Plug—⅜-in. Outside Plates			1½-in. Plug—¾-in. Outside Plates		
G1	0 to 45.0	6.5	I1	0 to 25.0	51.3
G2	0 to 25.0	67.2	I2	0 to 25.0	76.6
G3	0 to 20.0	270.8	I3	0 to 25.0	67.1
					Av. 65.0

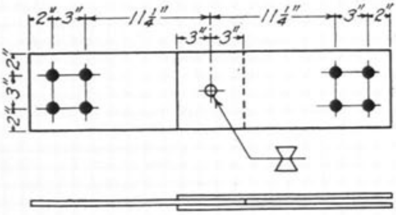
*Based upon area of hole in outside plates.

The results of the tests are given in Table 12. All specimens failed in the plugs and, usually, by tearing out the base plate for a depth of 1/16 in. to ⅛ in. at the root of the plug.

The number of cycles for failure decreased with an increase in the diameter of the plug, the average number being 380 600, 167 800, and 65 000 for ¾-in., 1-in., and 1½-in. plugs, respectively. This may have been due to the fact that, because of fusion of the base metal, the effective diameter of the plug was greater than the nominal diameter and the effect of this oversize was greater, relatively, for a small than for a large plug.* Although the tests of the G and H specimens are not directly comparable, it would seem that changing the plate thickness for a 1-in. plug from ⅜ in. to ¾ in. increased the fatigue strength of the plug by a small amount for this series.

The second series of tests of plug-weld specimens was more extensive than the first series, and was planned to give the fatigue strength of plugs of various diameters when connecting plates of various thicknesses. The details of the specimens are shown in Fig. 14. All specimens were tested on a cycle in which the load varied from 0 to tension. Most of the specimens were tested on a cycle in which the stress varied from 0 to 20 000 lb. per sq. in. shear on the nominal diameter of the plug. One specimen from each group, except PA, PB,

*See Metallurgical Studies, Section 16, p. 56.



Specimen Number	Plug Diameter	Plate Thickness Outside	Plate Thickness Inside
PA		1/4"	1/2"
PB	13/16"	3/8"	1/2"
PC		1/2"	1/2"
PD		5/8"	5/8"
PE		5/16"	1/2"
PF		3/8"	1/2"
PG	15/16"	1/2"	1/2"
PH		5/8"	5/8"
PI		3/4"	3/4"
PJ		3/8"	1/2"
PK		1/2"	1/2"
PL	1 1/16"	5/8"	5/8"
PM		3/4"	3/4"
PN		7/8"	3/4"

Fig. 14. Details of Plug-Weld Specimens Designed to Fail in Plugs; Second Series

and PF, was subjected to a static test. All specimens failed by shear on the plug for both static and fatigue tests. The results of the individual tests are given in Table 13.

The data in Table 13 have been summarized and rearranged in the following tabulations so as to indicate the relation between the fatigue strength and the geometrical characteristics of the specimen. The values in the first tabulation show a small but quite consistent increase in the fatigue strength with an increase in the thickness of the outside plates. The values in the second tabulation show a slight but not always consistent decrease in the unit fatigue strength of the plugs with an increase in their diameter, the unit stress being based upon the nominal diameter of the plugs in all instances. Because of the penetration, the actual diameter was greater than the nominal diameter of the plugs. With equal penetration for all, the oversize would be greater, relatively, for a small than for a large plug. This may account for the decrease in unit fatigue strength with the increase in the diameter of the plug.

The plug welds of the second series were consistently about 5000 lb. per sq. in. weaker in fatigue than the specimens of the first series. The specimens of the first series had two plugs in a line. The specimens of the second series were one-plug joints. Plug welds do not clamp the plates together and there is a possibility that the flexural stress in the plugs was greater for the one-plug than for the two-plug joints. This

Thickness of Inside Plate, in.	Plug Diameter, in.	Thickness of Outside Plates, in.	Average Number of Cycles to Failure, thousands
		1/4	91.3
1/2	13/16	3/8	162.8
		1/2	204.4
		5/16	110.0
1/2	15/16	3/8	123.3
		1/2	246.2
1/2	1 1/16	3/8	74.0
		1/2	77.7
3/4	1 1/16	3/4	279.6
		7/8	292.8

is a possible explanation of the relatively low fatigue strength of the one-plug joints.

The static strength of the plugs was of the order of 50 000 lb. per sq. in. shear on the nominal diameter, a strength approximately equal to the strength in shear of driven carbon-steel rivets such as are used for carbon-steel bridges and buildings. Moreover, the fracture of the plug resulting from the static test was similar in appearance to the fracture of a carbon-steel rivet subjected to a similar test.

The fatigue strength corresponding to failure at 200 000 repetitions

Thickness of Inside Plate, in.	Thickness of Outside Plates, in.	Plug Diameter, in.	Average Number of Cycles to Failure, thousands
		13/16	162.8
1/2	3/8	15/16	123.3
		1 1/16	74.0
		13/16	204.4
1/2	1/2	15/16	246.2*
		1 1/16	77.7
		13/16	229.8
5/8	5/8	15/16	179.2
		1 1/16	157.4
3/4	3/4	15/16	185.3
		1 1/16	279.6*

*Inconsistent with general trend.

TABLE 13
FATIGUE STRENGTH OF PLUG-WELD JOINTS DESIGNED TO FAIL IN PLUGS; SECOND SERIES

Specimens detailed on Fig. 14.

Specimen No.	Plate Thickness, in.		Stress in 1000's of lb. per sq. in. Shear on Plug†	Number of Cycles for Failure in 1000's
	Inside	Outside		
Plug Diameter—1³⁄₁₆ in.				
PA-1	½	¼	0 to 20.0	94.8
PA-2			0 to 23.0	72.2*
PA-3			0 to 20.0	87.8
PA-4			0 to 27.5	36.9*
				Av. 91.3
PB-1	½	⅜	0 to 20.0	192.4
PB-2			0 to 20.0	150.9
PB-3			0 to 20.0	158.4
PB-4			0 to 20.0	149.3
				Av. 162.8
PC-1	½	½	0 to 20.0	230.7
PC-2			0 to 20.0	178.1
PC-3			0 to 15.0	1 996.4*
				Av. 204.4
Static strength—50 250 lb. per sq. in. shear on plug.				
PD-2	⅝	⅝	0 to 20.0	444.2
PD-3			0 to 20.0	95.3
PD-4			0 to 20.0	150.0
				Av. 229.8
Static strength—54 000 lb. per sq. in. shear on plug.				
Plug Diameter—1⁵⁄₁₆ in.				
PE-1	½	⁵⁄₁₆	0 to 20.0	66.5
PE-2			0 to 20.0	173.5
PE-3			0 to 20.0	90.1
				Av. 110.0
Static strength—48 000 lb. per sq. in. shear on plug.				
PF-1	½	⅜	0 to 20.0	118.2
PF-2			0 to 20.0	84.4
PF-3			0 to 20.0	167.2
				Av. 123.3
PG-1	½	½	0 to 20.0	345.9
PG-2			0 to 20.0	124.3
PG-3			0 to 20.0	268.3
				Av. 246.2
Static strength—50 000 lb. per sq. in. shear on plug.				
PH-1	⅝	⅝	0 to 20.0	168.7
PH-2			0 to 20.0	298.0
PH-3			0 to 20.0	70.9
				Av. 179.2
Static strength—49 300 lb. per sq. in. shear on plug.				
PI-1	¾	¾	0 to 20.0	116.0
PI-2			0 to 20.0	86.4
PI-3			0 to 20.0	353.4
				Av. 185.3
Static strength—57 600 lb. per sq. in. shear on plug.				

TABLE 13 (CONCLUDED)
FATIGUE STRENGTH OF PLUG-WELD JOINTS DESIGNED TO FAIL IN PLUGS; SECOND SERIES

Specimens detailed on Fig. 14.

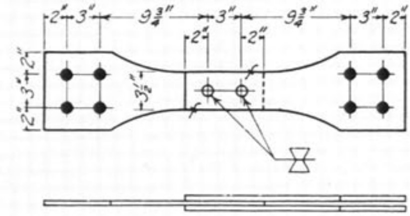
Specimen No.	Plate Thickness, in.		Stress in 1000's of lb. per sq. in. Shear on Plug†	Number of Cycles for Failure in 1000's
	Inside	Outside		
Plug Diameter—1 1/16 in.				
PJ-1	1/2	3/8	0 to 20.0	68.1
PJ-2			0 to 20.0	69.0
PJ-3			0 to 20.0	84.8
				Av. 74.0
Static strength—48 650 lb. per sq. in. shear on plug.				
PK-1	1/2	1/2	0 to 15.5	190.7*
PK-2			0 to 20.0	97.6
PK-3			0 to 20.0	57.9
				Av. 77.7
Static strength—48 800 lb. per sq. in. shear on plug.				
PL-1	5/8	5/8	0 to 20.0	135.7
PL-2			0 to 20.0	109.4
PL-3			0 to 20.0	227.2
				Av. 157.4
Static strength—49 300 lb. per sq. in. shear on plug.				
PM-1	3/4	3/4	0 to 20.0	147.1
PM-2			0 to 20.0	576.8
PM-3			0 to 20.0	115.0
				Av. 279.6
Static strength—51 300 lb. per sq. in. shear on plug.				
PN-1	3/4	7/8	0 to 15.6	1 439.9*
PN-2			0 to 20.0	372.8
PN-3			0 to 20.0	212.9
				Av. 292.8
Static strength—47 900 lb. per sq. in. shear on plug.				

*Not included in average because the stress was different for this from that for the other specimens.
†Based upon area of hole in outside plates.

of a cycle in which the shear varied from 0 to a maximum was of the order of 25 000 lb. per sq. in. for the two-plug joints and of the order of 20 000 lb. per sq. in. for the one-plug joints.

11. *Fatigue Strength of Plates Connected With Plug Welds.*—Tests were made to determine the fatigue strength of plates connected with plug welds. The details of the specimens are shown in Fig. 15. Some specimens were designed to fail in the outside plates, others were designed to fail in the inside plates. One specimen of each plate thickness was tested statically. Most of the fatigue tests were made on a cycle in which the stress varied from 0 to 25 000 lb. per sq. in. tension on the gross section of the plate.

The results of the tests of specimens designed to fail in the outside



Specimen Number	Plug Diameter	Plate Thickness	
		Outside	Inside
To Fail in Inside Plate			
PO	13/16"	1/4"	3/8"
PP	15/16"	3/8"	1/2"
PR	1 1/16"	1/2"	5/8"
To Fail in Outside Plate			
PS	13/16"	3/16"	1/2"
PT	15/16"	1/4"	5/8"
PU	1 1/16"	5/16"	3/4"

Fig. 15. Details of Plug-Weld Specimens Designed to Fail in Plates

plates are given in Table 14. All specimens broke in the outside plates as planned. The plates for all specimens were 3½ in. wide and the number of cycles for failure was a little more than twice as great for the specimens with 13/16-in. plugs as it was for the specimens with 15/16-in. and 1 1/16-in. plugs. This corresponds to a difference of 10 to 15 per cent in the fatigue strength. The static strength of the plate had values of 62 000, 63 200, and 53 250 lb. per sq. in. on the gross section of the plate for specimens with 13/16-in., 15/16-in., and 1 1/16-in. plugs, respectively. The fatigue strength of the plates was of the order of 26 000 to 30 000 lb. per sq. in. on the gross section of the plates for failure at 100 000 cycles. The corresponding value for a continuous ⅞-in. carbon-steel plate, 5 in. wide with the mill scale on was 49 800 lb. per sq. in.*

The results of the tests of specimens designed to fail in the inside plates are given in Table 15. Specimens PR-1 and PR-2 failed in the plugs, the others failed in the inside plates as planned. The fatigue strength of the inside plates was of the order of 25 000 to 27 000 lb. per sq. in. of gross section for failure at 100 000 cycles.

12. *Fatigue Strength of Fillet-Plug Joints Designed to Fail in Plugs.*—The plug welds in the specimens described in Sections 10 and 11 completely filled the holes in the outside plates. The plug in the specimens described in this section consisted of a circular fillet weld at the bottom of the hole in the outside plate which connected the outside plate to the inside plate. Tests were made to determine the relative fatigue strength of fillet plugs of the two designs shown in Fig. 16. Each specimen consisted of a single plug connecting two outside ⅜-in. plates to a middle ½-in. plate, the specimens being designed to fail in

*Univ. of Ill. Eng. Exp. Sta. Bul. 327, p. 23.

TABLE 14

FATIGUE STRENGTH OF PLUG-WELD JOINTS DESIGNED TO FAIL IN OUTSIDE PLATES

Specimens detailed on Fig. 15.

Specimen No.	Plate Thickness, in.		Stress in 1000's of lb. per sq. in. Tension on Gross Area of Plate	Number of Cycles for Failure in 1000's
	Inside	Outside		
Plug Diameter—13/16 in.				
PS-1	½	3/16	0 to 25.0	406.7
PS-2			0 to 25.0	459.7
PS-3			0 to 25.0	605.3
				Av. 490.6
Static strength—62 000 lb. per sq. in.*				
Plug Diameter—15/16 in.				
PT-1	5/8	¼	0 to 25.0	121.0
PT-2			0 to 25.0	248.2
PT-3			0 to 25.0	145.4
				Av. 171.5
Static strength—63 200 lb. per sq. in.*				
Plug Diameter—11/16 in.				
PU-1	¾	5/16	0 to 30.2	62.5†
PU-2			0 to 30.2	44.5†
PU-3			0 to 25.0	199.9
				Av. 199.9
Static strength—53 250 lb. per sq. in.*				

*Tension on gross area of plates.
†Not included in average.

the plug. The two types of specimens differed in the diameter of the hole in the outer plate and in the size of the fillet. The 42A specimens had a hole diameter of 13/16 in. and a 3/8-in. fillet, the 42B specimens had a hole diameter of 1 1/16 in. and a 5/16-in. fillet. One specimen of each type was subjected to a static test and three to fatigue tests.

The results of the tests are given in Table 16. The unit shear on the plug was computed on two bases, as follows: (1) based on the area of the hole in the outside plate, the same as for a filled plug; and (2) based on the area of a 45-degree conical section normal to the fillet at its root, as required by specifications.* The 42A specimens were identical with the PB specimens of Table 13, except that the former had a fillet plug, whereas the latter had a filled plug. Likewise, the 42B specimens were identical with the PJ specimens of Table 13 except for the type of plug. Moreover, the unit shear based upon the area of the hole in the outside plates was the same for the fatigue tests

*A.W.S. 1941 Specifications for Welded Highway and Railway Bridges, Article 217c.

Table 15
Fatigue Strength of Plug-Weld Joints Designed to Fail in Inside Plates
Specimens detailed on Fig. 15.

Specimen No.	Plate Thickness, in.		Stress in 1000's of lb. per sq. in. Tension on Gross Area of Plate	Number of Cycles for Failure in 1000's
	Inside	Outside		
Plug Diameter—13/16 in.				
PO-1	3/8	1/4	0 to 25.0	169.3
PO-2			0 to 25.0	118.9
PO-3			0 to 25.0	164.8
				Av. 151.0
Static strength—66 000 lb. per sq. in.*				
Plug Diameter—15/16 in.				
PP-1	1/2	3/8	0 to 21.4	177.4†
PP-2			0 to 25.0	105.1
PP-3			0 to 25.0	104.6
				Av. 104.9
Static strength—58 500 lb. per sq. in.*				
Plug Diameter—1 1/16 in.				
PR-1	5/8	1/2	0 to 25.0	85.7‡
PR-2			0 to 25.0	108.6‡
PR-3			0 to 25.0	193.3
				Av. 193.3

*Tension on gross area of plate.
†Not included in average.
‡Failed in plug; not included in average.

of the 42A and 42B specimens as it was for the fatigue tests of the PB and PJ specimens, so the results of the tests on the two types of plugs are directly comparable. The data given in Tables 13 and 16 show that the average number of cycles for failure was 123 700 for the three 42A specimens as compared with 162 800 for the four PB specimens; and the average number of cycles for failure was 134 300

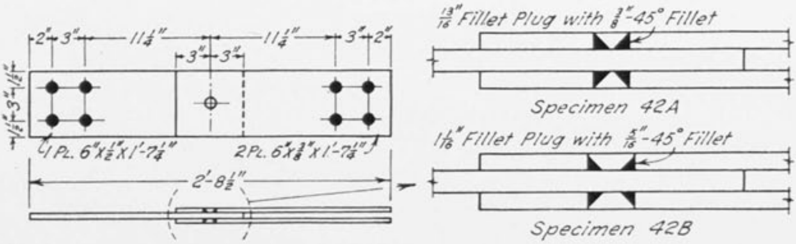


Fig. 16. Fillet-Plug Joints Designed to Fail in Plugs

TABLE 16

FATIGUE STRENGTH OF FILLET-WELD PLUGS CONNECTING PLATES

Specimens detailed on Fig. 16.
3/8-in. outside and 1/2-in. inside plates for all specimens.
All specimens broke in the plugs.

Specimen No.	Stress in 1000's of lb. per sq. in. Shear on Plug Based on		Number of Cycles for Failure in 1000's	Specimen No.	Stress in 1000's of lb. per sq. in. Shear on Plug Based on		Number of Cycles for Failure in 1000's
	Area of Hole	Area of Throat of Fillet*			Area of Hole	Area of Throat of Fillet*	
Plug Diameter, 13/16 in.; 3/8-in., 45-degree Fillet				Plug Diameter, 1 1/16 in.; 5/16-in., 45-degree Fillet			
42A-1	0 to 20.0	0 to 19.9	179.4	42B-1	0 to 20.0	0 to 28.2	115.0
42A-2	0 to 20.0	0 to 19.9	90.4	42B-2	0 to 20.0	0 to 28.2	136.5
42A-3	0 to 20.0	0 to 19.9	101.2	42B-3	0 to 20.0	0 to 28.2	151.3
			Av. 123.7				Av. 134.3
Static strength—shear 45 400 lb. per sq. in. area of hole in outside plate				Static strength—shear 39 600 lb. per sq. in. area of hole in outside plate			

*See A.W.S. 1941 Specifications for Welded Highway and Railway Bridges, Article 217 c.

for the three 42B specimens as compared with 74 000 for the three PJ specimens. That is, the unit fatigue strength of the fillet-weld plugs was not significantly different from the unit fatigue strength of filled plugs when both values were based upon the diameter of the holes in the outside plates. When the unit strength is computed by the method required by the specifications, the unit fatigue strength was greater for the fillet plugs of the 42B specimens than for the filled plugs of the PJ specimens. The fatigue failure of all fillet plugs was by tearing a piece out of the middle plate, the same as for a filled plug, and there was no indication of impending failure at the throat of the weld.

The static failure of the fillet plugs was by shear in the plane of the outside surface of the middle plate, the same as for filled plugs, but there was a small hole in the weld at the section of failure due to the fact that the radius of the hole in the outside plate exceeded the size of the fillet. The values of the unit static strength of the fillets were computed on three bases, as indicated in Table 17. The unit strength in shear based upon the area on which failure actually occurred, which lies in the plane of contact between the outside and inside plates, had values of 45 700 and 47 700 lb. per sq. in. for the 13/16-in. and 1 1/16-in. fillet plugs, respectively. The strength of the filled plugs, based upon the area of the hole in the outer plate, was 50 250 and 48 650 lb. per sq. in. for the 13/16-in. and 1 1/16-in. plugs, respectively.

TABLE 17
STATIC STRENGTH OF FILLET AND FILLED PLUGS

Kind of Plug	Strength in Shear in lb. per sq. in. Based on		
	Area of Hole in Outer Plate	Area of Hole in Outer Plate Less Area of Hole in Plug at Bottom	Area at Root of Fillet in Accordance With Specifications
13/16 filled plug	50 250		
13/16 fillet plug	45 400	45 700	45 300
1 1/16 filled plug	48 650		
1 1/16 fillet plug	39 600	47 700	55 900

13. *Fatigue Strength of Plates Connected With Fillet Plugs.*—Tests were made to determine the fatigue strength of plates connected with fillet plugs. The details of the specimens are shown in Fig. 17. Parallel tests were made on two types of specimens, 42K and 42L, that were identical except that the 42K specimens had filled plugs and the 42L specimens had fillet plugs.

The results of the tests are given in Table 18. The average number of cycles for failure, when tested on a cycle in which the stress in the outside plate varied from 0 to 14 000 lb. per sq. in. tension, was 635 000 for the filled-plug joints and 204 900 for the fillet-plug joints. Unfortunately, the tests 0 to 20 000 lb. per sq. in. for the filled-plug joints and 0 to 10 000 lb. per sq. in. for the fillet-plug joints are not directly comparable, due to the difference in the stresses used, and also to the fact that the 42K specimens broke in the plugs.

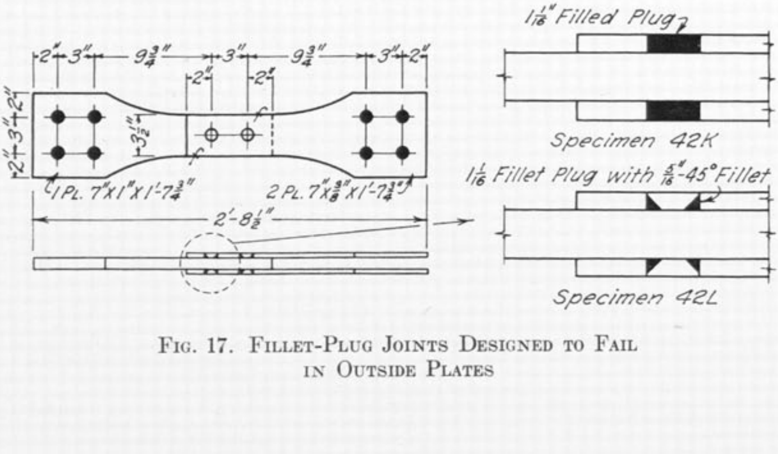


FIG. 17. FILLET-PLUG JOINTS DESIGNED TO FAIL IN OUTSIDE PLATES

TABLE 18

FATIGUE STRENGTH OF OUTSIDE PLATES; FILLED-PLUG AND FILLET-PLUG JOINTS

Specimens broke in outside plate except as noted.

Specimen No.	Stress in 1000's of lb. per sq. in. Tension on Gross Area of Outside Plates	Number of Cycles for Failure in 1000's	Specimen No.	Stress in 1000's of lb. per sq. in. Tension on Gross Area of Outside Plates	Number of Cycles for Failure in 1000's
Filled Plugs			Fillet Plugs		
42K7	0 to 20	55.5*	42L7	0 to 10	903.2
42K8	0 to 20	69.4*	42L8	0 to 10	875.3
42K9	0 to 20	49.4†	42L9	0 to 10	1 214.5
		Av. 58.1			Av. 997.7
42K10	0 to 14	640.0	42L10	0 to 14	217.3
42K11	0 to 14	263.5	42L11	0 to 14	223.1
42K12	0 to 14	1 001.4	42L12	0 to 14	174.4
		Av. 635.0			Av. 204.9

*Broke in plugs.
†Broke in plate and plugs.

14. *Effect of Plug Pattern Upon Fatigue Strength of Plug-Weld Joints Designed to Fail in Plugs.*—Studies of the elastic behavior of riveted joints with a number of rivets in a row in the direction of stress indicate that, within the range of elastic action, the end rivets will take more than their proportionate share of the load. Because of their similarity of action, the same uneven distribution of load among a number of plugs in a plug-weld joint might be expected. A series of tests was therefore made to determine the relative fatigue strength of the plugs of plug-weld joints with various plug patterns. The specimens used in the first series of tests are shown in Fig. 18. All specimens consisted of $^{15}/_{16}$-in. filled plugs connecting ½-in. plates to ¾-in. plates. There were four plug patterns, two with four plugs each and two with six plugs each. The relation between the plate area and the total plug section was approximately the same for all specimens. Of the four-plug patterns, one had four plugs in a square and the other had four plugs in line. Of the six-plug patterns, one had two rows of three plugs each and the other had three rows of two plugs each. All specimens except N4 were tested on a cycle in which the stress varied from 0 to 15 000 lb. per sq. in. shear on the plugs. All specimens failed in the plugs except as noted.

The results of the tests are given in Table 19. As stated in the previous paragraph, N4 was tested at a stress different from that used for the other specimens. Moreover, the number of cycles for failure

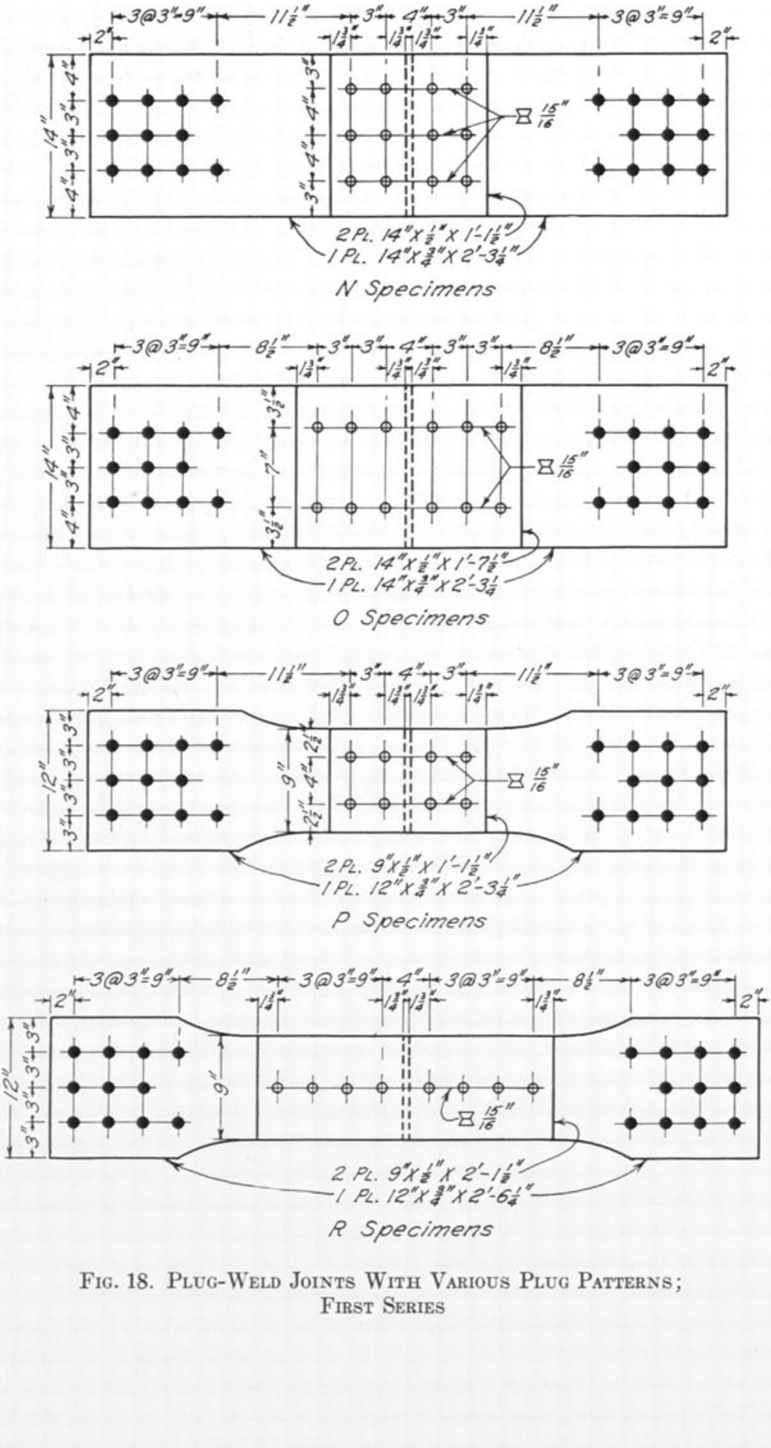


FIG. 18. PLUG-WELD JOINTS WITH VARIOUS PLUG PATTERNS; FIRST SERIES

TABLE 19

FATIGUE STRENGTH OF PLUG-WELD JOINTS WITH VARIOUS PLUG PATTERNS; FIRST SERIES

Specimens detailed on Fig. 18.
All specimens failed in the plugs except as noted.
1 5/16-in. plugs, 1/2-in. outside and 3/4-in. inside plates.

Specimen No.	Stress in 1000's of lb. per sq. in. Shear on Plug	Number of Cycles for Failure in 1000's	Specimen No.	Stress in 1000's of lb. per sq. in. Shear on Plug	Number of Cycles for Failure in 1000's
N4	0 to 20.0	80.6*	P1	0 to 15.0	464.5
N1	0 to 15.0	194.3	P2	0 to 15.0	269.2
N3	0 to 15.0	656.1	P4	0 to 15.0	450.2
		Av. 425.2			Av. 394.6
Static strength—41 800 lb. per sq. in. shear on plug.			Static strength—43 850 lb. per sq. in. shear on plug.		
O1	0 to 15.0	378.6	R2	0 to 15.0	1 645.0†
O2	0 to 15.0	306.8	R3	0 to 15.0	1 565.8‡
O3	0 to 15.0	577.6	R4	0 to 15.0	1 305.1‡
		Av. 421.0			Av. 1 505.3
Static strength—44 700 lb. per sq. in. shear on plug.			Static strength—no test.		

*Not included in average.
†Failed in outside plate.
‡Failed in inside plate.

for N1 and N3 differed greatly, so the average number of cycles for failure for the N specimens has not been satisfactorily established. However, the data do indicate that the number of cycles for failure for the two types of six-plug specimens, N and O, did not differ greatly. Of the two types of four-plug specimens, P and R, the number of cycles for failure was at least 3.75 times as great for the four-in-a-line pattern as it was for the four-in-a-square pattern. This was opposite to what might be expected, so a second series of tests was made.

The plug patterns for the specimens of the second series are shown in Fig. 19. The plug patterns for this series were four-in-a-square for the 42E specimens and four-in-a-line for the 42F specimens. The plug patterns were identical for these and for the P and R specimens of the first series. Some specimens were tested on a cycle in which the stress varied from 0 to tension, others were tested on a cycle in which the stress varied from tension to an equal compression. Some specimens were tested for failure at a small number of cycles, others for failure at a large number of cycles. The results of the tests are given in Table 20. Unfortunately, most of the specimens failed in the inside plate. The specimens tested on a cycle in which the stress varied from 14 000 lb. per sq. in. shear on the plugs in one direction to an equal shear in the opposite direction did, however, fail in the plugs. For this

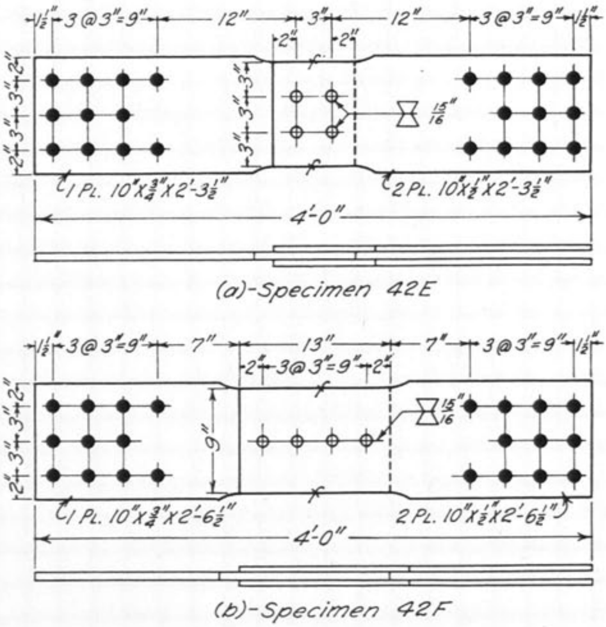


FIG. 19. PLUG-WELD JOINTS WITH VARIOUS PLUG PATTERNS; SECOND SERIES

cycle, the number of repetitions for failure was the same for the two plug patterns. There were two other 42E specimens that failed in the plugs. Specimen 42E-3 broke at 114 200 repetitions of a cycle in which the stress varied from 0 to 20 000 lb. per sq. in. shear. In contrast with this specimen with four plugs in a square, the three 42F specimens with four plugs in line which were tested on the same cycle, withstood an average of 262 100 repetitions without the failure of any plugs. It should be noted, however, that 42E-1 and 42E-2 withstood 245 700 and 238 900 repetitions, respectively, without the failure of any plugs. Likewise, 42E-13 broke at 340 500 repetitions of a cycle in which the stress varied from 9000 lb. per sq. in. shear in one direction to an equal shear in the opposite direction. In contrast with this, specimens 42F-11, 42F-12, and 42F-13, which were tested on the same cycle, withstood an average of 960 200 repetitions without the failure of any plugs. It should be noted, however, that 42E-11 and 42E-12 withstood 1 133 100 and 847 100 repetitions of the same cycle without the failure of any plugs. While the evidence is not conclusive, the few plugs that failed indicate that the fatigue strength of the plugs was at least as great in the four-in-a-line pattern as in the four-in-a-square pattern.

TABLE 20
FATIGUE STRENGTH OF PLUG-WELD JOINTS WITH VARIOUS PLUG PATTERNS; SECOND SERIES

Specimens detailed on Fig. 19.

Specimen No.	Stress in 1000's of lb. per sq. in.		Number of Cycles for Failure in 1000's	Part That Failed
	Shear on Plug	Tension on Inside Plate		
42E-1	0 to 20.0	16.4	245.7	Inside plate
42E-2	0 to 20.0	16.4	238.9	Inside plate
42E-3	0 to 20.0	16.4	114.2	Plugs
			Av. 199.6	
42F-1	0 to 20.0	16.4	258.9	Inside plate
42F-2	0 to 20.0	16.4	287.9	Inside plate
42F-3	0 to 20.0	16.4	239.4	Inside plate
			Av. 262.1	
42E-5	0 to 14.0	11.5	1 019.3	Inside plate
42E-6	0 to 14.0	11.5	1 371.3	Inside plate
42E-7	0 to 14.0	11.5	1 287.0	Inside plate
			Av. 1 225.9	
42F-5	0 to 14.0	11.5	846.0	Inside plate
42F-6	0 to 14.0	11.5	1 946.2	Inside plate
42E-7	0 to 14.0	11.5	1 109.2	Inside plate
			Av. 1 300.5	
42E-8	+14.0 to −14.0	11.5	37.9	Plugs
42E-9	+14.0 to −14.0	11.5	60.0	Plugs
42E-10	+13.0 to −13.0	10.6	115.3*	Plugs
			Av. 49.0	
42F-8	+14.0 to −14.0	11.5	90.4	Plugs
42F-9	+14.0 to −14.0	11.5	23.5	Plugs
42F-10	+12.0 to −12.0	9.8	84.8*	Plugs
			Av. 57.0	
42E-11	+9.0 to −9.0	7.4	1 133.1	Inside plate
42E-12	+9.0 to −9.0	7.4	847.1	Inside plate
42E-13	+9.0 to −9.0	7.4	340.5	Plugs
			Av. 773.6	
42F-11	+9.0 to −9.0	7.4	854.7	Inside plate
42F-12	+9.0 to −9.0	7.4	1 253.7	Inside plate
42F-13	+9.0 to −9.0	7.4	772.1	Inside plate
			Av. 960.2	

*Not included in average because of the difference in the stress cycle.

The fatigue strengths of the inside plates, for the specimens that failed in these plates, are also given in Table 20. On the basis of failure at 200 000 cycles, the fatigue strength of the inside plate, tested on a cycle in which the stress varied from 0 to tension, was 16 400 lb. per sq. in. for the 42E specimens with a four-in-a-square plug pattern and very slightly greater for the 42F specimens with a four-in-a-line plug pattern. On the basis of failure at 1 200 000 to 1 300 000 cycles, the fatigue strength of the inside plate, tested on a cycle in which the stress varied from 0 to tension, was 11 500 lb. per sq. in. for both plug patterns. When tested on a cycle in which the stress in the plate varied from tension to an equal compression, the fatigue strength corresponding to failure at slightly less than 1 000 000 cycles was of the order of 7400 lb. per sq. in. and was slightly greater and more consistent for the four-in-a-line plug pattern than it was for the four-in-a-square plug pattern. These values of the fatigue strength of the plates are somewhat less than the corresponding values given in Table 15 for the specimens shown in Fig. 15.

The data presented in this section apparently justify the following statements relative to the fatigue strength of plug-weld joints connecting plates.

The plug pattern of the plug-weld joints connecting plates that were tested had no significant effect upon the fatigue strength of either the plugs or of the inside plates.

15. *Composite Riveted and Plug-Weld Joints Connecting Plates.*—Tests of composite riveted and fillet-weld joints connecting plates are described in Section 7. Tests of similar composite riveted and plug-weld joints connecting plates are described in this section. The details of the specimens are shown in Fig. 20. The K specimens were riveted control specimens used as a base in evaluating the strength of the

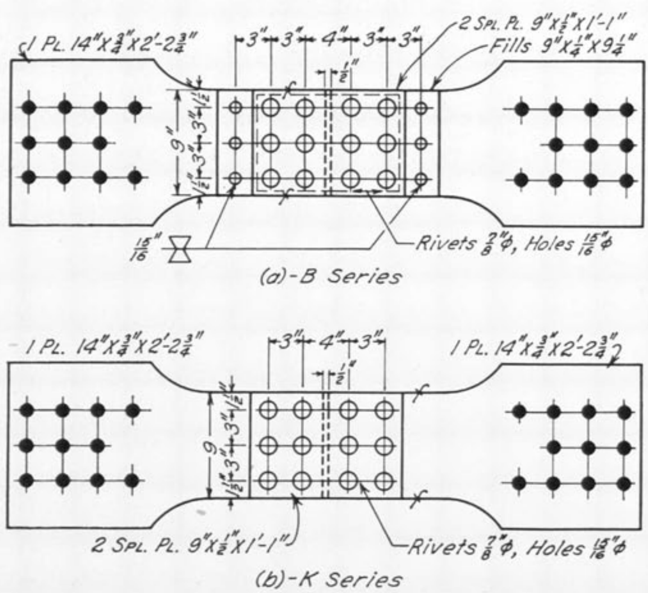


Fig. 20. Composite Riveted and Plug-Weld Joints Connecting Plates

TABLE 21
FATIGUE STRENGTH OF COMPOSITE RIVETED AND PLUG-WELD JOINTS CONNECTING PLATES

Specimens detailed on Fig. 20.

Specimen No.	Stress Cycle lb. per sq. in. Tension on Gross Section of ¾-in. Plate	Number of Cycles for Failure	Specimen No.	Stress Cycle lb. per sq. in. Tension on Gross Section of ¾-in. Plate	Number of Cycles for Failure
Riveted Joints			Riveted Joints With Plug-Weld Reinforcement*		
K1	0 to 22 000	438 000	B1	0 to 25 000	597 500
K2	0 to 22 000	1 015 100	B2	0 to 25 000	1 024 500
K3	0 to 25 000	315 900	B3	0 to 25 000	383 900
					Av. 668 600

*All reinforced specimens failed in the ¾-in. plate on the section through the center of the plugs.

composite joints of the B series. The three B specimens and one of the K specimens were tested on a cycle in which the stress varied from 0 to 25 000 lb. per sq. in. tension on the gross section of the ¾-in. plate. The other two K specimens were tested on a cycle in which the stress varied from 0 to 22 000 lb. per sq. in.

The results of the tests are given in Table 21. Unfortunately, the same unit stress was not used for all specimens and average values cannot be determined. However, the approximate number of cycles for failure at 25 000 lb. per sq. in. can be estimated from the empirical equation* $F_n = S\left(\frac{N}{n}\right)^K$, in which F is the fatigue strength corresponding to failure at n cycles, and N and S are the actual number of cycles for failure and the maximum stress in the stress cycle, respectively. K is an experimental constant. If K is taken as 0.15, n for a unit stress of 25 000 becomes 163 800 for specimen K1 and 379 600 for specimen K2, and the average value for K1 and K2 is 271 700. If K is taken as 0.20, the corresponding values of n are 231 000 and 535 000, and the average value for K1 and K2 is 383 000. That is, any probable value of the experimental constant K will give an average value for the number of cycles for failure at a unit stress of 25 000 not greatly different from the value that was obtained for K3, which was tested at 25 000 lb. per sq. in. It would seem, therefore, that the plug-weld reinforcement doubled, approximately, the number of cycles for failure. This is equivalent to an increase in the fatigue strength of

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

approximately 10 per cent. It should be noted, however, that the number of cycles for failure of the weakest reinforced specimen, B3, was almost as small as the number of cycles for failure for K3, the one specimen not reinforced that was tested on a cycle in which the stress varied from 0 to 25 000 lb. per sq. in. It would seem, therefore, that the plug reinforcement added but little to the fatigue strength of the riveted joint.

16. *Metallurgical Studies.*—Metallurgical studies were made to determine the microstructure and hardness of the weld metal and the heat-affected base metal, and to determine the penetration for both the inside and the outside plates of the plug-weld joints.

Penetration and Size of Plugs

Several plug welds from the specimens whose fatigue strength is reported in Table 13 were placed in a lathe and light cuts were taken to remove the reinforcement and a thin layer of metal from the surfaces of the outside plates. The resulting machined surfaces were rough polished and etched with a 5-per-cent Nital solution to bring out the boundaries of the weld metal and the heat-affected zone. The maximum and minimum diameters of the plug, including the fused area, were measured. The plug diameters measured on the outside surface of the outside plates were designated as d_1, and the plug diameters measured on the inside surface of the outside plates were designated as d_2. The depth of the penetration into the inside plate was measured on one

Table 22
Dimensions of Fused Region; Plug Welds Connecting Plates

Specimen No.	Nominal Dimensions, in.			Actual Plug Diameter, in.				Penetration, in.	
	Plug Diameter	Plate Thickness		d_1		d_2		p_1	p_2
		Outside	Inside	Max.	Min.	Max.	Min.		
PB4	13/16	3/8	1/2					0.07–0.11	0.03–0.05
PF3	15/16	3/8	1/2	1 7/16	1 5/16	1	15/16	0.12–0.18	0.04
PJ2	11/16	3/8	1/2	1 1/2	1 7/16	1 1/8	1 3/32	0.11–0.19	0.03–0.06
PD4	13/16	5/8	5/8	1 3/8	1 3/16	7/8	13/16	0.10–0.14	0.04
PH2	15/16	5/8	5/8	1 1/2	1 3/8	1 1/16	15/16	0.09	0.05
PL3	11/16	5/8	5/8	1 3/4	1 7/8	1 1/8	1 1/16	0.12	0.07
PC2	13/16	1/2	1/2	1 3/16	1 1/8	7/8	13/16	0.11–0.13	0.05–0.08
PG3	15/16	1/2	1/2	1 9/16	1 7/16	1 1/16	1	0.12	0.08
PK3	1 1/16	1/2	1/2	1 1/2	1 3/8	1 1/8	1 1/16	0.13	0.10
PB3	13/16	3/8	1/2	1 7/32	1 3/32	1 3/16	13/16		
PB2	13/16	3/8	1/2	1 5/16	1 1/8	15/16	13/16	0.12	0.07
PB1	13/16	3/8	1/2	1 5/32	1 3/32	13/16	13/16	0.16	0.05

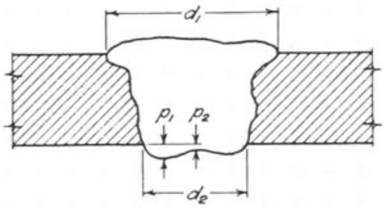


FIG. 21. TYPICAL CONTOUR OF FUSED REGION; PLUG WELD CONNECTING PLATES

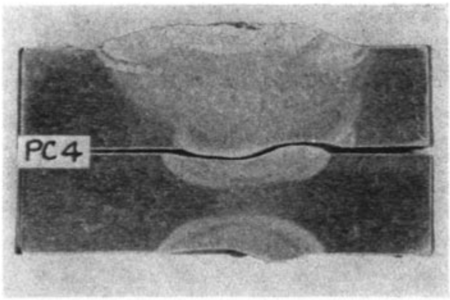


FIG. 22. SHEAR FRACTURE OF PLUG WELD CONNECTING PLATES SUBJECTED TO STATIC LOAD

diametrical section of the plugs, the penetration being designated as p_2 at the center and as p_1 at the periphery of the hole. The resulting data are summarized in Table 22 and the contour of the penetrated region is shown in Fig. 21.

The diameter of the fused region was always greater than the diameter of the hole in the outer plate, and was always greater at the outside than at the inside of the outer plate. There was no consistent relation between the oversize and either the diameter of the hole or the thickness of the plates. The penetration into the inside plate was consistently less at the center of the plug than at the periphery, as shown in Fig. 21.

Character of Plug Fractures

The character of the shear fracture of the plug of specimen PC4, which was subjected to a static test, is shown in Fig. 22. Failure occurred by shearing the plug in the same manner on both sides of the middle plate. The fatigue failure of plug-weld joints designed to fail in the plugs is illustrated in Fig. 23. Specimen PF1 failed on both

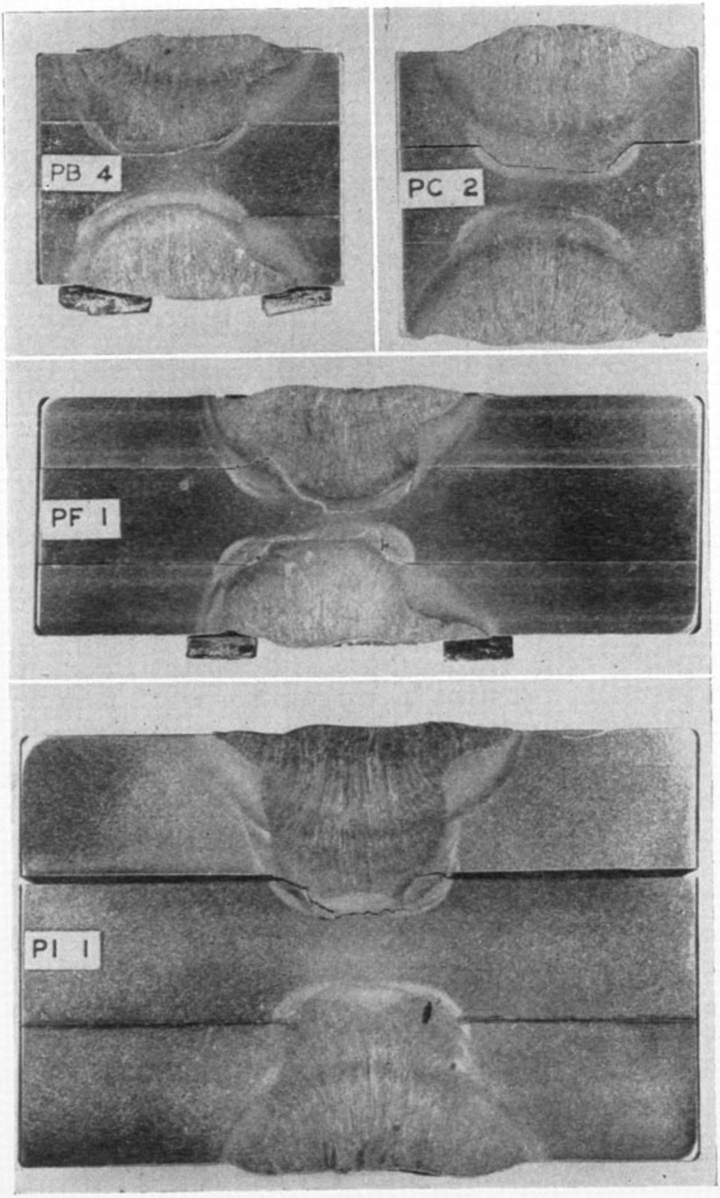


FIG. 23. TYPICAL FATIGUE FRACTURES OF PLUG WELDS CONNECTING PLATES

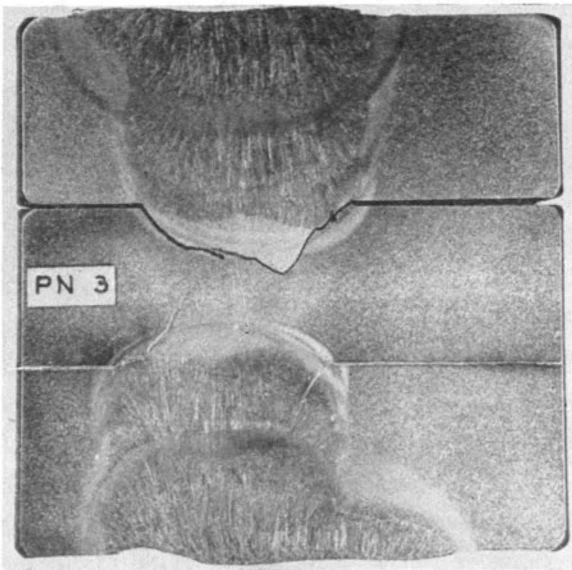


FIG. 24. FATIGUE FRACTURE EXTENDING INTO INNER PLATE AND INTO PLUG IN OUTER PLATE

sides and specimens PB4, PC2, and PI1 failed on only one side of the plate. The fracture of PI1, extending considerably into the middle plate and following the boundary of the heat-affected zone, is characteristic for these failures. An occasional fracture extended into the middle plate and also into the weld metal of the plug in the outer plate, as shown in Fig. 24. Occasionally the fracture extended into the middle plate and the plug pulled out a portion of the unfused base plate. The resulting woody fracture indicated a striated or laminated base plate, as shown for specimen PF3 in Fig. 25. It is interesting to note, however, that the number of cycles for failure was greater for PF3 than for the other two specimens of the PF series tested on the same cycle. The typical fracture of a one-plug joint designed to fail in the middle plate is shown in Fig. 26. The dark ring on the surface of the middle plate, which had been machined, polished, and etched, indicates the heat-affected base metal. Close inspection of this and other specimens revealed an irregular path of the crack from one blowhole to another, the blowholes being located in the weld metal close to the fusion line. Typical failures of joints designed to fail in the outside plates are shown in Fig. 27. The fracture started at the inside of the

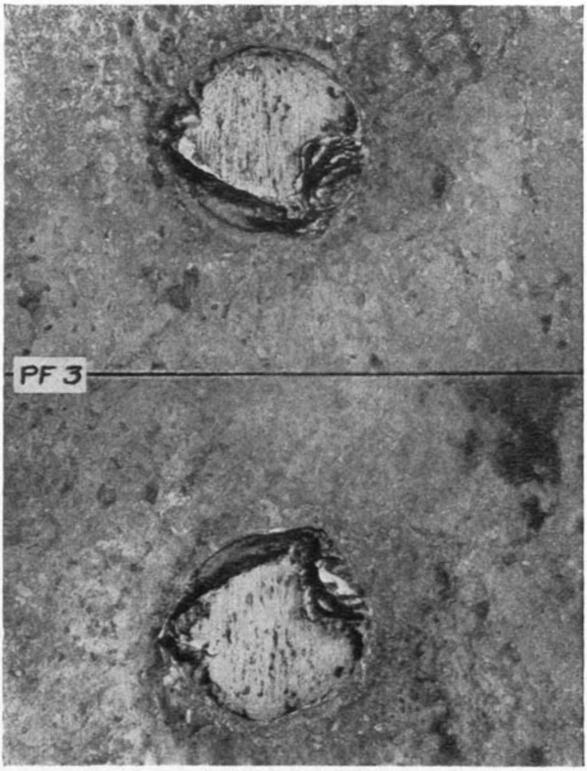


FIG. 25. WOODY TYPE OF FATIGUE FRACTURE INDICATING STRIATED OR LAMINATED BASE METAL IN MIDDLE PLATE

outer plate and progressed in a direction normal to the applied load and tangent to the original hole in the plate.

Hardness Survey

Exploratory hardness tests were made on specimen PA3, as indicated by the hardness indents shown in Fig. 28, to determine the regions of maximum hardness. As a result of these tests, hardness readings for the other plug welds were taken at points indicated by the indents for specimen PE2, shown in the same figure. The results are summarized in Table 23. The maximum hardness numbers are not high except for specimen PD3. The macrograph of specimen PD3, Fig. 29, indicates that a small addition was made to the plug of this specimen at the upper left-hand corner subsequent to the main deposit. Apparently the rapid cooling of the small volume of metal

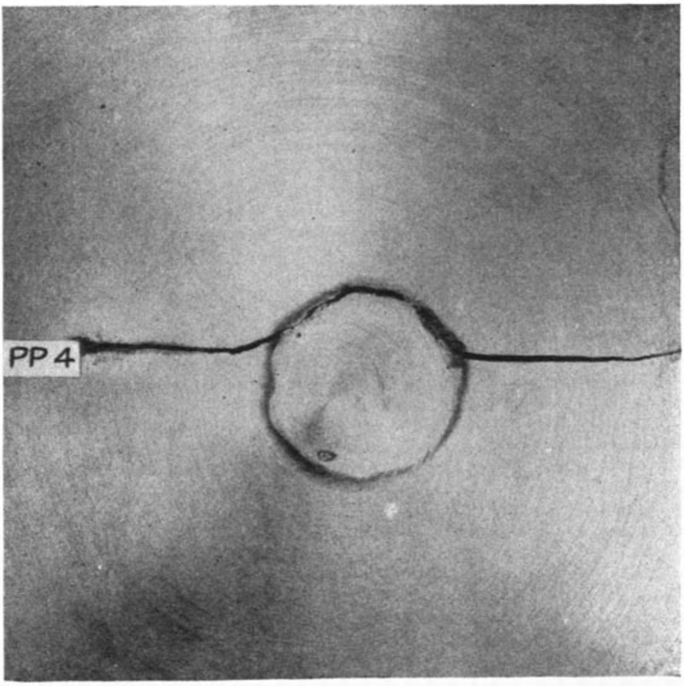


Fig. 26. Typical Fatigue Fracture of One-Plug Joint Designed to Fail in Middle Plate

resulted in the high Vickers values of 375 and 310 for the heat-affected base metal and weld metal, respectively, for this specimen. The only other specimen that had a hardness number for the heat-affected base metal greater than 200 was PA3, the highest value for this specimen being 219 Vickers. The weld metal was, generally, harder than the heat-affected base metal, the greatest hardness being 310 Vickers for PD3, as stated above. There were several values somewhat greater than 200 Vickers.

All of the hardness values shown in Table 23 were obtained from one diametrical section of the weld in question. A survey was made on specimen PB3 to determine the uniformity of the hardness around the periphery of the weld on a plane parallel with the plate surface. Previous tests indicated that the maximum hardness of the heat-affected zone was usually found about 0.08 in. below the surface. Metal to the depth of 0.08 in. was therefore machined from PB3 and the resulting surface was polished and etched. The macrograph of Fig. 30 shows the heat-affected zone and the weld metal. Sixteen hardness

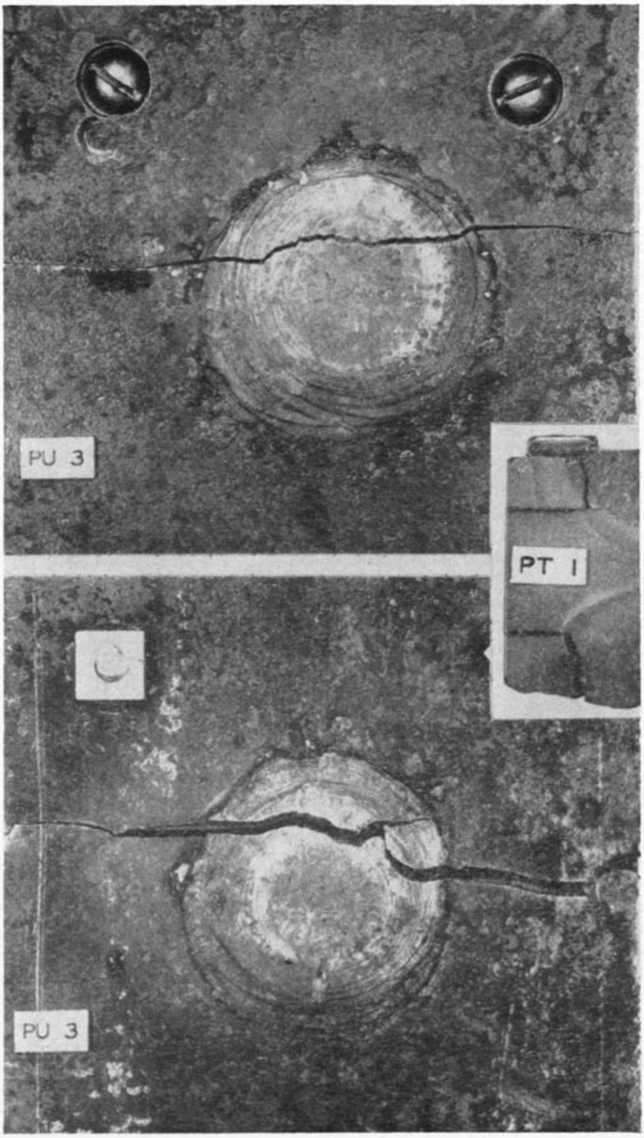


Fig. 27. Typical Fatigue Fracture of One-Plug Joint That Failed in Outside Plates

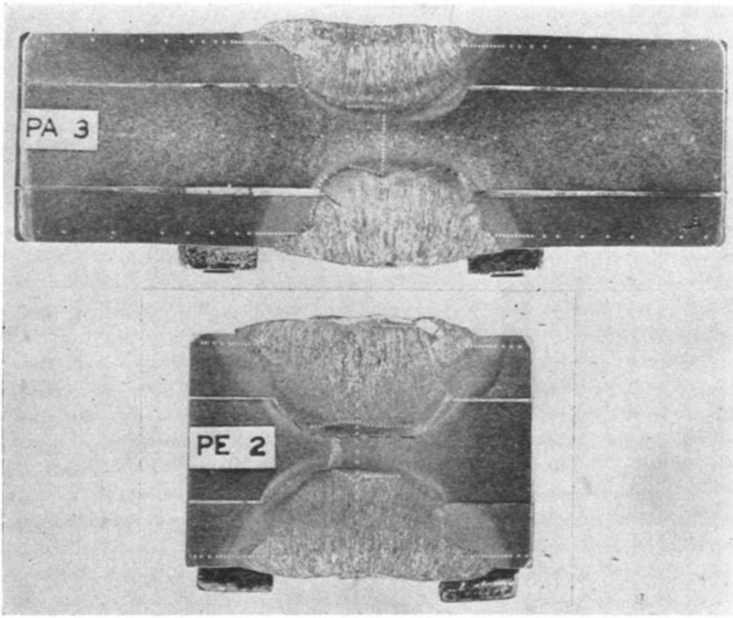


FIG. 28. INDENTS FROM HARDNESS TESTS; PLUG-WELD SPECIMENS PA3 AND PE2

TABLE 23

VICKERS HARDNESS NUMBERS FOR PLUG-WELD JOINTS

Specimen No.	Diameter of Plug in.	Thickness of Plate		Maximum Value in Heat-Affected Zone		Weld Metal	
		Outside in.	Inside in.	Outside Plate	Inside Plate	Minimum	Maximum
PA3	1 3/16	1/4	1/2	176	219	170* 153*	212 231
PB4	1 3/16	3/8	1/2	196	172	170 163	192 215
PC2	1 3/16	1/2	1/2	172	158	150 141	195 206
PD3	1 3/16	5/8	5/8	186 (375)	185	165 146	310 204
PE2	1 3/16	5/16	1/2	185	166	164 151	182 195
PF1	1 5/16	3/8	1/2	198	159	160 154	198 220
PI1	1 5/16	3/4	3/4	203	177	153 142	170 175
PJ1	1 1/16	3/8	1/2	194	195	149 139	187 175
PN1	1 1/16	7/8	7/8	182	182	158 126	174 181

*Values in upper line for plug on one side, values in lower line for plug on other side.
NOTE: Unaffected Base Metal had an average hardness of 125 Vickers.
Vickers hardness in parentheses was obtained adjacent to a weld crater in Specimen PD3.

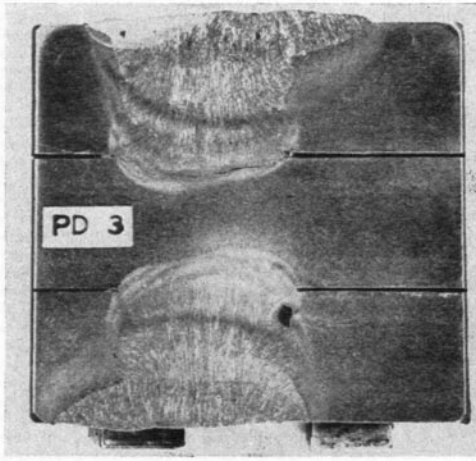


Fig. 29. Macrograph of PD3

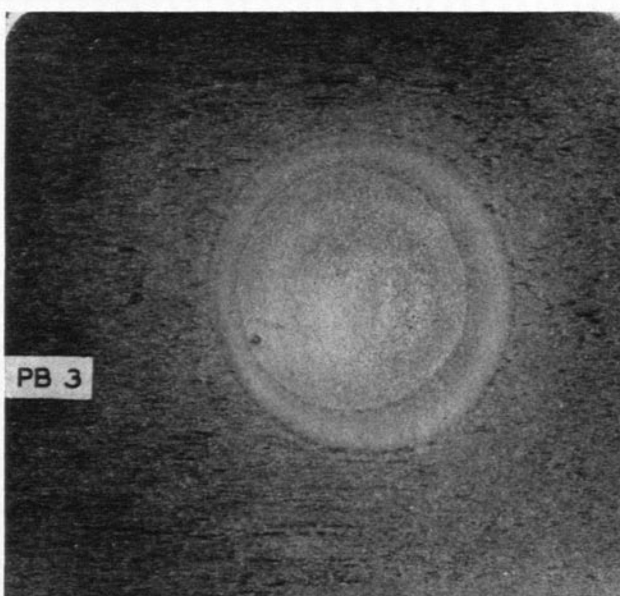


Fig. 30. Macrograph of Plug in Outside Plate of PB3

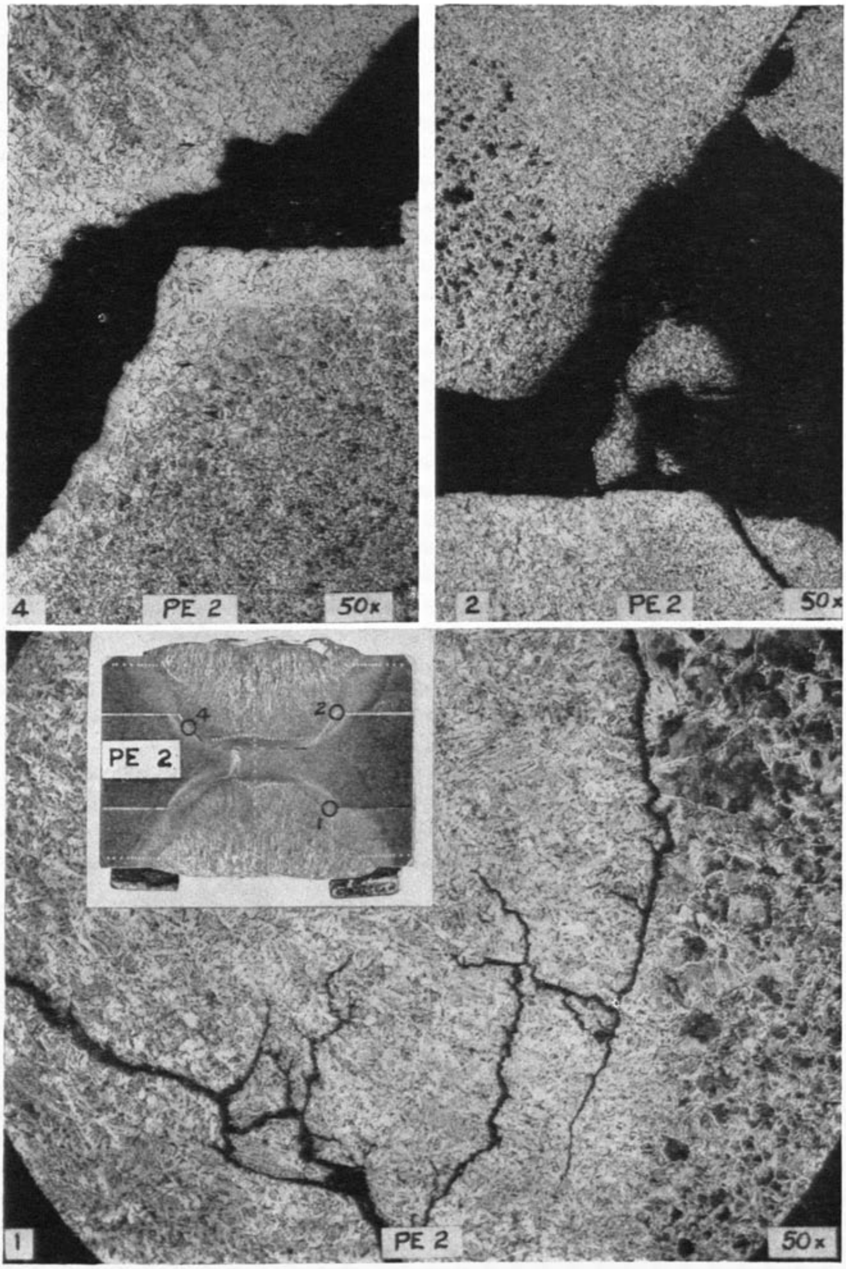


FIG. 31. MICROGRAPHS OF PE2

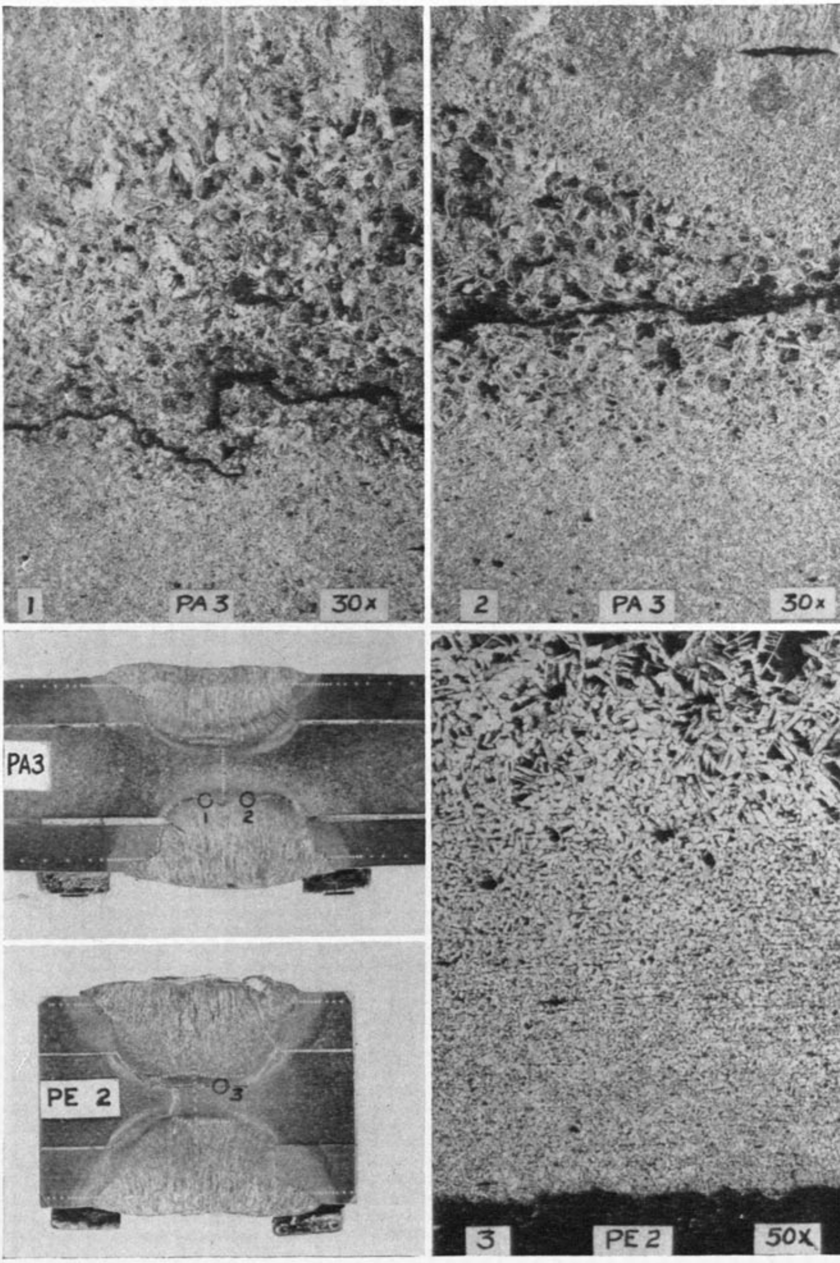


Fig. 32. Micrographs of PA3 and PE2

tests were made in the annular heat-affected zone at points equally spaced around the plug. The hardness variation from 191 to 210 Vickers, a spread of only 19 Vickers units, indicates a high degree of uniformity in the heat-affected base metal of this specimen. A careful examination of the plug did not reveal any additions of weld metal subsequent to the main welding of the plug.

Microstructure

The micrographs of Figs. 31 and 32 show that the fracture of PE2 extended through the weld metal in regions 1, 2, and 4, and extended through the outer fringe of the heat-affected zone at the base of the plug in region 3, the location of these regions being indicated in the macrographs. The fracture of PA3 passed through the heat-affected zone at the base of the plug in regions 1 and 2, as shown by the micrographs of Fig. 32.

Conclusions

(1) The diameter of the plug welds was greater than the diameter of the holes in the outer plates, the oversize being generally from $\frac{1}{16}$ in. to $\frac{1}{4}$ in. at the inside surface of the plate, and somewhat greater at the outside surface. There was no consistent relation between the oversize and either the diameter of the hole or the thickness of the plates.

(2) The hardness was not excessive for either the heat-affected base metal or the weld metal for plugs welded continuously. There was one plug to which a small amount of weld metal had been added after the original deposit had cooled. This produced a region in both the weld metal and in the heat-affected base metal that was excessively hard, but the fatigue strength was greater for this plug than for others tested on the same cycle that did not contain regions of high hardness.

(3) The fatigue cracks of the specimens that failed in the plug usually started near the junction of the weld metal and the base metal, then progressed, sometimes into the weld metal and sometimes into the heat-affected base metal.

IV. Miscellaneous Tests

In addition to the regular program of tests of fillet and plug welds, a number of miscellaneous tests have been included in this bulletin. These are described in Sections 17 to 25, inclusive. These tests were made for the Bureau of Ships, Navy Department, who planned the tests, furnished the specimens and provided the funds to pay the direct

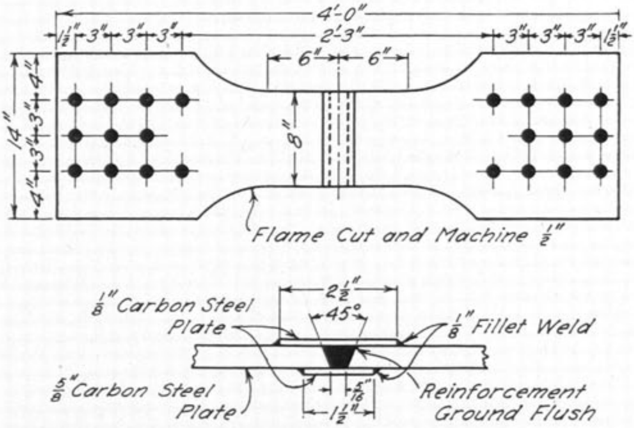


FIG. 33. SINGLE-V BUTT WELD WITH DOUBLE STRAP-PLATES

expenses involved. These tests have been included in this bulletin with the consent of the Bureau of Ships.

17. *Welded Butt Joints With Double Strap-Plates.*—The details of the specimen are shown in Fig. 33. The single-V butt weld connecting the ⅝-in. carbon-steel plates was ground flush with the base plate on both sides and reinforced with ⅛-in. carbon-steel strap plates attached to the main plates with ⅛-in. fillet welds, as shown in the figure. The physical properties of the ⅝-in. plates were as follows: Yield point 38 300 lb. per sq. in., ultimate strength 69 200 lb. per sq. in., elongation in 8 in. 22.8 per cent, and reduction of area 42.1 per cent.

All specimens were tested on a cycle in which the stress varied from tension to an equal compression.

Values of the fatigue strength corresponding to failure at 100 000 and at 2 000 000 cycles were determined by use of the equation* $F = S\left(\frac{N}{n}\right)^K$, in which F is the fatigue strength corresponding to failure at n cycles, S is the maximum stress in the stress cycle used in the test, N is the actual number of cycles for failure, and K is an experimental constant which, for these tests, had the value of 0.20 as given in Fig. 34.

The results of the tests, given in Table 24 and Fig. 34, are only fairly consistent. The fracture of the main plate for specimen 19 was

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

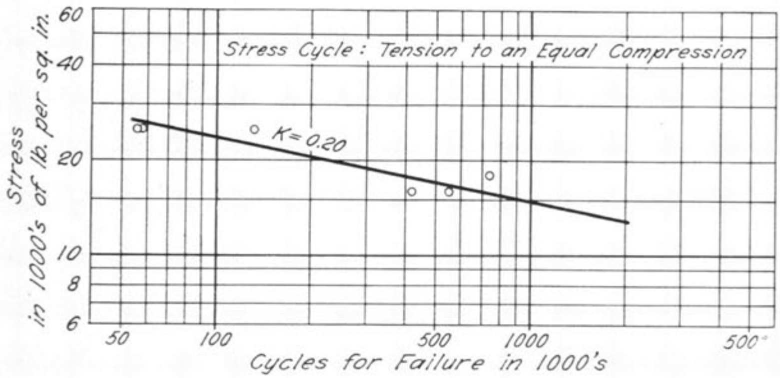


FIG. 34. *S–N* DIAGRAM FOR SINGLE-V BUTT WELD WITH DOUBLE STRAP-PLATES

partly in and partly along the edge of the butt weld. For all other specimens the main plate failed at the fillet weld which connected a butt strap to the main plate.

The average values of $F_{100\,000}$ and $F_{2\,000\,000}$, given in Table 24, were 23 700 lb. per sq. in. and 12 900 lb. per sq. in., respectively. The corresponding values for the fatigue strength of single-U butt welds in ⅞-in. carbon-steel plates made under the most favorable conditions of operator skill and expertness of supervision, were 22 300 and

TABLE 24
FATIGUE STRENGTH OF SINGLE-V BUTT WELDS WITH DOUBLE STRAP-PLATES
Stress cycle: Tension to an equal compression.

Specimen No.	Stress Cycle in 1000's of lb. per sq. in. Tension on Main Plates	Number of Cycles for Failure in 1000's	Fatigue Strength in 1000's of lb. per sq. in.		Location of Fatigue Fracture in Main Plate
			$n = 100\,000$	$n = 2\,000\,000$	
19	+18.0 to −18.0	737.5		14.7	Partially in and partially at edge of butt weld
20	+16.0 to −16.0	549.0		12.4	At fillet weld at edge of narrow strap plate
21	+16.0 to −16.0	420.8		11.7	At fillet weld at edge of narrow strap plate
22	+25.0 to −25.0	57.6	22.4		At fillet weld at edge of wide strap plate
23	+25.0 to −25.0	131.9	26.4		At fillet weld at edge of wide strap plate
24	+25.0 to −25.0	56.9	22.3		At fillet weld at edge of wide strap plate
			Av. 23.7	Av. 12.9	

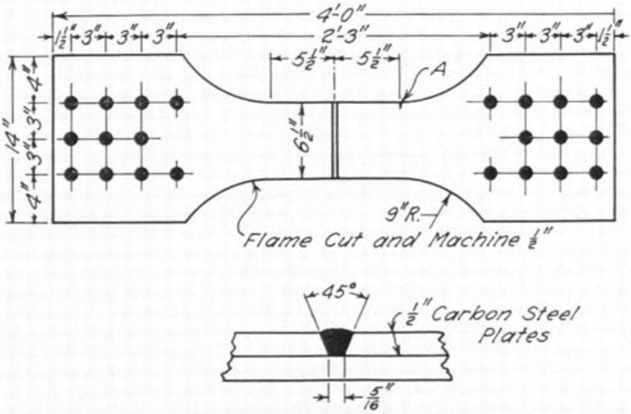


FIG. 35. TWO-COURSE SPECIMEN WITH BUTT WELD IN ONE COURSE

14 400 lb. per sq. in.* Inasmuch as the specimens were welded by the Bureau of Ships, which maintains very close inspection of its welding, the welding for the specimens reported in Table 24 was probably on a par with the welding for the basic series of Report No. 3. It would seem, therefore, that, for carbon-steel plates, the strength in fatigue was about the same for single-U butt welds in the as-welded condition and for single-V butt welds reinforced with double strap-plates, the welds for both types of joints being of equally good quality.

18. *Two-Course Specimen With Butt Weld in One Course.*—The details of the specimen are shown in Fig. 35. There were two courses; one was a continuous plate without a weld, the other consisted of two plates connected with a single-V butt weld. The continuous plate served as a backing-up plate for the butt weld in the other course. The weld penetrated into the continuous plate, thus directly connecting the two courses. The specimens were made of carbon steel with the following physical properties: yield point 38 200 lb. per sq. in., ultimate strength 69 300 lb. per sq. in., elongation in 8 in. 23.0 per cent, and reduction of area 47.1 per cent. All specimens were tested on a cycle in which the stress varied from tension to an equal compression.

The results of the tests, given in Table 25 and Fig. 36, are so inconsistent that values of $F_{100\,000}$ and $F_{2\,000\,000}$ cannot be determined with any confidence. It is believed, however, that the values given in Table 25, based upon a value of $K = 0.13$ as indicated in Fig. 36,

*Values given in Table 18, page 39, of Univ. of Ill. Eng. Exp. Sta. Bul. 327, and used as the values for the basic series, Report No. 3 of Committee on Fatigue Testing (Structural).

TABLE 25

FATIGUE STRENGTH OF TWO-COURSE SPECIMENS WITH BUTT WELD IN ONE COURSE

Stress cycle: Tension to an equal compression.

Specimen No.	Stress Cycle in 1000's of lb. per sq. in. Tension	Number of Cycles for Failure in 1000's	Fatigue Strength in 1000's of lb. per sq. in.		Location of Fatigue Fracture
			$n = 100\,000$	$n = 2\,000\,000$	
25	+23 to −23	209.8	25.3		A, Fig. 35
26	+22 to −22	269.7	25.0		At edge of reinforcement
27	+22 to −22	85.1	21.5		Partly in weld, partly at edge of reinforcement
28	+16 to −16	2 208.5		16.0	A, Fig. 35
29	+17 to −17	266.7	19.3		In weld
30	+17 to −17	171.3	18.2		In weld
			Av. 21.9	Av. 16.0	

represent the tests as well as any that could be selected. Additional tests might, however, give significantly different results. The weak specimens, 27, 29, and 30, broke either in the weld or partly in the weld and partly along the edge of the reinforcement. The strong specimens, 25, 26, and 28, broke either at the edge of the reinforcement or at a considerable distance from the weld. The fatigue strength for the latter was only slightly less than the fatigue strength of 7/8-in. carbon-steel plates without welds but with mill scale on.*

19. *Continuous Plates With Transverse Attachments.*—It is often convenient to attach a transverse plate, angle, or other rolled section

*Univ. of Ill. Eng. Exp. Sta. Bul. 327, Table 11, p. 23.

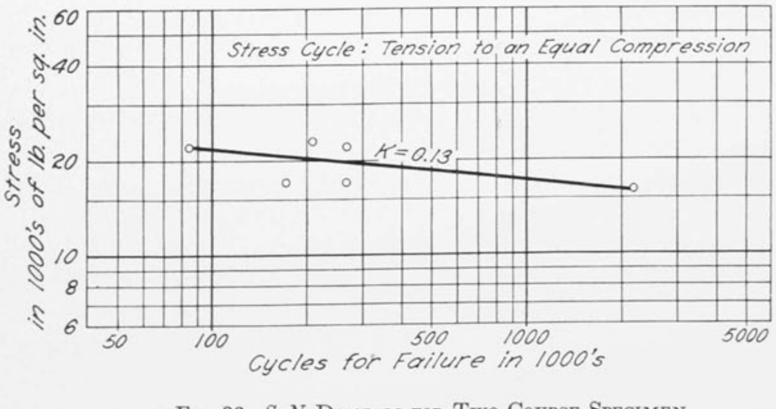


FIG. 36. *S–N* DIAGRAM FOR TWO-COURSE SPECIMEN WITH BUTT WELD IN ONE COURSE

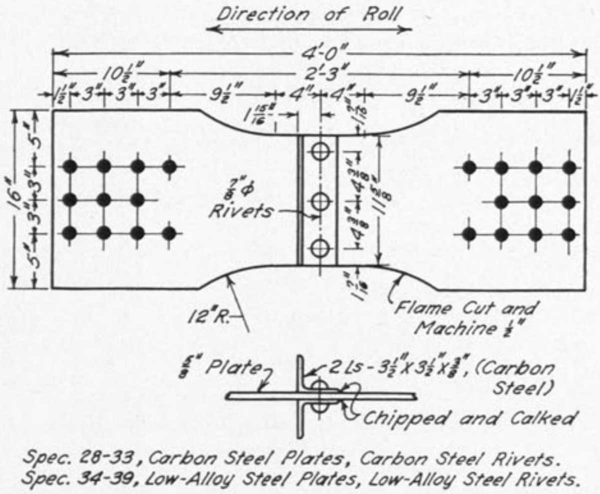


FIG. 37. CONTINUOUS PLATE WITH RIVETED TRANSVERSE ATTACHMENTS

to a principal stress-carrying member with welded or riveted connections. Tests were made to determine the extent to which attachments of this type affect the fatigue strength of the stressed member.

The details of the specimens are shown in Figs. 37 and 38. There were six types of specimens, two riveted and four welded. In addition, data from tests previously reported* are included in the summary. Some specimens were made of carbon-steel plates, others of low-alloy steel plates. Some of the plates were pickled and painted, others were galvanized. The details relative to the various types of specimens are given in Table 26. The main plate was continuous for all specimens, and all specimens were tested on a cycle in which the stress in the plate varied from tension to an equal compression, the magnitude of the stress being based on the gross section for both welded and riveted specimens.

The chemical composition and the physical properties of the plate materials are given in Tables 27 and 28.

The results of the individual tests are given in Tables 29, 30, and 31 and the *S–N* diagrams are given in Figs. 39, 40, and 41. The results are summarized in Table 32, each value being the average of three or more tests. In analyzing the results, the average fatigue strength of continuous low-alloy steel plates† without attachments

*Univ. of Ill. Eng. Exp. Sta. Bul. 327.

†The fatigue strength of continuous carbon-steel plates would have been the logical basis of comparison, but the results of the tests of these plates were so inconsistent that the value of $F_{2\,000\,000}$ could not be determined with sufficient accuracy to justify its use as a basis of comparison.

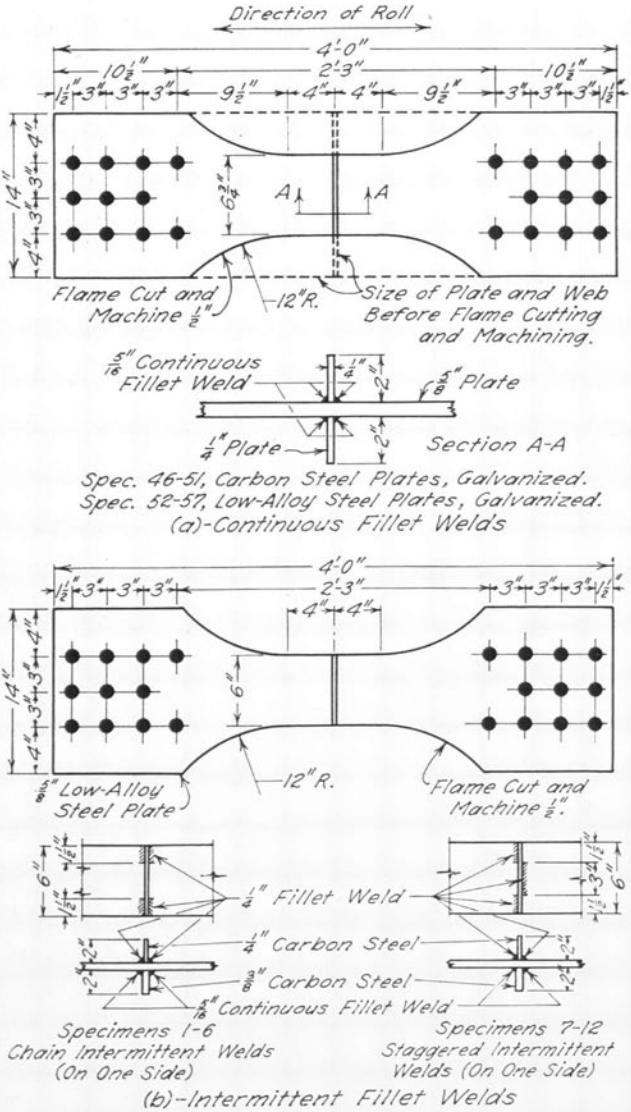


FIG. 38. CONTINUOUS PLATE WITH WELDED TRANSVERSE ATTACHMENTS

TABLE 26
DETAILS OF SPECIMENS WITH VARIOUS TYPES OF TRANSVERSE ATTACHMENTS

Specimen No.	Specimen Detailed in Fig. No.	Kind of Steel	Plates Pickled and Painted	Description of Specimen
1 to 6	38b	Low-alloy	Yes	Continuous plate with continuous transverse fillet weld on one side and chain intermittent fillet weld on other side
7 to 12	38b	Low-alloy	Yes	Continuous plate with continuous transverse fillet weld on one side and stagger intermittent fillet weld on other side
28 to 33	37	Carbon	Yes	Continuous plate with riveted transverse double-tee connections
34 to 39	37	Low-alloy	Yes	Continuous plate with riveted transverse double-tee connections
46 to 51	38a	Carbon	Galvanized	Continuous plate with welded transverse double-tee connections
52 to 57	38b	Low-alloy	Galvanized	Continuous plate with welded transverse double-tee connections
From Bulletin No. 327, page 63				
1 to 6	30 Type I	Carbon	No	Continuous plate; no attachments
7 to 12	30 Type II	Carbon	No	Continuous plate with transverse fillet weld on one side
13 to 18	30 Type III	Carbon	No	Continuous plate with transverse fillet welds on both sides
37 to 42	30 Type I	Low-alloy	No	Continuous plate; no attachments
43 to 48	30 Type II	Low-alloy	No	Continuous plate with transverse fillet weld on one side
49 to 54	30 Type III	Low-alloy	No	Continuous plate with transverse fillet welds on both sides

TABLE 27
CHEMICAL COMPOSITION OF PLATE MATERIALS; CONTINUOUS PLATES WITH TRANSVERSE ATTACHMENTS

Kind of Steel	Specimen No.	C	Mn	P	S	Si	Cu	Ni	V
Low-alloy	1 to 12	0.17	0.86	0.022	0.028	0.13	0.25	0.11	0.09
Low-alloy	34 to 39 52 to 57	0.13	0.91	0.018	0.035	0.19	0.20	0.22	0.09
Carbon	28 to 33 46 to 51	0.28	0.36	0.024	0.03	0.01	0.08	0.17	0.015

TABLE 28

PHYSICAL PROPERTIES OF PLATE MATERIALS; CONTINUOUS PLATES WITH TRANSVERSE ATTACHMENTS

Kind of Steel	Specimen No.	Yield Point lb. per sq. in.	Tensile Strength, lb. per sq. in.	Elongation in 8 in. per cent	Reduction of Area per cent
Low-alloy	1 to 12	49 800	71 000	26	64
Low-alloy	34 to 39 52 to 57	52 100	69 400	28.9	
Carbon	28 to 33 46 to 51	45 600	64 100	24.8	

TABLE 29

FATIGUE STRENGTH OF CONTINUOUS LOW-ALLOY STEEL PLATE WITH CONTINUOUS TRANSVERSE FILLET WELD ON ONE SIDE AND INTERMITTENT TRANSVERSE FILLET WELD ON OTHER SIDE

Plates pickled and painted.
Stress cycle: Tension to an equal compression.

Specimen No.	Stress in 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.	
			$n = 100\ 000$	$n = 2\ 000\ 000$
Chain Intermittent Transverse Fillet Weld. $K = 0.20$				
1	+18.5 to −18.5	78.6	17.6	
2	+18.0 to −18.0	672.1	26.5	
3	+20.0 to −20.0	437.3	27.0	
4	+14.0 to −14.0	4 435.6		14.0+
5	+16.0 to −16.0	758.9		13.1
6	+15.0 to −15.0	1 114.1		13.3
			Av. 23.7	Av. 13.5+
Stagger Intermittent Transverse Fillet Weld. $K = 0.20$				
7	+18.0 to −18.0	223.6	21.1	
8	+20.0 to −20.0	444.9	27.0	
9	+20.0 to −20.0	312.2	25.2	
10	+14.0 to −14.0	1 985.9		14.0
11	+14.0 to −14.0	2 347.7		14.0+
12	+14.0 to −14.0	1 482.5		13.2
			Av. 24.4	Av. 13.7+

All specimens failed at the edge of the weld.

TABLE 30
FATIGUE STRENGTH OF CONTINUOUS PLATE WITH RIVETED TRANSVERSE DOUBLE-TEE CONNECTION

Stress cycle: Tension to an equal compression.
Stress based upon gross section of the plates.

Specimen No.	Stress in 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.	
			$n = 100\ 000$	$n = 2\ 000\ 000$
Carbon-Steel Plates; Pickled and Painted. $K = 0.11$				
28	+20.0 to −20.0	26.3	17.3	
29	+16.0 to −16.0	86.1	15.7	
30	+16.0 to −16.0	90.1	15.8	
31	+14.0 to −14.0	379.9		11.7
32	+12.0 to −12.0	1 861.6		11.9
33	+12.0 to −12.0	1 434.9		11.6
			Av. 16.3	Av. 11.7
Low-Alloy Steel Plates; Pickled and Painted. $K = 0.18$				
34	+16.0 to −16.0	150.8	17.2	
35	+16.0 to −16.0	258.6	19.0	
36	+16.0 to −16.0	249.7	18.9	
37	+12.0 to −12.0	676.6		9.9
38	+12.0 to −12.0	1 140.1		10.8
39	+12.0 to −12.0	1 421.9		11.3
			Av. 18.4	Av. 10.7

All plates failed through the rivet holes.

or joints and with the plate in the as-rolled condition, line 2, has been used as a base (specimens 37 to 42, Table 32, Univ. of Ill. Eng. Exp. Sta. Bul. 327). There are two lines of values for each series. The upper line gives the average fatigue strength in thousands of lb. per sq. in. for the series in question; the lower line gives the ratio of the average fatigue strength of the series in question to the average fatigue strength of the basic series just described.

There are many relations of interest revealed by the values in Table 32.

For specimens with relatively small geometrical stress-raisers (no attachments, or a transverse fillet weld on only one side), the fatigue strength of the low-alloy steel specimens was somewhat greater than the fatigue strength of geometrically identical specimens of carbon steel. This was true for $n = 100\ 000$ and also for $n = 2\ 000\ 000$. For specimens with relatively large geometrical stress raisers (transverse fillet welds on both sides), the fatigue strength for $n = 100\ 000$ was about the same for low-alloy as for carbon-steel plates; for failure at

TABLE 31

FATIGUE STRENGTH OF CONTINUOUS PLATE WITH WELDED TRANSVERSE DOUBLE-TEE CONNECTION

Stress cycle: Tension to an equal compression.

Specimen No.	Stress in 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.	
			$n = 100\ 000$	$n = 2\ 000\ 000$
Carbon-Steel Plates; Galvanized. $K = 0.17$				
46	+16.0 to −16.0	90.5	15.7	
47	+16.0 to −16.0	201.9	18.0	
48	+16.0 to −16.0	189.6	17.8	
49	+12.0 to −12.0	841.8		10.4
50	+12.0 to −12.0	726.8		10.1
51	+11.0 to −11.0	1 494.8		10.5
			Av. 17.2	Av. 10.3
Low-Alloy Steel Plates; Galvanized. $K = 0.30$				
52	+16.0 to −16.0	207.5	19.9	
53	+16.0 to −16.0	115.3	16.7	
54	+16.0 to −16.0	148.9	18.0	
55	+12.0 to −12.0	314.0		6.9
56	+10.0 to −10.0	1 033.3		8.2
57	+10.0 to −10.0	520.3		6.7
			Av. 18.2	Av. 7.3

All specimens failed at edge of weld.

2 000 000 cycles the carbon steel had a higher fatigue strength than the low-alloy steel.

A large geometrical stress raiser caused a greater percentage reduction in the fatigue strength of the low-alloy steel than in that of the similar carbon-steel specimen. Likewise, for these tests, a large geometrical stress raiser caused a greater percentage reduction in the fatigue strength for failure at 2 000 000 cycles than for failure at 100 000 cycles.

Of the continuous low-alloy steel plates with transverse fillet welds on both sides, lines 6, 7, and 8 of Table 32, the fatigue strength for failure at 100 000 cycles was very nearly the same for all three types of welds; for failure at 2 000 000 cycles, the fatigue strength was considerably less for the specimens with continuous fillet welds on both sides, line 6, than it was for specimens with a continuous fillet weld on one side and either stagger or chain intermittent fillet welds on the other side, lines 7 and 8.

Of the specimens with continuous low-alloy steel plates with transverse fillet welds on both sides, those with galvanized plates had a

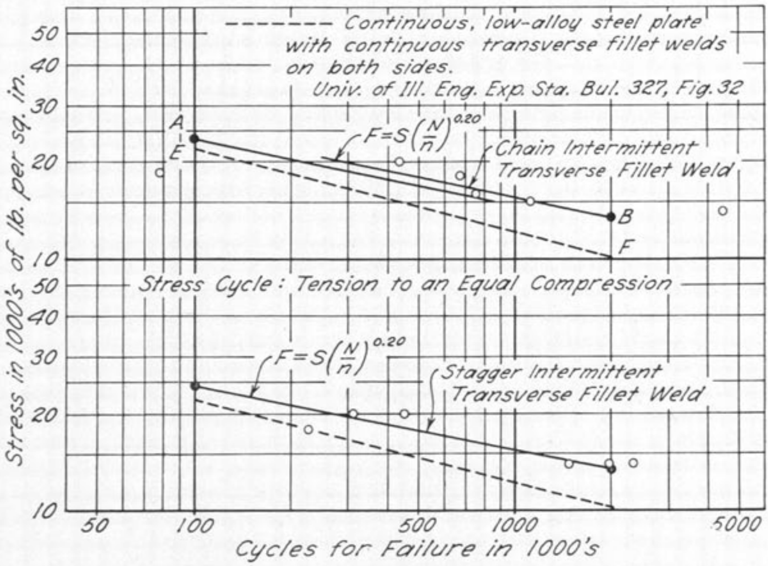


FIG. 39. S–N DIAGRAMS FOR LOW-ALLOY STEEL PLATES WITH CONTINUOUS TRANSVERSE FILLET WELD ON ONE SIDE AND INTERMITTENT TRANSVERSE FILLET WELD ON OTHER SIDE

lower fatigue strength than those with pickled and painted plates. This was true for $n = 100\ 000$ and for $n = 2\ 000\ 000$. There was no indication that pickling and painting had any significant effect upon the fatigue strength of the plates.

The continuous ungalvanized plates with double-tee riveted con-

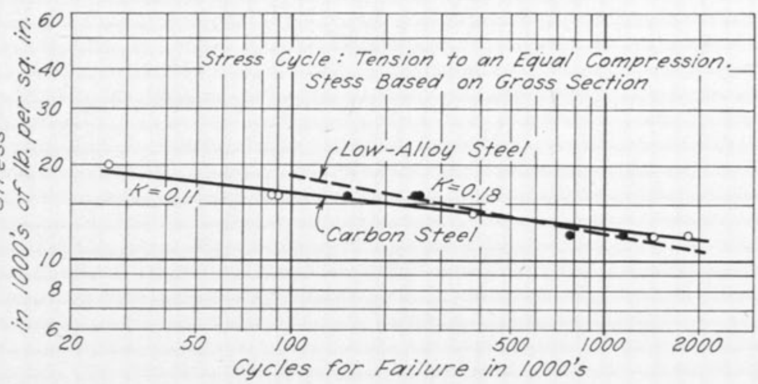


FIG. 40. S–N DIAGRAMS FOR CONTINUOUS PLATE WITH RIVETED TRANSVERSE DOUBLE-TEE CONNECTIONS

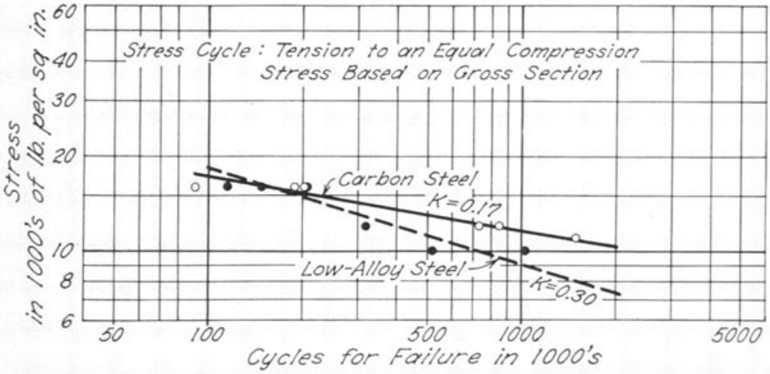


FIG. 41. *S–N* DIAGRAMS FOR CONTINUOUS PLATE WITH WELDED TRANSVERSE DOUBLE-TEE CONNECTIONS

TABLE 32

FATIGUE STRENGTH OF CONTINUOUS PLATES WITH TRANSVERSE ATTACHMENTS; SUMMARY OF RESULTS

Stress cycle: Tension to an equal compression. Stress based on gross section of plate. Each value is the average of three or more tests.

Description of Specimens	Line No.	Specimen No.	Kind of Plate Steel	Plates Pickled and Painted	Fatigue Strength in 1000's of lb. per sq. in.*	
					$n =$ 100 000	$n =$ 2 000 000
Continuous plate; no attachment or joint†	1	1 to 6	Carbon	No	25.8 0.73	
	2	37 to 42	Low-alloy	No	35.3 1.00	26.4 1.00
Continuous plate; continuous transverse fillet weld on one side†	3	7 to 12	Carbon	No	25.4 0.72	18.9 0.72
	4	43 to 48	Low-alloy	No	31.7 0.90	23.9 0.91
Continuous plate; continuous transverse fillet welds on both sides†	5	13 to 18	Carbon	No	22.9 0.65	13.1 0.50
	6	49 to 54	Low-alloy	No	22.2 0.63	10.1 0.38
Continuous plate with continuous transverse fillet weld on one side and chain intermittent fillet weld on other side	7	1 to 6	Low-alloy	Yes	23.7 0.67	13.5 0.51
Continuous plate with continuous transverse fillet weld on one side and stagger intermittent fillet weld on other side	8	7 to 12	Low-alloy	Yes	24.4 0.69	13.7 0.52
Continuous plate with riveted transverse double-tee connection	9	28 to 33	Carbon	Yes	16.3 0.46	11.7 0.44
Continuous plate with riveted transverse double-tee connection	10	34 to 39	Low-alloy	Yes	18.4 0.52	10.7 0.41
Continuous plate with welded transverse double-tee connection	11	46 to 51	Carbon	Galvanized	17.2 0.49	10.3 0.39
Continuous plate with welded transverse double-tee connection	12	52 to 57	Low-alloy	Galvanized	18.2 0.52	7.3 0.28

*Upper line is fatigue strength in 1000's of lb. per sq. in. based upon the gross section; lower line is ratio of fatigue strength for series in question to fatigue strength of continuous ½-in. low-alloy steel plate without attachments.

†From Bulletin 327, Table 33, page 70.

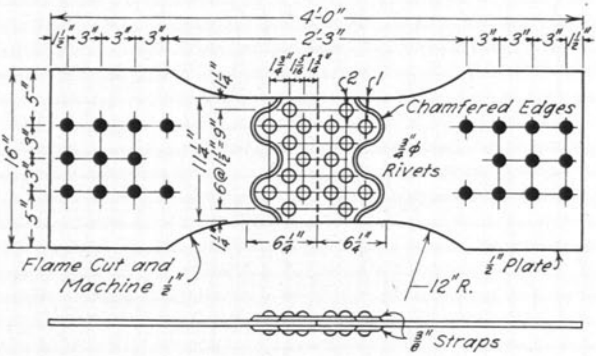


FIG. 42. DOUBLE-STRAP RIVETED BUTT JOINTS

nections had, in general, a lower fatigue strength than similar continuous plates with double-tee connections welded on, the unit stress being based upon the gross section of the plate in both instances. This was true for both carbon-steel and low-alloy steel plates, and for both $n = 100\ 000$ and $n = 2\ 000\ 000$.

The specimens that had the greatest percentage reduction in fatigue strength for failure at 2 000 000 cycles were the galvanized low-alloy steel plates with welded transverse double-tee connections. These had a fatigue strength equal to only 0.28 of the fatigue strength of similar low-alloy steel plates in the as-rolled condition and without joints or attachments.

20. *Double-Strap Riveted Butt Joints in Carbon-Steel and Low-Alloy Steel Plates.*—Fatigue tests were made on double-strap riveted butt joints fabricated of both carbon steel and low-alloy steel. The details of the specimens, which were the same for the two kinds of steels, are shown in Fig. 42. The chemical composition and physical properties of the plate material are given in lines 1 and 2 of Tables 33 and 34, respectively. All specimens were tested on a cycle in which the stress varied from tension to an equal compression, and the stress was based upon the gross section of the main plate. The results of the tests, given in Table 35, are summarized in Table 42 and discussed in Section 25.

21. *Single-Strap Riveted Butt Joints in Carbon-Steel and Low-Alloy Steel Plates.*—The details of the specimens, which were the same for the two kinds of steel, are shown in Fig. 43. The chemical composition and the physical properties of the plate material are given in lines 3 and 4 of Tables 33 and 34, respectively. All specimens were

TABLE 33
CHEMICAL COMPOSITION OF STEEL PLATES

Description of Joint	Line No.	Specimen No.	Chemical Content—per cent								
			C	Mn	P	S	Si	Cu	Ni	Cr	Va
Double-strap riveted butt joint; carbon-steel plate. 28 to 33 pickled and painted. 37 to 39 not pickled and painted	1	28 to 33 37 to 39	0.20	0.42	0.015	0.027	0.23		0.07	0.04	0.03
Double-strap riveted butt joint; low-alloy steel plate pickled and painted Single-V butt weld; low-alloy steel plate; plates pickled and painted	2	43 to 45 46 to 48	0.15	1.06	0.014	0.035		0.05	0.37		0.13
Single-strap riveted butt joint; carbon-steel plate pickled and painted	3	1 to 9	0.13	0.41	0.017	0.029	0.01	0.22	0.16		0.015
Single-strap riveted butt joint; low-alloy steel plate pickled and painted	4	10 to 18	0.15	1.26	0.026	0.028	0.22	0.08	0.02		0.09
Single-V butt weld; low-alloy steel plate; plates pickled and painted	5	13 to 18	0.18	0.96	0.019	0.026	0.15	0.20	0.04		0.10

TABLE 34
PHYSICAL PROPERTIES OF STEEL PLATES

Description of Joint	Line No.	Specimen No.	Yield Point lb. per sq. in.	Ultimate Strength lb. per sq. in.	Elongation in 8 in. per cent	Reduction of Area per cent
Double-strap riveted butt joint; carbon-steel plate	1	28 to 33* 37 to 39†	38 200	62 700	30.0	57.2
Double-strap riveted butt joint; low-alloy steel plate pickled and painted Single-V butt weld; low-alloy steel plate; plates pickled and painted	2	43 to 45 46 to 48	55 300	76 800	23.0	61.0
Single-strap riveted butt joint; carbon-steel plate pickled and painted	3	1 to 9	38 300	60 800	27.4	
Single-strap riveted butt joint; low-alloy steel plate pickled and painted	4	10 to 18	62 600	83 000	19.5	
Single-V butt weld; low-alloy steel plate; plates pickled and painted	5	13 to 18	60 400	79 700	30.0‡	68.0

*Plates pickled and painted.
†Plates not pickled and painted.
‡In 2 inches.

TABLE 35
FATIGUE STRENGTH OF DOUBLE-STRAP RIVETED BUTT JOINTS

Stress cycle: Tension to an equal compression.
Stress based on gross section of main plate.

Specimen No.	Stress in 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.	
			$n = 100\ 000$	$n = 2\ 000\ 000$
Carbon-Steel Plates; Pickled and Painted				
28	+16.0 to −16.0	298.7	19.9	
29	+16.0 to −16.0	278.3	19.7	
30	+16.0 to −16.0	287.2	19.8	
31	+10.0 to −10.0	2 963.3		10.0
32	+12.0 to −12.0	960.6		10.3
33	+12.0 to −12.0	1 866.9		11.8
			Av. 19.8	Av. 10.7
Carbon-Steel Plates; Not Pickled or Painted				
37	+14.0 to −14.0	219.9	16.0	
38	+18.0 to −18.0	53.1	16.9	
39	+11.0 to −11.0	1 362.8		10.1
			Av. 16.5	Av. 10.1
Low-Alloy Steel Plates; Pickled and Painted				
43	+21.0 to −21.0	113.5	21.4	
44	+16.0 to −16.0	836.7		13.8
45	+13.0 to −13.0	1 174.2		13.0
			Av. 21.4	Av. 13.4

Specimens 32 and 37 failed in strap plate at (2), Fig. 42; all others failed in the main plate at (1), Fig. 42.

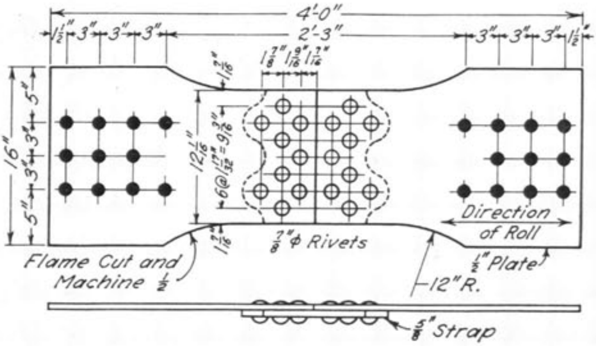


Fig. 43. Single-Strap Riveted Butt Joints

tested on a cycle in which the stress varied from tension to an equal compression, and the stress was based upon the gross section of the main plate. The results of the tests, given in Table 36, are summarized in Table 42 and discussed in Section 25.

22. *Single-V Butt Welds in Carbon-Steel Plates.*—There were two series of specimens each consisting of single-V butt welds in carbon-

Table 36

Fatigue Strength of Single-Strap Riveted Butt Joints

Stress cycle: Tension to an equal compression.
Stress based on gross section of ½-in. plates.
All specimens failed in the strap plate through the transverse row of rivet holes next to the center of the specimen.

Specimen No.	Stress in 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.	
			$n = 100\,000$	$n = 2\,000\,000$
Carbon-Steel Plates; Pickled and Painted				
1	+10.3 to −10.3	49.1	9.1	
2	+10.0 to −10.0	104.0	10.1	
3	+10.0 to −10.0	105.1	10.1	
7	+ 7.0 to − 7.0	860.0		6.1
8	+ 6.0 to − 6.0	2 309.7		6.0+
9	+ 6.0 to − 6.0	1 245.2		5.5
			Av. 9.8	Av. 5.9
Low-Alloy Steel Plates; Pickled and Painted				
10	+12.0 to −12.0	93.1	11.8	
11	+12.0 to −12.0	76.5	11.2	
12	+11.0 to −11.0	108.4	11.2	
16	+ 7.0 to − 7.0	772.4		5.5
17	+ 6.0 to − 6.0	1 150.1		5.2
18	+ 6.0 to − 6.0	1 209.3		5.3
			Av. 11.4	Av. 5.3

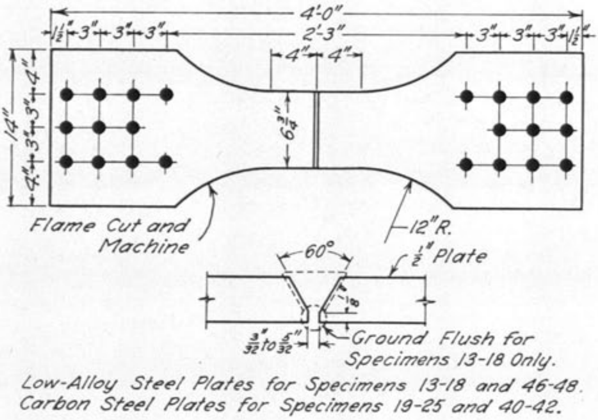


FIG. 44. SINGLE-V BUTT WELDS

steel plates. For one series the plates were pickled and painted, for the other they were not. The plates were of the same steel as the plates of the carbon-steel specimens used in the double-strap riveted butt joints described in Section 20. The details of the specimens are shown in Fig. 44, and the welding procedure is given in Table 37.

All specimens were tested on a cycle in which the stress varied from tension to an equal compression. The results, given in Table 38 and Fig. 45, are summarized in Table 42 and discussed in Section 25.

There were not enough data to determine the values of $F_{100\,000}$ and $F_{2\,000\,000}$ for the plates not pickled or painted. Instead, the *S–N* diagram was drawn for the plates pickled and painted, Fig. 45, and the results of the tests of plates not pickled or painted were plotted on the same field. The results for the plates pickled and painted are represented by open circles and the results for the plates not pickled or painted are represented by solid circles. It is apparent that pickling and painting the plates had no significant effect upon the fatigue strength of these specimens.

TABLE 37
WELDING PROCEDURE; SINGLE-V BUTT WELDS IN CARBON-STEEL AND LOW-ALLOY STEEL PLATES

Electrode A.W.S. classification	E 6010
Size of electrode	5/32 in.
Number of passes per weld	5
Open circuit voltage	61
Arc volts	27
Arc amps.	150
Polarity	Reversed
Preheat	None
Position	Flat

TABLE 38
FATIGUE STRENGTH OF SINGLE-V BUTT WELDS CONNECTING CARBON-STEEL PLATES

Stress cycle: Tension to an equal compression.

Specimen No.	Stress in 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.	
			$n = 100\,000$	$n = 2\,000\,000$
Plates Pickled and Painted				
19	+16.0 to −16.0	2 633.9		16.0
20	+18.0 to −18.0	431.8	20.3	
21	+18.0 to −18.0	191.8	18.9	
22	+20.0 to −20.0	144.7	20.6	
23	+16.0 to −16.0	479.1		14.2
24	+15.0 to −15.0	2 186.6		15.0
25	+16.0 to −16.0	2 396.4		16.0
			Av. 19.9	Av. 15.3
Plates Not Pickled and Painted				
40	+20.0 to −20.0	574.7		
41	+17.0 to −17.0	1 331.2		
42	+15.0 to −15.0	5 307.1	Did not break	

Location of fractures:
In weld for specimen 24.
At edge of weld for specimens 21, 23, 40 and 41.
Partially in weld and partially at edge of weld for specimens 19, 22 and 25.
Some distance from weld for specimen 20.

23. *Single-V Butt Welds in Low-Alloy Steel Plates.*—There were two series of specimens each consisting of a single-V butt weld connecting low-alloy steel plates. The two series differed in this respect. Specimens 46 to 48 were tested in the as-welded condition, whereas for specimens 13 to 18 the reinforcement was ground flush with the

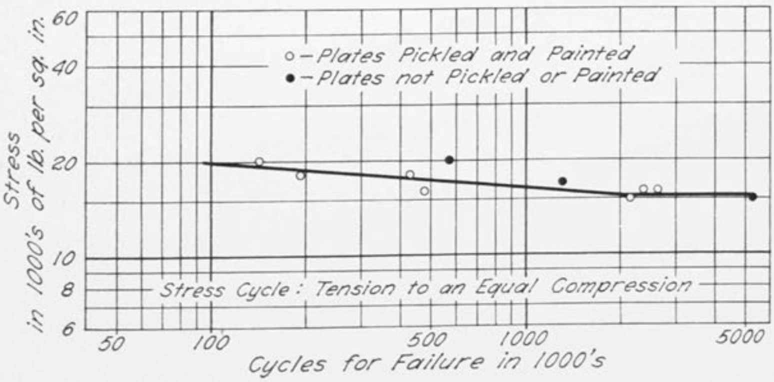


FIG. 45. *S–N* DIAGRAM FOR SINGLE-V BUTT WELD JOINTS CONNECTING CARBON-STEEL PLATES

TABLE 39

WELDING PROCEDURE FOR SPECIMENS 13 TO 18

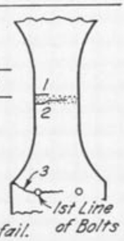
Electrode A.W.S. classification	E 6010
Size of electrode	5/32 in.
Number of passes per weld	6
Open voltage circuit	56
Arc volts	24
Arc amps.	130
Polarity	Reversed
Preheat	None
Position	Flat

base plate on the root side only. The chemical composition and the physical properties of the plate material are given in lines 2 and 5 of Tables 33 and 34, respectively. The details of the specimens are the same as for the specimens of Section 22, shown in Fig. 44. All plates were pickled and painted. The welding procedure for specimens 46 to 48 was the same as for the specimens of Section 22, and is given in Table 37. The welding procedure for specimens 13 to 18 is given in Table 39. All specimens were tested on a cycle in which the stress varied from tension to an equal compression. The results of the tests are given in Table 40 and Fig. 46. The tests of the specimens with the reinforcement ground flush with the base plate on the root side only were quite consistent, and the fatigue strength is represented fairly well by the *S–N* diagram in the lower portion of Fig. 46. The results of the tests of the present series, tested in the as-welded condition and represented by the small circles in the upper part of Fig. 46, were so inconsistent that they cannot be interpreted satisfactorily alone. The broken line, AB, in the upper portion of the same figure represents

TABLE 40

FATIGUE STRENGTH OF SINGLE-V BUTT WELDS CONNECTING LOW-ALLOY STEEL PLATES

Specimen No.	Stress, S, in 1000's of lb. per sq. in.	Number of Cycles for Failure, N, in 1000's	Fatigue Strength, F, in 1000's of lb. per sq. in.			Location of Failure
			n=100 000	n=600 000	n=2 000 000	
As-welded Condition						
46	+26.0 to −26.0	268.1	25.0			1
47	+19.0 to −19.0	372.6		18.6		1
48	+17.0 to −17.0	454.1			15.0	1
Reinforcement Ground Flush with Base Plate on Root Side Only						
13	+28.0 to −28.0	24.0	22.9			2
14	+24.0 to −24.0	301.1	28.0			3
15	+26.0 to −26.0	190.9	28.5			1
			Av. 26.4			
16	+20.0 to −20.0	1267.0			18.8	1
17	+19.0 to −19.0	974.5			17.2	1&2
18	+18.0 to −18.0	3697.8			18.0+	Did not fail.
					Av. 18.0+	



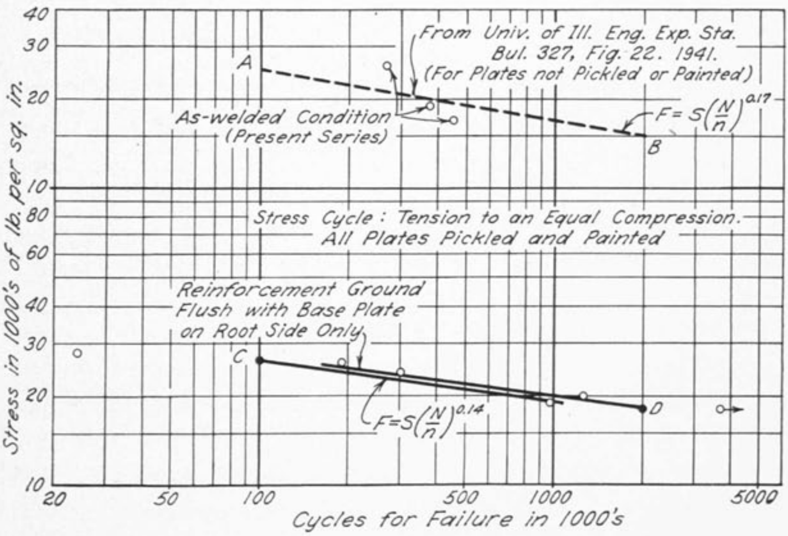


FIG. 46. *S–N* DIAGRAMS FOR SINGLE-V BUTT WELDS CONNECTING LOW-ALLOY STEEL PLATES

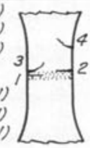
tests of specimens that were similar except that the plates were not pickled or painted. It closely approximates a gravity line for the three small open circles and, since the material and the geometrical details for the present series and the series represented by the line AB were identical except for pickling and painting, it is not unreasonable to suppose that the line AB approximates closely the *S–N* diagram for the present series. The values of $F_{100\,000}$ and $F_{2\,000\,000}$ for specimens 46, 47, and 48 of Table 40, are based upon the assumption that the line AB is also the *S–N* diagram for the specimens with plates that are pickled and painted.

24. *Single-V Butt-Weld Joints Connecting Carbon-Steel Plates to Low-Alloy Steel Plates.*—Tests were made on single-V butt-weld joints connecting carbon-steel plates to low-alloy steel plates. The chemical composition and the physical properties of the steel are given in line 3 of Tables 33 and 34 for the carbon-steel plates, and in line 4 of the same tables for the low-alloy steel plates. The dimensions of the specimens were the same as for the specimens of Sections 22 and 23, shown in Fig. 44 except that the reinforcement was not ground off. The results of the tests, given in Table 41 and Fig. 47, were fairly consistent. One specimen broke in both plates, the others all broke in the carbon-steel plate. The average values of the fatigue strength were 25 800 lb.

TABLE 41

FATIGUE STRENGTH OF SINGLE-V BUTT WELDS CONNECTING CARBON-STEEL PLATES TO LOW-ALLOY STEEL PLATES

Specimen No.	Stress, S, in 1000's of lb. per sq. in.	Number of Cycles for Failure, N, in 1000's	Fatigue Strength, F, in 1000's of lb. per sq. in.		Location of Failure
			n = 100 000	n = 2 000 000	
70	+24.0 to −24.0	154.7	26.2		4 (Carbon Steel)
71	+24.0 to −24.0	97.3	23.9		4 (Carbon Steel)
72	+24.0 to −24.0	183.2	27.2		1,2 (Both Plates)
			Av. 25.8		
73	+16.0 to −16.0	613.0		12.5	2,3 (Carbon Steel)
74	+16.0 to −16.0	1296.0		14.6	2,3 (Carbon Steel)
75	+15.0 to −15.0	1489.1		14.1	2,3 (Carbon Steel)
				Av. 13.7	



per sq. in. and 13 700 lb. per sq. in. for $F_{100\,000}$ and $F_{2\,000\,000}$, respectively. The value of $F_{100\,000}$ was somewhat greater for this composite specimen than it was for either carbon-steel or low-alloy steel specimens.

25. *Fatigue Strength of Various Types of Welded and Riveted Butt Joints.*—The results of the tests of the various types of welded and riveted butt joints described in Sections 17 to 24 are summarized in Table 42. Some tests reported in Univ. of Ill. Eng. Exp. Sta. Bul. 327 have also been included in this summary.

The first part of the table gives the fatigue strength of carbon-steel specimens, the second part gives the fatigue strength of low-alloy steel specimens. There are two lines of figures for each kind of specimen. The upper line is the fatigue strength in thousands of lb. per sq. in. gross section of the main plate of the specimen, the lower

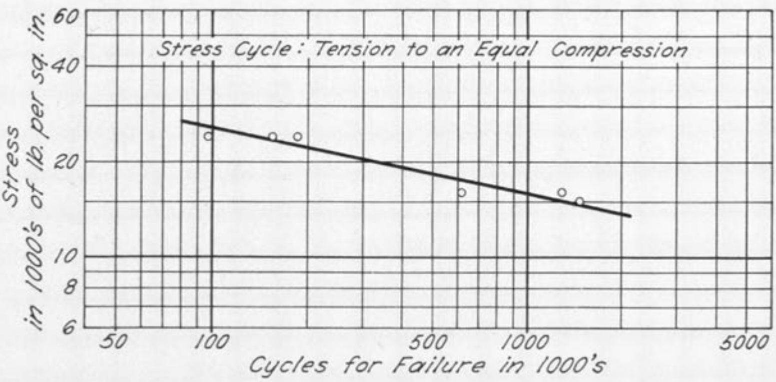


FIG. 47. S–N DIAGRAM FOR SINGLE-V BUTT WELDS CONNECTING CARBON-STEEL PLATES TO LOW-ALLOY STEEL PLATES

TABLE 42

FATIGUE STRENGTH OF VARIOUS TYPES OF WELDED AND RIVETED BUTT JOINTS; SUMMARY

Stress cycle: Tension to an equal compression; stress based on gross section of plates. In general, each value is the average of three or more tests.

Description of Specimens	Line No.	Reference Page No.*	Specimen No.	Plates Pickled and Painted	Fatigue Strength in 1000's of lb. per sq. in.†	
					$n =$ 100 000	$n =$ 2 000 000
Carbon-Steel Plates						
Continuous ⅞-in. plate	1	Bul. 327 23	G1 to G3 H1 to H4	No	27.7 1.00	17.1 1.00
Continuous ⅝-in. plate	2	Bul. 327 67	1 to 6	No	25.8 0.93	
Single-V butt weld; reinforcement on	3		19 to 25 40 to 42	Yes No	19.9 0.72	15.3 0.89
Single-V butt weld; reinforcement on; one plate carbon steel, one low-alloy steel	4		70 to 75	Carbon, No Alloy, Yes	25.8 0.93	13.7 0.80
Welded butt joint with double straps attached with fillet welds	5		19 to 24	No	23.7 0.86	12.9 0.75
Two-course specimen; one course continuous, other course with single-V butt weld	6		25 to 30	No	21.9 0.79	16.0 0.94
Double-strap riveted butt joint	7		28 to 33	Yes	19.8 0.71	10.7 0.63
Double-strap riveted butt joint	8		37 to 39	No	16.5 0.60	10.1 0.59
Single-strap riveted butt joint	9		1 to 9	Yes	9.8 0.35	5.9 0.35
Double-V butt weld in ⅞-in. plate; reinforcement on; good quality of weld	10	Bul. 327 17	C1 to C4 D1 to D3	No	21.3 0.77	14.4 0.84
Low-Alloy Steel Plates						
Single-V butt weld; reinforcement on	11		46 to 48	Yes‡	25.7 0.93	15.4 0.90
Single-V butt weld; reinforcement on	12	Bul. 327 49	101 to 106	No	25.7 0.93	15.4 0.90
Single-V butt weld; reinforcement planed flush with base plate on root side only	13		13 to 18	Yes	26.4 0.95	18.0 1.05
Double-strap riveted butt joint	14	Bul. 327 57	96 to 100	No	20.1 0.73	13.3 0.78
Double-strap riveted butt joint	15		43 to 45	Yes	21.4 0.77	13.4 0.78
Single-strap riveted butt joint	16		10 to 18	Yes	11.4 0.41	5.3 0.31

*References are to page numbers in this bulletin unless otherwise noted.
†Upper line is fatigue strength in 1000's of lb. per sq. in., lower line is ratio of fatigue strength for series in question to fatigue strength of a continuous ⅞-in. carbon-steel plate.
‡Values taken the same as for plates not pickled or painted; see Fig. 46.

line is the ratio of the average fatigue strength for the series in question to the fatigue strength of a continuous ⅞-in. carbon-steel plate.* A study of Table 42 reveals some interesting relations between the fatigue strengths of various types of butt joints.

In general, the fatigue strength was somewhat greater for single-V butt welds than for double-strap riveted joints.

*Univ. of Ill. Eng. Exp. Sta. Bul. 327, p. 23.

For failure at 2 000 000 cycles, the fatigue strength of single-V butt welds was very nearly the same for carbon-steel and low-alloy steel specimens. For failure at 100 000 cycles, the fatigue strength was considerably greater for the alloy-steel than it was for the carbon-steel specimens. The fatigue strength of double-strap riveted joints was considerably greater for low-alloy steel specimens than it was for carbon-steel specimens. This was contrary to the results of previous tests* in which the specimens were subjected to a cycle in which the stress varied from 0 to tension.

The fatigue strength was slightly more than one-half as great for the single-strap as for the double-strap riveted butt joints.

V. Summary

26. *Summary.*—The tests described in this bulletin were exploratory and did not include comprehensive investigations of any portion of the wide field of the fatigue strength of fillet-weld and plug-weld joints. The statements which follow are to be considered as a summary of the results of the particular tests described, and not as generalizations relative to the fatigue strength of fillet-weld and plug-weld joints in general.

The results of the various series of tests have been summarized as follows:

(1) Of the various types of fillet-weld joints connecting plates that were tested, there were none that had a significantly greater fatigue strength than the simple joint with longitudinal fillet welds along the sides and transverse fillet welds across the ends of the plates. Three joints of this type withstood an average of 283 000 repetitions of a cycle in which the tension in the plates varied from 0 to 18 000 lb. per sq. in.

(2) Of the various types of fillet-weld joints connecting channels to plates that were tested, the one with longitudinal fillet welds along the sides and transverse fillet welds across the ends of the channels had the greatest fatigue strength. Three joints of this type withstood an average of 849 000 repetitions of a cycle in which the average tension in the channels varied from 0 to 18 000 lb. per sq. in.

(3) The fatigue strength was somewhat lower for a channel box section connected to gusset plates by means of fillet welds than it was for two channels back-to-back connected with the same type of fillet welds to a gusset plate between. The fatigue strength was ap-

*Univ. of Ill. Eng. Exp. Sta. Bul. 302, p. 103.

proximately the same for channel box sections with welded connections as it was for similar channel box sections with riveted connections, the stress being based on the gross section in both instances.

(4) The fatigue strength of riveted and welded lateral connections may be summarized as follows:

(a) The values of the fatigue strength of the individual specimens were much more erratic for the riveted angles than they were for either the welded angles or the welded channels, and minimum values based upon the gross section were less for the riveted than they were for the welded angles.

(b) There was no significant difference in the fatigue strengths of the angles and channels when they were both eccentrically connected with fillet welds.

(c) The fatigue strength was 20 per cent less for the channels with longitudinal and transverse fillet welds and a relatively large eccentricity than for the channels with butt welds and no eccentricity.

(d) Failure of all specimens with longitudinal fillet welds occurred in the main member and at the end of the weld toward the center of the specimen. No welds failed.

(e) Failure of the specimens with butt welds occurred in the channel at the junction with the weld where the abrupt change in section caused a large stress concentration.

(f) Failure of the riveted angles occurred at the inner rivet hole and on the side away from the outstanding leg, as shown by the sketch in Table 7. The fatigue strength was probably reduced by the eccentricity of the rivet hole as well as by the hole itself. No rivets either failed or loosened.

(5) Peening increased the fatigue strength of transverse fillet welds and decreased the fatigue strength of longitudinal fillet welds. Neither the welding nor the peening procedures were under definite enough control to determine whether the differences in fatigue strength were due to peening or to other causes.

(6) The fatigue strength in shear of the plug welds of plug-weld joints connecting plates, corresponding to failure at 100 000 repetitions of a cycle in which the stress on the specimen varied from 0 to tension, was of the order of 20 000 to 25 000 lb. per sq. in., the stress being based upon the nominal diameter of the plugs. There was a small but quite consistent increase in the fatigue strength of the plugs with an increase in the thickness of the outside plates. There was a slight and not always consistent decrease in the fatigue strength of the plugs with an increase in their diameter.

(7) The fatigue strength of the plugs of multiple-plug joints was not appreciably affected by the plug pattern, the fatigue strength being as great for four plugs in a line in the direction of stress as for four plugs in a square and being as great for six plugs consisting of two lines of three plugs each as for six plugs consisting of three lines of two plugs each.

(8) The fatigue strength of plates connected with plug welds was somewhat greater for the outside than for the inside plates. The average fatigue strength corresponding to failure at 100 000 repetitions of a cycle in which the stress in the plate varied from 0 to tension, was of the order of 26 000 to 30 000 lb. per sq. in. for the outside plates, and of the order of 25 000 to 27 000 lb. per sq. in. for the inside plates. These values are based upon the gross area of the plate.

(9) The unit fatigue strength was approximately the same for fillet-weld plugs and for filled plugs, the unit stress being based upon the section of the hole in the outer plate in each instance. However, the fatigue strength of the outside plates of a plug-weld joint was significantly less for the joints with fillet plugs than it was for those with filled plugs.

(10) Metallurgical studies indicated that the diameter of the plug of plug-weld joints was greater than the diameter of the holes in the outer plates, the oversize resulting from the fusion of the base plate being from $\frac{1}{16}$ in. to $\frac{1}{4}$ in. at the inside surface of the plate, and being somewhat greater at the outside surface. There was no consistent relation between the oversize and either the diameter of the hole or the thickness of the plates.

(11) Riveted joints reinforced with plates to compensate for deductions due to rivet holes, the fills being attached with fillet welds in one instance and with plug welds in another instance, did not have a fatigue strength significantly higher than that of similar riveted joints without such reinforcement.

(12) Attachments either welded or riveted to a continuous plate reduced the fatigue strength of the plate, the magnitude of the reduction depending upon the geometrical characteristics of the attachment and the physical properties of the steel. Values of the fatigue strength of continuous plates with various types of attachments are given in Table 32, page 79.

(13) Values of the fatigue strength of various types of welded and riveted butt joints in carbon and low-alloy steels are given in Table 42, page 89.

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