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FATIGUE STRENGTH OF VARIOUS DETAILS USED FOR THE REPAIR OF BRIDGE MEMBERS

BY

WILBUR M. WILSON
AND
WILLIAM H. MUNSE
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THE ENGINEERING EXPERIMENT STATION,

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FATIGUE STRENGTH OF VARIOUS DETAILS
USED FOR THE REPAIR OF
BRIDGE 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

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UNDER THE SUPERVISION OF THE
COMMITTEE ON FATIGUE TESTING (STRUCTURAL),
WELDING RESEARCH COUNCIL, THE ENGINEERING FOUNDATION

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## CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>I. INTRODUCTION</strong></td>
<td>7</td>
</tr>
<tr>
<td>1. Object and Scope of Investigation</td>
<td>7</td>
</tr>
<tr>
<td>2. Acknowledgments</td>
<td>7</td>
</tr>
<tr>
<td><strong>II. DESCRIPTION OF TESTS</strong></td>
<td>11</td>
</tr>
<tr>
<td>3. Eyebars Shortened by Heating and Upsetting</td>
<td>11</td>
</tr>
<tr>
<td>4. Eyebars Shortened by Cutting and Splicing</td>
<td>15</td>
</tr>
<tr>
<td>5. Riveted and Composite Riveted-and-Welded Joints</td>
<td>19</td>
</tr>
<tr>
<td>6. Butt Welds Reinforced with Strap Plates</td>
<td>29</td>
</tr>
<tr>
<td>7. Reinforced Tension Members</td>
<td>35</td>
</tr>
<tr>
<td>8. Spliced and Reinforced I-Beams</td>
<td>39</td>
</tr>
<tr>
<td>(a) Beams with Cover Plates of Various Thicknesses Attached with Fillet Welds</td>
<td>42</td>
</tr>
<tr>
<td>(b) Beams with Butt-Welded Splices</td>
<td>45</td>
</tr>
<tr>
<td>(c) Beams with Riveted Splices</td>
<td>54</td>
</tr>
<tr>
<td><strong>III. SUMMARY</strong></td>
<td>57</td>
</tr>
<tr>
<td>NO.</td>
<td>Description</td>
</tr>
<tr>
<td>-----</td>
<td>-----------------------------------------------------------------------------</td>
</tr>
<tr>
<td>1.</td>
<td>Details of Eyebar Specimens Shortened by Heating and Upsetting</td>
</tr>
<tr>
<td>2.</td>
<td>Wrought-Iron Eyebar Specimens After Failure</td>
</tr>
<tr>
<td>3.</td>
<td>Typical Eyebars Shortened by Cutting and Splicing</td>
</tr>
<tr>
<td>4.</td>
<td>S-N Diagrams for Series 44P</td>
</tr>
<tr>
<td>5.</td>
<td>Riveted Joints</td>
</tr>
<tr>
<td>6.</td>
<td>Composite Riveted-and-Welded Joints</td>
</tr>
<tr>
<td>7.</td>
<td>S-N Diagrams for Plates Connected with Butt Straps</td>
</tr>
<tr>
<td>8.</td>
<td>Butt Welds Reinforced with Strap Plates</td>
</tr>
<tr>
<td>9.</td>
<td>Butt Welds Reinforced with Narrow Strap Plates</td>
</tr>
<tr>
<td>10.</td>
<td>Welding Procedure for Butt Weld Specimens</td>
</tr>
<tr>
<td>11.</td>
<td>S-N Diagrams for Series 44Sa-44Se</td>
</tr>
<tr>
<td>12.</td>
<td>Static Fractures of Reinforced Butt Welds</td>
</tr>
<tr>
<td>13.</td>
<td>Reinforced Tension Members</td>
</tr>
<tr>
<td>15.</td>
<td>112,000-lb Flexural Fatigue Testing Machine</td>
</tr>
<tr>
<td>16.</td>
<td>S-N Diagrams for Beams with Full-Length Cover Plates Attached with</td>
</tr>
<tr>
<td></td>
<td>Continuous Fillet Welds</td>
</tr>
<tr>
<td>17.</td>
<td>Fracture at Weld Crater in Lower Flange of Specimen A-1</td>
</tr>
<tr>
<td>18.</td>
<td>Specimen B-1 Clamped to H-Beam in Position for Welding</td>
</tr>
<tr>
<td>19.</td>
<td>S-N Diagrams for I-Beams Connected with Butt Weld Splices</td>
</tr>
<tr>
<td>20.</td>
<td>Fracture in Lower Flange at Edge of Weld Bead, Specimens B-1 and B-3</td>
</tr>
<tr>
<td>21.</td>
<td>Location of Fracture in Weld of Lower Flange, Specimen B-2</td>
</tr>
<tr>
<td>22.</td>
<td>Fracture of Specimen B-2, Showing Slag Inclusion at Center of Flange</td>
</tr>
<tr>
<td>23.</td>
<td>Location and Character of Fracture, Specimen C-1</td>
</tr>
<tr>
<td>24.</td>
<td>Location and Character of Fracture, Specimen C-2</td>
</tr>
<tr>
<td>25.</td>
<td>Location and Character of Fracture, Specimen C-3</td>
</tr>
<tr>
<td>26.</td>
<td>Specimen D, a Riveted Joint Connecting 12-in., 31.8-lb I-Beams</td>
</tr>
<tr>
<td>27.</td>
<td>S-N Diagram for Riveted Joints Connecting 12-in., 31.8-lb I-Beams</td>
</tr>
</tbody>
</table>
LIST OF TABLES

1. Chemical Composition of Wrought-Iron Eyebars: Specimens 44X and 44Y 12
2. Results of Fatigue Tests of Wrought-Iron and of Steel Eyebars 13
3. Results of Static Tests of Steel Eyebars 14
4. Results of Fatigue Tests of Eyebars Shortened by Cutting and Splicing 18
5. Results of Static Tests of Eyebars Shortened by Cutting and Splicing 19
6. Results of Fatigue Tests of Composite Riveted-and-Welded Joints 22
7. Results of Fatigue Tests of Riveted Joints 23
8. Results of Static Tests of Riveted and Composite Riveted-and-Welded Joints 24
9. Relative Fatigue Strength of Riveted and Composite Riveted-and-Welded Joints 26, 27
10. Physical Properties of Main Plates of Butt-Weld Specimens 32
11. Chemical Composition of Main Plates of Butt-Weld Specimens 32
12. Results of Fatigue Tests: Butt Welds With, and Without, Strap Plates 32
13. Results of Static Tests: Butt Welds With, and Without, Strap Plates 34
14. Results of Fatigue Tests: Reinforced Tension Members 36
15. Results of Static Tests: Reinforced Tension Members 37
16. Chemical Composition of Steel in Flexural Fatigue Specimens 40
17. Welding Procedure for I-Beams with \( \frac{1}{2} \)-in. and \( \frac{5}{16} \)-in. Cover Plates 43
18. Fatigue Strength of 12-in., 31.8-lb I-Beams with Full-Length Cover Plates Attached with Continuous Fillet Welds 43
19. Sequence of Weld Passes for Butt Welds Connecting I-Beams: Specimen B-1 46
20. Sequence of Weld Passes for Butt Welds Connecting I-Beams: Specimens B-2, B-3, C-1, C-2, and C-3 47
22. Fatigue Strength of 12-in., 31.8-lb I-Beams Connected with Riveted Splice Plates and Partial-Length Cover Plates Attached with \( \frac{3}{4} \)-in. Rivets: Series D 56
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FATIGUE STRENGTH OF VARIOUS DETAILS USED FOR THE REPAIR OF BRIDGE MEMBERS

I. INTRODUCTION

1. Object and Scope of Investigation

Various means have been used to strengthen or repair members of bridges in service. Some of these methods have been in use for many years, yet very little information is available as to either the static or the fatigue strength of the modified members. In fact, it has only been in recent years that the bridge engineer has had any considerable information relative to the factors that have the greatest effect upon the fatigue strength of structural members. It is now recognized, however, that the factors which have a major influence on the fatigue strength and which should be kept in mind by the designing engineer are 1) the magnitude of the strain-raising factor, 2) the ratio of the minimum to the maximum stress in the cycle, and 3) the number of cycles of near-maximum stress to which the member is subjected during its life.

The tests reported herein were planned to determine the fatigue strength of specimens that incorporate expedients which have been used to strengthen or repair the members of old bridges. The specimens for some tests are the product of methods that have been used to shorten eyebars which, due to the wear on the pins and pin holes, have become so loose that it is necessary that they be tightened by shortening. The specimens for other tests represent reinforced bridge members for which the increased area has become necessary because of an increase in the loads to which the structure is subjected. Other specimens represent expedients that have been used to splice members in service.

The objects of the tests are twofold: 1) to determine the relative fatigue strength of various devices that have been used or proposed to strengthen or repair old bridge members in order to eliminate those methods that involve details with a low fatigue strength, and 2) to determine quantitatively the fatigue strength of the members that have been strengthened or repaired by the various methods.

2. Acknowledgments

The tests described in this bulletin consist of two groups. The first, Sections 3–7, are 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
was then 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 Sub-Committee on Bridge Reinforcement Details, of which J. E. BERNHARDT was Chairman, a subcommittee of the Committee on Fatigue Testing (Structural), Welding Research Council of the Engineering Foundation, of which JONATHAN JONES was 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; the American Iron and Steel Institute; and the Association of American Railroads. The fatigue tests, made in the Arthur Newell Talbot Laboratory, were made in part by A. M. OZELSEL, Special Research Assistant in Civil Engineering, under the supervision of WILBUR M. WILSON, Research Professor of Structural Engineering of the Department of Civil Engineering.

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WILSON, W. M., Research Professor of Structural Engineering, Civil Engineering Department, 119 Talbot Laboratory, University of Illinois, Urbana, Ill.
The second group of tests, Section 8, is a continuation of the investigation of the flexural fatigue strength of steel beams conducted by the Committee on Fatigue Testing (Structural) of the Welding Research Council, reported in University of Illinois Engineering Experiment Station Bulletin 377. The tests were financed by the Association of American Railroads and planned by a Sub-Committee of the American Railway Engineering Association’s Committee 15, Iron and Steel Structures, of which E. S. Birkenwald is Chairman.
II. Description of Tests

3. Eyebars Shortened by Heating and Upsetting

Eyebars are sometimes shortened by heating and upsetting, a convenient, economical method. But the question has been raised whether heat treatment affects the strength of the member. Two groups of specimens (Fig. 1) were tested. Specimens for the first group—Series 44X and 44Y—were cut from wrought-iron eyebars that had been in service in a bridge for many years; specimens for the second group—Series 44A and 44B—from recently rolled carbon structural steel bars. The parts of the bar from which the 44X and 44A specimens were made were first heated and upset, thus increasing their thickness over their entire width, then milled on the edges to a constant width over the central portion (Fig. 1). The parts of the bar from which the 44Y and 44B specimens were cut were not upset, but the central portion was milled on the edges to a constant width, as shown in Figs. 1 and 2.

The composition of the wrought iron bars is given in Table 1. The mechanical properties of the unshortened steel bars are given in the last line of Table 3. The specimens were so machined that one end of the upset portion of the shortened specimen was within the constant-width portion near the center of the specimen. The shortened and unshortened specimens of each group had the same geometrical
**Table 1**

**Chemical Composition of Wrought-Iron Eyebars: Specimens 44X and 44Y**

(Etching showed metal to be wrought iron)

<table>
<thead>
<tr>
<th>Specimen No.</th>
<th>C</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Si</th>
</tr>
</thead>
<tbody>
<tr>
<td>44X-1, 2, 3</td>
<td>0.041</td>
<td></td>
<td>0.106</td>
<td>0.033</td>
<td>0.154</td>
</tr>
<tr>
<td>44Y-1</td>
<td>0.062</td>
<td>0.018</td>
<td>0.117</td>
<td>0.029</td>
<td>0.187</td>
</tr>
<tr>
<td>44Y-2, 3</td>
<td>0.044</td>
<td>0.017</td>
<td>0.116</td>
<td>0.027</td>
<td>0.205</td>
</tr>
</tbody>
</table>

**Figure 2. Wrought-Iron Eyebar Specimens After Failure**
characteristics and were tested on approximately the same stress cycle, to facilitate a comparison of the results. The minimum stress in the stress cycle was taken as a small tension, to eliminate the possibility of any slight compression on the slender specimens.

Three specimens of each series were tested in fatigue; results of the test are given in Table 2. The specimen number is given in

<table>
<thead>
<tr>
<th>Specimen Number</th>
<th>Stress Cycle in 1000's of lb. per sq. in.</th>
<th>Number of Cycles for Failure in 1000's</th>
<th>Fatigue Strength in 1000's of lb. per sq. in.</th>
<th>Location of Fracture</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>n=500,000 n=1,000,000</td>
<td></td>
</tr>
<tr>
<td><strong>Shortened Wrought Iron Bars</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>44X-1</td>
<td>+1.0 to +31.0</td>
<td>781.2</td>
<td>33.6</td>
<td>29.7</td>
</tr>
<tr>
<td>44X-2</td>
<td>+1.0 to +31.0</td>
<td>280.3</td>
<td>27.9</td>
<td>24.7</td>
</tr>
<tr>
<td>44X-3</td>
<td>+1.0 to +31.0</td>
<td>1284.5</td>
<td>36.8</td>
<td>32.4</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td></td>
<td>32.8</td>
<td>28.9</td>
<td></td>
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</tbody>
</table>

| **Unshortened Wrought Iron Bars**      |                                        |                                        |                                             |                      |
| 44Y-1           | +0.8 to +31.6                         | 837.6                                 | 34.6                                        | 30.6                 |
| 44Y-2           | +1.0 to +31.0                         | 760.8                                 | 33.4                                        | 29.6                 |
| 44Y-3           | +1.0 to +31.0                         | 504.3                                 | 31.1                                        | 27.4                 |
| **Average**     |                                        | 33.0                                  | 29.2                                        |                      |

| **Shortened Steel Bars**               |                                        |                                        |                                             |                      |
| 44A-1           | 0 to +33.5                            | 814.2                                 | 36.5                                        | 32.2                 |
| 44A-2           | 0 to +33.0                            | 941.9                                 | 37.0                                        | 32.6                 |
| 44A-4           | 0 to +33.0                            | 956.5                                 | 37.1                                        | 32.8                 |
| **Average**     |                                        | 36.9                                  | 32.5                                        |                      |

| **Unshortened Steel Bars**             |                                        |                                        |                                             |                      |
| 44B-1           | 0 to +32.0                            | 1333.9                                | 32.2                                        | 33.7                 |
| 44B-2           | 0 to +34.0                            | 687.3                                 | 36.1                                        | 31.8                 |
| 44B-3           | 0 to +32.0                            | 1017.0                                | 36.4                                        | 32.1                 |
| **Average**     |                                        | 36.9                                  | 32.5                                        |                      |

*K=0.18. Assumed for use in empirical equation \( F_n = S \left( \frac{N}{H} \right)^K \)
column 1; the stress cycle in 1000's of p.s.i. on the main plate in column 2; the number of cycles for failure in 1000's in column 3; and the fatigue strength in 1000's of p.s.i. corresponding to failure at 500,000 and 1,000,000 cycles in columns 4 and 5 respectively. The location of the fracture is shown in column 6.

The values of $F_{500,000}$ and $F_{1,000,000}$ were computed from the results of the tests by means of the empirical equation\(^1\) $F_n = S (N/n)^K$, in which $S$, numerically, is the maximum stress in the stress cycle, $N$ is the number of cycles for failure for the test in question, $K$ is an experimental constant whose value depends upon such factors as the geometrical characteristics of the specimen and the mechanical properties of the metal, and $F_n$ is the fatigue strength corresponding to failure at $n$ number of cycles. The value of $K$ for all series was assumed to be 0.18.

The appearance of the wrought-iron specimens after failure is shown in Fig. 2, the shortened portion being indicated by the arrows. Of the unshortened wrought-iron specimens, one broke near the middle and the other two near the end of the constant-width portion. The minimum values of $F_{500,000}$ and $F_{1,000,000}$ were 27,900 p.s.i. and 24,700 p.s.i. respectively for the shortened wrought-iron specimens, and 31,100 p.s.i. and 27,400 p.s.i. respectively for the unshortened wrought-iron specimens. The corresponding average values for the wrought-iron specimens were 32,800 p.s.i. and 28,900 p.s.i. respectively for the shortened specimens, and 33,000 p.s.i. and 29,200 p.s.i. respectively for the unshortened.

The minimum values of $F_{500,000}$ and $F_{1,000,000}$ were 36,600 p.s.i. and 32,200 p.s.i. respectively for the shortened steel specimens, and 36,100 p.s.i. and 31,800 p.s.i. respectively for the unshortened steel specimens. The corresponding average values for the steel specimens were

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\(^1\) Univ. of Ill. Eng. Exp. Sta. Bul. 302, p. 111.
36,900 p.s.i. and 32,500 p.s.i. respectively for the shortened specimens, and 36,900 p.s.i. and 32,500 p.s.i. respectively for the unshortened bars. The fatigue failure was at the end of the upset portion for all shortened steel specimens, as shown in Table 2.

One shortened and one unshortened steel specimen were tested statically; the results are given in Table 3. The yield point and ultimate strength have almost equal values for the two specimens. The elongation in 12 in., however, was much less for the shortened than for the unshortened specimen. This smaller elongation may be attributed to the fact that, of the 12-in. length on which the elongation was measured, a considerable portion was upset and had a greater area than the remaining portion of the gage length, and therefore a lower unit stress and a smaller unit elongation. The condition in a full-size structure is quite different, however; the upset portion is only a small fraction of the total length of the eyebar, and the percentage elongation of the bar as a whole would not be greatly influenced by the reduction of the elongation in the upset portion.

For the wrought-iron eyebars shortened by heating and upsetting, the fatigue strength was somewhat less for the shortened than for the unshortened bars; however, the difference was not significant. For the steel eyebars shortened by heating and upsetting, the fatigue strengths for the shortened and the unshortened eyebars were very nearly identical. These and other fatigue tests indicate that the fatigue strength of steel is not affected by the metallurgical changes incident to heating steel to a bright red and cooling. This, however, does not preclude the possibility of reducing the fatigue strength of an eyebar by heating and then upsetting unless care is taken to avoid the formation of geometrical stress-raisers in the form of grooves or bumps on the finished surfaces. All such geometrical stress-raisers should be avoided. As shown in Fig. 2, the edges of the specimens tested were machined to a smooth surface, but the other two sides were in the as-rolled and as-upset condition of a shortened eyebar diagonal web member of a truss.

4. Eyebars Shortened by Cutting and Splicing

Eyebars of bridges have sometimes been shortened by cutting out a piece and then splicing. Three types of typical eyebar splices are shown in Figs. 3a, 3b, and 3c. These have been designated as Series 44N, 44P, and 44Q respectively. The right-hand portion of each specimen represents one-half of an eyebar splice that has been used

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in repairing a bridge. The dimensions of all plates, rivets, and welds are the same for the specimen as for the actual eyebar splice of the bridge truss member to which it corresponds.

Four specimens of each type were tested—one statically and the other three in fatigue. The fatigue tests were planned to give, as nearly as possible, the fatigue strength corresponding to failure at 100,000 and 2,000,000 cycles. All specimens were tested on a cycle in which the stress varied from 0 to tension.

**FIG. 3. TYPICAL EYEBARS SHORTENED BY CUTTING AND SPlicing**
The results of the fatigue tests are given in Table 4. The values for the 44P specimens, those that failed in the main plate, determine the S-N diagram of Fig. 4. Specimen 44N-2 failed in the main plate; specimens 44N-1 and 44N-3, in the side plates. All specimens of Series 44P failed in the main plate, and all specimens of Series 44Q failed in the side plates. The fatigue strength of the joints that failed in the side plates might have been increased somewhat by increasing the width of the side plates.

From the numbers of cycles for failure given in Table 4 it is found that the values of $F_{100,000}$ and $F_{2,000,000}$ for specimens of the 44P Series, the only type of specimen for which all failures were in the main plate, were 23,900 p.s.i. and 11,300 p.s.i. respectively. The corresponding values for a 5-in. by 5/8-in. plain bar tested on the same cycle (0 to tension) were 49,800 p.s.i. and 31,600 p.s.i. respectively.\(^1\) The corresponding values for steel eyebars shortened by heating and upsetting were 50,000 p.s.i. and 28,000 p.s.i. respectively.\(^2\) The value of $F_{100,000}$ for 44N-2, the only one of the 44N series that failed in the main plate, was 22,500 p.s.i., a value considerably less than half the corresponding value for the steel eyebars shortened by heating and upsetting.

None of the 44Q specimens failed in the main plate; but inasmuch as the geometrical stress-raisers for the main member were of approximately the same severity for the 44Q specimens as for the 44P and 44N specimens, there is no basis for believing that the fatigue strength would be appreciably greater for the former than for the latter two.

---

\(^1\) Univ. of Ill. Eng. Exp. Sta. Bul. 327, p. 23. For plates without welds $K = 0.18$.

\(^2\) Extrapolated from Table 2.
### Table 4

**Results of Fatigue Tests of Eyebars Shortened by Cutting and Splicing**

<table>
<thead>
<tr>
<th>Specimen No.</th>
<th>Stress Cycle in 1000's of p.s.i.</th>
<th>Number of Cycles for Failure, 1000's</th>
<th>Fatigue Strength in 1000's of p.s.i.†</th>
<th>Location of Fracture</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Main Plate (gross area)</td>
<td>Side Plates (gross area)</td>
<td>Main Plates</td>
<td>Side Plates</td>
</tr>
<tr>
<td></td>
<td>(2)</td>
<td>(3)</td>
<td>(5)</td>
<td>(6)</td>
</tr>
<tr>
<td></td>
<td>(1)</td>
<td>(4)</td>
<td>(7)</td>
<td>(8)</td>
</tr>
<tr>
<td></td>
<td>(9)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>44N-1</td>
<td>0 to +15.9*</td>
<td>0 to +13.4</td>
<td>22.5</td>
<td>13.5</td>
</tr>
<tr>
<td>44N-2</td>
<td>0 to +14.0*</td>
<td>0 to +11.4</td>
<td>1 066.3</td>
<td>17.2</td>
</tr>
<tr>
<td>44N-3</td>
<td>0 to +13.4</td>
<td>0 to +10.1*</td>
<td>24.4</td>
<td>13.0</td>
</tr>
<tr>
<td>Av</td>
<td>0 to +14.0*</td>
<td>0 to +11.4</td>
<td>23.4</td>
<td>11.5</td>
</tr>
<tr>
<td>44P-1</td>
<td>0 to +15.9*</td>
<td>0 to +13.8*</td>
<td>23.9</td>
<td>11.3</td>
</tr>
<tr>
<td>44P-2</td>
<td>0 to +15.6*</td>
<td>0 to +10.0*</td>
<td>1 469.8</td>
<td>10.3</td>
</tr>
<tr>
<td>44P-3</td>
<td>0 to +13.8</td>
<td>0 to +12.0*</td>
<td>27.8</td>
<td>10.3</td>
</tr>
<tr>
<td>Av</td>
<td>0 to +12.0*</td>
<td>0 to +11.0*</td>
<td>27.8</td>
<td>10.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Did not fail in this part.
† Italic values of the fatigue strength are less than the true values. The true values could not be determined, inasmuch as the parts involved did not fail.

Values of $F_{100,000}$ and $F_{1,000,000}$ are based on $K = 0.25$ for the 44P series, the only series for which all failures were in the main plate.
One of each of the fatigue-type of specimens was tested statically. The results of these tests are given in Table 5.

The tests reported in Sections 3 and 4 indicate that the fatigue strength is less than half as great for steel eyebars shortened by cutting and splicing as it is for similar eyebars shortened by heating and upsetting.

5. Riveted and Composite Riveted-and-Welded Joints

Some plate girders in service have web splices that were not designed to take moment. The tests described in this section were planned to determine whether the flexural resistance of such girders could be increased by connecting the splice plates to the web by fillet welds, the hypothesis being that the action at the edges of a girder web in flexure is similar to the action of a narrow plate in tension or compression.

Four series of specimens (Figs. 5 and 6) were tested. The RA and SA specimens shown in Fig. 5 consist of plates connected with butt straps attached with rivets only; the R and S specimens shown in Fig. 6 consist of plates connected with butt straps attached with both rivets and fillet welds.

The tests were made on a cycle in which the stress, parallel to the long axis of the specimen, varied from zero to a maximum tension. It should be noted that the action on these narrow specimens loaded in this manner is similar to the action on a longitudinal strip adjacent to the edges of a girder web, except for the small shear carried at the center of the girder span. The tests were designed to give information

### Table 5

**Results of Static Tests of Eyebars Shortened by Cutting and Splicing**

<table>
<thead>
<tr>
<th>Specimen No.</th>
<th>Ultimate Stress, p.s.i.*</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Main Plate</td>
</tr>
<tr>
<td>44N-4</td>
<td>69,000</td>
</tr>
<tr>
<td></td>
<td>53,400</td>
</tr>
<tr>
<td>44P-4</td>
<td>70,800†</td>
</tr>
<tr>
<td></td>
<td>58,900</td>
</tr>
<tr>
<td>44Q-4</td>
<td>87,000</td>
</tr>
<tr>
<td></td>
<td>70,000</td>
</tr>
</tbody>
</table>

* Upper values based on net section. Lower values based on gross section.
† Part that failed.
on two questions, relative to the action of a combined riveted-and-welded splice: 1) are the strengths of the welds and rivets additive? and 2) do the two transverse fillets, one on each side of the web plate, seriously affect the fatigue strength of the web plate?

These two features were incorporated in a program of tests of specimens for which the butt straps were 3/8-in. and 5/8-in. plates riveted to the main plates with 3/4-in. rivets. The main plates were 1/2 in. thick for Series 44R and 44RA, and 1 in. thick for Series 44S and 44SA. The strap plates of Series 44R and 44S were welded to the main plates with 1/4-in. fillet welds. Only four specimens of each type were tested—one statically and three in fatigue. The fatigue tests were planned to give, as nearly as possible, the fatigue strength corresponding to failure at 100,000 and 2,000,000 cycles.
The results of the fatigue tests are given in Tables 6 and 7. These data, plotted to a log-log scale, determine the $S$-$N$ diagrams of Fig. 7.

All the fatigue specimens with welds, Series 44R and 44S, failed in the main plate at the edge of a transverse fillet weld. The specimens of Series 44RA, 1/2-in. plates without welds, all failed through the rivet holes in the main plate; the 44SA specimens, 1-in. plates without welds, either failed in the rivets or did not fail.

One specimen of each type was tested statically; a summary of the results is given in Table 8. The yield point was not detectable by the drop-of-the-beam for the static tests of either Series 44R or 44S. The yield point of the 44RA and 44SA specimens was definite; it occurred at a shear on the rivets of 41,800 p.s.i. and 38,500 p.s.i. respectively.

A fillet weld along a transverse edge of the butt straps of a double-strap riveted butt joint affects the fatigue strength of the joint in two ways: 1) It tends to increase the strength by protecting the rivets and by protecting the section of the main plate through the transverse row of rivet holes; 2) it tends to decrease the strength of the main plate because the fillet weld acts as a geometrical stress-raiser.

Whether the net effect of transverse fillet welds along the edges of the butt straps of riveted joints connecting plates is to increase or decrease the fatigue strength of the resulting joint depends on such factors as the thickness of the main plate and of the butt straps and on the number of rivets in a transverse row. The addition of the fillet welds on the transverse edges of the butt straps increased the fatigue strength for both types of specimens tested, because, for the specimens with 1/2-in. main plates, the fatigue strength was slightly greater on a section along the welds than on a section through the rivet holes for the specimen without welds. For the specimen with 1-in. main plates the fatigue strength was nearly twice as great for the section of the plate along the edge of the weld as for the rivets of the specimens without welds.

Fatigue tests of riveted joints are reported in University of Illinois Engineering Experiment Station Bulletin 302; fatigue tests of riveted joints and of composite riveted-and-welded joints, in Bulletin 350. The results of these tests and of the tests made in connection with the present investigation are reported in Table 9. All specimens are double-strap butt joints. Since most specimens tested in connection with the present investigation failed at considerably less than 1,000,000 cycles, the values of the fatigue strengths
### Table 6

Results of Fatigue Tests of Composite Riveted-and-Welded Joints

*K = 0.22 for 44S; K = 0.11 for 44R*

<table>
<thead>
<tr>
<th>Specimen No.</th>
<th>Stress Cycle in 1000's of p.s.i.</th>
<th>Number of Cycles for Failure, 1000's</th>
<th>Fatigue Strength in 1000's of p.s.i.*</th>
<th>Location of Fracture</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Main Plate (gross)</td>
<td>Side Plate (gross)</td>
<td>Welds, Throat</td>
<td>Rivets</td>
</tr>
<tr>
<td>(1)</td>
<td>(2)</td>
<td>(3)</td>
<td>(4)</td>
<td>(5)</td>
</tr>
<tr>
<td>44R-1</td>
<td>0 to +18.5</td>
<td>0 to +12.3</td>
<td>0 to +20.2</td>
<td>0 to +30.2</td>
</tr>
<tr>
<td>44R-2</td>
<td>0 to +25.0</td>
<td>0 to +16.7</td>
<td>0 to +28.1</td>
<td>0 to +41.5</td>
</tr>
<tr>
<td>44R-3</td>
<td>0 to +21.0</td>
<td>0 to +14.0</td>
<td>0 to +23.3</td>
<td>0 to +33.6</td>
</tr>
<tr>
<td><strong>Av</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>44S-1</td>
<td>0 to +10.7</td>
<td>0 to +14.3</td>
<td>0 to +25.0</td>
<td>0 to +35.2</td>
</tr>
<tr>
<td>44S-2</td>
<td>0 to +13.7</td>
<td>0 to +18.3</td>
<td>0 to +29.2</td>
<td>0 to +45.5</td>
</tr>
<tr>
<td>44S-3</td>
<td>0 to +17.0</td>
<td>0 to +22.6</td>
<td>0 to +34.0</td>
<td>0 to +55.3</td>
</tr>
<tr>
<td><strong>Av</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Based on gross area of the main plate.
<table>
<thead>
<tr>
<th>Specimen No.</th>
<th>Stress Cycle in 1000's of p.s.i.</th>
<th>Number of Cycles for Failure, 1000's</th>
<th>Fatigue Strength in 1000's of p.s.i.†</th>
<th>Location of Fracture</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Main Plate Tension*</td>
<td>Rivet Shear</td>
<td></td>
<td>Based on Main Plate Stress</td>
</tr>
<tr>
<td></td>
<td>(2)</td>
<td>(3)</td>
<td>(5)</td>
<td>(6)</td>
</tr>
<tr>
<td>44RA-1</td>
<td>0 to +17.8</td>
<td>0 to +30.3</td>
<td>849.6</td>
<td>.....</td>
</tr>
<tr>
<td>44RA-2</td>
<td>0 to +19.7</td>
<td>0 to +33.6</td>
<td>122.5</td>
<td>20.0</td>
</tr>
<tr>
<td>44RA-3</td>
<td>0 to +18.5</td>
<td>0 to +32.1</td>
<td>192.5</td>
<td>19.3</td>
</tr>
<tr>
<td>Av</td>
<td></td>
<td></td>
<td></td>
<td>19.6</td>
</tr>
<tr>
<td>44SA-1</td>
<td>0 to +11.7</td>
<td>0 to +39.7</td>
<td>38.6</td>
<td>.....</td>
</tr>
<tr>
<td>44SA-2</td>
<td>0 to +9.4</td>
<td>0 to +32.0</td>
<td>263.2</td>
<td>.....</td>
</tr>
<tr>
<td>44SA-3</td>
<td>0 to +7.8</td>
<td>0 to +26.5</td>
<td>3022.8</td>
<td>.....</td>
</tr>
<tr>
<td>Av</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Stresses are based upon gross area of main plate.
† Based on $K = 0.07$ for plate and $K = 0.08$ for rivets.
TABLE 8

RESULTS OF STATIC TESTS OF RIVETED AND COMPOSITE RIVETED-AND-WELDED JOINTS

<table>
<thead>
<tr>
<th>Specimen No.</th>
<th>Ultimate Stress, p.s.i. of Net Section of Plates*</th>
<th>Ultimate Shear, Stress in p.s.i. on Rivets</th>
<th>Location of Fracture</th>
</tr>
</thead>
<tbody>
<tr>
<td>44R-4</td>
<td>60 000</td>
<td></td>
<td>Strap plates, through the rivet holes</td>
</tr>
<tr>
<td>44SA-4</td>
<td>62 700</td>
<td>55 700</td>
<td>Strap plates, through the rivet holes</td>
</tr>
<tr>
<td>44SA-4</td>
<td></td>
<td>56 800</td>
<td>Failure by rivet shear</td>
</tr>
<tr>
<td>44RA-4</td>
<td></td>
<td></td>
<td>Rivets pulled out of middle plate</td>
</tr>
</tbody>
</table>

* Stress based upon net area of the splice plates.

used in this comparison are expressed in terms of $F_{500,000}$. A value of $K$ of 0.15 was used for all specimens in computing the value of $F_{500,000}$. This procedure is followed in the interpretation of the tests previously reported in Bulletins 302 and 350 as well as for the tests first reported in the present bulletin. The fatigue strengths reported in Bulletin 302 are based on the net section and for $F_{2,000,000}$. These values of $F_{2,000,000}$ converted into $F_{500,000}$ for the gross area of the main plates, are given in Table 9.

The types of joints used in this study are described in column 1 of Table 9. The plate thickness and rivet grip for the specimens...
are given in columns 2, 3, and 4; the values of the fatigue strength, $F_{500,000}$, in column 11.

The average value of $F_{500,000}$ is 23,130 p.s.i. of gross section for the Type A riveted joints. The corresponding average value for the composite joint B, with the same rivet pattern as A but reinforced with $\frac{1}{4}$-in. plates attached with $\frac{15}{16}$-in. plug welds, is 25,850 p.s.i. The corresponding average value for the composite joint C, with the same rivet pattern as A but reinforced with $\frac{1}{4}$-in. plates attached with transverse $\frac{1}{4}$-in. fillet welds, is 24,280 p.s.i. Though the specimens with composite riveted-and-welded joints had a slightly greater fatigue strength than the riveted joints, the difference is not great.

The average value of $F_{500,000}$ is 17,100 p.s.i. for the riveted joint of Type F. The corresponding average value for the composite joint G, with the same rivet pattern as F but reinforced with $\frac{3}{8}$-in. plates attached with $\frac{1}{4}$-in. transverse fillet welds, is 20,020 p.s.i. The failure was in the main plate for all specimens. For these series also, the specimens with composite riveted-and-welded joints had a slightly greater fatigue strength than the riveted joints, but the difference was not great.

The H and I specimens were similar to the F and G specimens respectively, except that the thickness of the main plate was 1 in. for the former and $\frac{1}{2}$ in. for the latter. The H and F specimens contained riveted joints; the I and G specimens contained composite riveted-and-welded joints. The fatigue strengths of H and I specimens are not comparable, because the H specimens failed in the rivets.

Comparing the results of fatigue tests of riveted joints given in various reports is fruitful. The values of $F_{500,000}$ for the double-strap riveted butt joints of Types A and D, originally reported in Bulletin 350, are 23,130 and 24,025 p.s.i. respectively; the corresponding value for similar double-strap riveted butt joints of Type E, reported in Bulletin 302, is 23,200 p.s.i. Each value is the average from three or more tests, and the three averages are quite consistent with one another.

In contrast with the values given in the previous paragraph, $F_{500,000}$ for Type F specimens is 17,100 p.s.i. The most apparent difference between the latter type and the three former types is in the number of transverse rows of rivets. The Type F specimens had a single transverse row of rivets in each half of the joint; each of the other three types had two transverse rows of rivets. For Series A, D, and E, the tension values based on the gross section of the
### Table 9

**Relative Fatigue Strength of Riveted and Composite Riveted-and-Welded Joints**

<table>
<thead>
<tr>
<th>Type of Joint</th>
<th>Thickness of Plate, inches</th>
<th>Grip of Rivet, inches</th>
<th>Reference</th>
<th>Stress Cycle on Gross Section of Main Plate</th>
<th>Number of Cycles for Failure</th>
<th>Location of Fracture</th>
<th>$F_{50,000}$ p.s.i. of Gross Section of Main Plate, $K = 0.15$</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1)</td>
<td>(2)</td>
<td>(3)</td>
<td>(4)</td>
<td>(5)</td>
<td>(6)</td>
<td>(7)</td>
<td>(8)</td>
</tr>
<tr>
<td>Double-strap riveted butt joint</td>
<td>$\frac{3}{4}$</td>
<td>$\frac{1}{2}$</td>
<td>$\frac{1}{2}$</td>
<td>350</td>
<td>54 and 55</td>
<td>20</td>
<td>0 to 22,000</td>
</tr>
<tr>
<td>Same as A above except reinforced with $\frac{3}{4}$&quot; plates attached with $\frac{3}{4}$&quot;&quot; fillet weld (Transverse)</td>
<td>$\frac{3}{4}$</td>
<td>$\frac{1}{2}$</td>
<td>$\frac{1}{2}$</td>
<td>350</td>
<td>54 and 55</td>
<td>20</td>
<td>0 to 25,000</td>
</tr>
<tr>
<td>Double-strap riveted butt joint</td>
<td>$\frac{3}{4}$</td>
<td>$\frac{1}{2}$</td>
<td>$\frac{1}{2}$</td>
<td>350</td>
<td>28 and 29</td>
<td>8</td>
<td>0 to 27,000</td>
</tr>
<tr>
<td>Double-strap riveted butt joint</td>
<td>$\frac{1}{2}$</td>
<td>$\frac{1}{2}$</td>
<td>$\frac{1}{2}$</td>
<td>350</td>
<td>28 and 29</td>
<td>20</td>
<td>0 to 27,000</td>
</tr>
<tr>
<td>Double-strap riveted butt joint</td>
<td>Average of 3 specimens for each of 3 series: B-18, B-19, and B-20</td>
<td>$\frac{1}{2}$</td>
<td>$\frac{1}{2}$</td>
<td>302</td>
<td>86 and 87</td>
<td>40</td>
<td>B-18</td>
</tr>
</tbody>
</table>

* The specimens for these two series are geometrically identical.

† The values as reported in Table 28, p. 87, Bul. 302 are based on the net section and are for $F_{100,000}$. As reported in this table, they have been converted into $F_{50,000}$ based on the gross section.
<table>
<thead>
<tr>
<th>Type of Joint</th>
<th>Thickness of Plate, inches</th>
<th>Grip of Rivet, inches</th>
<th>Reference</th>
<th>Stress Cycle on Gross Section of Main Plate, p.s.i.</th>
<th>Number of Cycles for Failure</th>
<th>Location of Fracture</th>
<th>$F_{acc}^o$ p.s.i. of Gross Section of Main Plate, $K = 0.15$</th>
</tr>
</thead>
<tbody>
<tr>
<td>(F) Double-strap riveted butt joint. Series 44RA.</td>
<td>½</td>
<td>½</td>
<td>1⅜</td>
<td>Present Bul. (882)</td>
<td>20 and 22</td>
<td>0 to 17 800 and 0 to 18 500</td>
<td>All failed in main plate through rivet holes</td>
</tr>
<tr>
<td>(G) Same as F above except reinforced with ¼&quot; transverse fillet weld. Series 44R.</td>
<td>½</td>
<td>½</td>
<td>1⅜</td>
<td>382</td>
<td>20 and 22</td>
<td>0 to 18 500 and 0 to 21 000</td>
<td>All failed in main plate along edge of fillet weld</td>
</tr>
<tr>
<td>(H) Same as F above except the plate thickness. Series 448A.</td>
<td>1</td>
<td>½</td>
<td>1⅜</td>
<td>382</td>
<td>20 and 22</td>
<td>0 to 11 700 and 0 to 7 800</td>
<td>Failed in the rivets</td>
</tr>
<tr>
<td>(I) Same as H above except reinforced with ½&quot; transverse fillet weld. Series 44S.</td>
<td>1</td>
<td>½</td>
<td>1⅜</td>
<td>382</td>
<td>20 and 22</td>
<td>0 to 10 700 and 0 to 17 000</td>
<td>All failed in main plate along edge of fillet weld</td>
</tr>
</tbody>
</table>

Av 17 100
Av 20 020
plate and the bearing values based on the nominal diameter of the rivet, corresponding to values of $F_{600,000}$, are:

- 23,130 p.s.i. and 39,600 p.s.i. (T:B 1.0:1.71) for Type A.
- 24,025 p.s.i. and 41,100 p.s.i. (T:B 1.0:1.71) for Type D.
- 23,200 p.s.i. and 47,500 p.s.i. (T:B 1.0:2.05) for Type E.

In contrast, the corresponding values for the F type are 17,100 p.s.i. and 68,000 p.s.i. (T:B 1.0:4.0)

FIG. 8. BUTT WELDS REINFORCED WITH STRAP PLATES

The values of $F_{500,000}$ for Series A, D, and E, specimens with low values of rivet bearing, agree fairly well, but the F specimens with a high rivet bearing have a much lower fatigue strength. Tests are not available showing the effect of high rivet bearing upon the fatigue strength of plates connected with rivets.\(^1\) There is a possibility, however, that the low value of $F_{500,000}$ for the plates of the F specimens is due to the high rivet bearing.

There is also the possibility that the low value of the fatigue strength is due to the fact that the critical section is nearer to the end of the main plate for the joints with a single transverse row than it is for joints with two transverse rows of rivets in the main plate. Tests show that the ratio of the maximum to the average stress on a section of a plate through the center of a pin in bearing is greater for small than for large end distances.\(^2\) Moreover, when two trans-

\(^1\) Tests are now under way in the Talbot Laboratory to determine the effect of rivet bearing upon the fatigue strength of the plates of riveted joints.

verse rows of rivets are used, the rivets in the end row will tend to
distribute a portion of the load across the plate width, whereas with
one transverse row of rivets the entire load is applied at the three
rivet holes. Hence the stress distribution will be different in the two
types of joints considered.

6. Butt Welds Reinforced with Strap Plates

Some engineers have "reinforced" butt-weld joints connecting
plates by grinding the weld reinforcement flush with the base plate
and attaching strap plates across the joint with fillet welds. The tests
described in this section were planned to determine the effect of these
straps on the fatigue strength of the "reinforced" joint. The fact
should be noted that, although the addition of the strap plates reduces
the load on the butt weld, the fillet welds with which the straps are
attached may act as geometrical stress-raisers, thus reducing the
fatigue strength of the main plate.

Two factors that might influence the effect of the reinforcement
upon the fatigue strength of the joint have been considered: 1) the
ratio of the thickness of the straps to the thickness of the main plate;
and 2) the ratio of the width of the strap to the width of the main
plate. These two factors were incorporated in the test program. The
section of the main plate at the center was the same for all specimens,
4\(\frac{3}{4}\) in. x \(\frac{3}{8}\) in., approximately the same as for the butt weld speci-
mens previously tested.\(^1\)

The specimens of Series 44Se, which were used as a basic series,
were 4\(\frac{3}{4}\)-in. x \(\frac{3}{8}\)-in. plates connected with a double-V butt weld
without straps but with the reinforcement ground off. The strap
plates for the specimens of Series 44Sa, detailed in Fig. 8, were
4\(\frac{3}{4}\) in. x \(\frac{3}{8}\) in. x 6 in. on one side and 4\(\frac{3}{4}\) in. x \(\frac{3}{8}\) in. x 3 in. on the
other side. For the specimens of Series 44Sb, also detailed in Fig. 8,
the corresponding strap plates were 4\(\frac{3}{4}\) in. x \(\frac{3}{8}\) in. x 6 in. and 4\(\frac{3}{4}\) in.
x \(\frac{3}{8}\) in. x 3 in. The strap plates for the specimens of Series 44Sc,
detailed in Fig. 9, were 4 in. x \(\frac{3}{8}\) in. x 6 in. on one side and 4 in.
x \(\frac{3}{8}\) in. x 3 in. on the other. For the specimens of Series 44Sd, de-
tailed in Fig. 9, the corresponding strap plates were 4 in. x \(\frac{3}{8}\) in.
x 6 in. and 4 in. x \(\frac{3}{8}\) in. x 3 in.

Four specimens of each type were tested. Of these, three were
tested in fatigue, one at 0 to 20,000 p.s.i., one 0 to 25,000 p.s.i.,
and the third at 0 to 30,000 p.s.i. tension. The fourth specimen in
each group was tested statically.

\(^1\) Univ. of Ill. Eng. Exp. Sta. Buls. 327 and 344.
Fillet welds on all four edges of strap plates: 1/8" for 44Sc and 3/16" for 44Sd.

Reinforcement on butt weld ground flush with main plate on both sides.

1. First pass.
2. Turn over — chip out root of first pass to make second pass.
3. Clean second pass and make third pass.
4. Turn over and clean first pass to make fourth pass.
5. Clean fourth pass to make fifth pass.
6. Turn over — clean third pass to make sixth pass.
7. Clean sixth pass to make seventh pass.
8. Clean seventh pass to make eighth pass.
9. Turn over — clean fifth pass to make ninth pass.
11. Tack strap plates on test bars.

FIG. 9 (ABOVE). BUTT WELDS REINFORCED WITH NARROW STRAP PLATES

FIG. 10 (BELOW). WELDING PROCEDURE FOR BUTT WELD SPECIMENS
The welding procedure for the specimens of this series is given in Fig. 10. The physical properties and chemical composition of the steel, obtained from coupons cut from the main plates of specimens, 44Sa, 44Sb, and 44Sc, are given in Tables 10 and 11. Since the specimens for all series were cut from the same parent plate, the values given therein are representative of the specimens of all series.

The results of the fatigue tests are given in Table 12. These data, plotted to a log-log scale, determine the $S$-$N$ diagrams of Fig. 11. The $S$-$N$ diagrams for four Series — 44Sa, 44Sb, 44Sc, and 44Sd — specimens with butt welds reinforced with strap plates, all had values of $K$ of approximately 0.32. The $K$ value for Series 44Se, specimens with butt welds ground flush with the base plate but without strap plates, was taken as 0.18.¹ The values of the fatigue strength corresponding to failure at 100,000 and at 2,000,000 cycles were determined by use of the equation $F_n = S \left( \frac{N}{n} \right)^K$. An average $S$-$N$ diagram was drawn which represents the results of the fatigue tests of all specimens with butt straps. This diagram, the broken line of Fig. 11, is superimposed as a broken line upon the full-line $S$-$N$ diagrams representing each of the several series, as shown in Fig. 11. A comparison of this average $S$-$N$ diagram with the $S$-$N$ diagram for each of the various series indicates that:

1. The ratio of the thickness of the straps to the thickness of the main plate had no significant effect on the fatigue strength of the joint.

2. Specimens with strap plates of the same width as the main plates had very nearly the same fatigue strength as did specimens with strap plates narrower than the main plates and welded on all four edges.

3. The butt-weld joints with the reinforcement ground flush with the main plate on both sides and with no strap plates had a higher fatigue strength than the butt-weld joints which were reinforced with strap plates. In other words, the so-called “reinforcement” actually decreased the fatigue strength of the butt-weld joints connecting the plates.

One specimen of each type was tested statically. A summary of the results is given in Table 13. The yield point was not detectable by the drop-of-the-beam for any of the static tests. The stress at the ultimate load, which was about the same for all specimens, was of the order of 60,400 p.s.i. All static specimens failed in the main

### Table 10
**Physical Properties of Main Plates of Butt-Weld Specimens**

<table>
<thead>
<tr>
<th>Specimen Cut from</th>
<th>Yield Stress, p.s.i.</th>
<th>Ultimate Stress, p.s.i.</th>
<th>Elongation in 8 in., percent</th>
<th>Reduction of Area, percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>44Sa-1</td>
<td>30 200</td>
<td>58 200</td>
<td>30.0</td>
<td>54.8</td>
</tr>
<tr>
<td>44Sb-1</td>
<td>32 000</td>
<td>63 100</td>
<td>39.0</td>
<td>45.2</td>
</tr>
<tr>
<td>44Sc-1</td>
<td>31 900</td>
<td>58 800</td>
<td>29.1</td>
<td>52.8</td>
</tr>
</tbody>
</table>

### Table 11
**Chemical Composition of Main Plates of Butt-Weld Specimens**

<table>
<thead>
<tr>
<th>From Specimen</th>
<th>Chemical Composition, percent</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>C</td>
</tr>
<tr>
<td>44Sa-1</td>
<td>0.12</td>
</tr>
<tr>
<td>44Sb-1</td>
<td>0.15</td>
</tr>
<tr>
<td>44Sc-1</td>
<td>0.18</td>
</tr>
</tbody>
</table>

### Table 12
**Results of Fatigue Tests: Butt Welds With, and Without, Strap Plates**

<table>
<thead>
<tr>
<th>Specimen No.</th>
<th>Stress Cycle in 1000's of p.s.i.</th>
<th>Number of Cycles for Failure in 1000's</th>
<th>Fatigue Strength in 1000's of p.s.i.*</th>
<th>Location of Fracture</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(1)</td>
<td>(2)</td>
<td>(3)</td>
<td>(4)</td>
</tr>
<tr>
<td>44Sa-1</td>
<td>0 to +30.0</td>
<td>86.3</td>
<td>28.6</td>
<td>End of short strap</td>
</tr>
<tr>
<td>44Sb-1</td>
<td>0 to +25.0</td>
<td>86.0</td>
<td>30.7</td>
<td>End of short strap</td>
</tr>
<tr>
<td>44Sc-1</td>
<td>0 to +20.0</td>
<td>310.0</td>
<td>29.0</td>
<td>End of long strap</td>
</tr>
<tr>
<td>Av</td>
<td></td>
<td></td>
<td>30.3</td>
<td>End of short strap</td>
</tr>
<tr>
<td></td>
<td>0 to +30.0</td>
<td>111.7</td>
<td>31.1</td>
<td>End of short strap</td>
</tr>
<tr>
<td>44Sb-2</td>
<td>0 to +25.0</td>
<td>187.1</td>
<td>30.7</td>
<td>End of short strap</td>
</tr>
<tr>
<td>44Sc-2</td>
<td>0 to +20.0</td>
<td>310.0</td>
<td>29.0</td>
<td>End of long strap</td>
</tr>
<tr>
<td>Av</td>
<td></td>
<td></td>
<td>30.3</td>
<td>End of short strap</td>
</tr>
<tr>
<td></td>
<td>0 to +30.0</td>
<td>115.8</td>
<td>31.4</td>
<td>End of long strap</td>
</tr>
<tr>
<td>44Sb-3</td>
<td>0 to +25.0</td>
<td>194.4</td>
<td>31.2</td>
<td>End of long strap</td>
</tr>
<tr>
<td>44Sc-3</td>
<td>0 to +20.0</td>
<td>375.7</td>
<td>31.0</td>
<td>End of long strap</td>
</tr>
<tr>
<td>Av</td>
<td></td>
<td></td>
<td>31.2</td>
<td>End of long strap</td>
</tr>
<tr>
<td>44Se-1</td>
<td>0 to +30.0</td>
<td>572.3</td>
<td>41.1</td>
<td>Edge of weld</td>
</tr>
<tr>
<td>44Se-2</td>
<td>0 to +27.5</td>
<td>181.5</td>
<td>30.7</td>
<td>Weld</td>
</tr>
<tr>
<td>44Se-3</td>
<td>0 to +20.0</td>
<td>2965.7</td>
<td>21.5</td>
<td>Did not fail</td>
</tr>
<tr>
<td>Av</td>
<td></td>
<td></td>
<td>35.9</td>
<td>22.7</td>
</tr>
</tbody>
</table>

* Based on a value of \( K \) of 0.32 for all series except 44Se, for which a value of \( K = 0.18 \) was used. See Fig. 11.
plate. Specimens 44Sa-4, 44Sb-4, and 44Sc-4 all broke 2 in. outside of the longer strap plate; Specimen 44Se-4 broke about 3 in. from the butt weld; and Specimen 44Sd-4 broke at the edge of the transverse fillet weld across the end of the longer strap plate. The fracture was of a brittle type for the latter, but of a ductile type for all the others.
TABLE 13
RESULTS OF STATIC TESTS: BUTT WELDS WITH AND WITHOUT, STRAP PLATES
Series 44Sa to 44Se, inclusive

<table>
<thead>
<tr>
<th>Specimen No.</th>
<th>Ultimate Stress, p.s.i.</th>
<th>Location of Fracture</th>
</tr>
</thead>
<tbody>
<tr>
<td>44Sa-4</td>
<td>60 600</td>
<td>About 2 in. outside of long strap plate</td>
</tr>
<tr>
<td>44Sb-4</td>
<td>60 800</td>
<td>About 2 in. outside of long strap plate</td>
</tr>
<tr>
<td>44Sc-4</td>
<td>60 400</td>
<td>About 2 in. outside of long strap plate</td>
</tr>
<tr>
<td>44Sd-4</td>
<td>60 200</td>
<td>At edge of transverse fillet weld at end of long strap plate</td>
</tr>
<tr>
<td>44Se-4</td>
<td>60 250</td>
<td>About 3 in. from the weld</td>
</tr>
</tbody>
</table>
The brittle character of the fracture of Specimen 44Sd-4 and the ductile character of the fracture of Specimen 44Sb-4 are shown in Fig. 12.

![Diagram of Specimen 44Sd-4 and 44Sb-4]

**Fig. 13. Reinforced Tension Members**

7. **Reinforced Tension Members**

The specimen detailed in Fig. 13a represents a tension member reinforced with plates attached to the gusset plates at the ends with single-V butt welds, welded from one side only. It is intended to simulate the procedure that would be followed in the field if this method were used to strengthen web members of a truss. The specimen detailed in Fig. 13b is a similar tension member without the reinforcement, used as a basis of comparison in judging the effectiveness of the reinforcement.
Four specimens of the reinforced type were tested, one statically and three in fatigue. Six nonreinforced specimens were tested, one statically and five in fatigue. All fatigue specimens were tested on a cycle in which the stress varied from 0 to tension.

The results of the fatigue tests are given in Table 14. The data for the reinforced specimens of Series 44V, plotted to a log-log scale, determine the $S-N$ diagrams of Fig. 14a. All the fatigue specimens in Series 44V failed in the reinforcing plates at the edge of the butt weld.
The specimens that were not reinforced, Series 44W, were fabricated in two groups. Of the first group (44W-1, 44W-2, 44W-3, and 44W-4), 44W-2 and 44W-3 had not failed at 4,000,000 cycles, and the tests were discontinued. Specimens 44W-5 and 44W-6 were then obtained\(^1\) and tested successfully in fatigue.

The results of the fatigue tests of the 44W Series, specimens that were not reinforced, are given in the lower part of Table 14. Figure 14a is for the member with reinforcement; Fig. 14b is for the member without reinforcement. The unit stress is based on the gross section.

The values of \(F_{1,000,000}\) and \(F_{2,000,000}\), based on the gross section, were 23,400 p.s.i. and 11,500 p.s.i. respectively for the members that were not reinforced, and 26,800 p.s.i. and 13,500 p.s.i. respectively for the members that were reinforced.

Both the unit fatigue strength based on the gross section and the area of the section were increased by the reinforcement. The greater unit fatigue strength is attributed to the fact that the reinforced specimen is more free of geometrical stress-raisers than the specimen that was not reinforced.

One specimen of each series was tested statically; a summary of the results is given in Table 15. The unit static strength, based on the gross section, was greater for the reinforced specimen than for the unreinforced, and its total strength was more than twice as great.

The reinforced members tested were short, and no intermediate connection between the reinforcing plate and the flanges of the main section was necessary. Actually, the web members of a truss are long; some intermediate connections between the reinforcing plate and the main section would be needed. A small continuous fillet weld would serve the purpose. What its effect on the fatigue strength of the reinforced members would be is somewhat problematic. Values of \(F_{1,000,000}\) and \(F_{2,000,000}\) for the reinforced wide-flange tension members, for the flanges of rolled I-beams without reinforcement tested in

\(^1\) These specimens were contributed by the Chicago Bridge and Iron Company of Chicago.
flexure, for the flanges of rolled I-beams reinforced with plates attached with continuous fillet welds, and for the flanges of I-beams with reinforcement attached with intermittent fillet welds are given in the following tabulation. Some members were tested in tension, others in flexure, as indicated:

<table>
<thead>
<tr>
<th>Kind of Member</th>
<th>$F_{100000}$* p.s.i.</th>
<th>$F_{200000}$* p.s.i.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beams 1, 2, and 3 tested in flexure; Members 4 and 5 tested in tension</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1** 12-in., 31.8-lb rolled I-beam as rolled</td>
<td>41 100</td>
<td>31 200</td>
</tr>
<tr>
<td>2** 12-in., 31.8-lb rolled I-beam reinforced with full-length cover plates attached with continuous 5/16-in. fillet welds</td>
<td>42 000</td>
<td>16 500</td>
</tr>
<tr>
<td>3** 12-in., 31.8-lb rolled I-beams reinforced with cover plates attached with 5/16-in. intermittent fillet welds</td>
<td>26 800</td>
<td>13 500</td>
</tr>
<tr>
<td>4 Wide-flange tension member of truss reinforced with plates attached to gusset plates, Series 44V</td>
<td>23 400</td>
<td>11 500</td>
</tr>
<tr>
<td>5 Wide-flange tension member of truss not reinforced, Series 44W</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Based on gross sections.

Both the continuous and the intermittent fillet welds reduced the unit fatigue strength of the I-beam flanges. However, the I-beam flanges reinforced with plates attached with intermittent fillet welds had a greater unit fatigue strength than the reinforced tension truss member shown in Fig. 13a. As a consequence, it would seem that fillet welds connecting the reinforcing plates to the flanges of the 44V specimens probably would not decrease the fatigue strength of the member.

The tests described in this section would seem to justify the following statements:

Reinforcing the 44W wide-flange truss tension member by adding flange plates in the planes of the gusset plates, and connecting them to the gusset plates with transverse single-V butt welds, increased the gross area of the section 97 percent, increased the fatigue strength somewhat more than 100 percent, and increased the static strength approximately 125 percent. The merit of this particular type of reinforcement is attributed to the fact that the reinforcing plates lie in the planes of the gusset plates and are terminated without an abrupt change in section, thus eliminating the geometrical stress-raisers which sometimes accompany the addition of reinforcing plates. The success
of this method of reinforcing presupposes that the strength of the gusset plate equals or exceeds the strength of the reinforced member.

The low unit fatigue strength of wide-flange tension members of a truss attached to gusset plates at the panel points by the flanges only, is attributed to the fact that the web, which is a considerable part of the section, is so far from the rivets from which the stress is derived. This is a matter of vital concern to the designing engineer if the member is one for which the fatigue strength is a vital factor.

8. **Spliced and Reinforced I-Beams**

The flexural fatigue strength of steel beams is a matter of growing interest to structural engineers and has received considerable attention in recent years. Previous tests \(^1\) determined the fatigue strength of a number of kinds of flexural members. These included: steel I-beams as-rolled, rolled beams reinforced with full-length cover plates attached with fillet welds, rolled beams reinforced with partial-length cover plates attached with fillet welds, rolled beams reinforced with cover plates attached with rivets, and beams fabricated by attaching flange plates to a web plate with longitudinal fillet welds.

The tests reported herein supplement the previous work. Three specimens of each of the following types were tested in flexural fatigue.

**Series A.** Specimens A-1, A-2, and A-3 were 12-in., 31.8-lb rolled I-beams with 6-in. by \(\frac{3}{8}\)-in. full-length cover plates attached with \(\frac{3}{16}\)-in. continuous fillet welds. Specimens A-4, A-5, and A-6 have 6-in. by \(\frac{5}{8}\)-in. full-length cover plates attached with \(\frac{3}{16}\)-in. continuous fillet welds.

**Series B** consisted of 12-in., 31.8-lb rolled I-beams spliced with transverse butt welds in the as-welded condition.

**Series C** consisted of 12-in., 31.8-lb rolled I-beams spliced with transverse butt welds with the reinforcement ground off.

**Series D** consisted of 12-in., 31.8-lb rolled I-beams spliced with moment-resisting riveted joints.

The details of the specimens are shown in Fig. 26 and in the figures at the tops of Tables 18, 21, and 22. All specimens were fabricated from beams which were rolled from the same heat. The chemical composition of the steel is given in Table 16.

The testing machine used in making flexural fatigue tests (shown in Fig. 15) is the same machine that was used for the previous tests. Its operation is described in detail in Bulletin 377.

All tests were made on a cycle in which the stress at the critical

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\(^1\) Univ. of Ill. Eng. Exp. Sta. Bul. 377.
section of the bottom flange varied from a tension of 1000 p.s.i. to a maximum tension. The maximum tension in the stress cycle was so chosen as to obtain the fatigue strength corresponding to failure at 2,000,000 cycles, designated as $F_{2,000,000}$.

The determination of the value of $K$ for a given type of specimen requires that there be some tests for which failure occurs at a relatively small number of cycles and other tests for which failure occurs at a relatively large number of cycles. The number of tests of each type of specimen required to determine the value of $K$ in such a manner is greater than the number contemplated for this investigation. For this reason, and because of the similarity of the specimens, the value of $K$ that has been used in determining $F_{2,000,000}$ is based on the results of the flexural tests of similar beams reported in.

---

**TABLE 16**

**CHEMICAL COMPOSITION OF STEEL IN FLEXURAL FATIGUE SPECIMENS**

<table>
<thead>
<tr>
<th></th>
<th>C</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
</tr>
</thead>
<tbody>
<tr>
<td>I-Beams</td>
<td>0.22</td>
<td>0.47</td>
<td>0.010</td>
<td>0.030</td>
</tr>
<tr>
<td>¼-In. Plates (Laboratory Tests)</td>
<td>0.27</td>
<td>0.54</td>
<td>0.012</td>
<td>0.039</td>
</tr>
<tr>
<td>½-In. Plates (Laboratory Tests)</td>
<td>0.27</td>
<td>0.59</td>
<td>0.012</td>
<td>0.035</td>
</tr>
</tbody>
</table>

---

**Fig. 15. 112,000-lb Flexural Fatigue Testing Machine**
Bulletin 377. A value of $K$ equal to 0.20 has been used for all tests included in the present report.

The error in $F_n$ resulting from an error in the value of $K$ depends upon the amount by which the ratio $N/n$ differs from unity. However, a considerable error in the value of $K$ results in a relatively small error in the value of $F_n$ even when $N/n$ differs appreciably from unity. This fact is apparent from the following tabulation. All values of $K$ and $N$ are hypothetical and do not represent the results of tests. They are presented solely for the purpose of illustrating the error in $F_n$ due to the use of an inaccurate value of $K$ when $N/n$ has values ranging from 0.20 to 1.0.

<table>
<thead>
<tr>
<th>Line</th>
<th>Number of Cycles for Failure, $N$</th>
<th>Value of $N/n$</th>
<th>Values of $F_{2,000,000}$ Based on Three Assumed Values of $K$ as follows</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>$K = 0.20$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$F_{2,000,000}$</td>
</tr>
<tr>
<td>(1)</td>
<td>400,000</td>
<td>0.20</td>
<td>0.7248 $S$</td>
</tr>
<tr>
<td>(2)</td>
<td>700,000</td>
<td>0.35</td>
<td>0.8106 $S$</td>
</tr>
<tr>
<td>(3)</td>
<td>1,000,000</td>
<td>0.50</td>
<td>0.8706 $S$</td>
</tr>
<tr>
<td>(4)</td>
<td>1,500,000</td>
<td>0.75</td>
<td>0.9441 $S$</td>
</tr>
<tr>
<td>(5)</td>
<td>2,000,000</td>
<td>1.00</td>
<td>1.0000 $S$</td>
</tr>
</tbody>
</table>

This table contains values of $F_{2,000,000}$ based on three values of $K$, as determined from five hypothetical tests involving a maximum stress in the stress cycle represented by $S$. These five tests are considered as having ended in a failure of the specimen at 400,000, 700,000, 1,000,000, 1,500,000 and 2,000,000 cycles respectively. The value of $F_{2,000,000}$ has been computed for each test using the three values of $K$: 0.20, 0.15, and 0.25. For purposes of illustration it is assumed that the correct value of $K$ is 0.20. This being true, the value of $F_{2,000,000}$ for the test that results in failure at 400,000 cycles will be 0.7248 $S$, as given in line 1 of column 3 of the tabulation. If, however, the value of $F_{2,000,000}$ had been computed on the basis that $K = 0.15$, the computed value of $F_{2,000,000}$ would have been 0.7855 $S$, 8 percent greater than the true value. Or if the value of $F_{2,000,000}$ had been computed on the basis that $K = 0.25$, the computed value would have been 0.6688 $S$, 8 percent less than the true
value. That is, for this test with failure at 400,000 cycles and for which \( \frac{N}{n} = 0.20 \), a 25 percent error in the value of \( K \) results in an 8 percent error in \( F_{2000000} \).

Consider now the hypothetical case presented in line 3 of the tabulation for which \( \frac{N}{n} = 0.50 \). For it, the error in the computed value of \( F_{2000000} \) is 4 percent if computed from a value of \( K \) either 25 percent too small or 25 percent too large. For still larger values of \( \frac{N}{n} \) the errors in the computed values of \( F_{2000000} \) are correspondingly smaller.

The determination of the values of \( F_{2000000} \), based on a value of \( K \) of 0.20 and given in Tables 18, 21, and 22, is open to some criticism, because the value of \( K \) is not accurately known. However, the error cannot be large except possibly for specimens B-2 and C-1 of Table 21, for which the value of \( n \) is relatively small. It is believed that the method used gives the best interpretation possible for the limited amount of data available. Further, it is believed that the values of \( F_{2000000} \) given in Tables 18, 21, and 22 differ from the true values by considerably less than 10 percent and also by considerably less than the difference between the true fatigue strengths of two specimens that are supposedly identical.

The fact that two supposedly identical specimens have widely differing values for the fatigue strength does not indicate an error in the interpretation of the tests. Consider specimens B-2 and B-3, Table 21. They were made of the same steel, were fabricated by the same procedure and by the same operator, and were tested on the same cycle. One failed at 170,900 cycles; the other at 584,400 cycles. There is no question that specimen B-3 was appreciably stronger in fatigue than specimen B-2. The computed value reported in Table 21 is 16 percent greater for specimen B-3 than for B-2.

The welded specimens were fabricated by a skilled and reliable welder who used extreme care in welding the specimens. The fact that specimens fabricated by the procedure used for these specimens may vary greatly in their fatigue strengths is one of the important findings resulting from this investigation.

(a) Beams with Cover Plates of Various Thicknesses Attached with Fillet Welds.—The beams of Series A consisted of 12-in., 31.8-lb I-beams with full-length cover plates, some \( \frac{1}{2} \) in., others \( \frac{5}{8} \) in. thick, attached with continuous fillet welds. The welding procedure used in the fabrication of these specimens is given in Table 17. The results of the fatigue tests are given in Table 18. The data in Table 18, plotted
### Table 17
Welding Procedure for I-Beams with 1/4-in. and 3/8-in. Cover Plates

<table>
<thead>
<tr>
<th>Sequence and Direction of Weld Passes</th>
<th>(\frac{3}{8})-in. Fillet Welds</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrode:</td>
<td>(\frac{3}{16})-in. A.W.S. A.S.T.M. E6012</td>
</tr>
<tr>
<td>Polarity:</td>
<td>Straight</td>
</tr>
<tr>
<td>Position:</td>
<td>Horizontal</td>
</tr>
<tr>
<td>Voltage:</td>
<td>Center of Normal Welding Range</td>
</tr>
<tr>
<td>Amperes:</td>
<td>175 Amperes</td>
</tr>
</tbody>
</table>

### Table 18
Fatigue Strength of 12-in., 31.8-lb I-Beams with Full-Length Cover Plates Attached with Continuous Fillet Welds

Series A

<table>
<thead>
<tr>
<th>Specimen No.</th>
<th>Maximum Stress in Cycle 1000's of p.s.i.</th>
<th>Number of Cycles for Failure in 1000's</th>
<th>Fatigue Strength in 1000's of p.s.i.</th>
<th>Location of Fracture</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6-in. x 3/4-in. Cover Plates</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A-1</td>
<td>+26.0</td>
<td>1431.4</td>
<td>24.3</td>
<td>1</td>
</tr>
<tr>
<td>A-2</td>
<td>+26.0</td>
<td>1464.2</td>
<td>24.4</td>
<td>2</td>
</tr>
<tr>
<td>A-3</td>
<td>+26.0</td>
<td>776.9</td>
<td>21.5</td>
<td>3</td>
</tr>
<tr>
<td>Av</td>
<td></td>
<td></td>
<td>23.4</td>
<td></td>
</tr>
<tr>
<td>6-in. x 3/8-in. Cover Plates</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A-4</td>
<td>+27.0</td>
<td>663.3</td>
<td>21.6</td>
<td>3</td>
</tr>
<tr>
<td>A-5</td>
<td>+26.0</td>
<td>480.7</td>
<td>19.5</td>
<td>3</td>
</tr>
<tr>
<td>A-6</td>
<td>+25.0</td>
<td>521.2</td>
<td>19.9</td>
<td>4</td>
</tr>
<tr>
<td>Av</td>
<td></td>
<td></td>
<td>20.3</td>
<td></td>
</tr>
</tbody>
</table>

* Based on a value of \(K = 0.20\).
to a log-log scale, determine the S-N diagrams of Fig. 16. The dash line of Fig. 16 presents the results of the previous tests\(^1\), which were made on similar beams with 3/8-in. cover plates.

The data listed in Table 18 and plotted in Fig. 16 indicate that the average fatigue strength for failure at 2,000,000 cycles for the beams with the 1/2-in. cover plates was slightly higher than for those with the 3/8-in. cover plates. However, the difference is not large.

\(^1\) Univ. of Ill. Eng. Exp. Sta. Bul. 377.
The previous tests with $\frac{3}{8}$-in. cover plates gave values of the fatigue strength that fall in between the strengths of the present beams with $\frac{1}{2}$-in. and $\frac{5}{8}$-in. plates.

The fractures of all Series A specimens started in the fillet weld of the lower flange at the locations shown in Table 18. All cracks started at a weld crater, as shown in Fig. 17.

The relative merits of the beams without cover plates and of the beams reinforced with 6-in. cover plates of various thickness, the latter attached with continuous fillet welds, is apparent from the following tabulation.

<table>
<thead>
<tr>
<th>Description of Specimen</th>
<th>Modulus, in.²</th>
<th>Fatigue Strength in 1000's of in.-lb of moment. Failure at 2,000,000 Cycles</th>
<th>Fatigue-Strength Ratio</th>
<th>Weight Ratio</th>
<th>Fatigue-Strength Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>12-in., 31.8-lb I-Beam</td>
<td>36.0</td>
<td>1 115</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>12-in., 31.8-lb I-Beam Reinforced with two 6-in. x $\frac{5}{8}$-in. Plates</td>
<td>64.7</td>
<td>1 475</td>
<td>132</td>
<td>148</td>
<td>89</td>
</tr>
<tr>
<td>12-in., 31.8-lb I-Beam Reinforced with two 6-in. x $\frac{5}{8}$-in. Plates</td>
<td>75.2</td>
<td>1 760</td>
<td>158</td>
<td>164</td>
<td>97</td>
</tr>
<tr>
<td>12-in., 31.8-lb I-Beam Reinforced with two 6-in. x $\frac{5}{8}$-in. Plates</td>
<td>85.8</td>
<td>1 745</td>
<td>156</td>
<td>180</td>
<td>87</td>
</tr>
</tbody>
</table>

Attaching flange plates to 12-in., 31.8-lb rolled I-beams with fillet welds increased their fatigue strength, but the relative increase in fatigue strength was slightly less than the relative increase in weight and, due to the cost of welding, is considerably less than the relative increase in cost.

(b) Beams with Butt-Welded Splices.—The specimens of Series B and C consisted of 12-in., 31.8-lb I-beams spliced with two butt welds, one at a distance of 10 in. on either side of the center of the span. The Series B specimens were tested in the as-welded condition, but for the Series C specimens the weld reinforcement was ground flush with the base metal. The welding procedure and sequence of weld passes are given in Tables 19 and 20.

The procedure of Table 19 was used for Specimen B-1 (flanges welded first and then the web) and the procedure of Table 20 was used for Specimens B-2, B-3, C-1, C-2, and C-3 (web welded first and then the flanges). A series of tiedown clamps were used to hold the short lengths of beams which form a specimen in line during welding. Figure 18 shows these beams clamped in place for Speci-
TABLE 19
SEQUENCE OF WELD PASSES FOR BUTT WELDS CONNECTING I-BEAMS: SPECIMEN B-1

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>⅝₂₂</td>
<td></td>
<td>145</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>⅝₂₂</td>
<td></td>
<td>145</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>⅝₁₆</td>
<td></td>
<td>215</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>⅝₁₆</td>
<td></td>
<td>215</td>
</tr>
<tr>
<td>5</td>
<td>5</td>
<td></td>
<td>Beam turned over and pass 1 and 2 back-chipped</td>
<td>165</td>
</tr>
<tr>
<td>6</td>
<td>6</td>
<td>⅝₂₂</td>
<td></td>
<td>165</td>
</tr>
<tr>
<td>7</td>
<td>7</td>
<td>⅝₁₆</td>
<td></td>
<td>215</td>
</tr>
<tr>
<td>8</td>
<td>8</td>
<td>⅝₁₆</td>
<td></td>
<td>215</td>
</tr>
<tr>
<td>9</td>
<td>9</td>
<td></td>
<td>Beam set on its side for web welds</td>
<td>165</td>
</tr>
<tr>
<td>10</td>
<td>10</td>
<td>⅝₁₆</td>
<td></td>
<td>215</td>
</tr>
<tr>
<td>11</td>
<td>11</td>
<td>⅝₂₂</td>
<td></td>
<td>165</td>
</tr>
<tr>
<td>12</td>
<td>12</td>
<td>⅝₁₆</td>
<td></td>
<td>215</td>
</tr>
<tr>
<td>13</td>
<td>13</td>
<td></td>
<td>Beam turned over and pass 9 back-chipped</td>
<td>165</td>
</tr>
<tr>
<td>14</td>
<td>14</td>
<td>⅝₂₂</td>
<td></td>
<td>215</td>
</tr>
<tr>
<td>15</td>
<td>15</td>
<td>⅝₁₆</td>
<td></td>
<td>215</td>
</tr>
<tr>
<td>16</td>
<td>16</td>
<td></td>
<td>Cope in web filled in</td>
<td>215</td>
</tr>
</tbody>
</table>

Note: All welds were made with straight polarity, in the flat position, and with A.W.S.-A.S.T.M. E6012 electrodes.

*Amperage reported is that set on the indicator of the welding machine.
### TABLE 20
**SEQUENCE OF WELD PASSES FOR BUTT WELDS CONNECTING I-BEAMS:**
Specimens B-2, B-3, C-1, C-2, and C-3

![Diagram of weld passes and web](image)

<table>
<thead>
<tr>
<th>Step No.</th>
<th>Pass No.</th>
<th>Electrode Size and Type</th>
<th>Voltage*</th>
<th>Amp. Setting</th>
<th>Measured* Amp.</th>
<th>Polarity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>5/32 - E6012</td>
<td>20</td>
<td>125</td>
<td>240</td>
<td>Straight</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>5/32 - E6012</td>
<td>22</td>
<td>240</td>
<td>240</td>
<td>Straight</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>Beam turned over and pass 1 back-chipped</td>
<td>22</td>
<td>130</td>
<td>240</td>
<td>Straight</td>
</tr>
<tr>
<td>4</td>
<td>3</td>
<td>5/32 - E6012</td>
<td>21</td>
<td>120</td>
<td>240</td>
<td>Straight</td>
</tr>
<tr>
<td>5</td>
<td>4</td>
<td>5/32 - E6012</td>
<td>22</td>
<td>240</td>
<td>240</td>
<td>Straight</td>
</tr>
<tr>
<td>6</td>
<td>5</td>
<td>Beam set on one flange for flange welds</td>
<td>22</td>
<td>150</td>
<td>240</td>
<td>Straight</td>
</tr>
<tr>
<td>7</td>
<td>6</td>
<td>5/32 - E6010</td>
<td>21</td>
<td>120</td>
<td>240</td>
<td>Reversed</td>
</tr>
<tr>
<td>8</td>
<td>7</td>
<td>5/32 - E6010</td>
<td>22</td>
<td>240</td>
<td>240</td>
<td>Reversed</td>
</tr>
<tr>
<td>9</td>
<td>8</td>
<td>5/32 - E6012</td>
<td>22</td>
<td>240</td>
<td>240</td>
<td>Straight</td>
</tr>
<tr>
<td>10</td>
<td>9</td>
<td>5/32 - E6012</td>
<td>22</td>
<td>240</td>
<td>240</td>
<td>Straight</td>
</tr>
<tr>
<td>11</td>
<td>10</td>
<td>5/32 - E6010</td>
<td>21</td>
<td>130</td>
<td>240</td>
<td>Reversed</td>
</tr>
<tr>
<td>12</td>
<td>11</td>
<td>5/32 - E6012</td>
<td>22</td>
<td>240</td>
<td>240</td>
<td>Reversed</td>
</tr>
<tr>
<td>13</td>
<td>12</td>
<td>5/32 - E6012</td>
<td>22</td>
<td>240</td>
<td>240</td>
<td>Straight</td>
</tr>
</tbody>
</table>

**NOTE:** All welds were made in the flat position.

* A special calibrated volt-amp. meter was installed on the welding machine and was used to obtain an average value of the voltage and amperage for Specimen C-3.
TABLE 21
FATIGUE STRENGTH OF 12-IN., 31.8-LB I-BEAMS WITH BUTT-WELD SPLICES: SERIES B AND C

<table>
<thead>
<tr>
<th>Specimen No.</th>
<th>Maximum Stress in Cycle at weld 1000's p.s.i.</th>
<th>Number of Cycles for Failure in 1000's</th>
<th>Fatigue Strength in 1000's of p.s.i.</th>
<th>Location of Fracture</th>
</tr>
</thead>
<tbody>
<tr>
<td>B-1</td>
<td>+24.0</td>
<td>603.5</td>
<td>18.9</td>
<td>1</td>
</tr>
<tr>
<td>B-2</td>
<td>+22.0</td>
<td>170.9</td>
<td>13.5</td>
<td>2</td>
</tr>
<tr>
<td>B-3</td>
<td>+22.0</td>
<td>584.4</td>
<td>15.7</td>
<td>3</td>
</tr>
<tr>
<td>Av</td>
<td></td>
<td></td>
<td>16.0</td>
<td></td>
</tr>
</tbody>
</table>

Weld Reinforcement On

<table>
<thead>
<tr>
<th>Specimen No.</th>
<th>Maximum Stress in Cycle at weld 1000's p.s.i.</th>
<th>Number of Cycles for Failure in 1000's</th>
<th>Fatigue Strength in 1000's of p.s.i.</th>
<th>Location of Fracture</th>
</tr>
</thead>
<tbody>
<tr>
<td>C-1</td>
<td>+25.0</td>
<td>151.3</td>
<td>14.9</td>
<td>1</td>
</tr>
<tr>
<td>C-2</td>
<td>+20.0</td>
<td>965.9</td>
<td>17.3</td>
<td>2</td>
</tr>
<tr>
<td>C-3</td>
<td>+20.0</td>
<td>1170.1</td>
<td>18.0</td>
<td>3</td>
</tr>
<tr>
<td>Av</td>
<td></td>
<td></td>
<td>16.7</td>
<td></td>
</tr>
</tbody>
</table>

Weld Reinforcement Machined Off

* Based on a value of $K = 0.20$.

Fig. 18. Specimen B-1 Clamped to H-Beam in Position for Welding
men B-1, the parts of B-1 being bolted to the top flange of a continuous beam. The latter beam is not clearly shown in the figure but is similar to the one in the foreground.

The results of the fatigue tests for Series B and Series C are given in Table 21. These data, plotted to a log-log scale, determine the S-N diagrams of Fig. 19. The data indicate that, in the case of the beams spliced with butt welds, the removal of the weld reinforcement did not improve the fatigue properties of the specimen by any significant amount. They also indicate that these splices were not very efficient for splicing beams, the average values of $F_{200000}$ for Series B and C being 16,000 p.s.i. and 16,700 p.s.i. respectively, as compared with 31,200 p.s.i. for a beam without a splice as determined in previous tests. That is, the butt-weld splices connecting three 12-in., 31.8-lb I-beams had an efficiency of approximately 50 percent.

The fractures of Specimens B-1 and B-3 occurred along the edge of the weld bead as shown in Fig. 20. The weld beads acted as a geometrical stress-raiser and are responsible for the low fatigue strength of these beams, as compared with beams without welds. The third beam of this Series, B-2, failed through the center of the weld due, presumably, to the slag inclusions in the weld. The location of the fracture and the nature of the inclusions can be seen in Figs. 21 and 22 respectively. The slag inclusion in the flange of Specimen B-2 acted as a stress-raiser which, apparently, was more severe than the weld-bead reinforcement.

---

Fig. 20. Fracture in Lower Flange at Edge of Weld Bead, Specimens B-1 and B-3
Fig. 21. Location of Fracture in Weld of Lower Flange, Specimen B-2

Fig. 22. Fracture of Specimen B-2, Showing Slag Inclusion at Center of Flange
The fractures of Specimens C-1, C-2, and C-3 are shown in Figs. 23-25. Here, also, the inclusions can be seen in the fractures. All these cracks started in the vicinity of the junction between the web and the lower flange.

FIG. 23. LOCATION AND CHARACTER OF FRACTURE, SPECIMEN C-1
In considering the low fatigue strength of the butt-weld joints connecting I-beams, it should be noted that the welds were carefully made by a qualified welder. However, the placing of weld metal in two double-V grooves intersecting at right angles to each other is very difficult. Moreover, the complete removal of slag under these conditions is likewise difficult.

FIG. 24. LOCATION AND CHARACTER OF FRACTURE, SPECIMEN C-2
(c) Beams with Riveted Splices.—The specimens of Series D each consisted of two 12-in., 31.8-lb I-beams connected with a riveted moment-resisting joint. The details of the joint are shown in Fig. 26. It consists of a web splice and two flange splices. The specimens were designed for fatigue failure on the offset section C, which passes

Fig. 25. Location and Character of Fracture, Specimen C-3
through the inside row of rivets in both the cover plates and the side plates. To make section C the weak section it was necessary to extend the cover plates far enough so that failure would not occur at section A, taking into account the fact that the unit fatigue strength at A is quite low.\(^1\)

The results of the fatigue tests are given in Table 22. These data, plotted to a log-log scale, determine the S-N diagram of Fig. 27. The dash line of Fig. 27 represents the results of previous tests\(^2\) which were made on beams with full-length riveted cover plates.

These diagrams indicate that the unit flexural fatigue strength based on the gross section was slightly greater for the beam splice than for the beam with full-length cover plates. However, the difference was not great; the values of \(F_{2000000}\) were 18,000 p.s.i. and 15,800 p.s.i. respectively for the two types of beams, the values being based on the gross section in each instance.

The point of vital interest is the moment-resisting capacity in fatigue of the spliced beams relative to the moment-resisting capacity of similar rolled beams without splices. The moment-resisting capacity in fatigue of the beam in the as-rolled condition was 36.0 in.\(^3\) x 31,200 p.s.i., or 1,123,000 in.-lb. The moment-resisting capacity in fatigue of the spliced beams of Fig. 26 was 44.2 in.\(^3\) x 18,000 p.s.i., or 795,000 in.-lb. That is, the total fatigue strength in flexure was only 70.7 percent as great for the spliced beams as for the original beams in the as-rolled condition.*

### Table 22
**Fatigue Strength of 12-in., 31.8-lb I-Beams Connected with Riveted Splice Plates and Partial-Length Cover Plates Attached with \( \frac{3}{4} \)-in. Rivets: Series D**

<table>
<thead>
<tr>
<th>Specimen No.</th>
<th>Maximum Stress in Cycle at C. 1000's of p.s.i.*</th>
<th>Number of Cycles for Failure in 1000's</th>
<th>Fatigue Strength in 1000's of p.s.i. ( F_{1000} )</th>
<th>Location of Fracture</th>
</tr>
</thead>
<tbody>
<tr>
<td>D-1</td>
<td>+17.8</td>
<td>3032.4+</td>
<td>17.8+</td>
<td>Did not fail</td>
</tr>
<tr>
<td>D-2</td>
<td>+19.2</td>
<td>1102.4</td>
<td>17.1</td>
<td>1</td>
</tr>
<tr>
<td>D-3</td>
<td>+19.2</td>
<td>3267.0</td>
<td>19.2+</td>
<td>1</td>
</tr>
<tr>
<td>Av</td>
<td></td>
<td></td>
<td>18.0+</td>
<td></td>
</tr>
</tbody>
</table>

* Stress based on gross section of the cover plates and side plates, the splice material at C.

Based on a value of \( K = 0.20 \).

---

**Fig. 27. S-N Diagram for Riveted Joints Connecting 12-in., 31.8-lb I-Beams**
III. Summary

The results of the tests described in this bulletin seem to justify the following conclusions.

1. For the wrought-iron eyebars shortened by heating and upsetting, the fatigue strength was somewhat less for the shortened than for the unshortened eyebars, but the difference was not significant. For the steel eyebars shortened by heating and upsetting, the fatigue strengths for the shortened and the unshortened eyebars were very nearly identical. These, and other fatigue tests, indicate that the fatigue strength of steel is not affected by the metallurgical changes incident to heating steel to a bright red and cooling. This fact, however, does not preclude the possibility of reducing the fatigue strength by heating and then upsetting unless care is exercised to avoid the formation of geometrical stress-raisers in the form of grooves or bumps on the finished surfaces. All such geometrical stress-raisers should be avoided.

2. The tests reported in Sections 3 and 4 indicate that the fatigue strength is less than half as great for steel eyebars shortened by cutting and splicing as it is for similar eyebars shortened by heating and upsetting.

3. A fillet weld along a transverse edge of the butt straps of a double-strap riveted butt joint affects the fatigue strength of the joint in two ways: a) It tends to increase the strength by protecting the rivets and by protecting the section of the main plate through the transverse row of rivet holes; b) it tends to decrease the strength of the main plate at the weld, since the fillet weld acts as a geometrical stress-raiser. This is apparent, since for specimens with \( \frac{1}{2} \)-in. main plates, the fatigue strength was slightly greater on a section along the welds than on a section through the rivet holes for the specimen without welds. For the specimen with 1-in. main plates, the fatigue strength was nearly twice as great for the section of the plate along the edge of the weld as for the rivets of the specimens without welds.

4. The butt-weld joints connecting 4\( \frac{3}{4} \)-in. x 7\( \frac{3}{8} \)-in. plates that were "reinforced" by grinding the weld reinforcement flush with the base plate and attaching butt-straps with transverse fillet welds had a lower fatigue strength than similar butt welds with the reinforcement ground off but without reinforcing plates.

5. Reinforcing the 44W wide-flange truss tension member by adding flange plates in the planes of the gusset plates and connecting

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them to the gusset plates with transverse single-V butt welds increased the gross area of the section 97 percent, increased the fatigue strength somewhat more than 100 percent, and increased the static strength approximately 125 percent. The merit of this particular type of reinforcement is attributed to the fact that the reinforcing plates lie in the planes of the gusset plates and are terminated without an abrupt change in section, thus eliminating the geometrical stress-raisers that sometimes accompany the addition of reinforcing plates.

6. The low unit fatigue strength of wide-flange tension members of a truss attached to gusset plates at the panel points by the flanges only, is attributed to the fact that the web, which is a considerable part of the section, is so far from the rivets from which the stress is derived. This is a matter of vital concern to the designing engineer if the member is one for which the fatigue strength is a vital factor.

7. The value of $F_{2000000}$ for 12-in., 31.8-lb rolled I-beams reinforced with full-length 6-in. cover plates attached with $\frac{3}{16}$-in. continuous fillet welds was of the order of 22,000 p.s.i. That statement applies to beams reinforced with $\frac{3}{8}$-in., $\frac{1}{2}$-in., and $\frac{5}{8}$-in. cover plates respectively. This value is comparable with a value of 31,200 p.s.i. for a similar beam without cover plates, and a value of 16,500 p.s.i. for similar beams with full-length cover plates 6 in. wide attached with intermittent fillet welds.

8. The butt-weld joints connecting 12-in., 31.8-lb I-beams had average values of the flexural fatigue strength $F_{2000000}$ of 16,000 p.s.i. and 16,700 p.s.i. for joints in the as-welded condition and joints with the reinforcement ground flush with the base metal, respectively. These values are comparable with a value of 31,200 p.s.i. for similar beams without splices. They represent values of joint efficiencies only slightly greater than 50 percent for both types of butt-weld joints.

9. The moment-resisting capacity in fatigue of the riveted joints connecting 12-in., 31.8-lb I-beams was 795,000 in.-lb. This is comparable to a moment-resisting capacity in fatigue of the same beam without joints of 1,123,000 in.-lb. That is, the total fatigue strength in flexure was only 70.7 percent as great for the spliced beams as for the original beams in the as-rolled condition.
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