FATIGUE OF BOLTED HIGH STRENGTH STRUCTURAL STEEL

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INTRODUCTION

High strength steels are now used widely in building and bridge structures with savings in size, cost and weight on many structural components. However, design specifications until recently did not provide any significant advantage for the use of such steels in members subjected to repeated loading. Many tests of high strength steels in conventional connection details have indicated only modest improvement in fatigue performance over that of mild structural steels.

In structural applications steel generally is most sensitive to repeated loading at or in the vicinity of a connection whether bolted or welded. A study of the fatigue behavior of steel as it is used in a connection is essential for a meaningful evaluation or improvement of present design specifications. Exploratory fatigue tests of bolted ASTM A514 and A440 steels conducted at the University of Illinois indicated that further study of both steels in bolted applications might suggest higher allowable stresses for high strength steels subjected to repeated loading.

Results of extensive tests of A514 steel which followed the exploratory tests have been reported (2) this data further enhanced the need for similar information about high-strength low-alloy steels. This information is presented in this paper. Although the material used in the tests was supplied as A440 steel, the tensile properties also met the requirements of several low-alloy steels, e.g., ASTM A242, A441, A572 (grades 42, 45, 50), A588. These

Note.—Discussion open until August 1, 1971. To extend the closing date one month, a written request must be filed with the Executive Director, ASCE. This paper is part of the copyrighted Journal of the Structural Division, Proceedings of the American Society of Civil Engineers, Vol. 97, No. ST3, March, 1971. Manuscript was submitted for review for possible publication on July 23, 1970.

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tests thus provide an indication of the fatigue performance of high-strength low-alloy steels in bolted connections (using either ASTM A325 or A490 bolts).

DESCRIPTION OF INVESTIGATION

Connection Details.—A compact double lap butt type joint with center plate critical was chosen for this study as a representative model of tension connection details. Two such joints were proportioned: one for A325 and the other for A490 bolts. Relative proportions for the joints were determined on the basis of a stress in tension of 30 ksi (60% of the minimum yield strength) and shear stresses of 15 ksi for the A325 bolts and 22.5 ksi for the A490 bolts. The stresses used for the fasteners are in accordance with the recommendations of the 1964 ASTM A194 grade 2H heavy hex nuts on the Rockwell C scale. All fastener parts exceeded the respective ASTM minimum requirements.

Specimen Fabrication and Bolt Calibration.—Plates were flame cut to one of the heats; for the other heat of steel that was used, an average static yield strength of 46.2 ksi and an average tensile strength of 77.3 ksi were obtained. Specified minimum yield and tensile strengths for ASTM A440 are 50.0 ksi and 70.0 ksi, respectively. Refer to Table 1 for details on mechanical properties. The chemical composition of the two heats of steel plates as obtained from tests on samples are given in Table 2.

The high-strength ASTM A325 and A490 bolts were obtained from single production lots. Hardness tests conducted in accordance with ASTM specifications on samples cut from the bolts gave an average hardness value of 28 on the Rockwell C scale for A325 bolts and an average hardness value of 39 on the Rockwell C scale for the A490 bolts. Average values for the corresponding nuts were 93 (ASTM A325 heavy hex nuts) on the Rockwell B scale and 54 (ASTM A194 grade 2H heavy hex nuts) on the Rockwell C scale. All fastener parts exceeded the respective ASTM minimum requirements.

Specimen Fabrication and Bolt Calibration.—Plates were flame cut to
BOLTED STEEL FATIGUE

Connections which are designed for repeated load applications transmit load primarily via friction at the faying surfaces. A parameter of particular interest is the coefficient of slip, \( \mu \), a measure of frictional resistance. This coefficient was calculated using the following

\[
\mu = \frac{P_e}{n_f \cdot m \cdot T_f}
\]  

\( \text{ST 3} \)

FIG. 2.—LOAD-ELONGATION BEHAVIOR FOR HIGH-STRENGTH BOLTS IN TORQUED TENSION

The bolt calibrations necessary to compute the bolt tension from the elongation data were performed on several bolts of each type (A325-A490). The fasteners were tested by manual torquing to failure. A special solid-steel load transducer was used to measure bolt load and to simulate the stiffness of the connected steel parts in the joints. Average results from the bolt calibrations are shown in Fig. 2. The shaded areas shown on the load versus elongation curves of this figure correspond to the elongations that resulted in the bolts which were tightened to the snug plus one-half turn condition. The total elongation varied from 0.02 to 0.035 in. but resulted in relatively uniform tension. The bolt tensions at installation were 50 % to 60 % greater than the minimum bolt tension requirements. In general this method of bolt installa-

Prior to the application of cyclic loading each specimen was loaded incrementally through one cycle of test loading to note the occurrence of slip, if any. The fatigue machine was then set for automatic operation. Periodic measurements of bolt elongations and joint slip were made during the test.

The development of a crack, which by means of a preset microswitch caused the machine to shut down, usually indicated that constant maximum load could not be maintained. Further propagation of the crack was rapid and substantial fracture of the critical section occurred within a few additional load cycles. The number of cycles corresponding to the shutdown of the machine was used as a criterion for failure. Completion of fracture for subsequent closer inspection was done by pulling the plates in static tension.

Analysis and Interpretation of Data.—Results of the fatigue tests were plotted as S-N diagrams on a log-log basis, in which \( S \) denotes the maximum net section stress in ksi and \( N \) the number of cycles to failure for a given specimen type and stress ratio (ratio of minimum to maximum stress). The results can be empirically related for lives between approximately 50,000 cycles and 2,000,000 cycles by

\[
F_n = S_n^{(N/n)^k}
\]

In which \( F_n \) = fatigue strength at \( n \) cycles or the maximum stress that can be expected to cause failure at \( n \) cycles of loading; \( k \) = slope of the empirical straight line log-log relationship relating the maximum stress and the number of cycles to failure; and \( S_n \) = stress corresponding to failure at \( N \) cycles on the empirical curve. Thus, determination of the coordinates of a point on the best fit empirical curve \((S_n, N)\), and the slope, \( k \), of that curve establishes an empirical relation (Eq. 1) between \( F_n \) and \( n \). An iterative technique in conjunction with Eq. 1 was used to determine a best fit empirical representation of data. Details of this procedure have been described in an earlier study (2). Analysis using the method of least squares was also done to compare the fatigue strengths obtained by the two techniques. In general the two data analysis techniques were found to be in close agreement with each other.

Connections which are designed for repeated load applications transmit load primarily via friction at the faying surfaces. A parameter of particular interest is the coefficient of slip, \( \mu \), a measure of frictional resistance. This coefficient was calculated using the following

\[
\mu = \frac{P_e}{n_f \cdot m \cdot T_f}
\]
Variation of Joint Efficiency.—Theoretically, the ultimate strength of a bolted member is related directly to the net cross sectional area and not the gross area; thus, if the ratio of the net cross sectional area to gross area of a connected member is increased, the theoretical efficiency of the connection is similarly increased. Within limitations this has also been found to be generally true of the actual or measured efficiency.

<table>
<thead>
<tr>
<th>Specimen number</th>
<th>Stress cycle on net section, in kips per square inch</th>
<th>Cycles to failure, in thousands</th>
<th>Computed Fatigue Strength, in kips per square inch</th>
<th>Average initial bolt tension, in kips</th>
<th>Coefficient of slip</th>
</tr>
</thead>
<tbody>
<tr>
<td>L4B-1</td>
<td>0 to +50.0</td>
<td>790</td>
<td>72.7</td>
<td>54.3</td>
<td>0.20</td>
</tr>
<tr>
<td>L4B-2</td>
<td>0 to +50.0</td>
<td>920</td>
<td>75.7</td>
<td>53.0</td>
<td>0.22</td>
</tr>
<tr>
<td>L4B-3</td>
<td>0 to +50.0</td>
<td>154</td>
<td>70.5</td>
<td>50.0</td>
<td>0.18</td>
</tr>
<tr>
<td>L4B-4</td>
<td>0 to +50.0</td>
<td>248</td>
<td>77.1</td>
<td>45.8</td>
<td>0.20</td>
</tr>
<tr>
<td>L4B-5</td>
<td>0 to +50.0</td>
<td>4,000*</td>
<td>72.2</td>
<td>49.0</td>
<td>0.12</td>
</tr>
<tr>
<td>L4B-13b</td>
<td>-28.0 to +28.0</td>
<td>3,200</td>
<td>Average 74.4</td>
<td>52.1</td>
<td></td>
</tr>
<tr>
<td>L4B-14b</td>
<td>-28.0 to +28.0</td>
<td>3,200</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Specimen number</th>
<th>Stress cycle on net section, in kips per square inch</th>
<th>Cycles to failure, in thousands</th>
<th>Computed Fatigue Strength, in kips per square inch</th>
<th>Average initial bolt tension, in kips</th>
<th>Coefficient of slip</th>
</tr>
</thead>
<tbody>
<tr>
<td>L2B-10</td>
<td>0 to +50.0</td>
<td>585</td>
<td>66.1</td>
<td>41.3</td>
<td>0.16</td>
</tr>
<tr>
<td>L2B-1</td>
<td>0 to +50.0</td>
<td>585</td>
<td>65.5</td>
<td>41.0</td>
<td>0.17</td>
</tr>
<tr>
<td>L2B-2</td>
<td>0 to +50.0</td>
<td>192</td>
<td>65.5</td>
<td>41.5</td>
<td>0.17</td>
</tr>
<tr>
<td>L2B-3</td>
<td>0 to +50.0</td>
<td>259</td>
<td>65.5</td>
<td>41.5</td>
<td>0.17</td>
</tr>
<tr>
<td>L2B-4</td>
<td>0 to +50.0</td>
<td>2,499f</td>
<td>65.5</td>
<td>41.5</td>
<td>0.17</td>
</tr>
<tr>
<td>L2B-5</td>
<td>0 to +50.0</td>
<td>2,582</td>
<td>Average 70.0</td>
<td>43.7</td>
<td>0.16</td>
</tr>
<tr>
<td>L2B-7</td>
<td>-38.0 to +38.0</td>
<td>1,420</td>
<td>83.3</td>
<td>43.9</td>
<td>0.19</td>
</tr>
<tr>
<td>L2B-8</td>
<td>-38.0 to +38.0</td>
<td>1,365</td>
<td>Average 81.1</td>
<td>43.9</td>
<td>0.19</td>
</tr>
</tbody>
</table>

* T/S: B = 1.00: 0.69: 1.81: 0.6: 1.81: 3.0.

† Specimens from Heat No. 38L587.
‡ Fatigue strengths computed using \( F_p = S_p W / n^p \), \( p = 0.157 \).

§ Absence of coefficient of slip indicates that the specimen did not slip as a result of the applied load.

Examination of the net section stress with respect to fatigue performance in other studies (1,2) indicates that a reverse effect may be true for behavior under repeated loading. The results of the limited testing (7 specimens) of the L4BX series (Fig. 5) show a distinct reduction of fatigue strength compared to the results from the L4B series curves which are replotted for comparison.

Often, the quantity \( g/d \) is used as a parameter for comparison. It is ap-

\begin{align*}
\text{in which } P_e &= \text{load causing slip in the bolted joint}; \\
T_b &= \text{the average bolt tension at installation}; \\
n_y &= \text{number of fasteners in the joint}; \text{ and } m &= \text{the number of shear planes in the joint.}
\end{align*}
proximately related to the theoretical efficiency, $\epsilon$, by

$$\epsilon = 1 - \frac{1}{(g/d)^2}$$

in which $g$ = the transverse fastener spacing; and $d$ = the nominal bolt diameter. Although only one bolt is present at the net section of the joint the L4BX series can be visualized as having an increase in $(g/d)$ (approximately a factor of 2) over the basic series.

To say that this reduction in fatigue strength is solely the result of the variation of the theoretical joint efficiency is an over simplification. Certainly the geometry of the critical net section may have a related or even independent influence; generally an increase in theoretical efficiency is accomplished by a decrease in the number of bolts at the critical net section with an increase or no reduction in the number of bolts in adjacent rows. Thus the plate geometry, i.e., the arrangement of holes, is changed in the vicinity of the highly stressed net section.

The $T:S:B$ ratio for each connection series is given in Figs. 3, 4 and 5. The tension:shear:bearing ratio is the ratio of net section tensile stress; to the shear stress on the cross-sectional area of the bolts to the bearing stress; all are nominal stresses. The $T:S:B$ ratio indicates indirectly, the relative proportions of tension, shear and bearing areas. The decrease in the relative shear and bearing areas of the L4BX series compared to the L4B series may be a contributing factor to the severe reduction in fatigue strength found in the L4BX series, but previous studies of connection behavior indicate that these are minor changes in proportions relative to their effect on fatigue performance.

**OBSERVATIONS AND EXAMINATION OF RESULTS**

A close observation of the fatigue crack initiation in the steel was made after complete fracture of the center plate and disassembly of the connection. Although it is difficult if not impossible to study crack initiation in the center plate during testing, these later observations yield some information relative to initiation and propagation.

Fatigue cracks initiated on the faying surface of the center plate in the vicinity of the critical net section. Three photographs, one sample from each series, are shown in Fig. 6; it is apparent that the fractures were completed statically because of the visible spalling of the mill scale over a portion of the plane and the necking down at the net section. Fig. 6(a) shows how the photographs were taken; note, by means of the arrow at the top of each picture, that these are oblique views toward the externally loaded end of the center plate. Although the precise point of initiation is not clearly evident in all photographs, the brittle nature of the fatigue cracks is apparent. Note for example, Fig. 6(c) of Specimen L4B-5, the initiation was at the net section at the intersection of the plate surface and the left hole. A few specimens from each series had crack initiation at the gross section just ahead of the holes as in Fig. 6(b) and (d). Here, crack initiation occurred at the surface of the plate in the region where some differential movement during load cycling was in evidence. Note in Fig. 6(b) and (d), the portions of dark annular rings on
Several explanations for this can be put forth, one being that A514 steel may be more susceptible to initiation and therefore more initiations are likely to occur. Another contributing factor may have been the surface condition of the steel. The A440 steel was delivered with a smooth continuous mill scale which was preserved during fabrication; on the other hand the A514 steel had discontinuities in the mill scale which appeared to have influenced the location and the occurrence of fretting damage. Numerous studies have shown that high strength quenched and tempered steels are more notch sensitive in fatigue than lower strength steels.

FATIGUE DESIGN

Two of the principal structural steel design specifications American Association of State Highway Officials (AASHO) (10) and American Institute of Steel Construction (AISC) (8) have been revised during the past year to include fatigue design provisions for a variety of steels from mild structural steel (A36) through the high strength quenched and tempered steel (A514).

A fatigue diagram (Fig. 7) displays the results of the experimental data for A325 bolted connections of A440 steel. The fatigue diagram is a plot of maximum versus minimum net section stresses to cause failure at a specified location and the occurrence of fretting damage. Numerous studies have shown that high strength quenched and tempered steels are more notch sensitive in fatigue than lower strength steels.

FIG. 7.—FATIGUE DIAGRAM—COMPARISON OF TEST RESULTS AND AISC SPECIFICATIONS (A440 STEEL IN A325 BOLTED CONNECTIONS)

<table>
<thead>
<tr>
<th>Loading Condition</th>
<th>Number of Loading Cycles</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>20,000 to 100,000</td>
</tr>
<tr>
<td>2</td>
<td>100,000 to 500,000</td>
</tr>
<tr>
<td>3</td>
<td>500,000 to 2,000,000</td>
</tr>
<tr>
<td>4</td>
<td>Over 2,000,000</td>
</tr>
</tbody>
</table>

FIG. 6.—FATIGUE FRACTURES OF A440 STEEL IN BOLTED CONNECTIONS: (a) LOCATION OF FATIGUE CRACKS AND FRACTURES; (b) VIEW OF SPECIMEN L3B-7; (c) VIEW OF SPECIMEN L4B-5; (d) VIEW OF SPECIMEN LAB-5-9

There seemed to be no significant difference between the L3B and the L4B series with regard to location of crack initiation. Examination of the average fatigue strengths of the zero-to-tension tests at 100,000 and 2,000,000 cycles (Tables 3 and 4) indicate an equivalent behavior at 2,000,000 cycles and slightly improved behavior for A490 bolted joints at 100,000 cycles. Although some error results from the natural scatter of the data, the steeper slope, k of the S-N curves for A490 bolted joints versus k for A325 bolted joints follows the trend of similar comparisons of A514 joints at stress ratios of -1 and 0.

With respect to the number of initiation points in an individual specimen, the A440 results differ from earlier A514 results (2). A514 steel showed in many instances, numerous (on the order of 5 or 6) initiations at the fracture surface while the A440 generally showed few initiations (on the order of 1 or 2).
in which parallel the experimental data in Fig. 7; \( R \) = the stress ratio and
\( f = \text{a constant for a particular design life, detail type, and material. Moreover, data for A36 and A514 steels in bolted connections have shown agreement with formulas in the form of Eq. 4.}

Another comparison of experimental fatigue data and design specifications is found in Fig. 8. Here the maximum net section stresses to cause failure in 2,000,000 cycles of full reversal loading in plain plates and bolted joints of the A36, A440 and A514 steel are compared to appropriate design recommendations for bolted joints from AASHO and AISC. The data for the bolted joints of A36 steel are for galvanized steel which was found to have equivalent fatigue performance to ungalvanized steel in bolted connections (3). The strength of a bolted joint has generally been shown to exceed that of a plain plate of the same material when a comparison is made on the basis of net section stress; this is the case with the A36 and A440 results but is not so for A514 steel. The lower strength of the A514 steel in connections (Fig. 8) is particularly evident in full-reversal loading; as previously stated, this is apparently related to the fatigue notch sensitivity of A514 steel. In the comparison of results and specifications for full reversal loading, the requirements of the AASHO and AISC specifications differ greatly. The AISC specifications are generally more conservative for full reversal than AASHO, especially for A514 steel.

Previous studies and the results contained herein indicate that permissible variations in proportioning and detailing can significantly affect the fatigue strength based on net section stress in bolted joints. Thus, a design specification based on net section stress should necessarily have a sufficiently large margin of safety to account for all such variations or be further complicated by special relationships to account for the effect of numerous connection parameters.

When a comparison is made of the results of this study and other results for high-strength low-alloy steels, such as those from Northwestern University reported by Hansen (5) and those obtained in Germany by Steinhart and Mohler (7), the fatigue data which show wide divergence on net section basis...
shows very good agreement based on gross section stress in Fig. 9. All specimens are butt type plate connections, however, the variations in material, T:S:B ratio, theoretical efficiency, net section geometry seem to cause no disagreement when the data are plotted on the basis of gross section stress. The zero-to-tension stress cycle was chosen for comparison here because it shows very good agreement based on gross section stress in Fig. 9. All specimens are butt type plate connections, however, the variations in material, T:S:B ratio, theoretical efficiency, net section geometry seem to cause no disagreement when the data are plotted on the basis of gross section stress.

CONCLUSIONS

This investigation has provided quantitative information on the fatigue performance of high-strength low-alloy steel in high strength bolted structural connections. The conclusions presented herein are based on the results of constant amplitude fatigue tests and comparisons of these results with those for tests of other steels of higher and lower ultimate strengths:

1. Tests of high strength steel in bolted joints reported herein show improved fatigue strength compared to similar tests of structural steel (A36). Also, the results indicate that the high strength steel (yield stress ≈ 50 ksi) slightly exceeds the high strength quenched and tempered alloy steel (A514) in fatigue strength at long life (approximately 2 million cycles) and reversal loading ($R = 0$).

2. High strength steel (A440) whether fastened with A325 or A490 bolts showed comparable fatigue performance at long lives (approximately 2,000,000 cycles) under zero-to-tension loading; an improvement in performance of A440 steel in A490 joints was indicated at lower fatigue lives (approximately 200,000 cycles).

3. Clean dry mill scale surfaces of A440 steel exhibited low values of frictional resistance ($\mu = 0.18$) compared to the value of $\mu = 0.35$ assumed in specifications (9).

4. A comparison of a variety of fatigue tests of high strength steel in bolted connections from three independent sources, suggests that the fatigue life of steel plate in bolted connections is a function of gross section rather than net section stress.

ACKNOWLEDGMENTS

The study reported herein is part of a research investigation on the fatigue strength of high strength steels being conducted in the Structural Engineering Laboratory of the Civil Engineering Department, at the University of Illinois in Urbana, Illinois. The investigation constitutes a part of the structural research program of the Department of Civil Engineering under the general direction of N. M. Newmark, Head of the Department, and was sponsored by the Research Council on Riveted and Bolted Structural Joints under the Chairmanship of J. L. Rumpf.

The writers wish to express their appreciation to W. H. Munse, general supervisor of this research project and many other staff members at the University who have assisted in the conduct of this investigation and also to the many members of the Research Council on Riveted and Bolted Structural Joints, whose helpful comments and suggestions have made possible the development and conduct of this investigation.

APPENDIX I.—REFERENCES


APPENDIX II.—NOTATION

The following symbols are used in this paper:

- $d =$ nominal bolt diameter;
- $F =$ allowable fatigue stress;
- $F_n =$ fatigue strength at $n$ cycles or maximum stress that can be expected to cause failure at $n$ cycles of loading;
\( g \) = transverse spacing (gage) of two consecutive holes;
\( k \) = slope of empirical straight line relating maximum stress and number of cycles to failure on log-log plot;
\( m \) = number of shear planes in joint;
\( N, n \) = number of complete cycles of repeated loading to failure;
\( n_f \) = number of fasteners in joint;
\( P_s \) = load causing slip of bolted joint;
\( R \) = algebraic ratio of minimum to maximum stress;
\( S_N \) = stress corresponding to failure at \( N \) cycles on empirical curve;
\( T_b \) = average bolt tension at time of installation;
\( T:S:B \) = tension:shear:bearing ratio, ratio of the net section tensile stress to shear stress on cross-sectional area of bolts to nominal bearing stress; all are nominal stresses;
\( \epsilon \) = theoretical efficiency of joint; and
\( \mu \) = coefficient of slip.