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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

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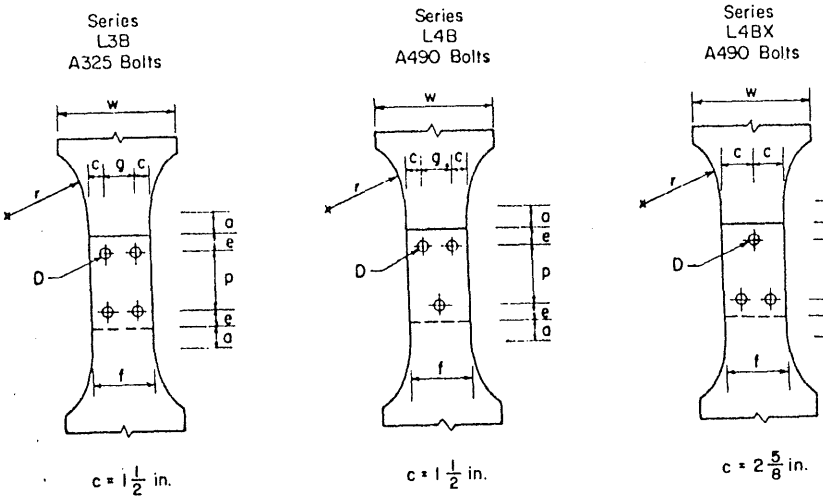
tests thus provide an indication of the fatigue performance of high-strength low-alloy steels in bolted connections (using either ASTM A325 or A490 bolts).

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 Specification for Structural Joints Using ASTM A325 or A409 Bolts. Current specifications (1966) reduce the allowable stress for A490 fasteners to 20 ksi (9). The design stress for the center plate was selected to be the maximum basic tensile stress which might be employed in structural design using A440 steel. In an attempt to keep the geometry at the critical section the same for the two series mentioned, a four-bolt A325 joint (L3B) and a three-bolt A490 joint (L4B) resulted and are shown in Fig. 1.



Constant dimensions for all Series, in inches

e = $1\frac{1}{4}$ f = $5\frac{1}{4}$ g = $2\frac{1}{4}$ p = $4\frac{1}{2}$ D = $\frac{13}{16}$ — diameter of drilled hole

Center Plate Thickness = $\frac{1}{2}$, Lap Plate Thickness = $\frac{5}{16}$, w = 9 r = 6 a = $1\frac{1}{2}$

FIG. 1.—FATIGUE SPECIMEN DETAILS

Inadvertently several specimens from the L4B series were drilled with one hole at the critical net section instead of two, i.e., the three hole pattern was reversed. In this case the center plate remained critical; only the geometry at the net section and the net cross-sectional area were changed. Other studies have examined the effect of increasing the gage at the critical section. The L4BX series represents a similar change in geometry, but this change cannot be referred to as a change of gage. It can however be visualized as an increase in net section efficiency. (The theoretical efficiency is the ratio of the area of the net section to the area of the gross section expressed as a percentage.)

Materials.—ASTM A440 steel plates for the 1/2 in. center plates were obtained from two different heats. Several standard plate coupons were cut from the two heats and were tested in a universal testing machine in accordance with ASTM standards. An average static yield strength of 50.3 ksi and an average tensile strength of 87.0 ksi were obtained for the coupons cut from one of the heats; for the other heat of steel that was used, an average static yield strength of 48.2 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.

TABLE 1.—MECHANICAL PROPERTIES OF ASTM A440 STEEL

Heat number (1)	Thickness, in inches (2)	Mechanical Properties			
		Yield strength, in kips per square inch (3)	Tensile strength, in kips per square inch (4)	Elongation in 2 inches, as a percentage (5)	Reduction in area, as a percentage (6)
38L587	1/2	50.3	87.0	23.4	61.0
18L080	1/2	48.2	77.3	27.0	64.0

TABLE 2.—CHEMICAL COMPOSITION OF ASTM A440 STEEL

Heat number (1)	Chemical Composition, as a percentage					
	C (2)	*Mn* (3)	*Si* (4)	*P* (5)	*S* (6)	*Cu* (7)
38L587	0.23	1.60	0.04	0.020	0.023	0.14
18L080	0.20	1.50	0.03	0.026	0.023	0.15

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 34 (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 rough size and then milled to correct dimensions. All holes were match drilled directly to 13/16 in. Before assembly, the faying (contact) surfaces were cleaned with acetone to remove any cutting oil that remained from drilling and machining and also to provide a clean, dry mill scale surface. A hardened washer was used under tha nut in all connections. The bolts were installed using the turn-of-nut method; they were initially brought to a snug-tight condition by the application of about 75 ft-lb of torque (this corresponds to approximately 5 kips to 10 kips of bolt tension in 3/4-in. bolts). An additional half turn was applied to each nut to complete the installation. Bolt tension was monitored by means of elongation readings which were taken at various stages of installation and testing using a special extensometer.

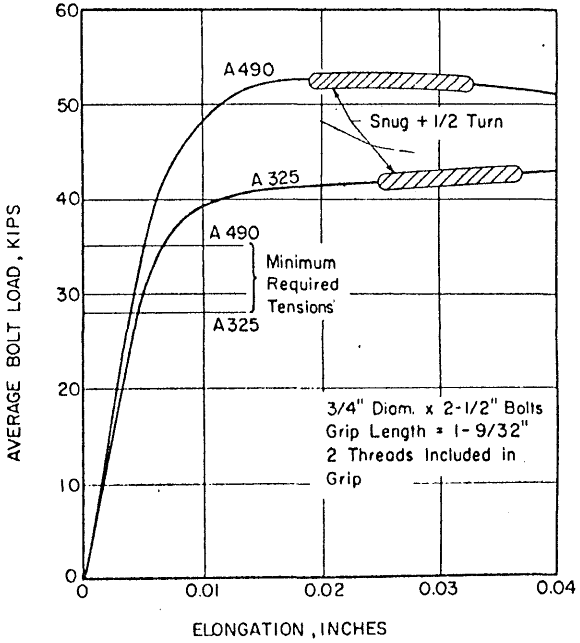


FIG. 2.—LOAD-ELONGATION BEHAVIOR FOR HIGH-STRENGTH BOLTS IN TORQUED TENSION

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 installation is known to produce bolt tensions that are 20 % to 30 % above the minimum requirements. The high bolt tensions obtained in this study are due largely to the short grip (1-9/32 in.) of the joint and small number of threads (2 threads) included in the grip. Similar observations have been made in other studies.

Equipment and Test Procedure.—All fatigue tests were performed on a 200 kip capacity constant amplitude Illinois' fatigue machine having a frequency of about 200 cycles per min. To measure the movement of the center plate relative to the side plates during the test a slip-measurement apparatus was mounted on each edge at the critical section of the joint. This consisted of a plastic lug glued to the center plate and a dial extensometer attached to the side plates.

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

$$F_n = S_N\left(\frac{N}{n}\right)^k \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

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, μ, a measure of frictional resistance. This coefficient was calculated using the following

$$\mu = \frac{P_s}{n_f\, m\, T_b} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

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 4.—RESULTS OF FATIGUE TESTS ON A440 STEEL JOINTS USING A490 BOLTS[a]

Specimen number (1)	Stress cycle on net section, in kips per square inch (2)	Cycles to failure, in thousands (3)	Computed Fatigue Strength, in kips per square inch[c] (4)	(5)	Average initial bolt tension, in kips (6)	Coefficient of slip[d] (7)
L4B-1	0 to +50.0	790	73.7	41.8	54.3	0.20
L4B-2	0 to +50.0	920	75.7	43.2	53.8	0.22
L4B-3	0 to +65.0	154	70.5	40.3	54.2	0.19
L4B-4	0 to +65.0	248	77.1	44.0	52.8	0.20
L4B-5	0 to +43.0	4,000[e]	75.2	43.0	54.0	0.18
			Average 74.4	42.5		
L4B-13[b]	-28.0 to +28.0	1,365			54.2	—
L4B-14[b]	-28.0 to +28.0	1,038			54.2	—

[a] $T:S:B$ = 1.00: 0.69: 1.61, g/d = 3.0.
[b] Specimens from Heat No. 18L080; others from Heat No. 38L587.
[c] Fatigue strengths computed using $F_n = S_N (N/n)^k$, (k = 0.187).
[d] Absence of coefficient of slip indicates that the specimen did not slip as a result of the applied load.
[e] Specimen did not fail; on increasing the stress cycle to 0 ksi to 65.0 ksi it failed after 253,100 cycles.

TABLE 5.—RESULTS OF FATIGUE TESTS ON A440 STEEL JOINTS USING A490 BOLTS[a]—VARIATION OF JOINT EFFICIENCY

Specimen number[b] (1)	Stress cycle on net section, in kips per square inch (2)	Cycles to failure, in thousands (3)	Computed Fatigue Strength, in kips per square inch[c] $F_{100,000}$ (4)	$F_{1,000,000}$ (5)	Average initial bolt tension, in kips (6)	Coefficient of slip[d] (7)
L4BX-6	0 to +50.0	158	52.6	37.6	54.2	0.16
L4BX-7	0 to +37.0	930	47.6	34.0	54.0	0.16
L4BX-10	0 to +50.0	32	44.0	31.4	54.3	0.16
L4BX-11	0 to +34.5	1,494[e]	46.0	32.8	54.3	0.18
L4BX-12	0 to +34.5	1,049[e]	46.4	32.0	54.3	0.19
			Average 47.3	33.6		
L4BX-8	-22.6 to +22.6	1,147			54.3	
L4BX-9	-21.0 to +21.0	1,802			54.2	

[a] $T:S:B$ = 1.00: 0.84: 1.97.
[b] All specimens from Heat No. 18L080.
[c] Fatigue strengths computed using $F_n = S_N (N/n)^k$, (k = 0.113).
[d] Absence of coefficient of slip indicates that the joint did not slip as a result of the applied load.
[e] Failure did not occur in the joint.

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-

in which P_s = load causing slip in the bolted joint; T_b = the average bolt tension at installation; n_f = number of fasteners in the joint; and m = the number of shear planes in the joint.

FATIGUE BEHAVIOR OF BOLTED CONNECTIONS

Basic Series.—A total of 19 connections of the basic configurations (12 with A325 and 7 with A490 bolts) were tested. Since stress cycles from zero-to-tension through complete reversal provide the most severe constant amplitude fatigue loading, most specimens were tested at stress ratios of -1 and 0. Attempts to obtain short life conditions in full reversal were unsuccessful because of slip in the joints; the clean mill scale surfaces had very low frictional resistance as evidenced from the values of coefficient of slip which are presented in Tables 3, 4, and 5 with the fatigue results. The value of μ obtained for this steel is only 1/2 of that normally assumed (μ = 0.35) for joints having mill scale surfaces. Therefore, rather than test at loads which would cause continual slip reversal, the stress ratio for some tests was changed to -1/2, i.e., compression-to-tension; although these specimens slipped once on first loading in tension they did not slip subsequently.

TABLE 3.—RESULTS OF FATIGUE TESTS ON A440 STEEL JOINTS USING A325 BOLTS[a]

Specimen number[b] (1)	Stress cycle on net section, in kips per square inch (2)	Cycles to failure, in thousands (3)	Computed Fatigue Strength, in kips per square inch[c] $F_{100,000}$ (4)	$F_{1,000,000}$ (5)	Average initial bolt tension, in kips (6)	Coefficient of slip[d] (7)
L3B-10	0 to +50.0	588[e]	66.1	41.3	43.4	0.16
L3B-1	0 to +50.0	562	65.6	41.0	43.7	
L3B-2	0 to +60.0	192	66.5	41.5	43.9	0.16
L3B-3	0 to +60.0	250	69.3	43.3	43.8	0.17
L3B-4	0 to +40.0	2,499[f]	66.2	41.4	43.9	0.16
L3B-6	0 to +42.0	2,582	70.0	43.7	43.4	0.16
			Average 67.3	42.0		
L3B-5	-28.0 to +28.0	1,420			43.7	
L3B-7	-28.0 to +28.0	1,234			43.9	
L3B-11	-28.0 to +56.0	25			43.8	0.18
L3B-12	-24.0 to +48.0	197			43.8	0.18
L3B-8	+34.7 to +69.3	529			43.7	0.19
L3B-9	+34.7 to +69.3	811			43.7	0.17

[a] $T:S:B$ = 1.00: 0.51: 1.21, g/d = 3.0.
[b] All specimens from Heat No. 38L587.
[c] Fatigue strengths computed using $F_n = S_N (N/n)^k$, (k = 0.157).
[d] Absence of coefficient of slip indicates that the joint did not slip as a result of the applied load with the exception of specimen L3B-1 for which the slip load was not recorded.
[e] Failure did not occur in the joint.
[f] Specimen did not fail; on increasing the stress cycle to 0 to 67.5 ksi, it failed after 2,500 cycles.

Figures 3 and 4 show graphically the data obtained from the fatigue tests in the basic series. It is evident that for the zero-to-tension results which predominate, the log S versus log N curve (Eq. 1) provides a good approximation of the data. The dashed lines in Figs. 3 and 4 are approximately the way curves for other stress ratios would be expected to look based on the limited data and experience with test results for other steels in similar bolted connections.

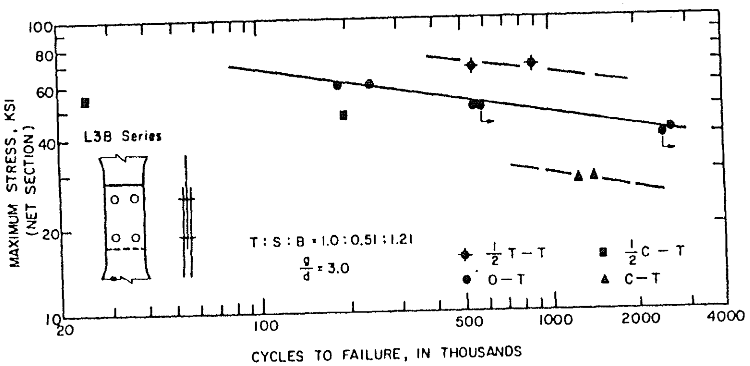


FIG. 3.—FATIGUE TESTS ON A440 STEEL IN CONNECTIONS USING A325 BOLTS (NET SECTION STRESS)

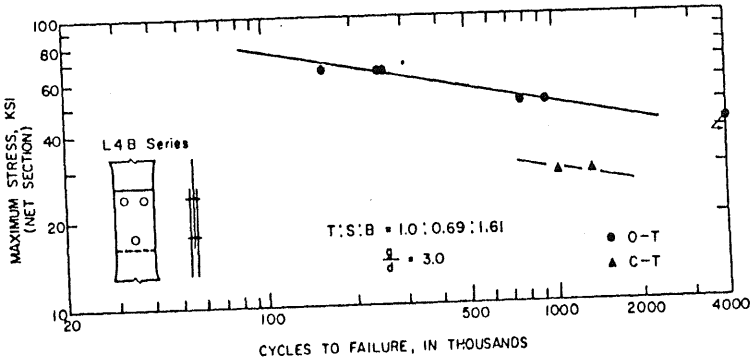


FIG. 4.—FATIGUE TESTS ON A440 STEEL IN CONNECTIONS USING A490 BOLTS (NET SECTION STRESSES)

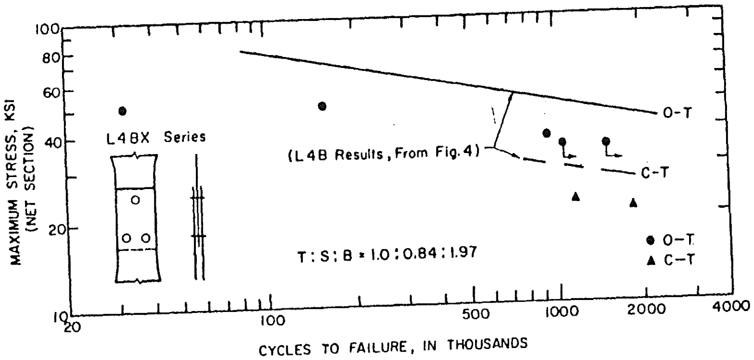


FIG. 5.—INFLUENCE OF VARIATIONS IN CONNECTION DETAILS AND PROPORTIONS—A440 CONNECTIONS USING A490 BOLTS (NET SECTION STRESSES)

proximately related to the theoretical efficiency, ϵ, by

$$\epsilon \cong 1 - \frac{1}{\left(\frac{g}{d}\right)} \quad \text{. . . . .} \quad (3)$$

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 plate 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 the plate surface approximately 1/2 the hole diameter in width, surrounding the holes. This shiny region which records as black on the photograph is mill scale which has been polished as a result of relative movement of the contacting plates in the region of very high contact pressure. Fretting or rubbing of the plates at the boundary of this region appears to be a prime factor contributing to crack initiation in steel connected by high strength bolts.

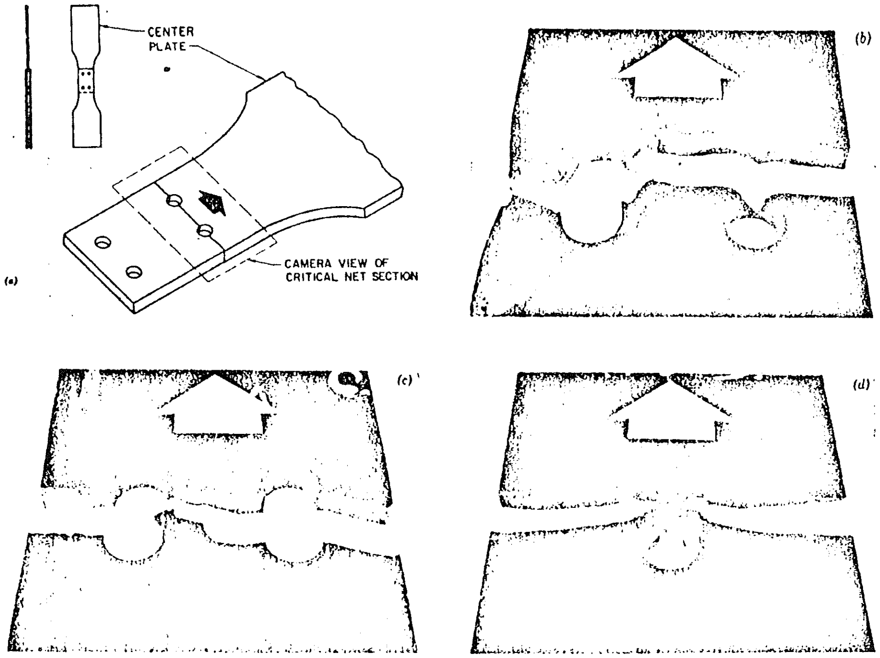


FIG. 6.—FATIGUE FRACTURES OF A440 STEEL IN BOLTED CONNECTIONS: (a) LOCATION OF FATIGUE CRACKS AND FRACTURES; (b) VIEW OF SPECIMEN L3B-7; (c) VIEW OF SPECIMEN L4B-5; (d) VIEW OF SPECIMEN L4BX-9

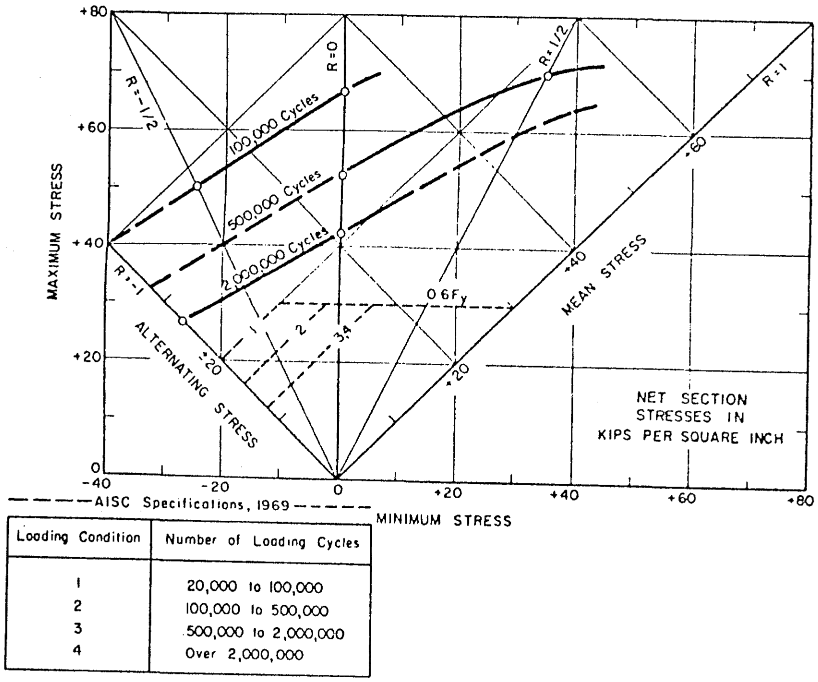
There seemed to be no significant difference between the L3B and the L4B series with regard to location of crack initiation. Examination of the average fatigue strengths of the zero-to-tension tests at 100,000 and 2,000,000 cycles (Tables 3 and 4) indicate an equivalent behavior at 2,000,000 cycles and 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).

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).



Loading Condition	Number of Loading Cycles
1	20,000 to 100,000
2	100,000 to 500,000
3	500,000 to 2,000,000
4	Over 2,000,000

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

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 number of cycles. Data points taken from Fig. 3 are indicated in the figure; curves are shown dashed where there is no supporting data. Superimposed on the fatigue diagram are the new AISC (1969) allowable stresses for bolted steel having a yield point of 50 ksi. These new provisions base design on the range of stress and not the stress ratio and maximum stress as was previously done. The result is a design process which is somewhat simplified. Note that the allowable stress curves do not parallel the experimental curves although they do show a margin of safety in all cases. An allowable stress formula which is similar to that used by AASHO is

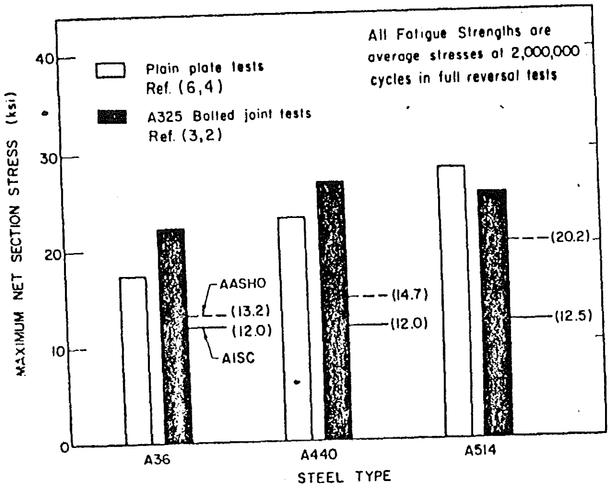


FIG. 8.—COMPARISON OF FATIGUE STRENGTHS OF VARIOUS STEELS AND DESIGN SPECIFICATIONS—FULL REVERSAL LOADING

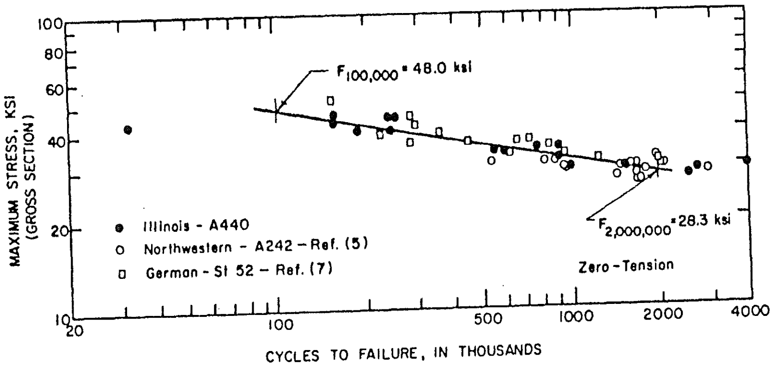


FIG. 9.—COMPARISON OF FATIGUE DATA FOR HIGH-STRENGTH STEELS IN VARIETY OF BOLTED CONNECTIONS (GROSS SECTION STRESSES)

$$F = \frac{f}{1 - 0.6R} \quad \text{. . . . .} \quad (4)$$

in which parallel the experimental data in Fig. 7: R = the stress ratio and f = 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.

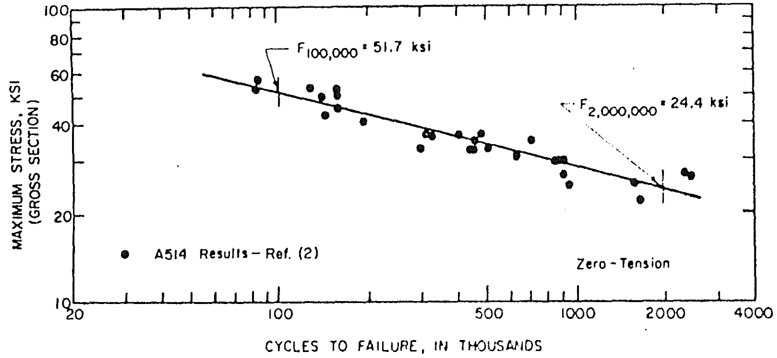


FIG. 10.—FATIGUE RESULTS FOR A514 STEEL IN BOLTED CONNECTIONS HAVING VARIETY OF DETAILS AND ASSEMBLY PRACTICE (GROSS SECTION STRESSES)

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 Steinhardt 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 more data were available. Further evidence of the role of gross section stress as an indication of the fatigue strength of bolted joints is presented in Fig. 10. Fatigue data for A514 steel in bolted connections (2) which includes tests of a variety of details and assembly practice show little scatter when the maximum gross section stress is plotted versus cycles to failure. Note also in Figs. 8, 9, and 10, that the average fatigue strength at 2,000,000 cycles for the high strength steel A440 slightly exceeds that of the quenched and tempered alloy steel (A514).

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 $\cong$ 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 ($R \leq 0$).
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 ($\mu \cong 0.18$) 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.

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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;
ϵ = theoretical efficiency of joint; and
μ = coefficient of slip.