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16. Abstract

This is the second and final report of an experimental investigation sponsored by the Texas Department of Highways and Public Transportation to determine the behavior of steel anchor bolts. One hundred and eight specimens were tested under fatigue and static loading. The parameters examined in the fatigue tests were

(1) Strength of steel (F_y = 27 to 171 ksi)
(2) Thread size or pitch (4-1/2, 6, 8 threads/in.)
(3) Bolt diameter (1-3/8", 1-3/4" and 2")
(4) Method of forming threads (rolled and cut)
(5) Galvanizing
(6) Double nuts

A summary of the tests results is presented and the effect of these parameters is analyzed. The stress corrosion behavior of anchor bolts was also investigated in laboratory and field environments.

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FATIGUE OF ANCHOR BOLTS

by

Karl H. Frank

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Research Project 3-5-75-172

conducted for

Texas
State Department of Highways and Public Transportation

In Cooperation with the
U. S. Department of Transportation
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by the

CENTER FOR HIGHWAY RESEARCH
THE UNIVERSITY OF TEXAS AT AUSTIN

July 1978

The contents of this report reflect the views of the authors who are responsible for the facts and accuracy of the data presented herein. The contents do not necessarily reflect the views or policies of the Federal Highway Administration. This report does not constitute a standard, specification or regulation.

There was no invention or discovery conceived or first actually reduced to practice in the course of or under this contract, including any art, method, process, machine, manufacture, design or composition of matter, or any new and useful improvement thereof, or any variety of plant which is or may be patentable under the patent laws of the United States of America or any foreign country.

S U M M A R Y

This is the second and final report of an experimental investigation sponsored by the Texas Department of Highways and Public Transportation to determine the behavior of steel anchor bolts. One hundred and eighty specimens were tested under fatigue and static loading. The parameters examined in the fatigue tests were

(1) Strength of steel (F_y = 27 to 171 ksi)
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(3) Bolt diameter (1-3/8", 1-3/4" and 2")
(4) Method of forming threads (rolled and cut)
(5) Galvanizing
(6) Double nuts

A summary of the tests results is presented and the effect of these parameters is analyzed. The stress corrosion behavior of anchor bolts was also investigated in laboratory and field environments.

The fatigue tests and analysis of others' data showed that type of steel, thread size, bolt diameter, galvanizing, and method of forming the threads were not significant for design purposes. The lower bound to the stress range-fatigue life relationship for anchor bolts with single nuts and anchor bolts with loose double nuts (one above and below the base plate) was given by the AASHTO Fatigue Category E allowable stresses.

Double nut anchor bolts tightened to 1/3 of a turn past snug tight gave fatigue lives three times that of single nut anchor bolt. A similar fatigue performance was found for bolts in bending. For both of these type of specimens, the failure occurred outside of the connection. The lower bound to the fatigue strength for tight double nut anchor bolts in bending and tension was given by the AASHTO Fatigue Category C allowable stresses.

No evidence of stress corrosion cracking was found in the bolts tested. It is recommended, based on other tests of high strength bolts, that the maximum yield strength material used for anchor bolts be less than 125 ksi. This should insure that failures do not occur due to stress corrosion cracking in environments not tested.

The 8N constant thread pitch is recommended for anchor bolts greater than one inch diameter to facilitate tightening and to increase the tensile efficiency of the bolt.

IMPLEMENTATION

This report summarizes the fatigue and stress corrosion behavior of anchor bolts. The fatigue data generated was correlated with the AASHTO fatigue provisions. The design stress ranges for anchor bolts recommended are:

(1) Single nut anchor bolts and double nut base plate connection not tightened to 1/3 of a turn past snug tight should be designed using the Category E fatigue stress provision of the AASHTO specification.

(2) Double nut anchor bolts subjected to cyclic tension and bending stresses tightened to 1/3 of a turn past snug tight should be designed using the Category C fatigue stress provisions of the AASHTO specifications.

The bending and axial stress is to be calculated on the tensile stress area of the threaded portion of the bolt.

The following material specifications are recommended:

(1) All anchor bolts greater than one inch in diameter should be specified with an 8N-2 thread.

(2) The yield stress of anchor bolts should be less than 125 ksi.

(3) Galvanized anchor bolts which meet the ANSI uncoated thread tolerances may have their nuts tapped oversize to a maximum of 0.033 in.

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CHAPTER 1

INTRODUCTION

This is the second and final report of an experimental investigation of the behavior of steel anchor bolts. The behavior of anchor bolts used to anchor bridge elements, sign supports, luminaries, and other structures was examined under fatigue and static loading. One hundred and eighty specimens were tested. The details of the test results are given in the first report, ref. 1, and for the subsequent tests in the Appendices. This report summarizes the results of all the tests performed and the significance of the variables investigated. The last section of the report contains design fatigue stress and anchor bolt specification recommendations.

CHAPTER 2

TEST VARIABLES AND EXPERIMENTAL PROCEDURES

Four types of specimens were tested in this study. The majority of the specimens were bolts with a single nut tested in fatigue. Specimens with double nuts, one on each side of the loading plate, were tested to determine the fatigue behavior of typical base plate connections in axial tension. This base plate connection consisting of a leveling nut under the base plate and a nut on the top of the plate was also tested in bending to determine its fatigue strength. The stress corrosion cracking behavior of the anchor bolts was investigated in both laboratory and field environments using full size bolt specimens.

2.1 Axial Fatigue Tests

The variables examined to determine their influence on the axial fatigue strength of anchor bolts were:

(1) Strength of steel

(2) Thread size or pitch

(3) Bolt diameter

(4) Method of forming thread

(5) Galvanizing

(6) Double Nuts

Table 1 gives the specimen series and test variables included in the axial fatigue tests. The experiment design is shown in Table 2. The factorial experiment design allowed the effects of each variable to be directly determined. All specimens of the same diameter and steel strength were from the same heat of steel for all experiments. For example, the specimens in Series D, E and G were made from the same heat of round stock as are series A and DN. Therefore, the difference in the results among such series are not

TABLE 1. SPECIMEN SERIES AND TEST VARIABLES

Specimen	Steel Type	Yield Strength (ksi)	Bolt Diameter	Thread Series	Forming Method
A	A193 Gr. B7	115	1-3/8 in.	8N	Cut
B	A193 Gr. B7	110	1-3/4 in.	8N	Cut
C	4340	171	1-3/8 in.	8N	Cut
D (1)	A36	38.3	1-3/8 in.	6UNC	Cut
E	A36	38.3	1-3/8 in.	8N	Rolled
F (1)	A36	26.7	2 in.	4-1/2UNC	Cut
G	A36	38.3	1-3/8 in.	8N	Cut
H (1)	A36	26.7	2 in.	8N	Cut
DN (2)	A193 Gr. B7	110	1-3/4 in.	8N	Cut
BB (3)	A193 Gr. B7	115	1-3/8 in.	8N	Cut
BG (3)	A193 Gr. B7	115	1-3/8 in.	8N	Cut

[1]Hot Dipped Galvanized after threading

[2]Double nut specimens

[3]Bending specimens

TABLE 2. SINGLE NUT EXPERIMENT DESIGN

Stress Range (ksi)	Specimen Series							
	A	B	C	D	E	F	G	H
30	2*	2	2					
25				3	3	1	2	3
20	2	2	2	3	4	3	2	
15					1		1	1
10	2	2	2	2	2	2	2	2

*Number of specimens tested at level of stress range.

due to variation in the steels. The controlled variable used in all the axial fatigue tests was the stress range on the tensile stress area of the threaded portion of the bolt. The tensile stress area is given by the equation:

$$A_T = \pi/4 \left(D - \frac{0.9743}{n}\right)^2 \qquad (1)$$

where D = major diameter of the bolt thread and

n = the number of threads per inch.[2]

Static strength tests were performed on the fatigue specimens to determine the correlation between the tensile properties measured in standard materials tension tests and those obtained from the full size threaded bars. All of the full size bars failed in the section of the bar reduced by the threading operation and not in the nut. The results showed that the yield and ultimate load of the full size threaded bars could be estimated using the strength measured in the standard tensile specimens times the tensile stress area.

The maximum stress on the tensile stress area for all the axial tests was constant for a particular material and equal to 75 percent of the nominal specified minimum yield strength of the steel. The yield strength used was 150 ksi for the 4340, 105 ksi for the A193 Gr. B7 and 36 ksi for the A36 steel.

The specimens were purchased on the open market and were ordered to a class 2 fit for the threads.[2] The dimensions of the basic specimen are shown in Fig. 1 and the method of loading for the single nut specimens is shown in Fig. 2. The double nut specimens were loaded in a similar manner with the addition of a nut on the inside of each bearing plate.

The effect of tightening of the outer nut before applications of the cyclic fatigue was examined in the double nut specimens. The tightening of the nuts at each end of a specimen was varied from 200 ft-lbs of torque to 1/6 and 1/3 of a turn past the snug position. The latter tightening was done with an air-powered impact wrench.

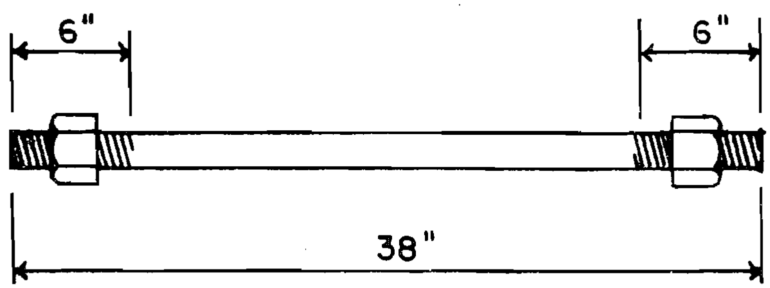

Fig. 1. Basic Test Specimen.

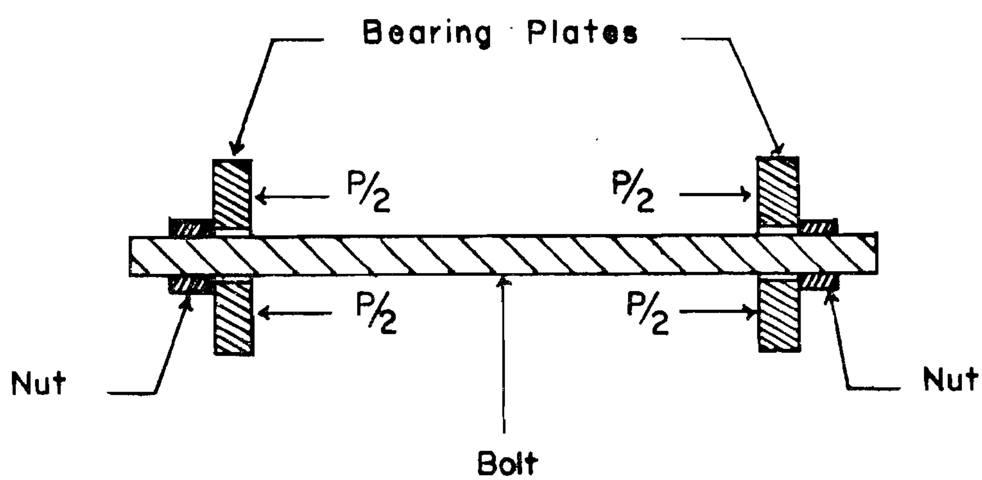

Fig. 2. Specimen Loading Geometry.

The specimens were placed through the center of a 200-ton center hole hydraulic ram which was connected to a Rhiele-Los Pulsator. The pulsator supplied a sinousoidal cyclic pressure to the ram. The testing frequency varied with each specimen from 7 to 9 Hz. The loading apparatus is shown in Fig. 3.

Each specimen was strain gaged in the center unthreaded portion of the bar to determine the applied stress range and maximum stress in the specimen under cyclic load. The strains were measured during the test with amplitude measurement system. This system enabled the pulsator to be adjusted to produce the desired stress within ± 1%.

2.2 Bending Fatigue Tests

All anchor bolts in this study were approximately 16 in. long, with a threaded section on one end, and supplied with two nuts, as shown in Fig. 4. These units were tested as shown in Fig. 5. This testing apparatus provided a linearly increasing moment along the specimen from the loading point to the connection with the plate. This specimen configuration was selected because of the ease of fabrication and testing. Also, it could simulate the actual bolt connection by letting the load point represent the point of inflection occurring between the base plate and the foundation. The specimens were fabricated from the same A193 Gr. B7 material 1-3/8 in. diameter as Series A.

Special attention was given to the cutting of 8N threads on the specimens to realistically simulate the type of thread normally found on anchor bolts in actual construction. Typical practice for threading anchor bolts is to use a die of the correct size, and turn it down the bar the required amount, automatically cutting the threads. This leaves a transition at the termination of the threads. This transition leaves a sharp notch adjacent to a region of smooth bar, and it is this notch which has shown to be a stress concentration important in the initiation of fatigue cracks. Since specimens for these tests were threaded on a lathe, this transition was formed by backing out the cutting tool completely in three-quarters revolution

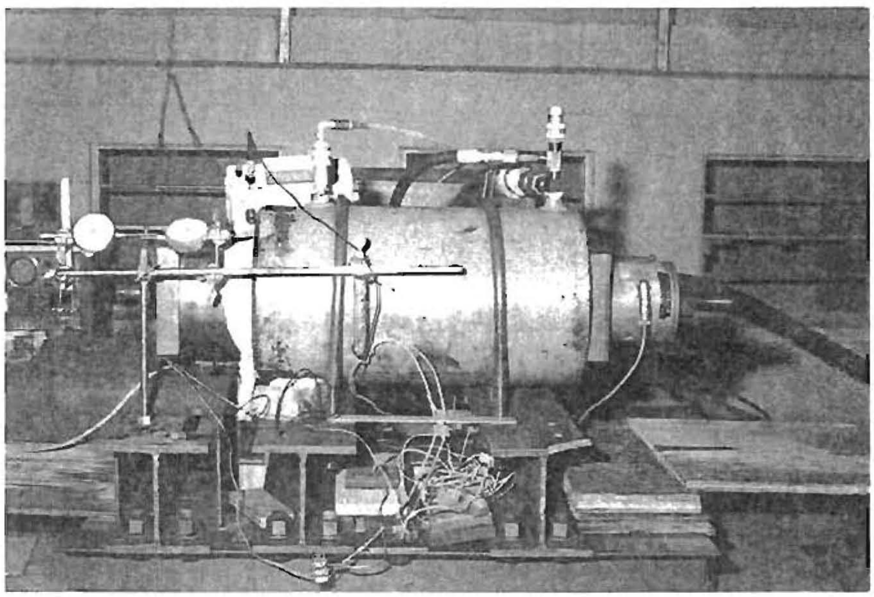

Fig. 3 Axial Fatigue Test Setup

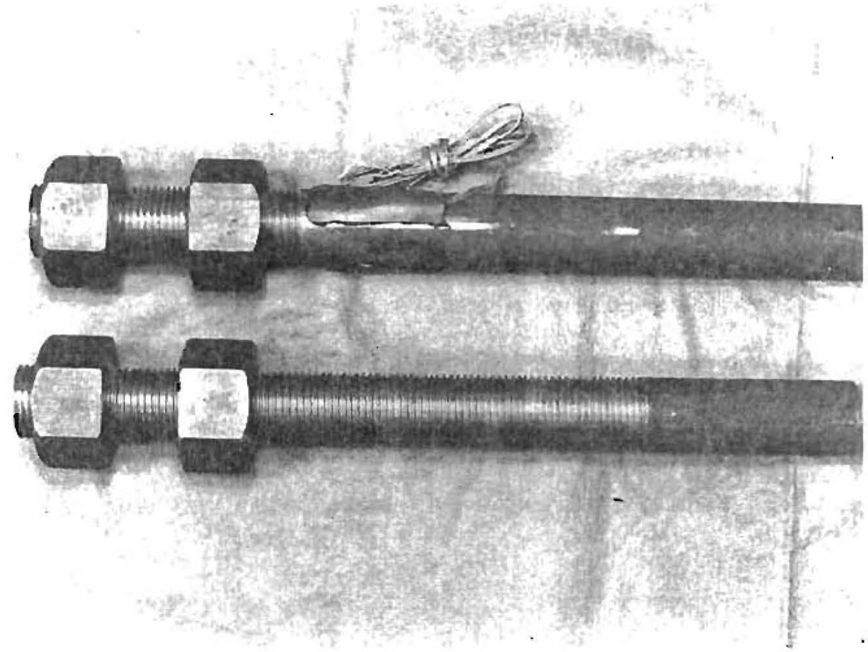

Fig. 4 Bending Fatigue Specimens

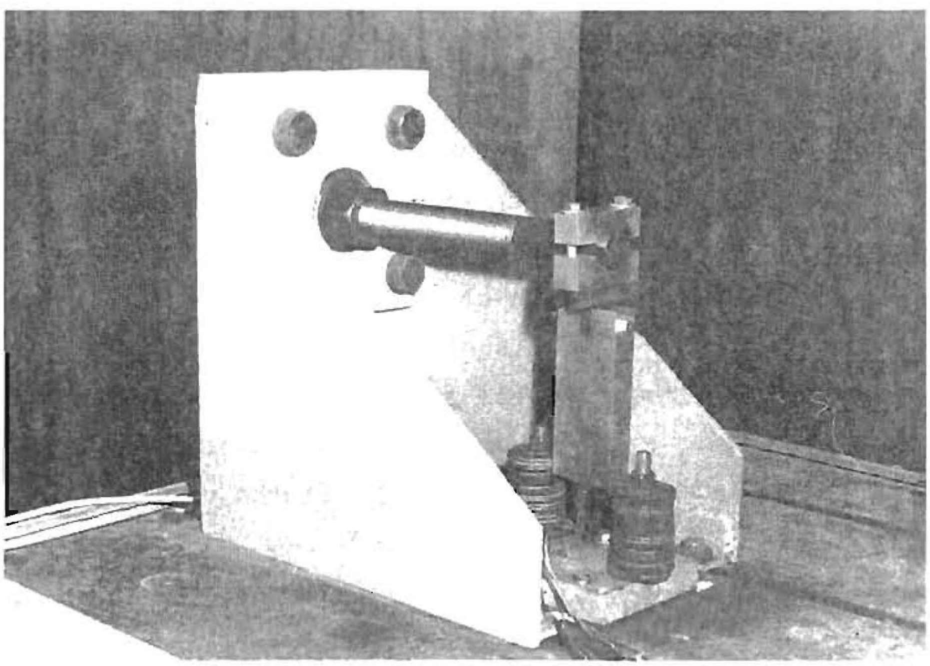

Fig. 5 Bending Fatigue Test Setup

of the bar. This transition modeled the die-cut threads and the resulting threads were very close to what would be expected from a commercial supplier. Thread measurements of all bars showed them to be within ANSI[3] standards for a Class 2A fit.

The specimens were tested as cantilever beams. This gave the desired moment gradient and proved to be the most efficient means of utilizing the loading machine. A Sonntag universal fatigue loading machine provided the loading. This machine uses a rotating shaft with an eccentric weight to excite a spring-mass system to resonance, which then applied a sinusoidal cyclic loading pattern. The machine also has a manual jack which compresses the springs to allow the mean load to be adjusted to any given level. This enables the fluctuating load to remain the the same direction. Testing frequency was constant at 30 Hz.

The loading frame, as shown in Fig. 5, was composed of a main vertical plate and two side plates used to mount the vertical plate to the bed of the testing machine. The specimens were mounted to this main plate with two nuts, in the same way they would be attached to the base plate of a structure. The frame was positioned to bring the end of the specimen directly above the loading platen of the test machine. The link used to transfer load from the platen to the specimen was designed to act as a rigid bar hinged on both ends. A knife-edge was used on the upper end of this link. The upper half of the knife edge was clamped to the end of the specimen. The lower end of the link was reduced in cross section to lower its flexural stiffness, providing a hinge.

The specimens and the loading link were strain gaged to monitor the load in the specimen. The output of these were measured in the amplitude measuring module. The loads were set to produce strain ranges within ± 1 percent of desired. The output of the link and specimen gages were correlated to allow the loads of some of the G specimens to be determined without the mounting of gages on the threaded test section of the bar. On selected specimens, gages were mounted between the nuts holding the bars to the support plate to determine the bending moment in the connection. The stress in the threaded part of the specimen was calculated using the diameter, D_t, corresponding to the tensile stress area

$$D_t = (D - 0.9743/n). \tag{2}$$

Preliminary tests had indicated that failures were most likely to occur outside of the joint. Therefore, two different configurations of specimens were designed to allow investigation of this. These specimens are described as follows, and are shown in Fig. 4.

B-specimens: These specimens had threads extending only 2 in. from the face of the mounting plate. This placed the first cut thread in a region of comparatively high moment. This location then proved to be the critical location for fatigue crack initiation and growth, with all but one specimen of this type failing at this location.

G-specimens: These specimens had threads extending 10 in. from the mounting plate. This placed the first cut thread in a region of low moment, and forced the fatigue cracks to initiate in the root of one of the threads near the nut, from which it then propagated.

2.3 Stress Corrosion Tests

Stress corrosion cracking is the term given to cracking of a material under the application of a static or constant stress in the presence of an aggressive environment. The life of a particular steel in an environment which causes cracking is inversely proportional to the applied stress and the severity of the stress concentrations present in the specimen. High strength bolts have been found to be susceptible to cracking in the presence of salt water if they are above a certain strength level.[4] Typically, for a particular alloy steel, the higher the strength level of steel the more susceptible they become to stress corrosion cracking.

Bolts from Series A, B, C, D and F were tested to determine their stress corrosion behavior. They were tested in four environments, two laboratory and two field environments, and at two applied stress levels. The two laboratory environments were distilled water and 3.5% Sodium Chloride salt water solution. The specimens were subjected to a continuous exposure cycle of 5 min. in the solutions and 55 min. in air for 6,000 hours. The specimens were inspected before the tests, during the tests and after the tests ultrasonically using the techniques covered in ref. 1.

The two field environments selected were the Houston Ship Channel and the Aransas Pass Ferry slip. These locations were selected since they provided a typical industrial location with its attendant airborne pollutants and a salt spray seashore location. The specimens placed at these locations were inspected before placement and during their exposure. These field tests are still continuing.

Table 3 shows the experiment design used in these tests. Two replicate specimens were tested at each condition. The stressing levels were based on the nominal yield strength of the material, F_y, and were equal to F_y and 3/4 F_y on the tensile stress area of the bolt. The specimens consisted of threaded section of the material bolted by two nuts to a two-inch thick A36 steel plate. Figure 6 shows the plates and a stressed specimen in the bottom near corner. Each plate contained four bolts from one series of specimens. Two of the bolts were stressed to F_y and two to 3/4 F_y in each plate. The bolts were strain gaged in the area between the nuts to measure the stress level. The strain gages were calibrated using the hydraulic ram shown in Fig. 6. After the force strain calibration was determined, the nuts were tightened to the desired force level as indicated by the strain gages. The long unthreaded portion of the bar was then removed by cutting with a saw. Figure 7 shows a close-up of the end of the plate. The lower left specimen has been stressed. Each plate was notched as shown on both sides to allow access of the environment to the bolt between the plates.

TABLE 3. STRESS CORROSION EXPERIMENT FOR EACH ENVIRONMENT

Stress Level	Series				
	A	B	C	D	F
F_y [2]	2[1]	2	2	2	2
3/4 F_y	2	2	2	2	2

[1] Number of specimens tested at this condition

[2] F_y = minimum specified yield strength

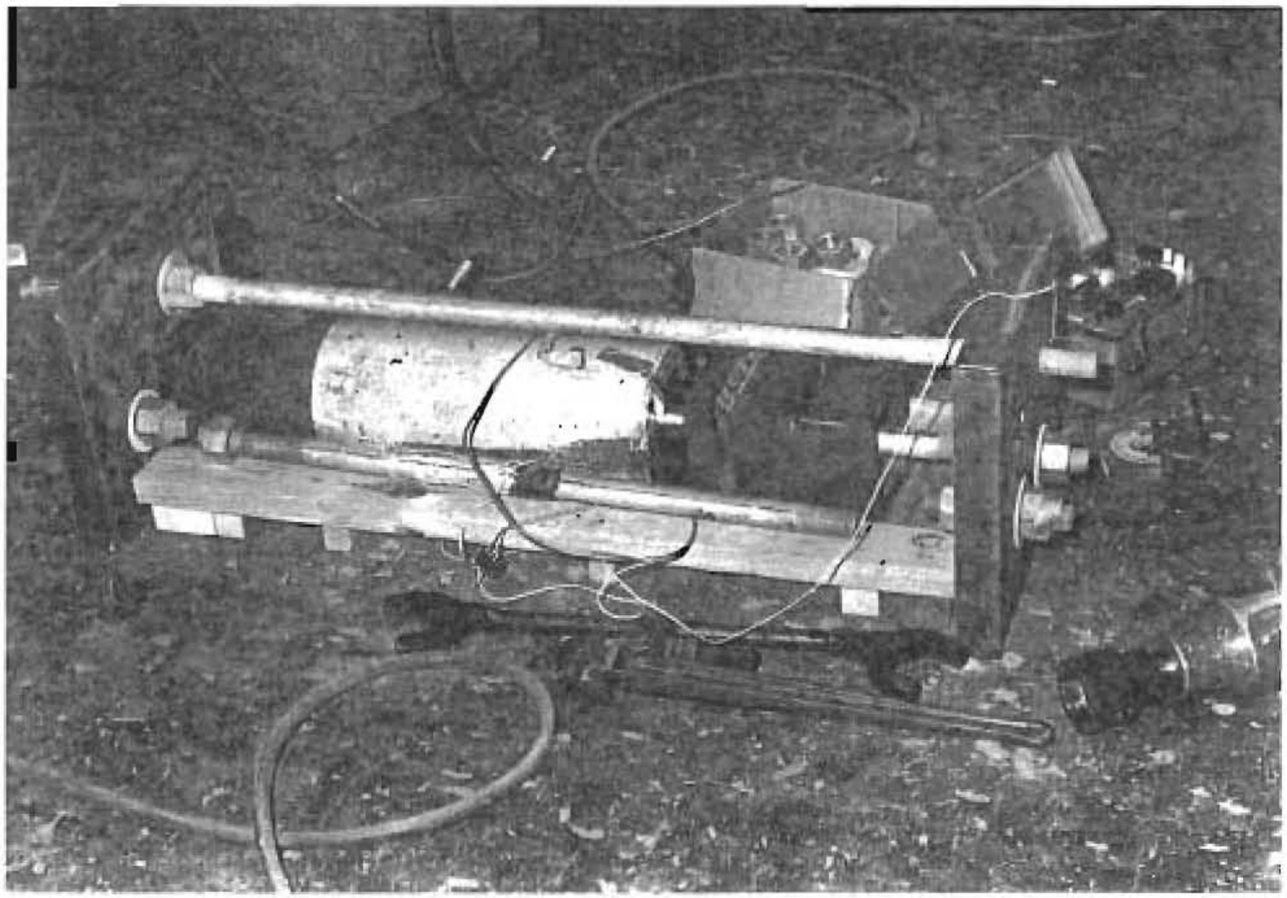

Fig. 6 Stress Corrosion Stressing Setup

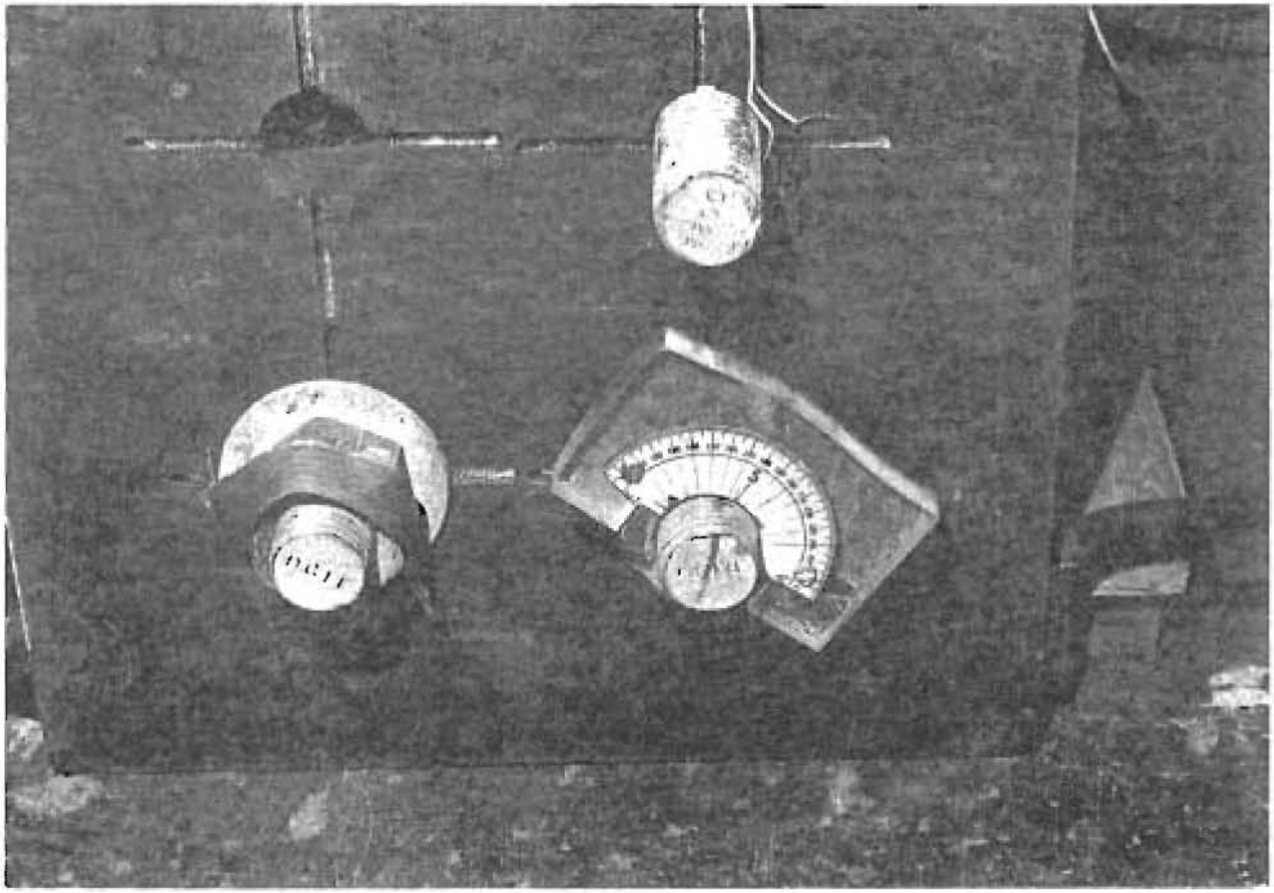

Fig. 7 Stress Corrosion Specimen and Mounting Plate

CHAPTER 3

TEST RESULTS AND INTERPRETATION

3.1 Axial Fatigue Tests

Three failure modes were observed in these tests. Fig. 8 shows the three crack locations corresponding to these modes. In the single nut fatigue tests all of the high strength specimens, Series A, B and C; and Series E and G of A36 steel, failed from cracks which initiated at the root of the first engaged thread in the nut, location 1 in Fig. 8. Specimen in Series D, G and H exhibited a multiple cracking mode as shown by location 2 in Fig. 8. The first crack to form in these specimens was in the back half of the nut as indicated in Fig. 9. This crack would extend by fatigue until a second crack ahead of it towards the stressed end of the bolt would form. This process of cracking would continue until a crack would be generated near the first thread in the nut and lead to failure of the specimen. Typical fracture surfaces of the test specimens are shown in Fig. 10.

The double nutted specimens exhibited cracking at location 1, the first engaged thread of the outside nut, and at location 3, the first engaged thread of the interior nut. The double nut connections tightened to 1/3 of a turn all failed at location 3 outside of the connection.

The failure of the specimens at the first thread in the nut would be expected in the single nut connections. The thread shear, as shown in Fig. 11, is highest at this location as is the axial force in the bolt. The highest thread root stress consequently occurs at this location. The multiple cracking behavior exhibited by the D, G and H specimens would suggest that thread shear distribution was such that the maximum thread shear and the major part of the load transfer between the nut and bolt occurred in the last half

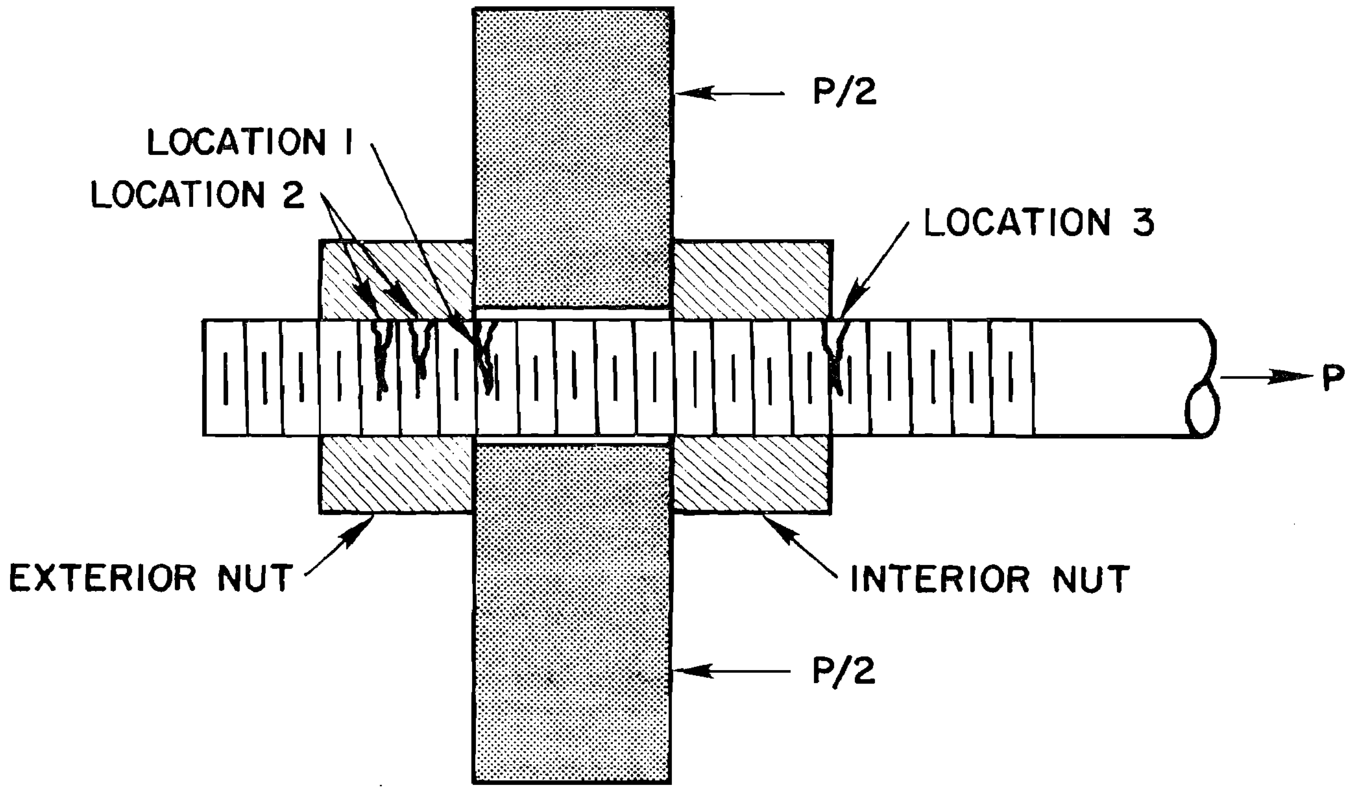

Fig. 8 Fatigue Failure Locations

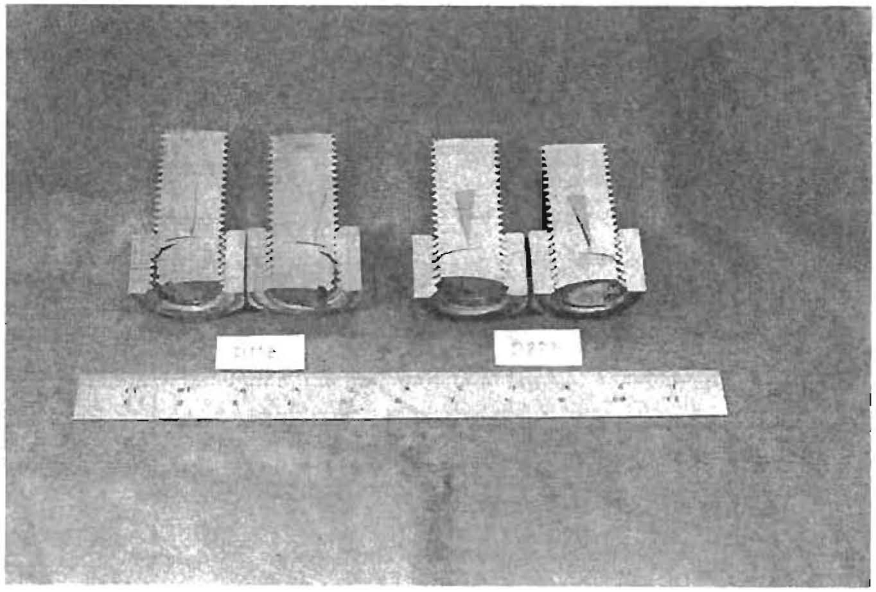

Fig. 9 Cross Section Showing Multiple Cracking

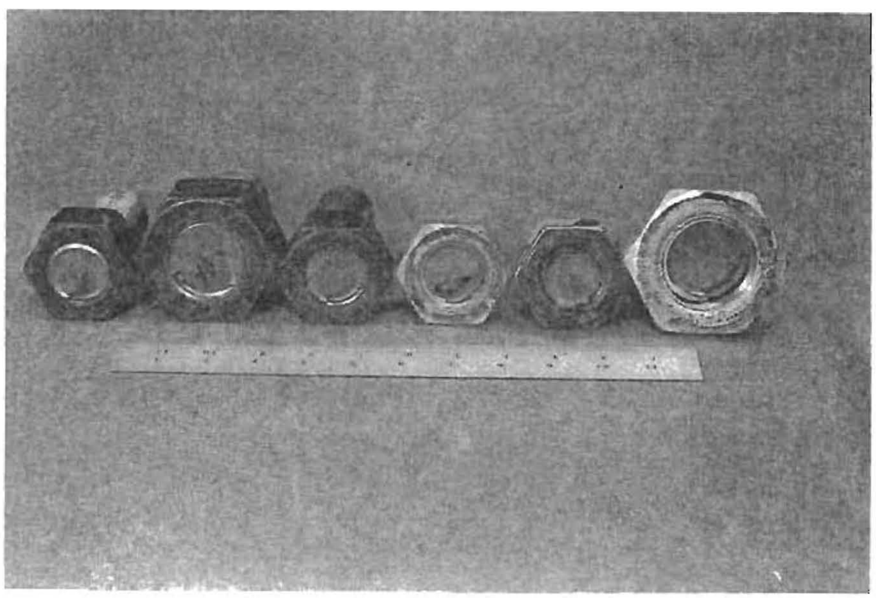

Fig. 10 Characteristic Failure Surfaces (Left to Right: Series A, B, C, D, E, and F)

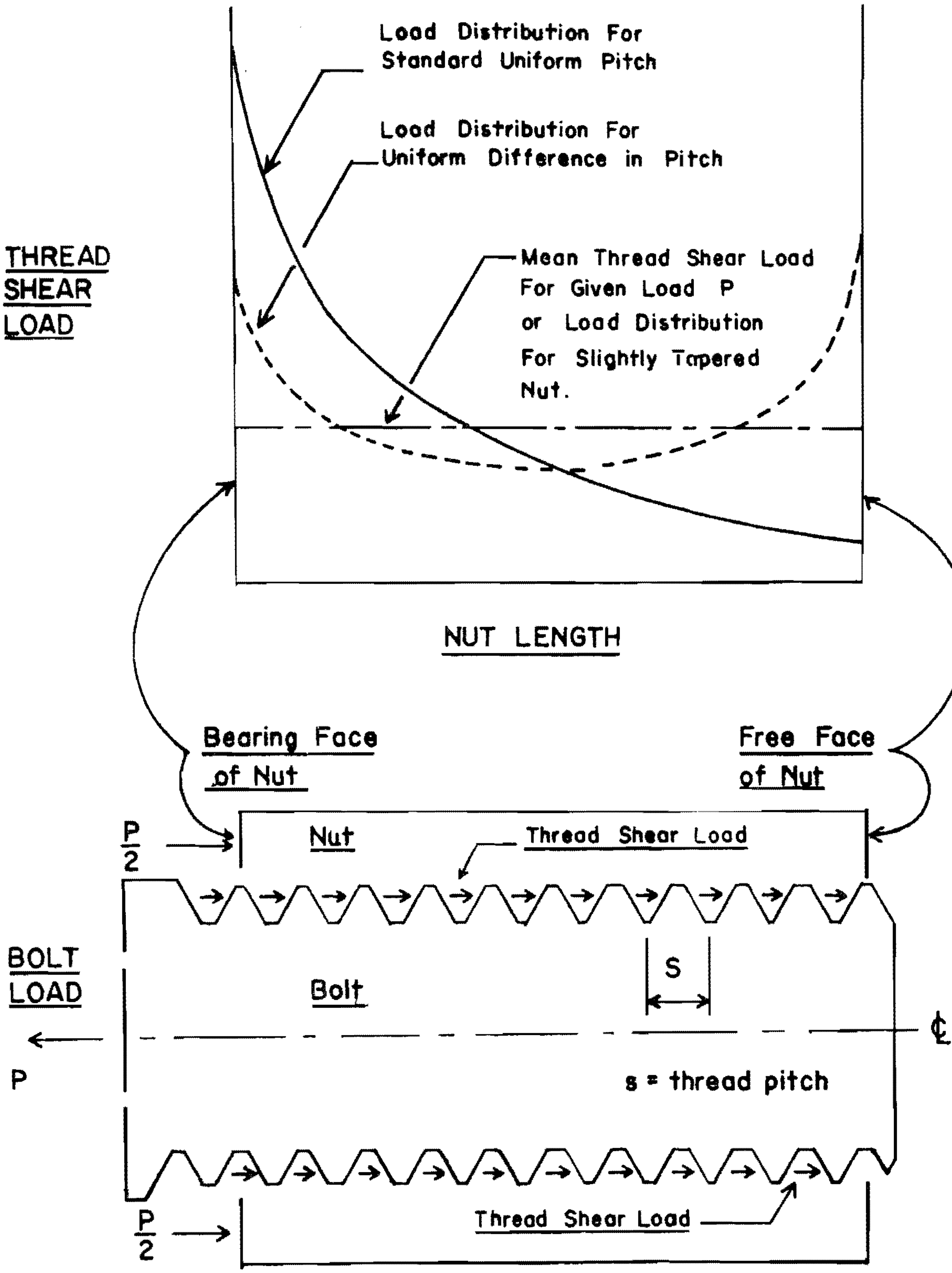

Fig. 11 Thread Shear Load Distribution
in Single Nut Connection

of the nut. The two dashed line curves in Fig. 11 show how a difference in pitch or nut stiffness can change the thread shear distribution (3). In addition, yielding of the threads can reduce the magnitude of the shear at the bearing face of the nut. It appears that the cracking mode in these specimens is due to a combination of the normal tolerances in the threads and yielding of the threads. The net result was an improved fatigue performance since these specimens fractured as many as four times before they finally failed.

3.2 Effect of Steel Strength

The effect of steel strength can be determined by examining the results of Series G, A and C shown in Fig. 12. The diameter and thread type are identical for these series. The higher strength 4340 171 ksi and A193 Gr. B7 115 ksi yield strength steels are seen to yield identical fatigue lives. The 38 ksi yield strength A36 bolts produced fatigue lives ten times larger than the higher strength bolts at the same stress range. The A36 Series G specimens, however, failed by multiple cracking mechanism discussed above. The Series F specimens, 2 inch 27 ksi yield strength bolts, which failed by single cracks formed at the first engaged thread in the nut are seen to produce results comparable to the higher strength steels. The long fatigue life of the 1-3/8 inch diameter A36 Series G specimens was attributed to their multiple cracking failure mode, not due to inherently better performance of the material. This failure mode is due to a change in the stress distribution in the threaded connection as evidenced by the similar fatigue performance of the 2-inch A36 specimens and the higher strength steels. Based on these results, it is felt that steel strength should not be considered as significant variable in the design of anchor bolts for fatigue.

The longer life of the Series G A36 steel specimens show that considerable improvement in fatigue life can be developed by changing the shear transfer in the nut to reduce the shear transferred at the front of the nut. This is an area where further study may be fruitful.

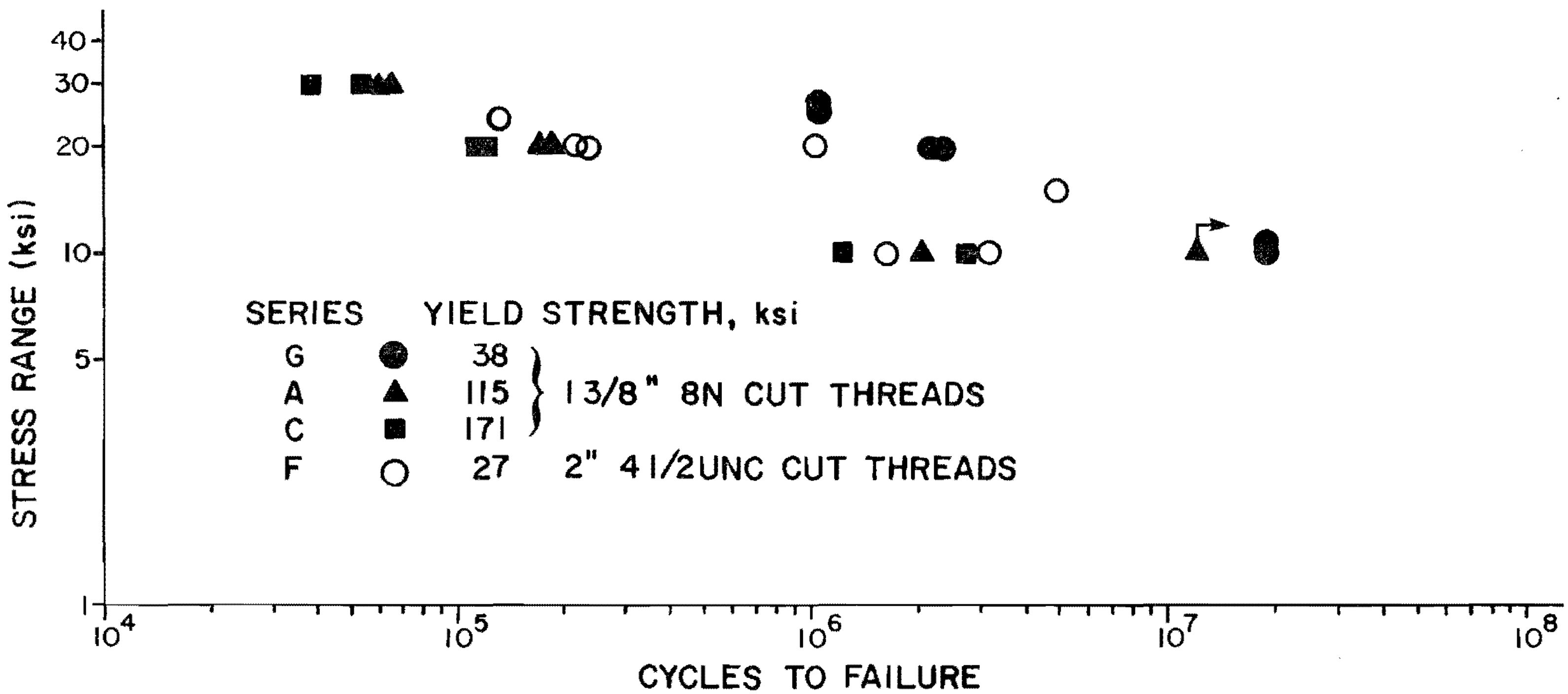

Fig. 12 Effect of Steel Strength on Axial Fatigue Strength

3.3 Effect of Thread Size or Pitch

The size and pitch are directly related in the standard American threads. The number of threads per inch, n, the inverse of the thread pitch, also determines the depth of the thread. The relationship

$$H = 0.866/n$$

relates the thread form depth H to the number of threads per inch.[2] As the number of threads per inch decreases, the depth of the thread increases which causes a larger notch in the threaded bar. The number of threads engaged in the nut also decreases since the nut length is typically constant and equal to the bolt diameter. The tensile stress area also decreases with a decrease in the number of threads per inch.

Figure 13 shows the results of the Series H and F specimens. The bar diameter and steel was the same for both of these series: the only difference was the thread size. The Series F specimens had the standard coarse series thread and Series H had the 8N series thread, a constant pitch thread series often used on bolts one inch and larger.[2] The two series are seen to produce similar fatigue lives. The actual load range capacity of the Series H specimens is 11% higher than the F Series due to its larger tensile stress area. It is recommended that the 8N constant pitch thread be specified on bolts greater than one inch diameter rather than the coarse series thread due to their greater load carrying capacity and, as will be discussed later, the reduction in tightening effort required. Bolts less than an inch in diameter should be specified with the standard UNC threads which are equal to the 8N at one-inch diameter and increase the number of threads per inch as the diameter decreases.

3.4 Effect of Bolt Diameter

Figure 14 shows the results of Series A and B specimens. The thread size and steel are the same for the series. The only difference was the size of the bar. The fatigue lives were almost identical for these specimens indicating that bolt diameter does not influence fatigue behavior.

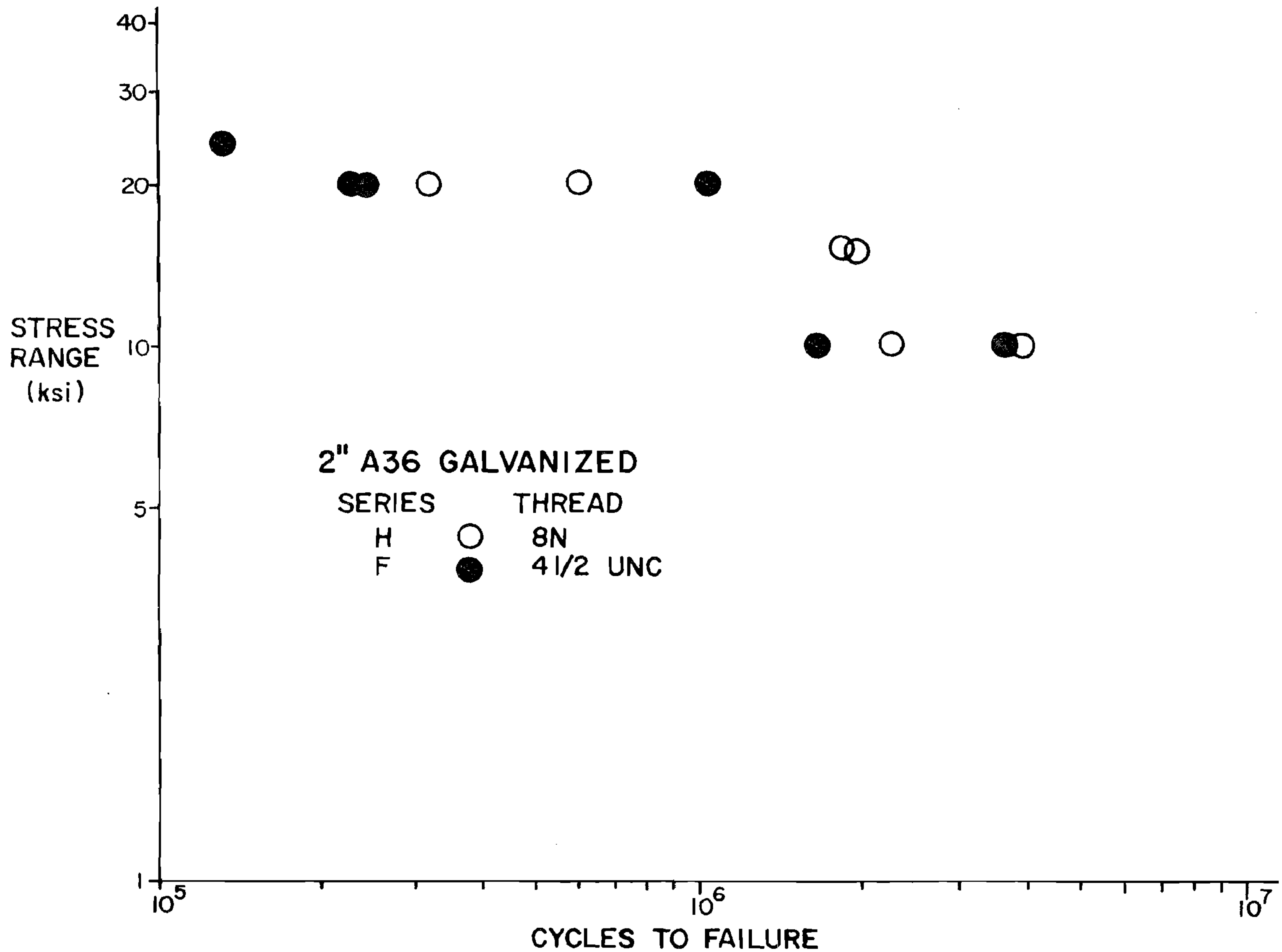

Fig. 13 Effect of Thread Pitch on Axial Fatigue Strength

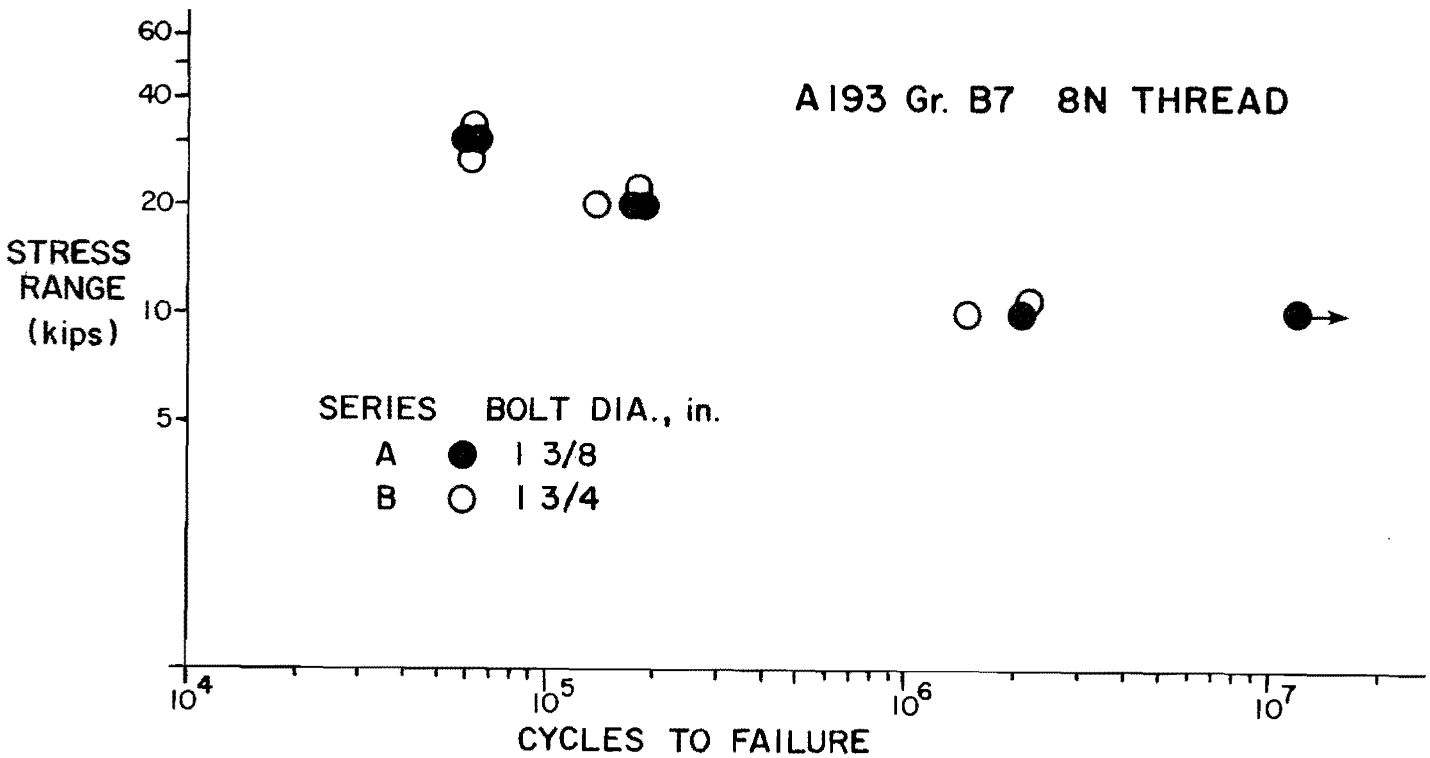

Fig. 14 Effect of Bolt Diameter on Axial Fatigue Strength

3.5 Effect of Method of Forming Thread and Galvanizing

The results shown in Fig. 15 for the 1-3/8 inch A36 bolts Series D, E and G indicate no significant influence of either thread forming method or galvanizing. The Series E specimens with rolled threads did not fail at stress ranges of 15 ksi and 10 ksi. This better performance may be due to the compressive residual stresses at the thread root generated by the thread rolling operation. The cut thread specimens shown in this figure all exhibited the multiple cracking mode explained previously. The specimens with rolled threads failed from the first engaged thread. The specimen with rolled threads provided the longest fatigue life of all specimens tested which failed in the first engaged thread. Consequently, the rolling of the threads does appear to be beneficial to the fatigue performance of the bolt and is recommended for use when available. The fatigue life of a bolt is not only a function of the bolt thread but also the thread of nut. A mismatch in nut and bolt threads due to normal tolerances may override the increase in fatigue life due to rolling of the threads. Due to this uncertainty and results of others to be presented later, the design stress life relationships developed in this study are based on the lower bound cut thread data.

3.6 Effect of Double Nuts

Figure 16 shows the results for the double nut specimens. The mean repression line of the Series B specimens which is an identical steel and thread size is also shown. The single nut failures shown are from control specimens used to compare the life of the bolts manufactured for the double nut specimens with those from Series B. The threads were made to the same specifications as the Series B specimens but were cut by different manufacturers. The single nut data is seen to agree with the regression line of the Series B specimens indicating the two threads produce similar fatigue lives.

The tightness of the bolts was varied in these specimens to ascertain its influence on fatigue performance. The tightening

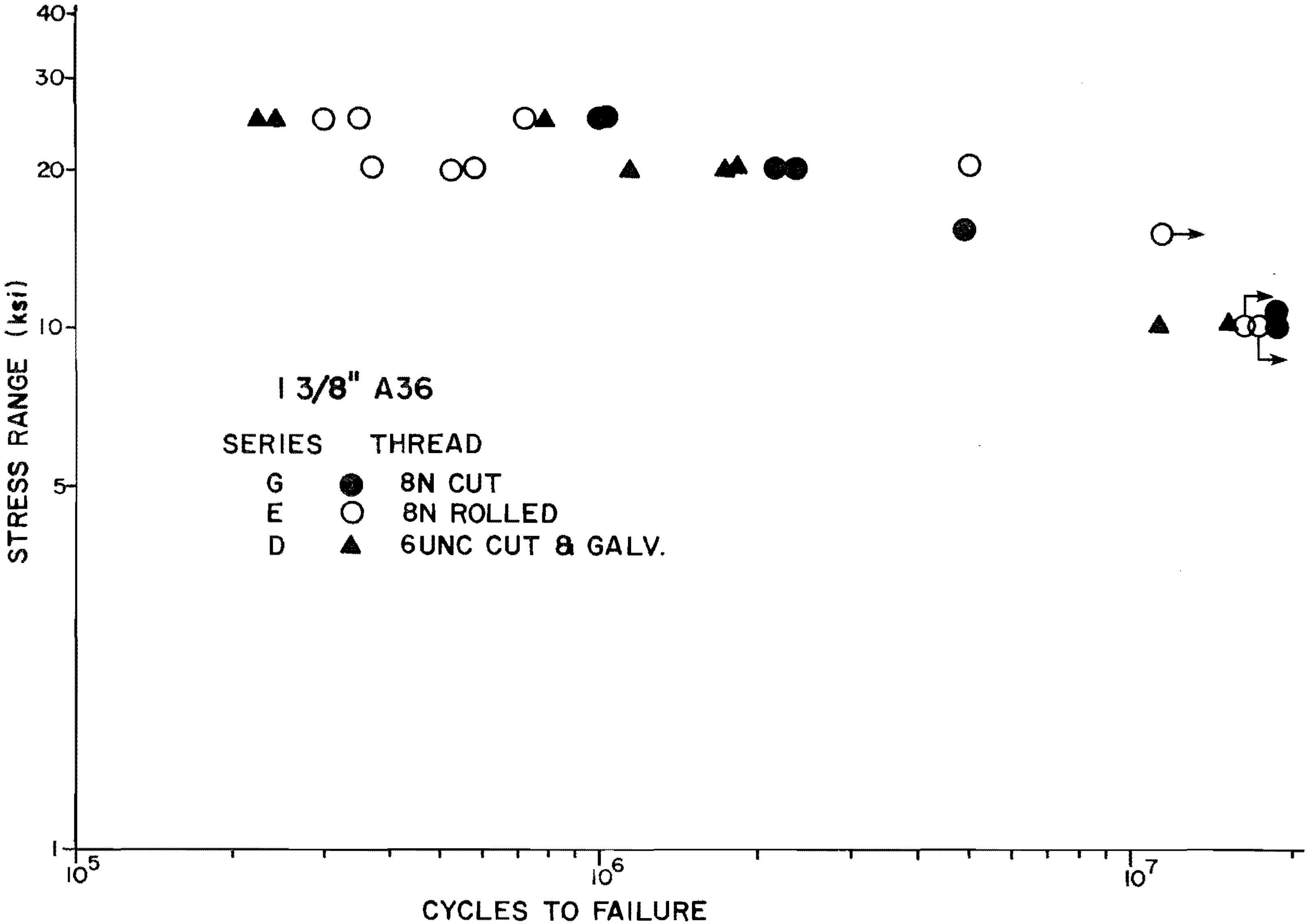

Fig. 15 Effect of Thread Forming on Axial Fatigue Strength

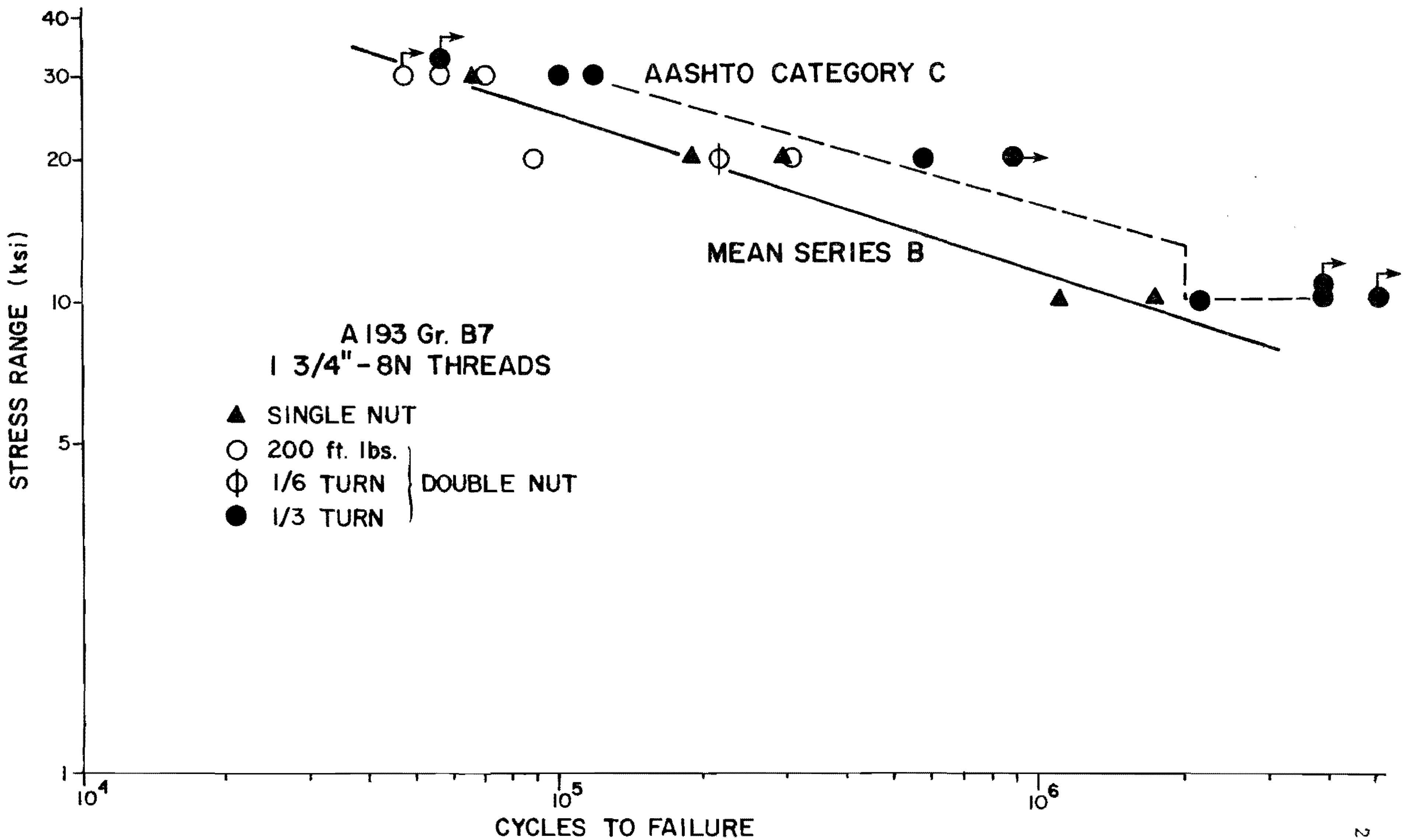

Fig. 16 Double Nut Axial Fatigue Data

of the nuts prestress the joint. The exterior nut stress range is reduced. Strain gage measurements of the force in the bar between the nut showed that approximately one-third the applied load is taken by the interior nut. The increase in fatigue life resulting from the prestressing of the joint is evident in Fig. 16. The joints tightened to 200 ft-lbs and 1/6 of a turn past snug tight are seen to yield fatigue lives comparable to the single nut specimens. The joints tightened to 1/3 of a turn yield fatigue lives 1.5 times longer. The mode of the failure of the 1/3 of a turn specimens was outside of the connection at location 3 in Fig. 8. The other specimens failed in a manner similar to the single nut specimen at the first engaged thread of the exterior nut.

These results indicate that the fatigue performance of anchor bolts utilizing a leveling and top nut can be improved if the nuts are tightened to 1/3 of a turn past snug tight. The use of 8N threads facilitates tightening of large bolts and is recommended. The large diameter bolts typically used for many structures require large pneumatic wrenches to be tightened to this degree. Also, consideration should be given to lubricating the bolt threads and nut bearing face to reduce the required torque. Lubrication is a necessity on galvanized threads due to galling which occurs in the soft galvanizing.

3.7 Bending Fatigue Tests

The results of the cantilever bending fatigue tests are shown in Fig. 17. The results are divided into two categories. The specimens which failed at the first thread cut into the bar are shown as solid symbols and the specimens which failed along the thread after the first cut thread are shown as the open symbols. The failure along the thread was a condition which resulted when the thread was extended along the bar to a point of low bending stress range. No specimens failed in the actual connection. Some specimens failed in the first engaged thread of the interior nut shown as location 3 in Fig. 8. These specimens are included in the along the thread data in Fig. 17.

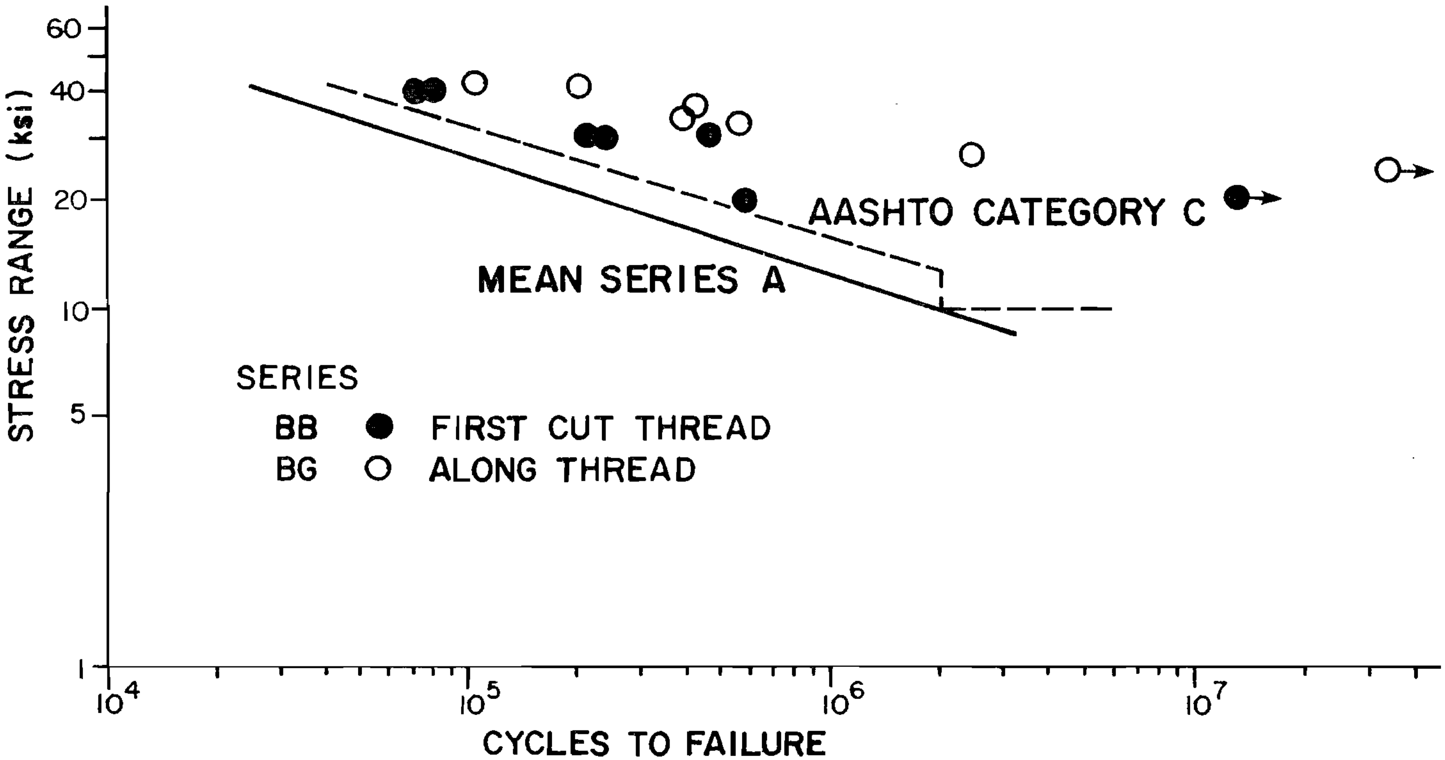

Fig. 17 Bending Fatigue Data

The lower fatigue life provided by the failures at the first cut thread is also evident in Fig. 17. This is due to the larger stress concentration at this location.

The bending fatigue strength was found to be three times the axial fatigue strength of single nut bolts, as shown by the mean line of the Series A single nut axial tension tests. This series was selected for comparison since it is identical steel, thread size and diameter.

The high fatigue strength of the bolts in bending coupled with the high fatigue strength of the properly tightened double nutted axial specimens indicate that the fatigue strength of typical anchor double nutted bolt base plate connections exceed that of a single nut connection by a factor 3. Both of these types of specimens failed outside of the connection, consequently, the bending and axial stress would be added to determine the fatigue stress and life under combined loading.

3.8 Results of Stress Corrosion Tests

No evidence of cracking was found in the laboratory tests after 6,000 hours of exposure. The specimens in the 3.5% salt water environment exhibited gross corrosion and loss of cross section. The specimen in distilled water with a Ph of 7 showed little corrosion. The field environment tests were ultrasonically inspected after 2,200 hours and no cracks were found. These tests are continuing.

The likelihood of cracking in statically stressed anchor due to stress corrosion for the range of steels tested is minimal. However, based on the results of refs. 3 and 4, the use of high strength bolts, F_y greater than 125 ksi, should be avoided. Steels above this strength may be susceptible to cracking in environments other than those tested. Since the design engineer has no control over the possible pollutants to which the bolts are subjected, eliminating bolts that may be susceptible to cracking is prudent. In no case should high strength bolts, $F_y > 125$ ksi, be used in the galvanized condition due to the problems of hydrogen induced cracking.[3, 4]

CHAPTER 4

DESIGN RECOMMENDATIONS

4.1 Allowable Fatigue Stresses

The allowable fatigue stresses are based on the current AASHTO fatigue categories. The creation of new fatigue categories was not found to be necessary.

4.1.2 Single Nut Anchor Bolts and Untightened Double Nut Anchor Bolts

The results of all the tests performed on these type of specimens is shown in Fig. 18 along with the results from refs. 6 and 7. The dashed line corresponding to the AASHTO Category E fatigue allowable stress ranges is seen to provide a reasonable lower bound to the data. The data shown is from tests of both rolled and cut threads, steels with yield strengths from 27 to 171 ksi, and specimens subjected to variable amplitude loading, ref. 7. The threads in the specimens from ref. 6 were micro-polished, rolled and other combinations of finish. The correlation of these specimens with the data generated in this study indicates that thread finishing and forming is not a significant factor on fatigue strength. Therefore, it is recommended that the axial fatigue strength of single nut anchor bolts and double nut anchor bolts tightened to less than 1/3 of a turn past snug tight be determined using the AASHTO Category E allowable stress ranges.

4.1.2 Tightened Double Nut Connection

The axial tension fatigue double nut connections tightened to 1/3 of a turn shown in Fig. 16 and the bending test results shown in Fig. 17 are seen to be reasonably represented by the AASHTO Category C allowable stresses. It is recommended that these connections be designed using Category C allowable stress ranges. The computed design stress range should be calculated by adding the axial tension stress range and to the bending stress range when checking fatigue.

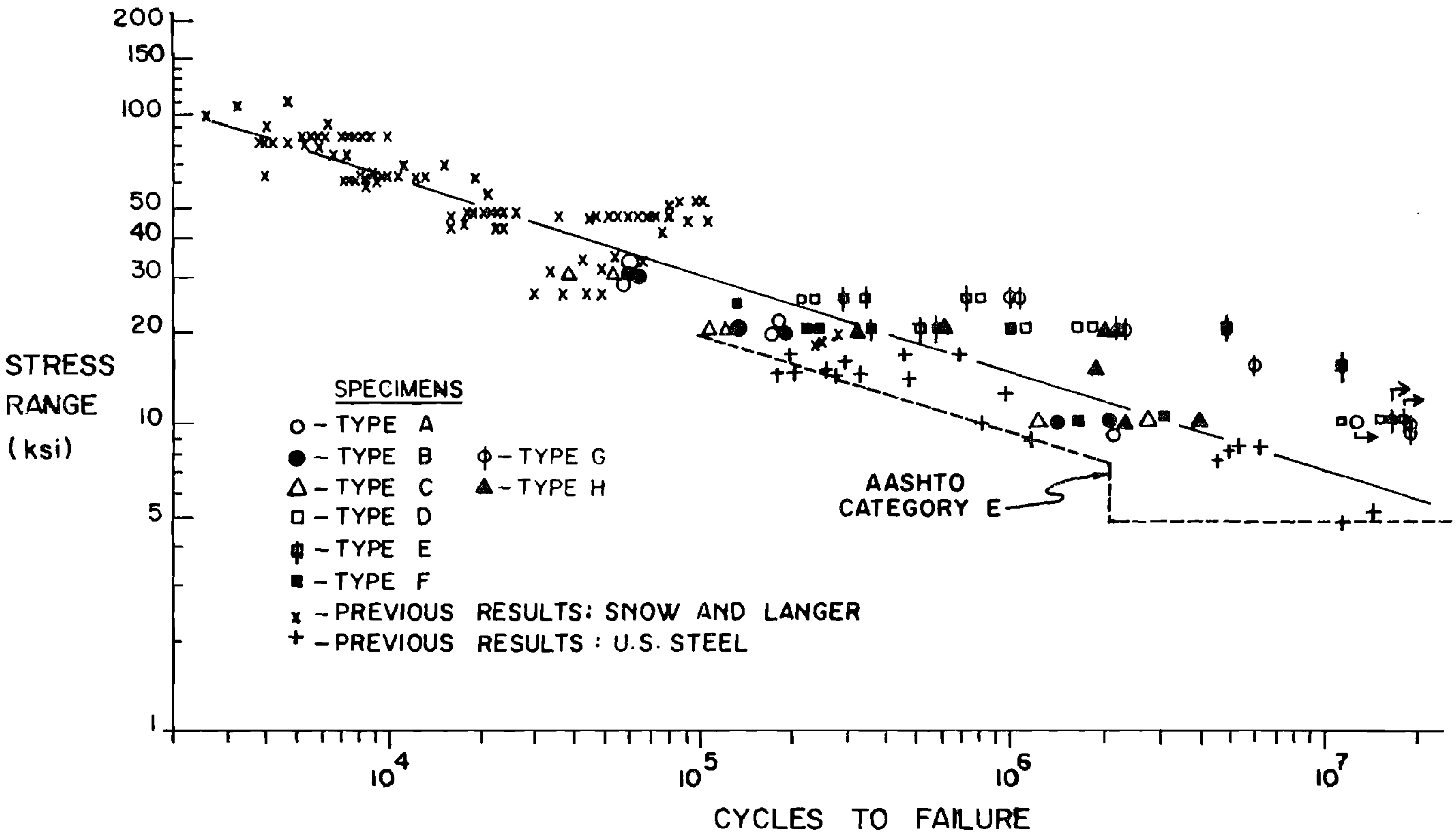

Fig. 18 Comparison of Axial Loaded Single Nut Fatigue Data With Category E Fatigue Stress Level

4.2 Material Specifications

4.2.1 Material Strength

Maximum yield strength of anchor bolts should be limited to 125 ksi to eliminate the possibility of stress corrosion cracking. This requirement also serves to reduce the amount of torque required to tighten nuts in the field.

4.2.2 Thread Size and Fit

The uniform national coarse, UNC, thread series is recommended for bolts one-inch and less in diameter.[2] Bolts greater than one-inch should be specified with the constant thread pitch of 8 threads per inch or 8N series thread.[2] The 8N series thread provides a finer thread which reduces the tightening torque required and also increases the tensile stress area for a given diameter. The latter increases the load carrying capability of the bolt both under static and fatigue loadings.

The class 2 fit, the common thread fit specified for anchor bolts, is adequate. The thread fit should be checked before the anchor bolts are installed using the dimensions in ref. 2. The minor diameter of the threads of nuts used on galvanized bolts should be oversized no more than 0.033 to allow for the increase in bolt diameter due to the galvanized coating. (See detailed discussion in ref. 1.)

4.2.3 Method of Forming Threads

Rolled threads are preferred over cut threads due to their better finish and good fatigue performance. The data generated in this study indicates that rolled threads perform better in fatigue than cut threads. The results from ref. 6 as shown in Fig. 18 indicate rolled threads are not superior at high levels of stress range. No adverse effect of thread rolling has been found. If rolled threads of the size required are available, it is recommended they be used.

APPENDIX A

TEST RESULTS FOR SERIES G AND H

SERIES G

Specimen Number	Stress Range (ksi)	Cycles to Failure
G21	20	2,119,810
G22	20	2,318,500
G11	10	18,550,000
G31	25	1,027,680
G12	15	4,814,460
G13	10	18,480,000
G25	25	1,002,070

SERIES H

H21	20	593,180
H11	10	3,886,310
H151	15	1,814,780
H12	10	2,253,580
H22	20	1,913,070
H23	20	319,240

APPENDIX B

DOUBLE NUT AXIAL TEST RESULTS

Specimen Number	Tightness Connection	Stress Range (ksi)	Cycles to Failure
DN11L	200 ft/lbs	30	56,000
DN11H	1/3 of a turn	30	56,000[3]
DN12L	200	30	70,000
DN12LR[1]	200	30	47,000[3]
DN12H	1/3	30	117,000
DN13L	S.N.[2]	30	66,000
DN13LR	S.N.	30	34,000[3]
DN13H	1/3	20	100,000
SN21L	S.N.	20	188,000
DN21H	1/6	20	217,000
DN21HR	1/6	20	88,000[3]
DN21L	200	20	305,000
DN22H	1/3	20	569,000
DN22HR	S.N.	20	296,000
DN22L	1/3	20	865,000[3]
DN31L	1/3	10	2,115,000
DN31LR	S.N.	10	1,733,000
DN31H	1/3	10	3,848,000[3]
DN32L	1/3	10	3,838,000
DN32LR	S.N.	10	1,104,000
DN32H	1/3	10	4,942,000

[1]R indicates retest

[2]S.N. - single nut control specimen

[3]No cracks detected, test stopped

APPENDIX C

BENDING FATIGUE TEST RESULTS[1]

Specimen Number	Stress Range (ksi)	Cycles to Failure
B2A	40	82,100
B3A	30	246,700
B3B	30	462,700
B2B	20	13,190,000[2]
B1	32	560,970[3]
B4B	40	60,230
B2C	20	578,400
B3C	30	217,700
G15A	41.2	201,700
G4A	33.8	393,900
G4B	36.3	422,000
G5B	42.7	101,500
G24A	24	33,400,000[2]
G3A	26.7	2,432,000

[1]B series failed at first cut thread except as noted, G series failed along the threads.

[2]No cracks detected, test stopped.

[3]Failed along threads similar to G series.

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