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Strength of Bolted and Welded Connections in Stainless Steel

by

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TABLE OF CONTENTS

2. BOLTED CONNECTIONS

3. WELDED CONNECTIONS

4. BUTT WELD CONNECTION TESTS

5. FILLET WELD CONNECTION TESTS

TABLE OF CONTENTS (Cont'd)

LIST OF TABLES

LIST OF TABLES (continued)

LIST OF FIGURES

LIST OF FIGURES (continued)

1. INTRODUCTION

In 1968 the American Iron and Steel Institute published the first edition of the "Specification for the Design of Light Gage Cold-Formed Stainless Steel Structural Members"(1)*, based largely on research sponsored by AISI at Cornell University.(2) That Specification covers the design of members cold-formed from six common types of austenitic stainless steel in the annealed and strain flattened condition. Additional research has been underway at Cornell on austenitic Type 301 stainless steel in the 1/4 and 1/2 hard tempers, to determine the structural behavior of these higher strength materials(3), including the behavior of structural connections .

The properties of cold-rolled austenitic stainless steel are attractive for potential use in cold-formed construction. These properties include excellent corrosion resistance, exceptionally high strength, and good ductility associated with this high strength. Furthermore, all types of austenitic stainless steel, except the free machining grades, exhibit excellent weldability which greatly enhances their usefulness.

This report will discuss the behavior of structural connections in Type 301 quarter and half hard stainless steel. An earlier report(3) summarizes all other phases of the Cornell investigation.

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* Superscripts in parentheses refer to corresponding items in References.

A survey of industry practice in joining methods for stainless steel was conducted by AISI. The percentages of production using a particular joining method as estimated by each of the sixteen companies responding to the survey are given in Table 1. The table indicates that fusion welds are the most popular joining method, followed by resistance welds, bolted connections, and other techniques. According to the survey, fusion arc welding, resistance spot welding and bolted connections account for 90% or more of the connections currently used in stainless steel fabrication.

The minimum shear strength for spot welds in 1/4 and 1/2 hard Type 301 Stainless steel has been tabulated by the American Welding Society(4). The AWS recommendations will be discussed briefly later in this report; there seems to be no need for further investigation of spot welds at this time. Therefore, the investigation described herein was limited primarily to bolted connections and to fusion welded connections using butt welds, longitudinal fillet welds and transverse fillet welds. Information on these joining methods, together with the existing AWS data, can provide the basis for design of a large majority of the structural connections in Type 301 1/4 and 1/2 hard stainless steel.

2. BOLTED CONNECTIONS

2.1 Object and Scope of Bolted Connection Investigation

In general, the requirements for bolted connections in the AISI Specification for annealed and strain flattened stainless steel follow the provisions for cold-formed carbon steel of approximately the same yield strength(5,6). The carbon steel connection requirements are based on research at Cornell(7), supported by additional data from the University of Michigan(8). The investigation reported here was undertaken to determine what modifications, if any, were required for bolted connections in the higher strength stainless steels.

Tests to determine mechanical properties of stainless steel bolts, which probably would be used in connections of stainless steel structural members, were considered beyond the scope of this research. However, based on available information, the sheer strength of certain stainless steel bolts is discussed in Section 2.7.

2.2 Description of Specimens

Twenty-five bolted connection tests were made using Type 301 half-hard stainless steel sheets. All specimens were single-row connections, and all test blanks had 4" x 20" outside dimensions as shown in Fig. 1. The blanks were cut from 16, 21 and 25 gage material (approximately .060", .033" and .021" thick, respectively) manufactured by three different producers. The mechanical properties of the materials listed in Table 2 indicate that cold-rolled stainless steel, unlike ordinary mild carbon steel, shows pronounced anisotropy and has different stress-strain relationships in tension and compression.

The fasteners used in the tests were quenched and tempered medium carbon steel bolts furnished by Lake Erie Screw Corporation. These bolts have a specified minimum proof stress of 85,000 psi and minimum tensile strength of 120,000 psi up to a bolt size of 1" inclusive, and hence meet the requirements for ASTM A325 high strength structural bolts(9). Considering the mechanical properties of the base materials and the bolts, specimens were designed so that failures were much more likely to occur in the sheets than in the bolts.

Variables in the investigation included:

Sheet thickness: 16, 21 and 25 gage

Type of joint: single shear or double shear

Type of fit: bearing or clearance

Bolt diameter: 1/4", 3/8", 1/2" and 3/4"

Number of bolts: one bolt, or two bolts in a single row

e/d ratio: 1.5, 2.5, 3.5 and 4.5

where e is the longitudinal distance from the center of the bolt hole to the edge of the sheet, and d is the diameter of the bolt.

The diameter of the bolt hole was the bolt diameter plus 1/32" for fasteners up to 3/8" inclusive, and the bolt diameter plus 1/16" for larger fasteners.

The basic test program consisted of 19 different specimen configurations, as shown in Table 3. Duplicate tests were conducted on three configurations, one test with initial bearing and the other with initial clearance. Three single shear specimens failed in a very complex manner because severe warping of the sheets occurred near the joint before total separation. These three specimens were repeated with a double shear connection to reduce, as much as possible, any eccentricity of the load. Thus, a total of 25 tests were carried out.

2.3 Fabrication of Specimens

All test blanks were sheared from sheets to the standard size shown in Fig. 1. The longer sides of the blanks were parallel to the rolling direction of the sheets, which is also the direction in which load was applied. Holes in the blanks were punched, with clearances as stated in Section 2.2. Actual dimensions of each test blank were measured before a specimen was assembled, using a micrometer to determine sheet thickness, and a scale with 1/64" graduations to measure blank width, edge distance and hole size.

Single shear specimens were composed of two blanks, and double shear specimens of three blanks. Washers were used both under the bolt heads and under the nuts. The bolts were tightened with a torque wrench to values as follows: 11-ft lbs for 1/4" bolts, 37.5 ft-lbs for 3/8" bolts, 95 ft-lbs for 1/2" bolts, and 335 ft-lbs for 3/4" bolts. Bolts at these torques are believed to be slightly above their proof loads. Calibrated torque wrenches of 50 ft-lbs, 100 ft-lbs, and 600 ft-lbs capacity were used. While tightening the bolt, special attention was paid to obtaining (1) good alignment of the test blanks, and (2) either immediate bearing or maximum clearance between the bolt and the blanks, as desired. In most cases, several trials were necessary to assemble a satisfactory specimen.

2.4 Test Procedure

The tests were conducted in a Baldwin Southwark hydraulic testing machine with loading ranges of 4 kips, 16 kips, 80 kips, and 400 kips. A test set-up is shown in Fig. 2. A microformer type autographic recorder (as shown on the extreme right of Fig. 2) was used to record load and deformation simultaneously, using the signal from an O. S. Peters extensometer (left side of Fig. 2) to indicate the deformation.

The test procedure was as follows. Each end of the specimen was inserted for the full 7 3/4" length of the grips, to prevent or minimize any possible slippage between the specimen and the grips. Then the specimen was preloaded to about 15% of its estimated failure load for the same purpose. Special care was given in centering the 4" width of the specimen in the 4 3/8" width of the grips (Fig. 3). Next, an adapter bar and plate, with apertures for receiving the arms of the extensometer, were properly placed and clamped on the specimen, as shown in Fig. 4. The apertures in the plate and adapter bar were placed 2" apart and on the centerline of the specimen. The upper and lower arms of the extensometer were oriented in a vertical plane coinciding with the centerline of the specimen, before they were placed into the apertures of the plate and bar, respectively. An appropriate magnification factor for deformation and a scale factor for load were selected, and the rotating drum of the recorder was allowed to reach its balance position before the test was started.

Load was continuously applied to the specimen, until the test blanks totally separated. At the start of a test the specimen was pre-loaded and the distance between the two arms of the extensometer was 2". As the test proceeded, the load was gradually applied through the smooth motion of the upper (moveable) head relative to the lower (stationary) head. Simultaneously, the vertical plate moved upwards with respect to the adapter bar, carrying with it the upper arm of the extensometer. Hence, the relative movement of the two arms of the extensometer was identical to the relative movement of the plate with respect to the adapter bar. This relative movement represents the deformation of the specimen at a particular instant. It may come from one or more of the following sources: (1) slipping between the blanks and the bolt; (2) elongation of the test blanks in a 9" gage length (Fig. 4); and (3) deformation of the bolt or the blanks bearing on the bolt. Both the relative movement and the corresponding load were automatically recorded on the load-deformation graph paper, which was wound around the rotating drum. When the maximum load of the specimen was reached, the load was also read from the dial of the testing machine and the deformation was measured directly from the specimen, using a precision steel ruler. (The measurement was made as follows: Before the specimen was placed in the grips, one of the test blanks was scratched along the edge of the other blank. As the test progressed, the scratched line displaced from the edge. At the maximum load the distance between the scratched line and the edge was measured, using a steel ruler. This reading was not precise because the displacement was very small. However, it was useful when, due to some technical difficulties, the relative movement of the arms of the extensometer at the maximum load was not recorded on the graph paper.) These two data were helpful in interpretating the load-deformation graph. Next, the testing machine was accelerated to speed the specimen's failure. The arms of the extensometer were removed from the specimen when the relative movement of the plate and the adapter bar exceeded the range of the movement of the two arms, to prevent damage to the extensometer during total separation of the test blanks.

2.5 Test Results

The behavior of a specimen throughout the test is characterized by its slip load, proof load and failure load on the load-deformation graph. These characteristic loads are described in Section 2.5a. One double shear specimen failed unexpectedly in the bolt. This was because the bolt thread was cut through along a single inclined plane and, consequently, the bolt did not produce any double shear action. Failure of the rest of the specimens occurred in the sheets, with negligible damage to the bolts. Four basic types of failure were observed. The reliability of the results was verified by performing duplicate tests on three pairs of specimens.

2.5a Load-Deformation Graphs

On the basis of some common features exhibited from the beginning to the highest peak of the graph, the 25 load-deformation graphs are divided into 3 groups, which will be described below:

GROUP I (Figs. 5 and 6):

The graph as a whole is smooth. A break may occur at the very beginning of the graph, or a sudden drop followed by a jump may occur right after the highest peak (Fig. 6).

GROUP II (Figs. 7 and 8):

One distinct peak or two appears in the initial portion of the graph, and the remainder of the graph is relatively smooth. Again, a sharp drop and jump may occur after the highest peak (Fig. 8).

GROUP III (Fig. 9):

The graph is composed entirely of several distinct peaks with very sharp drops and jumps. When these drops and jumps were being recorded on the graph paper, cracking sounds in the specimen were noticed.

The concepts of slip load , proof load and failure load are helpful in interpretating the load-deformation graphs. The slip load of a specimen is defined as the load at which static friction between the bolt and the blanks is overcome. It usually varies with the tightening torque. The slip load in Figs. 7 and 8 is evidently at the first peak of the graph. In some cases, however, the slip load is difficult to determine because of the smoothness of the graph (Fig. 5).

In Figs. 6 and 9 the load at the break shown is believed to be the slip load. It can be seen that the deformation is very small up to the slip load. At the slip load a sudden increase in deformation occurs, mainly due to slippage between the bolt and the blanks.

The proof load is the load at which the slope of the graph starts to flatten noticeably (Figs. 5, 7 and 8). The deformation at this load is large, as compared to the deformation at the slip load. Thus, the proof load is significant when control of excessive deformation is of primary consideration in design. The proof load such as in Fig. 9 may be easily located if the envelope of the graph is drawn.

The maximum load that a specimen can undergo shall be known as the failure load. The failure load thus defined is at the highest peak of the graph (Figs. 7 and 9). It is also indicated by the loading dial of the testing machine. It should be emphasized that the maximum load of a specimen is reached well before total separation of the test blanks. Thus, the deformation at failure load is smaller than the deformation when total separation occurs.

The slip load, proof load and failure load of each of the 25 specimens were determined in a manner just described. The deformation at the proof load and the deformation at failure were read from the graph. These data are presented in Table 4, which will be described later.

2.5b <u>Type of Failure</u>

Careful examination of the tested specimens and a correlation study of the test results suggest four fundamental types of failure in the specimens, similar to those previously described by Winter(7) and denoted by I, II, III and IV in Fig. 10. The first three types refer to sheet failure while the fourth one represents bolt failure. The characteristics of each of the four types are as follows (see Figs. 10 and 11):

TYPE I

Longitudinal shearing along two practically parallel planes.

TYPE II

Bearing-Shearing along two planes with (i) considerable "piling up" of the material in front of the bolt and the sheet, and (ii) formation of rough surfaces in the vicinity of the planes.

TYPE III

Transverse tearing across the net section of the sheet, accompanied by considerable necking of the sheet.

TYPE IV

Shearing of the cross section of the bolt.

About 15 (out of 25) specimens failed in one of the basic types just described. Failure in the rest of the specimens is complex; however, failure in 7 of these specimens can be considered as a variation of one, or a combination of two, of the four basic types, as described below (see Fig. 11):

TYPE Ia

Similar to Type I, except that longitudinal shearing was followed by tearing along two distinctly inclined planes.

TYPE IIa

Similar to Type II, except that bearing-shearing was followed by tearing along two distinctly inclined planes.

TYPE IIIa

Transverse tearing across the sheet on one side of the bolt, and tearing along a distinctly inclined plane on the other side.

TYPE IIIb

Transverse tearing across the sheet on both sides of the bolts, accompanied by longitudinal shearing along one plane.

TYPE IIIc

A combination of transverse and longitudinal tearing.

Three specimens, denoted by 6, 17, and 19 in Fig. 11, failed in a very complex manner, because of severe warping and bending around the joint. Their failure cannot be classified into one of the four fundamental types, neither a variation nor a combination of any two of the four. Thus, it was decided to exclude these tests from the analysis in Section 2.6.

The type of failure for each specimen is given in Column (22) of Table 4.

2.5c Test Data

The complete results of the 25 tests are presented in Table 4. Dimensions of the test blanks are shown in Column (3) through Column (12). The test data for each specimen are given in Columns (13) to (22), inclusive. Each of the columns in Table 4 is as follows:

Column (1): self-explanatory.

Column (2): gives the specimen designation, composed of eight numbers and letters, which have the following meaning: The first two numbers indicate the gage of the test blank. The following letter denotes the type of assembly: "B" stands for bearing, and "C" for clearance. The next two numbers represent the e/d ratio with a decimal point between the two numbers omitted, e.g. "15" means an e/d ratio of 1.5. The letter following the e/d ratio shows the type of joint: "S" for single shear and "D" for double shear. The last two numbers provide information about the bolts. The first of the two numbers gives the number of bolts in the specimen; and the second specifies the bolt size in terms of eighths of an inch: e.g. "12" indicates one bolt of 2/8" diameter in the specimen.

Columns (3) to (10) inclusive are self-explanatory. In case of two bolts in a single row, Column (7) is the average of the two edge distances, and Column (10) is the average of the two hole sizes.

Column (11): Column (7) divided by Column (9).

Column (12): Column (9) divided first by Column (6) and then by Column (8).

Columns (13) and (14): read from the load-deformation graph according to the criteria established earlier in Section 2.5a.

Column (15): read from the dial of the testing machine, and checked with the maximum peak load in the graph.

Column (16): Column (14) divided by the triple product of Columns (5), (8) and (9).

Column (17): read from the graph with Column (14).

Column (18): Column (15) divided by the product of Column (5) and Column (6).

Column (19): Column (15) divided by the product of Column (5) and the net width. The net width is the difference of Column (6) and the product of Column (8) and Column (10).

Column (20): Column (15) divided by the triple product of Columns (5), (8) and (9).

Column (21): read from the graph with Column (15), and checked with that from direct measurement, if any.

Column (22): gives the type of failure for each specimen. (See Fig. 11 for illustration).

2.5d Reliability of Test Results

To check the reliability of the test results reported in this section, three pairs of duplicate specimens (marked with an asterisk in Table 3) were tested: one test with bearing and the other with clearance. The results of the duplicate tests are summarized in Table 5. It can be seen from the table that (i) the deviation of failure load in each set of duplicate tests ranges from 0.34% to 4.28%; (ii) types of failure in each set are identical; (iii) deformations at failure load are comparable to each other; and (iv) load-deformation graphs in duplicate tests are similar, except for Specimens 13 and 14. The graphs of these two specimens are slightly different in nature, but quite smooth. The results of the duplicate tests can be said to be satisfactory, and indicate that there was very little difference in the behavior of "bearing" and "clearance" type connections.

2.6 Analysis of Test Results

As was stated earlier, one double shear specimen failed unexpectedly in the bolt (Type IV in Fig. 11), and three other single shear specimens failed in a very complex manner (Specimens 6, 17 and 19 in Fig. 11), due to severe bending and warping. The data from these four specimens will be excluded from the analysis in this section.

The remaining 21 specimens all failed in the sheets, and their failure can be classified into one of the fundamental types, or a variation of it, or a combination of two. In what follows, the test data are evaluated for each of the basic types of failure involved:

(i) Type I (Longitudinal Shearing): This type of failure, which was observed in tests with relatively small e/d ratios (say, up to 2.50), suggests that the applied force is resisted by two shear forces along the two parallel planes shown in Fig. 11. Analysis of the test data was made with each of the following mechanical properties: a) $\sigma_{y(avg)}$, the average of the four yield strengths for tension and compression in the longitudinal and transverse directions; b) $\sigma_{t(avg)}$, average of the two tensile strengths in the longitudinal and transverse directions; and c) $\sigma_{y(LC)}$, yield strength for the compressive stress-strain curve in the longitudinal direction. Better correlation was obtained with $\sigma_{y(avg)}$ or $\sigma_{t(avg)}$ than with

$\sigma_{y(LC)}$. In Fig. 12 the quantities $\frac{P_f}{n\ t\ \sigma_{y(avg)}}$ and $\frac{P_f}{n\ t\ \sigma_{t(avg)}}$ are plotted against the edge distance e, where P_f is the failure load of the specimen and n is the number of bolts.

It is logical that the equation governing Type I failure should be related to $\sigma_{y(avg)}$. This is supported by the fact that, in practice, the yield strength in shear is computed from $\sigma_{y(avg)}$, using an appropriate affinity factor for stress. The proposed equation is

$$\frac{P_f}{n\ t\ \sigma_{y(avg)}} = 1.20\ e \tag{1}$$

By simple transformation of (1), the average shear stress (τ_s) along the two shear planes at failure is given by

$$\tau_s = \frac{P_f}{2\ n\ t\ e} = 0.60\ \sigma_{y(avg)} \tag{2}$$

This may be compared with a value $\tau_s = 0.7\ \sigma_y$ obtained for carbon steel connections (7). Equations (1) and (2) are valid for e/d ratio up to 2.50. They may be used for specimens with slightly higher e/d ratios, as discussed below.

(ii) Type II (Bearing-Shearing): This type of failure is characterized by "piling up" of material in front of the bolt. The amount of "piling up" of the material normally depends upon the e/d ratio: the larger the e/d ratio, the more the "piling up" of the material. No "piling up" was found in the specimens with e/d ratio of 1.50, which, in fact, exhibited Type I failures. But, in one specimen with e/d of 2.50 (Specimen 11), whose failure was classified into Type Ia

(Fig. 11) based on the appearance of the failure planes, the bolt hole was slightly crushed and the apparent beginning of "piling up" of the material was observed. This indicates that Type I and Type II failures should be treated together, not separately. The test data for Type I and Type II failures have been studied; again, better correlation was obtained with $\sigma_{y(avg)}$ or $\sigma_{t(avg)}$ than with $\sigma_{y(LC)}$. In Fig. 13 the quantities $\frac{\sigma_b}{\sigma_{y(avg)}}$ and $\frac{\sigma_b}{\sigma_{t(avg)}}$ are plotted against e/d, where σ_b is the bearing stress.

In what follows the failure formula will be determined based on $\sigma_{y(avg)}$. The experimental points in Fig. 13 can be best fitted by a curve of high degree; however, for simplicity in design they may be represented by a broken line as shown. The broken line can be expressed in the following analytical form:

$$\frac{\sigma_b}{\sigma_{y(avg)}} = \begin{cases} 1.20\ e/d & \text{for } e/d \leq 3.0 \quad (3a) \\ 3.60 & \text{for } e/d \geq 3.0 \quad (3b) \end{cases}$$

Eq. (3b) implies that the bearing stress at failure load is

$$\sigma_b = 3.60\ \sigma_{y(avg)} \tag{4}$$

This may be compared with a value of $\sigma_b = 4.9\ \sigma_y$ obtained for carbon steel connections (7).

(iii) Type III (Transverse Tearing): For this type of failure, tearing occurs across the net section of the sheet. Thus, the data are likely to be related to the mechanical properties of the sheet in the direction the load is applied, that is, in the longitudinal direction. Evaluation of the data shows that experimental points based on the tensile strength in the longitudinal direction $\sigma_{t(Lt)}$ give a better correlation than those based on the longitudinal yield strength $\sigma_{y(LT)}$, although they scatter considerably. In Fig. 14, $\frac{\sigma_{net}}{\sigma_{t(LT)}}$ is plotted against $\frac{d}{s}$, where σ_{net} is the average stress on the net section and s is the bolt spacing. No attempt has been made to establish, based on the results reported here, a prediction equation for Type III failures. However, for comparison purposes, the formula for this type of failure in light-gage carbon steel(7) is reproduced below, and is plotted in Fig. 14 with $\sigma_{t(Lt)}$ used for σ_t:

$$\frac{\sigma_{net}}{\sigma_t} = 0.1 + 3.0 \frac{d}{s} \leq 1 \qquad (5)$$

It can be seen that Eq. (5) predicts Type III failure for stainless steel sheets reasonably well, if $\sigma_{t(LT)}$ is used for σ_t in Eq. (5).

2.7 Shear Strength of Stainless Steel Bolts

The growing demand for stainless steel fasteners in structural applications is attributed to the overall economy (including in-place costs and service life costs) in relation to the endurance of satisfactory performance. Choice of stainless steel as a fastener material is also encouraged by the following fact: The ratio of the cost of stainless steel fasteners to the cost of mild steel fasteners of comparable mechanical properties is 3 or even lower, although the price ratio for raw materials of stainless steel to mild steel may be as high as 7 to 1(10).

Mechanical properties of stainless steel bolts are available in published form(11); however, the shear strength of the bolts is not tabulated. In general the shear strength of the bolts depends upon the bolt material (grade and temper) and, in some cases, the bolt size. To estimate the shear strength at this stage, it may be appropriate to follow the customary practice; that is, to take 60% of the ultimate tensile strength of the bolt material as the shear strength of the root area. A safety factor of 2.50 may be used to obtain the allowable shear stress. Table 6 lists the mechanical properties for certain types of stainless steel bolts(11) and the computed allowable shear stress. The computed allowable shear stress is 18,000 and 24,000 psi, respectively, for solution annealed and cold worked austenitic stainless steel bolts up to 1 1/2" in diameter. For strain-hardened austenitic stainless steel bolts the computed allowable shear stress is 30,000 psi for sizes up to 5/8"; 25,200 psi for sizes over 5/8" through 1"; 21,600 psi for sizes over 1" to 1 1/2". These values are quite comparable to those for high-strength carbon steel structural bolts(12). The allowable shear stress ranges from 15,000 to 22,000 psi for A325 bolts, and from 30,000 to 32,000 psi for A490 bolts.

2.8 Summary

The following statements can be made as a summary of this investigation of bolted connections:

(1) A total of 25 tests were conducted using half hard stainless steel sheets. Test results suggested four basic types of failure, similarly as in Winter's previous carbon steel connection investigation; one type occurred in bolts and the other three in sheets. The three basic types of sheet failure are significant in proposing design formulas.

(2) Evaluation of data shows that Type I and Type II failures correlated best with the yield strength for the average of the four stress-strain curves for tension and compression in the longitudinal and transverse directions, whereas Type III failure seems to be related to the tensile strength in the longitudinal direction.

(3) The nominal shear stress in the two shear planes at failure is 60% of $\sigma_{y(avg)}$ (Type I) in contrast to 70% for carbon steel, and the nominal bearing stress at failure load is 3.60 $\sigma_{y(avg)}$ (Type II) in contrast to 4.9 σ_y for carbon steel.

(4) Type I failure is governed by Eq. (1) while Type I and Type II failures are related by Eqs. (3a, b). No formula has been proposed for Type III, i.e., for net section tearing, but the experimental points are predicted fairly well by the formula for light-gage carbon steel (Eq. 5), if σ_t is replaced by $\sigma_{t(LT)}$ in the formula.

(5) For certain austenitic stainless steel bolts, the allowable shear stress was computed based on 0.6 of the tensile strength and a factor of safety of 2.50 (Table 6).

3. WELDED CONNECTIONS

3.1 General Discussion

Type 301 1/4- and 1/2-hard stainless steels obtain their high strength through cold-rolling. In the so-called heat-affected zone subjected to elevated temperature during welding, the following problems must be examined:

(1) Intergranular Carbide Precipitation: If subjected to a temperature range of 800 to 1,500°F., the austenitic structure of chromium-nickel stainless steels is susceptible to a microstructural change due to intergranular carbide precipitation--a process in which the carbon diffuses to the grain boundaries and combines with chromium to form chromium-carbide precipitates. Corrosion resistance in some severe environments is then impaired because the precipitation reduces the chromium content at the grain boundaries to an amount less than that needed for good corrosion resistance. However, intergranular corrosion resulting from welding or heating operations generally will not impair the mechanical properties of the base metal.

(2) Warping and Thermal Stress: As compared with carbon steel, austenitic stainless steel possesses higher electrical resistance, larger coefficient of thermal expansion and lower heat conductivity, all of which affect the severity of warping and thermal stress around the weld.

(3) Annealing Effects: Since the welding zone is exposed to an annealing temperature during fabrication, mechanical properties of cold-rolled stainless weldments are certainly impaired to some extent, as compared to those of unwelded

cold-rolled base metal. The extent of this reduction in strength has not yet been agreed upon.

Generally speaking the first two problems can be satisfactorily solved or avoided by several alternative methods. Further consideration of these is beyond the scope of this discussion, which is concerned with the mechanical properties and structural behavior of welded cold-rolled stainless steel connections.

3.2 Recommendations for Resistance Welding

Spot welding has gained popularity in light-gage stainless steel construction because of its efficiency, economy, and low heat production during welding. Data on the minimum shear strength per spot weld are available in American Welding Society's Recommended Practices for Resistance Welding (AWS Designation C1.1-66)(13). The shear strength given depends upon (i) thickness of the thinnest outside sheet and (ii) temper (in terms of the ultimate tensile strength) of the base material. The range of thickness shown for spot welding is from 0.006" (34 gage) to 0.125" (11 gage), inclusive. For sheet thickness greater than 0.125", it is recommended to modify the spot welding procedure; that is, perform welding by intermittent surges of current rather than by a single application of current. The modified procedure is known as pulsation welding, its purpose being to force the greatest amount of heat into the weld with minimum damaging effect on the electrode. The cited booklet also gives data on pulsation welding up to sheet thickness of 0.250" (3 gage).

It appears that those data can be reliably inserted into the future AISI stainless steel design specification, if an appropriate factor of safety (say 2.5) is applied and if the practices recommended in the quoted booklet are strictly followed. However, it should be borne in mind that, as noted in the Recommended Practices, those data on pulsation welding should be used only as a guide and should remain so until more information becomes available. Tables 7 and 8 list the AWS values for minimum shear strength of spot welds and pulsation welds, respectively, along with allowable stresses based on a factor of safety of 2.5.

3.3 Review of Fusion Welding Information

The current AISI Specification for annealed and strain-flattened stainless steels(1) states that "The allowable unit stress in tension or compression on butt welds shall be the same as prescribed for the base metal being joined...". (The basic design stresses are 18,000 psi in longitudinal compression and 20,000 psi in tension and transverse compression.) The Specification states also that "Stresses in a fillet weld... shall be considered as shear on the throat for any direction of the applied stress". Based on an expected minimum tensile yield strength of the weld metal of 44,000 psi, an allowable shear stress of 11,000 psi is permitted.

For harder tempers of Type 301 stainless steel, because of the local annealing effect of welding, it is current practice to design welded connections on the basis of the strength of annealed material. A review of available data(14,15,16,17) suggested that allowable stresses on butt welds in cold-rolled stainless steel might be increased above the values for annealed material. Very little information is available on fillet welds. Available data on butt welds are reviewed below.

Experimental data on joint strength of butt-welded Type 301 cold-rolled stainless steel scatter widely(14,15,16). Data in Ref. 14 covering parameters of our interest are reproduced and further analyzed herein.

Mechanical properties of annealed and quarter-hard Type 301 base metal as reported in Reference 14 (and reproduced in Table 9) meet all the ASTM requirements (Table 10). The shape of the stress-strain curves is characterized by the ratio of ultimate tensile strength to 0.2% offset yield strength as recorded in the tables.

Tables 11 through 13 summarize the Reference 14 data on mechanical properties of quarter-hard Type 301 butt-joint weldments with TIG (Tungsten Inert Gas, or Gas Tungsten-Arc), MIG (Metal Inert Gas, or Gas Metal-Arc) and coated electrode welding processes, respectively. ER 308 electrode was used in the coated electrode welding process (Table 13). The tensile-yield strength ratio is also given for each test in all tables. The term "joint efficiency (%)" is defined as the ratio of weldment strength to the strength of base metal, times 100. For discussion purposes, joint efficiency based on annealed material is also given.

The customary practice--the use of annealed-strength values for welded joints in cold-rolled stainless steel is found to be inappropriate and wasteful, based on the following observations:

(1) Tables 11 through 13 show that the tensile strengths of quarter-hard weldments and annealed sheet are comparable for each thickness (Column 7); however, the yield strength of quarter-hard weldments in all tests (as measured by 0.2% offset on a 2" gage length) well exceeds that of annealed material (Column 6). This means that, if yield strength determines the allowable stress in butt welds (as is the actual case for hgih tension-yield ratio), the customary practice seems to be too conservative.

(2) As seen in Fig. 15, stress-strain behavior (characterized by the ratio of tensile to yield strength) of butt-joints of cold-rolled stainless sheets for a given gage correlates better with that of unwelded cold-rolled material than with that of unwelded annealed sheet. This implies that the joint strength of a cold-rolled weldment could be determined based on the base metal itself, with due consideration of the annealing effect around the weld, and the strength of the weld metal.

Before further discussion, one thing should be remembered-data in Tables 11 through 13 are calculated based on sheet thickness rather than weld thickness. Thus, these joint efficiencies are a little too high. Table 14 shows the calculated joint efficiencies for machined welds and those for which the weld reinforcement has not been removed.

Fig. 16 reveals the effects of sheet thickness and welding processes on the mechanical strength of 1/4-hard weldments. Mechanical strengths are slightly higher when the sheet is thinner. One reason behind this is that reinforcement is more significant in thin sheets.

Data on half-hard weldments are too scarce to be discussed. However, it appears that the tensile and yield strengths of 1/2-hard weldments were usually higher than those of 1/4-hard weldments(16).

In summary then, Tables 11 through 14 indicate that the minimum yield strength of the 1/4 hard butt weldments as determined by 0.2% offset in a 2" gage length is about 55% of the yield strength of the cold rolled base metal, and well above the yield strength of annealed material. The minimum tensile strength of the weldments is about 65% of the tensile strength of the base metal. For quarter-hard Type 301, there is sufficient evidence in the literature to indicate that the allowable stress on butt welds can be increased above the values for annealed material; for half-hard Type 301 data is lacking on butt welds and for both tempers on fillet welds. The test results presented in Sections 4 and 5 of this report are intended to supply some of the lacking information.

4. BUTT WELDED CONNECTION TESTS

4.1 General Discussion

A butt weldment may be regarded as an assembly consisting of three components: weld metal, heat affected zone, and unaffected base metal. In autogenous welding, no filler metal is used in the welding process, and the "weld metal" is essentially the base metal that has been melted and re-solidified. For cold-rolled stainless weldments, two points have been observed: (1) the strength of the cast weld metal is usually lower than the strength of the unaffected wrought base metal, and (2) the base metal in the heat-affected zone loses part of the strength increase previously gained during the cold reducing process.

While tests of butt weldments usually have been analyzed on the basis of joint efficiency as discussed in Section 3, it may be more enlightening to consider the behavior in terms of the individual components making up the weldment. As an example, the properties of the base metal and weld metal for quarter hard stainless steel realistically may be as follows:

	Yield Strength (ksi)	Tensile Strength (ksi)
1/4 Hard Base Metal	90	130
Annealed Base Metal	36	110
Weld Metal	50	100

If the base metal is assumed to be fully annealed for some short distance in the vicinity of the weld, then, under increasing load, the sequence of events would be:

1. Yielding of the annealed base metal
2. Yielding of the weld metal
3. Yielding of the 1/4 hard base metal
4. Fracture of the weld metal

The significance of such a sequence of events will be discussed in Sections 4.4 and 4.6.

4.2 Description of Butt Weld Test Specimens and Procedure

To determine the behavior of butt weldments, 24 specimens were prepared, 14 in the machined condition and 10 in the as-welded condition (Fig. 17). In the machined condition the weld was ground flush with the sheets it connected. There were five sets of specimens in each of the two categories. Table 15 gives all of the pertinent dimensions. Material variables were temper (quarter-hard and half-hard) and thickness: 16 and 22 gage (.060" and .030", respectively) in quarter-hard, and 16, 21 and 25 gage (.060", .033" and .021", respectively) in half-hard. The specimen designations identify hardness, sheet gage, type of weld, and number of test; e.g. Q16B-1 means quarter-hard, 16 gage, butt weld, test No. 1.

All specimens were welded using the Tungsten Inert Gas (TIG) process. Commercially available tungsten electrodes with 2 percent thorium (AWS-ASTM Classification EWTh-2 were used, and the filler rod, when used, was AWS-ASTM Classification ER308, whose composition matches most closely the base metal under investigation, and which is recommended for use with this base metal.

Several 5" x 8" blanks were sheared from each of five stainless sheets. The 5-inch sides of the blanks were parallel to the rolling direction of the sheets, in which direction the load was later applied. A pair of blanks from the same sheet, without any edge preparation, were placed in the specially designed jig and fixture shown in Fig. 18. All welding was performed manually by a skilled operator in Cornell University's laboratories according to the procedure in Table 16. Tack welds were made first, followed by continuous welds. Four butt-joint groove-weld specimens with 0.50" test width were cut from each of the welded blanks (Fig. 19).

To obtain ductility data from the butt welds, gage marks were scribed at 1/4" intervals on each side of the center line of the weld. The gage lengths were measured before and after testing with a toolmaker's microscope.

All butt weld tests were performed on the 6 kip range of a 30 kip capacity Tinius Olsen screw-type testing machine. Load-elongation curves were obtained using an autographic recorder and an extensometer with a 2-inch gage length across the weld, from which the 0.2 per cent offset yield strength of the weldment was determined.

4.3 Butt Weld Test Results

Table 17 gives the yield and tensile strength of the butt weld specimens in both the machined and as-welded condition, as well as the strengths of the annealed and cold-rolled base metal of the sheets from which the specimens were cut. All yield strengths were determined by the 0.2 per cent offset method on a 2" gage length. In both the machined and as-welded condition, ductile failure of the specimens occurred in the weld metal. Ductility data are given in Table 18 for gage lengths of 1/2, 3/4, 1 and 2 inches across the fracture.

Load-elongation curves for four of the butt weld specimens are given in Figs. 20 through 23.

4.4 Discussion of Butt Weld Test Results

a. Comparison of Quarter and Half Hard Specimens

An important point observed in Table 17 is that there was very little difference in the strength of the quarter hard and half hard weldments. The yield strengths averaged 54.2 and 53.1 ksi for the quarter and half hard machined specimens, respectively, while the tensile strengths averaged 108.4 and 103.5 ksi.

b. Joint Efficiencies

In Tables 18 and 19, the test results are analyzed in the usual fashion as described in Section 3. The yield and tensile strength of the machined weldments are compared with the yield and tensile strength of the cold rolled base metal and annealed base metal in Table 18, where the joint efficiencies are calculated in the same manner as described for Tables 11 through 14. Similar trends are observed as in the earlier investigations; most notably, the yield strength of the weldments exceeds that of annealed material by about 50%, as shown in Column 7. The tensile strength of the machined weldments is about equal to that of annealed base material as indicated in Column 8.

Similar comparisons are made for the as-welded specimens in Table 19. The same general trends are observed, with slightly higher "efficiencies" due to the influence of the weld reinforcement.

c. Component Behavior

An attempt now will be made to analyze the test results in terms of the individual components of the weldment.

The yield strength and tensile strength of the weld metal can be determined from examination of the test results from machined weldments in the following manner. All the butt weld specimens failed in the weld metal, hence σ_t of the machined weldments listed in Table 17 is in fact the tensile strength of the weld metal, and averages about 105 ksi. Also, it is noted in Table 20 that for the machined half-hard specimens the percentage elongation in the 1/2" weld zone is approximately four times the percentage elongation in 2". This indicates that virtually no permanent elongation occurred in the adjacent base metal (which had a yield strength higher than the tensile strength of the weld metal). Therefore, σ_y of the machined weldment as listed in Table 17 is approximately equal to the yield strength of the weld metal; this averages about 54 ksi.

The as-welded specimens, which also failed in the welds, show somewhat higher yield and tensile strength (based on the thickness of the sheet), because of the reinforcing effect of the additional thickness of the weld metal. The load-elongation curves in Figs. 20 through 23 give no evidence that the cold-rolled base metal adjacent to the weld was fully annealed. If the base material was fully annealed over any significant length, then the load-elongation curves would show greater departure from a straight line at stresses above about 35 ksi, the yield strength of annealed material as determined from tension coupon tests.

d. Weldment Ductility

Table 21 presents the ductility data differently than Table 20. The per cent elongation in 2 inches for the cold-rolled and the annealed base metal is compared with measured elongation in 2 inches for the welded specimens. With the exception of the quarter hard 16 gage as-welded specimens, the comparison shows that most of the elongation took place in the weld metal or in the immediately adjacent partially annealed base metal. The ductility of the weldments, while considerably less than that of the base metal, appears fully adequate structurally. It should be noted, however, that if the tensile strength of the weld metal were much less than the yield strength of the base metal, fracture might occur at the weld before overall yielding of the member could take place. This could be important in special situations where an overall strain or extension requirement exists.

e. Autogeneous Welds

The 25 gage specimens of half hard material were welded autogenously; that is, no filler metal was used in the welding process (see Table 16). Therefore the "weld metal" for these specimens was essentially the base metal which was melted and resolidified. Moreover, autogenously welded specimens have little or no reinforcement at the welds. In Table 17 the two "machined" 25 gage specimens show a slightly higher average yield and tensile strength than the other machined weldments.

This indicates that the autogeneous weld metal was of about the same strength as the weld metal deposited by the ER 308 filler rods. Similar results were obtained also in Reference 14. The "as welded" 25 gage specimens have essentially the same strength as the "machined" 25 gage specimens (since there was little or no reinforcement), and have slightly lower strength than the as-welded specimens with reinforcement.

The autogeneously welded specimens in this investigation yielded and failed in the weld metal, indicating that the heat-affected zone had a higher yield and tensile strength than the cast weld metal had. The same was true when filler metal of the same composition as the base metal was used in the weldment. Furthermore, the cooling rate of the weld and the time-at-temperature and cooling rate of the heat affected base metal were evidently such that yield strengths higher than the full annealed yield strength were obtained for both the weld and the heat affected zone.

f. Influence of Strain Hardening

It has also been suggested that the strain hardening characteristics of austenitic stainless steels produce most of the weld metal strength increase above the annealed base material strength levels. "During cooling, after solidification of the weld metal, contraction of the weld metal strain hardens the austenite to the strength levels shown in the data"(18).

g. Comparison with Published Data

Table 22 permits comparison of the butt weld strengths obtained in this investigation with data published by others(14,15,16). It is seen that for quarter-hard material, within the usual scatter, present results agree reasonably well with published data, both for as-welded and machined weldments. However, for the half-hard material, present test results are below the limited previously published values. The as-welded half hard specimens of Reference 16 showed an average yield strength 58% higher and an average ultimate strength 12% higher than the current comparable test results. Also, the autogenously welded half hard specimens of Reference 15 showed an average of 28% higher yield strength and 44% higher ultimate strength than the machined or autogenously welded comparable specimens in the current tests. The same welding process (TIG) was used in References 15 and 16 and in the present investigation. In Reference 16 a uniform weld build-up of 20% of the base metal thickness was prescribed. X-ray inspection was used to determine weld quality, and a strict selection procedure was used. "Areas which contained porosity and other defects, even though they were not large enough to be cause for rejection in production welds, were not used for testing"(16). Also, the strength of the half hard specimens in Reference 16 was generally higher than for comparable quarter hard or full hard specimens in the same investigation. In Reference 15 the specimens were made with a single pass without the addition of filler metal. More effective reinforcement, a difference in weld metal composition, stricter inspection, a faster cooling rate, or increased strain hardening due to greater restraint in the welding jig may have contributed to the higher strengths observed for half hard specimens in References 15 and 16.

4.5 Summary of Butt Weld Test Results

The butt weld test results may be summarized as follows:

1. The yield and ultimate strengths of butt welds in quarter and half hard material tested in this investigation are practically equal. This is evidently because these strengths were controlled by the yield and tensile strength of the weld metal, respectively, which was approximately the same for all specimens.

2. The results obtained in the present set of tests for quarter hard material agree with published data for as-welded and machined weldments.

3. For half hard material, the results from the present set of tests for weldments with and without reinforcement are lower than scattered previously published results.

4. Results show that welding produced only partial annealing of the cold-rolled base metal; the yield strength in the heat affected zone was probably reduced, but not down to the fully annealed value. The yield strength of annealed material had little or no influence on the behavior of the cold-rolled stainless steel weldments.

5. The ductility of the weldments, while somewhat less than that of the base metal, appears fully adequate structurally for most applications.

4.6 Recommended Basis for Design of Butt Welds

As stated previously, a butt weldment may be regarded as an assembly consisting of three components: weld metal, heat affected zone, and unaffected base metal. In the tabulation below, the properties which have a strong influence on the behavior of a butt weld specimen of cold-rolled stainless steel are indicated by an "X".

	Yield Strength	Tensile Strength
Cold-Rolled Base Metal	X	
Annealed Base Metal		X
Weld Metal	X	X

That is, the yield strength of annealed base metal has little or no influence on the behavior of the weldment because (1) only partial annealing rather than complete annealing seems to occur, and (2) even if complete annealing did take place over a short length of the specimen adjacent to the weld, this yielding would have negligible influence on the load-elongation curve of the specimen or of an actual structural member under static load. Also, the tensile strength of the cold-rolled base metal is greater than that of the annealed (or partially annealed) base metal and, more important, is usually greater than the tensile strength of the weld metal; hence it will not govern the ultimate strength of the weldment.

It follows that allowable design stresses for butt welds in cold-rolled stainless steels can be based on one of the following values, whichever is smallest:

Cold-rolled Base Material Yield Strength ÷ K1
(to avoid overall yielding) (6a)

Weld Metal Yield Strength ÷ K2
(to avoid yielding of the weld metal) (6b)

Annealed Base Material Tensile Strength ÷ K3
(to avoid fracture of the annealed base metal) (6c)

Weld Metal Tensile Strength ÷ K4
(to avoid fracture of the weld metal) (6d)

K1....K4 are safety factors to be selected in a rational manner. However, it seems reasonable that K2 should be substantially smaller than K1, recognizing the lesser significance of highly localized yielding in the weld compared to overall yielding. In fact, for static loading with no stress reversals, local yielding of the weld metal may be harmless, and the criterion involving K2 could be omitted. Of course K3 and K4 would be larger than K1, thus providing a larger factor of safety against fracture than against overall yielding. K4 might be taken somewhat larger than K3 because of the less certain properties of deposited weld metal.

The specification for allowable stress could be simplified, of course, if there were a known relationship between the yield strengths and the tensile strengths of the weld metal and the base material. ASTM Specification A-298 lists minimum as-deposited properties of E-308 coated electrode as 80,000 psi tensile strength and 35% elongation in 2". No requirement is given for yield strength. Typical rather than minimum values are listed in Reference 19 as 80 to 90 ksi tensile strength, 50 to 60 ksi yield strength, and 35 to 50% elongation in 2". ASTM Specification A-371 gives composition requirements for ER 308 filler wires, but mechanical property requirements are not listed, since these are affected by the welding process. Typical values for 0.252-in. diameter all-weld-metal tension coupons are given in Reference 19 as 52.6 ksi yield strength (0.2% offset), 87.0 ksi tensile strength, and 39% elongation in 2".

If allowable stresses were to be based on the minimum values quoted above, and on ASTM minimum requirements for base material yield and tensile strengths as shown in Table 10, with selected values of K1 = 1.85, K2 = 1.2, K3 = 2.0 and K4 = 2.5, then the allowable stress in a butt weldment of quarter hard Type 301 stainless steel would be computed as follows:

To avoid overall yielding of cold-rolled base material

$$75 \div 1.85 = 40.5 \text{ ksi}$$

To avoid yielding of the weld material

$$50 \div 1.2 = 41.7 \text{ ksi}$$

To avoid fracture of annealed base metal

$$75 \div 2.0 = 37.5 \text{ ksi}$$

To avoid fracture of the weld metal

$$80 \div 2.5 = 32.0 \text{ ksi (governs)}$$

Thus, the allowable stress in a butt weldment of quarter hard stainless steel would be 32.0 ksi. This allowable stress would result in actual values of K1 = 2.3, K2 = 1.56, K3 = 2.3 and K4 = 2.5. Using the same electrode, and the same K-values, and allowable stress of 32.0 ksi would be obtained also for half hard Type 301 stainless.

5. FILLET WELD CONNECTION TESTS

5.1 Test Specimens and Procedure

To study the behavior of fillet welds in cold-rolled stainless steel, 20 lap joint specimens were prepared, 10 with longitudinal fillets and 10 with transverse fillets (Figs. 24 and 25). A transverse weld specimen was composed of two 4" x 20" blanks, and a longitudinal weld specimen was made from one 4" x 20" and one 5" x 20" blank. The test blanks were sheared from Type 301 quarter hard 16 and 22 gage sheets, and half hard 16 and 21 gage sheets. Nominal connection dimensions are given in Table 23. All welds were made manually by a major stainless steel producer using the TIG method with or without ER 308 filler metal, as required. Welding currents ranged from 70 to 80 amperes, and the welding speed was about 10 inches per minute.

Tests were conducted on the 16 and 80 kip ranges of a 400 kip capacity Baldwin Southwark hydraulic testing machine. An attempt was made to autographically obtain load-elongation curves, but because of jarring caused by slip between the specimen and the jaws of the machine, the results were erratic.

5.2 Discussion of Fillet Welds

The standard design procedure for fillet welds usually assumes (1) that all the load is carried by shear on the throat of the weld, and (2) that the cross section of the fillet is an equal-legged right triangle. The first assumption is reasonable for longitudinal fillet welds, but probably is conservative for transverse fillet welds, as shown in Fig. 26. For transverse fillet welds, a normal stress component σ_o can act on the throat of the fillet, and thus reduce the shear stress τ_o required to carry the load P. Also, for thin elements such as used in this investigation, the leg of the fillet perpendicular to the thickness direction of the sheets is usually considerably longer than the leg parallel to the thickness direction. Specifications often state that "the effective throat thickness of a fillet weld shall be the shortest distance from the root to the face of the diagrammatic weld"(20). Adherence to this statement would lead to a proper determination of the minimum throat thickness, but in addition, this flatter shape also produces a more favorable stress distribution in a transverse fillet weld, by increasing the normal stress component and decreasing the shear stress component on the throat.

Examination of the fillet welds in the test specimens in the program indicated (1) the shape of the weld cross section usually was not a 45° right triangle, but rather more like that shown in Fig. 27, where the leg perpendicular to the thickness of the sheet is three to six times the length of the leg parallel to the sheet, and (2) in the welding process, the upper corner of the lap plate "breaks down" as shown in Fig. 27. These two factors tend to counteract each other, and the throat dimension of the weld may be about 2/3 to 3/4 of the thickness of the sheet. Hence, it was estimated that the effective throat thickness was approximately equal to $t/\sqrt{2}$ as is the case for equal-legged welds with leg length t. Therefore, shear stress values in the subsequent table were computed in the usual fashion assuming a throat thickness of $t/\sqrt{2}$.

5.3 Fillet Weld Test Results

Test results for the fillet weld specimens are given in Tables 24 and 25. For fillet welds, meaningful values of yield strength in any conventional sense (e.g. elongation in 2" gage length) cannot be easily defined. For this reason, only ultimate strengths have been recorded. Figs. 28 and 29 illustrate the best load-elongation curves obtained with the autographic recorder. Failure of the fillet welded quarter and half hard stainless steel specimens would be expected in either (1) the weld metal, or (2) the annealed or partially annealed base metal of the weldment. Examination of the specimens showed that failures occurred in the weld metal or near the interface of the base metal and weld metal. The manner in which the specimens failed is described below.

a. Transverse Fillets (Quarter Hard)

All of the quarter hard transverse specimens followed an identical pattern from load initiation to failure. At between 80 and 90% of the failure stress, warping was observed in the plate with the free end, along an axis parallel to the weld. Once the ultimate load was reached, the load dropped slightly and failure occurred quickly, usually by fracture in the weld metal or at the fusion line and sometimes extending into the heat affected zone. The fracture stress for the 16 gage, 2 inch weld specimen was 89% of the ultimate stress. Table 25 gives the warping, ultimate, and subsequent fracture stress for the quarter hard transverse fillet specimens.

b. Transverse Fillets (Half Hard)

Again, all specimens followed an identical pattern of failure. Warping was observed at approximately 90% of the ultimate stress. Failure in the weld metal or at the fusion line again occurred rapidly by a quick fracture. For the 16 gage, 3 inch weld and the 21 gage, 2 1/2 inch weld, the load dropped off considerably and fracture occurred at a load 50% below the ultimate. One exception occurred within this group, in the 16 gage, 1 inch specimen, where no noticeable warping occurred in the plates. Table 25 gives the warping, ultimate, and fracture stresses.

c. Longitudinal Fillets (Quarter Hard)

In general, these specimens warped in the 4" plate convexly along a longitudinal axis at stresses between 60 and 90% of the ultimate shear stress. Once one of the two welds failed in the weld metal or along the fusion line, the load dropped considerably, but then rose again to between 11 and 32% of the ultimate. Tests that deviated from this pattern will be discussed separately. Table 25 gives warping, ultimate, and failure shear stresses on the nominal throat.

Q16FL-3: In this specimen, the general failure pattern was the same as described above, except for the initiatiion of a transverse crack in the base metal of the 4" blank at the end of the weld nearest the applied load. The first weld failed at a shear stress of 77 ksi. The second weld failed at a nominal shear stress of 17 ksi, while the crack was propagating.

Q22FL-1: Warping began in the 4 inch plate at a stress of 83 ksi. At the ultimate load, warping along a longitudinal line disappeared due to undercurling of the 4-inch plate and left the plate with local convex warping at the weld, along a transverse line.

Q22FL-2: As in specimen Q16FL-3, one weld failed, while the other did not. Crack propagation in the 4-inch plate caused the final failure. One difference from specimen Q16FL-3 was that a crack in the heat affected zone was also forming at the time of the crack propagation in the base metal.

d. Longitudinal Fillets (Half Hard)

Again, these specimens showed warping convexly in the 4-inch plate along a longitudinal axis at stresses around 75% of the ultimate shear stress. Once a weld failed in the weld metal or fusion line, the load dropped, rose again, and caused final failure in the specimen by the second weld also failing. The second weld failed at stresses either equal to those of the first weld (when both welds failed simultaneously) or at about 50% of the failure shear stress of the first weld.

H16FL-1: This specimen deviated from the general pattern in two ways. The final shape of the specimen was not warped, and both welds failed simultaneously.

H16FL-2: This specimen again had no warping in the plates.

H16FL-3: This specimen had a small amount of warping, but again both welds failed simultaneously.

H21FL-2: Here, failure was similar to that in specimen Q22FL-2. It differed in that the plate began tearing transversely before the weld failed. In spite of this initial plate tearing, the specimen continued to take more load until one of the welds failed at a stress of 82 ksi. The second weld did not fail, but tearing of the plate caused final failure. At a nominal weld stress of 7.6 ksi, after the ultimate load had been reached, it was noticed that a crack initiated in the heat affected zone.

5.4 Discussion of Longitudinal Fillet Weld Test Results

The longitudinal fillet weld specimens failed primarily in the weld or at the fusion line. It is recalled that the tension strength of weld metal as previously determined in butt weld tests is slightly less than the tensile strength of the annealed base metal as listed in Table 17. Table 24 indicates that there is very little difference in the strength of longitudinal fillet welds in the quarter and half hard specimens; τ_o averages 80.3 and 83.0 ksi, respectively.

The test results were represented graphically in a number of ways in an attempt to determine the best functional relationship. In Fig. 30, the calculated shear strength, τ_o, is plotted against (a) length of weld, L, (b) sheet thickness, t, and (c) 2L/t. Fig. 30a shows a tendency toward decreasing weld strength (in ksi) with increasing weld length. A similar trend was observed in light gage carbon steel fillet weld pilot tests at Cornell many years ago, and also in recent tests at IITRI, presumably in consequence of stress concentrations at the ends of the welds. On the other hand, recent fillet weld tests in heavier hot rolled plate specimens showed a very slight tendency toward increased unit strength as the length of the weld was increased(21). Fig. 30b indicates a decrease in unit weld strength with increasing sheet thickness.

Attempts were made to correlate weldment strength with (a) the tensile strength of the cold-rolled base metal, σ_{tb}, (b) the tensile strength of the weld metal, σ_{tw}, and (c) the tensile strength of annealed base metal, σ_{ta}. The strength of the weld metal was assumed to be 105 ksi as determined in the butt weld tests. Graphical representation of these correlations are shown in Figs. 31a, b and c, respectively, where the abscissa in each case is the weld length, and in Figs. 32a, b and c where the abscissa is 2L/t. Good correlation would be indicated by minimum vertical scatter of the test points. However, each of the graphs shows about the same amount of scatter.

In an earlier stage of this research, longitudinal fillet weld strength predictions were obtained in terms of L/t. Because of the limited number of tests, however, it may be just as well to use a simpler expression to predict failure. As indicated above, most of the longitudinal fillet weld specimens failed primarily in the weld or at the interface between the weld metal and base metal. From Figs. 31 and 32, a lower bound to the failure stress is given by

$$\tau_o = 0.6\ \sigma_{tw} \tag{7a}$$

or

$$\tau_o = 0.6\ \sigma_{ta} \tag{7b}$$

There is some logical basis for these simple expressions, since the shear strength of steel is often taken as about 0.6 of the tensile strength.

5.5 Discussion of Transverse Fillet Weld Test Results

Failures in the transverse fillet weld specimens were about evenly divided between the weld metal and the fusion line. Table 24 again indicates that there is very little difference in the strength of fillet welds in the quarter and half hard specimens; τ_o averages 127 ksi for the quarter hard transverse fillets, and 126 ksi for the half hard transverse fillets.

The failure stresses, τ_o, computed on the basis stated in Section 5.2, are considerably higher for the transverse than for the longitudinal fillet welds, which is usually the case.

In Fig. 33, τ_o is plotted against L/s and the sheet thickness, t. A slight trend toward decreasing weld strength (per unit area) with increasing weld length is again indicated. Fig. 33b shows a definite but moderate decrease in weld strength with increasing sheet thickness for the transverse fillet welds, a doubling of the thickness producing a strength decrease of less than 20%.

Once again, attempts were made to correlate weldment strength with (a) the tensile strength of the cold-rolled base metal, σ_{tb}, (b) the tensile strength of the weld metal, σ_{tw}, and (c) the tensile strength of the annealed base metal, σ_{ta}. Graphical representation of these correlations are shown in Figs. 34a, b and c, respectively, where the abscissa is the ratio of weld length to specimen width, L/s. Again, good correlation would be indicated by minimum vertical scatter of the test points, and as before, each of the graphs shows about the same amount of scatter. From Fig. 34, a lower bound to the faulure stress for transverse fillets is given by

$$\tau_o = 1.0\ \sigma_{tw} \tag{8a}$$

or

$$\tau_o = 0.9\ \sigma_{ta} \tag{8b}$$

As discussed in Section 5.2, two reasons for the high ratio between the apparent failure stress in shear and the failure stress in tension are (1) the computation method overestimates the actual shear stress in a transverse fillet, and (2) the fillet cross section was not a 45° right triangle, but a flatter triangle, which further reduces the actual shear stress in a transverse fillet weld. The results could be interpreted as indicating that these transverse fillet welds failed primarily in tension on a section with minimum throat thickness of approximately $t/\sqrt{2}$.

5.6 Summary of Fillet Weld Test Results

The fillet weld test results may be summarized as follows:

1. All the fillet weld specimens failed in the weld metal or at the interface of the base metal and weld metal.

2. The strength of the fillet welds in quarter and half hard material tested in this investigation were practically equal.

3. There was a decrease in the failure stress of the fillet welds with increased thickness of the sheets.

4. There was a slight decrease in the failure stress of fillet welds with increased weld length.

5. A lower bound to the failure stress for longitudinal fillet welds is given by $\tau_o = 0.6\ \sigma_{tw}$ or $\tau_o = 0.6\ \sigma_{ta}$.

6. A lower bound to the failure stress for transverse fillet welds is given by $\tau_o = 1.0\ \sigma_{tw}$ or $\tau_o = 0.9\ \sigma_{ta}$.

5.7 Suggested Basis for Design of Fillet Welds

It appears from the above that fillet welds in cold-rolled stainless steel can be designed on the basis of allowable shear stresses on the throat of the fillet computed in the customary fashion. For longitudinal fillet welds, the allowable shear stress can be based on the smallest of the following values:

0.6 x Yield Strength of the Weld Metal in Tension ÷ K5 (9a)
0.6 x Tensile Strength of the Weld Metal ÷ K6 (9b)
0.6 x Tensile Strength of Annealed Base Metal ÷ K7 (9c)

K5 is a factor of safety against yielding, and K6 and K7 are factors of safety against fracture. As discussed under butt welds, local yielding of the weld metal may be of no consequence, and the criterion involving K5 could be omitted.

Test results indicate that failure stresses in shear in transverse fillet welds computed in the usual fashion are much higher than maximum computed shear stresses in longitudinal fillets. Most specifications neglect this because of the possible uncertainty of the direction of the applied stress, but it could be the basis for as much as a 40 percent increase in allowable stresses on fillet welds that are subjected to transverse loads only.

Following the reasoning described in Section 4.6 for butt welds, with K5 = 1.2, K6 = 2.5 and K7 = 2.0, and assuming minimum values for the tensile strength of the annealed base metal and for the yield and tensile strength of the weld metal, the allowable shear stress on the throat of fillet welds in quarter hard Type 301 stainless steel would be computed as follows:

To avoid yielding of the weld metal,

$$0.6 \times 50 \div 1.2 = 25 \text{ ksi}$$

To avoid fracture of the weld metal,

$$0.6 \times 80 \div 2.5 = 19.2 \text{ ksi} \quad \text{(governs)}$$

To avoid fracture of the annealed base metal

$$0.6 \times 75 \div 2.0 = 22.5 \text{ ksi}$$

Thus the allowable shear stress on the throat of a fillet weld in quarter hard Type 301 stainless steel would be 19.2 ksi. Using the same welding procedures and the same K-values, an allowable shear stress of 19.2 ksi would be obtained also for half-hard Type 301 stainless.

It is interesting to note that recent revisions in the AISC Specification(20) provide a basic allowable shear stress on the effective throat of fillet welds of 0.3 of the tensile strength of the weld. The present numerical example, above, produces an allowable shear stress of 0.24 of the tensile strength of the weld for cold-rolled Type 301 stainless steel, in fair agreement with the quoted AISC Specification.

If advantage is to be taken of the greater strength of transverse fillet welds,for such welds the coefficient 0.6 in Eqs. 9 and in the numerical example could be replaced by 0.8. This would take advantage of the more favorable stress state on transverse fillets, but would not require the low profile obtained in the current tests.

6. SUMMARY AND CONCLUSIONS

A survey of industry practice has shown that fusion welds, resistance (spot) welds and bolted connections account for 90% or more of the connections currently used in stainless steel fabrication. The research described herein was undertaken to obtain information on the static strength and behavior of structural connections of Type 301 stainless steel in the 1/4 and 1/2 hard tempers. The minimum shear strength for resistance welds in these materials has been tabulated by the American Welding Society, and is included in Tables 7 and 8. Therefore this investigation was limited primarily to bolted connections and to fusion welded connections using butt welds, longitudinal fillet welds and transverse fillet welds. Expressions for the failure loads or stresses for the connections as a function of the appropriate material properties and geometric parameters are given in the respective sections of the report. These failure loads or stresses can be reduced by appropriate safety factors to arrive at allowable design stresses for connections in cold-rolled stainless steel.

A total of 25 bolted connection tests were conducted using 1/2 hard stainless steel sheets. The results are summarized in Section 2.8. They indicate the same type of failures as encountered in earlier tests of low carbon steel sheets, and the same form of equations can be used to predict failure, with some modification of empirical coefficients. The strengths of certain austenitic stainless steel bolts reported in the literature are given in Table 6.

All twenty-four of the butt welded specimens tested in this investigation failed in the weld, and the yield and tensile strength of the specimens were controlled by the yield and tensile strength, respectively, of the weld metal. The results are summarized in Section 4.5. These tests, as well as tests conducted earlier by others, indicate that the use of the annealed material yield strength values for butt welded joints in cold-rolled stainless steel is overly conservative. Alternative recommendations for a basis for design are given in Section 4.6.

Results of ten longitudinal fillet weld tests led to the following expressions as a lower bound to the nominal shear stress on the throat of a fillet weld at failure:

$$\tau_o = 0.6\ \sigma_{tw}$$

or

$$\tau_o = 0.6\ \sigma_{ta}$$

where σ_{tw} is the tensile strength of the weld metal and σ_{ta} is the tensile strength of the annealed base metal. The corresponding lower bounds from the ten transverse fillet weld tests were

$$\tau_o = 1.0\ \sigma_{tw}$$

$$\tau_o = 0.9\ \sigma_{ta}$$

A suggested basis for design of fillet welds in quarter hard and half hard Type 301 stainless steel is outlined in Section 5.7.

7. ACKNOWLEDGMENTS

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TABLE 1 PERCENTAGE OF PRODUCTION USING VARIOUS FASTENING TECHNIQUES

COMPANY*			(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)
WELDING	FUSION	ARC	100	100	100	100	100	95	90	81	70	40	36	.1	5	16	70	100
		GAS						4					1		1			
	RESISTANCE	SPOT							5	3		25	24		10	8	10	
		PROJ.											15		1			
		SEAM						1					18			1		
		FLASH											3		1	1		
	OTHERS										10		3					
BOLTS										10	15					2	25	25
RIVETS	HOT DRIVEN																	
	COLD DRIVEN														10	3	5	
SCREW									5	5	5				2			
ADHESIVES										1		25						
OTHER DEVICES												10		.3				
Σ			100	100	100	100	100	100	100	100	100	100	100	.4**	30**	31**	110**	125**

* Companies responding are identified by a number only.

** Summation of the percentages not equal to 100

TABLE 2
MECHANICAL PROPERTIES OF BASE MATERIALS - BOLTED CONNECTIONS

SOURCES		*				CORNELL TEST†				PRODUCER			
Base Matls.	σ-ε Curve	E $\times 10^{-3}$ ksi	σ_y ksi	σ_t ksi	Elong. in 2" %	E $\times 10^{-3}$ ksi	σ_y ksi	σ_t ksi	Elong. in 2" %	E $\times 10^{-3}$ ksi	σ_y ksi	σ_t ksi	Elong. in 2" %
Heat 840731 16 gage (.060")	LT ††	27.0	123.1	166.6	24.1	29.3	123.4	165.8	23.8	**	**	**	**
	LC	28.1	97.7	--	--	26.2	101.0	--	--	**	**	--	--
	TT	28.8	136.6	170.0	18.1	28.8	138.5	167.3	22.3	**	**	**	**
	TC	28.8	157.6	--	--	28.2	152.7	--	--	**	**	--	--
	AVE	28.4	127.3	--	--	**	**	--	--	**	**	--	--
Heat 3342415 21 gage (.033")	LT	27.5	134.0	193.8	19.8	29.4	129.2	188.0	21.5	27.4	125.0	182.5	27.5
	LC	28.3	98.9	--	--	27.1	97.5	--	--	27.8	80.2	--	--
	TT	28.8	124.2	192.5	16.0	30.0	115.6	188.0	21.1	28.4	120.0	185.0	24.5
	TC	32.0	155.1	--	--	28.9	149.6	--	--	31.1	139.5	--	--
	AVE	29.1	127.8	--	--	**	**	--	--	**	**	--	--
Heat 19386 25 gage (.021")	LT	29.4	132.2	165.4	28.5	29.6	132.5	165.4	28.9	27.4	142.2	166.5	27.0
	LC	27.2	86.1	--	--	27.6	85.0	--	--	33.0	86.3	--	--
	TT	30.0	123.5	165.9	25.0	29.9	124.2	166.4	25.0	29.9	127.7	166.6	20.5
	TC	28.5	141.3	--	--	28.6	141.2	--	--	32.6	150.2	--	--
	AVE	28.6	120.4	--	--	**	**	--	--	**	**	--	--

* From coupon tests for particular sheets used for bolted connection specimens. These data are used in reduction of data in Section 2.6 of this report.

** Not Available.

† Adopted from Reference 3 for Type 301 - 1/4 and 1/2 Hard Stainless Steel.

†† LT = Longitudinal Tension, LC = Longitudinal Compression

TT = Transverse Tension, TC = Transverse Compression

TABLE 3
BOLTED CONNECTION TEST PROGRAM

Sheet	Bolt		Bolt Diameter / Bolt Spacing d/s	e/d	Edge Dist. e (in)	Con-nec-tion	Remarks
	Size	No.					
Heat	3/8"	1	.0938	1.5	.563	SS	*
840731	"	1	"	4.5	1.688	DS	
16 gage	1/2"	1	.1250	3.5	1.750	DS	
	3/4"	1	.1875	2.5	1.875	SS	
t= .0622"	"	1	"	3.5	2.625	SS	**
	"	1	"	4.5	3.375	SS	**
	1/4"	1	.0625	1.5	.375	SS	*
Heat	"	1	"	4.5	1.125	DS	
3342415	3/8"	1	.0938	2.5	.938	SS	
21 gage	"	1	"	4.5	1.688	DS	
	1/2"	1	.1250	2.5	1.250	SS	*
t= .0325"	"	2	.2500	4.5	2.250	SS	
	"	1	.1250	3.5	1.750	SS	
	3/4"	1	.1875	2.5	1.875	SS	
	"	2	.3750	3.5	2.625	SS	
	"	1	.1875	4.5	3.375	SS	**
Heat	1/4"	2	.1250	4.5	1.125	DS	
19386	1/2"	2	.2500	4.5	2.250	DS	
t= .0204"	3/4"	2	.3750	4.5	3.375	DS	

* Duplicate Tests: one test with bearing and the other with clearance.

** Repeated test with double shear connection.

TABLE 4 - BOLTED CONNECTION TEST RESULTS

SPECIMEN		Type of Fit	Connection	SHEET		Edge Distance (in)	BOLT			e/d	d/s	Slip Load (lb)	Proof Load (lb)	Failure Load (lb)	AT PROOF LOAD		AT FAILURE LOAD				Type of Failure
No.	Designation			Thickness (in)	Width (in)		No.	Size (in)	Hole (in)						Bearing Stress (ksi)	Deformation (in)	Gross Stress (ksi)	Net Stress (ksi)	Bearing Stress (ksi)	Deformation (in)	
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)	(19)	(20)	(21)	(22)
1	16C15S13	C	SS	.0620	3.992	0.551	1	3/8	.414	1.47	.094	1,740	4,750	5,820	204.30	.14	23.51	26.23	250.32	.29	I
2	16B15S13	B	SS	.0624	4.000	0.559	1	3/8	.414	1.49	.094	1,840	5,130	5,780	219.23	.14	23.16	25.83	247.00	.24	I
5	16B25S16	B	SS	.0624	4.008	1.871	1	3/4	.758	2.49	.187	6,500	10,800	15,400	230.77	.11	61.58	75.94	329.06	.27	IIIc
4	16B35D14	B	DS	.0622	4.008	1.739	1	1/2	.570	3.48	.125	3,900	10,950	13,400	352.09	.16	53.75	62.67	430.87	.46	II
6	16C35S16	C	SS	.0620	4.008	2.621	1	3/4	.758	3.50	.187	7,600	8,000	16,300	172.04	.03	65.60	80.89	350.54	**	***
20	16C35D16	C	DS	.0622	4.000	2.633	1	3/4	.766	3.51	.188	*	20,800	22,900	445.87	.13	92.04	113.83	490.89	.43	II
3	16C45D13	C	DS	.0621	3.992	1.684	1	3/8	.414	4.49	.094	3,500	5,700	8,060	244.76	.05	32.51	36.27	346.10	.22	IV
7	16B45S16	B	SS	.0619	4.000	3.371	1	3/4	.758	4.49	.188	7,750	12,500	15,200	269.26	.09	61.39	75.74	327.41	.22	IIIa
21	16B45D16	B	DS	.0624	4.008	3.332	1	3/4	.758	4.49	.187	9,600	20,400	24,250	435.89	.20	96.97	119.58	518.16	.59	II
8	21C15S12	C	SS	.0322	4.008	0.371	1	1/4	.258	1.48	.062	1,120	1,530	2,510	190.06	.02	19.45	20.79	311.80	**	I
9	21B15S12	B	SS	.0326	4.000	0.367	1	1/4	.250	1.47	.063	660	2,340	2,595	287.12	.14	19.90	21.23	318.40	.25	I
11	21C25S13	C	SS	.0324	4.000	0.922	1	3/8	.406	2.46	.094	1,900	4,100	4,950	337.45	.23	38.19	42.51	407.41	.39	I
13	21C25S14	C	SS	.0325	3.992	1.246	1	1/2	.570	2.49	.125	3,000	3,980	6,340	244.92	.25	48.86	57.01	390.15	.49	Ia
14	21B25S14	B	SS	.0325	4.000	1.239	1	1/2	.570	2.48	.125	3,050	5,000	5,820	307.69	.18	44.77	52.21	358.15	.34	Ia
17	21C25S16	C	SS	.0322	3.992	1.849	1	3/4	.758	2.46	.188	6,480	7,800	9,000	322.98	.12	70.01	86.42	372.67	.29	***
16	21C35S14	C	SS	.0325	4.000	1.739	1	1/2	.570	3.48	.125	2,800	5,030	6,100	309.54	.31	46.92	54.73	375.38	.68	IIa
18	21C35S26	C	SS	.0326	4.008	2.605	2	3/4	.758	3.48	.375	1,820	12,300	16,600	251.53	.13	127.05	204.32	339.47	.23	III
10	21B45D12	B	DS	.0325	4.000	1.117	1	1/4	.250	4.47	.063	*	3,800	4,100	467.69	.04	31.54	33.64	504.61	.19	II
12	21B45D13	B	DS	.0320	3.992	1.680	1	3/8	.422	4.48	.094	2,010	4,000	6,380	333.33	.16	49.94	55.84	531.67	.53	II
15	21B45S24	B	SS	.0327	4.008	2.239	2	1/2	.570	4.48	.125	6,400	11,100	12,500	339.45	.27	95.38	133.32	382.26	.48	IIIb
19	21C45S16	C	SS	.0324	4.008	3.364	1	3/4	.758	4.49	.187	6,450	8,240	11,260	339.09	.10	86.71	106.93	463.37	.20	***
22	21C45D16	C	DS	.0327	4.008	3.379	1	3/4	.766	4.50	.187	7,600	14,100	16,020	574.92	.13	114.74	151.10	653.21	.18	IIIa
23	25B45D22	B	DS	.0209	4.008	1.131	2	1/4	.262	4.52	.125	2,300	3,850	4,700	368.42	.16	56.11	64.54	449.76	.31	II
24	25C45D24	C	DS	.0210	4.016	2.231	2	1/2	.539	4.46	.249	7,100	10,200	10,620	485.71	.13	125.94	172.17	505.71	.18	III
25	25B45D26	B	DS	.0210	4.016	3.348	2	3/4	.570	4.46	.373	6,100	12,600	12,970	400.00	.06	153.80	214.82	411.75	.22	III

Remarks:
* : difficult to determine from the load-deformation graph.
** : not recorded.
*** : failed in complex manner.

TABLE 6

MECHANICAL PROPERTIES FOR STAINLESS STEEL BOLTS

Material	Condition	Diameter (in)	Mechanical Requirements*			Computed Allowable** Shear Stress ksi
			0.2% Y.S. (min) ksi	T.S. (min) ksi	Elongation (min) %	
AISI 303,305, 316	Solution Annealed	Up to 1 1/2" inclusive	30	75	20	18
AISI 305,316	Cold Worked	up to 1 1/2" inclusive	50	100	20	24
AISI 305,316	Strain Hardened	to 5/8"	100	125	20	30
		over 5/8" to 1"	70	105	20	25.2
		over 1" to 1 1/2"	50	90	20	21.6

* Adopted from Industrial Fasteners Institute's Specification for Mechanical and Quality Requirements for Stainless Steel and Nonferrous Bolts, Screws, Studs and Nuts. (14)

** 60% of the min. tensile strength divided by a safety factor of 2.5.

TABLE 7

SHEAR STRENGTH OF SPOT WELDS

Thickness of Thinnest Outside Sheet in.	Min. Shear Strength lb. per spot*		Allowable Shear Str. lb. per spot**	
	1/4 Hard	1/2 Hard	1/4 Hard	1/2 Hard
.006	70	85	28	34
.008	130	145	52	58
.010	170	210	68	84
.012	210	250	84	100
.014	250	320	100	128
.016	300	380	120	152
.018	360	470	144	188
.021	470	500	188	200
.025	600	680	240	272
.031	800	930	320	372
.034	920	1,100	368	440
.040	1,270	1,400	508	560
.044	1,450	1,700	580	680
.050	1,700	2,000	680	800
.056	2,000	2,450	800	980
.062	2,400	2,900	960	1,160
.070	2,800	3,550	1,120	1,420
.078	3,400	4,000	1,360	1,600
.109	5,000	6,400	2,000	2,560
.125	6,000	7,600	2,400	3,040

TABLE 8

SHEAR STRENGTH OF PULSATION WELDS

Thickness of Thinnest Outside Sheet in.	Min. Shear Strength lb. per spot*		Allowable Shear Str. lb. per spot**	
	1/4 Hard	1/2 Hard	1/4 Hard	1/2 Hard
.156	7,600	10,000	3,040	4,000
.187	9,750	12,300	3,900	4,920
.203	10,600	13,000	4,240	5,200
.250	13,500	17,000	5,400	6,800

*(1) Adopted from American Welding Society's *Recommended Practices for Resistance Welding* (AWS Designation C1.1-66).(13)
(2) Type of steel - 301, 302, 303, 304, 308, 309, 310, 316, 321, 347 and 349.

**A factor of safety 2.5 is used to obtain allowable shear stress.

TABLE 9

MECHANICAL PROPERTIES OF TYPE 301 BASE METAL[†]
(Annealed and Quarter-hard)

Sheet Thickness (in.)	Heat Number	Temper	.2% Offset Y.S. (ksi)	Tensile Strength (ksi)	Elongation in 2" Gage (%)	T.S./Y.S.
.019	3343108	Annealed	34.3	131.9	60.5	3.84
		1/4-Hard	83.0	146.5	50.5	1.77
.050	3343617	Annealed	36.9	103.8	74.0	2.81
		1/4-Hard	95.5	129.0	42.0	1.35
.093	3570453	Annealed	33.6	100.0	72.0	2.98
		1/4-Hard	93.0	134.5	37.0	1.45
.187	3570644	Annealed	33.4	111.9	65.5	3.35
		1/4-Hard	94.0	129.5	33.5	1.38

[†] Data from Reference 14

Remarks: 1. Average of two tests for each thickness.
2. Annealed at 1900 degrees F, AC.

TABLE 10

ASTM MECHANICAL PROPERTY REQUIREMENTS FOR TYPE 301 STAINLESS
(Annealed and Quarter-hard)

Thickness	Temper	Min. .2% Offset Y.S. (ksi)	Tensile Strength Min. (ksi)	Elongation in 2" Gage (%) Min.	T.S.*/Y.S.
< 3/16"	Annealed	30	75	40	2.50
< 3/16"	1/4-Hard	75	125	25	1.67

Remarks: Adopted from ASTM Standard Specifications: A167-69 and A177-69.

*Not a requirement.

TABLE 12

MECHANICAL PROPERTIES OF 1/4-HARD TYPE 301 BUTT-JOINT WELDMENTS[†]
MIG PROCESS

Thickness (in) Heat No.	0.2% Offset Y.S. (ksi)	Tensile Strength (ksi)	Elong. in 2" Gage (%)	T.S./Y.S.	Joint Efficiency based on: Annealed Sheet Y.S. (%)	Annealed Sheet T.S. (%)	1/4-Hard Sheet Y.S. (%)	1/4-Hard Sheet T.S. (%)	Remark
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	
.019 3343108	71.0	150.0	48	2.11	207.0	113.8	85.5	102.4	
	71.0	146.0	40	2.06	207.0	110.8	85.5	99.7	
	71.0	153.0	50	2.16	207.0	116.0	85.5	104.5	
	71.0	149.7	46.0	2.11	207.0	113.5	85.5	102.2	Average
.050 3343617	65.0	110.0	11	1.69	176.2	106.0	68.1	85.3	
	68.0	113.0	15	1.66	184.2	108.9	71.2	87.6	
	68.0	115.0	17	1.69	184.2	110.8	71.2	89.2	
	67.0	112.7	14.3	1.68	181.6	108.6	70.1	87.4	Average
.093 3570453	67.0	122.0	23	1.82	199.4	122.0	72.0	90.7	
	67.0	123.0	23	1.84	199.4	123.0	72.0	91.4	
	68.5	120.0	22	1.75	203.9	120.0	73.6	89.2	
	67.5	121.7	22.7	1.80	200.9	121.7	72.6	90.5	Average
.187 3570644	64.0	106.0	10	1.66	191.6	94.8	68.1	81.8	
	62.0	106.0	10	1.71	185.6	94.8	65.9	81.8	
	63.0	110.0	13	1.75	188.6	98.4	67.0	84.9	
	63.0	107.3	11.0	1.70	188.6	96.0	67.0	82.9	Average

Notes:

1. MIG with ER-308 filler metal; (pulsed type).
2. $$\text{Joint Efficiency (\%)} = \frac{\text{Weldment Strength}}{\text{Base Metal Strength}} \times 100$$
3. Weld reinforcement not removed but base metal thickness used to calculate stresses.

[†] Data from Reference 14

TABLE 13

MECHANICAL PROPERTIES OF 1/4-HARD TYPE 301 BUTT-JOINT WELDMENTS †
Coated Electrode Process

Thickness (in) Heat No.	0.2% Offset Y.S. (ksi)	Tensile Strength (ksi)	Elong. in 2" Gage (%)	$\frac{\text{T.S.}}{\text{Y.S.}}$	Joint Efficiency based on Annealed Sheet		Joint Efficiency based on 1/4-Hard Sheet		Remark
					Y.S. (%)	T.S. (%)	Y.S. (%)	T.S. (%)	
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	
.050 3343617	79.0	109.0	10	1.38	214.1	105.0	82.8	84.5	
	93.0	127.0	25	1.37	252.0	122.4	97.4	98.5	
	93.0	125.0	25	1.34	252.0	120.5	97.4	96.9	
	88.3	120.3	20.0	1.36	239.4	116.0	92.5	93.3	Average
.093 3570453	89.0	120.0	20	1.35	264.9	120.0	95.7	89.2	
	83.0	113.0	15.	1.36	247.0	113.0	89.3	84.0	
	87.0	121.0	20	1.39	258.9	121.0	93.5	90.0	
	86.3	118.0	18.3	1.37	256.9	118.0	92.8	87.7	Average
.187 3570644	80.5	109.0	9	1.35	241.0	97.5	85.6	84.2	
	74.0	112.5	10	1.52	221.6	100.6	78.7	86.9	
	88.0	123.0	15	1.40	264.5	110.0	93.6	94.9	
	80.8	114.8	11.3	1.42	242.4	102.6	85.9	88.6	Average

Remarks: 1. With E-308 electrode.

2. Joint Efficiency (%) = $\frac{\text{Weldment Strength}}{\text{Base Metal Strength}} \times 100$

3. Weld reinforcement not removed but base metal thickness used to calculate stresses.

† Data from **Reference** 14

TABLE 14

MECHANICAL PROPERTIES OF 1/4-HARD TYPE 301 BUTT-JOINT WELDMENTS TIG PROCESS WITH OR WITHOUT REINFORCEMENT †

Welding Condition	Thickness (in) Heat No.	0.2% Offset Y.S. (ksi)	Tensile Strength (ksi)	Elong. in 2" Gage (%)	$\frac{\text{T.S.}}{\text{Y.S.}}$	Joint Efficiency based on			
						Annealed Sheet		1/4-Hard Sheet	
						Y.S. (%)	T.S. (%)	Y.S. (%)	T.S. (%)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
As-weld	.093	65.0	111.0	20	1.71	193.5	111.0	69.9	82.5
As-weld	.093	65.0	114.0	23	1.75	193.5	114.0	69.9	84.8
As-weld	.093	65.0	112.0	22	1.72	193.5	112.0	69.9	83.3
(Average)		65.0	112.3	21.7	1.73	193.5	112.3	69.9	83.5
Machined	.078	46.8	92.2	11.5	1.97	139.3	92.2	50.3	68.5
Machined	.090	53.5	85.2	12.5	1.59	159.2	85.2	57.5	63.6
Machined	.091	54.6	89.4	13.5	1.61	162.6	89.4	58.7	66.5
(Average)		51.6	88.9	12.5	1.72	153.6	88.9	55.5	66.1

Remarks:

1. TIG with ER-308 filler metal.
2. Joint Efficiency (%) = $\frac{\text{Weldment Strength}}{\text{Base Metal Strength}} \times 100.$
3. For as-welded condition, weld reinforcement has not been removed, but base metal thickness was used to calculate stresses.

   For machined condition, thickness was measured after machining to remove weld bead.
4. All weldments were made of quarter-hard sheet of thickness .093" and heat no. 3570453.

† Data from Reference 14

TABLE 15

BUTT WELD CONNECTION DIMENSIONS

	Weldments(Machined)				Weldments(As Welded)			
Spec. No.	Weld Thick. in.	Plate Thick. in.	Plate Width in.	Plate Area Sq.in.	Weld Thick. in.	Plate Thick. in.	Plate Width in.	Plate Area Sq.in.
Q16B-1	0.061	0.060	0.50	0.030	0.078	0.060	0.499	0.030
Q16B-2	0.061	0.060	0.50	0.030	0.094	0.061	0.499	0.030
Q22B-1	0.033	0.032	0.50	0.016	0.069	0.031	0.50	0.016
Q22B-2	0.040	0.031	0.50	0.016	0.057	0.031	0.50	0.016
Q22B-3	0.041	0.031	0.50	0.016				
Q22B-4	0.032	0.032	0.50	0.016				
H16B-1	0.063	0.062	0.50	0.031	0.081	0.062	0.50	0.031
H16B-2	0.063	0.063	0.50	0.032	0.076	0.063	0.50	0.032
H21B-1	0.040	0.032	0.50	0.016	0.057	0.030	0.50	0.015
H21B-2	0.032	0.032	0.50	0.016	0.031	0.031	0.50	0.016
H21B-3	0.032	0.032	0.50	0.016				
H21B-4	0.032	0.032	0.50	0.016				
H25B-1	0.037	0.022	0.50	0.011	0.031	0.020	0.50	0.010
H25B-2	0.036	0.021	0.50	0.011	0.039	0.020	0.50	0.010

TABLE 16

BUTT WELD PROCESS DATA

Sheet Gage	Back-up Groove	Back-up Opening	Tungsten Electrode	Filler Metal	Argon Flow	Welding Speed	Voltage	Current
	in.	in.	in.	in.	cfh	ipm	v	amp
16	0.200	1/2	1/16	1/16	10	10-12	15	90
21-22	0.125	1/2	1/16	1/16	10	10-12	15	45-50
25	0.125	3/8	1/16	none	10	10-12	15	25

TABLE 17

BASE METAL AND BUTT WELD STRENGTHS

Spec. No.	Cold-Rolled Metal		Annealed Metal		Weldment (Machined)		Weldment (As Welded)	
	σ_y ksi	σ_t ksi	σ_y ksi	σ_t ksi	σ_y ksi	σ_t ksi	σ_y ksi	σ_t ksi
Q16B-1	91.7	130.6	35.5	106.4	56.6	116.5	60.0	131.5
Q16B-2	91.1	130.0	-	-	53.5	117.0	56.4	131
Avg.	91.4	130.3	35.5	106.4	55.1	116.8	58.2	131.5
Q22B-1	91.3	143.4	37.5	117.1	53.7	103.9	69.5	140
Q22B-2	90.1	143.5	36.0	116.7	53.4	101.8	67.7	137
Q22B-3					54.9	104.0		
Q22B-4					53.1	107.0		
Avg.	90.7	143.5	36.8	116.9	53.6	104.2	68.6	138.5
H16B-1	115.7	165.9	33.1	112.2	55.0	110.5	58.1	132
H16B-2	-	-	33.0	111.9	53.6	107.0	61.0	133.5
Avg.	115.7	165.9	33.1	112.1	54.3	108.8	58.6	133
H21B-1	122.0	192.0	35.8	142.6	-	93.6	-	157
H21B-2	123.5	186.9	34.4	137.2	48.1	91.0	63.1	175
H21B-3					53.1	97.4		
H21B-4					46.2	82.0		
Avg.	122.8	189.5	35.1	139.9	49.2	91.0	63.1	166
H25B-1	134.0	164.1	35.8	118.7	56.6	115.2	57.0	124
H25B-2	134.5	165.0	36.8	120.7	59.0	126.0	57.5	127
Avg.	134.3	164.6	36.3	119.7	57.8	120.6	57.3	125.5

Notes: 1. Stress calculations based on sheet areas

2. Base metal properties are from longitudinal tension tests

TABLE 18

BUTT WELD TEST RESULTS - MACHINED SPECIMENS

				Joint Efficiency† Based on			
				Cold Rolled Sheet		Annealed Sheet	
Spec. No.	$P_{Fail.}$ kips	σ_y ksi	σ_t ksi	Y.S.(%)	T.S.(%)	Y.S.(%)	T.S.(%)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Q16B-1	3.50	56.6	116.5				
Q16B-2	3.51	53.5	117.0				
Avg.		55.1	116.8	0.604	0.896	1.55	1.10
Q22B-1	1.60	53.7	103.9				
Q22B-2	1.61	53.4	101.8				
Q22B-3	1.62	54.9	104.0				
Q22B-4	1.72	53.1	107.0				
Avg.		53.6	104.2	0.591	0.726	1.46	0.89
H16B-1	3.42	55.0	110.5				
H16B-2	3.37	53.6	107.0				
Avg.		54.3	108.8	0.470	0.656	1.64	0.97
H21B-1	1.50	--	93.6				
H21B-2	1.55	48.1	91.0				
H21B-3	1.45	53.1	97.4				
H21B-4	1.31	46.2	82.0				
Avg.		49.2	91.0	0.401	0.480	1.40	0.65*
H25B-1	1.27	56.6	115.2				
H25B-2	1.39	59.0	126.0				
Avg.		57.8	120.6	0.430	0.734	1.59	1.01
Quarter Hard Avg.				0.598	0.811	1.50	1.00
Half Hard Avg.				0.434	0.623	1.54	0.99

* Excluded from average because $\sigma_{t_{annealed}}$ value is questionable.

† Joint Efficiency (%) = $\frac{\text{weldment strength}}{\text{base metal strength}} \times 100$

TABLE 19

BUTT WELD TEST RESULTS - AS-WELDED SPECIMENS

Spec. No.	P_{Fail} kips	y ksi	t ksi	Joint Efficiency Based on Cold Rolled Sheet		Joint Efficiency Based on Annealed Sheet	
				Y.S.(%)	T.S.(%)	Y.S.(%)	T.S.(%)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Q16B-1	3.95	60.0	131.5				
Q16B-2	3.95	56.4	131.0				
Avg.		58.2	131.3	0.637	1.01	1.64	1.24
Q22B-1	2.17	69.5	140.0				
Q22B-1	2.12	67.7	137.0				
Avg.		68.6	138.5	0.757	0.965	1.86	1.19
H16B-1	4.10	58.1	132.0				
H16B-2	4.17	61.0	133.5				
Avg.		59.6	132.8	0.506	0.803	1.77	1.19
H21B-1	2.37	--	157.0				
H21B-2	2.70	63.1	175.0				
Avg.		63.1	166.0	0.515	0.876	1.80	1.19
H25B-1	1.25	57.0	124.0				
H25B-2	1.27	57.5	127.0				
Avg.		57.3	125.5	0.426	0.764	1.58	1.05
Quarter Hard Avg.				0.697	0.988	1.75	1.22
Half Hard Avg.				0.482	0.814	1.72	1.14

Notes:

1. Joint Efficiency = $\frac{\text{weldment strength}}{\text{base metal strength}} \times 100$

2. Weld reinforcement not removed, but base metal thickness used to calculate stresses.

TABLE 20

DUCTILITY OF BUTT WELDMENTS

	Weldments (Machined)				Weldments (As Welded)			
Spec. No.	% Elongation in: 1/2"	3/4"	1"	2"	% Elongation in: 1/2"	3/4"	1"	2"
Q16B-1	52.0	39.5	32.9	19.9	60.8	63.8	55.7	42.3
Q16B-2	50.0	38.0	32.0	20.1	54.2	47.0	42.8	35.4
Q22B-1	30.0	22.0	17.2	9.5	45.5	39.0	36.0	28.4
Q22B-2	29.1	21.9	16.8	8.6	41.1	35.5	32.3	27.0
Q22B-3	30.0	20.9	16.0	8.4				
Q22B-4	31.0	21.5	16.0	8.4				
H16B-1	38.1	26.5	20.0	10.0	36.9	25.0	18.4	9.85
H16B-2	40.0	27.1	20.9	10.5	39.3	26.3	19.8	9.96
H21B-1	24.1	16.1	12.6	6.5	24.9	18.6	15.2	10.0
H21B-2	24.8	16.1	12.5	6.5	33.8	25.7	21.7	14.9
H21B-3	20.1	17.0	12.5	6.6				
H21B-4	24.1	16.1	10.8	5.5				
H25B-1	31.0	21.0	16.0	7.8	19.9	13.5	9.91	4.66
H25B-2	33.5	23.0	17.3	8.7	27.0	18.0	13.6	6.63

TABLE 21

BUTT WELD DUCTILITY COMPARISON

		Average Percent Elongation in Two Inches			Elongation Across Weld ÷ Elongation of As-Rolled Metal	
Gage	Cold Rolled Metal	Annealed Metal	Machined Weldment	As Welded Weldment	Machined Weldment	As Welded Weldment
Quarter Hard						
16	38.9	71.4	20.0	38.9	0.511	1.00
22	44.2	78.6	8.70	27.7	0.198	0.629
Half Hard						
16	28.2	70.5	10.3	9.91	0.365	0.350
21	24.2	55.4	6.30	12.5	0.260	0.518
25	29.7	84.0	8.30	5.65	0.280	0.190

TABLE 22

COMPARISON OF BUTT WELD TEST RESULTS WITH PUBLISHED DATA

	As Welded Weldments						Machined or Autogeneous Weldments					
	Present Test Results		Ref. 14		Ref. 16		Present Test Results		Ref. 14		Ref. 15	
t (in.)	σ_y ksi	σ_t ksi	σ_y ksi	σ_t ksi	σ_y ksi	σ_t ksi	σ_y ksi	σ_t ksi	σ_y ksi	σ_t ksi	σ_y ksi	σ_t ksi
Quarter Hard												
0.019			75	133								
0.026					78	122						
0.031	69	139					54	104			62*	146*
0.050			65	122								
0.060	58	131					55	117			60*	131*
0.078									47	92		
0.091			65	112					54	87		
0.125					63	118						
0.187			66	111								
Half Hard												
0.021	57	126			90	142	58*	121*				
0.032	63	166					49	91			65*	158*
0.060	60	133			95	147	54	109			67*	150*
0.106					88	131						

* Autogeneous Welds

TABLE 23

FILLET WELD TEST PROGRAM

Spec. No.	Plate Thick. in.	Nominal Weld Length in.	L/S*
TRANSVERSE WELDS			
Q16FT-1	0.059	1-1/2	0.375
2	0.059	2	0.500
3	0.059	3	0.750
Q21FT-1	0.031	1-1/2	0.375
2	0.031	2-1/2	0.625
H16FT-1	0.062	1	0.250
2	0.062	2	0.500
3	0.062	3	0.750
H21FT-1	0.033	1-1/2	0.375
2	0.033	2-1/2	0.625
LONGITUDINAL WELDS			2L/t*
Q16FL-1	0.059	1	34.0
2	0.059	2	68.0
3	0.059	2-1/2	85.0
Q21FL-1	0.031	3/4	48.5
2	0.031	1-1/2	97.0
H16FL-1	0.062	1	32.0
2	0.062	2	64.5
3	0.062	2-1/2	80.5
H21FL-1	0.033	3/4	45.5
2	0.033	1-1/2	91.0

* L = Nominal length of each weld, in.
s = width of specimen, in.
t = plate thickness, in.

TABLE 24

FILLET WELD TEST RESULTS

Spec. No.	Sheet Thickness (in)	Measured Weld Length (in)	Failure Load (kips)	τ_o* (ksi)	Failure Location
TRANSVERSE WELDS					
Q16FT-1	.059	1.70	8.82	125	Fusion Line
Q16FT-2	.059	2.26	11.64	124	Weld
Q16FT-3	.059	3.13	14.30	109	Weld
Q22FT-1	.031	1.63	5.20	144	Fusion Line
Q22FT-2	.031	2.61	7.70	135	Weld
H16FT-1	.062	1.22	6.40	119	Weld
H16FT-2	.062	2.12	11.16	120	Weld
H16FT-3	.062	3.06	16.10	120	Fusion Line
H21FT-1	.033	1.65	5.52	142	Fusion Line
H21FT-2	.033	2.52	7.46	129	Fusion Line
Quarter Hard Average				127	
Half Hard Average				126	
LONGITUDINAL WELDS					
Q16FL-1	.059	1.12	6.68	71.4	Weld
Q16FL-2	.059	2.07	11.18	64.6	Weld
Q16FL-3	.059	2.54	16.40	77.4	Weld
Q22FL-1	.031	0.83	3.86	106	Weld
Q22FL-2	.031	1.51	5.44	82.3	Weld
H16FL-1	.062	1.02	7.96	89.0	Weld
H16FL-2	.062	1.98	13.00	74.7	Weld
H16FL-3	.062	2.52	16.40	74.2	Weld
H21FL-1	.033	0.81	3.50	92.6	Fusion Line
H21FL-2	.033	1.50	5.96	84.4	Fusion Line
Quarter Hard Average				80.3	
Half Hard Average				83.0	

* $\tau_o = \frac{\sqrt{2}\, P_f}{Lt}$ for transverse welds, $\frac{\sqrt{2}\, P_f}{2Lt}$ for longitudinal welds

where P_f = failure load, L = length of each weld,

t = thickness of plate

TABLE 25

WARPING, ULTIMATE AND FRACTURE STRESSES FOR FILLET WELD SPECIMENS

Spec. No.	Measured Weld Length (in.)	τ_{warp} (ksi)	τ_{ult} (ksi)	τ_{fract} (ksi)
TRANSVERSE FILLET WELDS				
Q16FT-1	1.70	99.5	125	--
2	2.26	112	124	111
3	3.13	99	109	
Q22FT-1	1.63	123	144	--
2	2.61	114	135	--
H16FT-1	1.22	None	119	--
2	2.12	108	120	--
3	3.06	108	120	59.6
H21FT-1	1.65	129	142	--
2	2.52	113	129	63.8
LONGITUDINAL FILLET WELDS				
Q16FL-1	1.12	64.3	71.4	--
2	2.07	41.7	64.6	56.7
3	2.54	47.2	77.4	47.2
Q22FL-1	0.83	82.7	106	--
2	1.51	--	82.3	45.3
H16FL-1	1.02	--	89.0	--
2	1.98	55.3	74.7	42.0
3	2.52	--	74.2	49.8
H21FL-1	0.81	69.0	92.6	31.8
2	1.50	--	84.4	42.5

TABLE 26

FILLET WELD STRENGTH COMPARISONS

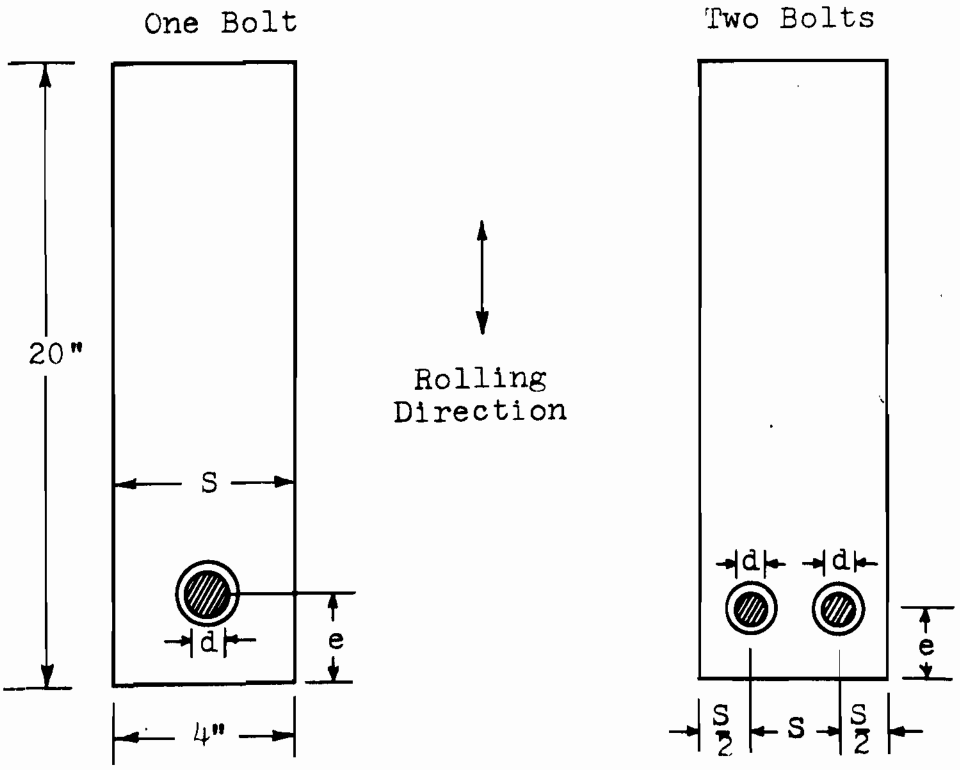
Spec. No.	P_{fail} (kips)	τ_o (ksi)	τ_o/σ_{tb}	τ_o/σ_{tw}	τ_o/σ_{ta}
LONGITUDINAL FILLET WELDS					
Q16FL-1	6.68	71.4	0.55	0.68	0.67
2	11.18	64.6	0.50	0.62	0.61
3	16.40	77.4	0.59	0.74	0.73
Q22FL-1	3.86	106	0.74	1.01	0.91
2	5.44	83.2	0.57	0.78	0.70
H16FL-1	7.96	89.0	0.54	0.85	0.79
2	13.00	74.7	0.45	0.71	0.66
3	16.40	74.2	0.45	0.71	0.66
H21FL-1	3.50	92.6	0.49	0.88	0.66
2	5.96	84.4	0.45	0.80	0.60
Quarter Hard Avg.		80.3	0.59	0.77	0.72
Half Hard Avg.		83.0	0.48	0.79	0.67
TRANSVERSE FILLET WELDS					
Q16FT-1	8.82	125	0.96	1.19	1.17
2	11.64	124	0.95	1.18	1.16
3	14.30	109	0.84	1.04	1.02
Q22FT-1	5.20	144	1.00	1.37	1.23
2	7.70	135	0.94	1.28	1.15
H16FT-1	6.40	119	0.72	1.13	1.06
2	11.16	120	0.72	1.14	1.07
3	16.10	120	0.72	1.14	1.07
H21FT-1	5.52	142	0.75	1.35	1.02
2	7.46	129	0.68	1.23	0.92
Quarter Hard Avg.		127	0.94	1.21	1.15
Half Hard Avg.		126	0.72	1.20	1.03

Notes: τ_o is defined in Table 24

τ_{tb} = tensile strength of cold-rolled base metal, see Table 17

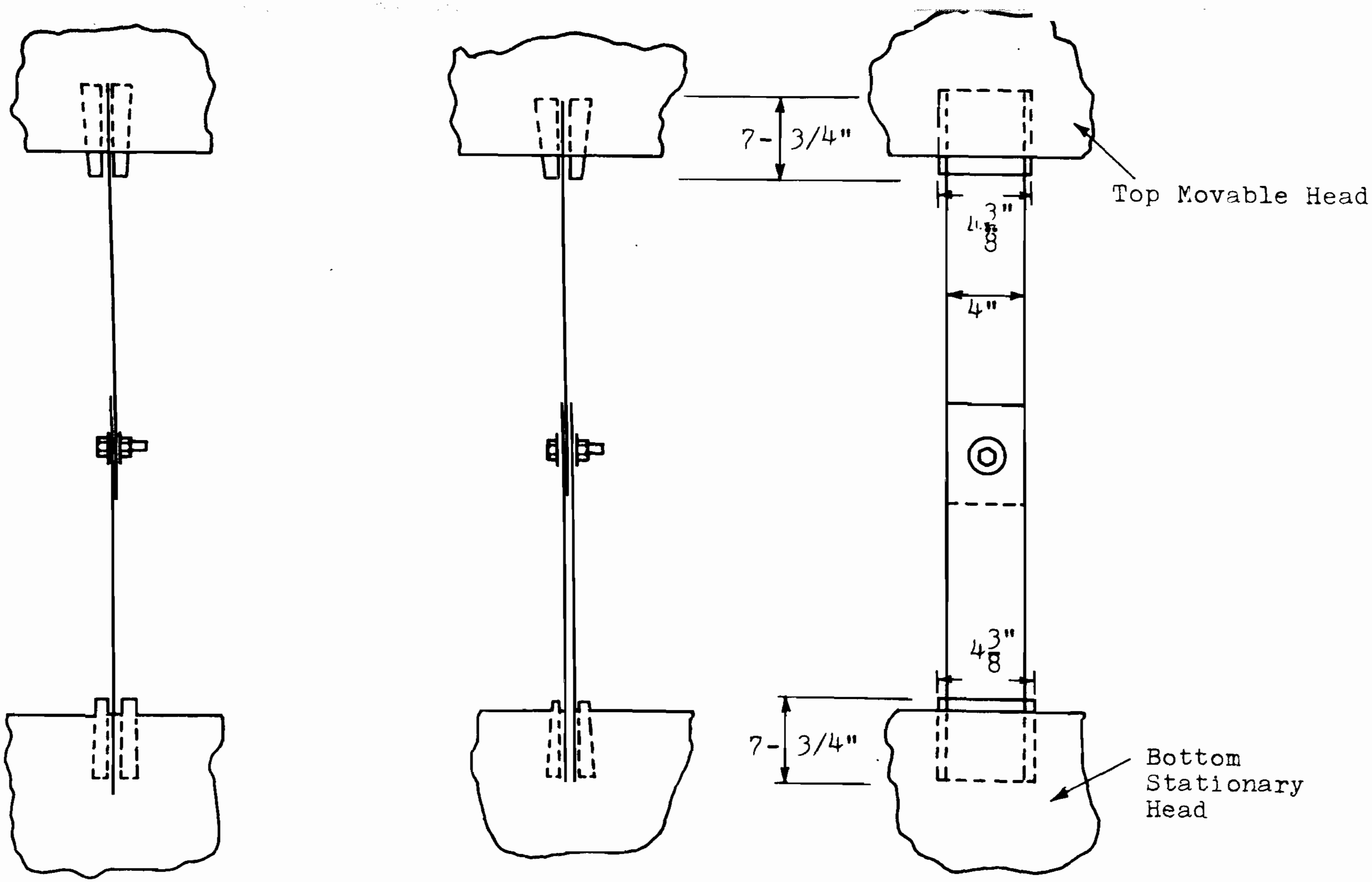
τ_{tw} = 105 ksi, the avg. strength of weld metal from machined butt weld tests, Table 17

τ_{ta} = tensile strength of annealed base metal, see Table 17



e = Edge Distance; S = Bolt Spacing; d = Bolt Diameter.

Fig.1&2 Typical Test Blanks for Bolted Connections



SIDE VIEW (Single Shear) 3a.

SIDE VIEW (Double Shear) 3b.

FRONT VIEW 3c.

Fig. 3 Typical Bolted Connection Specimens

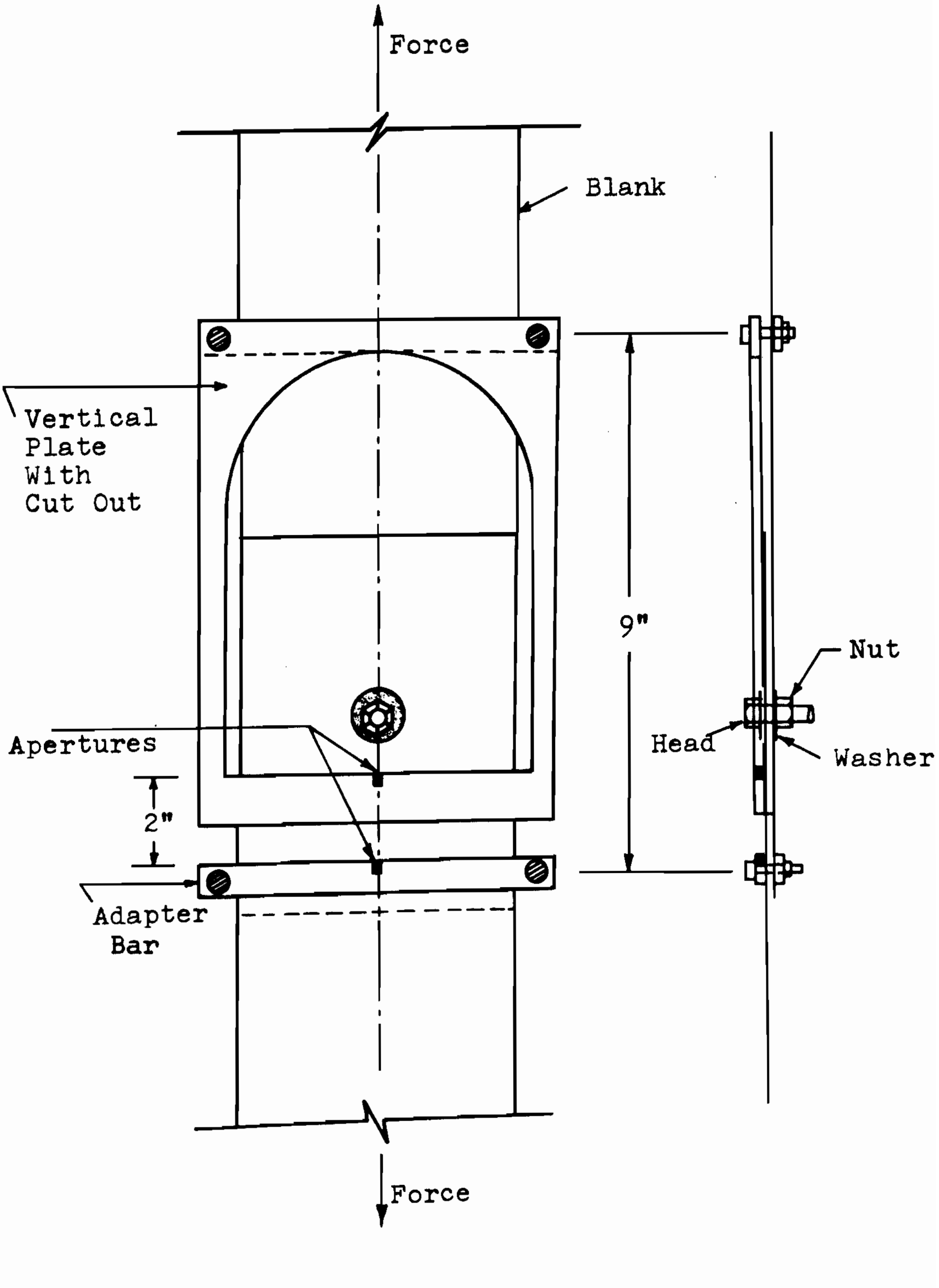


Fig. 4 Close-Up of Bolted Connection

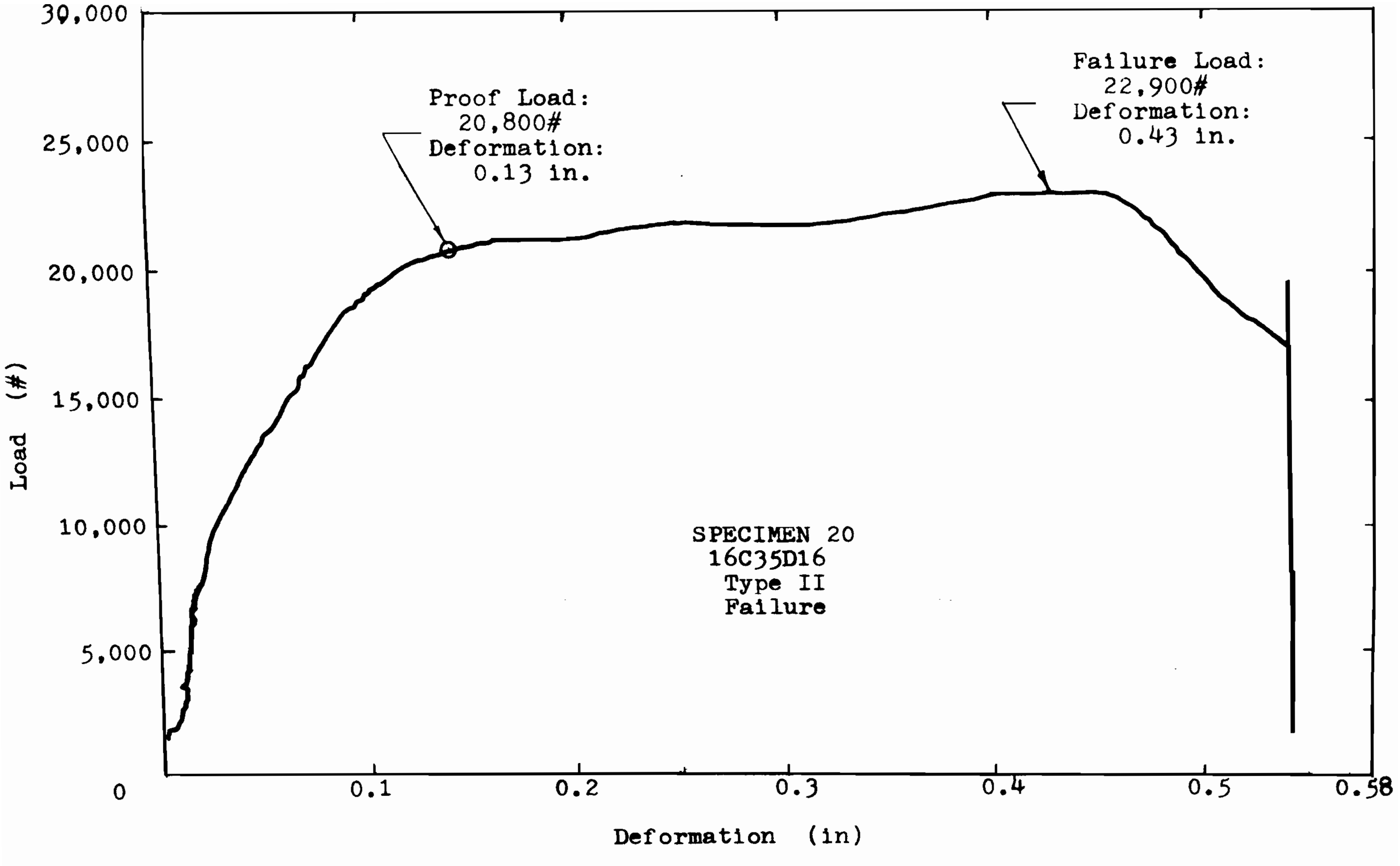


Figure 5 Load-Deformation Graph, Bolted Specimen 20

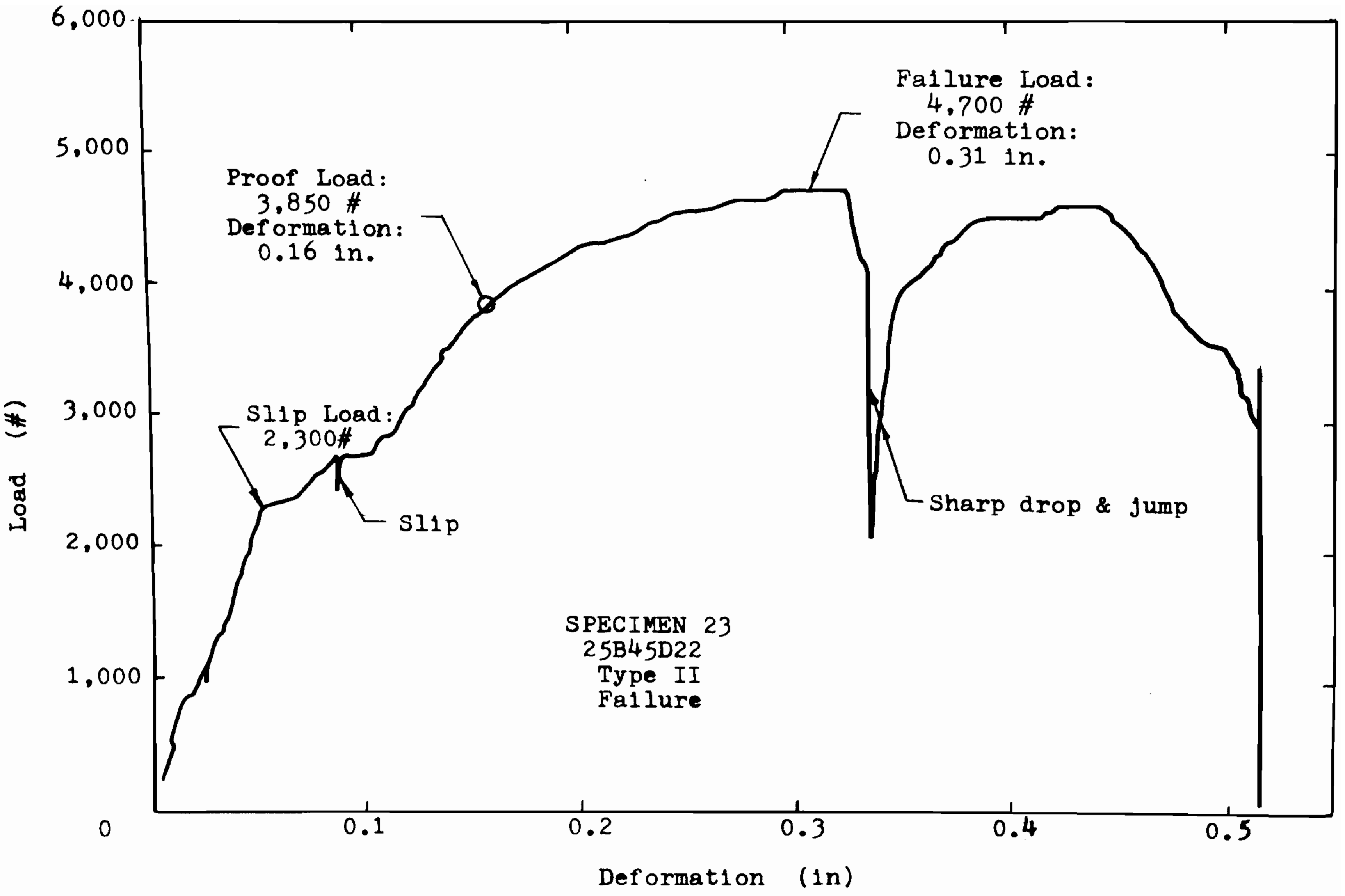
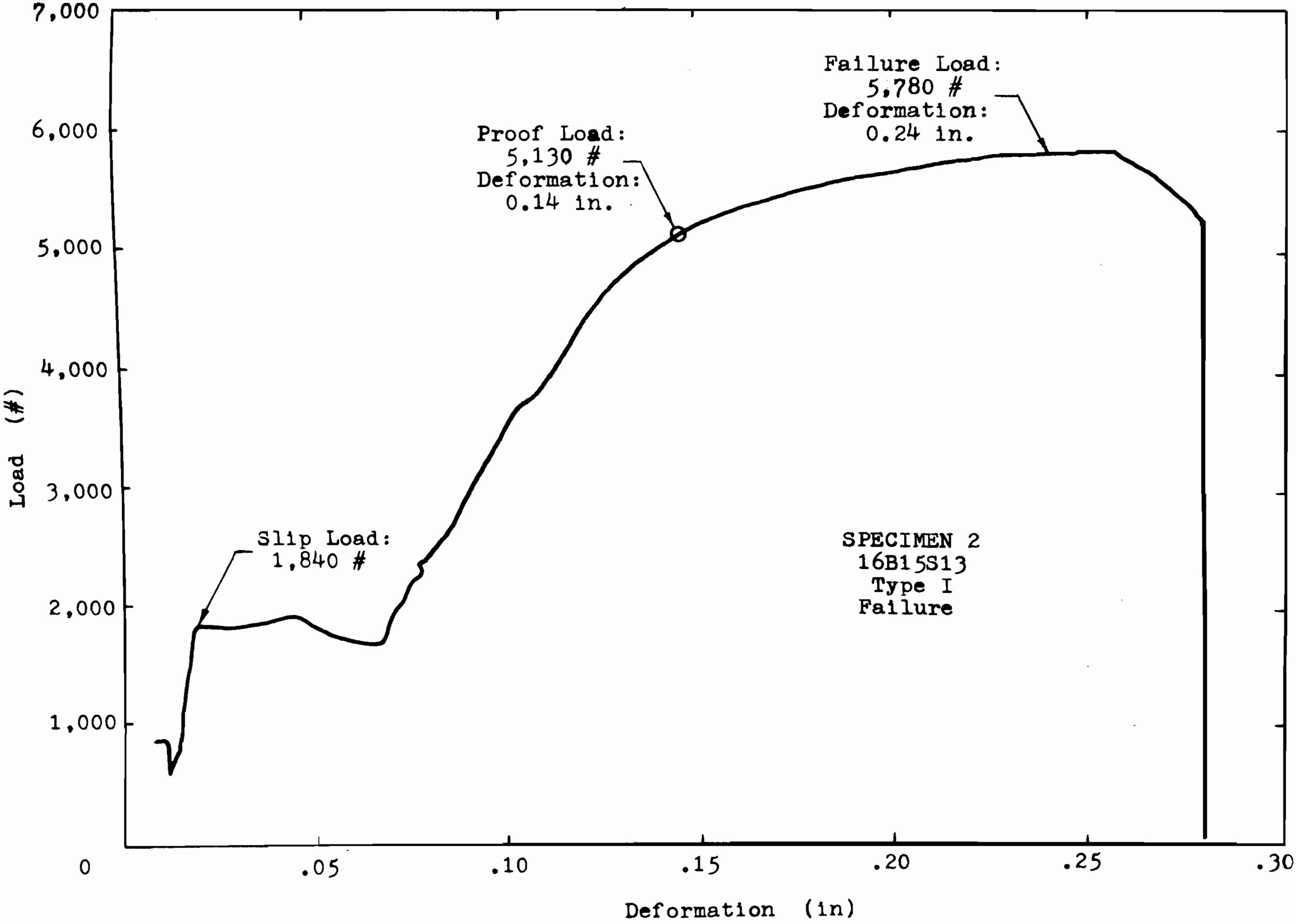


Figure 6 Load-Deformation Graph, Bolted Specimen 23


7,000
6,000
5,000
4,000
3,000
2,000
1,000
0
Load (#)
.05
.10
.15
.20
.25
.30
Deformation (in)
Failure Load:
5,780 #
Deformation:
0.24 in.
Proof Load:
5,130 #
Deformation:
0.14 in.
Slip Load:
1,840 #
SPECIMEN 2
16B15S13
Type I
Failure

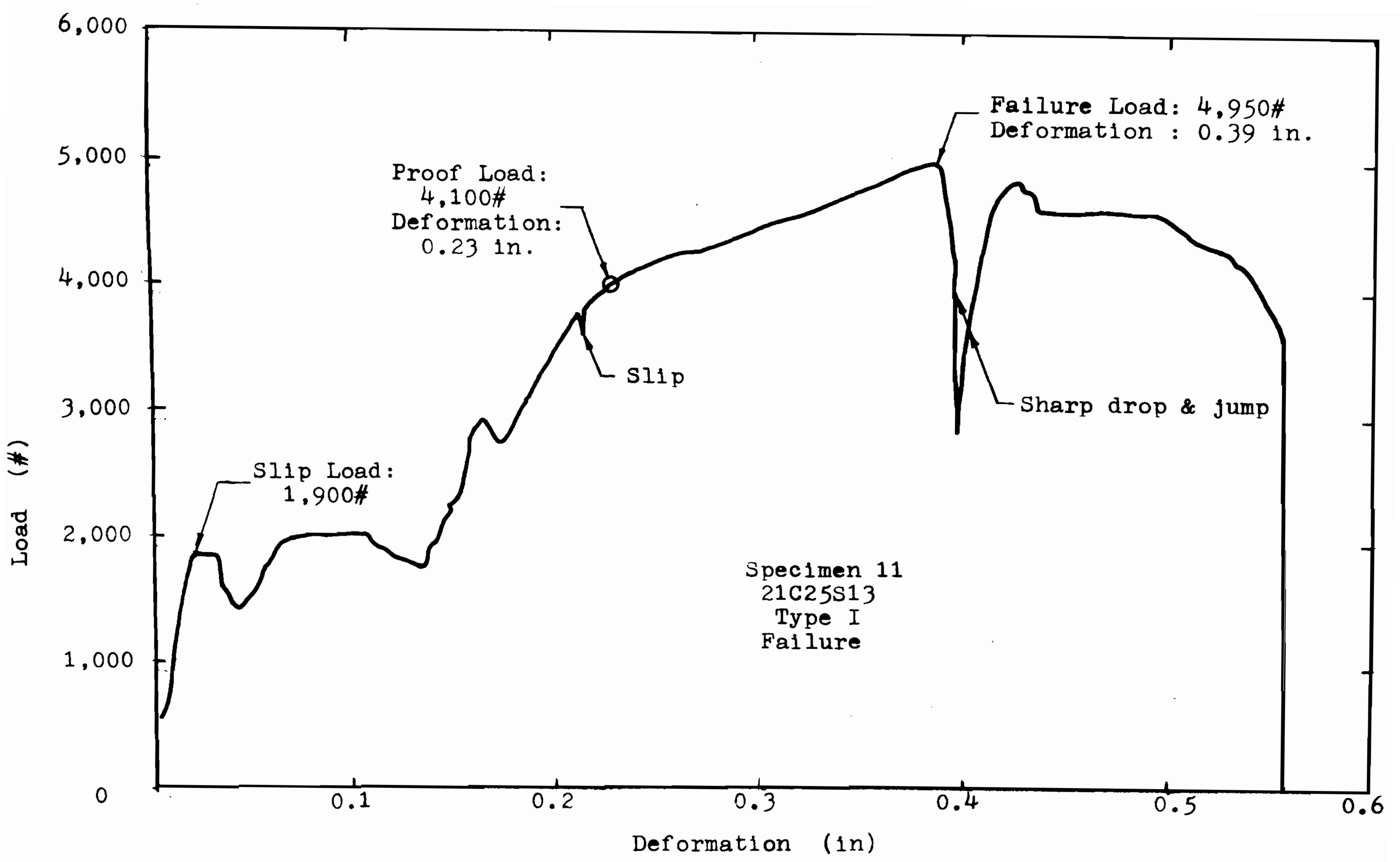


Figure 8 Load-Deformation Graph, Bolted Specimen 11

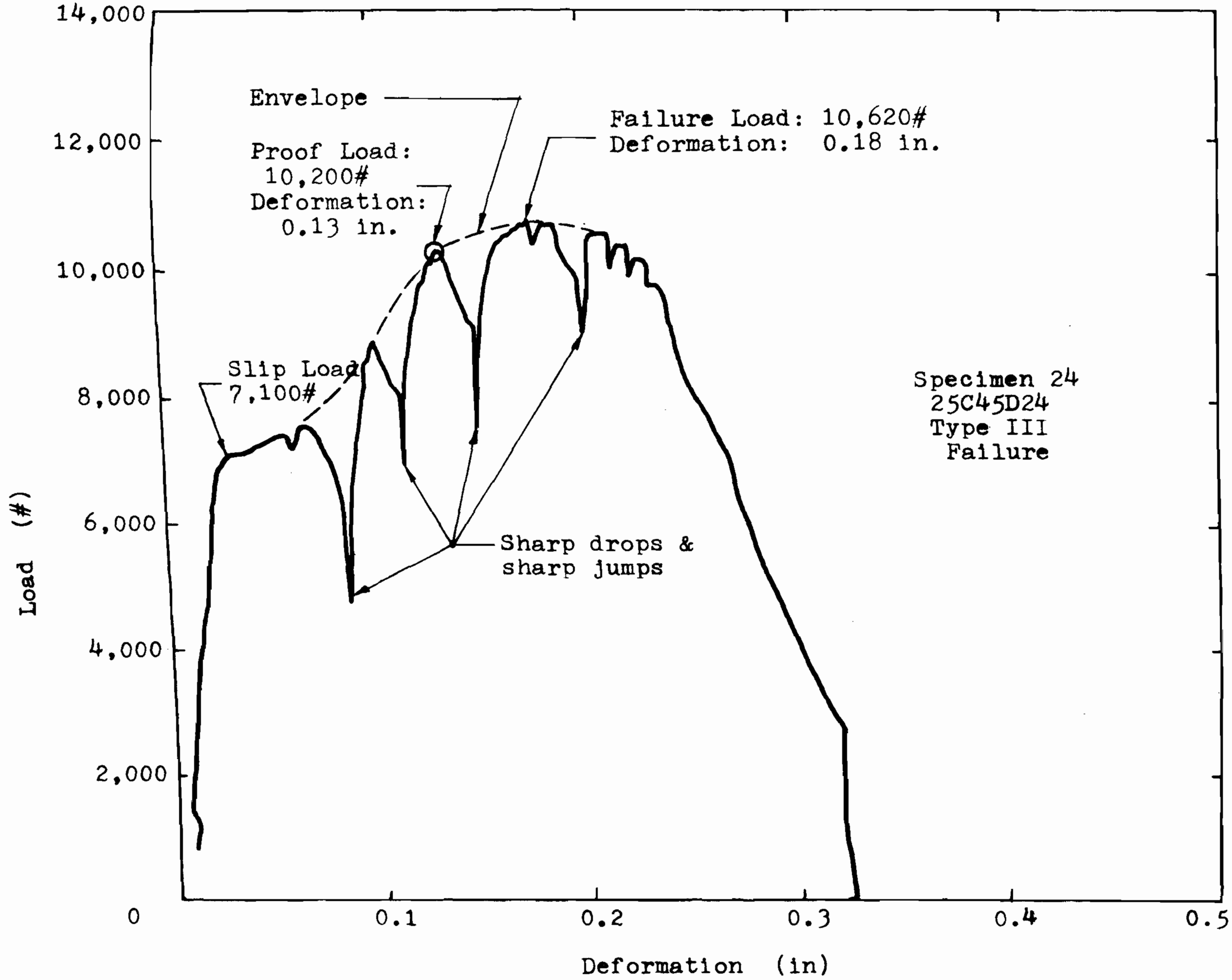
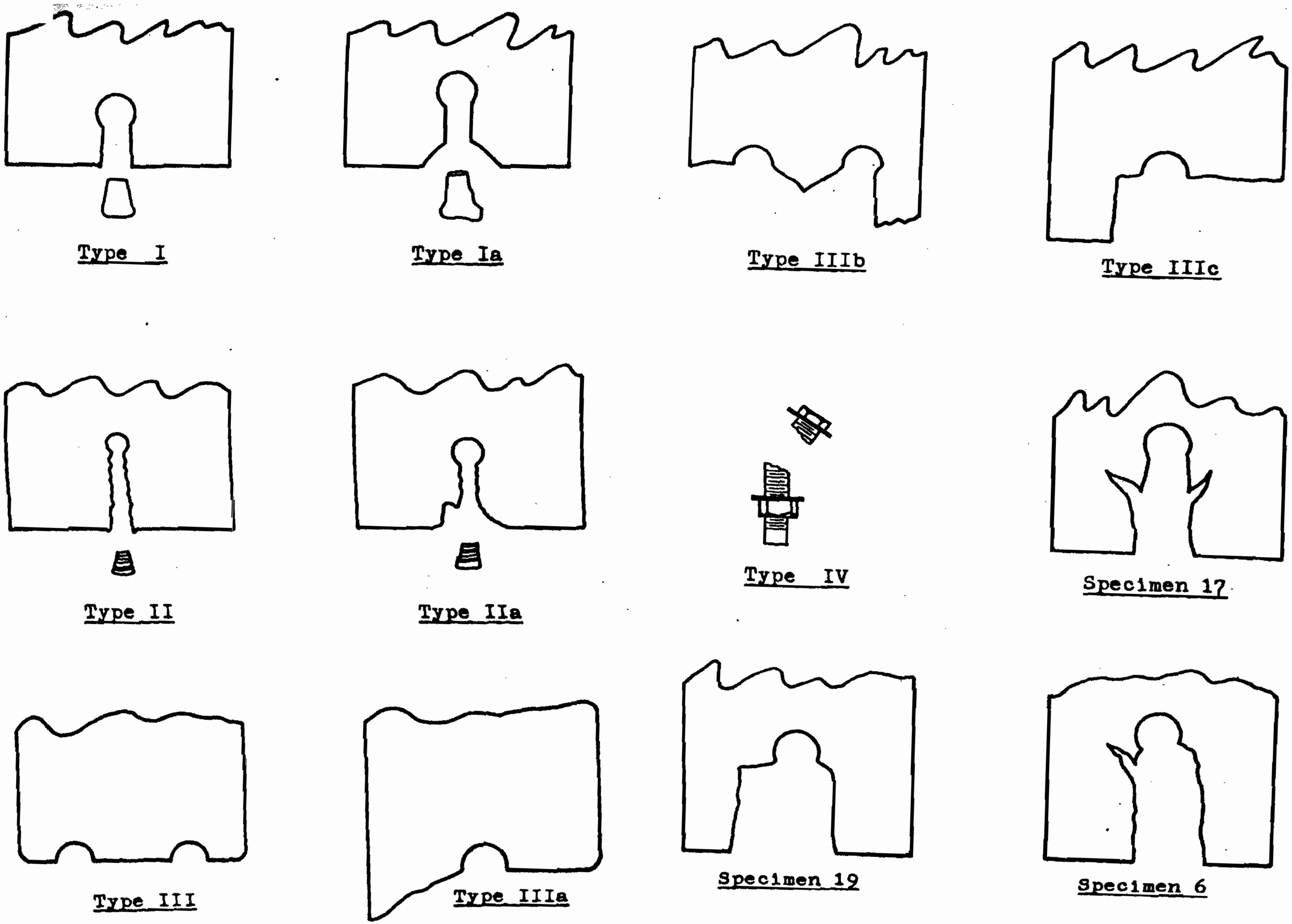


Figure 9 Load-Deformation Graph, Bolted Specimen 24



Type I

Type Ia

Type IIIb

Type IIIc

Type II

Type IIa

Type IV

Specimen 17

Type III

Type IIIa

Specimen 19

Specimen 6

Figs. 10 & 11 Typical Types of Bolted Connection Failure

[redacted]

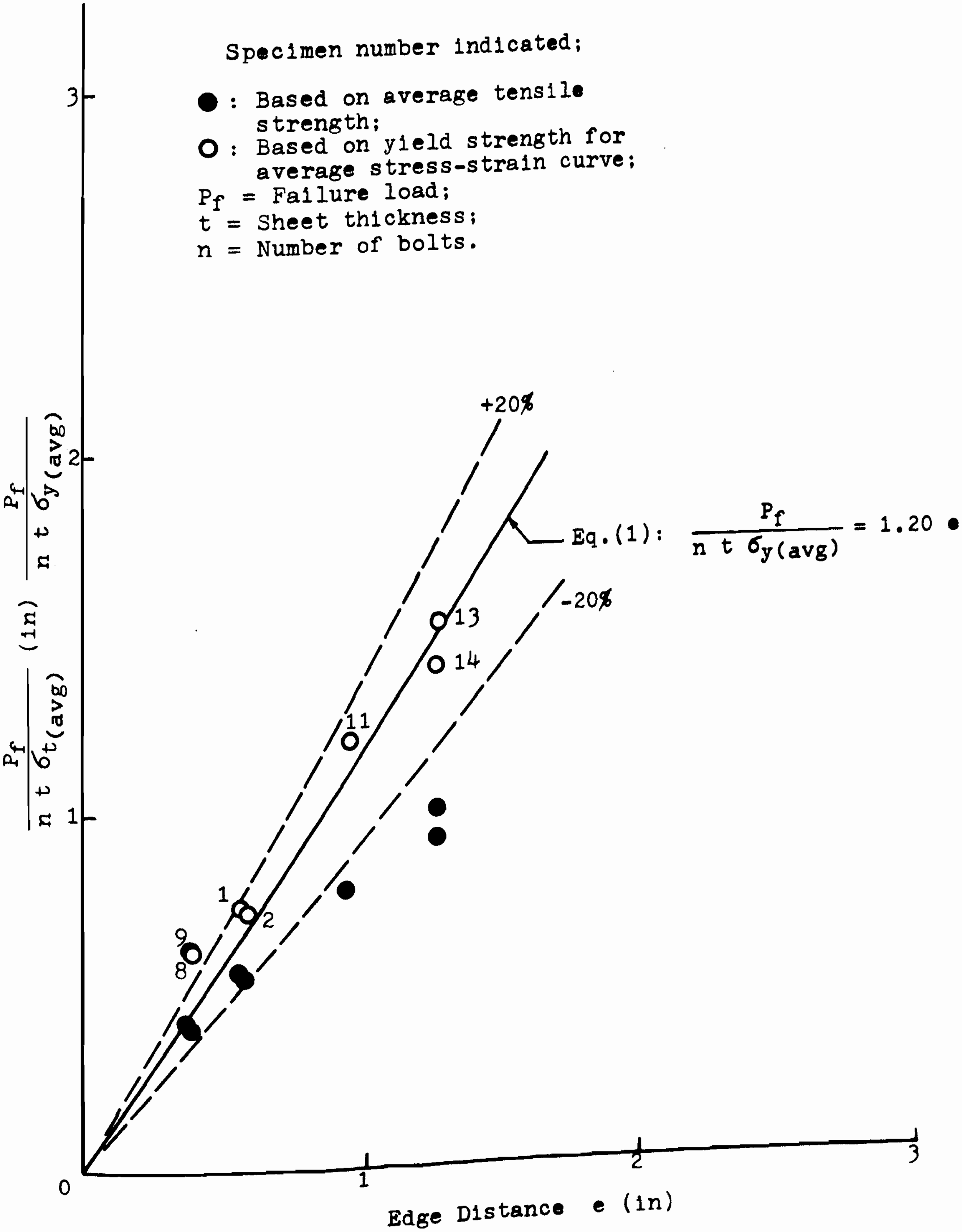


Figure 12 Longitudinal Shearing Failure (Type I)-
Bolted Connections

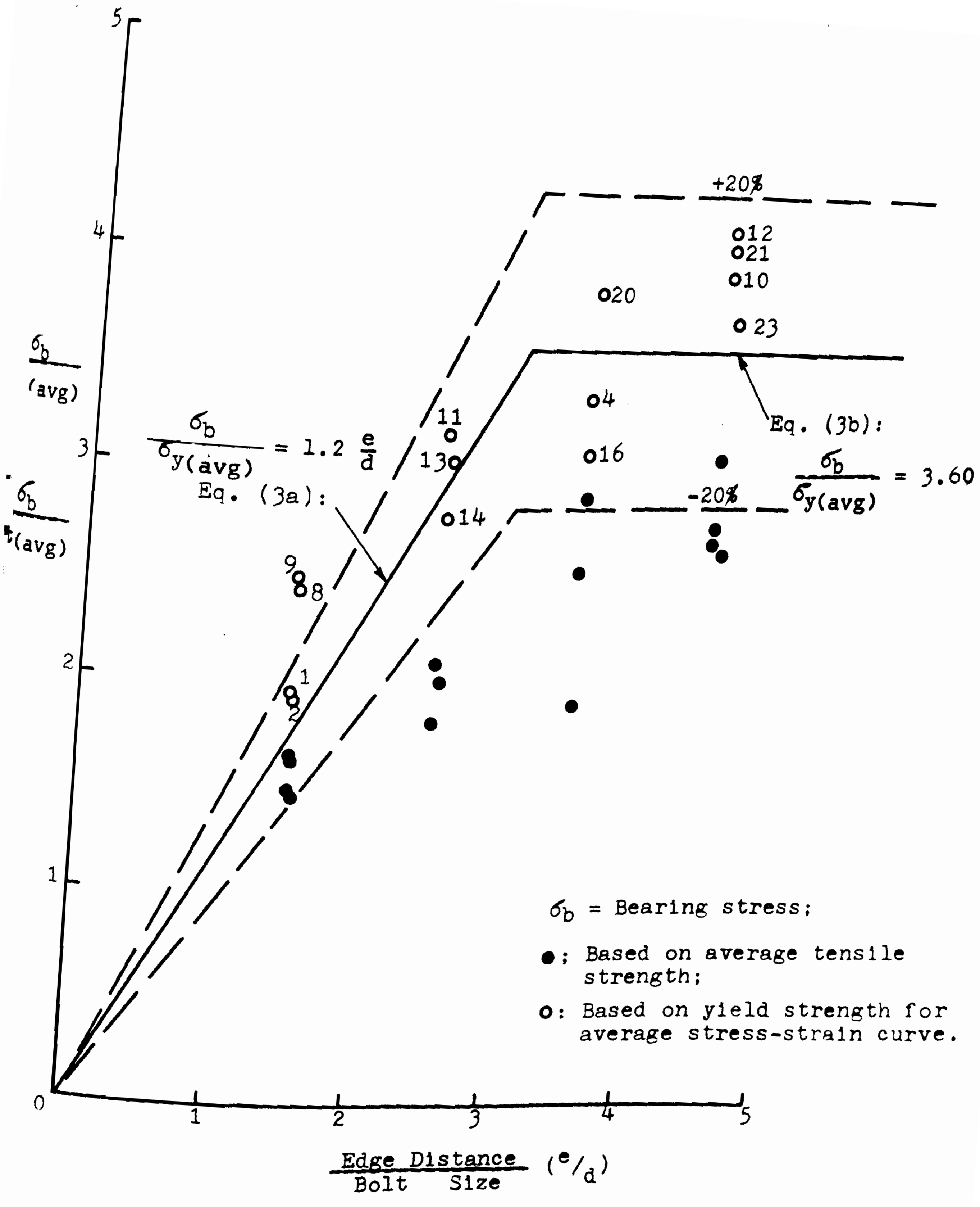
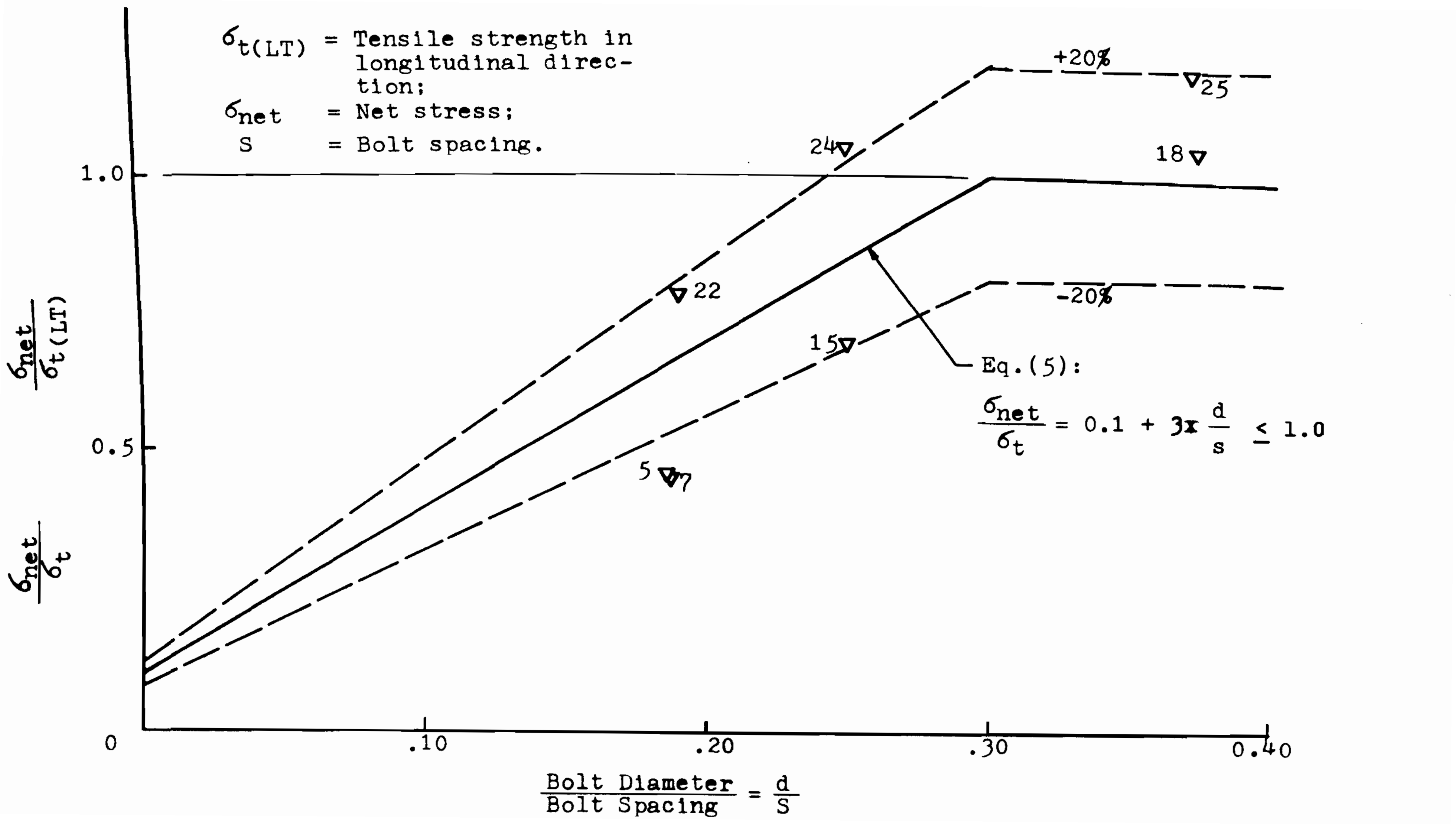


Figure 13 Bolted Connection Longitudinal Shearing Failure (Type I) and Bearing-Shearing Failure (Type II)


$\sigma_{t(LT)}$ = Tensile strength in longitudinal direction;
σ_{net} = Net stress;
S = Bolt spacing.
+20%
25
24
18
22
15
-20%
5
7
Eq.(5):
$\frac{\sigma_{net}}{\sigma_t} = 0.1 + 3x \frac{d}{s} \leq 1.0$
1.0
0.5
0
.10
.20
.30
0.40
$\frac{\sigma_{net}}{\sigma_{t(LT)}}$
$\frac{\sigma_{net}}{\sigma_t}$
$\frac{\text{Bolt Diameter}}{\text{Bolt Spacing}} = \frac{d}{S}$

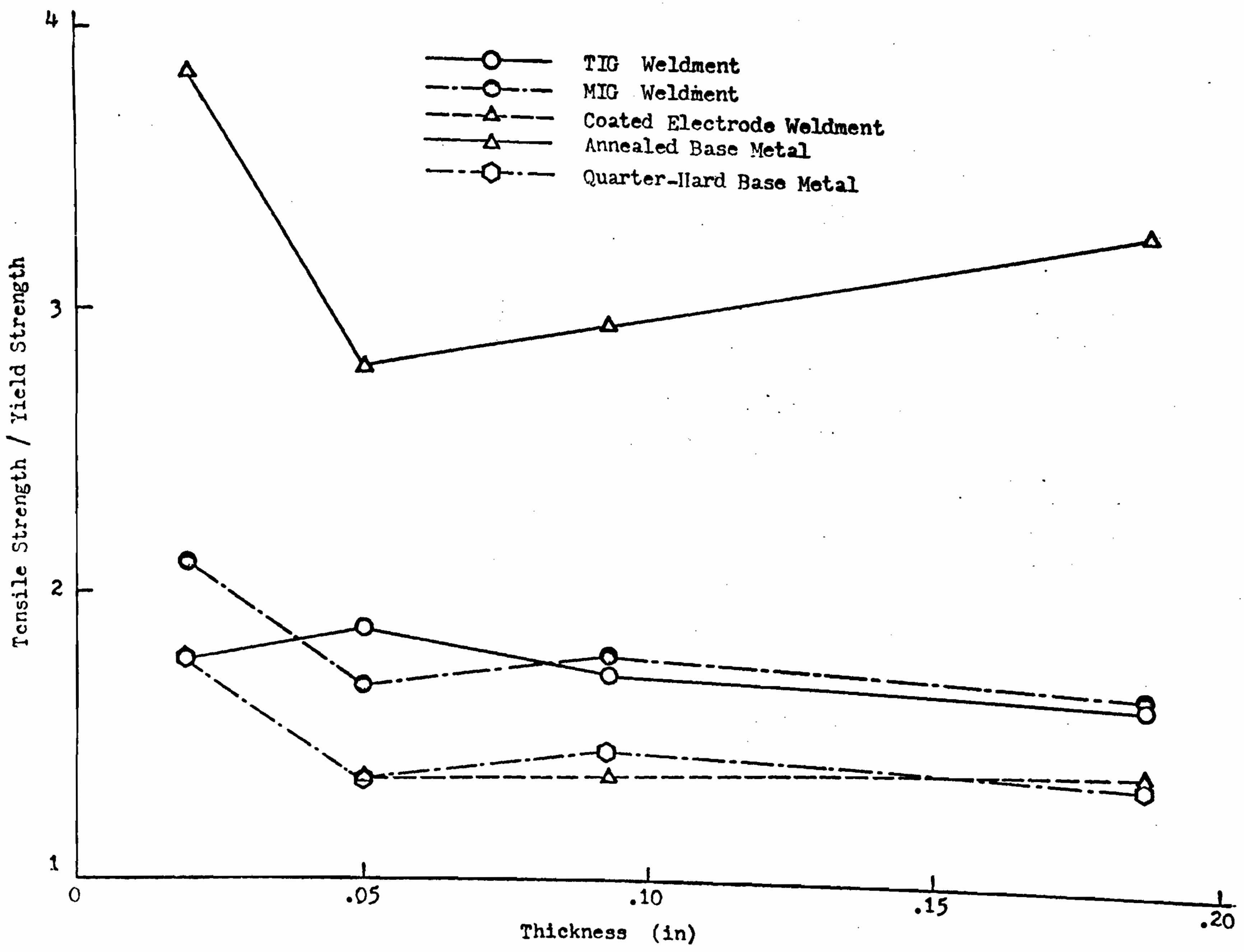
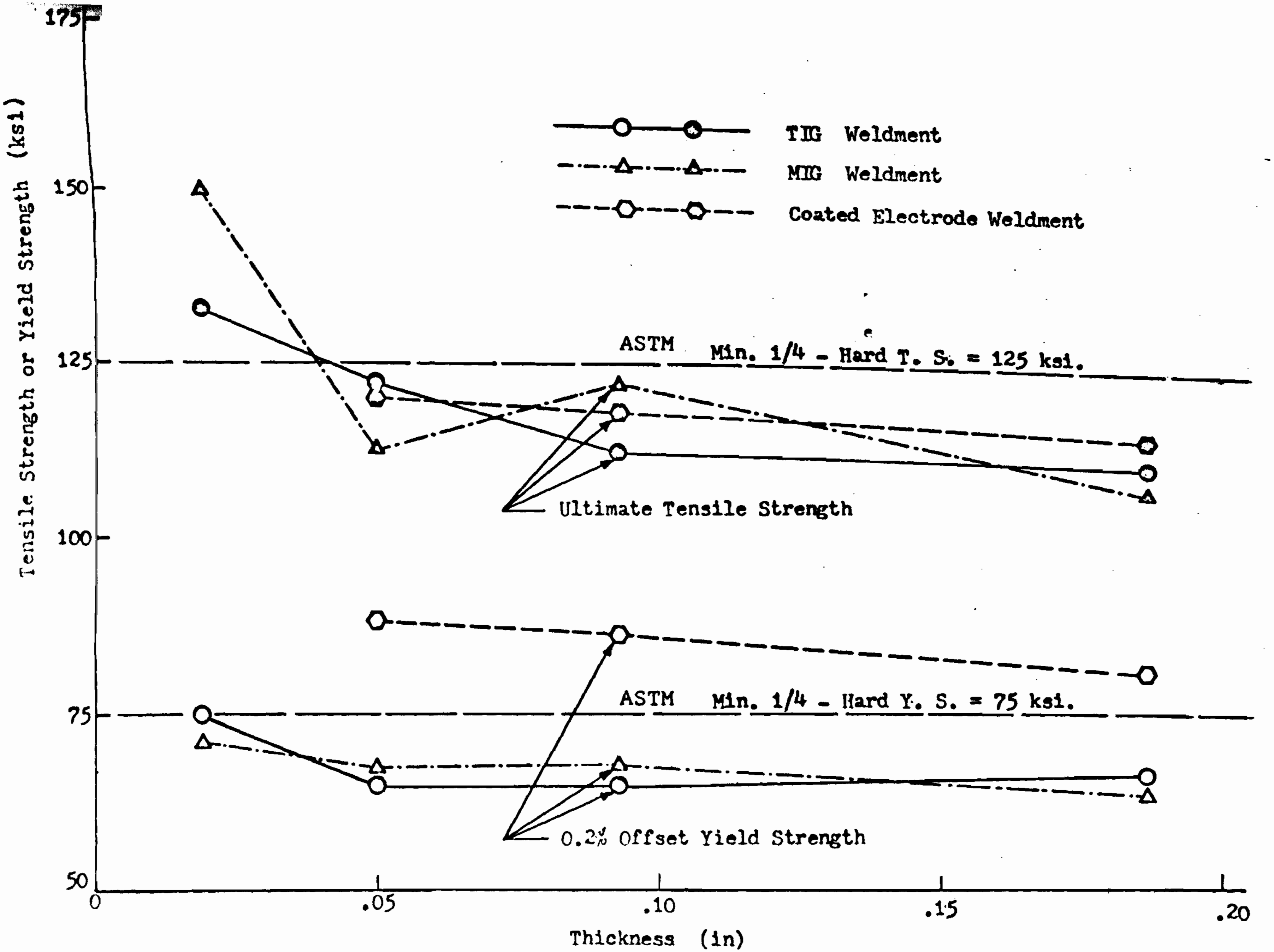


Fig. 15 Tension-Yield Strength Ratio for Annealed and Quarter-Hard Type 301 Stainless Sheets and Weldments


175
150
125
100
75
50
Tensile Strength or Yield Strength (ksi)
0
.05
.10
.15
.20
Thickness (in)
TIG Weldment
MIG Weldment
Coated Electrode Weldment
ASTM Min. 1/4 - Hard T. S. = 125 ksi.
ASTM Min. 1/4 - Hard Y. S. = 75 ksi.
Ultimate Tensile Strength
0.2% Offset Yield Strength

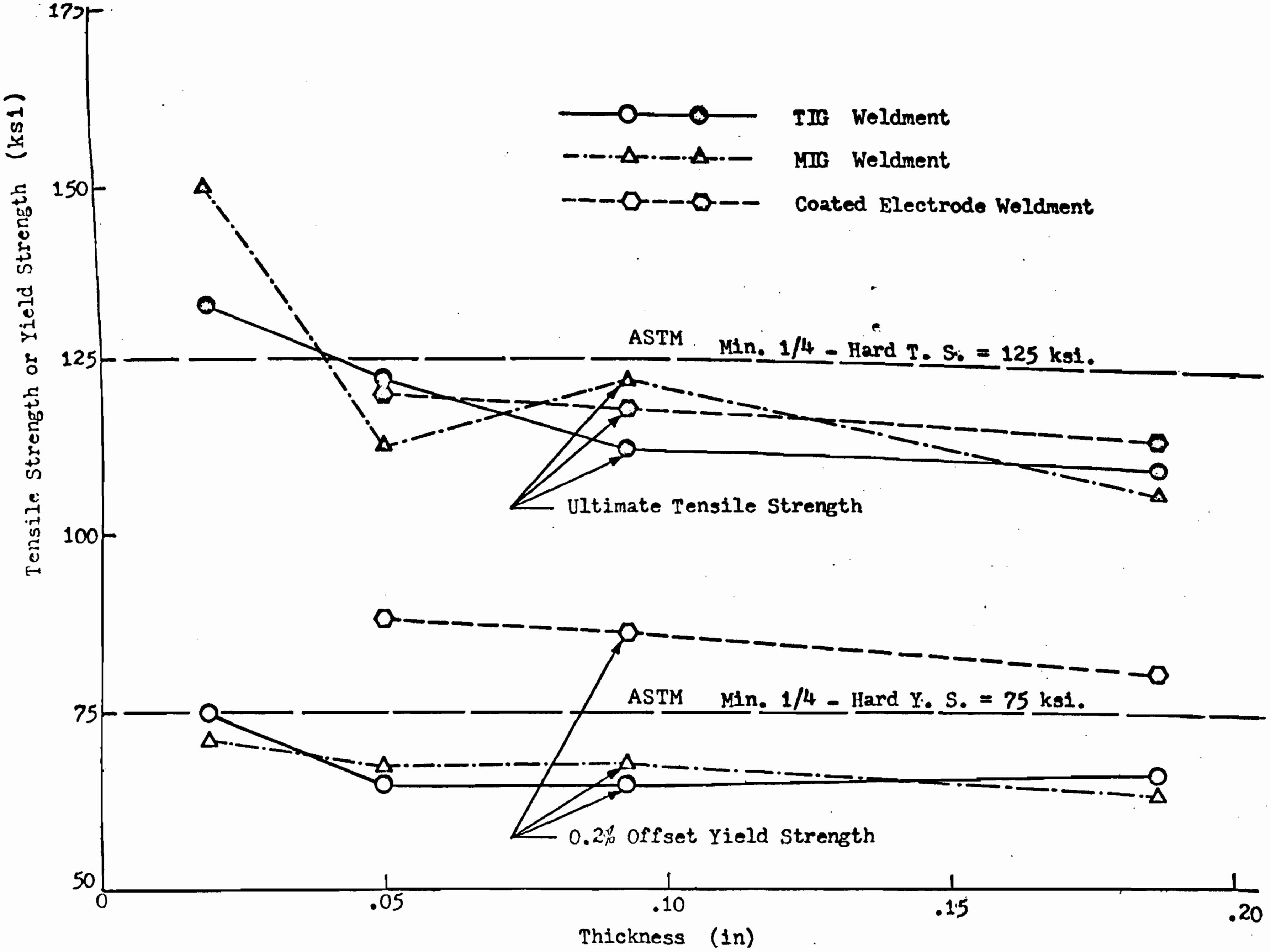


Fig. 16 Mechanical Strength of Quarter-Hard Type 301 Stainless Steel Weldments

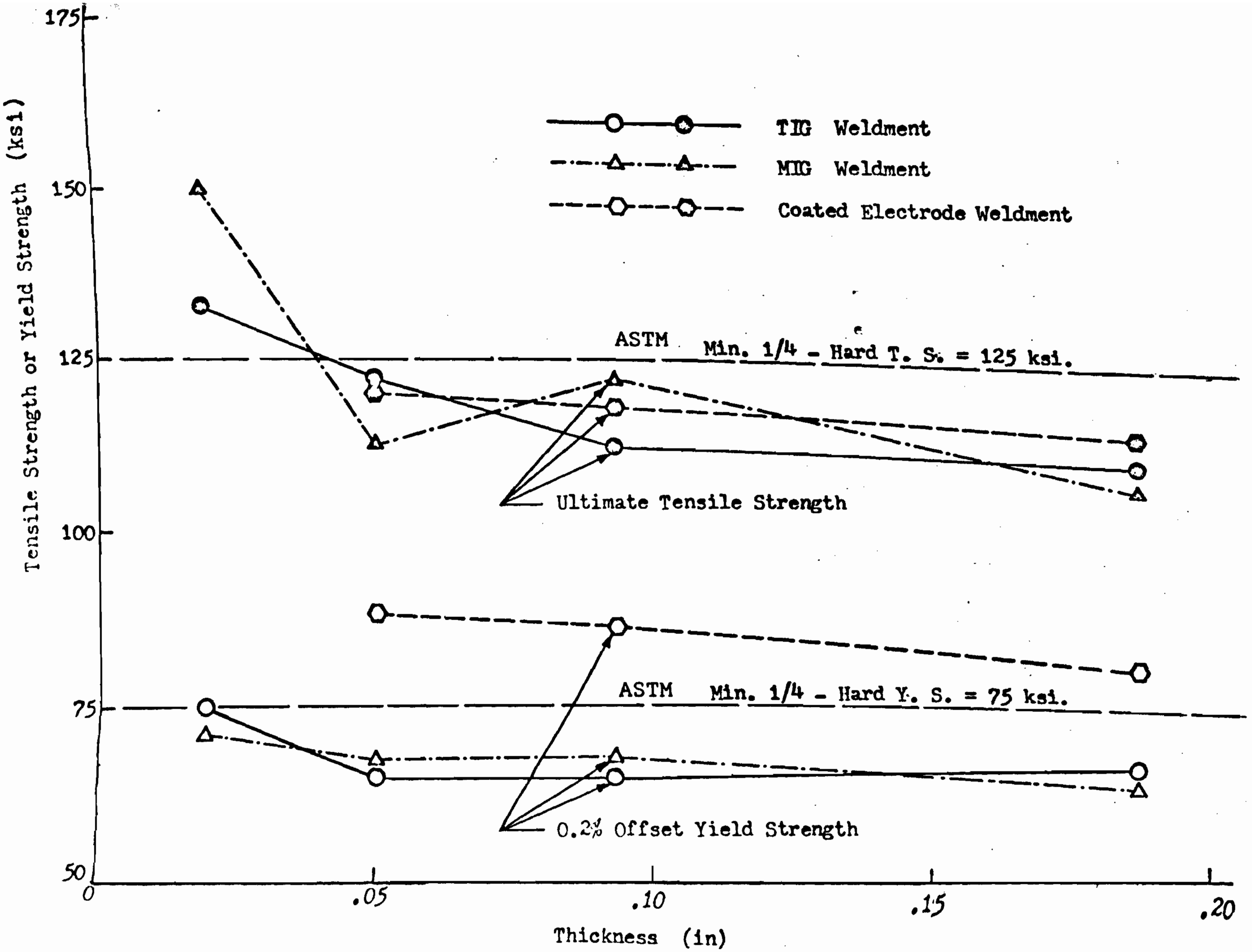


Fig. 16 Mechanical Strength of Quarter-Hard Type 301 Stainless Steel Weldments (From Reference 14)

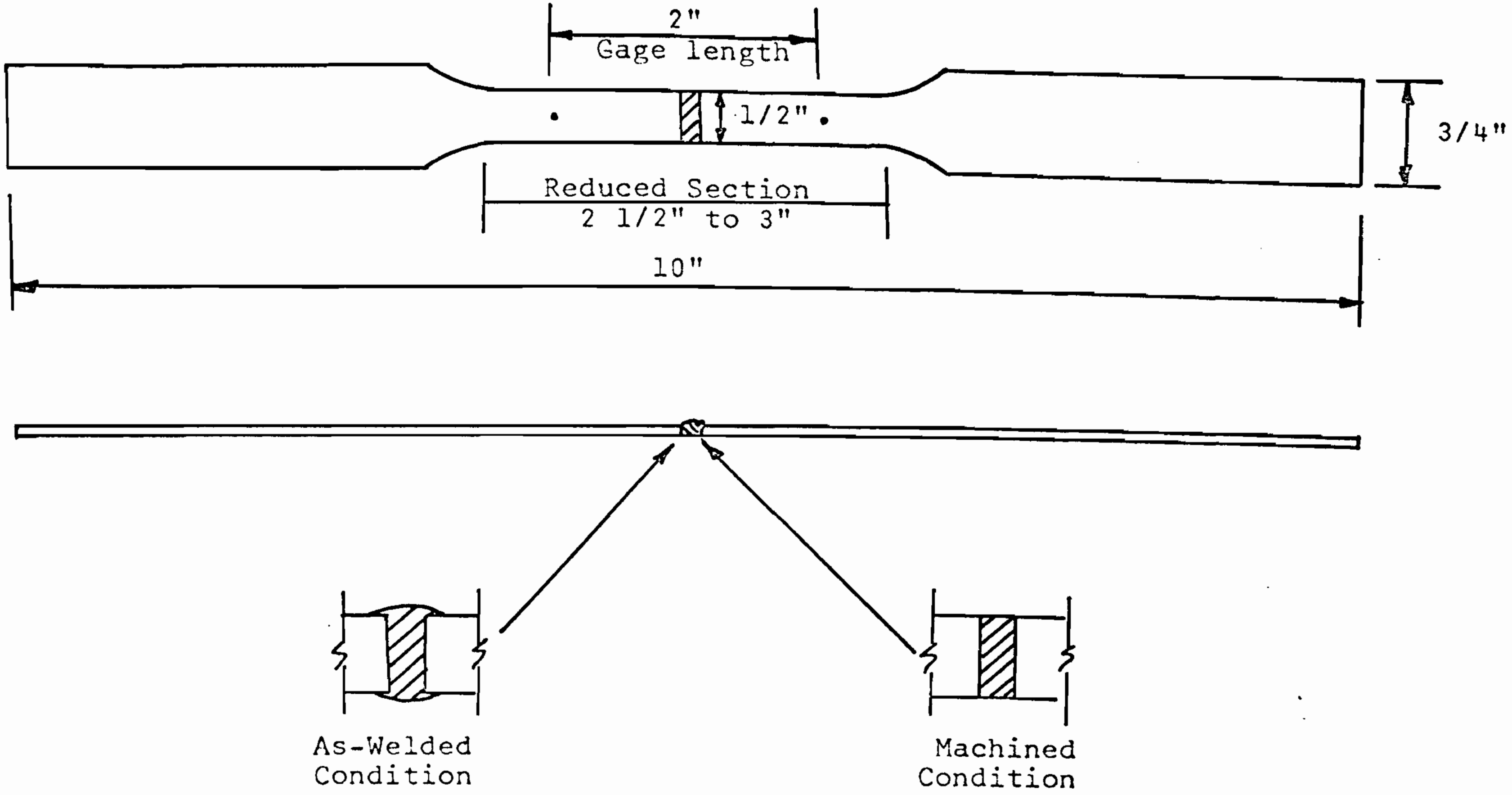


Fig. 17 Typical Butt-Joint, Groove-Welded Specimen

Note: "X" indicates tack weld location.

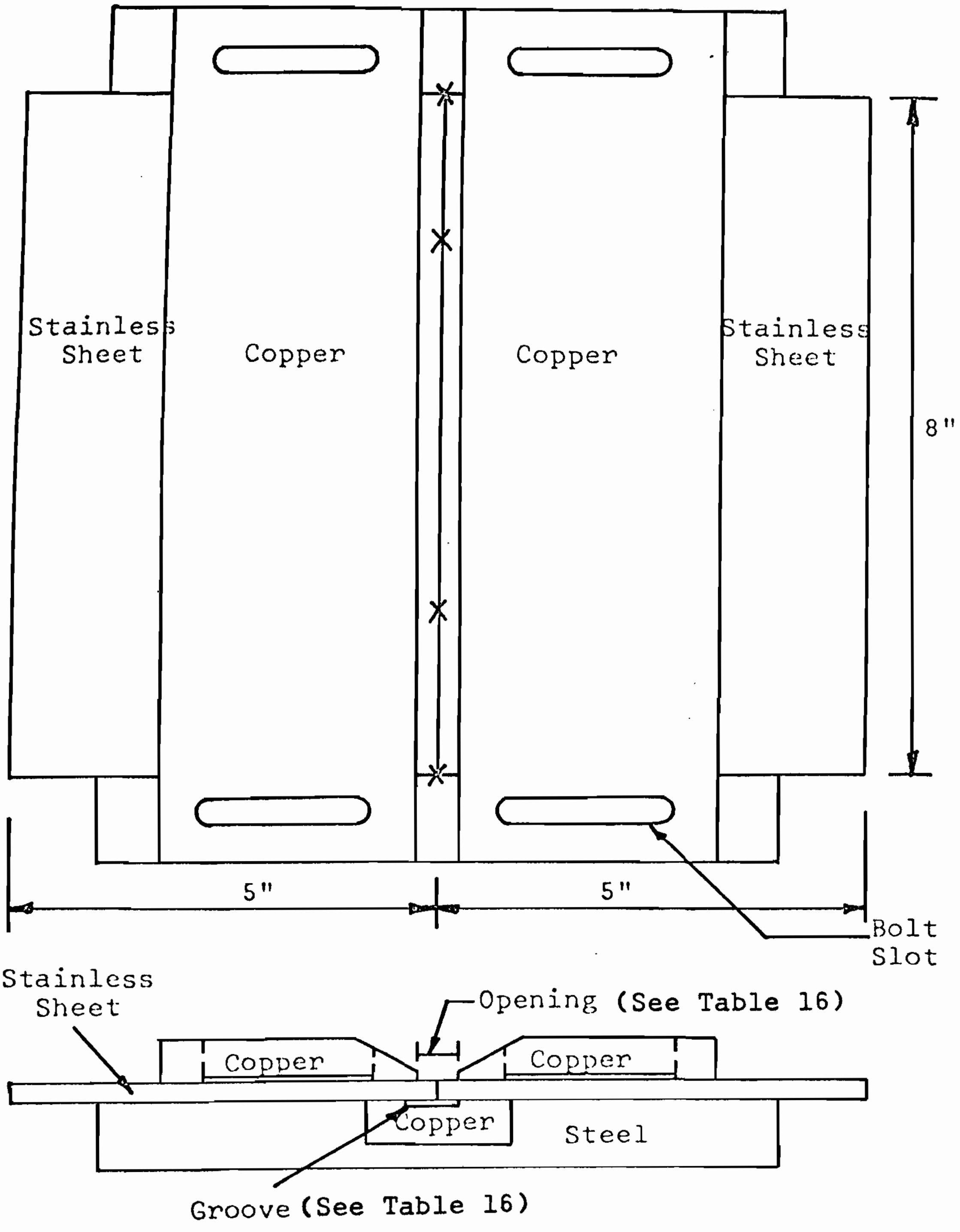


Fig. 18 **Welding Fixture, Butt Weld Specimens**

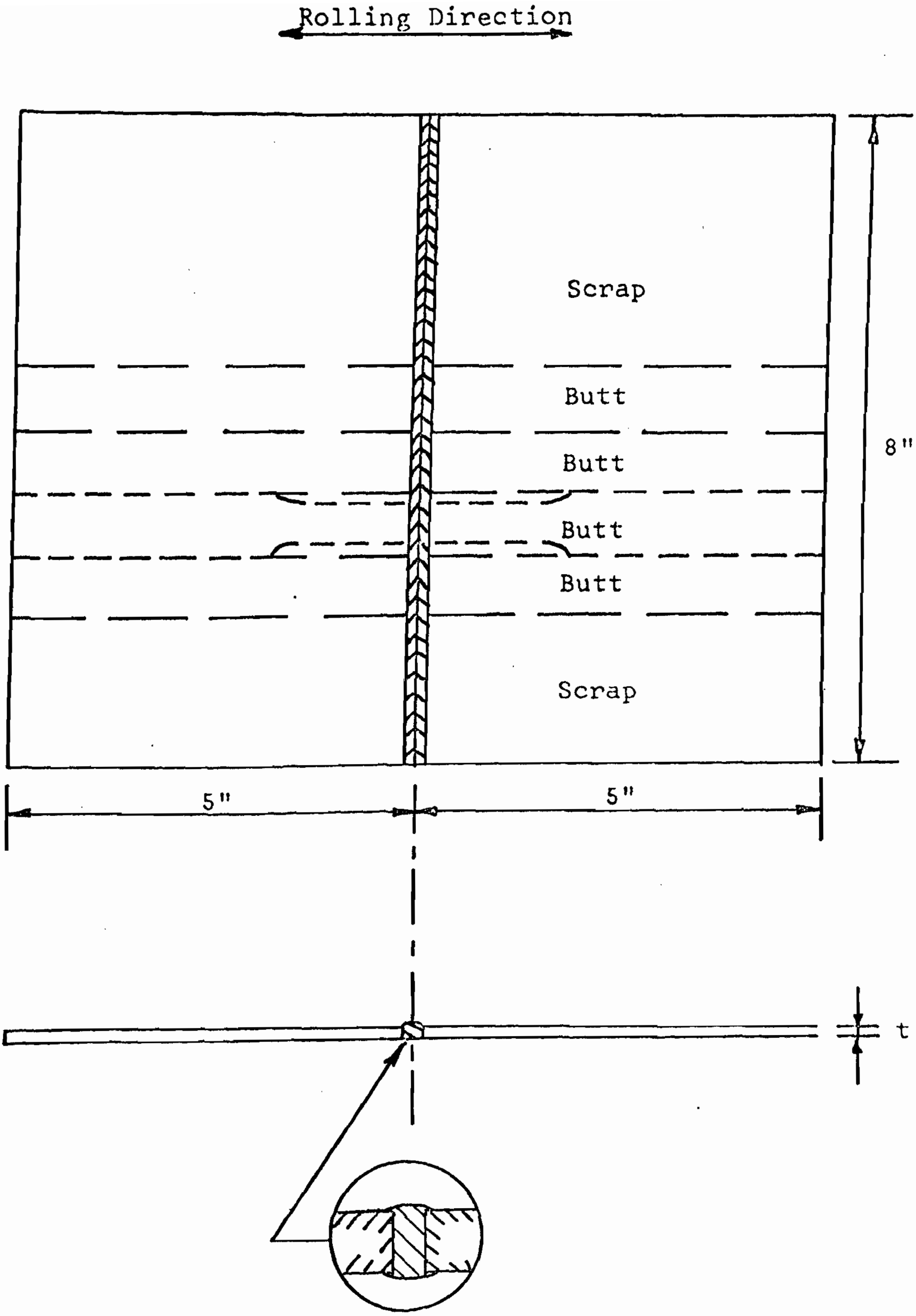


Fig. 19 Fabrication of Butt-Joint, Groove-Weld Specimens

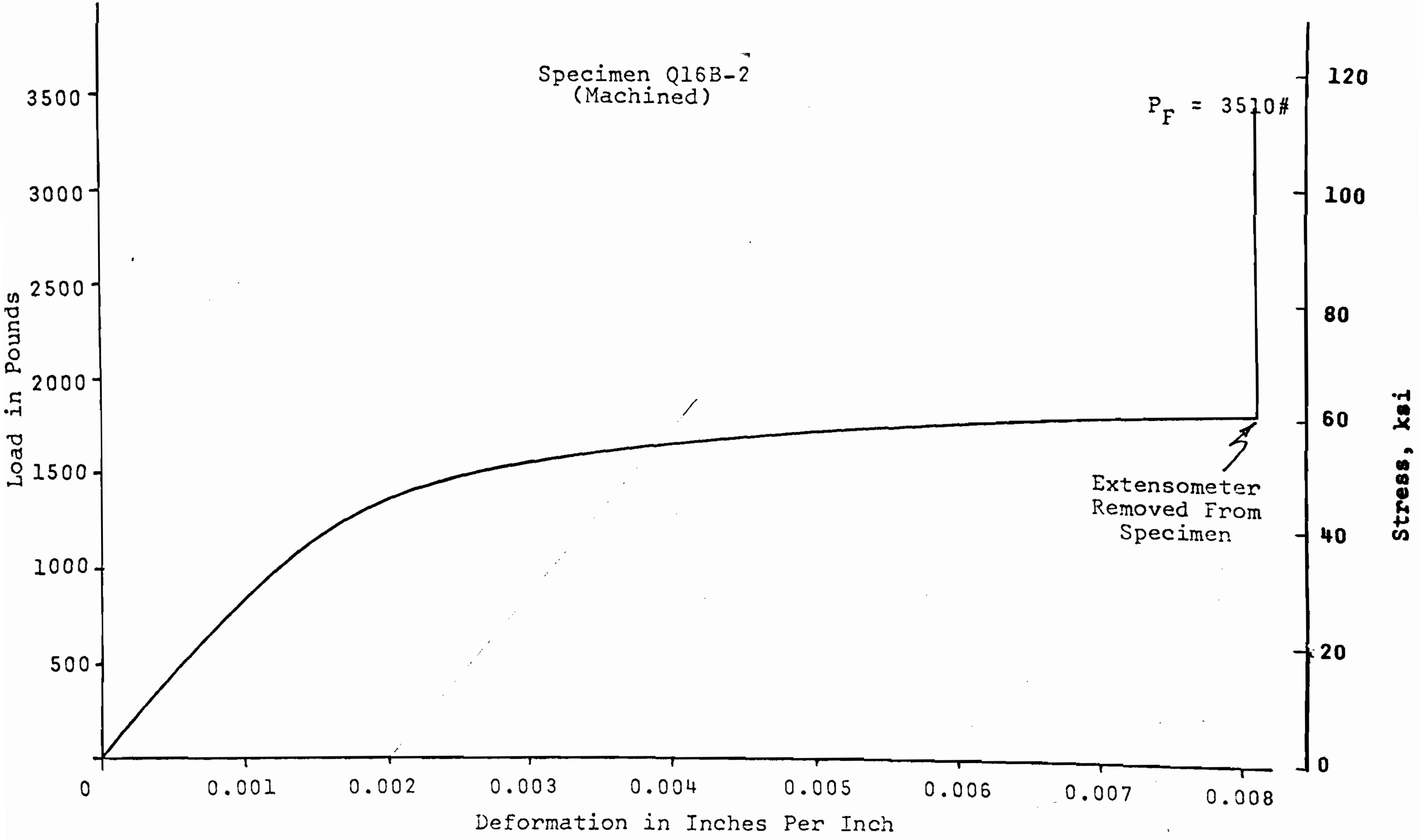


Fig. 20 Load-Elongation Curve For Butt Weld Specimen Q16B-2(Machined)

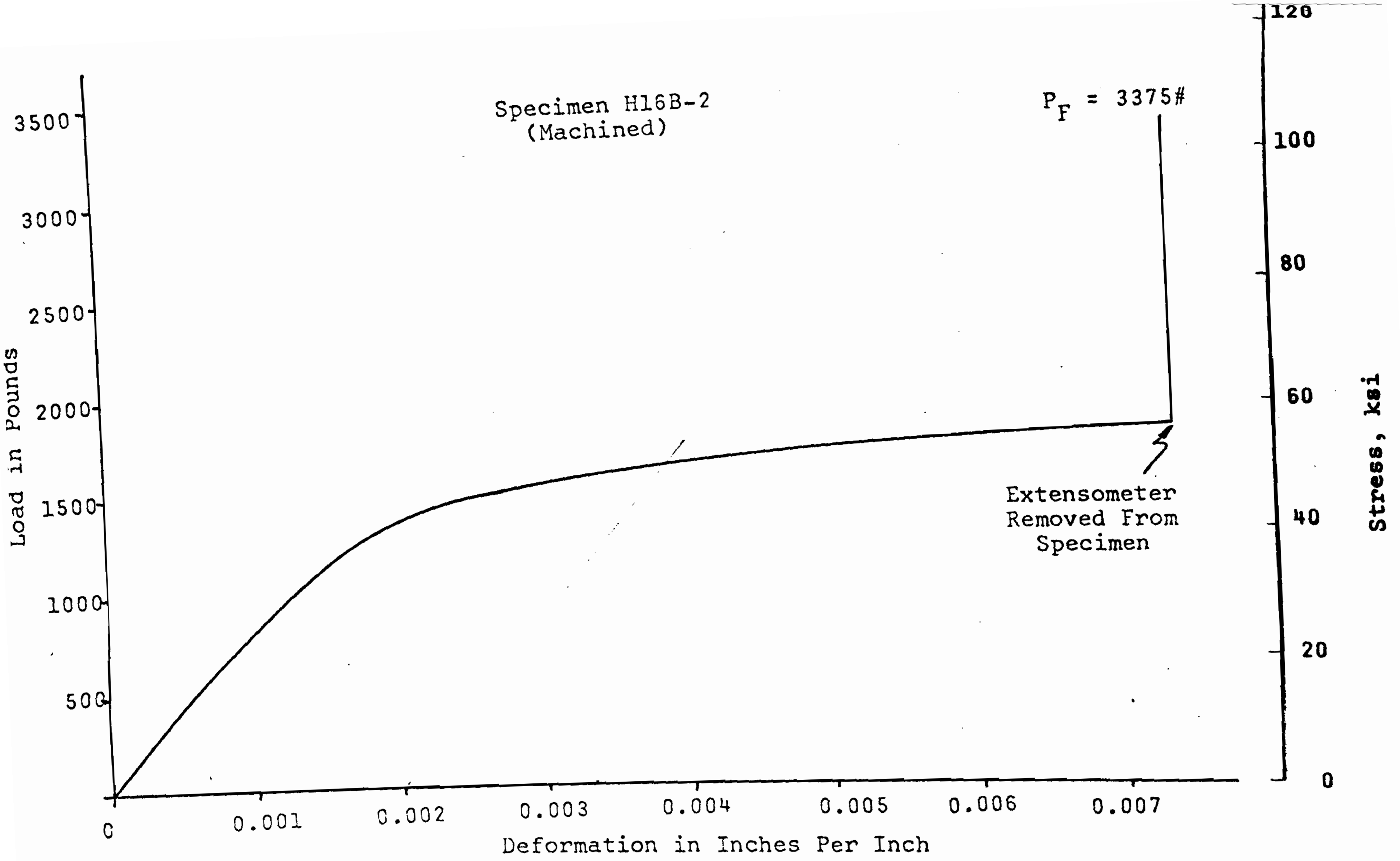


Fig. 21 Load-Elongation Curve For Butt Weld Specimen H16B-2(Machined)

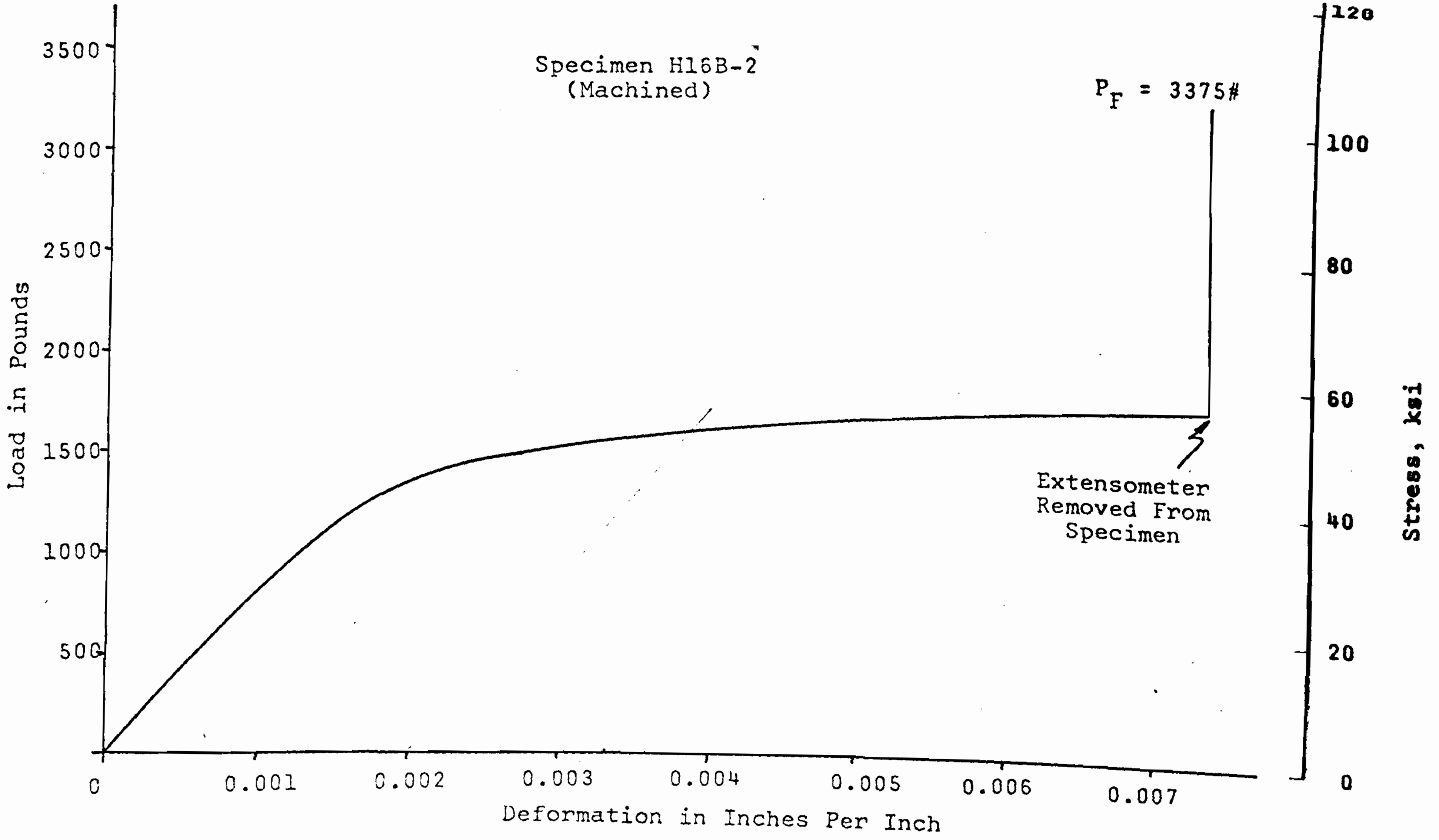


Fig. 21 Load-Elongation Curve For Butt Weld Specimen H16B-2(Machined)

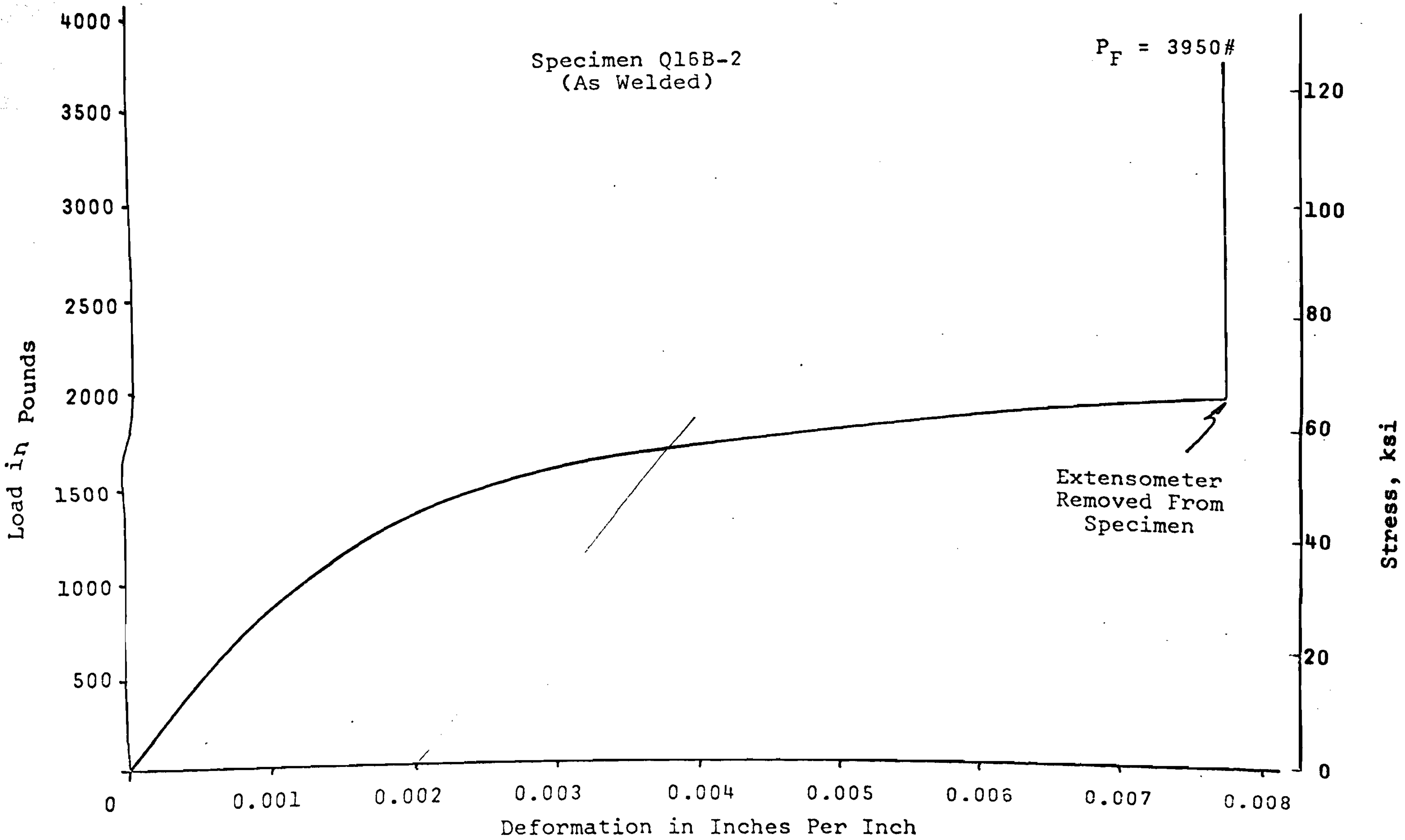


Fig. 22 Load-Elongation Curve For Butt Weld Specimen Q16B-2(As-Welded)

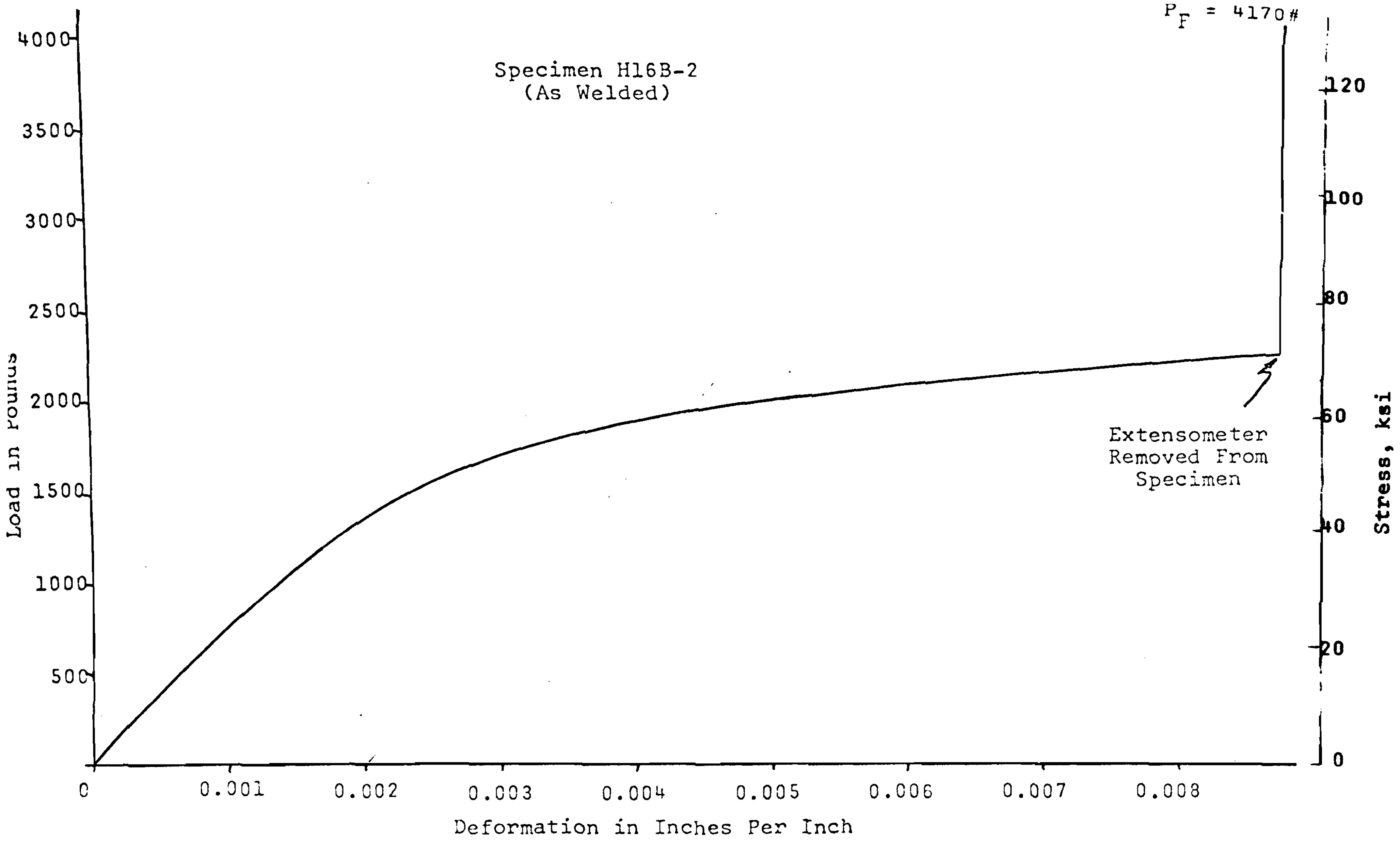


Fig. 23 Load-Elongation Curve For Butt Weld Specimen H16B-2(As-Welded)

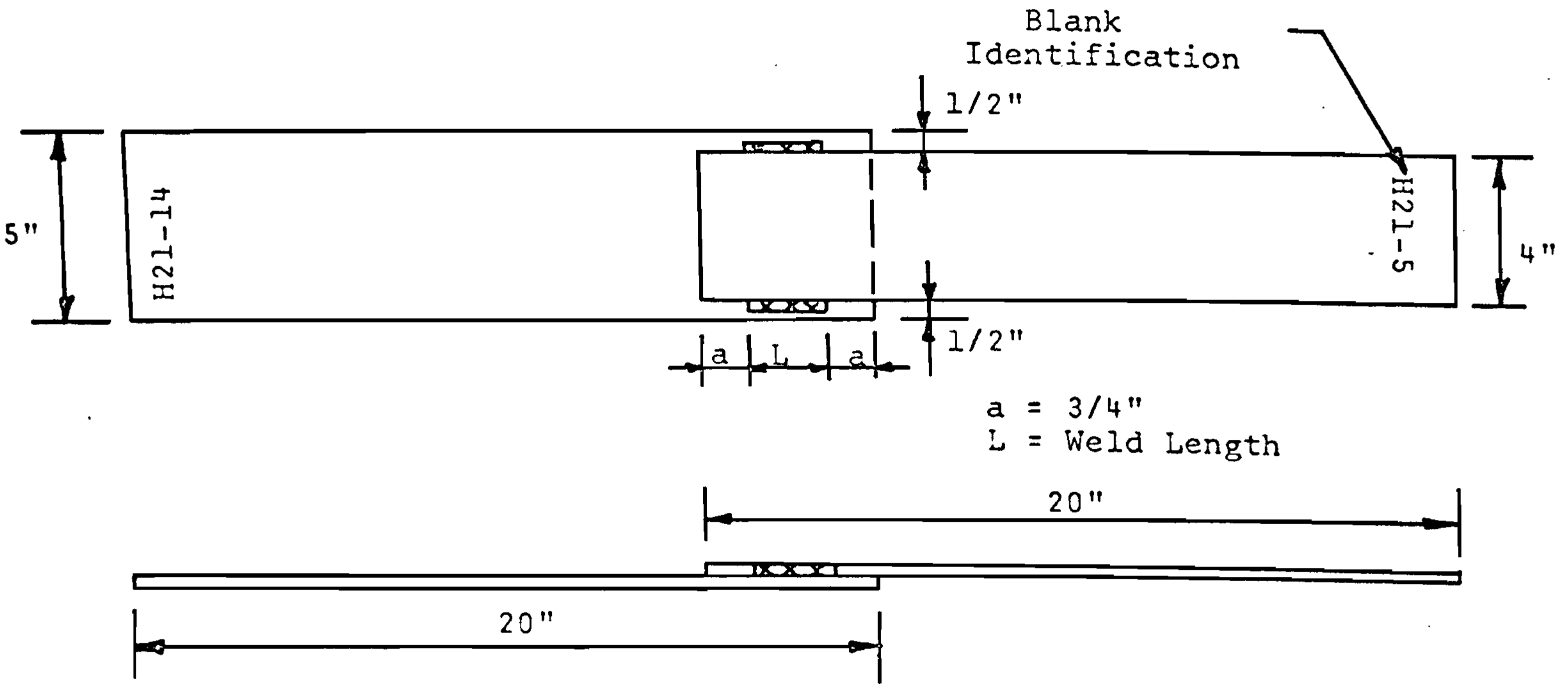


Fig. 24 Lap-Joint, Longitudinal Fillet Weld Specimen

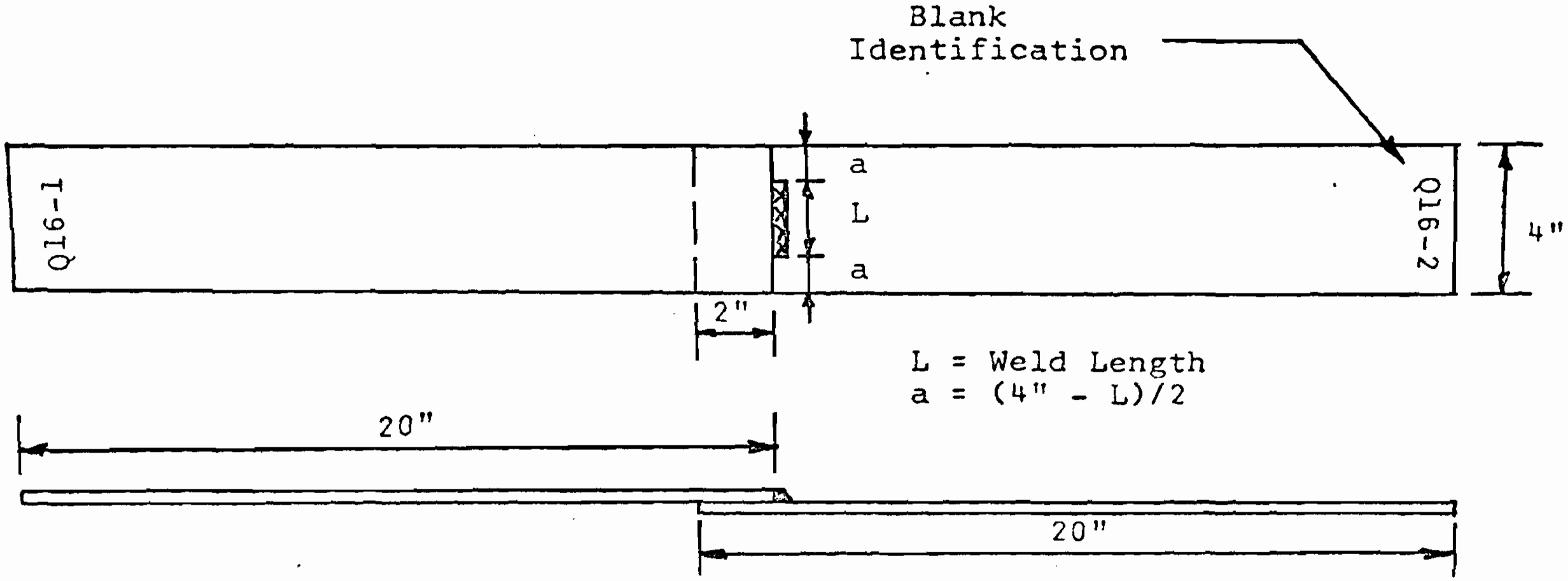
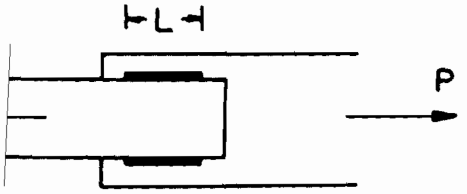
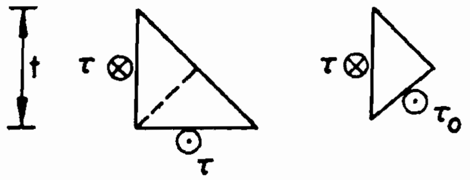


Fig. 25 Lap-Joint, Transverse Fillet Weld Specimen

Longitudinal Fillet Welds



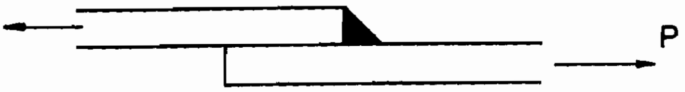


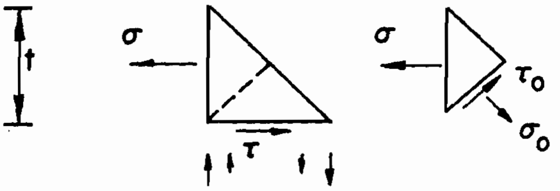
Shear Stresses on Longitudinal Fillet Weld

"Standard" Calculation:

$$\tau = \frac{P}{2Lt}; \quad \tau_o = \frac{P}{2Lt} \times \sqrt{2} = \frac{P}{\sqrt{2}\,Lt}$$

Transverse Fillet Welds





Stresses on Transverse Fillet Weld

$$\sigma = \tau = \frac{P}{Lt};$$

Assuming no shear stresses on vertical face of fillet,

$$\tau_o = \sigma_o = \sigma; \quad \tau_o = \frac{P}{Lt}$$

"Standard" Calculation:

$$\tau_o = \sqrt{2}\,\frac{P}{Lt}$$

Fig. 26 Stresses on Fillet Welds

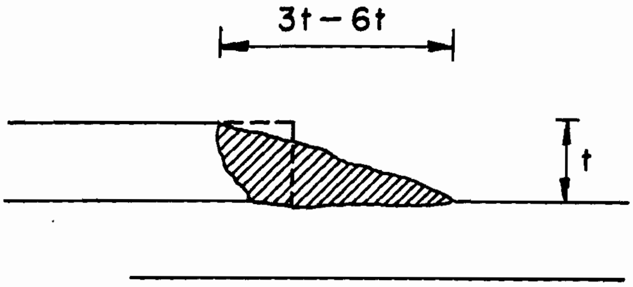


Fig. 27 Approximate Shape of Fillet Welds in Current Investigation

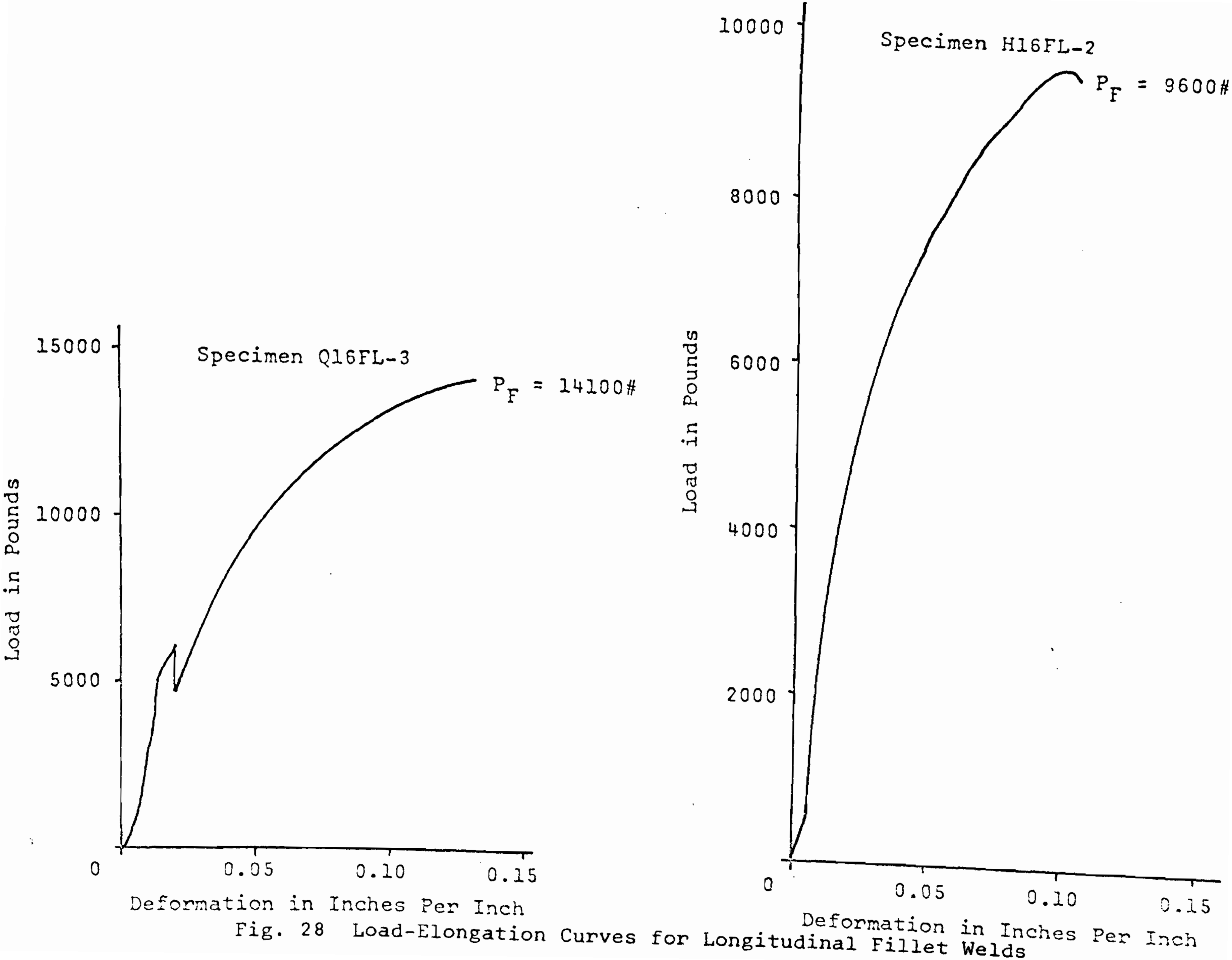


Fig. 28 Load-Elongation Curves for Longitudinal Fillet Welds

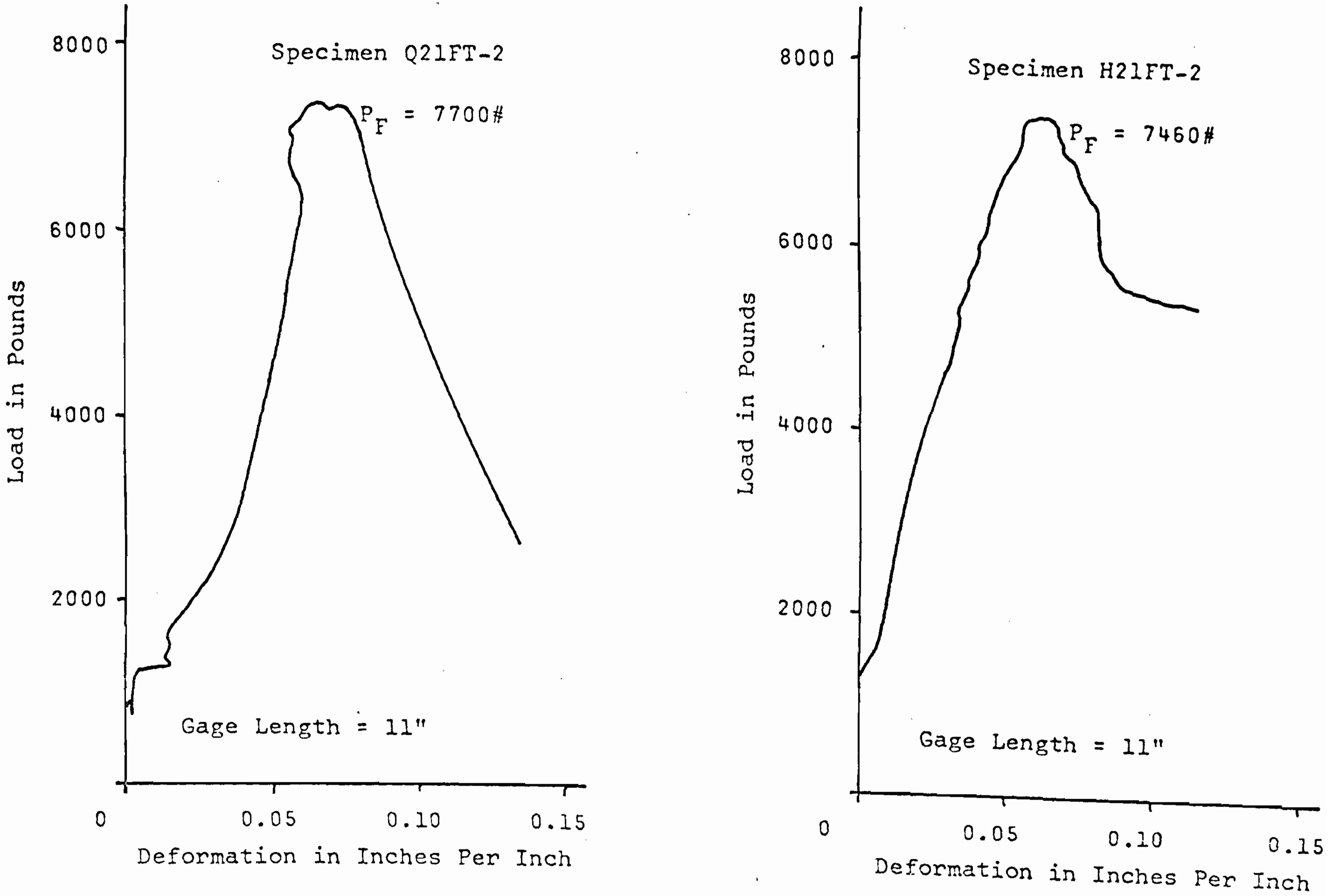


Fig. 29 Load-Elongation Curves For Transverse Fillet Welds

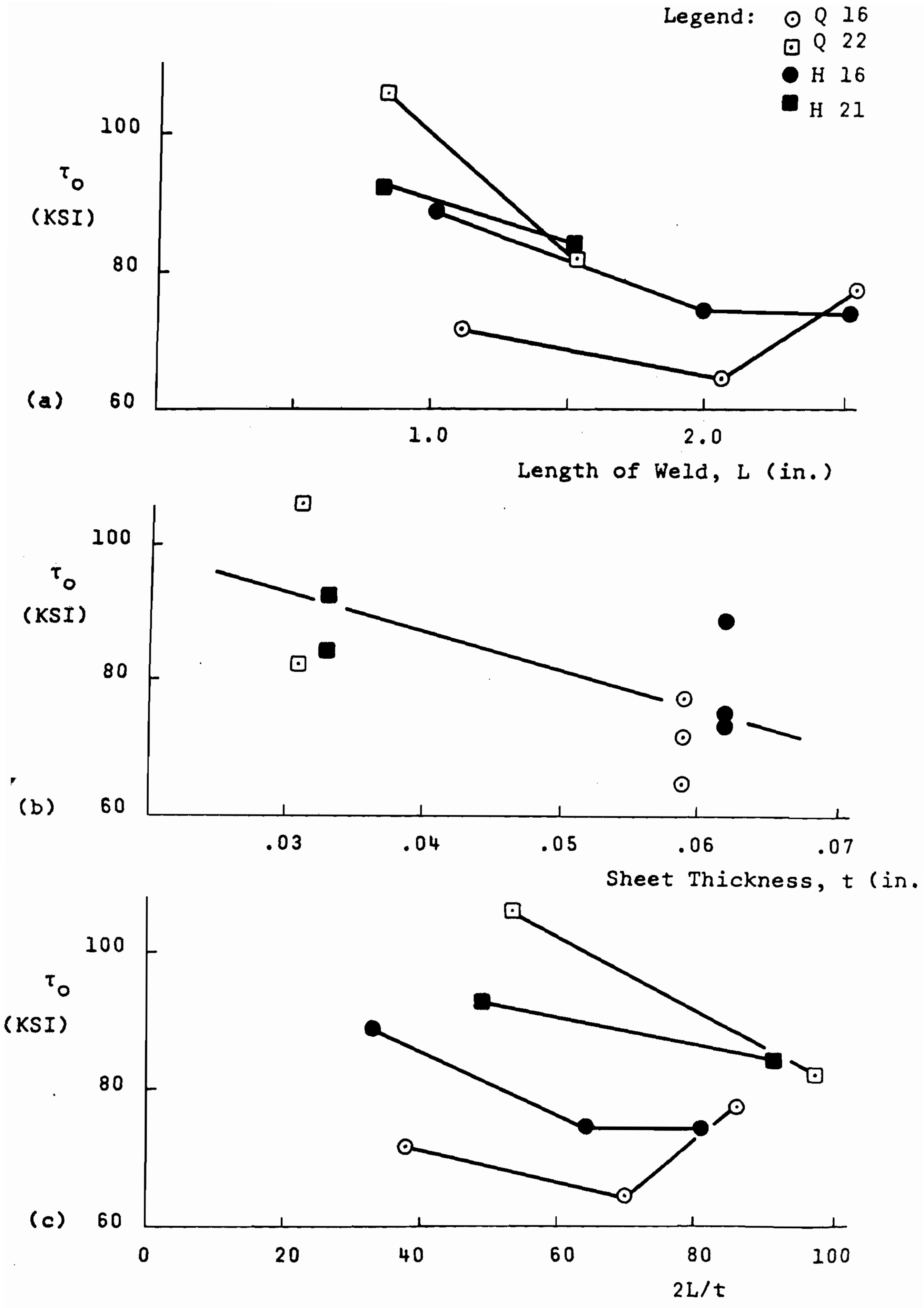


Fig. 30 Longitudinal Fillet Weld Test Results

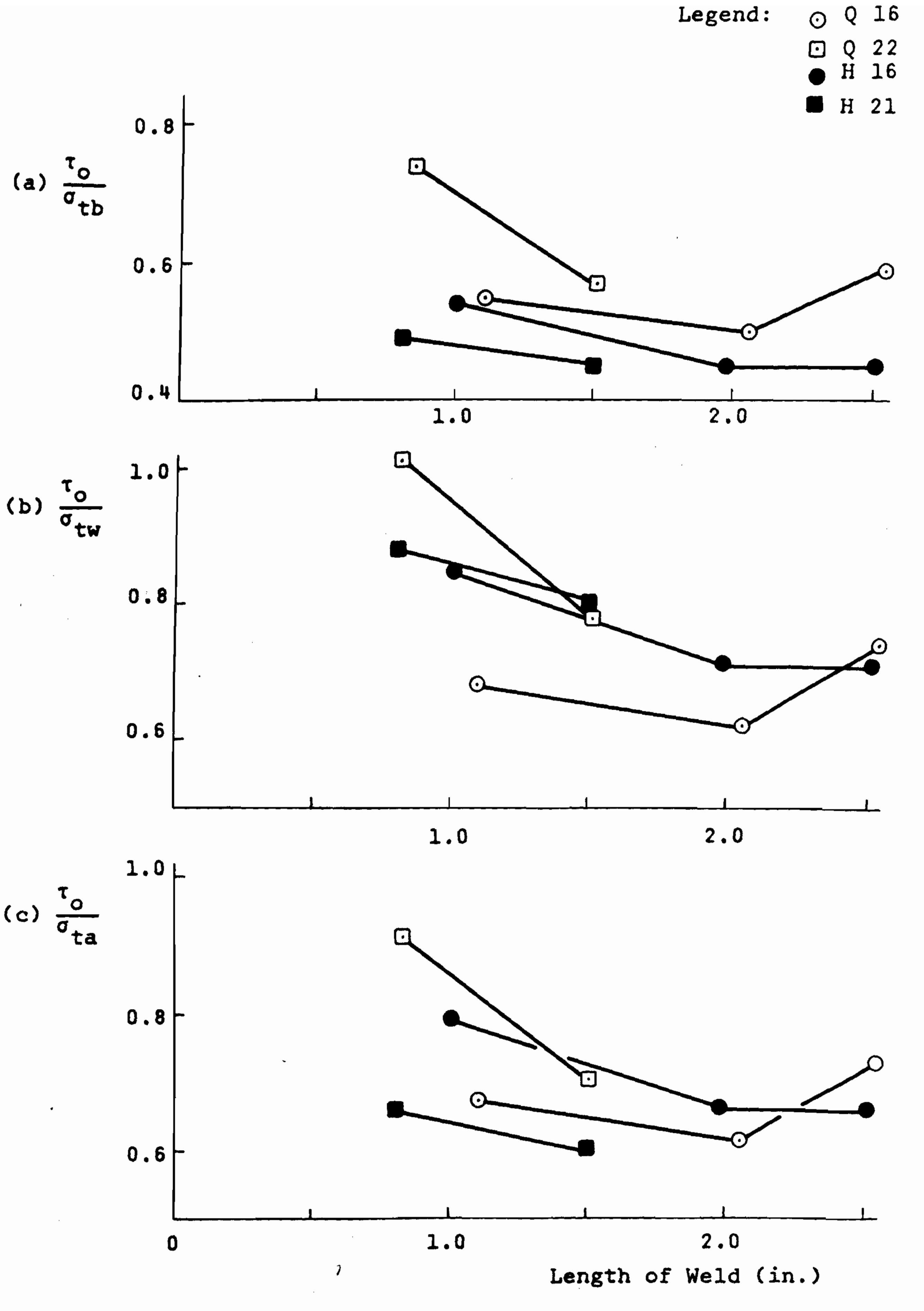


Fig. 31 Longitudinal Fillet Weld Test Results

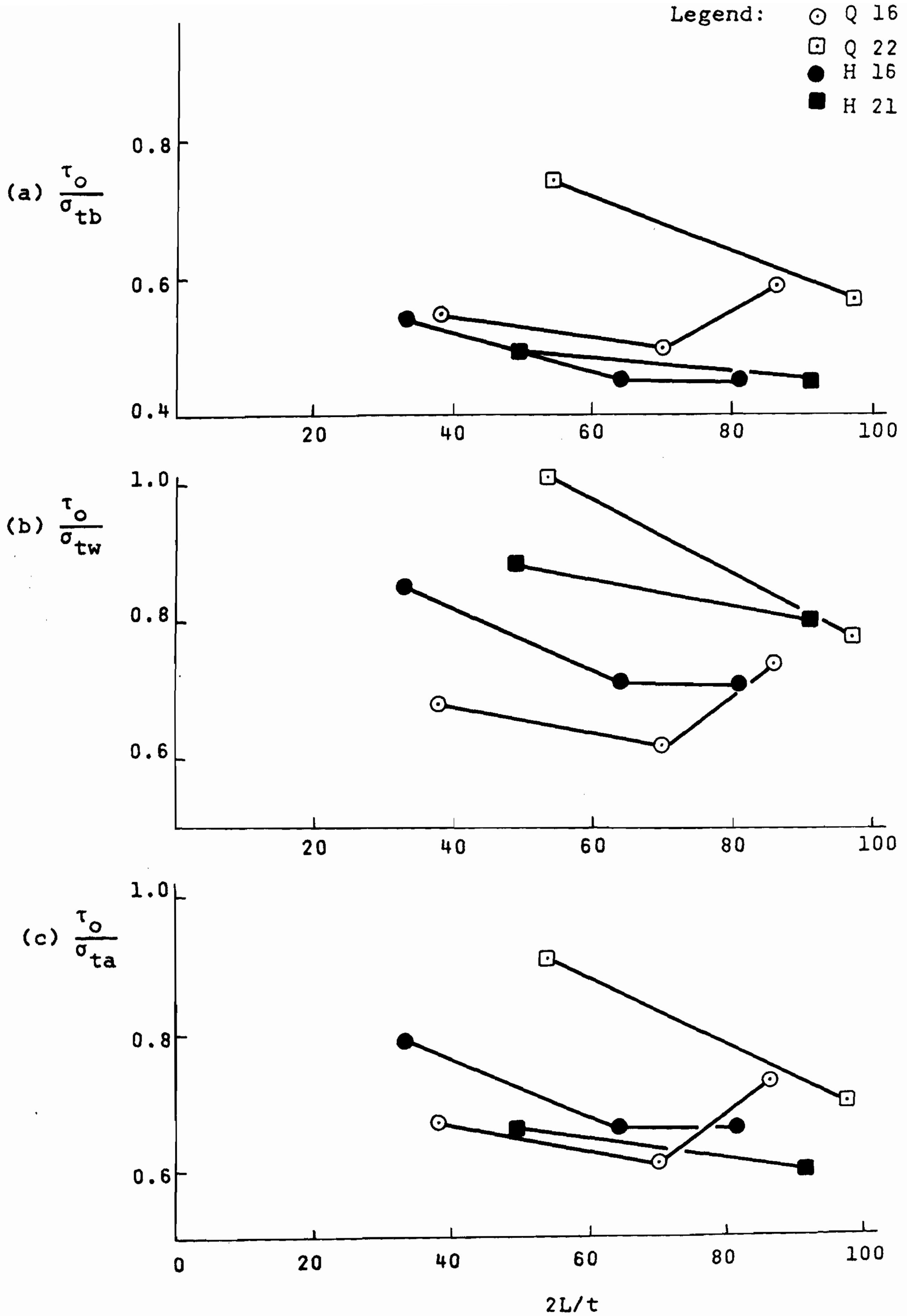


Fig. 32 Longitudinal Fillet Weld Test Results

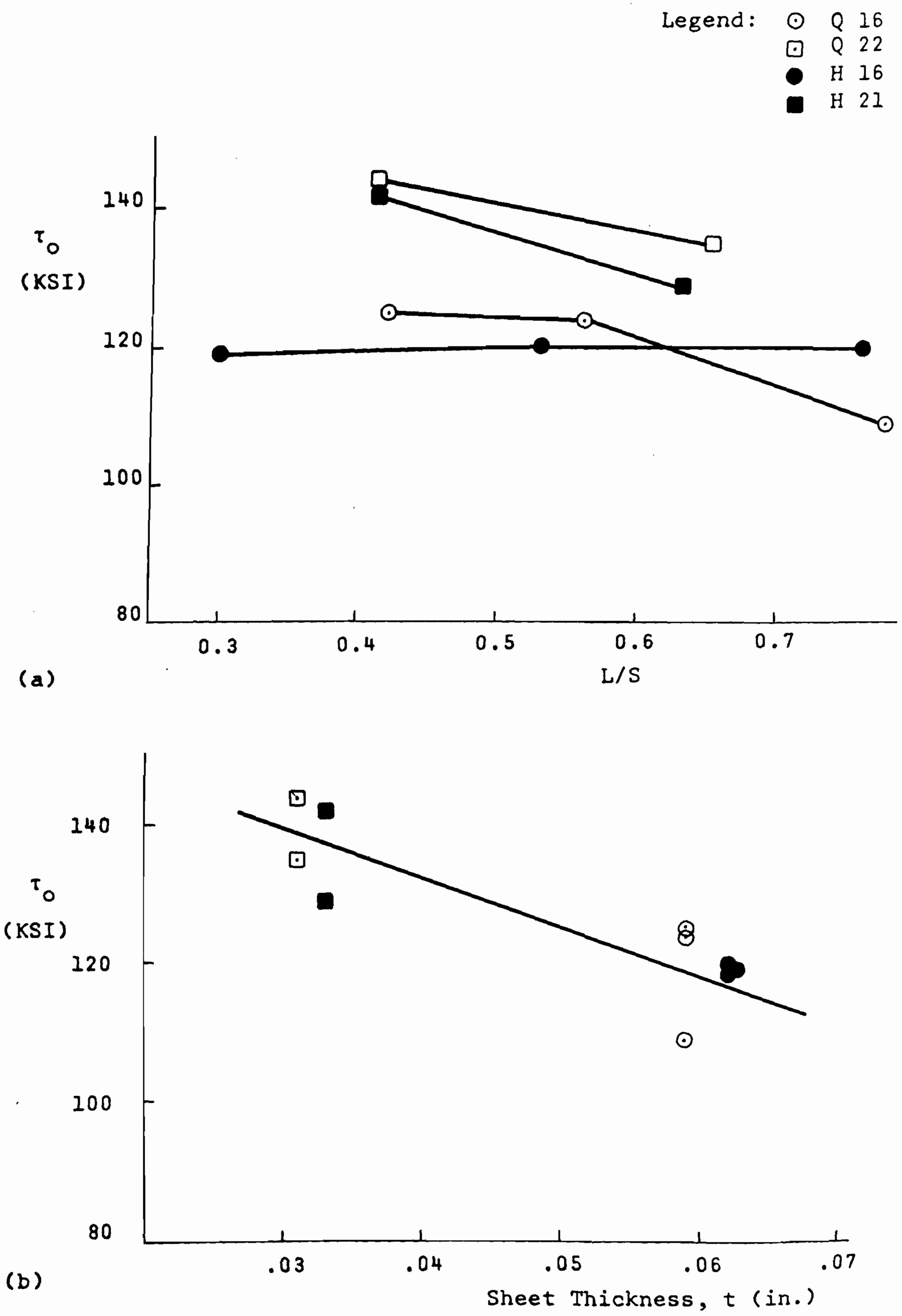


Fig. 33 Transverse Fillet Weld Test Results

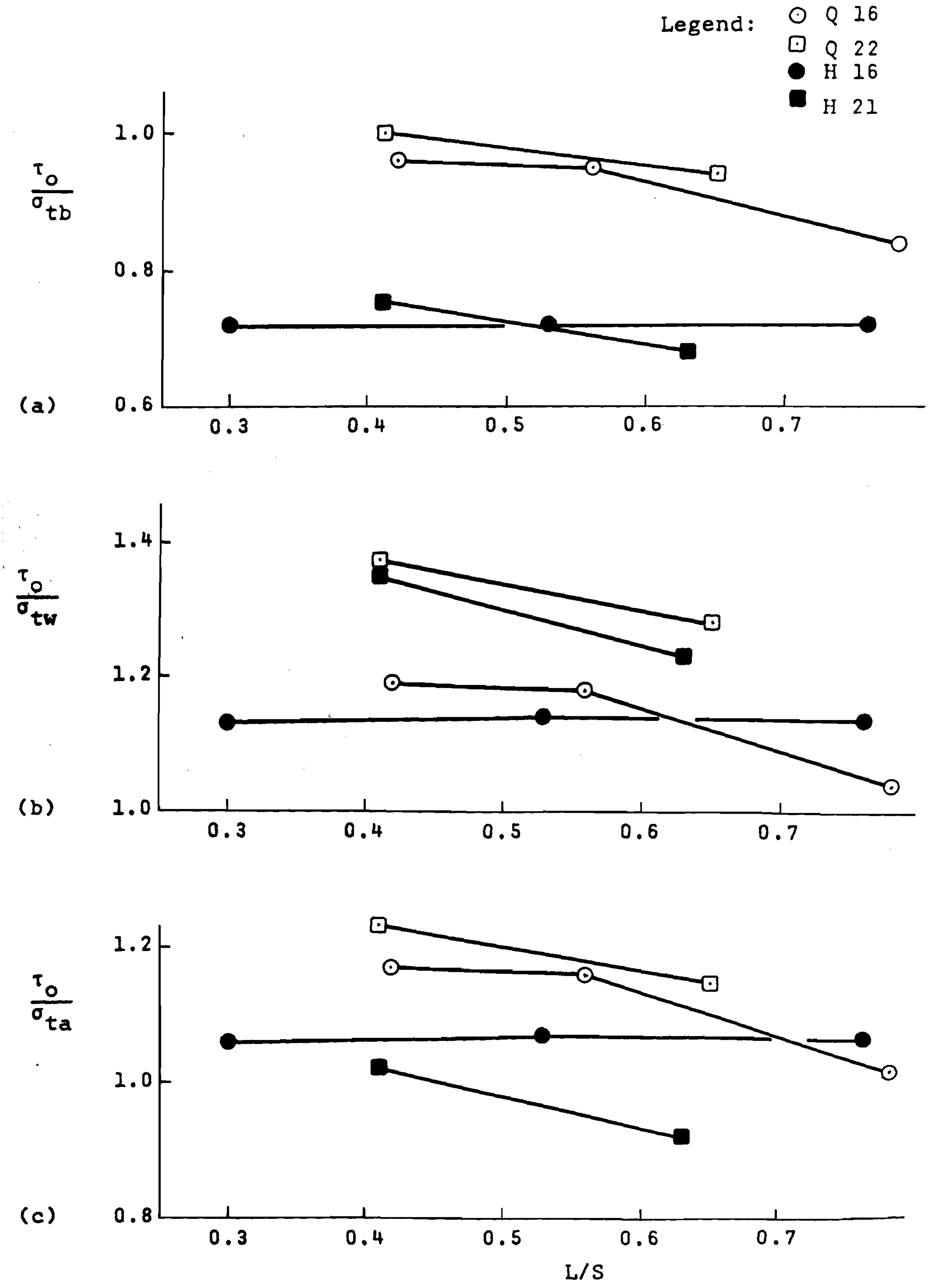


Fig. 34 Transverse Fillet Weld Test Results