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James J. Wallaert

John W. Fisher

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THE SHEAR STRENGTH OF HIGH-STRENGTH BOLTS

by

James J. Wallaert

John W. Fisher

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ABSTRACT

In many bolted connections the fasteners are subjected to shear loading. The objective of this study was to determine the behavior of single high-strength bolts under static shear loadings.

A total of 75 A354 BC, A354 BD and A490 bolts were tested in jigs made of A440 and constructional alloy steel. In addition, 72 A325 bolts were tested, 66 in A7 steel jigs and 6 in A440 steel jigs.

The effect of a number of variables upon the ultimate shear strength and deformation at ultimate load was studied. The variables were internal bolt tension, location of the shear planes, condition of the faying surfaces, bolt grade and diameter, connected material, grip and loading span, end restraint in the tension jigs, and type of testing device. The only variables which significantly affected the ultimate shear strength were the location of the shear plane, the grade of bolt, and the type of testing device.

1. INTRODUCTION

1.1 PURPOSE AND OBJECTIVE

Before evaluating the behavior of a bolted or riveted structural connection the behavior of the component parts must be determined. The static strength of the connected material is determined by coupon tests of plate material from the same ingot and rolling as the connected material. The other component of the structural connection is the fastener or the connecting medium. The fasteners in a butt-type splice joint under load are subjected mainly to a shearing force. A means of determining the shear strength and behavior of individual fasteners is desirable so that their performance may be compared to that of fasteners in a large connection. Also, a knowledge of their behavior is necessary if theoretical studies of large joints is undertaken.

Figure 1 depicts the results of typical double shear tests conducted on the A141 rivet, the high-strength A325 bolt, and the new higher-strength A490 bolt. The ordinate in Fig. 1 is average shear stress on the fastener, while the abcissa is the deformation of the fastener under applied load. This figure shows that the A490 bolt has a higher load-carrying capacity than the A325 bolt and that both can carry more load than the hot-driven rivet. It also shows that ductility decreases as fastener strength increases.

Because the A354 BD and A490 bolts have greater proof loads and tensile strengths than the A325 bolt, they create greater slip resistance and have higher shear strengths. When the higher-strength bolts are used in high-strength steel joints, the joints will be better proportioned because fewer bolts are required. A research program was initiated to study the basic tensile and shear properties of the A354 BC, A354 BD, and A490 bolts. The behavior of these bolts in direct tension and torqued tension, and their response to other special tests can be found in Ref. 1. Results of similar tests conducted on the A325 bolt can be found in Ref. 2.

The main objective of the study as reported herein was to determine the double shear strength of single A325, A354 BC, A354 BD, and A490 bolts and to investigate the effect of a number of variables on the shear strength and the deformation at ultimate load. A second objective was to establish the complete load-deformation relationship of the fasteners. With this information the analysis of the load-deformation behavior of large joints can be determined, since their performance depends not only on the strength of the fastener but also on its deformation capacity.

The test series described in this report represents one phase in the study of the ultimate strength of bolted joints. The interpretations and conclusions reported herein are based on the results of double shear tests of single 7/8 in. and 1 in. fasteners tested in A7, A440, and constructional alloy steel shear-inducing testing jigs.

1.2 HISTORICAL BACKGROUND

A considerable amount of experimental and theoretical work has been conducted on bolted and riveted joints. In general, most of these tests were on small scale specimens; only a few large specimens have been tested. Although many of the studies concerned with joint strength, the single and double shear behavior of single bolts has been investigated.

C. Batho(3) in 1931 used various grades of single black bolts installed in single and double shear tension jigs to determine the relationship between the installed torque and the slip load. Batho's tension jigs were very similar to those in the study reported herein. However, only one of the bolts was tested to failure. Load and deformation readings were taken up to slip load for all tests.

Wilson and Thomas(4) conducted static and fatigue tests on 1 in. rivets loaded in double shear. The number of fasteners in the joint varied from two to eight. Baron and Larson(5), who also conducted static and fatigue tests, showed that the substitution of high-strength A325 bolts for rivets does not change the plate efficiencies of a joint subjected to static load.

Munse, Wright, and Newmark(6) conducted an extensive test series using 3/4 in. A325 bolts to determine the static and fatigue behavior of bolted joints. They found that the initial bolt tension has little effect on the ultimate shear strength. Their tests of two-bolt and three-bolt lap joints and two-bolt butt joints indicated that the type of joint has little effect on the ultimate shear strength. The ultimate shear stress was about 77 ksi in the two-bolt butt joints in which bolt failure occurred.

Tests conducted on large bolted joints at Fritz Laboratory included material calibration(7)(8)(9). The basic shear strength of single A325 bolts was determined by placing a bolt in a loading jig that produced double shear. Bolts were installed in jigs with both lubricated and non-lubricated faying surfaces, and were torqued to various degrees of tightness. Bolts in the non-lubricated jigs failed at slightly higher loads, indicating that friction carries an insignificant portion of the ultimate load. Also, the internal tension of the bolts had no significant effect upon the ultimate shear stress.

Recent tests at the University of Illinois(10) demonstrated that the type of joint material has little effect on the single shear strength of A325 and A354 bolts. Also, it was found that the A354 BD bolts are about 25% stronger in direct shear than the A325 low-hardness bolt and 5% stronger than the A325 high-hardness bolt.

2. THE EXPERIMENTAL STUDY OF A325 AND ALLOY STEEL BOLTS

2.1 BOLT MATERIAL PROPERTIES AND BOLT DESCRIPTION

The A325 bolts used in the experimental program were manufactured from quenched and tempered medium carbon steel in accordance with ASTM A325(11). The A354 and A490 bolts were manufactured from quenched and tempered alloy steel in accordance with ASTM A354(12) and ASTM A490(13), respectively. The manufacturers were asked to supply bolts with tensile strengths near the minimum called for in the appropriate ASTM specifications so that minimum shear strengths could be determined. A number of A354 bolts used for this study were of a special manufacture. The heavy-head bolts were made to conform to the size requirements specified in ASTM A325 by reheat-treating AISI 4140 alloy steel bolts obtained from a Canadian firm. Because of this reheat-treating, these bolts had physical properties different from those of the other bolts tested.

Table 1 describes the various lots of bolts used in this investigation, including bolt types A354 BC, A354 BD, A325, and A490.

Lots AC, CC, and DC of A354 BC bolts were used. AC lot bolts had heavy heads while CC and DC lots both had regular heads. The three lots of A354 BD bolts, lots ED, FD, and GD, had regular heads. Although A490 bolt lots KK and JJ were originally not part of this investigation, the test results are included for completeness.

A325 bolts from lots Q, R, S, and T were from the same heat and heat-treatment. They were cut to length and threaded by cutting after heat-treatment as required. The A325 bolts from lots 8B, Y, and Z were from different heats and the threads were rolled after heat-treatment.

Both ends of each bolt were stamped with a lot designation and number. The bolts were center-drilled to accommodate the C-frame extensometer which was used to measure the changes in length due to tightening.

The bolt shanks were measured with a micrometer to see whether the actual bolt diameter varied greatly from the nominal diameter. The 7/8 in. diameter bolts were undersized by a maximum 0.003 in. and the 1 in. diameter bolts were undersized by a maximum of 0.005 in.

The mechanical properties of the bolts were determined from full-size tensile tests and 0.505 in. diameter tensile specimens. Table 2 summarizes the tensile test results. The full-size bolt tensile strengths are compared to the 0.505 in. coupon tensile strengths. Except for two lots of A325 bolts, the tensile strength of the full size specimens were greater, probably in part because the bolt threads prevented normal necking and thus increased the tensile strengths. Also, the full-size specimens were affected by variations in material strength due to the quench and tempering process, while the effects of this process were much less when the 0.505 in. specimens were machined to size. The difference in strength between bolt and coupon sample was greatest for the larger diameter bolts, lots DC and FD.

Additional details of the testing procedure and results are given in Refs. 1 and 2.

2.2 PLATE MATERIAL PROPERTIES

In order to determine the effect of the connected material on the ultimate shear strength of the bolt, some jigs were made with A440 steel plates and other were made with constructional alloy steel plates.

The tensile strengths of the jig materials were determined by tests of coupons cut from the same materials as the plates. The 40 A440 steel coupons and the 6 constructional alloy steel coupons tested were 1 in. thick and were machined to a 1.50 in. width. An 8 in. gage length was used in strain measurements. The A440 coupons had a mean static yield stress of 43 ksi and a tensile strength of 76 ksi. The A440 tests and results are detailed in Ref. 9. The constructional alloy coupons had a yield strength at 0.2% offset of 110.3 ksi and an ultimate strength of 120 ksi.

2.3 DESCRIPTION OF TEST JIGS

Two types of shear-inducing test jigs were used, as shown in Fig. 2, to determine the double shear strength of the single bolts. Double shear test jigs were used because they provide good symmetry and because the large bolted joints tested in Fritz Laboratory are usually double shear connections. The plates of the compression jigs (Fig. 2a) were subjected to axial compressive loads, while axial tensile loads were applied to the plates of the tension jigs (Fig. 2b).

The 4 in. compression test jig shown in Fig. 2a was composed of two 1 in. lap plates connected to two 1 in. main plates by a single test bolt. The 4 in. tension jig, shown in Fig. 2b, was similar to a butt-type joint with two 1 in. lap plates and two 1 in. main plates. Three bolts were used to connect the material in the tension jig so that only the test bolt was critical. As is the usual practice, the bolt holes in the plates of both test jigs were 1/16 in. larger than the nominal bolt diameter.

For grips exceeding 4 inches additional plies of 1 in. material were used to provide the desired grip lengths. Each lap plate in the 8 in. grip test jigs consisted of two 1 in. plies, and the main plate member was composed of four 1 in. plies to provide equal lap and main plate bearing area. This arrangement assured a constant loading span-grip ratio of 1:2, where the loading span is defined as the thickness of the main plate (2 in. or 4 in.) and the grip is defined as the thickness of the gripped material. All plies were arranged symmetrically about the bolt jig centerline. The jigs were wide enough to minimize axial strains. The bearing and bending conditions of the bolts in the test jigs were comparable to these conditions in the larger joint tests.

2.4 BOLTING UP PROCEDURE

The test jigs were assembled with the test bolts in bearing in order to minimize slip. The load-deformation relationship was needed in theoretical studies to help determine the load partition in bolted bearing-type connections after major slip occurred. Therefore, it was desirable to eliminate the joint slip from the observation. All faying surfaces were clean mill scale except for those test jigs in which the condition of the faying surface was a variable.

Bolts from each lot were calibrated(1)(2) in torqued tension to determine the internal tension-elongation relationship. The bolt preload could then be determined by measuring the bolt elongations and relating the elongations to the proper calibration curve. All bolts were installed in the tension and compression jigs to an elongation which corresponded to at least proof load, except for those bolts in which preload was the major variable. No attempt was made to tighten the bolts to the same elongation. As will be shown later, the initial bolt preload had little, if any, effect upon the ultimate shear strength of the bolt. The initial bolt tension was induced by turning the nut against the connected material with a hand torque wrench.

2.5 BOLT JIG INSTRUMENTATION

In the instrumentation of a typical tension jig, shown in Fig. 3, two 0.0001 in. Ames dial gages were attached to the main plates at the centerline of the bolt hole. The plungers of the dial gages rested on yokes tack-welded to the lap plates at the initial level of the dial gage support. This instrumentation permitted measurement of the relative movement of the centerlines of the bolts due to shear and bending. This measurement also included the deformation of the holes due to bearing stresses.

The deformation of the compression jigs was usually measured by placing one 0.0001 in. dial gage between the fixed and moving heads of the testing machine as shown in Fig. 4. The deformation measurement thus included the relative movement of the bolt due to shear and bending, the bearing deformation in the lap and main plates, the axial shortening of the plates, and the deformation within the testing machine itself.

To determine the order of magnitude of the deformations within the testing machine and other portions of the test assembly and to determine what influence these had on the compression test jig deformation readings, one test was conducted with the dial gages mounted on the test jig in a manner similar to that of a tension jig.

2.6 TEST PROCEDURE

In a few initial tests the shear jig was placed in the testing machine and loaded continuously until failure. However, slip occurred in both tension and compression jigs, indicating that the assembly process was not altogether successful. As a result it was necessary to remove residual slip by loading the jigs until they slipped into bearing and then removing the load before actual testing was begun. A load of approximately 30 kips was applied to jigs connected by 7/8 in. bolts and 60 kips was applied to jigs connected by 1 in. bolts.

The tension jig tests were conducted in a 300 kip universal hydraulic testing machine (Fig. 3). After the test jig was gripped and the residual slip was removed, the specimen was loaded continuously until failure occurred. Load and deformation readings were recorded at 10 kip intervals until the difference in deformation readings was 0.01 in. Thereafter, a deformation criteria was used to control the test, and load readings were taken at 0.02 in. intervals. On most of the tension specimens the gages were not removed from the test jigs after ultimate load had been reached.

The compression jig tests were also conducted in the hydraulic testing machine. The test jig was placed in the center of the testing heads with the bolt perpendicular to a line between the loading screws. The movable head was lowered until it was in contact with the test jig, the jig was loaded to remove residual slip, and then the load was removed. The dial gage was then placed between the heads and initial readings were taken. Load and deformation readings were recorded at 10 kip intervals until a deformation criterion of 0.02 in. controlled the load readings.

The load was applied to both jigs so that the cross head movement was 0.01 in. per min. in the elastic range and 0.02 in. per min. in the inelastic range.

Several tests of A325 bolts in tension test jigs indicated that the loading speed had little if any effect on the load-deformation curve.

At several load increments in the inelastic range the loading valve on the testing machine was closed and the load was allowed to stabilize. In most cases this took only a few minutes. It was found that the load dropped only 1 kip in 100 kips. Thus the difference between static and dynamic shear loading readings was negligible. All plotted points in the figures are dynamic readings.

2.7 THE EXPERIMENTAL PROGRAM

The experimental program was formulated to measure the effect of certain variables on the ultimate shear strength of the bolts and their deformation at ultimate load. The testing program was influenced by earlier work on rivets(14)(15) as well as by the behavior of bolts in tests on large bolted connections(7)(8)(9).

The variables investigated were (1) type of testing device (compression or tension jig), (2) initial bolt preload, (3) condition of faying surfaces, (4) location of shear planes, (5) bolt grade, (6) bolt diameter, (7) type of connected material, (8) grip and loading span, and (9) end restraint in tension jig. These variables are discussed in turn in this section of this paper.

The first variable, the type of testing jig, influenced the complete load-deformation curve of an A325 bolt in past tests(9). Bolts tested in compression jigs had ultimate strengths 10% greater than bolts tested in tension jigs. It was thought desirable to know how the type of testing jig influences the behavior of A354 BC and A354 BD bolts.

Whether initial bolt preload, the second variable, affects the shear strengths of bolts is an important consideration. It is generally believed that rivet clamping force, a factor similar to bolt preload, is removed when a rivet yields and that the ultimate shear strength of the rivet is not effected by the clamping force(15). This paper answers the question whether a similar assumption can be made for the bolts tested: engineers have asked how installing a bolt by moderate torquing or by torquing to near-failure affects its ultimate shear strength.

The third variable, the condition of the faying surfaces, was considered because it was thought that some load could be carried by frictional forces in the joint if all clamping forces were not removed. The effect of friction was evaluated by comparing clean mill scale joints with joints in which the faying surfaces had been lubricated.

The location of the shear planes, variable number four, was thought important because the shear planes may pass through the threads or the thread run-out. In these areas the shear strength is lower than elsewhere along the bolt, and whether the reduction in shear strength is proportional to the reduction in the shear area was studied.

The fifth variable, bolt grade, is obviously important. It was known that the A490 and A354 BD bolts are stronger than the A354 BC bolt, and that the A325 is weakest of all. However, it was of practical interest to determine exactly how large a shear load each bolt could carry.

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The effect on shear strength of variable number six, bolt diameter, had been questioned in the past. Tests of rivets had shown no consistent relationship between ultimate shear strength and rivet diameter(15), and it was thought desirable to determine the nature of this relationship for bolts.

The type of connected material, the seventh variable, was thought worthy of consideration because bolts are used to fasten a variety of steels with dissimilar properties that may influence bolt shear strength.

It was thought that shear strength might decrease with an increase in grip length, the eighth variable. It had been demonstrated that the ultimate strength of rivets decreases about 10% with an increase of grip length from 1 in. to 5 in.(15). Longer rivets were thought to be weaker because they did not fill the holes as well as shorter rivets and because they had different strength properties than shorter rivets because of the differences in working the material during driving. However, the effect of grip length on bolt strength had not been determined.

The ninth and last variable, end restraint in the tension jig, had already been studied for riveted aluminum joints(16). It was thought desirable to know whether minimization of lap plate prying action in a tension jig (to be explained later) would result in bolt shear strength approaching that obtained in a compression jig. In a joint using several fasteners the plates are restrained from bending freely between the interior fasteners and therefore cannot produce lap plate prying on any fasteners except those at the plate ends. If this restraint in tension jigs caused the bolts to shear at the same loads as in compression jigs, the use of the compression jig in testing could be justified to some extent.

Table 3 describes the bolt lots used in the study, together with the number of bolts tested in the A7, A440, and constructional alloy steel tension and compression jigs. The reported grip included the nominal grip of 4 or 8 in. plus one or two 1/8 in. hardened washers.

Except for A325 bolt lots Q, R, and S, the shearing plane passed through the full shank area and not through the thread or thread run-out. For bolt lots DC and FD, this requirement necessitated machining 0.16 in. and 0.20 in., respectively, off the underside of the bolt head so that the shear planes did not pass through the threads. As far as could be ascertained, the machining had no adverse effect upon the bolt behavior. 36 A354 bolts were tested in tension jigs and 39 A354 bolts were tested in compression jigs. In addition, 69 A325 bolts were tested in compression jigs and 3 A325 bolts were tested in tension jigs.

3. TEST RESULTS AND ANALYSIS

3.1 INTRODUCTION

The double shear test results are given in Tables 4 and 5 for the compression jig and tension jig tests, respectively. The ultimate strength and fracture load values are given in kips; the deformations are reported in inches. Average load and deformation values were computed at ultimate and fracture loads. The bolt grades include A325, A354 BC, A354 BD, and A490 high-strength.

The shear test results for the compression and tension jigs are summarized in Table 6. Included are mean values of the shear strength and the deformation at ultimate load of bolts tested in A440 and constructional alloy steel jigs. The shear stress was obtained by dividing the ultimate load by the appropriate shear area. For the bolts whose shear planes did not pass through the shank, the shear stress was obtained by dividing the load by the actual shear area. When both shear planes passed through the shank, twice the nominal shank area was used. When one shear plane passed through the thread run-out, the run-out diameter was measured and the area computed and added to the shank area. If one shear plane passed through the fully threaded portion of the bolt, the nominal root area was added to the shank area. When both shear planes passed through the fully threaded portion, twice the root area was added.

The special studies conducted on A325 bolts are summarized in Table 7. This includes tests of bolts with the shear planes through the threads or thread run-out and the tests comparing normal mill scale faying surfaces with lubricated mill scale faying surfaces.

The bolt tensile strengths given in Table 8 are based on the ultimate tensile load obtained from direct tension tests(1) and the stress area. The bolt tensile strengths were used to compute the minimum shear strengths given in Table 8 for bolts tested in A440 and constructional alloy steel jigs. These minimum shear strengths were computed on the basis of the formula:

$$\tau_{min} = \frac{\sigma_{min}}{\sigma_{act}} \tau_{act} \qquad (1)$$

where σ_{min} is the minimum bolt tensile strength as specified in ASTM's A325, A354, and A490. The actual bolt tensile strengths σ_{act} are given in Table 8 and were computed on the basis of the tensile test results on full-size bolts. The ultimate shear strength τ_{act} is the double shear strength of a single fastener in either a tension or a compression jig.

The following average minimum shear strengths for the three types of bolts tested were computed without regard to the type of connected material because it had no effect upon the ultimate shear strength. As would be expected, the tension jig test gave the lowest values for minimum shear strength. The minimum shear strengths for A325, A354 BC, and A354 BD (or A490) bolts tested in tension jigs was 76.7 ksi, 78.7 ksi, and 91.9 ksi respectively. However, for the same bolt grades tested in compression jigs, the minimum shear strengths were 86.5 ksi, 86.8 ksi and 102.8 ksi respectively.

The deformation of the fasteners in the tension jigs as reported in Table 5 included the effects of shearing, bending, and bearing deformation of the bolts as well as the localized bearing deformation of the main and lap plates. For the compression jigs, the deformation measurement included, in addition to the aforementioned deformations, axial deformation of the test jig and deformation within the testing machine. One test was conducted with the gages mounted on the compression jig in a manner similar to that of the tension jig. Figure 5 shows the load-deformation curves for the DC lot bolts tested in the two groups of compression jigs. It can be seen that the deformation at ultimate load is less for the bolt tested in the specially-instrumented compression jig than for the bolt tested in the normal compression jig.

Figure 6 illustrates A325 bolts at various stages of loading. The stress-deformation curve shows the points at which loading of the compression jig was stopped and the jig was removed to be sawed in half. The first three stages show little visible deformation. However, stages 4, 5, and 6 show an increasing amount of shear, bending, and bearing deformation, as can be seen from the photographs in Fig. 6. The photographs show that the plate bearing deformations were greater near the shear plane.

As was expected, the type of bolt head (regular or heavy) had no appreciable effect on the shear strength of single bolts in double shear.

3.2 EFFECT OF TESTING DEVICE

The influence of the type of testing device on the ultimate shear strength and deformation at ultimate load is illustrated in Fig. 7, where typical mean stress-deformation curves for bolts of the same lot tested in both tension and compression jigs are compared. Both Fig. 7 and the summary in Table 6 show that the ultimate shear strength of bolts tested in tension jigs is lower than that of bolts tested in compression jigs.

Considering all of the test results, the ultimate shear strength for bolts tested in A440 steel tension jigs is 6% to 13% lower than that obtained in A440 steel compression jigs. This same trend was observed in the constructional alloy steel jigs, where the reduction in strength varied from 8% to 13%. In general, the deformation at ultimate load can not be compared because different deformation measuring systems were used. However, one DC lot bolt was tested in a compression jig instrumented in a similar manner as the tension jig (see Fig. 5). The deformation at ultimate load for this bolt was 0.224 in. almost identical to that of DC lot bolts tested in a tension jig. Thus, the deformation within the testing machine itself due to compressive forces is appreciable.

The lower shear strength of a bolt tested in a tension jig is due to lap plate prying action, a phenomenon which tends to bend the lap plates of the tension jig outward. The lap plate prying mechanism is shown in Fig. 8. Due to the uneven bearing deformations of the test bolt, the resisting force P/2 does not act at the centerline of the lap plate, but acts at a distance "e" to the left of it. This sets up a clockwise moment $M_L = P/2(e)$ which tends to bend the lap plate away from the main plate. This moment is resisted by the tensile force ΔT in the bolt.

Catenary action may also contribute to the increase in bolt tension near ultimate load. However, it is believed that this effect is small in comparison to the tension induced by lap plate prying. In any case, the catenary effect is present in both the tension and compression jigs.

If, for the sake of illustration, Mise's Yield Criterion is extended to ultimate conditions, it can be shown that:

$$\sigma_u^2 = \sigma_t^2 + k^2 \tau_u \qquad (2)$$

where σ_u = ultimate tensile strength of the bolt
σ_t = tensile stress component
τ_u = shear stress component at ultimate load
k = a constant

If this equation must be satisfied, it follows that if σ_t increases due to ΔT, the ultimate shear stress τ_u must necessarily decrease because σ_u is a constant for a given bolt lot. Hence the lower shear strength for bolts tested in tension jigs is to be expected.

Lap plate prying action in tension tests has been observed in the past. Tests of large bolted joints have shown that the bolt under the highest combined tension and shear stress will be the first bolt in the joint to fail(17). Also, the lap plate prying action is visible in these large joint tests as can be seen in Refs. 8 and 9. Tests reported in Ref. 10 of bolts under combined tension and shear have indicated that the tensile component does reduce the ultimate shear strength of the fastener.

3.3 EFFECT OF INITIAL BOLT PRELOAD

The effect of initial bolt preload on shear strength is illustrated in Figs. 9 and 10 for A325 and A490 bolts respectively. Two different grades of bolts were tested. Lot 8B consisted of A325 bolts with heavy heads and short thread lengths. The A490 bolts (lot KK) had dimensions similar to the 8B lot bolts. All compression shear jigs of these bolts had a 4 in. grip and both shearing planes passed through the bolt shank. The preloads were induced by turning the nut against the resistance of the gripped material. The faying surfaces were clean mill scale and all bolts were from the same lot.

The A325 bolts were elongated to either a "snug" preload (about 8 kips), ½ turn-of-nut, or 1½ turn-of-nut. The A490 bolts (see Fig. 10) were tested at "snug" preload, ½ turn-of-nut, and 1 turn-of-nut. The torqued tension calibration curves for the 8B and KK lot bolts are given in the upper portion of Figs. 9 and 10 respectively. These curves were established by torquing bolts in a commercial bolt calibrator with 1/8 in. of thread in the grip. Both the bolt tension and bolt elongation were measured as described in Refs. 1 and 2. The lower portions of Figs. 9 and 10 show the relationship between bolt shear strength and initial preload as determined from measured bolt elongations. The figures show that there is no consistent variation of ultimate shear strength with initial bolt preload. The variation in mean shear strengths for the different magnitudes of induced preload was almost the same as the variation in the individual bolt shear strengths for a given preload.

A number of explanations may be advanced for these results. When a bolt is torqued to a certain preload, most of the inelastic deformations develop in the threaded portion of the bolt and not in the shank, and all failure planes in these bolts were through the bolt shanks. One would therefore expect the internal bolt tension to have little influence on the shear strength.

Furthermore, measurements of the internal tension in bolts installed in large joints have indicated(17) that at ultimate load there is little initial clamping force remaining in the bolt. Any tension introduced into the bolt by lap plate prying action would be present regardless of initial tension. Studies of bolts under combined tension and shear show that tensile forces up to 20 - 30 percent of the tensile strength do not greatly effect the shear strength(10).

3.4 CONDITION OF THE FAYING SURFACES

Tests with two different types of surface conditions were conducted using two different lots of A325 bolts. 27 compression jigs were tested for each bolt lot, 9 with clean mill scale faying surfaces and 18 with lubricated surfaces. The results of these tests are summarized in Table 7, and details of the individual tests are given in Ref. 18.

The condition of the faying surface had a slight influence on the ultimate shear strength. The mean test values given in Table 7 show that bolts tested in lubricated jigs had shear strengths which were 2 to 5% lower than those tested in clean mill scale jigs.

Because displacement readings were not taken during all tests it is impossible to compare the mean load-deformation curves. However, Fig. 11 shows typical results of two tests and clearly indicates that test jigs with lubricated faying surfaces produced lower shear strengths and greater flexibility than those with clean mill scale surfaces. Apparently, there is a certain amount of load transfer through friction in the compression test jig.

3.5 LOCATION OF THE SHEAR PLANES

The shear resistance of the high strength bolts is directly affected by the available shear area. Four different combinations of shear areas are possible: (1) both shear planes through the shank; (2) one shear plane through the shank, the other through the thread runout; (3) one shear plane through the shank, the other through the threads; and (4) both shear planes through the threads. Twelve shear tests of A325 bolts, 3 tests for each of 4 possible shear-plane combinations, were conducted in compression jigs in an effort to ascertain the relative influence of shear plane locations on shear strength and deformation of a bolt.

The influence of the shear plane location on the ultimate shear strength is illustrated by the test results in Table 7 and Fig. 12 for lots T, Q, R, and S which correspond to the four different shear combinations respectively. When both shear planes passed through the bolt shanks, the highest average shear strength and deformation capacity were obtained, the shear strength being about 70% of the tensile strength. When both shear planes passed through the threaded portion and calculations were based on the root area, the lowest average shear strength and deformation were obtained, the shear strength being about 60% of the tensile strength. The values for specimens with one shear plane through the threads were close to those for specimens with both planes through the threads. When one plane passed through the shank and the other through the thread run-out, the average shear strength lay between the two limiting values defined by the shear strength of the threads and the shank.

3.6 EFFECT OF BOLT GRADE

The effect of bolt grade is illustrated in Table 6 by a comparison of the test data for the different grades of bolts. Figure 13 contains typical stress-deformation curves for lots CC and ED of A354 bolts and, for comparison, lot 8B of A325 bolts. All bolts were tested in 4 in. A440 steel tension jigs. As was expected from a knowledge of the material properties of the bolts, the double shear strengths of the A354 BC and A354 BD (or A490) bolts were higher than the double shear strengths of the A325 bolts.

The data in Table 6 shows that the double shear strength was 72% of the tensile strength for A325 bolts, 63% for A354 BC bolts and 61% for A354 BD bolts (A490).

A comparison of the failures of the three types of fasteners is shown in Fig. 14. Comparing the ends of the tested bolts which are still intact reveals that there is an apparent decrease in the relative shear displacement with increasing bolt strength. This would confirm the hypothesis that the A325 bolts have more shear deformation capacity than either the A354 or the A490 bolts. However, as was noted earlier and can be seen visually in Fig. 6, the deformation of the bolts depends not only on the relative shearing displacement but also on the bending and bearing deformations in the bolt and in the connected plate material. Because of the relative increase in the shear strength, it was expected that, for a given connected material, the plate bearing deformations for the A490 bolts would be greater than for the A325 bolts. As a result, the total deformations for the three grades of bolts do not differ as much as one might expect. For the three bolt lots shown in Fig. 14, the total deformations at ultimate load were 0.183 in., 0.178 in., and 0.174 in. for the A325, A354 BC, and A354 BD bolts, respectively. Similar results were obtained for the other bolt lots and testing conditions.

3.7 EFFECT OF BOLT DIAMETER

The influence of diameter on the shear-deformation relationship was determined by tension and compression shear tests on 7/8 in. and 1 in.

bolts. The test data in Tables 4, 5, and 6 shows that 7/8 in. bolts and 1 in. bolts of the same grade have nearly identical shear strengths (ksi). Thus, the data indicates that bolt diameter has no appreciable effect on shear strength.

Figure 15 is a typical stress-deformation curve for 7/8 in. and 1 in. A354 BD bolts tested in A440 steel tension jigs. The figure shows that there is no appreciable difference in the shear strengths but that the total deformation for the 1 in. bolt is greater than that for the 7/8 in. bolt. The rate of increase of bearing area is only 14% while the rate of increase of shear area is 30%. Thus higher bearing stresses and greater bearing deformations occur for the 1 in. bolt than for the 7/8 in. bolt. Therefore, the deformation at ultimate load of a 1 in. bolt was greater than that of a 7/8 in. bolt when the plate thicknesses were identical.

3.8 EFFECT OF CONNECTED MATERIAL

The effect of connected material on the ultimate shear strength and deformation is illustrated by the data in Tables 4 and 5 for bolts that have been tested in both A440 and constructional alloy steel jigs. Figure 16 is a typical shear-deformation curve showing the effect of this variable. It can be seen that the ultimate shear strengths are very nearly the same, but the total deformation for the bolt tested in the A440 steel jig is 0.116 in. greater, almost twice as large as the deformation of the same bolt tested in the constructional alloy steel jig.

The test data shows that for a particular type of fastener the variation in shear strength due to the type of connected material is no greater than the difference in shear strengths between the different bolt lots for that type of fastener. Thus the test data indicates that the type of connected material has no influence on the ultimate shear strength.

However, because of the higher yield point of the constructional alloy steel, the plate bearing deformations at ultimate load for a bolt tested in a constructional alloy steel jig will be less than those of the same bolt tested in all A440 steel jig. Measurement of the final hole diameters in typical plates showed that the inelastic bearing deformations were larger in A440 steel than in constructional alloy steel. It would be expected that the final hole diameters would be larger yet for bolts tested in A7 steel jigs. Figure 17 shows sawed sections of an A325 bolt in A440 steel and an A490 bolt in constructional alloy steel. The bolt bending and bearing deformation is greater in the A440 steel. The A490 bolt is nearly rigidly sheared in the constructional alloy steel.

3.9 EFFECT OF GRIP AND LOADING SPAN

Research on A141 steel rivets showed that an increase in grip length reduced the shear strength(15). This reduction was due mainly to stresses caused by the greater bending of the longer rivets. Also, differences in the working of the rivet material during driving contributed to the reduction of ultimate shear strength. Consideration of these facts about A141 steel rivets led to the thought that an increase in grip length might possibly influence the shear strength of a high strength bolt.

The effect of grip length was investigated by comparing the behavior of a bolt installed in a 4 in. grip test jig (see Figs. 2a and 2b) to that of a bolt installed in an 8 in. grip test jig. The 8 in. tension and compression jigs were made by adding two 1 in. plates to the lap plates of the jig and two 1 in. plates to the main plates. In this manner, the ratio of loading span to grip was kept constant at 1:2. It should be noted, however, that this test jig configuration introduced two test variables, the total grip length and the loading span length.

The effect of loading span and grip length on the shear-deformation relationship for A440 steel tension jigs is illustrated in Fig. 18. The results shown are typical regardless of the type of test jig or types of connected material. The differences in the shear strength and deformation at ultimate load were negligible. Within the elastic and initially plastic portion of the load-deformation curve, the behavior of the 8 in. grip bolts was nearly the same as that of the 4 in. grip bolts.

3.10 EFFECT OF END RESTRAINT

In a large bolted joint which contains many fasteners, the lap plates are restrained from bending freely between the interior fasteners. Therefore, it was thought desirable to determine what effect the restraint of the free ends of the lap plates had on the shear strength and deformation of single bolted joints. Similar studies have been conducted on riveted aluminum joints(16). If some way could be found to eliminate the lap plate prying action in a tension jig, the shear strength of a bolt tested in this manner should approach the shear strength of the same lot of bolts tested in a compression jig. Special tests were conducted in an effort to determine the importance of lap plate prying and to determine why the tension test jig tests yielded shear strengths 8 to 13% lower than those obtained in a compression jig.

In tests of large bolted joints(8)(9), it was visually evident that only the end fasteners at the lap plate are subjected to lap plate prying. Hence, the interior bolts in large joints may behave in a manner similar to that of a bolt installed in a compression jig.

The special tension jig shown in Fig. 19 was used to eliminate lap plate prying. Bolt "A" was installed in a slotted hole and carried none of the shear load, its only function being to keep the lap plates from bending outward. The initial tension of this bolt was small in order to minimize the frictional load transfer.

Three special tension jigs fabricated from A440 steel were used to test three A325 bolts from Lot 8B. The results of these tests are compared in Fig. 19 with the average shear stress-deformation curve for the

8B lot bolts tested in compression jigs and standard tension jigs. This figure shows that the shear strength for a bolt tested in a special tension jig from which lap plate prying is eliminated approaches the shear strength of a bolt tested in a compression jig. This result could be expected if one considers Eq. 2. In the special tension jig, the tensile stress σ_t due to lap plate prying action is about zero. Thus the only tensile force is that induced by the catenary action which is present in both jigs.

4. SUMMARY AND CONCLUSIONS

The following conclusions are based on the results of 147 tests of 7/8 in. and 1 in. high strength A325, A354 BC, A354 BD, and A490 bolts installed in test jigs which subjected the bolts to double shear.

(1) The type of bolt head (heavy or regular) had no significant effect on the shear strength or deformation at ultimate load.

(2) The ultimate shear strength of A354 BD and A490 bolts tested in tension jigs was, on the average, 10% lower than the same bolts tested in compression jigs. Comparable reductions in shear strength may be obtained for A354 BC and A325 bolts. The actual bolt deformations at ultimate load were not affected by the type of testing device (Fig. 7).

(3) The amount of initially induced bolt preload, as determined by measuring the bolt elongation, did not influence the ultimate shear strength of either A325 or A490 bolts (Figs. 9, 10).

(4) The ultimate shear strength of an A325 bolt based on the root diameter was reduced 14% when one or both shear planes pass through the threads.

(5) Compression test jigs with lubricated faying surfaces had slightly lower shear strengths than those with clean mill scale faying surfaces.

(6) The shear strength of A354 BD and A490 bolts is 16% greater than the shear strength of A354 BC bolts and 25% greater than A325 bolts (Fig. 13).

(7) There was no apparent influence of bolt diameter on the shear strength for the diameters considered. However, because the bolt shearing area increases faster than the bolt bearing area, the deformations at ultimate load are greater for the 1 in. bolt than for the 7/8 in. bolt (Fig. 15).

(8) The type of connected material had little or no influence on the shear strength. However, the higher the yield point of the connected material, the lower the plate bearing deformations (Fig. 16).

(9) For a grip-loading span ratio of 2:1, the grip and loading span had no significant effect on the shear strength or deformation at ultimate load for either A325 or A354 BD bolts (Fig. 18).

(10) When lap plate prying action in a tension jig was minimized, the shear strength of bolts tested in tension jigs approaches the shear strength of bolts tested in compression jigs (Fig. 19).

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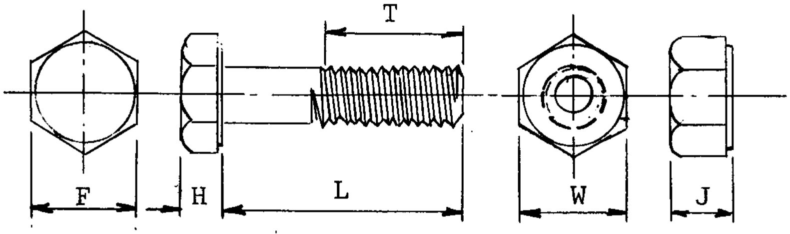
Table 1

0.505" COUPON TEST RESULTS

Bolt Grade	Lot	Bolt Dia.	No.of Tests	0.505" Tensile Strength	Bolt Tensile Strength	% Elong. in 2"±	% Reduct. in area
A354 BC	AC	7/8	3	140.3ksi	140.8ksi	21.2	57.2
	CC	7/8	3	133.0	134.8	21.6	62.2
	DC	1	3	131.6	137.0	22.6	63.1
A354 BD	ED	7/8	3	164.9	168.3	16.6	59.1
	FD	1	3	149.8	163.8	16.7	58.1
	GD	7/8	3	160.9	163.3	18.8	58.1
A490	KK	7/8	3	153.4	168.6	20.0	55.5
A325	8B	7/8	3	106.8	115.2	21.0	-
	Q,R,S,T	7/8	3	121.7	116.5	20.7	-
	Y	1	3	123.6	120.6	22.3	-
	Z	7/8	3	112.9	130.7	19.7	-

Table 2

BOLT DESCRIPTION



BOLT							NUT	
Bolt Grade	Lot	Dia.	Length L	Width Across Flats, F	Height H	Thread Length T	Width Across Flats, W	Height J
A354 BC	AC	7/8	5¼	1-7/16	35/64	1½	1-7/16	55/64
A354 BC	CC	7/8	5¼	1-5/16	35/64	2	1-5/16	3/4
A354 BC	DC	1	5½	1½	39/64	2¼	1½	55/64
A354 BD	ED	7/8	5½	1-5/16	35/64	2	1-5/16	3/4
A354 BD	FD	1	5½	1½	39/64	2¼	1½	55/64
A354 BD	GD	7/8	9½	1-5/16	35/64	2½	1-5/16	3/4
A490	KK	7/8	5½	1-7/16	35/64	1½	1-7/16	55/64
A490	JJ	1	5½	1-5/8	39/64	1-3/4	1-5/8	63/64
A325	8B	7/8	5½	1-7/16	35/64	1½	1-7/16	55/64
A325	Q	7/8	5½	1-5/16	35/64	2¼	1-5/16	3/4
A325	R	7/8	5½	1-5/16	35/64	3¼	1-5/16	3/4
A325	S	7/8	5½	1-5/16	35/64	5½	1-5/16	3/4
A325	T	7/8	6½	1-5/16	35/64	2¼	1-5/16	3/4
A325	Y	1	5½	1½	35/64	2¼	1½	55/64
A325	Z	7/8	5½	1-5/16	35/64	2	1-5/16	3/4

Table 3

THE TESTING PROGRAM

Bolt Grade	Lot	Dia.	Head*	Length Under Head	Thread Length	Grip	Jigs Tested				
							A440 Comp.	A440 Tens.	Q & T Comp.	Q & T Tens.	A7 Comp.
A354 BC	AC	7/8	H	5¼	1½	4-1/8	3	-	3	-	-
	CC	7/8	R	5½	2	4¼	3	3	3	3	-
	DC	1	R^{o}	5½	2¼	4-1/8	3	3	3	3	-
A354 BD	ED	7/8	R	5½	2	4¼	3	3	3	3	-
	FD	1	R^{o}	5½	2¼	4-1/8	3	3	3	3	-
	GD	7/8	R	9½	2¼	8¼	3	3	3	3	-
A490	KK	7/8	H	5½	1½	4-1/8	3	3	-	-	-
	JJ	1	H	5½	1-3/4	4-1/8	-	-	-	3	-
A325	8B	7/8	H	5½	1½	4-1/8	3	3	-	-	-
	Q	7/8	R	5½	2¼$^{+}$	4	-	-	-	-	3
	R	7/8	R	5½	3¼$^{++}$	4	-	-	-	-	3
	S	7/8	R	5½	5½$^{+++}$	4	-	-	-	-	3
	T	7/8	R	6½	2¼	4-3/4	-	-	-	-	3
	Y	1	R	5½	2¼	4	-	-	-	-	27
	Z	7/8	R	5½	2	4	-	-	-	-	27

Note: Shear planes passed through the full shank except where noted.

* H - Heavy Head, R - Regular Head, o - Machined to avoid shear plane through thread run-out.

\+ One shear plane through thread run-out.

++ One shear plane through threads.

+++ Two shear planes through threads.

Table 4

INDIVIDUAL BOLT TEST RESULTS FOR COMPRESSION JIGS

Bolt Lot and No.	Bolt Dia.	Steel	Ultimate Strength, kips	Deform at Ult., inches	Fracture Load, kips	Deform at Fracture inches
1. A354 BC Bolts						
AC-12	7/8	A440	119.4	.2465	92	.265
AC- 2	7/8	A440	114.0	.2141	50	.270
AC-32	7/8	A440	114.5	.2044	82	.245
Ave. AC	7/8	A440	116.0	.2217	75	.260
AC-25	7/8	Q & T	119.3	.1662	80	.195
AC-18	7/8	Q & T	119.3	.1662	80	.195
AC- 4	7/8	Q & T	117.3	.1647	100	.224
Ave. AC	7/8	Q & T	115.6	.1583	86	.199
CC-37	7/8	A440	112.5	.2024	90	.216
CC-1	7/8	A440	120.3	.2174	80	.258
CC-15	7/8	A440	118.1	.2232	104	.243
Ave. CC	7/8	A440	117.0	.2143	91	.239
CC- 3	7/8	Q & T	108.6	.1561	72	.192
CC-31	7/8	Q & T	110.9	.1610	50	.211
CC-19	7/8	Q & T	109.8	.1651	66	.200
Ave. CC	7/8	Q & T	109.8	.1607	63	.201
DC-28	1	A440	148.6	.2599	124	.276
DC-35	1	A440	150.5	.2400	120	.277
DC-12	1	A440	144.8	.2290	120	.260
Ave. DC	1	A440	147.9	.2429	121	.271
DC- 9	1	Q & T	152.3	.1765	128	.207
DC-11	1	Q & T	142.2	.1600	89	.211
DC-10	1	Q & T	161.0	.1700	141	.194
Ave. DC	1	Q & T	151.8	.1688	119	.204
2. A354 BD bolts						
ED-20	7/8	A440	128.8	.1796	115	.199
ED- 1	7/8	A440	132.7	.1934	93	.260
ED-11	7/8	A440	134.2	.1700	124	.180
Ave. ED	7/8	A440	131.2	.1810	111	.213
ED- 3	7/8	Q & T	145.7	.1530	136	.165
ED- 7	7/8	Q & T	141.1	.1435	128	.160
ED-30	7/8	Q & T	130.7	.1480	121	.157
Ave. ED	7/8	Q & T	139.2	.1482	128	.161
FD- 2	1	A440	177.4	.2100	161	.225
FD- 3	1	A440	181.0	.2300	160	.250
FD- 9	1	A440	183.3	.2480	160	.267
Ave. FD	1	A440	180.6	.2293	160	.247
FD-14	1	Q & T	176.6	.1642	168	.177
FD-29	1	Q & T	169.3	.1768	153	.196
FD-20	1	Q & T	179.0	.1870	160	.205
Ave. FD	1	Q & T	174.9	.1760	160	.193

Table 4 (cont'd)

Bolt Lot and No.	Bolt Dia.	Steel	Ultimate Strength, kips	Deform at Ult., inches	Fracture Load, kips	Deform at Fracture inches
GD- 8	7/8	A440	139.3	.1989	120	.225
GD-40	7/8	A440	133.7	.1852	125	.198
GD-22	7/8	A440	131.7	.2036	120	.225
Ave. GD	7/8	A440	134.9	.1959	122	.216
GD- 6	7/8	Q & T	146.6	.1359	133	.162
GD-28	7/8	Q & T	137.3	.1650	126	.179
GD-20	7/8	Q & T	136.8	.1490	131	.157
Ave. GD	7/8	Q & T	140.2	.1500	130	.166
3. A490 Bolts						
KK-34	7/8	A440	137.5	.2744	90	-
KK-63	7/8	A440	140.0	.2662	125	.286
KK-14	7/8	A440	135.0	.2479	108	-
Ave. KK	7/8	A440	137.5	.2628	108	.286
4. A325 Bolts						
8B-29	7/8	A440	102.9	.262	42	.292
8B-34	7/8	A440	103.2	.228	80	.242
8B-137	7/8	A440	105.9	.260	85	.283
Ave. 8B	7/8	A440	104.0	.250	72	.272
T-17	7/8	A7	110.2	.259	95	.304
T-25	7/8	A7	111.6	.279	90	.322
T-26	7/8	A7	109.1	.250	85	.271
Ave. T	7/8	A7	110.3	.263	90	.299
Q- 2	7/8	A7	95.7[+]	.213	-	-
Q- 3	7/8	A7	93.3[+]	.189	-	-
Q-11	7/8	A7	99.6[+]	.265	-	-
Ave. Q	7/8	A7	99.2[+]	.222	-	-
R- 5	7/8	A7	85.0[++]	.164	65	.282
R- 8	7/8	A7	81.1[++]	.150	-	-
R-12	7/8	A7	81.6[++]	.156	-	-
Ave. R	7/8	A7	82.6[++]	.157	65	.282
S- 9	7/8	A7	63.2[+++]	.107	-	-
S-10	7/8	A7	68.5[+++]	.131	63.6	.145
S-14	7/8	A7	70.5[+++]	.123	60.0	.140
Ave. S	7/8	A7	67.4[+++]	.120	61.8	.142

[+] One shear plane through thread run-out.

[++] One shear plane through threads.

[+++] Two shear planes through threads.

Table 5

INDIVIDUAL BOLT TEST RESULTS FOR TENSION JIGS

Bolt Lot and No.	Bolt Dia.	Steel	Ultimate Strength, kips	Deform at Ult., inches	Fracture Load, kips	Deform at Fracture inches
1. A354 BC Bolts						
CC-13	7/8	A440	102.8	.1781	93	.205
CC-27	7/8	A440	104.9	.1904	100	.201
CC-10	7/8	A440	103.5	.1658	90	.185
Ave. CC	7/8	A440	103.7	.1781	94	.197
CC-11	7/8	Q & T	101.2	.1432	89	.157
CC-28	7/8	Q & T	101.3	.1433	87	.168
CC-20	7/8	Q & T	100.9	.1248	83	.160
Ave. CC	7/8	Q & T	101.1	.1371	86	.162
DC-39	1	A440	138.5	.2135	133	.233
DC- 4	1	A440	140.4	.1950	130	.205
DC-16	1	A440	135.8	.2284	125	.245
Ave. DC	1	A440	138.2	.2123	129	.228
DC-38	1	Q & T	130.7	.1488	118	.181
DC- 7	1	Q & T	132.5	.1632	122	.179
DC-36	1	Q & T	131.2	.1572	120	.213
Ave. DC	1	Q & T	131.5	.1564	122	.191
2. A354 BD Bolts						
ED-32	7/8	A440	124.5	.1800	113	.200
ED-24	7/8	A440	123.2	.1677	108	.221
ED-12	7/8	A440	124.0	.1732	115	.203
Ave. ED	7/8	A440	123.9	.1736	112	.208
ED-10	7/8	Q & T	128.8	.1192	103	.160
ED-35	7/8	Q & T	120.0	.1165	115	.128
ED-29	7/8	Q & T	120.7	.1033	101	.142
Ave. ED	7/8	Q & T	123.2	.1130	106	.143
FD-13	1	A440	151.2	.2474	130	.279
FD-5	1	A440	156.3	.2557	132	.292
FD-27	1	A440	165.7	.2233	152	.252
Ave. FD	1	A440	157.7	.2476	138	.274
FD-31	1	Q & T	160.7	.1357	155	.145
FD-28	1	Q & T	152.0	.1327	143	.162
FD-30	1	Q & T	157.5	.1253	145	.150
Ave. FD	1	Q & T	156.6	.1312	148	.152

Table 5 (cont'd)

Bolt Lot and No.	Bolt Dia.	Steel	Ultimate Strength, kips	Deform at Ult., inches	Fracture Load, kips	Deform at Fracture inches
GD-39	7/8	A440	120.5	.1706	112	.190
GD-37	7/8	A440	-	.1836	-	-
GD-26	7/8	A440	124.2	.1632	110	.195
Ave. GD	7/8	A440	122.2	.1725	111	.192
GD-11	7/8	Q & T	123.5	.1408	-	-
GD- 6	7/8	Q & T	122.5	.1377	-	-
GD-26	7/8	Q & T	124.3	.1760	-	-
Ave. GD	7/8	Q & T	123.4	.1515	-	-
3. A490 Bolts						
KK-38	7/8	A440	124.0	.2008	110	-
KK-35	7/8	A440	125.1	.2139	120	-
KK-54	7/8	A440	124.2	.1910	115	-
Ave. KK	7/8	A440	124.4	.2019	115	-
JJ-14	1	Q & T	151.2	.1703	148	.215
JJ-52	1	Q & T	149.0	.1491	145	.160
JJ-1	1	Q & T	154.9	.1448	-	-
Ave. JJ	1	Q & T	151.7	.1547	147	.188
4. A325 Bolts						
8B-109	7/8	A440	94.0	.2000	75	-
8B-12	7/8	A440	90.0	.1730	74	.181
8B-188	7/8	A440	93.3	.1760	76	.195
Ave. 8B	7/8	A440	92.4	.1830	75	188

Table 6

Summary of Test Results

Bolt Grade	Lot	Dia.	Compression Jig: Ultimate Shear Stress, ksi			Compression Jig: Deform. At Ultimate, inches		Tension Jig: Ultimate Shear Stress, ksi			Tension Jig: Deform. At Ultimate, inches	
			A440	Q & T	Avg.	A440	Q & T	A440	Q & T	Avg.	A440	Q & T
A354BC	AC	7/8	96.6	96.4	96.5	.2217	.1583	-	-	-	-	-
	CC	7/8	97.3	91.3	94.3	.2143	.1607	86.3	84.2	85.2	.1781	.1371
	DC	1	94.2	96.6	95.4	.2429	.1688	88.0	83.7	85.9	.2123	.1564
A354BD	ED	7/8	110.0	116.0	113.0	.1810	.1482	103.3	102.7	103.0	.1736	.1130
	FD	1	115.0	111.4	113.2	.2293	.1760	100.3	99.7	100.0	.2476	.1312
	GD	7/8	112.3	116.8	114.1	.1959	.1500	102.0	102.9	102.5	.1725	.1515
A490	KK	7/8	114.5	-	114.5	.2628	-	103.8	-	103.8	.2019	-
	JJ	1	-	-	-	-	-	-	96.5	96.5	-	.1547
A325	8B	7/8	86.7	-	86.7	.250	-	76.9	-	76.9	.1830	-

Note: All the stresses and deformations are the average of three tests.

Table 7

SUMMARY OF SPECIAL TESTS OF A325 BOLTS*

Bolt Grade	Lot	Dia. in.	Grip in.	No. Test	Faying Surface Condition	Location of Shear Planes	Ult. Shear Stress, ksi	Deform at Ult. in.
A325	T	7/8	4-3/4	3	Mill Scale	Shank	91.7	0.250
	Q	7/8	4	3	Mill Scale	Shank & Thread Run-out	84.8	0.223
	R	7/8	4	3	Mill Scale	Shank & Threads	77.7	0.158
	S	7/8	4	3	Mill Scale	Threads	72.9	0.123
	Z	7/8	4	9	Mill Scale	Shank	93.2	-
	Z	7/8	4	18	Lubricated	Shank	88.2	-
	Y	1	4	9	Mill Scale	Shank	81.6	-
	Y	1	4	18	Lubricated	Shank	79.4	-

* Tests conducted in A7 steel compression jigs.

Note!

Table 8

MINIMUM BOLT SHEAR STRENGTHS

Minimum Shear Strengths, Ksi.

Bolt Grade	Lot	Dia.	Bolt Tensile Strength*	Compression Jig			Tension Jig		
				A440	Q & T	Avg.	A440	Q & T	Avg.
A354 BC	AC	7/8	140.8ksi	85.9	85.5	85.7	-	-	-
	CC	7/8	134.8	90.2	84.6	87.4	80.0	78.0	79.0
	DC	1	137.0	85.9	88.0	87.0	80.5	76.4	78.4
A354 BD	ED	7/8	168.3	98.0	103.2	100.6	92.0	91.4	91.7
	FD	1	163.8	105.3	102.0	103.7	91.9	91.3	91.6
	GD	7/8	163.3	103.0	107.0	105.0	93.5	94.5	94.0
A490	KK	7/8	168.6	102.0	-	102.0	92.1	-	92.1
	JJ	1	163.5	-	-	-	-	88.7	88.7
A325	8B	7/8	115.2	86.5	-	86.5	76.7	-	76.7

* Based on tests of full size bolts. The tensile strength was computed as P/A_s where:

$$A_s = 0.7854\ \left(D - \frac{0.9743}{n}\right)^2$$

A_s = tensile stress area

D = nominal bolt diameter

n = threads per inch

P = average ultimate tensile strength

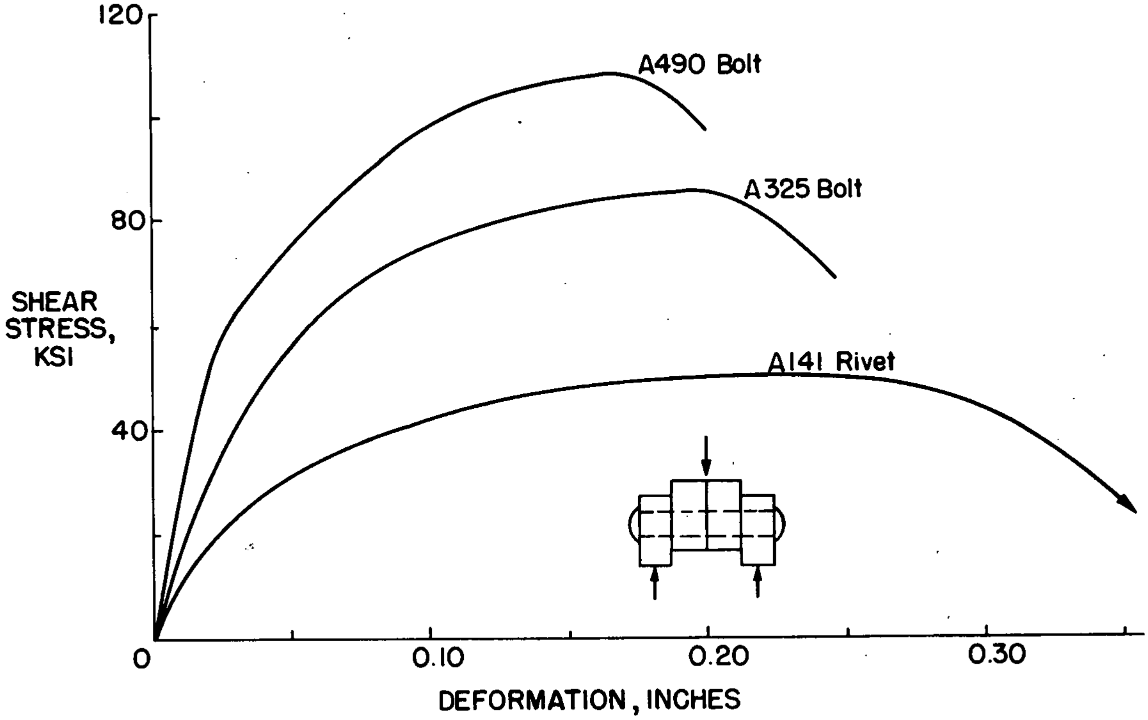


Fig. 1 Typical Shear-Deformation Curves for A141 Steel Rivet, A325 and A490 Bolts

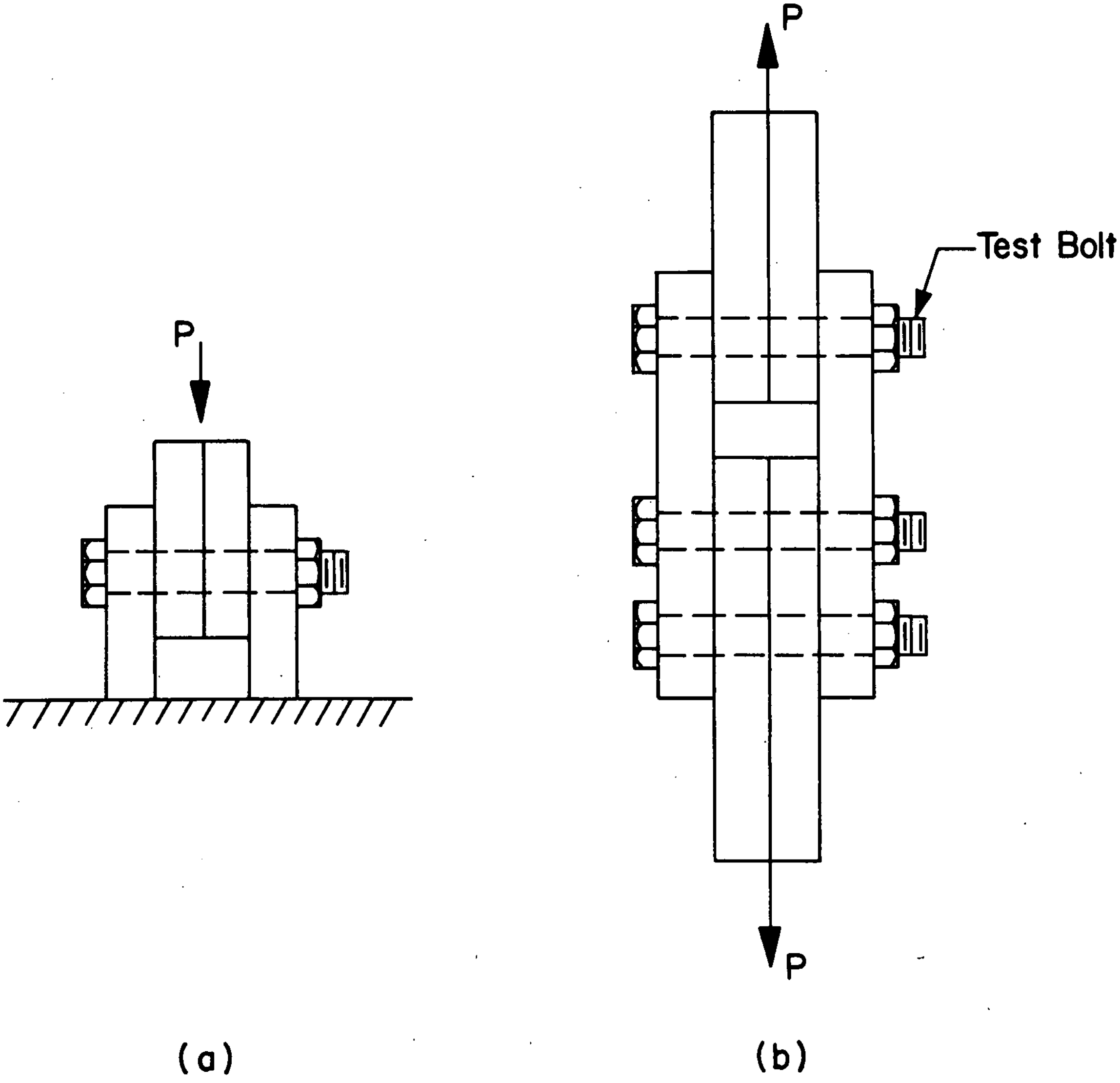
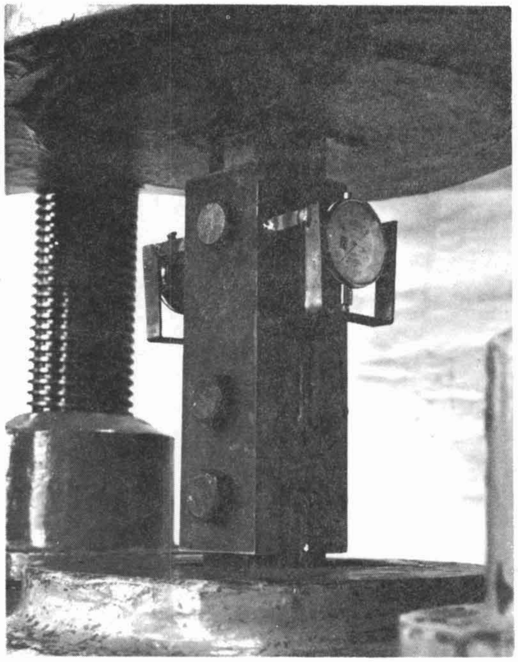


Fig. 2 Schematic of Testing Jigs for Single Bolts



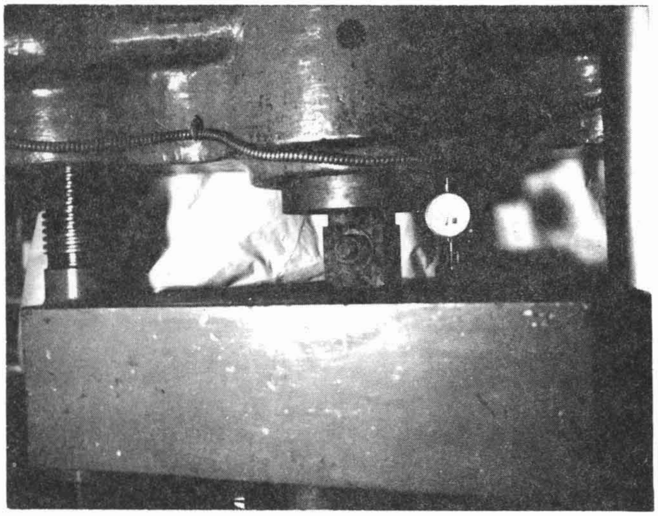


Fig. 4 Compression Jig Set-Up and Instrumentation

Fig. 3 Tension Jig Set-Up and Instrumentation

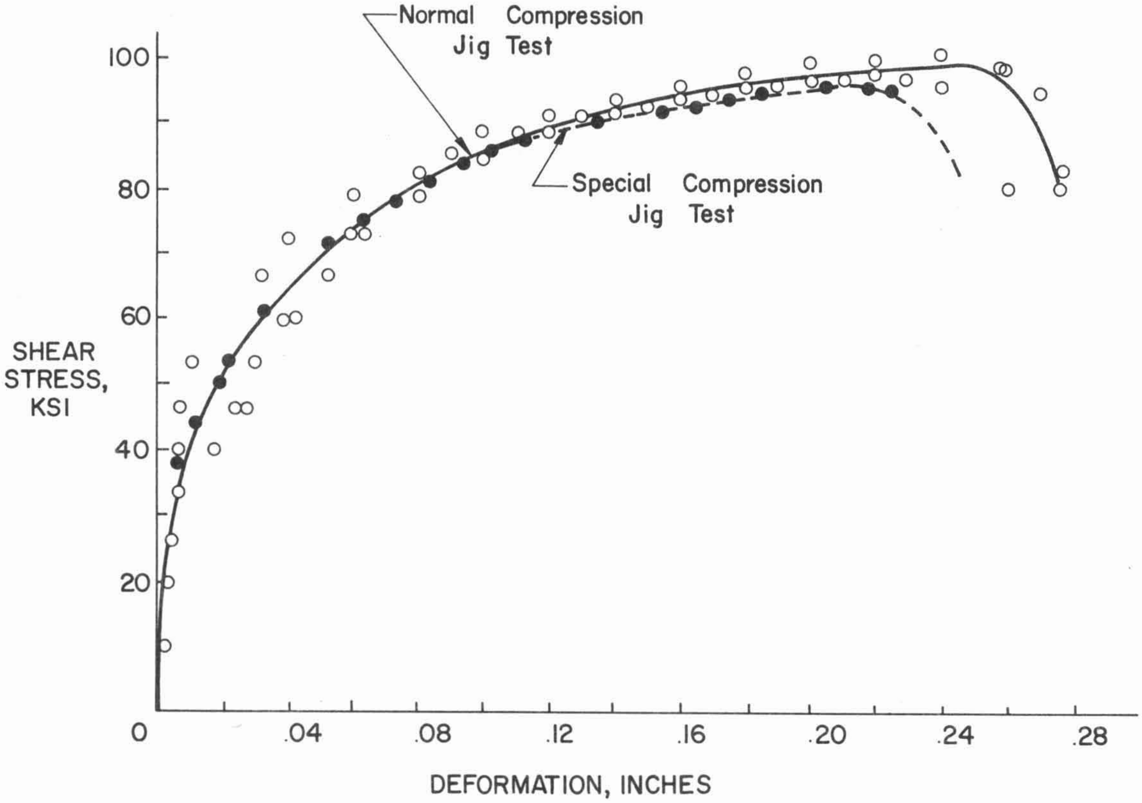


Fig. 5 Effect of Deformations within the Compression Jig Assembly on the Deformation at Ultimate Load

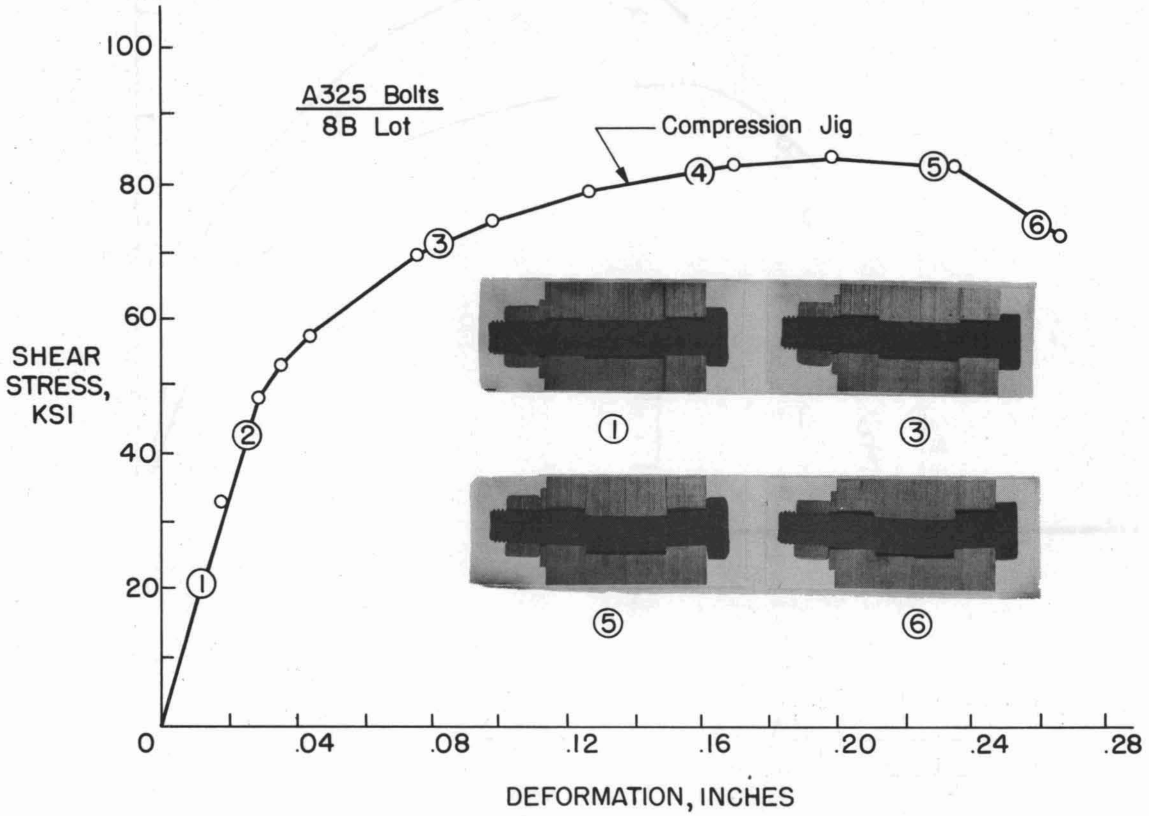


Fig. 6 Deformation of A325 Bolts at Various Stages of Loading

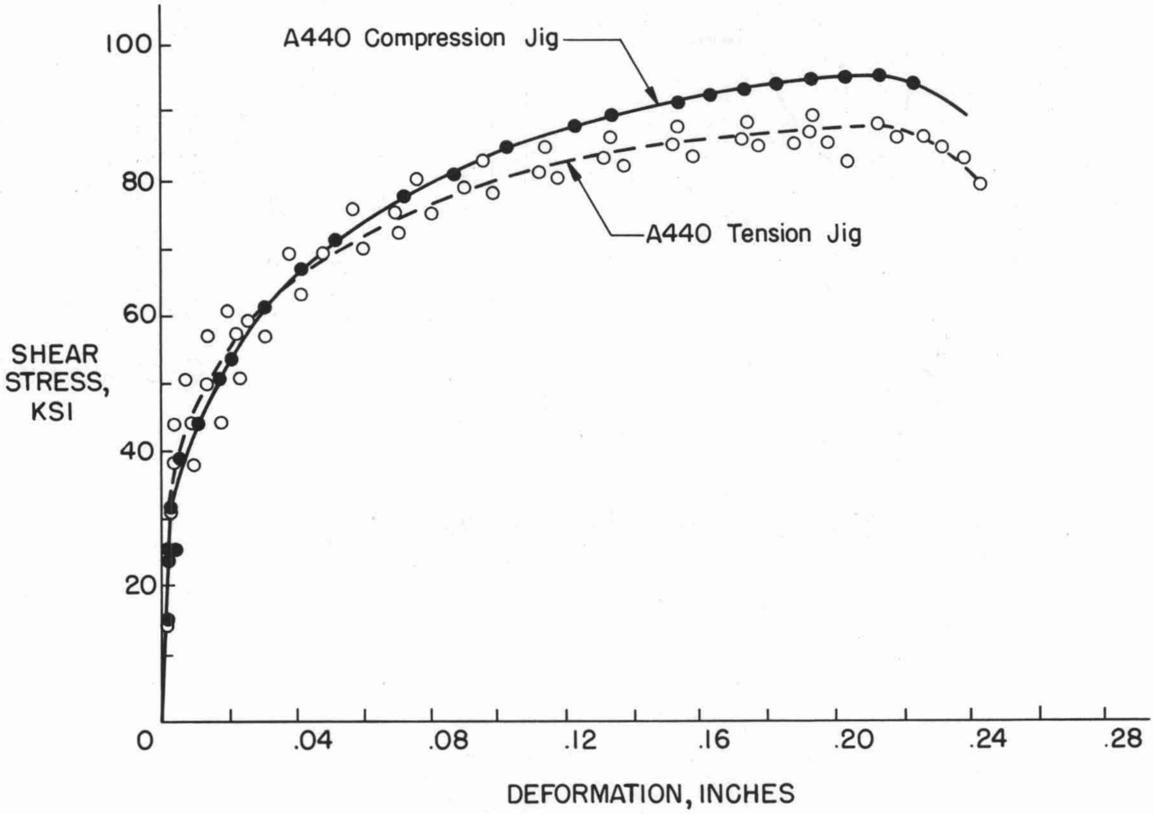


Fig. 7 Typical Shear-Deformation Curves for A354 BC Bolts Tested in Tension and Compression Jigs

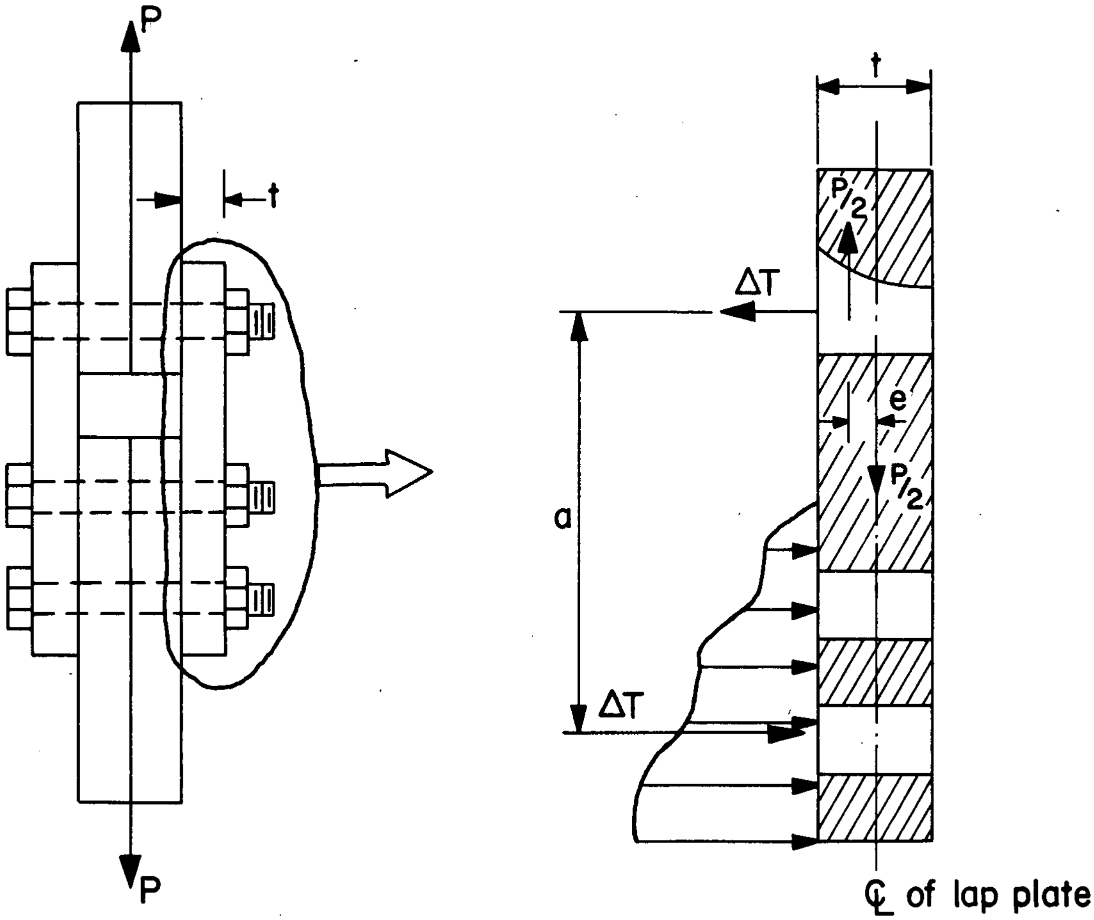


Fig. 8 Lap Plate Prying Mechanism

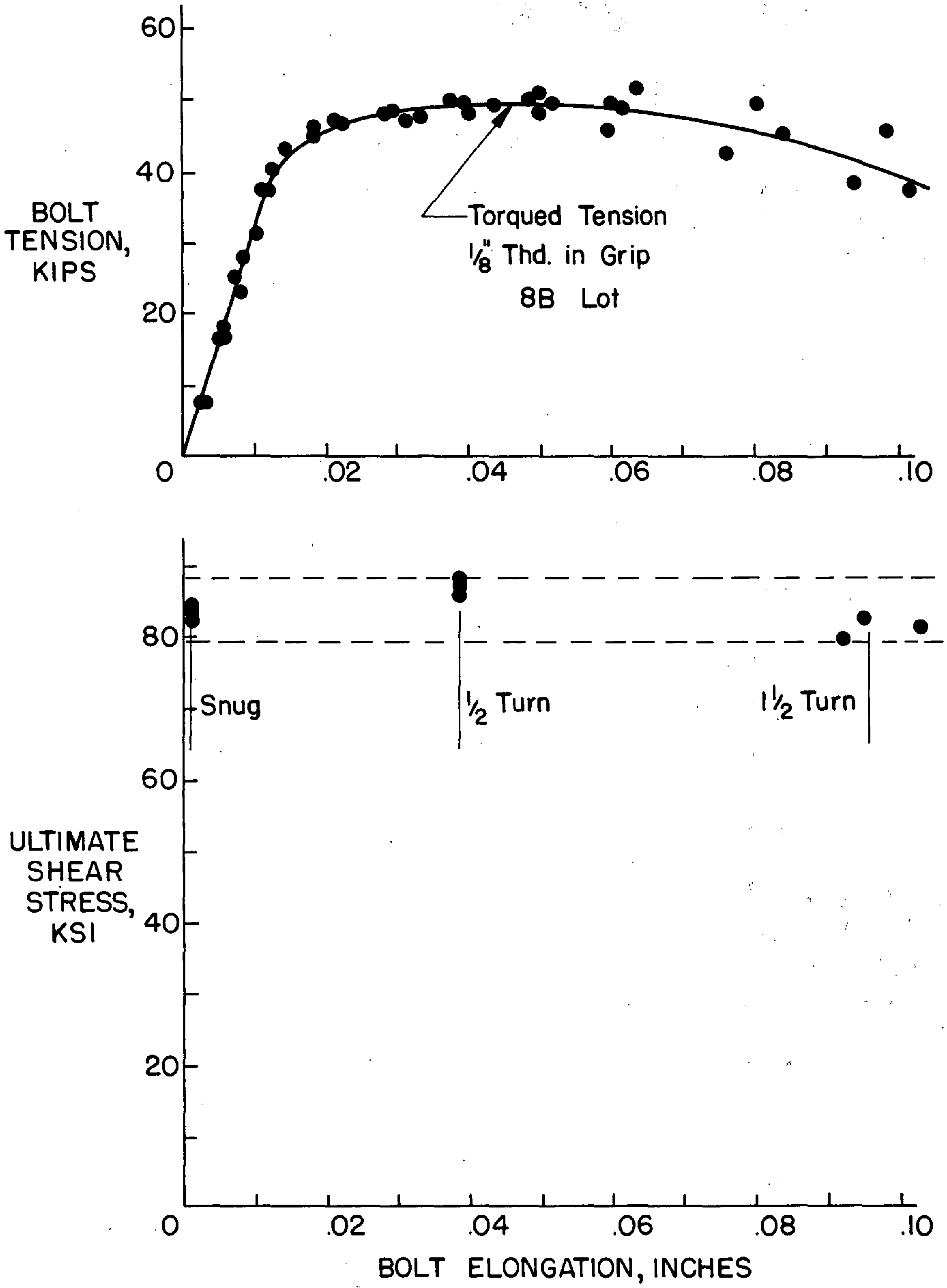


Fig. 9 Effect of Bolt Preload on the Shear Strength of A325 Bolts

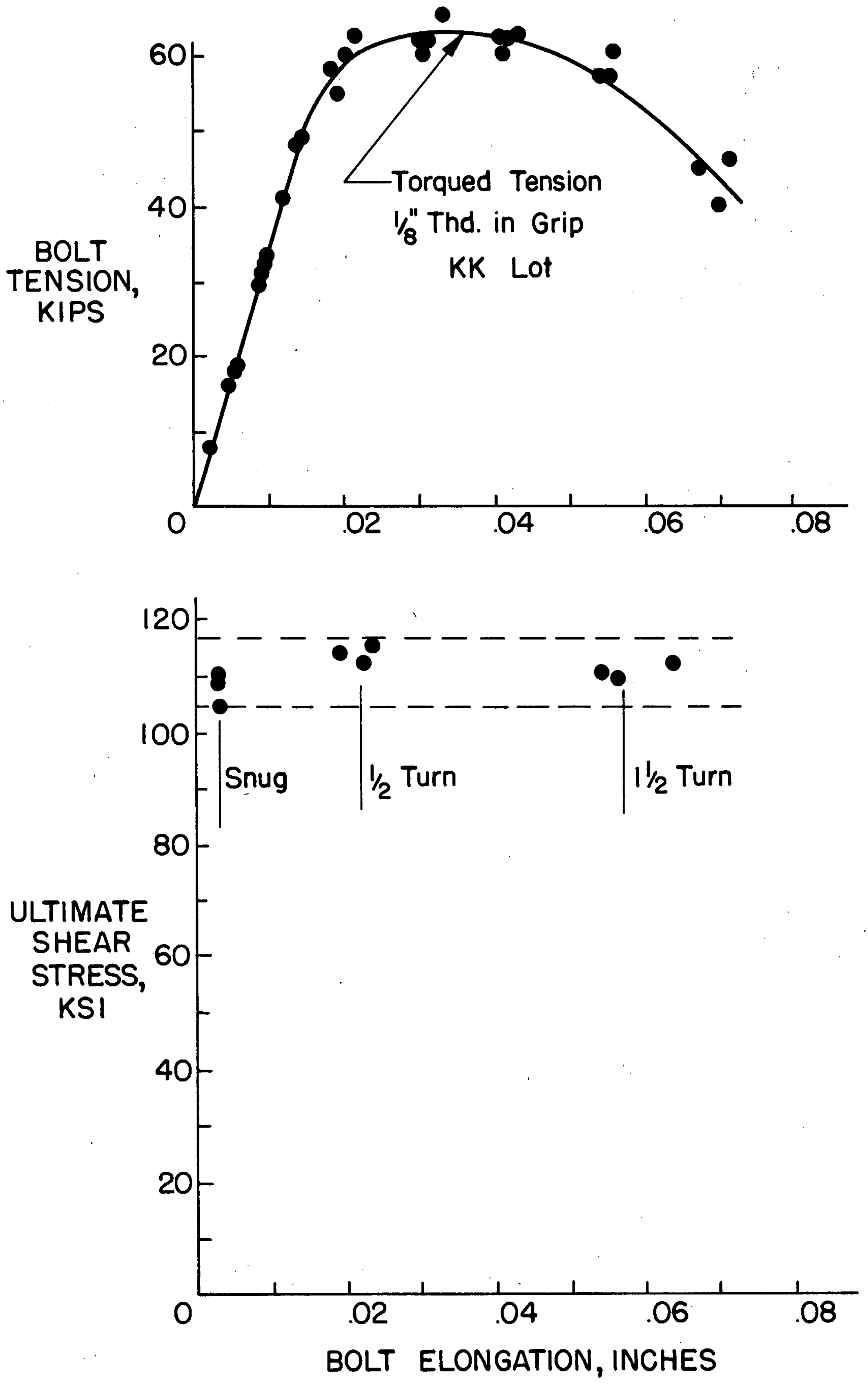


Fig. 10 Effect of Bolt Preload on the Shear Strength of A490 Bolts

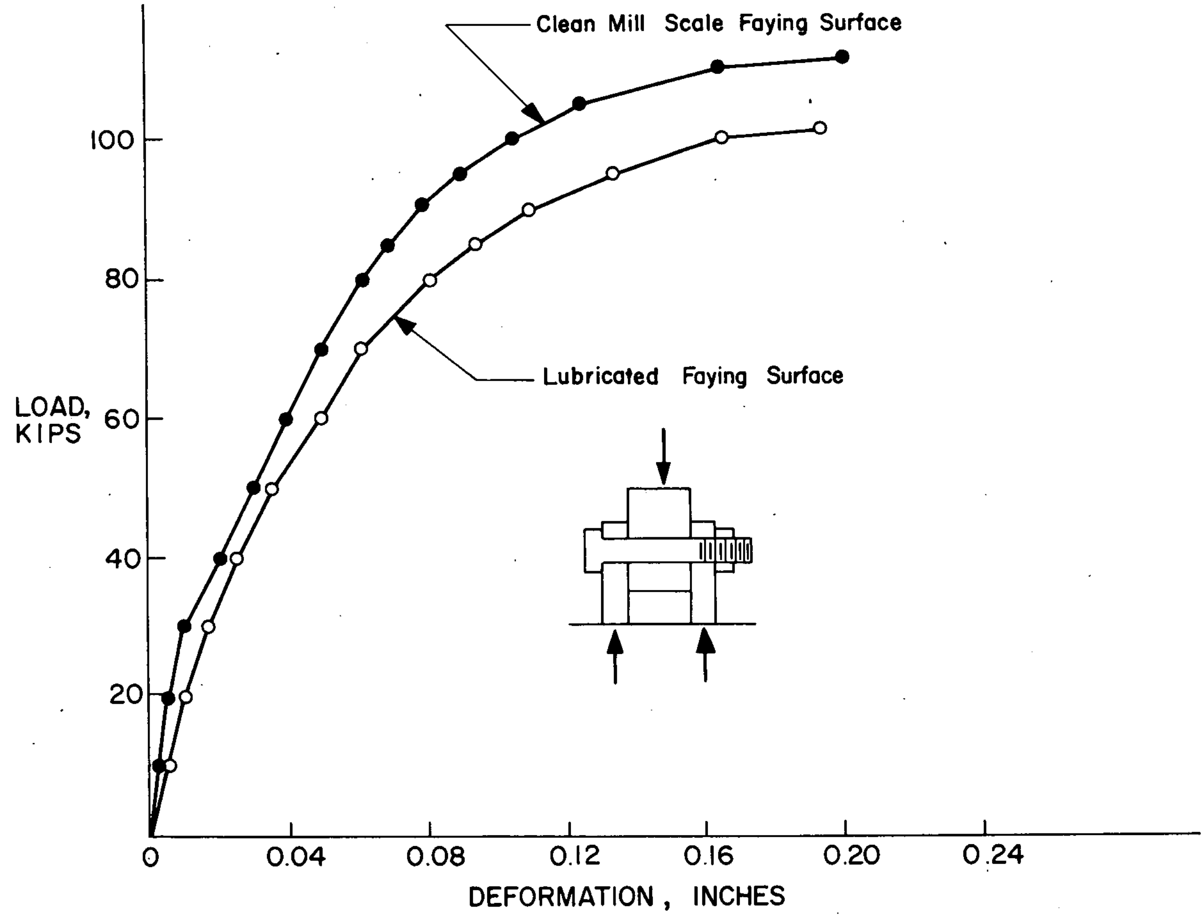


Fig. 11 Effect of Lubrication on the Shear-Deformation Relationship

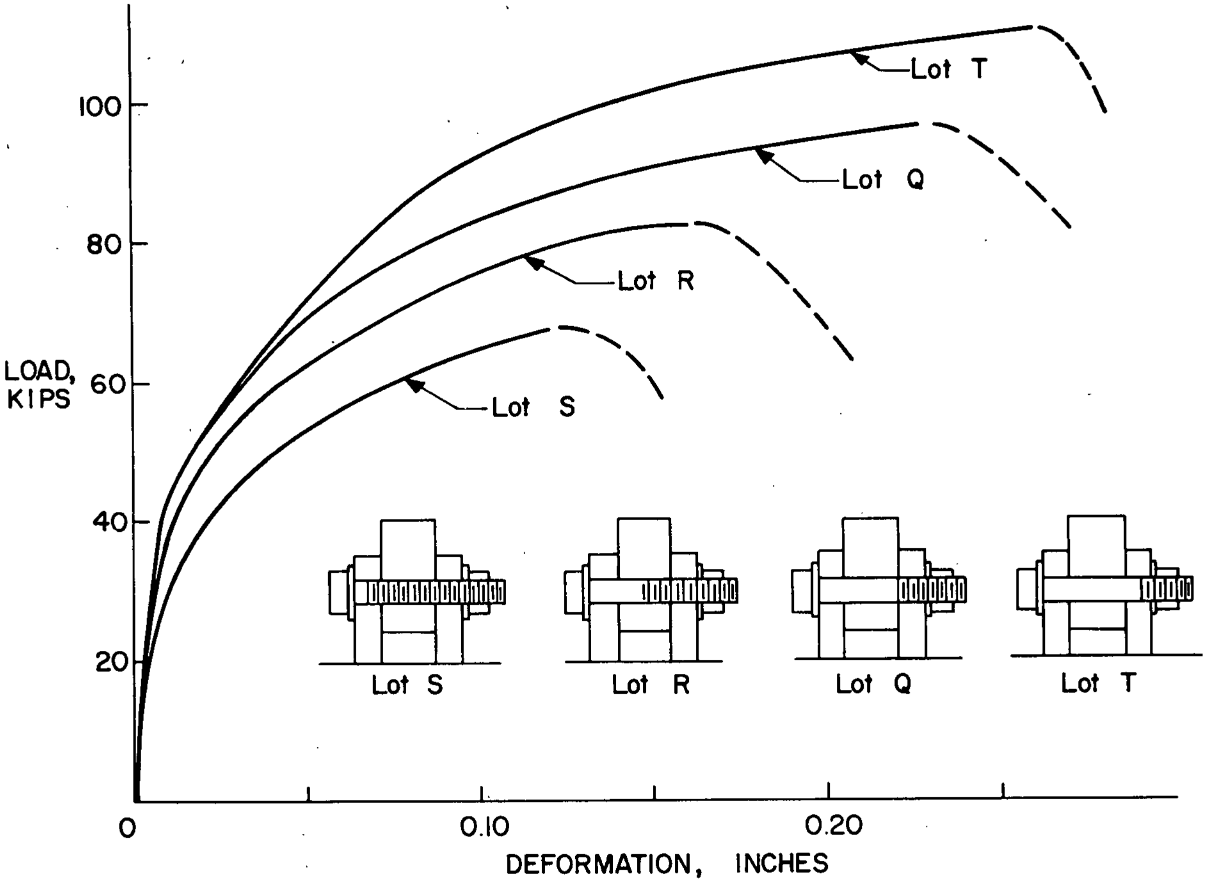


Fig. 12 Shear-Deformation Curves for Different Failure Planes

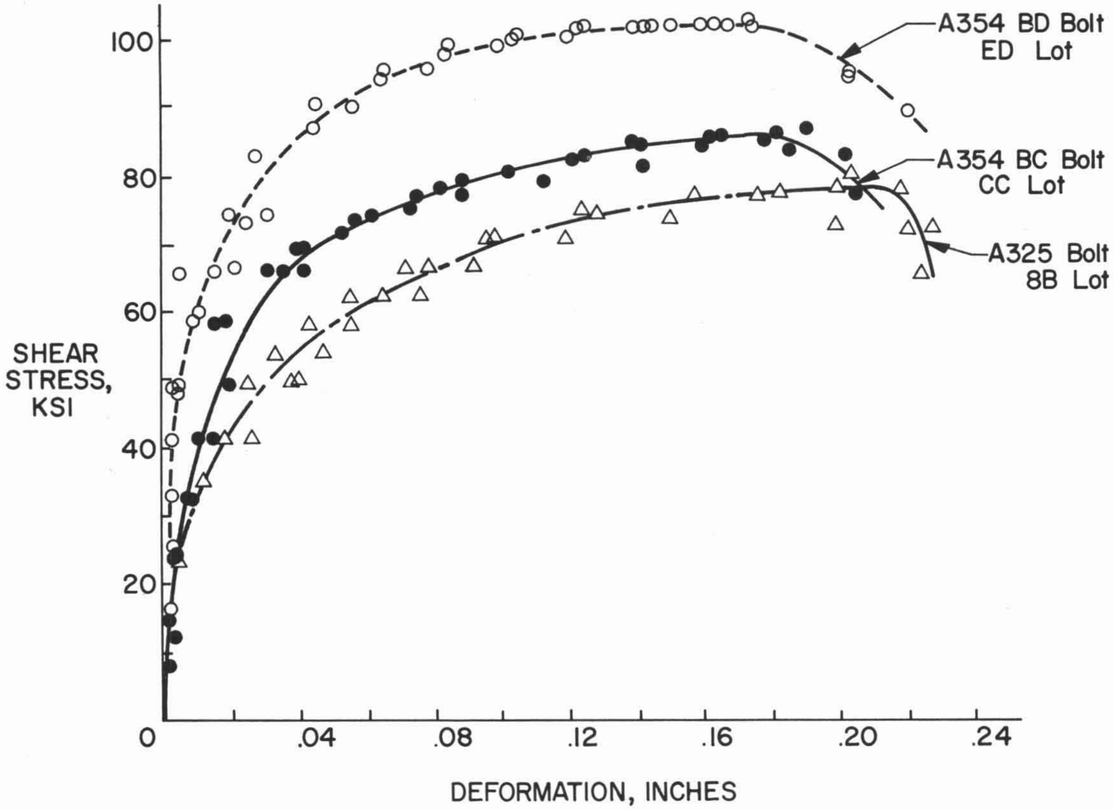


Fig. 13 Typical Shear-Deformation Curves for Bolts Tested in A440 Steel Tension Jigs

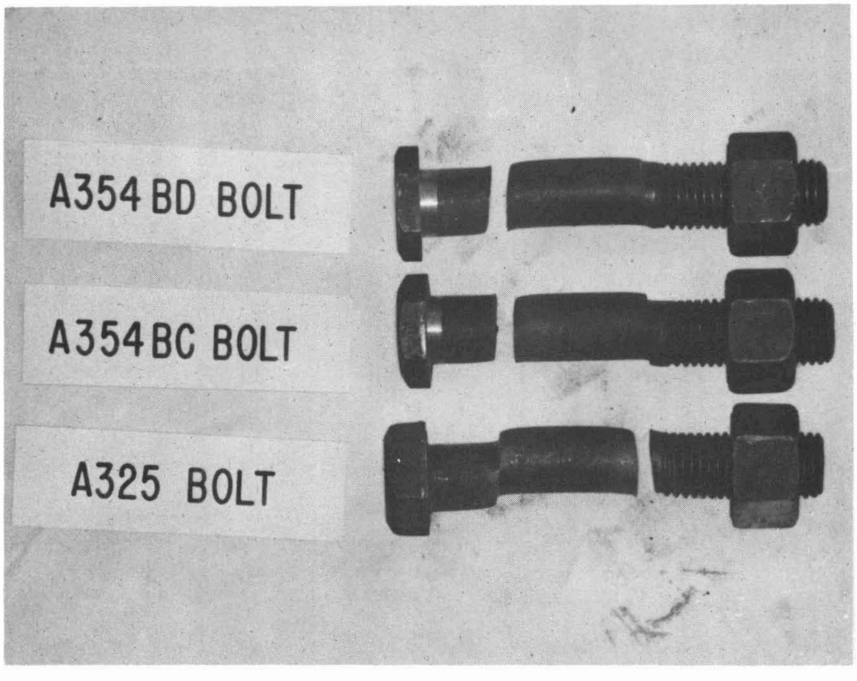


Fig. 14 Bolts After Failure in Shear

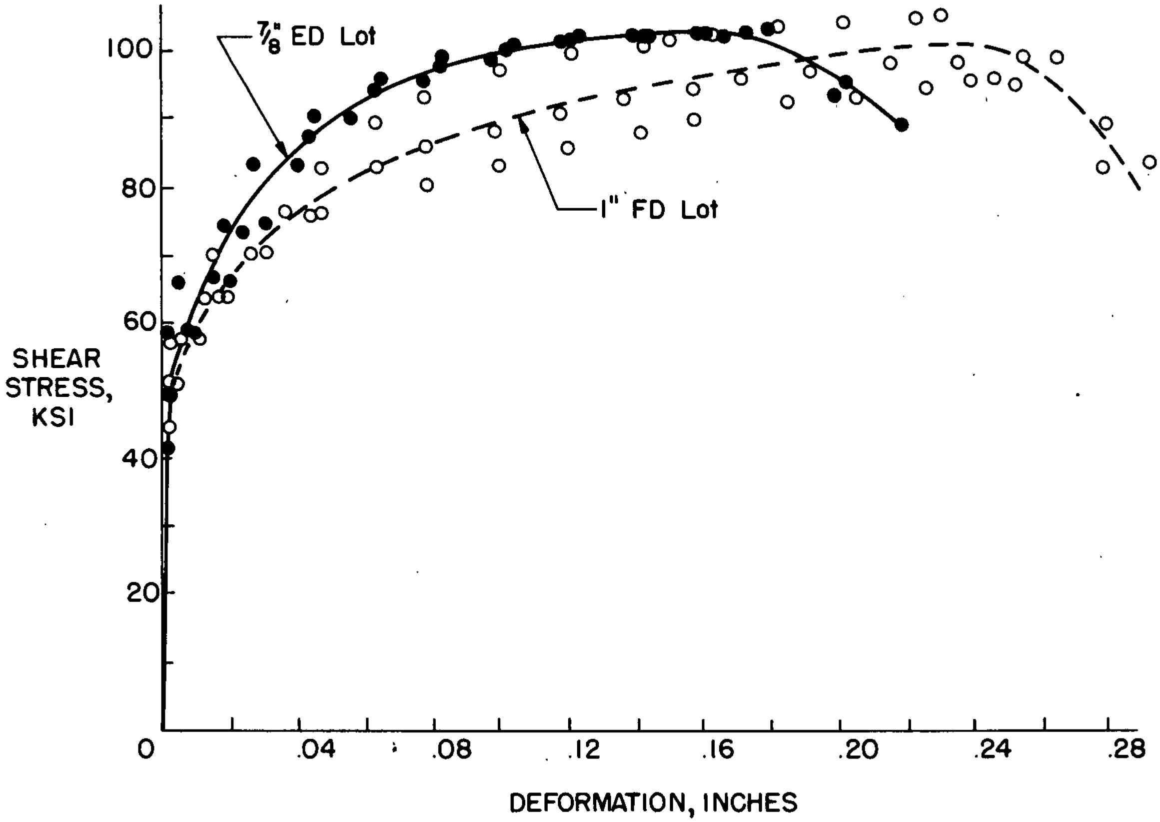


Fig. 15 Typical Shear-Deformation Curves for 7/8 in. and 1 in. Bolts Tested in A440 Steel Tension Jigs

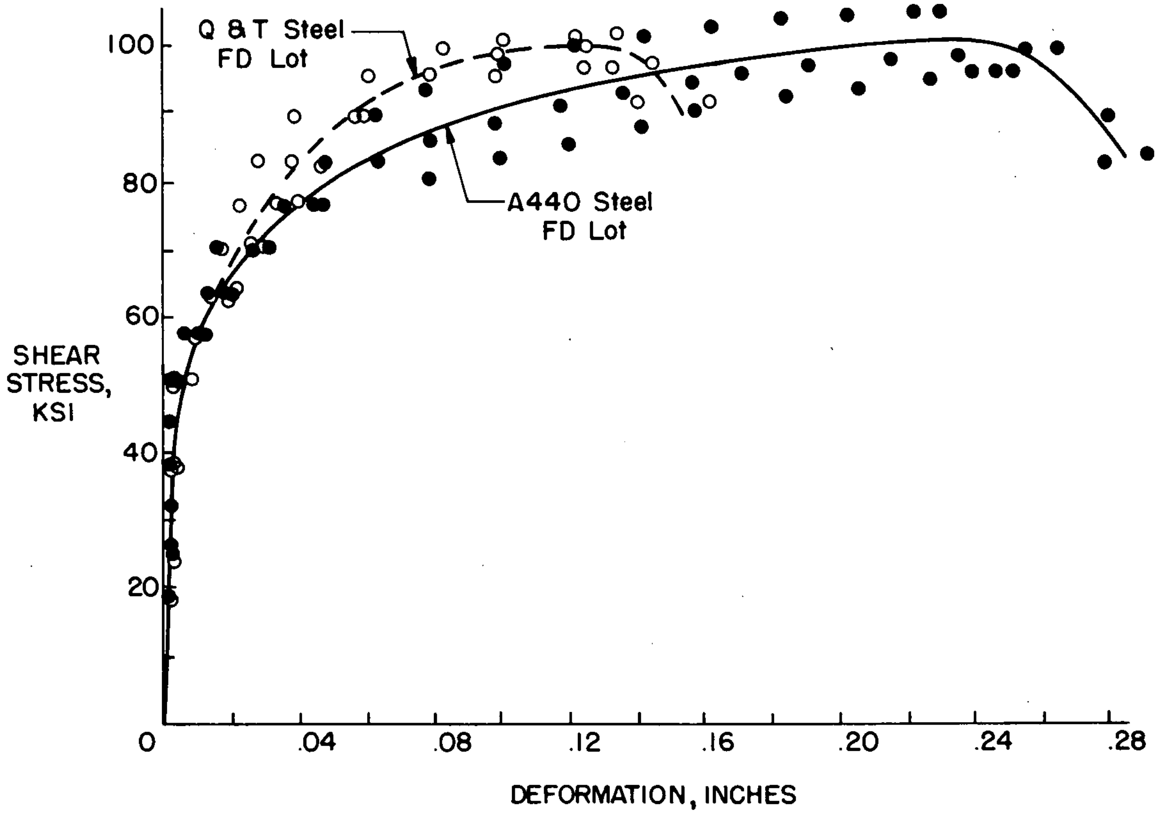
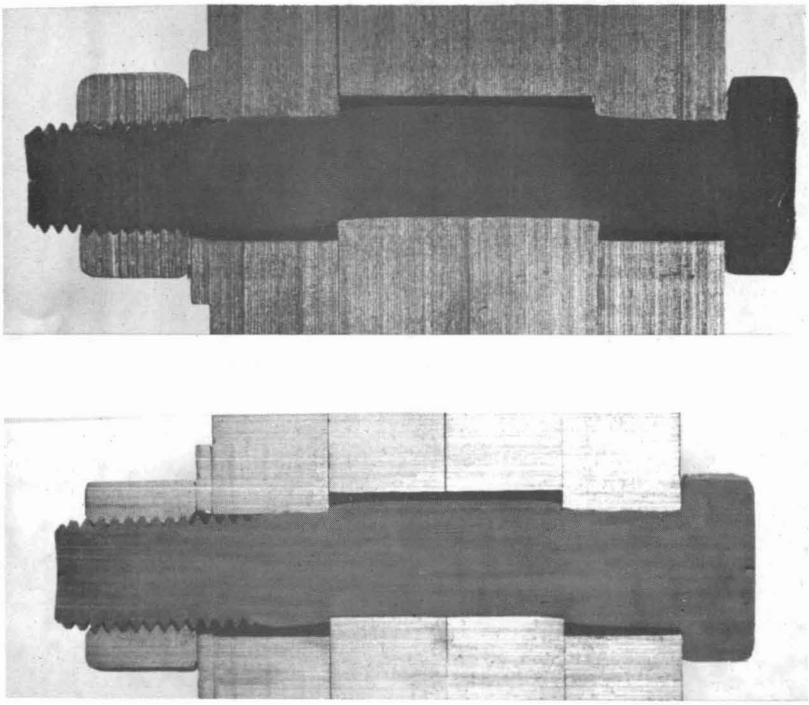


Fig. 16 Typical Shear-Deformation Curves for A354 BD Bolts Tested in Tension Jigs of Different Steel



A325 Bolt
A440 Steel

A490 Bolt
Q & T Steel

Fig. 17 Sawed Sections of A325 Bolt in A440 Steel and A490 Bolt in Constructional Alloy Steel

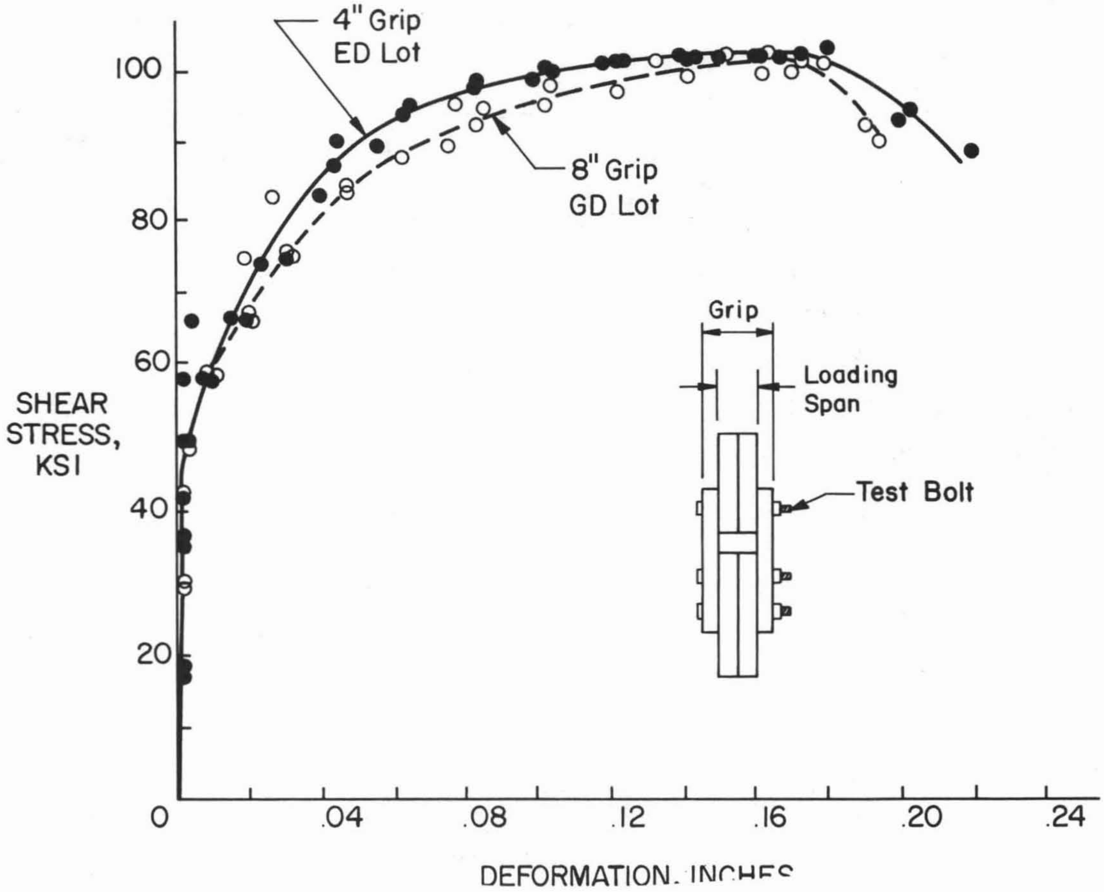


Fig. 18 Effect of Grip and Loading Span on the Shear-Deformation Curve

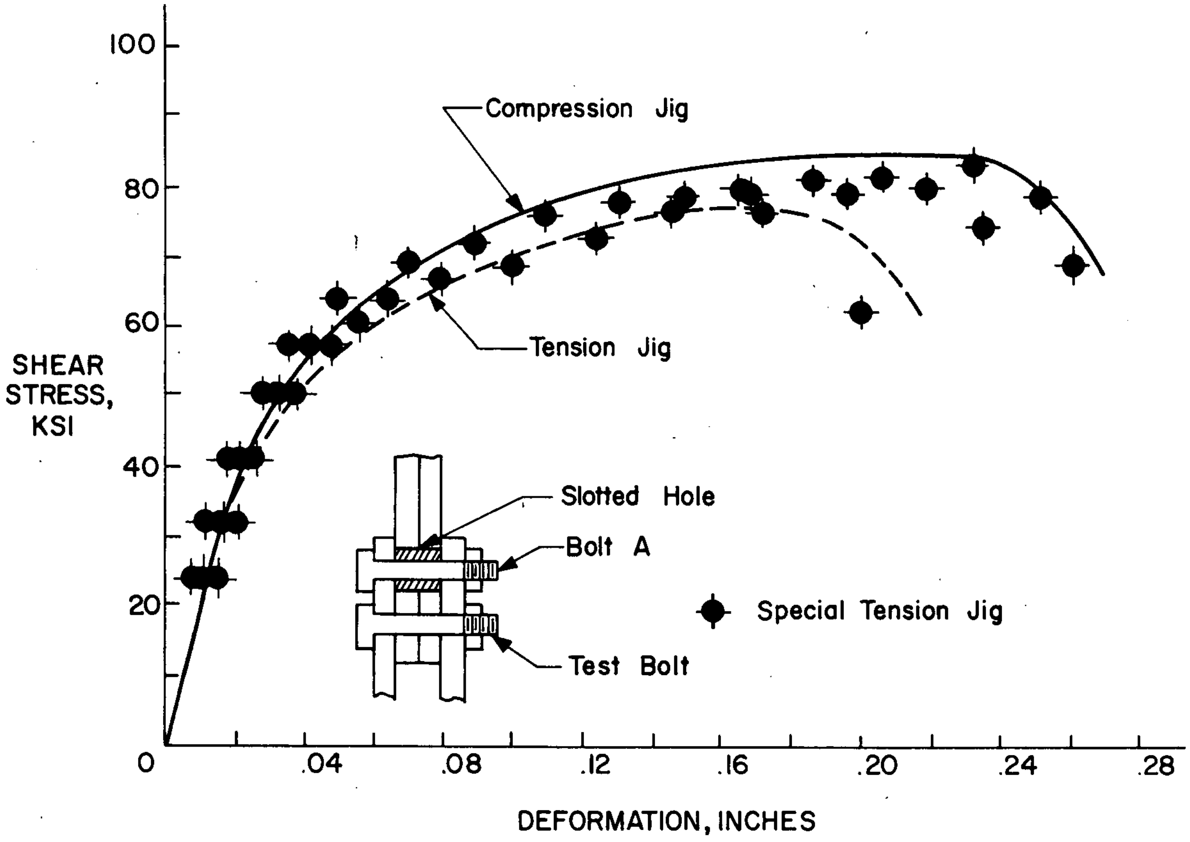


Fig. 19 Influence of End Restraint on the Shear Strength of A325 Bolts

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