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Autor(en): **Fisher, John W. / Ramseier, Paul O. / Beedle, Lynn S.**

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Strength of A 440 Steel Joints Fastened with A 325 Bolts

Résistance des joints d'éléments en acier A 440, assemblés par boulons HR A 325

Festigkeit von aus Stahl A 440 mit HV-Schrauben A 325 ausgeführten Stößen

JOHN W. FISHER

Research Instructor, Fritz Engineering Laboratory, Lehigh University, Bethlehem, Pennsylvania

PAUL O. RAMSEIER

Dipl. Ing. ETH, Wartmann & Cie. AG, Brugg, Switzerland; formerly Research Assistant, Fritz Engineering Laboratory, Lehigh University, Bethlehem, Pennsylvania

LYNN S. BEEDLE

Research Professor of Civil Engineering and Director of Fritz Engineering Laboratory, Lehigh University, Bethlehem, Pennsylvaniy, U.S.A.

1. Introduction

Applications of high-strength bolts have been expanded considerably since the Research Council on Riveted and Bolted Structural Joints adopted its specification for bolted joints in 1960 [1]. One of the most important provisions of this specification was the change in the allowable shear stress for bearing-type connections [1]). This allowed the substitution of two bolts for three rivets. The experimental and theoretical research on which these design rules were based considered only connections fabricated with ASTM A 7 steel.

The increased use in recent years of high strength steel for construction purposes has created a need for research to investigate the behavior of these steels when used in connections fabricated with A 325 high-strength bolts. With the higher yield stress level, the overall behavior of connections made with ASTM A 440 steel may differ from that of connections made with ASTM A 7 steel.

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[1]) In bearing-type connections, the bolts may bear against the holes in the connected parts. In friction-type connections, the high clamping force in the bolts provides a rigid assembly and the load transfer is due to friction on the faying surfaces.

A great deal of information has been obtained on the behavior of connections using A 7 steel in previous research programs [2, 3]. With this information as background material, it was the purpose of the present work to study:

1. The basic behavior of ASTM A 440 steel connected with ASTM A 325 bolts;
2. The appropriate shear stress to be used in compact joints;
3. The possible reduction of shear strength associated with long connections of this material;
4. The effect of internal lateral forces caused by plate necking near the ultimate strength of the joint; and
5. Any effect on the behavior of the joint caused by the presence or absence of washers.

In addition to the large scale tests, the behavior of the individual elements of a joint was established in this study. The properties of the plate material and the bolts were determined from plate coupon tests, plate calibration tests, direct-tension and torqued tension tests of the bolts, and double shear tests of the bolts. A theoretical analysis was made to predict the ultimate strength of the connections tested.

Very little previous research has been carried out on large bolted bearing-type connections using high-strength steels. In 1957 a demonstration test of a compact A 242 high-strength steel specimen connected by nine A 325 and nine A 354 BD bolts was performed at Northwestern University [4]. The joint was designed in such a way that plate failure occurred. Other tests of small specimens were conducted at the same University in connection with a fatigue test program [5].

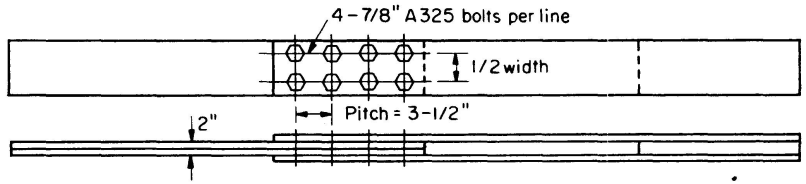
2. Description of Test Specimens

a) Pilot Tests

Six compact joints were tested to determine the appropriate shear stress for such joints. Each specimen was one half of a double shear butt joint as shown in Table 1. These tests were designed to determine the ultimate strength of the fasteners in shear that would develop the tensile capacity of the net section of the plate material. Coupon tests had established the ultimate tensile strength as approximately 75 ksi, the shear strength of a single bolt was found to be approximately 85 ksi, and therefore the required shear area of fasteners would seem to be only slightly less than the net plate area. The pilot tests also were conducted to determine if variations in the net plate area had any influence on the shear strength of bolts in a joint. In addition, a study was made of the effect the presence or absence of washers had on the behavior of these joints.

In previous investigations of riveted and bolted joints [2, 3, 6] the concept

Table 1. Nominal Dimensions and Test Results: Pilot Tests



Item	Units	E 41a	E 41b	E 41c	E 41e	E 41f*)	E 41g*)
Bolts — Regular Head							
Nominal Shear Area	in.^{2}	9.62	9.62	9.62	9.62	9.62	9.62
Washers Used	—	2	2	2	2	1	0
Plates							
Mean Width	in.	6.12	6.42	6.59	7.15	6.66	6.68
Mean Thickness (two plates)	in.	2.01	2.01	2.01	2.02	2.00	2.01
Mean Gross Area	in.^{2}	12.31	12.87	13.25	14.43	13.34	13.43
Mean Net Area	in.^{2}	8.54	9.11	9.49	10.65	9.58	9.66
$A_s : A_n$ *(T : S)*							
Nominal	—	1 : 0.90	1 : 0.95	1 : 1.00	1 : 1.10	1 : 1.00	1 : 1.00
Actual	—	1 : 0.89	1 : 0.95	1 : 0.99	1 : 1.11	1 : 1.00	1 : 1.00
Slip Load (Test)	kips	262	198	260	282	270	282
Bolt Shear Stress	ksi	27.2	20.6	27.0	29.3	28.1	29.3
Avg. Ext. of Bolts	in.	0.0389	0.0399	0.0333	0.0463	0.0364	0.0392
Clamping Force Per Bolt	kips	51.1	51.2	50.3	51.6	48.3	51.2
Slip Coefficient	—	0.32	0.24	0.32	0.34	0.35	0.34
Type of Failure		Plate	All bolts sheared	All bolts sheared	All bolts sheared	All bolts sheared	All bolts sheared
Load at Failure	kips	730	754	770	782	727	767
Bolt Shear Stress	ksi	75.9	78.4	80.1	81.3	75.6	79.8

*) These connections had heavy head bolts; in all connections the threads were excluded from the shear plane.

of tension-shear ratio ($T:S$) [2]) at "balanced design" has figured prominently in determining allowable stresses. As discussed in Ref. [7], it is likely that this concept is not applicable in general to materials other than A 7 steel used in relatively short joints. Nonetheless, for reference purposes the $T:S$ ratios are shown in the tables. As indicated in Table 1 the tension-shear ratio used in these tests ranged from 1 : 1.10 to 1 : 0.90.

The difference in behavior of joints fabricated with regular head bolts with the 1960 ASA standard thread [8] and of joints fabricated with heavy head bolts with the shorter thread length was also studied. In all joints the shearing planes passed through the shank portion of the bolts.

The first four joints, E 41 a, E 41 b, E 41 c, and E 41 e consisted of two lines of four 7/8-inch diameter A 325 regular head bolts. The shear area to tensile area ratio for these specimens was varied from 1 to 0.90 to 1 to 1.10 by varying the plate widths in the joints. Each regular head bolt in these four joints was provided with one washer under the head and one under the nut.

Joints E 41 f and E 41 g were fabricated in the same manner and from the same plate material used for the other four joints. Heavy head bolts were installed in these two joints instead of regular head bolts.

Joint E 41 f was provided with a washer under the nut only and joint E 41 g had no washers under head or nut.

The test specimens for the pilot series were proportioned so that at ultimate load the shear strength of the fasteners was nearly equal to the tensile capacity of the net section. Hence,

$$A_n \sigma_n \cong A_s \tau_t \tag{1}$$

where A_n = net tensile area
A_s = bolt shear area
σ_n = stress on the net section (ultimate)
τ_t = shear strength of the bolt (ultimate)

When the ultimate loads are "balanced"

$$\frac{\sigma_n}{\tau_t} = \frac{A_s}{A_n} = \frac{T}{S} \quad \text{(tension-shear ratio)}. \tag{2}$$

For two lines of four 7/8-inch bolts with 15/16-inch drilled holes, a main plate thickness of 2 inches, and two shear planes, the plate width changed from 6.12 to 7.15 inches as the ratio T/S was varied from 0.90 to 1.10.

b) Long Joints

Each of the long joints had two lines of 7/8-inch A 325 heavy head bolts with a pitch of 3.5 inches. Each bolt had a washer under the nut only. The number of bolts in line varied from joint to joint, from four to sixteen (Table 2).

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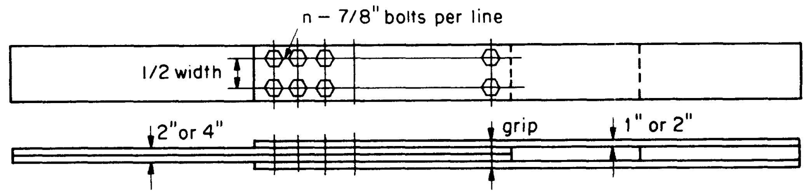
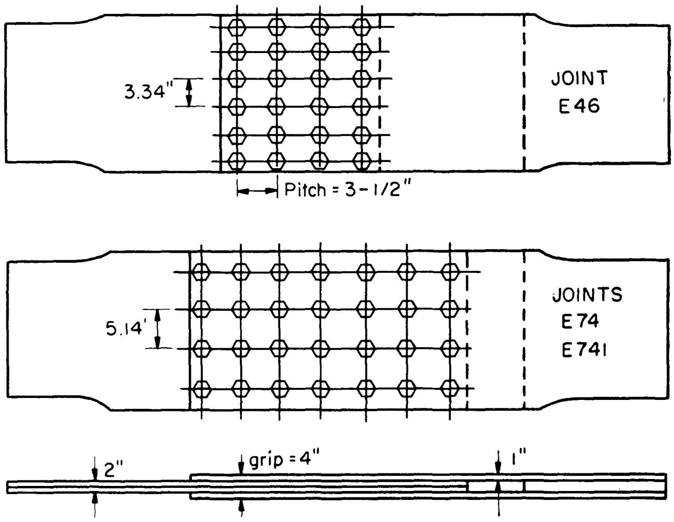
[2]) See list of symbols and glossary of terms.

Table 2. Nominal Dimensions and Test Results: Long Joints



Item	Units	E 41	E 71	E 101	E 131	E 161
Bolts — Heavy Head, 1 Washer						
No. in Line	—	4	7	10	13	16
Nominal Shear Area	in.²	9.62	16.83	24.04	31.25	38.46
Plates						
Grip (excluding washer)	in.	4.04	4.00	4.00	7.96	7.98
Mean Width	in.	6.67	10.28	13.88	9.67	11.47
Mean Thickness	in.	2.02	2.00	2.00	3.98	3.99
Mean Gross Area	in.²	13.49	20.56	27.79	38.53	45.67
Mean Net Area	in.²	9.70	16.81	24.04	31.06	38.23
$A_s : A_n$ $(T : S)$						
Nominal	—	1 : 1.00	1 : 1.00	1 : 1.00	1 : 1.00	1 : 1.00
Actual	—	1 : 1.01	1 : 1.00	1 : 1.00	1 : 0.99	1 : 0.99
Slip Load (Test)	kips	250	400	614	824	1028
Bolt Shear Stress	ksi	26.0	23.8	25.5	26.4	26.7
Avg. Ext. of Bolts	in.	0.0406	0.0361	0.0453	0.0552	0.0570
Clamping Force Per Bolt	kips	48.6	48.3	48.9	48.1	48.2
Slip Coefficient	—	0.32	0.30	0.31	0.33	0.33
Type of Failure	—	All bolts sheared	One bolt sheared	One bolt sheared	One bolt sheared	One bolt sheared
Load at Failure	kips	728	1188	1610	2125	2545
Bolt Shear Stress	ksi	75.7	70.6	67.0	68.0	66.2

Table 3. Dimensions and Test Results: Wide Joints



Item	Units	E 46	E 74	E 741
Bolts — Heavy Head, 1 Washer				
Nominal Shear Area	in.^{2}	28.85	33.67	33.67
Plates				
Mean Width	in.	20.04	20.57	20.55
Mean Thickness	in.	2.03	1.99	2.01
Mean Gross Area	in.^{2}	40.62	40.99	41.22
Mean Net Area	in.^{2}	29.22	33.51	33.70
$A_s : A_n$ $(T : S)$				
Nominal	—	1:1.00	1:1.00	1:1.00
Actual	—	1:1.01	1:1.00	1:1.00
Slip Load (Test)	kips	798	912	680
Bolt Shear Stress	ksi	27.7	27.1	20.2
Avg. Ext. of Bolts	in.	0.0456	0.0403	0.0360
Clamping Force Per Bolt	kips	48.9	48.6	48.3
Slip Coefficient	—	0.34	0.34	0.25
Type of Failure	—	All bolts sheared	One bolt sheared	One bolt sheared
Load at Failure	kips	2180	2410*)	2250
Bolt Shear Stress	ksi	76.5	71.6	66.9

*) Earlier fracture of the plate occurred at a load of 2240 kips.

Based on results obtained from the pilot tests, these subsequent test specimens were proportioned by providing a net plate area equal to the shear area of the bolts. Since the shear area in a joint is dependent upon the number of bolts, the shear area varied for the long joints. In order to maintain equality between shear and tension areas, it was therefore necessary to vary the net area of the joint. This was accomplished by varying the width and the thickness of the plate material. As the number of 7/8-inch bolts in line varied from 4 to 10, the plate width varied from 6.68 to 13.88 inches with a 4-inch grip. In the case of the joints having 13 to 16 bolts in line, the plate width varied from 9.70 to 11.50 inches with an 8-inch grip. Table 2 outlines the nominal dimensions for these specimens.

c) Wide Joints

The three specimens in this group to study the effect of joint width were designed as described previously and as shown in Table 3. Heavy head 7/8-inch A 325 bolts were used with a washer under the nut only.

Joint E 46 was similar to joint E 41 in the "long joint" series except that the number of lines of bolts and the plate width were three times as great.

Joint E 74 was similar to joint E 71 except that it had twice the number of lines of bolts and was twice as wide. Because of premature failure of the main plate outside the connected region, another joint was fabricated and tested. This duplicate of joint E 74 was called E 741. Table 3 outlines the nominal dimensions of specimens E 46, E 74 and E 741.

3. Material Properties

a) Plates

The plate for all joints in this series of tests was ASTM A 440 steel cut from Universal Mill strips 8 or 26 inches wide by 1 inch thick and approximately 36 ft. long. Two different heats of steel were used, one for the pilot investigation and one for the other tests.

At least two plate coupons were cut from the material of each joint tested. These coupons were 1 inch thick and were milled to 1.5 inches in width. Table 4 gives a complete summary of all coupon properties and lists mean values and corresponding standard deviations.

A typical stress-strain diagram is shown in Fig. 1. The initial portion as determined from an autographic strain recorder is shown expanded, and the complete curve as measured with a caliper is also shown.

In all tests both the yield stress and the static yield stress levels were recorded. The "dynamic" yield stress level is reported for a strain offset of 0.2%. The static yield stress level for each coupon was taken as the mean of the minimum values as shown in Fig. 1. Standard deviations are also shown in Table 4, and in order to determine whether or not there was a significant difference between the means for the yield stress levels and the ultimate strengths of the different heats, the "t" test for a five percent level of significance was applied [9]. There were no significant differences found in the yield stress levels or ultimate strengths of the two heats of material.

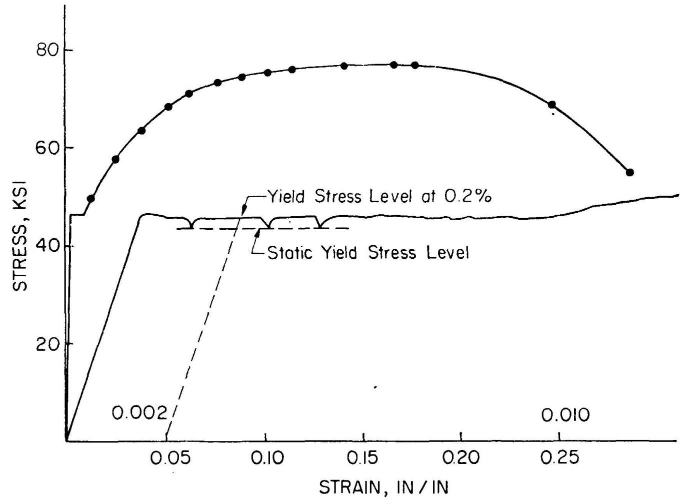


Fig. 1. Typical stress-strain diagram for plate material.

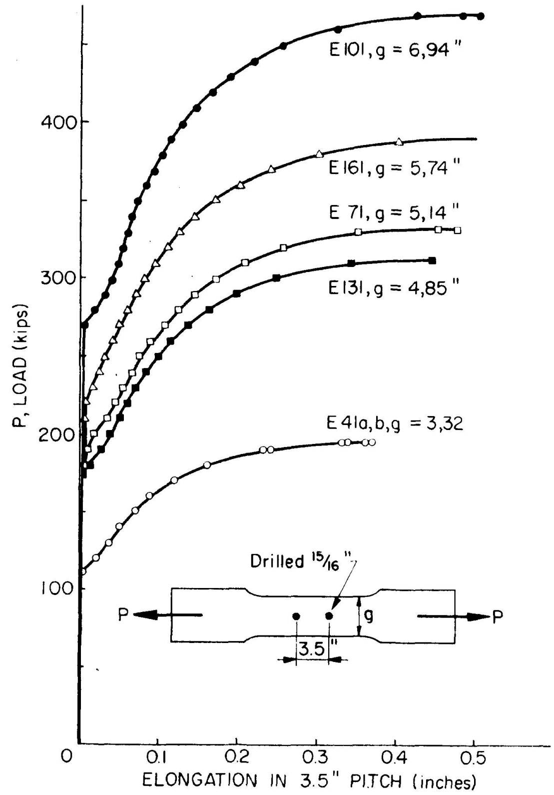


Fig. 2. Results of plate calibration test.

The plate material was purposely ordered near the minimum requirements specified by ASTM for A 440 steel.

In order to establish the behavior of the plate elements, special plate calibration tests were conducted by testing a plate of the same material used in the large joints. The plate had a width equal to the gage distance, a thickness of 1 inch, and two holes drilled 3.5 inches on center as shown in the inset in Fig. 2. The tension-elongation relationship was recorded for the material with the distance between the hole-centers as test length, which was equal to the pitch length in the large joints. The load-elongation curves for these tests are shown in Fig. 2. These curves are essential to the theoretical prediction of the ultimate strength of the bolted joints.

b) Bolts

The bolts were 7/8-inch ASTM A 325 bolts. The length of the bolt under the head varied from 5.25 to 9.5 inches. All bolts were the heavy-head type with short thread length except for the bolts in four of the pilot tests in which regular-head bolts were used. The thread lengths are listed in Table 5.

Table 4. Properties of Plate

Test Series	Coupons Number of	Static Yield Stress Level, ksi		Yield Stress, ksi*)		Ult. Ten. Str., ksi		% Elong. in 8 inches	% Reduction in area
		Mean	Std. Dev.**)	Mean	Std. Dev.	Mean	Std. Dev.		
Pilot	10	43.0	1.17	45.3	1.15	75.4	1.71	28.9	64.5
All Others	30	42.9	0.73	45.3	0.70	76.0	1.01	27.7	61.7
Combined	40	42.9	0.84	45.3	0.82	75.8	1.22	28.0	62.4

*) Taken at a 0.2% strain. **) Std. Dev. = Standard deviation.

Table 5. Properties of 7/8-in. Bolts)*

Used in Joints	Bolt Lot	Length Under Head, inches	Thread**) Length, inches	Direct Tensile Strength, kips			Torqued Tensile Strength, kips			Compression Shear Strength, τ_c, ksi			Tension Shear Strength, τ_t, ksi		
				No.	Mean	Std. Dev.	No.	Mean	Std. Dev.	No.	Mean	Std. Dev.	No.	Mean	Std. Dev.
E41a, b, c, e	D	5.5	2	5	56.9	0.55	4	51.1	0.77	3	88.9	1.14	3	84.4	1.95
E41g	8A	5.25	1.5	5	59.4	1.11	5	52.2	1.91	3	85.1	2.00	3	82.0	0.54
E41f and E41–E101	8B	5.5	1.5	5	55.5	1.12	5	49.3	1.68	3	86.1	1.46	3	76.9	1.78
E131, E161	H	9.5	1.75	7	58.3	1.28	6	48.3	1.69	3	86.0	2.04	3	79.2	0.46

*) The proof load of 7/8-in. A 325 bolts is 36.05 kips. **) There were no threads in the shearing planes.

Each bolt lot was calibrated according to the procedures described in Ref. [10] to determine its direct tension and torqued tension behavior. A brief summary for each lot is given in Table 5.

Bolt shear tests were conducted to establish the relationship between the shearing load carried by a single bolt and its deformation. Two different types of tests were conducted as indicated by the sketches in Fig. 3. In one type the

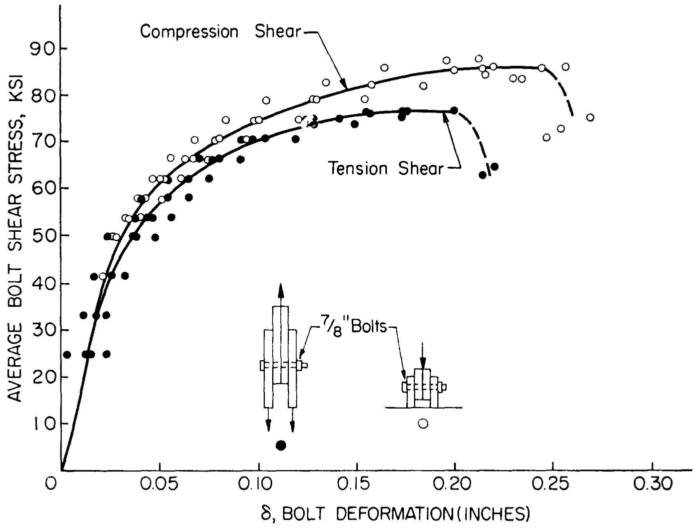


Fig. 3. Shear-deformation relationship for A 325 bolts in A 440 steel.

bolts were subjected to double shear by plates loaded in tension, and in the other test the bolts were subjected to double shear by applying a compression load to the plates. The plates were fabricated form the same material and had the same grip length as the corresponding assembled joints. Three bolts were tested from each lot in each type of test. The results of the tests of the 8 B lot bolts are given in Fig. 3.

The shear strength of single bolts tested in plates loaded in tension was approximately 10% less than the shear strength from the compression test. When bolts are loaded by plates in tension, the bearing condition near the end shear planes causes a prying action and results in an additional tensile component which reduces the bolt shear strength. The catenary action resulting from the deformations may also contribute to the tensile component. In addition to reducing the bolt shear strength some reduction in the deformation capacity is also apparent. When bolts are loaded by plates in compression it simulates the condition of bolts in the interior of joints where the prying action is minimized.

4. Fabrication of Test Joints

a) Fabrication

All shop work necessary for the fabrication of the test joints was done by a local fabricator. The shop procedure was the same for all specimens. Plates were first cut by torch and then machined to the final dimensions. Loose mill scale was removed by hand brushing with a wire brush. Oil and grease were wiped from the plates in order to establish a faying surface condition which would prevail in field assembly.

For the wider joints it was necessary to reduce slightly the width at the ends in order to grip the specimens in the testing machine. This was done with a torch in the case of Joints E 46 and E 74. Special attention to this transition was given with Joint E 741, where all edges were ground to a smooth transition after the rough burning.

The plates for each joint were assembled into the required joint configuration and then clamped together. The four corner holes were subdrilled and reamed for alignment. Pins machined to fit the reamed holes were inserted to hold the joint in alignment while the remainder of the holes were drilled through all plies of the joint. All holes were drilled 15/16-inch in diameter to allow 1/16-inch clearance for the 7/8-inch bolts.

b) Assembly

The bolting-up operation was carried out at the Fritz Engineering Laboratory by a field erection crew of the fabricator. This arrangement made it possible to gather information concerning the bolt tension.

With a few exceptions, the bolts were snugged with the impact wrench and then given one-half turn-of-nut. (The bolts in joints E 181 and E 161 were given three-quarters turn-of-nut). All bolts in joint E 41b and four bolts in joint E 471 were installed with a hand torque wrench and tightened to the corresponding average bolt elongation. The diameter of all bolts used was 7/8-inch and the grip was 4 inches for all the joints except two in the long series (E 131 and E 161).

Complete records of bolt elongations were kept for each bolt in every joint of the test series. The initial length was measured prior to the bolting-up operation. The final length was measured after installation. The average extension of the bolts in the joints are reported in Tables 1, 2 and 3.

5. Instrumentation

The instrumentation for all of the test specimens was essentially the same except for joints having more than two lines of bolts. Fig. 4 shows joint E 74 in the testing machine with instrumentation attached. Included were SR 4 strain gages, a mechanical extensometer and dial gages. Following is a short description of the purpose of these gages and measuring devices.

SR 4 electrical resistance strain gages were generally attached only to the edges of the main and lap plates. These gages were used to detect eccentricity

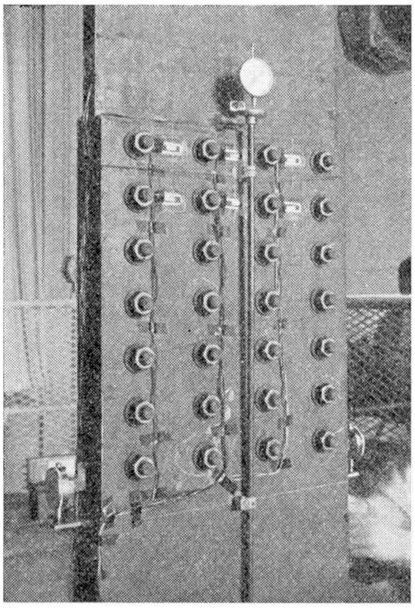


Fig. 4. Joint mounted in testing machine with instrumentation attached.

due to any uneven gripping and to pick up the onset of yielding of the gross section. Additional gages were attached to the faces and dead end of the lap plate of wide joints E 46 and E 74 in order to study the effect of any internal lateral forces caused by plate necking near ultimate load.

The elongation of each pitch of the joint was measured along the edges of the plates with a mechanical extensometer. These measurements were used to check the accuracy of the theoretical solution for the load partition and ultimate strength of the bolted joints. Details of this type of measurement are available in Ref. [2].

During the tests of joints E 46 and E 74 the mechanical extensometer was used to record the transverse and longitudinal plate deformations between bolts of one of the lap plates. The transverse measurements gave some indication of the forces due to plate necking. The longitudinal measurements were compared with the pitch measurements made on the edges of the plates.

Dial gages (0.001 in.) were used to measure the over-all elongation of the joint and provide control during the testing operation. More sensitive gages (0.0001 in.) were used to measure the slip between the lap and main plates as well as the relative displacement between plies of material making up the lap and main plates of joints E 131 and E 161.

6. Test Procedure

The joints were loaded in static tension by a 5,000,000-lb. hydraulic testing machine using wedge grips. The specimen was gripped, and testing proceeded in equal load increments until major slip occurred. Close observation of the dial gages as the expected slip load was approached made it possible to record the displacement at the instant prior to the occurrence of slip. After slip, load was again applied in equal increments until major yielding of the plate material occurred. In the inelastic region, after applying an increment of load the specimen was allowed to stabilize at a constant strain value. The amount of additional strain which took place during stabilization of the load was small as attested by dial gage readings. This procedure was followed until failure of the joint occurred. The load-deformation relationship shown in Fig. 5 was typical for all specimens. In the longer joints failure occurred when an end bolt sheared. All joints with four bolts in line (except E 41 a) showed a sudden and complete shearing of all bolts.

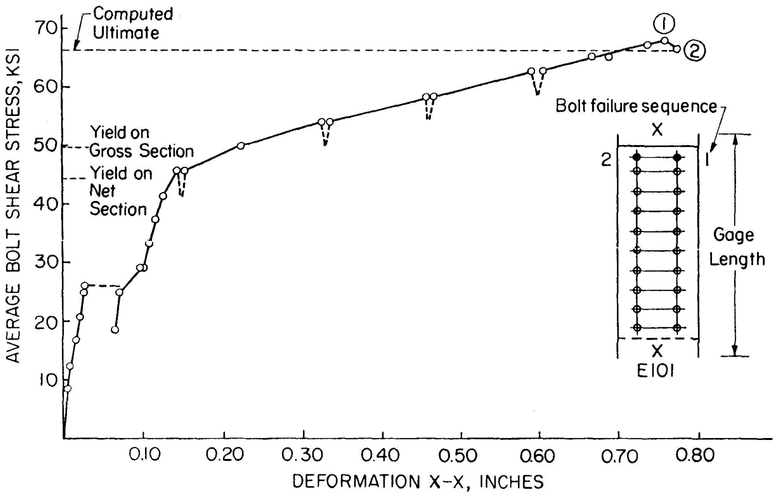


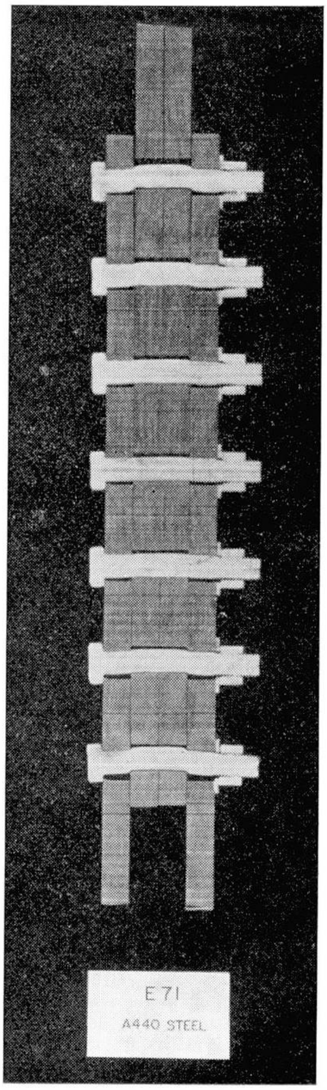
Fig. 5. Typical load-deformation curve.

7. Test Results and Discussion

a) Ultimate Strength

As expected, all joints with equal tension and shearing areas failed by shearing of one of more bolts. In joints with four rows of bolts, simultaneous shearing of all the bolts occurred. The nominal bolt shear stress at failure varied from 75.6 to 81.3 ksi as shown in Tables 1 and 2. Joint E 41 a failed by a tearing of the plate as the plate area was only 90% of the bolt shear area.

In the longer joints one or more of the bolts in the lap plate end unbuttoned due to their larger deformations and the combined stress state. The test was then stopped so that the rest of the joint remained intact. The load at which the first bolt sheared has been considered the failure load even though complete rupture had not occurred. As a check, in the case of joint E 101, load was reapplied until a second bolt unbuttoned — at a slightly lower load. The results are summarized in Table 2.



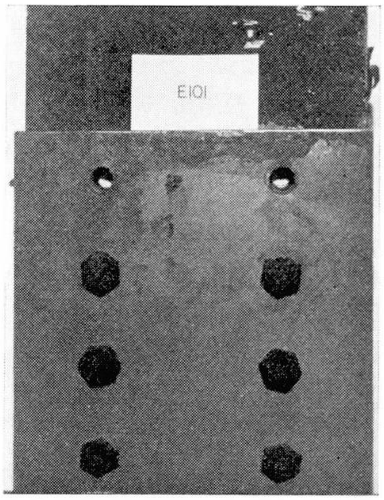


Fig. 7. Joint E 101 showing sheared bolt shanks after unbuttoning.

Fig. 6. Sawed section of joint E 71.

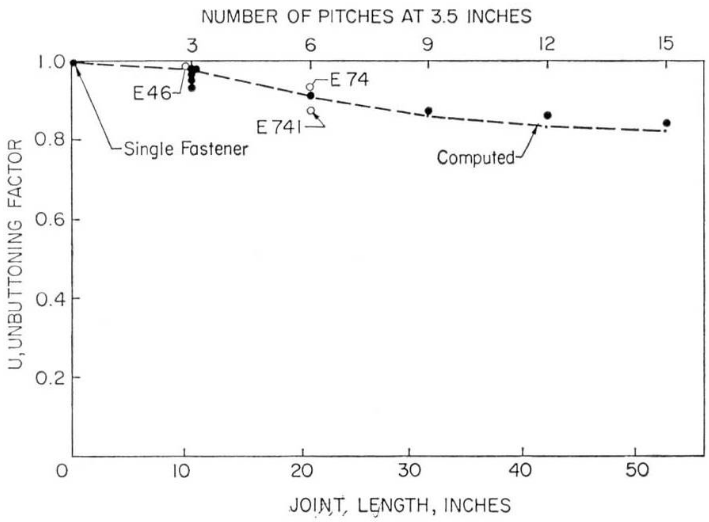


Fig. 8. Effect of joint length on the unbuttoning factor.

A visual record of deformation of bolts along the length of joint E 71 is given in Fig. 6. The high stress in the plates at the ends of the joint is revealed by the larger elongation at the end holes. The prying action at the lap plate end is revealed by the separation of the plates. Fig. 7 shows joint E 101 after unbuttoning of both top bolts. The offset of the bolt shank remaining in the joint can be seen. The load-deformation relationship for this joint was given in Fig. 5.

The results of the tests are shown in Fig. 8 as solid dots where the ultimate strength of the joints are represented by an "unbuttoning factor". The length of each joint is shown both as actual length and in terms of the number of pitches (3.5 in.).

Because bolts of several lots and strengths were used, it is convenient to represent the average shearing stress at failure in non-dimensional form. This non-dimensional quantity is called the unbuttoning factor (U) and is computed by dividing the average ultimate shear stress of the joint (τ_{av}) as given in Tables 1, 2 and 3 by the tension shear strength of a single bolt (τ_t) as given in Table 5. Thus,

$$U = \frac{\tau_{av}}{\tau_t}. \tag{3}$$

The unbuttoning factor U describes, in effect, the extent to which the bolts in a joint are able to redistribute forces. If it was equal to unity then all fasteners would carry an equal share of the load at ultimate — just like a single fastener.

In Fig. 8, a decrease in the unbuttoning factor can be seen between the compact and the longer joints. However, this decrease is at a decreasing rate and appears to approach an asymptotic value of approximately 0.80.

The test results are compared with the theoretical solution in Fig. 8, the latter being shown by a dashed line. The ultimate strength of the test joints was computed with the equilibrium and compatibility conditions formulated in Ref. [11]. The method is based on the load-deformation relationship of the plate material loaded in tension (Fig. 2) and that of the high strength bolts loaded in shear (Fig. 3). A similar method was used in Ref. [12] for aluminum alloy riveted joints. Since the behavior of the bolt in shear is somewhat different depending on whether the shear jig is loaded in compression or in tension, the theoretical result will depend upon which shear curve is used.

The theoretical curve in Fig. 8 is based on the behavior of a bolt loaded in a tension shear jig. It is seen that the actual strength is somewhat greater than the predicted value for the longer joints. This is to be expected as not all bolts are subjected to the prying action experienced by the end rows. This same information is given in Table 6 in comparison with the test results in the column shown as "Method 2". Along with these data, are shown the results obtained using the shear deformation relationship given by the com-

Table 6. Comparison of Test Results and Computed Strength

Joint	Computed Ultimate Strength, Kips			Load at Failure Kips
	Method 1 Compression Jig	Method 2 Tension Jig	Method 3 *) Combined	
E 41	806	729	—	728
E 41f	806	729	—	727
E 41g	800	776	—	767
E 71	1282	1178	1200	1188
E 101	1696	1588	1612	1610
E 131	2163	2062	2102	2125
E 161	2599	2496	2538	2545

*) The bolts in the end two rows at each end of the joint, were assumed to be represented by the tension shear-deformation relationship. The remaining bolts by the compression shear-deformation relationship.

pression test of a single fastener ("Method 1"). As expected, the latter predicts a higher strength because the compression strength is greater (Fig. 3). The reason for the greater compression shear strength was discussed earlier. The results from a third method are also shown in Table 6: The bolts in the end

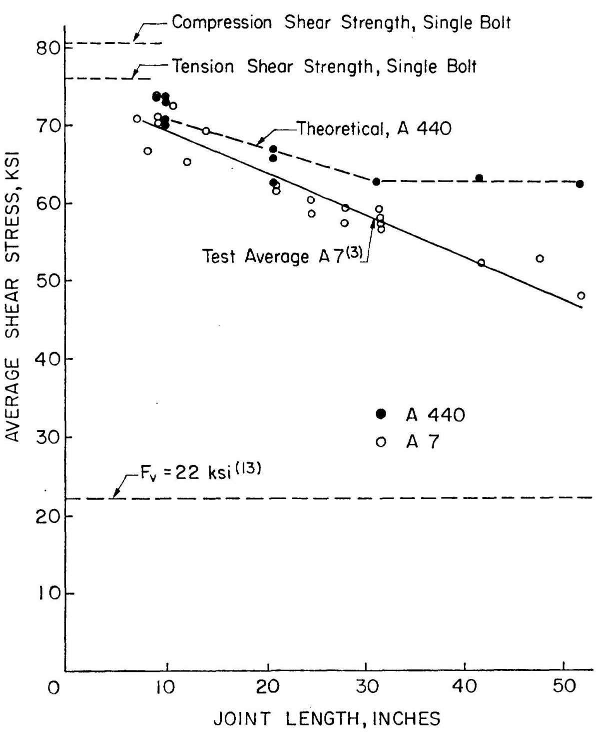


Fig. 9. Comparison of A 440 steel butt joints and A 7 steel butt joints.

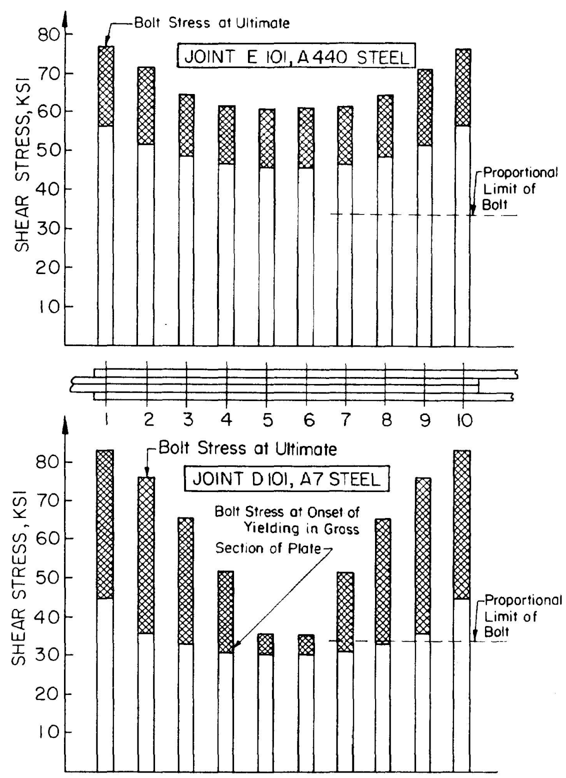


Fig. 10. Load partition in bolted joints.

two rows at each end of the joint were assumed to be represented by tension loading because of the prying action, and for the remaining bolts the compression shear-deformation relationship was used. Although this method gives the most precise agreement (within one percent) the refinement may not justify the added work.

Fig. 9 shows the comparison of these joints of A 440 steel with those of A 7 steel. The average shear stress has been taken as the product of the unbuttoning factor and the minimum tension shear strength of a single bolt. The "compression and tension" shear strengths of single bolts are also shown in the figure. For short joints the higher strength steel results were about the same as A 7, the test average for the latter being shown by the solid line; but in the long joints the performance of A 325 bolts was better in the A 440 steel. The dotted line shown at $F_v = 22$ ksi is the value permitted by the AISC Specification [13].

A part of the reason for the improved performance of the A 325 bolt when used with higher strength steels is illustrated in Fig. 10. Here the computed bolt shear stress in each row at two different stages are shown for joints of equal length and the same number of A 325 fasteners[3]). The upper set (joint E 101) is for A 440 steel, and the lower set (D 101) is for A 7 steel. The geometry of the joint is shown between the two graphs. The two stages are: (1) onset of yielding in the gross section of the plate designated by the end of the open portion of each bar, and (2) bolt stress at ultimate load (designated by the top of the shaded portion).

The figure indicates that the higher yield strength steel effects a better distribution of the bolt forces, the stresses being more uniform in joint E 101 than in the case of D 101. At failure, in D 101 (A 7 steel) the stresses in the bolts near the middle of the joint were less than half those of the end bolts. The higher yield stress of the A 440 steel in E 101 allowed a better redistribution because inelastic deformations occurred in all bolts while the plate material was still elastic and relatively rigid (compare with proportional limit of bolt as shown in Fig. 10). In the A 7 steel (with lower yield stress), inelastic deformations occurred first in the plate (and nearly simultaneously in the end fasteners), and this caused increased deformation in the end fasteners. As a result the end bolts continued to pick up load at a faster rate and did not allow redistribution to occur as well as in the higher yield strength steel. As illustrated in Fig. 10 the interior bolts in the mild steel joint showed little change in load from the onset of yielding until an end bolt failed.

These results suggest that allowable stresses to be used for long A 440 joints might well be higher than that permitted for similar A 7 steel joints. A more detailed discussion concerning this aspect of the design of bolted joints can be found in Ref. [7].

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[3]) The computations are based on the methods described in Ref. [11].

b) Effect of Joint Width

The effect of internal lateral forces caused by plate necking near the ultimate tensile strength of a wide joint was investigated with tests of three joints (E 46, E 74 and E 741 as shown in Table 3).

Joint E 46 had a width three times as great as joint E 41. By comparing the results in Table 3 with those in Table 2, the failure load of 2180 kips for A 46 is seen to be exactly three times the ultimate load of E 41. Joint width thus had no effect on the ultimate strength in this case. The test point is plotted in Figs. 8 and 9 as an open circle at a length of about 10 inches.

Joint E 74 (seven bolts in a line with four lines) unbuttoned at a load of 2410 kips (Table 3). This was slightly more than twice the ultimate strength of joint E 71 with seven bolts in line but with only two lines of fasteners. Again joint width had no effect on the ultimate strength. After slip occurred, but prior to bolt fracture, joint E 74 failed prematurely in the region near the grips. The above result was obtained after the gripping area was repaired. In Fig. 8 the test point for E 74 can be seen as the topmost of the three shown at six pitches.

Joint E 741 was a duplicate of joint E 74. This joint was fabricated and tested because of the failure in the grip region experienced in joint E 74. Joint E 741 failed when a corner bolt unbuttoned at a load of 2250 kips. This load was about 5% less than twice the ultimate strength of joint E 71, and the corresponding test point is shown in Fig. 8 as the lowest of the open circles at six pitches.

Strain gages, placed transverse to the line of load on the "dead" end of the lap plates of joints E 46 and E 74, indicated compressive strains between bolts. This constituted a direct indication of the presence of lateral forces because of the suspected Poisson's effect in the wide joints. The corresponding bolt shear force acting perpendicular to the joint load was estimated to be approximately 4 to 12 ksi. However, once major yielding occurred in the main plate and large shear deformation developed in the bolts, the transverse strains were reduced until the transverse bolt shear stress was estimated to be 1 to 5 ksi.

With these results it is thus concluded that the effect of joint width is not significant in butt joints of A 440 steel plate fastened with A 325 bolts. This finding differs from prior tests in A 7 steel joints in which plate necking was found to contribute to "premature" corner bolt failures [2].

c) Effect of Variations in Plate Area

The pilot test series for the A 440 steel joints allowed an evaluation of the performance of the bolts when the tensile area was varied. As the plate area at the net section was increased from 95 to 110% of the bolt shear area, the bolt shear stress increased from 78.4 to 81.3 ksi as indicated in Table 1. This increase is to be expected as the larger plate area has a greater "stiffness" and allows a better redistribution.

The results of tests of A 7 steel joints which had large variations in the plate area were analyzed and discussed in Ref. [7]. The same type behavior was found for both A 7 and A 440 steel when the plate area was varied.

When the net plate area is decreased relative to the bolt shear area, the joints invariably fail by tearing of the plate such as was the case for joint E 41 a (see Table 1). As a result, there is no way to determine the shear strength of the fasteners. For the compact A 440 steel joints this occurred when the plate area was 90% of the bolt shear area. This same phenomenon was observed in compact A 7 steel joints at approximately 95% of the bolt shear area [2].

d) Joint Slip

The factor which determines the load at joint slip is called the "nominal coefficient of friction" or "slip coefficient" (K_s). This slip coefficient necessarily depends on the condition of the faying surfaces and the clamping forces induced by the bolts. On the basis of a visual inspection, the rolled millscale surface of A 440 plate material used in the test joints was quite hard and smooth. The bolts were tightened according to the turn-of-nut method [1] and resulted in bolt clamping forces which showed no marked variations from the average bolt tension.

Bolt elongations were measured during fabrication. The histograms of the bolt tension distribution were similar to those reported in Ref. [2]. The average elongations and their corresponding bolt tension are given in Tables 1 to 3. The mean elongation ranges from 0.033 to 0.0463 inches for half of a turn and is about 0.0556 inches for three quarters of a turn. The corresponding bolt tension is approximately 1.3 times the proof load of 7/8-inch A 325 bolts in either case. The nominal slip coefficients obtained for each joint are recorded in Tables 1, 2, and 3. The average slip coefficient computed for these tests was $K_s = 0.32$ (see glossary).

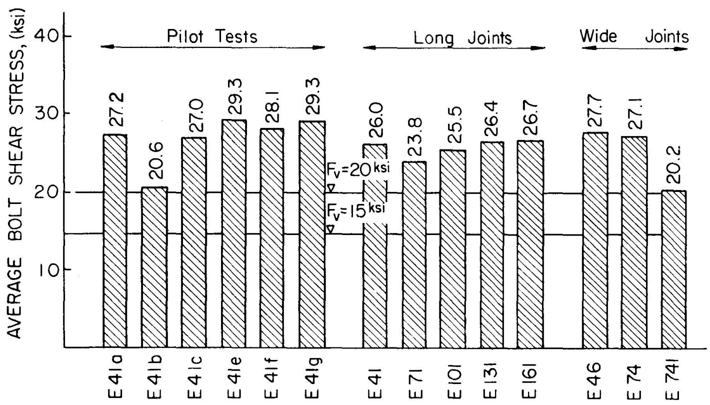

Fig. 11. Slip resistance of bolted joints tightened by turn-of-nut method.

Fig. 11 is a bar graph which illustrates the slip resistance of the A 440 steel joints. The horizontal line extending across the graph at $F_v = 15$ ksi represents the working stress level according to the AISC specifications for friction-type connections [13]. The horizontal line at $F_v = 20$ ksi would apply for connections subjected to static plus wind loading and in which a one-third increase in allowable stress is permitted. The height of each bar indicates the average bolt shear stress at slip. The relatively low slip resistance of joint E 41 b has been attributed to warping during the bolting-up operation.

The average slip coefficient of 0.32 obtained in these A 440 tests is but slightly less than the value of 0.35 obtained in the similar A 7 series [2, 3]. With this result, coupled with the fact that no joints slipped below an average stress of 20 ksi, it is clear that these joints also meet the requirements of the specification [14].

8. Summary and Conclusions

These conclusions are based on the results of fourteen tests of large bolted joints of A 440 steel connected with A 325 high-strength bolts and upon related theoretical analysis. Many of the conclusions are reinforced by the results of tests of joints of A 7 steel connected with A 325 bolts. The joints were butt-type plate splices proportioned with the area of the plate material at the net section equal to the shear area of the bolts. The effect of joint length upon the ultimate strength of the connection was investigated and a few tests were conducted to determine the effect of joint width.

1. Joints of A 440 steel with up to four A 325 fasteners in line were capable of developing about 96% of the shear strength of a single bolt (Fig. 8). This result did not differ significantly from the shear strength of A 325 bolts in similar A 7 steel joints (Fig. 9).

2. In joints with more than four fasteners in line, the differential strains in the connected material caused the end bolts to shear before all bolts could develop their full shearing strength. At seven fasteners in line (24.5-in.) about 87% of the shear strength of a single bolt was developed. This decreased to about 80% for a joint with sixteen fasteners in line (52.5-in.) as shown in Fig. 8. As can be seen in Fig. 9 this decrease was not nearly as great as was experienced in A 7 steel joints.

3. Good agreement was obtained between the test results and the theoretical analysis (Fig. 8). When the tension-shear deformation relationship of the bolts was considered the computed strength was within 3% of the test results (Table 6).

4. An increase in joint width had no appreciable effect on the ultimate strength of the joint. Evidently the lateral forces due to necking in the plate material were not as serious as was the case with earlier tests of A 7 steel joints [2].

5. The presence or absence of washers under the bolt head and nut had no appreciable effect on the behavior of the joint. Any differences between the test joints could be attributed directly to the variations in the bolt shear strengths as reported in Table 5.

6. Controlled variation in the plate area at the net section affected the bolt shear strength as would be expected. As the plate area increased greater rigidity was achieved and corresponding higher shear strength of the bolt groups resulted.

7. The experimental and analytical results suggest that the allowable bolt shear stress to be used in long A 440 steel joints might well be higher than that permitted for similar A 7 steel joints.

8. All bolts were tightened by the turn-of-nut method and consistently had preloads approximately 1.3 times the proof load of the bolt.

9. These tests gave mean coefficient of slip for tight mill scale faying surfaces of $K_s = 0.32$. Neither joint length nor width had any appreciable effect on the slip coefficient.

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Nomenclature

1. Symbols

A_n	The net tensile area of the plate.
A_s	The bolt shear area (for butt-type splices there are two shear planes).
K_s	The slip coefficient or nominal coefficient of friction.

T/S Ratio of the tensile stress on the net section of plate to the shear stress on the nominal area of the fasteners (A_s/A_n).

U The unbuttoning factor — defined as the ratio of the average bolt shear stress in the connection when the first bolt shears to the ultimate strength of a single bolt of the same lot and of the same grip.

σ_n The ultimate tensile stress on the net section.

τ_{av} The average bolt shear stress in the bolted connection at failure.

τ_c The shear strength of a single bolt subjected to double shear by plates loaded in compression.

τ_t The shear strength of a single bolt subjected to double shear by plates loaded in tension.

2. Glossary

Balanced Design Failure of the bolts at the coupon ultimate of the plate material.

Fitting-up Bolt A bolt used to draw the plies of plate material into firm contact before the remaining bolts are tightened.

Gage The transverse spacing of the bolts.

Grip The total thickness of all plate material in the connection.

Major-Slip Sudden, large relative deformation of inner and outer plates of the test joint.

Pitch The longitudinal spacing of the bolts.

Prying Action The tendency for the lap plate ends to bend out due to the bearing condition.

Slip Coefficient $K_s = P_s/m \sum T_i$, where P_s is the major slip load, m is the number of slip planes and $\sum T_i$ is sum of the initial bolt tensions.

Snug The expression used to describe the tightness of a bolt before beginning the turn of the nut. "Snug" is indicated by the impact wrench when impacting begins.

Unbuttoning The sequential failure of fasteners which progresses from the ends of a joint inward.

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Summary

Tests of structural joints of A 440 steel, connected with A 325 high-strength bolts installed by the turn-of-nut method, were conducted to determine their slip resistance and ultimate strength. The purpose of the program was to establish an appropriate shear stress value for bearing-type connections and to determine the influence of joint length on the ultimate strength of higher strength steel connections. Eleven of the joints tested had two lines of fasteners, ranging from 4 to 16 fasteners in line. Other joints had four and six lines of fasteners.

The ultimate strength of the joints, with the theoretically predicted values based on the non-linear behavior of the component parts, shows good correlation between the theoretical analysis and the test results. These studies together with the earlier work with structural grade steel have aided in the development of a rational basis for design.

Résumé

Les auteurs décrivent des essais effectués pour déterminer la résistance au glissement et la charge de rupture de joints d'éléments en acier A 440, assemblés par des boulons à haute résistance A 325 précontraints par la méthode au «tour d'écrou». Le but de ces essais était de déterminer une valeur admissible des contraintes de cisaillement dans les assemblages du «type pression» et de déterminer l'influence de la longueur du recouvrement sur la charge de rupture des assemblages en acier à haute résistance. Onze des assemblages essayés comportaient deux rangées de boulons, avec 4 à 16 boulons par rangée. D'autres comportaient 4 et 6 rangées de boulons.

On a trouvé une concordance satisfaisante entre les résultats expérimentaux et les charges de rupture résultant de calculs théoriques basés sur le comportement non linéaire des éléments du joint. Ces études, s'ajoutant aux recherches antérieures relatives aux éléments en acier doux, ont contribué à la mise au point de bases d'étude rationnelles.

Zusammenfassung

Zur Bestimmung des Gleitwiderstandes und der Bruchfestigkeit wurden Versuche mit hochfest verschraubten Stößen aus Stahl A 440 durchgeführt, wobei die Schrauben, Güte A 325, durch Drehung der Mutter angezogen waren. Zweck des Versuchsprogramms war die Einführung eines geeigneten «Schubspannungswertes» für «bearing-type» Anschlüsse sowie die Bestimmung des Einflusses der Stoßlänge auf die Bruchfestigkeit bei Verbindungen von hochfesten Stählen. Elf Stöße hatten 2 Schraubenreihen mit 4 bis 16 hintereinanderliegenden Schrauben. Andere Versuche wurden mit 4 und 6 Schraubenreihen durchgeführt.

Wenn man die theoretische Bruchfestigkeit der Stöße auf Grund des nichtlinearen Verhaltens der Bestandteile voraussagt, zeigt sich eine gute Übereinstimmung zwischen den theoretischen und den Versuchsergebnissen. Diese Arbeit zusammen mit früheren Untersuchungen an Stahl 37 halfen vernünftige Entwurfsgrundlagen zu entwickeln.