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This work was carried out as part of the Large Bolted Connections Project sponsored by the Pennsylvania Department of Highways, the Department of Transportation - Bureau of Public Roads, and the Research Council on Riveted and Bolted Structural Joints.

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ABSTRACT

The results of experimental studies of constructional alloy (A514) steel butt splice fastened by A490 bolts are reported. Also included are results of experimental work on hybrid joints. This includes A36 - A440 steel joints and A440 - A514 steel joints fastened by A325 bolts as well as a A440 - A514 steel joint fastened by A490 bolts.

The joint tests are compared with predicted results. It is shown that the previously developed theoretical work and analytical studies are verified. Good agreement is obtained for ultimate strength and the distribution of load among the fasteners.

The study has also shown that the slip coefficient of grit blasted steel faying surfaces is about 0.34.

The use of higher allowable shear stresses for A325 and A490 bolts in bearing-type connectors is found appropriate for both types of joints.

1. Introduction

An extensive theoretical study of hybrid connections has been recently reported.[1] This study included an evaluation of A36 - A440 steel joints, A36 - A514 steel joints, and A440 - A514 steel joints. The use of both A325 and A490 bolts was considered.

Studies were also undertaken into the behavior of constructional alloy steel joints fastened by high-strength bolts. Theoretical studies of the behavior of both A325 and A490 bolts installed in this material were reported in Ref. 2.

This report presents the results of the experimental program that was carried out to provide supporting data for the theoretical studies.

2. Scope of Program

The research program described herein consisted of static tension tests of fifteen double-shear butt joints with four to nineteen high-strength bolts in a line. Ten of the test joints consisted of A514 steel plate connected by 1-1/8 in. A325 bolts. The remaining five joints provided information on joints in which different grades of steel were connected. Two were A36 - A440 steel joints and three were A440 - A514 steel joints.

Theoretical studies were also undertaken. These used actual material properties so that a direct comparison could be made between the test results and the analytical work.

3. Specimen Details

Dimensions - The details of the joint geometry for the A514 steel joints are summarized in Table 1. Details for the hybrid butt joints are given in Table 2.

Six of the constructional alloy steel joints were four-bolt-in-line specimens in which a total of four inches of plate was gripped by 1-1/8 in. A325 bolts. The geometry of the test specimens is shown in Fig. 1. All plate in these compact joints was 1 in. thick and came from the same rolling and all fasteners were from the same lot.

A test series of four large constructional alloy steel joints was developed on the basis of the previous theoretical studies.[2] All joints used 1-1/8 in. A325 bolts to fasten 15/16 in. plies of A514 steel plate. Two joints each of 13 and 19 fasteners in a line were designed. However, after the material properties were evaluated, it was apparent from theoretical studies that fastener failure would not occur as intended in joint F111. Hence two bolts were removed (one from each end) so as to ensure the desired failure mode. The geomety of the test joints is shown schematically in Fig.1 and the specimen details are summarized in Table 1.

Originally, the specimens were paired - one of each pair designed to fail by tearing of the plates, the other by shearing of the fasteners. The mode of failure is governed by the relative proportions of the plate and fasteners. As an index of this relationship, the A_n/A_s ratio is provided in each table. Joints F131 and F191 were proportioned to fail in the plates and FIII and F192 to fail in the bolts. The intent was to bracket the plate failure - fastener failure boundary line. As noted, the plate and bolt properties differed substantially from that assumed in the design and it was necessary to modify the specimen geometry after fabrication.

Five hybrid test joints were designed to provide confirming data for the theoretical studies previously reported.[1] All five joints had 13 fasteners in a line. Four of these joints were fastened by 7/8 in. A325 bolts. Two of these joints (HJ131 and HJ132) were fabricated from A36 and A440 steels. One was designed to fail in the plates and the other by a shearing of the bolts. As with the homogenous A514 joints, the failure mode is governed by the relative proportions of the fastener and plate. The other two joints (HJ135 and HJ136) were fabricated of A440 and A514 steels; one designed to fail in the plate and the other by fastener shear. The fifth joint was an A440 - A514 steel joint fastened by 7/8 in. A490 bolts.

Plates - All 1 in. plate for the A514 pilot joints came from the same rolling. Standard tensile specimens were tested. Fifteen-sixteenths in. thick A514 steel plate was used for the large A514 steel test joints and for the appropriate hybrid joints. The individual pieces were all cut from a single 112 in. x 24 ft. plate. The A440 steel plate for the hybrid joints was 1 in. thick and came from a 66-1/2 x 24 ft. plate. The pieces of A36 steel for hybrid joints were all cut from the same 5/8 in. x 34 in. x 19 ft. 6 in. plate. Results of standard tensile tests are summarized in Table 3 for each of the four plates used.

Bolts - The high strength bolts used in this study came from several lots, depending upon type, diameter and grip length. All lots were ordered to minimum strength requirements of the applicable ASTM specification.

Each bolt was subjected to standard calibration tests. This included direct and torqued tension calibrations and the determination of the shear-deformation characteristics of the bolts. Details of these types of tests are provided elsewhere.[3,4] Results of the direct tension and the shear-deformation tests are summarized in Table 4.

Fabrication and Assembly - All shop work was done by a recognized steel fabricator. All plate was blast cleaned with the Pangborne Roto-Blast using No. 50 chilled steel grit prior to layout and assembly. The plates were then flame-cut to rough size and then milled to specified dimensions.

The plates for each joint were assembled and clamped. The holes were then sub-drilled 1/4 in. through the entire assembly with a tape drill. All holes were then reamed to size. Grease was removed by wiping with solvent and the specimens reassembled and fastened with full size shipping bolts and washers.

The installation of the test bolts was done at Fritz Laboratory by Project personnel. The plates were first aligned and clamped. Bolts were inserted into the holes and snugged with an impact wrench. The fit-up bolts were then replaced by test bolts and all bolts were given the prescribed nut rotation.[5] The length of all bolts was measured before and after tightening so that the elongation could be used to evaluate the bolt tension.

4. Instrumentation and Testing Procedure

The instrumentation of the specimens included SR-4 strain gages and dial gages. The electric resistance strain gages were attached to the edges of the plate at various locations along the length of the joints. They provided a means of evaluating the load transfer mechanism and enabled a comparison to be made of theoretical and experimental plate loads through-out the joint.

Dial gages measuring 0.0001 in. were used to detect the slip between the main and lap plates. Other dial gages (0.001 in.) were used to measure the overrall elongation of the joint.

The joints were loaded in static tension by means of a 5000 kip universal testing machine using wedge grips. The specimen was first placed in the upper grips and the instrumentation fitted. After taking initial readings, the specimen was gripped in the lower head and the loading commenced. The load was applied at intervals suitable to the expected slip and failure loads. In order to minimize effects of dynamic loading, the load was applied as slowly as practicable. At each load increment, all strain and elongation dials were read and recorded. The test was continued until the specimen failed, either by shearing of a single bolt, shearing of all bolts, or by fracture of the plates.

5. Test Results and Analysis

The results of the 15 joint tests are summarized in Tables 1 and 2.

The load-deformation response of the joint was nearly linear up to major slip as expected. At this load, the main and lap plates moved relative to one another a little less than the amount of hole clearance. This movement was always sudden and well defined.

All homogeneous A514 joints except F111 failed by shearing of the bolts. Of the hybrid joints, only HJ136 failed by tearing of the plate. The remaining four hybrid joints failed by the shearing of one or more bolts.

Slip Resistance - Although the major variable being evaluated was the joint strength, valuable information was also obtained on the slip behavior. Slip coefficients were computed from the measured slip load and clamping force. These value are given in Tables 1 and 2. Variations in the value of the slip coefficient are greater for the hybrid joints. The maximum values were obtained for the A440 - A514 steel combination.

Homogeneous A514 steel joints yielded about the same slip coefficient as the bybrid joints. The mean value for 15 joints was 0.34 with a standard deviation of 0.04. The coefficient obtained from the hybrid A440 - A514 steel joints showed substantial scatter, varying from 0.32 to 0.45.

As noted, all steel plate used in these tests was blast cleaned with No. 50 chilled steel grit. It is of interest to note that such treatment yielded about the same resistance to slip, regardless of the type of connected material. As noted in previous tests of this type neither joint geometry or clamping force have a significant effect on the slip resistance. Also, clean mill scale faying surfaces can be expected to provide less slip resistance.

Ultimate Strength - All but one compact joint failed by shearing of the bolts. Theoretical studies showed that the compact A514 steel joints were expected to distribute the load to individual fasteners by nearly equal amounts as the ultimate load was approached.[2] The predicted joint loads are compared with the test values in Table 1. Good agreement was obtained between the predicted and test values.

The large homogeneous A514 steel joints all failed as predicted from their measured material properties. Joints F131 and F191 were proportioned so that plate failure would occur and this was the failure mode that was observed.

As was noted, joints F111 and F192 were designed to fail by fastener shear. After the basic bolt and plate properties were determined and theoretical studies made utilizing these characteristics, it was apparent that joint F111 would fail by tearing of the plate if tested as fabricated. Since it was desirable to provide a wider range of test data to confirm the theoretical studies, it was decided to remove two fasteners from the joint so that fastener failure would occur. This changed the geometrical properties so that the A_n/A_s ratio was increased from the design value of 0.60 to 0.74. Failure did then occur by a simultaneous shearing of all the bolts at a test load 5 percent greater than predicted.

Joint F192 was also evaluated prior to testing. The theoretical study showed that either type of failure mode could occur as the plate and fastener strengths were nearly identical. Failure occurred in the plate. The plate failures all occurred at loads about 2 percent less than that predicted from the material properties.

The reasons for the behavior of the long joints of the F Series is apparent from an examination of Fig. 2. The A_n/A_s ratio is plotted as a function of the joint length. The design of the large F joints was based on the properties obtained from the pilot study. However, the bolts provided for the long joints were substantially stronger than those used in the pilot program (See Table 4). This caused the plate failure - fastener failure boundary to shift as indicated so that joints F111 and F192, which were designed for $A_n/A_s = 0.60$ would most likely fail in the plate. Because F192 was the longer of the two joints and nearest the plate boundary, it was tested without modification. Joint F111 was modified as noted to force the failure to occur in the fasteners.

The analytical method[2] developed to predict the ultimate strength of A514 steel joints gave excellent agreement with the experimental results. The maximum error between theory and test is less than 5 percent.

All hybrid joints behaved as expected. An examination of the predicted and test values as given in Table 2 shows that excellent agreement was obtained. The test results are compared to predicted joint strength curves in Figs. 3 and 4. The experimental work reported herein, and the earlier analytical studies, have shown that A514 steel joints fastened by A325 bolts are unlikely to produce yielding of the connected members. The shear area required is substantially more than needed for A490 bolts. This causes a corresponding increase in joint length. The A490 bolts appear to be a better balanced fastener to use to fasten constructional alloy steel.

Figure 3 shows the behavior of A36 - A440 steel joints connected by A325 bolts. Two joint strength curves are shown and they are for the A_n/A_s ratios of the two test joints. Joint HJ132 with $A_n/A_s = 0.71$ (A440 steel) was proportioned to lie on the plate failure boundary. First failure was observed when an end fastener sheared. Both ends of the test joint were sectioned so that the plate and fastener deformations could be observed. These sections are compared in Figs. 5 and 6. Bolt failure was observed to occur in this instance at the joint end where the A36 steel was most highly stressed (See Fig. 6). An examination of Fig. 5 shows that plate failure was imminent in the A440 steel plate as revealed by the elongation of the bolt holes and the necking down of the net section.

As was predicted from the theoretical studies, the critical fastener for joints HJ131, HJ133, and HJ135 was the one at the joint end where the higher strength steel was most highly stressed. Reference 1 has discussed the distribution of load to individual fasteners and the reasons why, unlike the behavior of symmetrical homogeneous joints, one end of the joint is more critical than the other. This experimental study has confirmed the applicability of the theoretical predictions of hybrid joint strength.

Figure 4 shows that hybrid A440 - A514 steel joints also behaved as expected, both for A325 and A490 bolts.

6. Summary and Conclusions

This report has presented the results of experimental studies that were undertaken to provide confirmation of theoretical studies on: (1) the behavior of construction alloy (A514) butt joints connected by A325 bolts; and (2) the behavior of hybrid joints.

The actual properties of the plates and bolts were used in the theoretical solutions so that the degree of correlation between test and theory could be properly evaluated.

The following conclusions are based on the results of the tests described herein and on the theoretical studies.

1. The slip coefficient of steel (A36, A440, and A514) blast cleaned with No. 50 chilled steel grit is about 0.34.

2. The theoretical solutions for predicting the ultimate load of A514 steel joints and hybrid steel joints were confirmed.

3. Constructional alloy steel joints fastened by A325 bolts cannot produce yielding on the gross section if the elements of the joint are designed according to current (1967) practice. The A325 bolt is not as suitable a connector for A514 steel as is the A490 bolt.

4. The hybrid joint tests have confirmed the prediction that hybrid joints behave similarly to homogeneous joints and that their strength is equal to or greater than that obtained for similar homogeneous joints.

5. The use of higher allowable shear stresses for A325 and A490 bolts in bearing-type connections as suggested in Ref. 6 is suitable for both hybrid and A514 steel joints.

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TABLE I

JOINT DIMENSIONS AND TEST RESULTS A514 JOINTS USING A325 BOLTS

Item	Units	F42a	F42b	F42c	F42d	F42e	F42g	F191	F192	F131	F111
Bolts Type	-	A325	A325	A325	A325	A325	A325	A325	A325	A325	A325
Diameter	in.	1-1/8	1-1/8	1-1/8	1-1/8	1-1/8	1-1/8	1-1/8	1-1/8	1-1/8	1-1/8
No. in Line (n)*	-	4	4	4	4	4	4	19	19	13	11
Shear Area (A_s)	in.^{2}	15.90	15.90	15.90	15.90	15.90	15.90	37.6	37.6	25.8	21.8
Joint Length	in.	10.5	10.5	10.5	10.5	10.5	10.5	63	63	42	35
Plate Width	in.	5.56	6.36	6.76	7.16	7.56	7.96	5.203	7.27	6.70	9.45
nom. plate thick		1	1	1	1	1	1	15/16	15/16	15/16	15/16
Thickness (t)	in.	2.03	2.04	2.04	2.04	2.04	2.05	3.752	3.752	1.876	1.876
Gross Area (A_g)	in.^{2}	11.28	12.98	13.80	14.51	15.41	16.31	20.84	27.20	12.55	18.9
Net Area (A_n)	in.^{2}	6.40	8.07	8.90	9.66	10.52	11.40	15.15	22.75	10.30	15.5
A_n/A_s	-	0.40	0.51	0.56	0.61	0.66	0.72	0.40	0.60	0.40	0.74
Slip Load	kips	396	332	326	342	346	398	820	886	740	600
Clamping force/ bolt	kips	69.0	70.0	68.5	70.5	69.0	70.0	78	75.4	86.2	83.5
Slip Coefficient	-	0.36	0.30	0.30	0.30	0.31	0.36	0.28	0.31	0.33	0.33
Ultimate Load											
Predicted	kips	833	1050	1050	1050	1050	1050	1940	2905	1320	1762
Actual	kips	860	1052	1064	1056	1062	1074	1932	2850	1280	1846
Failure Mode	-	Plate	Bolts	Bolts	Bolts	Bolts	Bolts	Plate	Plate	Plate	All Bolts Sheared

* Pitch = 3.5 in. for all joints

TABLE II

JOINT DIMENSION AND TEST RESULTS - HYBRID JOINTS

Item	Units	HJ131	HJ132	HJ133	HJ135	HJ136
Bolts Type	-	A325	A325	A325	A325	A325
Diameter	in	7/8	7/8	7/8	7/8	7/8
No. in line *(n)	-	13	13	13	13	13
Shear Area	in^2	15.6	15.6	15.6	15.6	15.6
Joint length	in	42	42	42	42	42
Main Plate Type		A36	A36	A440	A440	A440
Width	in	5.63	6.5	8.44	7.5	5.94
Nominal Plate Thickness	in	5/8	5/8	in	1.0	1.0
Thickness (t)	in	3.75	2.5	4.0	4.0	4.0
Gross Area (A_g)	in^2	21.1	16.25	33.6	29.8	23.8
Net Area (A_n)	in^2	17.6	13.9	29.8	26.1	19.9
A_n/A_s		1.13	0.89	1.92	1.68	1.28
Lap Plate Type		A440	A440	A514	A514	A514
Width	in	5.63	6.5	8.38	7.48	5.90
Nominal Plate Thickness	in	1.0	1.0	15/16	15/16	15/16
Thickness	in	3.0	2.0	1.88	1.88	1.88
Gross Area	in^2	16.9	13.0	15.8	14.10	11.1
Net Area	in^2	14.1	11.1	13.98	12.26	9.30
A_n/A_s		0.91	0.71	0.90	0.79	0.60
Slip Load	kips	450	445	740	392	482
Clamping force/bolt	kips	49.2	53	63.5	47.3	45.7
Slip Coefficient	-	0.35	0.32	0.45	0.32	0.41
Ultimate Load						
Predicted	kips	1051	881	1495	1200	1190
Actual	kips	1114	908	1518	1244	1202
Failure Mode		one bolt	one bolt	All bolts failed	All bolts failed	plate (A514)

TABLE 3

PROPERTIES OF PLATE

Type Steel	Nominal Plate Thickness	No. of Coupons	Static Yield Point[a] in ksi		Tensile Strength in ksi	
	in.		Mean	Std. Dev.	Mean	Std. Dev.
A36	5/8	4	36.5	0.30	66.1	0.65
A440	1	4	44.1	0.33	76.3	0.61
A514	15/16	4	114.0	2.52	119.8	1.36
A514	1	5	114.0	2.48	121.4	2.33

(a) Yield strength at 0.2% offset strain for A514 steel.

TABLE 4

PROPERTIES OF BOLTS

Used in Joints	Bolt Grade	Bolt Dia. in.	Grip in.	Tensile Strength in kips		Shear Strength		Δ_u in.
				Specified	Measured	kips	ksi	
F42a - F42g	A325	1-1/8	4	80.1	81.4	131.4	66.1	0.21
F131, 132	A325	1-1/8	3-3/4	80.1	106.3	162.0	81.5	0.23
F191, 192	A325	1-1/8	7-1/2	80.1	104.5	169.6	85.0	0.24
HJ131	A325	7/8	6-3/4	53.2	68.3	113.0	94.0	0.25
HJ132	A325	7/8	4-1/2	53.2	69.3	113.0	94.0	0.25
HJ135, 136	A325	7/8	5-7/8	53.2	60.6	97.0	80.6	0.21
HJ133	A490	7/8	5-7/8	69.3	78.1	115.3	96.0	0.16

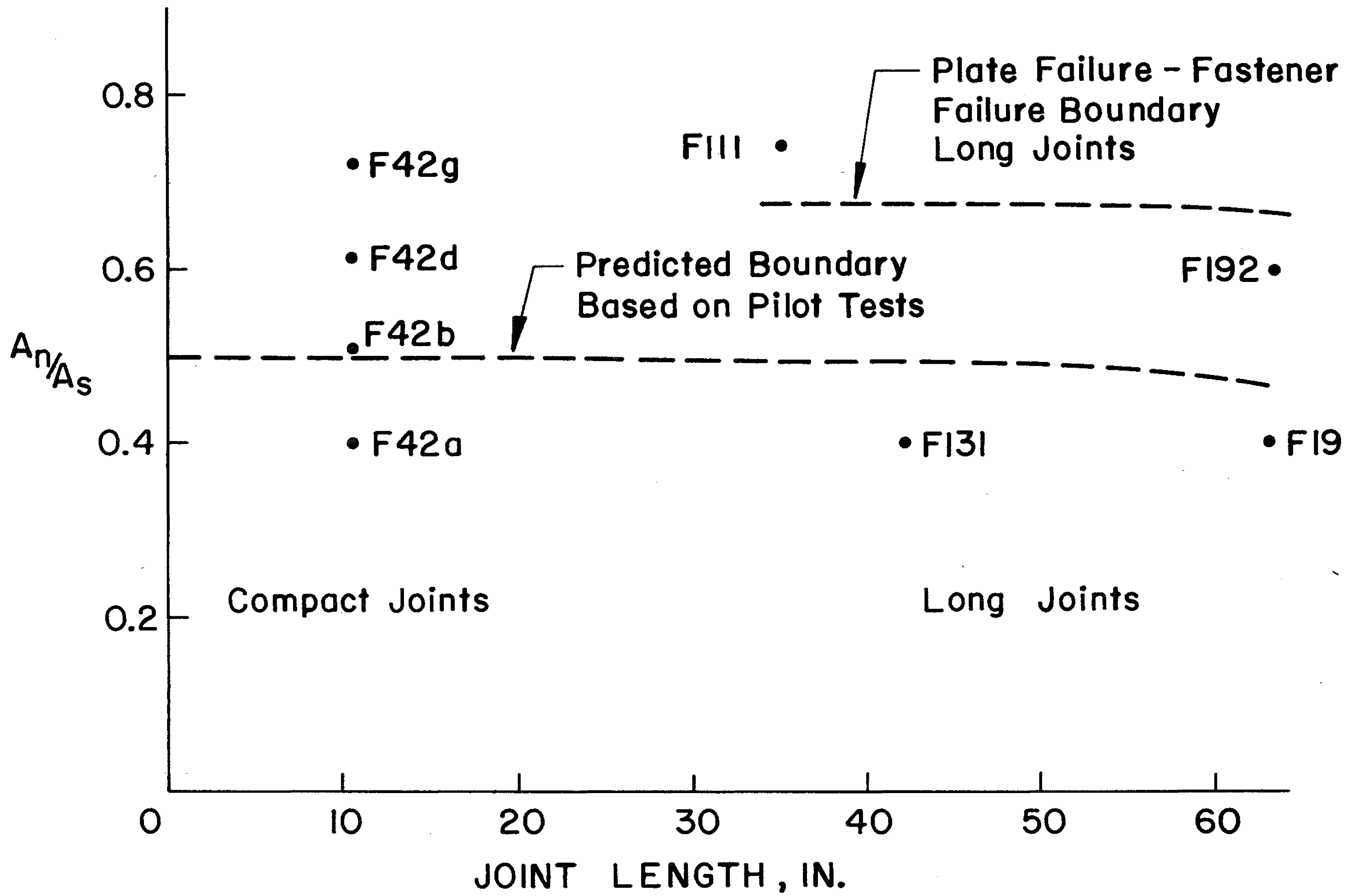

Fig. 2 Experiment Design - A514 Steel Joints Fastened by A325 Bolts

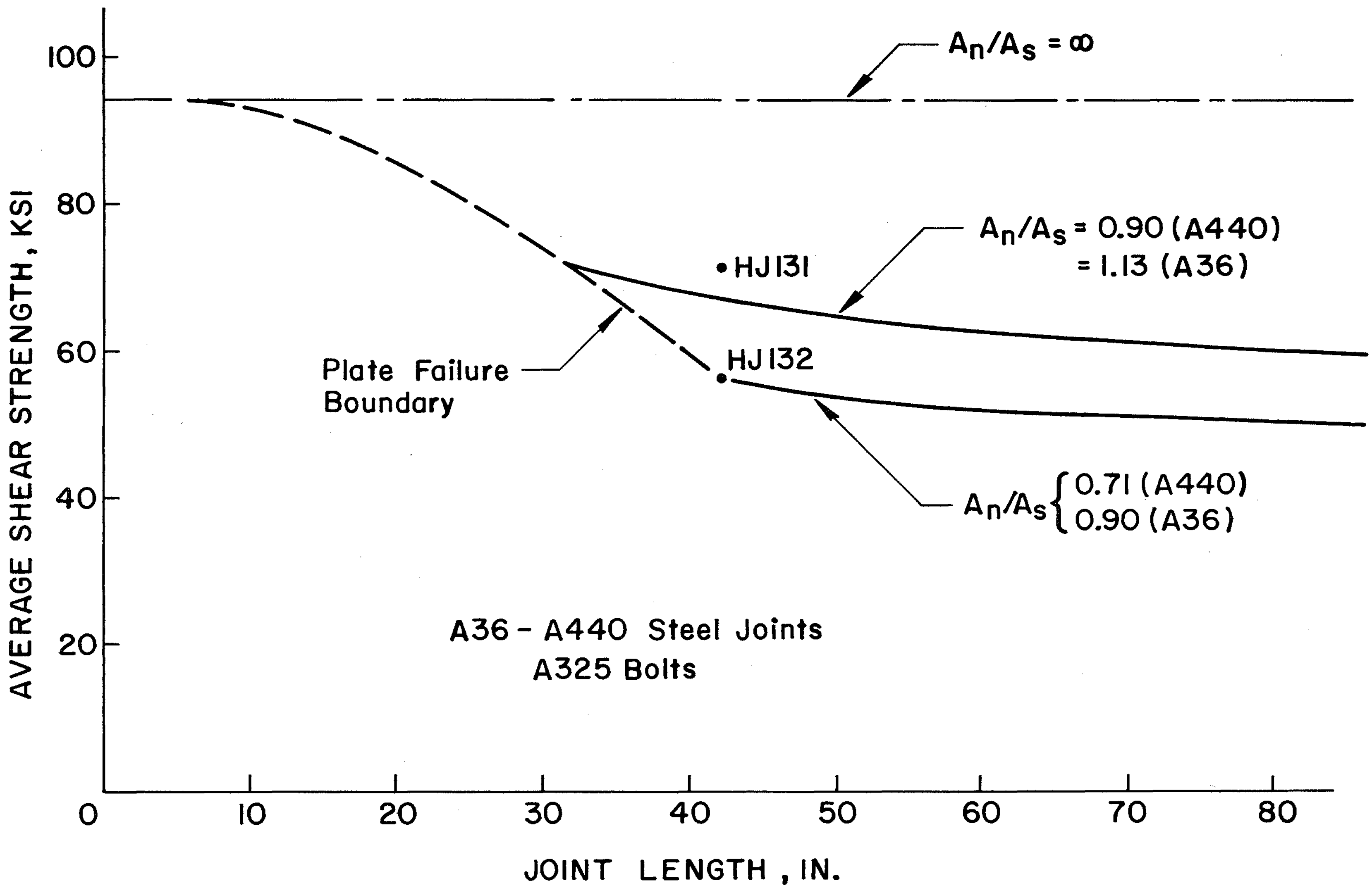

Fig. 3 Comparison of Theoretical Strength With Test Results (A36-A440 Hybrid Steel Joints)

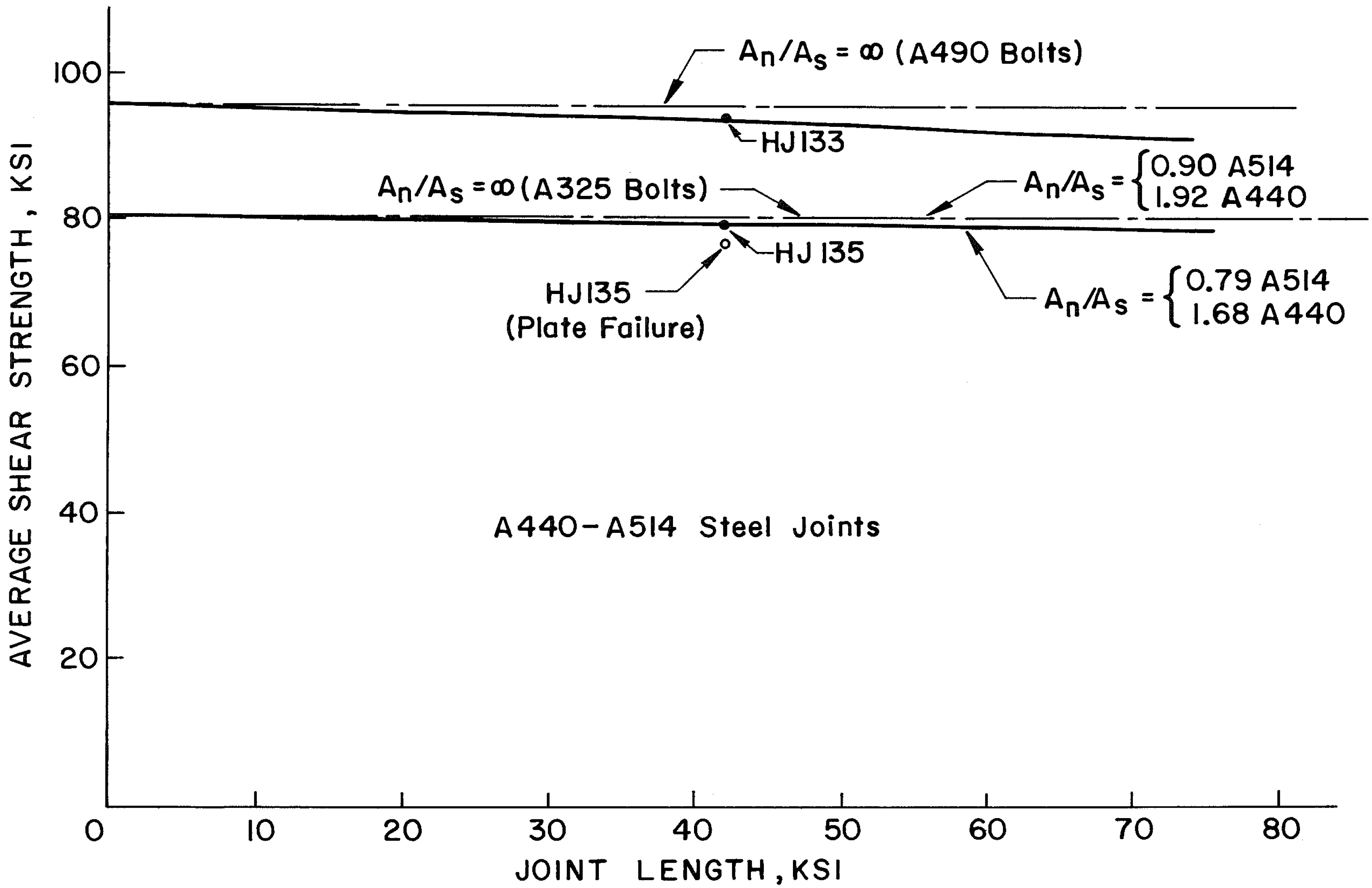

Fig. 4 Comparison of Theoretical Strength With Test Results
(A440-A514 Hybrid Steel Joints)

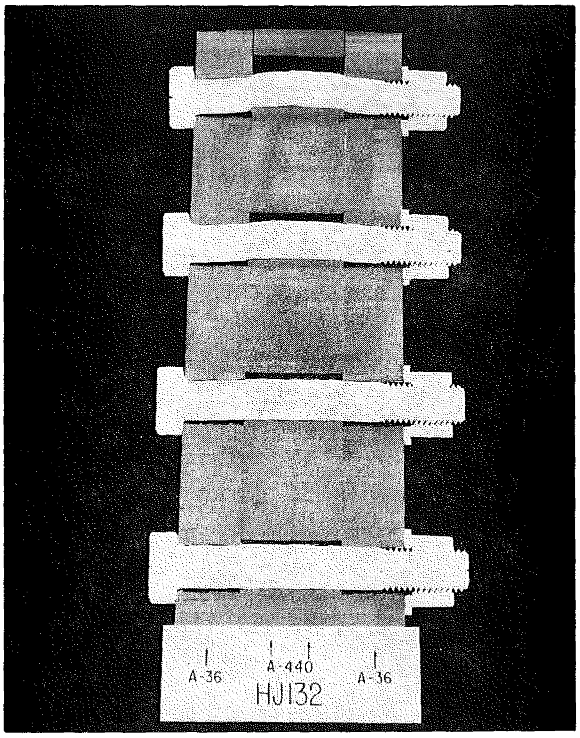

Fig. 5 Section of Joint HJ132 Showing Bolt and Plate Deformations after Failure (Main Plate End)

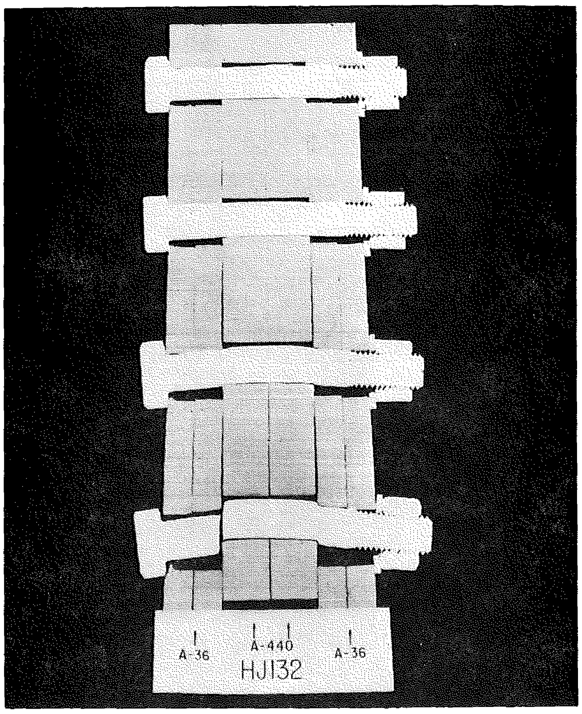

Fig. 6 Section of Joint HJ132 Showing Bolt and Plate Deformations after Failure (Lap Plate End)