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The effect of fastener material and fastener tension on the allowable bearing stresses of structural joints

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THE EFFECT OF FASTENER MATERIAL AND FASTENER TENSION ON THE ALLOWABLE BEARING STRESSES OF STRUCTURAL JOINTS

(Not for Publication)

by

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Project Report

C. E. 103 - Special Problems

Instructor--Professor F. W. Schutz, Jr.

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SYNOPSIS

Previous investigations of bolted joints have shown the need for investigating the possibility of raising the allowable bearing value for high tensile bolted connections. The purpose of the investigation reported herein is to obtain experimental data which might justify more intensive investigation in this field. The authors feel that the results of the tests performed do justify further experimentation, as will be shown in the body of the report.

I. INTRODUCTION

1. Object and Scope of Investigation

Previous investigations have shown the possibility of raising the ratio of shear stress to tensile stress for high tensile bolted structural joints. However, there are no recorded attempts to show the feasibility of raising the ratio of bearing stress to tension stress in the same proportion as the ratio of shear stress to tensile stress, thereby bringing joints designed with the raised allowable stresses back to the balance which they have under the present specification.

Because of this deficiency in previous reports on this subject, the test program reported here was originated in an attempt to furnish a good foundation for future investigations in this field.

The objects of this investigation were to determine the following:

1. The effect of fastener material on allowable bearing stresses.
2. The effect of fastener initial tension on allowable bearing stresses.

This report summarizes the results of tests made on 22 joints of 6 independent designs. The joints were of double strap butt types tested statically at room temperature. Ten control coupons from the parent plates were also tested under similar conditions.

2. Acknowledgments

This program of tests were carried out as a part of the undergraduate curriculum in Civil Engineering at Lehigh University, Bethlehem, Pennsylvania, under the direct supervision of F. W. Schutz, Jr., Research Assistant Professor of Civil Engineering. The work was carried out by W. H. Laub and J. R. Phillips, Sr.

Appreciation is expressed to the Bethlehem Steel Company of Bethlehem, Pennsylvania, for their donation of the machined plate material and fasteners.

II. DESCRIPTION OF TEST SPECIMENS AND EQUIPMENT

1. Description of Test Specimens

The method of determining the effective net width for design of the joints was the relative gage method(1)* in which the effective net width is described as follows:

$$E.\ N.\ W. = 1.05\ (G - 0.9D)\ KH$$

But not more than 0.87 GKH

Where:

D = Actual hole diameter

G = Transverse distance between any two successive holes

K = 0.82 plus 0.0032 R but not more than 1.00

R = Reduction in area of standard control coupon in per cent

H = 1.00 for drilled holes
0.862 for punched holes

Details of the joints which were tested are shown in Fig.1. The plate material was A.S.T.M. A7 structural steel. The fasteners used were 3/4"Ø hot driven rivets (A.S.T.M. A141), 3/4"Ø and 7/8"Ø common bolts (A.S.T.M. A307), and 3/4"Ø high tensile bolts (A.S.T.M. A325). Additional descriptive information may be found in Table II. The contents of this table include, T:S:B ratios (ratios of tensile, shear, and bearing stresses to tensile stress), fastener initial tension, edge distances, type of fastener, type of failure, theoretical efficiencies, test efficiencies, and coefficients of friction of the plate material. There are two sets of T:S:B ratios and theoretical efficiencies reported, one based on the relative gage method net area and another based on the net area as defined by A.I.S.C. Specifications (2) Section 19.

*Numbers in ( ) indicate reference number in Bibliography.

In order to identify the specimens they are designated by a letter and an Arabic numerial; the letter indicating the T:S:B ratio series and the number indicating the joint within the series. In the case of a retested joint as in the "C" series the prefix"1" indicates the original test, while the prefix "2" denotes a retested joint.

The center plates were cut from parent plates as indicated in Figs. 2a and 2b. The strips of plate marked "X" are control coupons.

The plates were cleaned except for normal mill scale and assembled with the predetermined fastener tension. Where the joints were too wide for the jaws of the testing machine, pull-ends were welded to the ends of the specimens previous to their assembly. A typical test set-up is shown in Photograph 1.

2. Material Control

It was realized at the outset that careful control of the plate material must be obtained. This control was accomplished in two ways, by specifying the direction of rolling on the plate lay-outs and by locating numbered control coupons throughout the parent plates. These coupons were machined and tested as recommended by A.S.T.M. standard precedure. The ultimate strengths varied transversely across the plates. Compensation for this was made by proportioning the strength of the coupons across the parent plates. The mechanical properties of the plates are given in Table I.

In order to insure proper bolt tension each bolt was independently calibrated. This was accomplished by applying an axial tension by means of special pullheads, while the total elongation was being measured with a bolt extensometer. In the case of the high tensile bolts the loads applied were 90% of elastic proof load, as recommended by the Research Council on Riveted and Bolted Structural Joints of The Engineering Foundation, and an increased value of 125% of elastic proof load. For the common bolts, Load-Elongation curves were plotted and a value close to the yield point was chosen for the bolt tension. These curves are shown on Fig. 3. The bolts were installed in the joints and torqued until the pre-determined elongation was attained.

3. Special Equipment

Since it was important to measure the elongation of the bolts, a special bolt extensometer was designed by the authors utilizing a 0.0001 in. dial gage. The extensometer is pictured in Photograph 2. In order to measure the slip between the plates as load was applied, slip gages were designed, as pictured in Photograph 2. These gages were mounted on either side of the joint by means of pointed set screws in punch marks. The mounted slip gages may be seen in Photograph 1.

4. Test Procedure

The following is the general test procedure that was carried out on all joints tested.

The joints were assembled and placed in the testing machine and a load sufficient to hold the joints in place was applied. The slip gages were then attached. Load increments were applied and slip readings taken. (Note: slip as used in this report includes local yielding as well as plate slip, since no provision was made to differentiate between them.) Slip gages were removed after general yielding was observed, and all specimens were loaded to failure. Yield load, ultimate load and type of failure were recorded.

The procedure was varied in the "C" series joints with 3/4"ϕ high tensile bolts and increased bearing to tension stress ratio. Several of the original joints failed by end tear outs or shear-outs. These joints were designed with an end distance of 1.5". Four of these joints were remade with a 2" end distance which was sufficient to remedy this undesired behavior. It is of interest to note that the A.I.S.C. Specification (2) Section 23(f) requires an end distance of 2" for this series of joints. The slip readings were taken on the original test, since the mode of failure had no effect on the slip readings, and only the ultimate load was recorded when the remade joints were tested.

III. RESULTS OF TESTS

1. Slip Relationships

Load - slip curves for the joints tested can be found on Figs. 4 to 8. It can be seen that the curves for bolts exhibit a definite slip load while the curve for a riveted connection (Fig.4) shows no definite slip load. At the working load, however, the riveted connection had slipped more than the high tensile bolt connection. Generally, with the exception of the "B" series, the high tensile bolts with an initial tension slipped at or above the working load (20,000 x Eff. Net Area). The slip curves for common bolts with an initial tension resemble those for high tensile bolts but the initial slip occurred at a much lower load except for joint D-1 which had 7/8"Ø common bolts with an initial tension of 16 kips. This joint slipped at the working load.

The coefficient of friction between the plates varies from 0.19 to 0.38. There seems to be little or no correlation between fastener type or bolt tension and the coefficient of friction. The coefficients of friction shown by the tests are given in Table II.

2. Efficiencies

The theoretical efficiencies computed by A.I.S.C. Specifications are between 6 and 10 percentage points lower than the theoretical efficiencies as computed by the relative gage method.

For joints with common bolts the relative gage predicted efficiency was a maximum of 5.6% greater than the test efficiency while the maximum difference for A.I.S.C. predicted efficiencies was 10% less than test efficiency. For riveted connections the relative gage predicted efficiency was a maximum of 4.2% greater than the test efficiency and the A.I.S.C. predicted efficiency was a maximum of 6% less than test efficiency. For the high tensile bolts the relative gage predicted efficiency was a maximum of 2.5% greater than test efficiency and A.I.S.C. predicted efficiency was a maximum of 8.8% less than test efficiency. For the high tensile bolts the relative gage efficiencies were 1.1% greater on the average than the test efficiencies while the A.I.S.C. efficiencies averaged 6.8% lower than test efficiencies.

3. Modes of Failure

The joints with the high bearing stresses and 1.5" edge distance (the "C" Series with T:S:B = 1:0.98:2.67) suffered tear out failures; pictures of these failures can be seen in Photograph 3. The nominal shearing stress intensity on these tear outs was 25,750 psi. By increasing the edge distance to 2" the shearing stress on the idealized tear out section would be 24,200 psi at ultimate load and the joints failed in tension. A picture of the plate failure with the increased edge distance may also be seen in Photograph 3.

In joint series "A" with T:S:B ratio of 1:0.745:2., joints A-3 and A-4 failed through shear in the 3/4"Ø common bolts. The shear intensity at the time of failure was 40,000 psi on the gross area of the fasteners.

The remainder of the joints failed across the net sections of the center plates. Photograph 4 shows pictures of joint failures with high tensile bolts as the T:S:B ratios varied from 1:0.75:2 to 1:1:2.67. Photograph 5 shows the failure in two joints of identical design with the only variable being bolt tension. One joint had 0 bolt tension and failed at 105.8 Kips; the other joint had an initial bolt tension of 90% elastic proof load (26 kips) and failed at 105.0 kips.

It is of interest to note that despite the fact that high bearing stresses were attained in the joints the high tensile bolts themselves suffered very little damage. Upon investigation it was found that the threads of the bolts embedded themselves into the plate material to such an extent that they could be more easily removed with a wrench than by driving them with a hammer.

IV. SUMMARY AND CONCLUSIONS

1. Summary

Generally speaking the high bearing to tension ratios (T:S:B=1:0.98:2.67) had little or no effect on the efficiencies of the high tensile bolted connections. It should be noted, however, that the high bearing values with the common bolt test series "E" (T:S:B=1:.46:2.00) may have caused the slight decrease in joint efficiency.

2. Conclusions

In Table III there is given a comparison of theoretical and actual test efficiencies as related to fastener material. It can be seen that at A.I.S.C. Specification allowable stresses the rivet proved to be the least efficient in developing the theoretical efficiency but the difference is small. The common bolts were more efficient than the rivets, and the high tensile bolts were most efficient. At a T:S:B of 1:0.98:2.67 the high tensile bolted connections lost no efficiency with the increased bearing stresses.

In the case of the common bolts, when the shear ratio was raised to 0.745 the result was a failure by shear in the fasteners. The average ultimate load for these joints was 70,500 lbs. and the average ultimate strength of the control coupons was 62,800 psi, therefore, the effective net area required for balance between tension and shear failure is 70.5 divided by 62.8 or 1.122 sq. in. The new necessary net area corresponds to a T:S ratios of 1:0.636. Due to the drop in efficiency as the bearing ratios for common bolted joints was increased in series "E", it is believed that the balanced bearing ratio lies between 1.25 and 2, probably in the vacinity of 1.8. It now seems feasible that the balanced design ratio for common bolted joints may be raised from 1:0.5:1.25 to 1:0.64:1.8. This would correspond to allowable stresses of 20,000 psi in tension, 12,700 psi in shear, and 36,000 psi in bearing. This supposition would definitely require further experimental verification.

Table IV shows the effect of initial bolt tension on the efficiency of high tensile bolted connections as indicated by the test results. It can be seen that there was no effect on the efficiency of the joints due to the increase in initial bolt tension from 0 lb. to 26,000 lbs. There is, however, a general trend towards higher slip loads as the bolt tension is increased.

In spite of the fact that initial bolt tension had no effect on the ultimate strength of the joints, there were no bearing failures observed during the test program as evidenced by the close correlation between the predicted efficiencies and actual test efficiencies. The authors feel that due to the superior quality of the high tensile bolt material it is feasible to raise the bearing and shear ratios from 1: 0.75:2 to 1:1:2.67 for high tensile bolts. This would correspond to A.I.S.C. allowable stresses of 20,000 psi in tension, 20,000 psi in shear and 53,400 psi in double shear bearing. Should such increased allowable stresses be used, revised end distances and minimum spacing which would protect against end tear outs should be established.

The authors realize that the results and conclusions presented here are based on a very limited test program and that furthere investigation should be conducted to support and expand these conclusions.

V. BIBLIOGRAPHY

1. Schutz, F. W., Jr., and Newmark, N. M., "The Efficiency of Riveted Structural Joints," Progress Report, Engineering Experiment Station, University of Illinois, Urbana, Illinois, September 1952.

2. American Institute of Steel Construction, "Steel Construction," New York, New York, 1952.

TABLE I

Plate Mechanical Properties

Coupon No.	Yield St. ksi	Ult. St. ksi	% Elong. in 8"	% Reduction in area
X-1	35.0	63.5	30.6	40.0
X-2	35.0	63.0	31.6	52.4
X-3	34.4	62.1	32.4	54.3
X-4	34.9	62.6	27.5	52.7
X-5	34.6	62.2	29.0	57.2
X-6	34.5	61.6	29.2	54.1
X-7	33.6	59.2	35.9	58.3
X-8	32.8	57.8	31.6	57.8
X-9	36.5	61.2	27.7	50.8
X-10	36.4	61.2	28.1	53.3

TABLE II

Part 1 - Specimen Details

	T:S:B Ratios A.I.S.C.	T:S:B Ratios Rel. gage	Fastener Tension	End Distance in inches	Fastener
A-1	1:0.676:1.818	1:0.745:2	----	1.5	3/4" ϕ Rivet
A-2	1:0.676:1.818	1:0.745:2	---	1.5	3/4" ϕ Rivet
A-3	1:0.676:1.818	1:0.745:2	9,000#	1.5	3/4" ϕ C.B.
A-4	1:0.676:1.818	1:0.745:2	9,000#	1.5	3/4" ϕ C.B.
A-5	1:0.676:1.818	1:0.745:2	26,000#	1.5	3/4" ϕ H.T.B.
A-6	1:0.676:1.818	1:0.745:2	26,000#	1.5	3/4" ϕ H.T.B.
B-1	1:0.868:1.818	1:0.955:2	26,000#	1.5	3/4" ϕ H.T.B.
B-2	1:0.868:1.818	1:0.955:2	26,000#	1.5	3/4" ϕ H.T.B.
1-C-1	1:0.915:2.48	1:0.984:2.67	0#	1.5	3/4" ϕ H.T.B.
2-C-1	1:0.915:2.48	1:0.984:2.67	0#	2.0	3/4" ϕ H.T.B.
1-C-2	1:0.915:2.48	1:0.984:2.67	0#	1.5	3/4" ϕ H.T.B.
2-C-2	1:0.915:2.48	1:0.984:2.67	0#	2.0	3/4" ϕ H.T.B.
C-3	1:0.915:2.48	1:0.984:2.67	26,000#	1.5	3/4" ϕ H.T.B.
1-C-4	1:0.915:2.48	1:0.984:2.67	26,000#	1.5	3/4" ϕ H.T.B.
2-C-4	1:0.915:2.48	1:0.984:2.67	26,000#	2.0	3/4" ϕ H.T.B.
C-5	1:0.915:2.48	1:0.984:2.67	26,000#	2.0	3/4" ϕ H.T.B.
1-C-6	1:0.915:2.48	1:0.984:2.67	35,600#	1.5	3/4" ϕ H.T.B.
2-C-6	1:0.915:2.48	1:0.984:2.67	26,000#	2.0	3/4" ϕ H.T.B.
D-1	1:0.499:1.10	1:0.51:1.25	16,000#	1.5	7/8" ϕ C.B.
D-2	1:0.449:1.10	1:0.51:1.25	16,000#	1.5	7/8" ϕ C.B.
E-1	1:0.418:1.835	1:0.456:2	16,000#	1.5	7/8" ϕ C.B.
E-2	1:0.418:1.835	1:0.456:2	16,000#	1.5	7/8" ϕ C.B.

TABLE II

Part 2 - Results of Tests

Joint	Type of Failure	Theoretical Eff. % A.I.S.C.	Theoretical Eff. % Rel. Gage	Test Eff. %	Coef. of Friction
A-1	Tension	75.6%	83.4%	80.0%	----- Rivets
A-2	Tension	75.6%	83.4%	80.4%	----- Rivets
A-3	Shear in the Fastener ✓	75.6%	83.4%	73.4%	0.278 C.B.
A-4	Shear in the Fastener ✓	75.6%	83.4%	71.4%	0.243 C.B.
A-5	Tension	75.6%	83.4%	82.2%	0.289
A-6	Tension	75.6%	83.4%	82.9%	0.3125
B-1	Tension	75.6%	83.3%	81.3%	0.192
B-2	Tension	75.6%	83.3%	81.9%	0.192
1-C-1	End tear out	80.8%	86.9%	81.4%	-----
2-C-1	Tension	80.8%	86.9%	85.9%	-----
1-C-2	End tear out	80.8%	86.9%	81.8%	-----
2-C-2	Tension	80.8%	86.9%	86.1%	-----
C-3	Weld failure	80.8%	86.9%	*	0.360
1-C-4	End tear out	80.8%	86.9%	79.0%	0.302
2-C-4	Tension	80.8%	86.9%	85.25%	0.302
C-5	Tension	80.8%	86.9%	85.6%	0.312
1-C-6	End tear out	80.8%	86.9%	83.5%	0.229
2-C-6	Tension	80.8%	86.9%	86.5%	0.229
D-1	Tension	65.7%	74.7%	72.7%	0.383 C.B.
D-2	Tension	65.7%	74.7%	73.2%	0.281 C.B.
E-1	Tension	76.2%	83.2%	78.8%	0.188 C.B.
E-2	Tension	76.2%	83.2%	80.1%	0.234 C.B.

* Weld connecting pullhead failed first.
Fasteners--H.T.B. except as noted.

TABLE II

Part 3 - Results of Tests

Joint	Yield Load Kips	Ultimate Load Kips	Slip Load Kips
A-1	57.5	78.50	----
A-2	57.5	78.75	----
A-3	57.0	71.5	10.0
A-4	57.0	69.5	8.75
A-5	68.5	80.5	30.0
A-6	68.5	81.0	30.5
B-1	60.0	98.0	20.0
B-2	61.5	98.3	20.0
1-C-1	72.50	100.0	0
2-C-2	---	105.3	----
1-C-2	72.50	101.0	0
2-C-2	---	106.3	----
1-C-3	75.0	102.0	37.50
C-3	Not remade ** weld failure in pullhead		
1-C-4	73.0	101.0	31.50
2-C-4	---	104.0	----
C-5	60.0	105.5	32.5
1-C-6	76.0	102.5	32.5
2-C-6	---	106.3	----
D-1	55.0	71.5	24.5
D-2	50.0	71.5	18.0
E-1	50.8	67.5	12.0
E-2	50.0	68.0	19.5

TABLE III

Table Comparing Effect of Fastener Material

on Joint Efficiency

Fastener Material	T:S:B	Ave. Test Eff.x100 / Ave. Rel. Gage Eff.
Rivet	1:0.745:2	96.3%
Common Bolt	1:0.51:1.25	97.7%
Common Bolt	1:0.745:2	86.8%*
Common Bolt	1:0.456:2	95.6%
High Tensile Bolts	1:0.745:2	99.1%
High Tensile Bolts	1:0.955:2	97.3%
High Tensile Bolts	1:0.984:2.67	99.0%

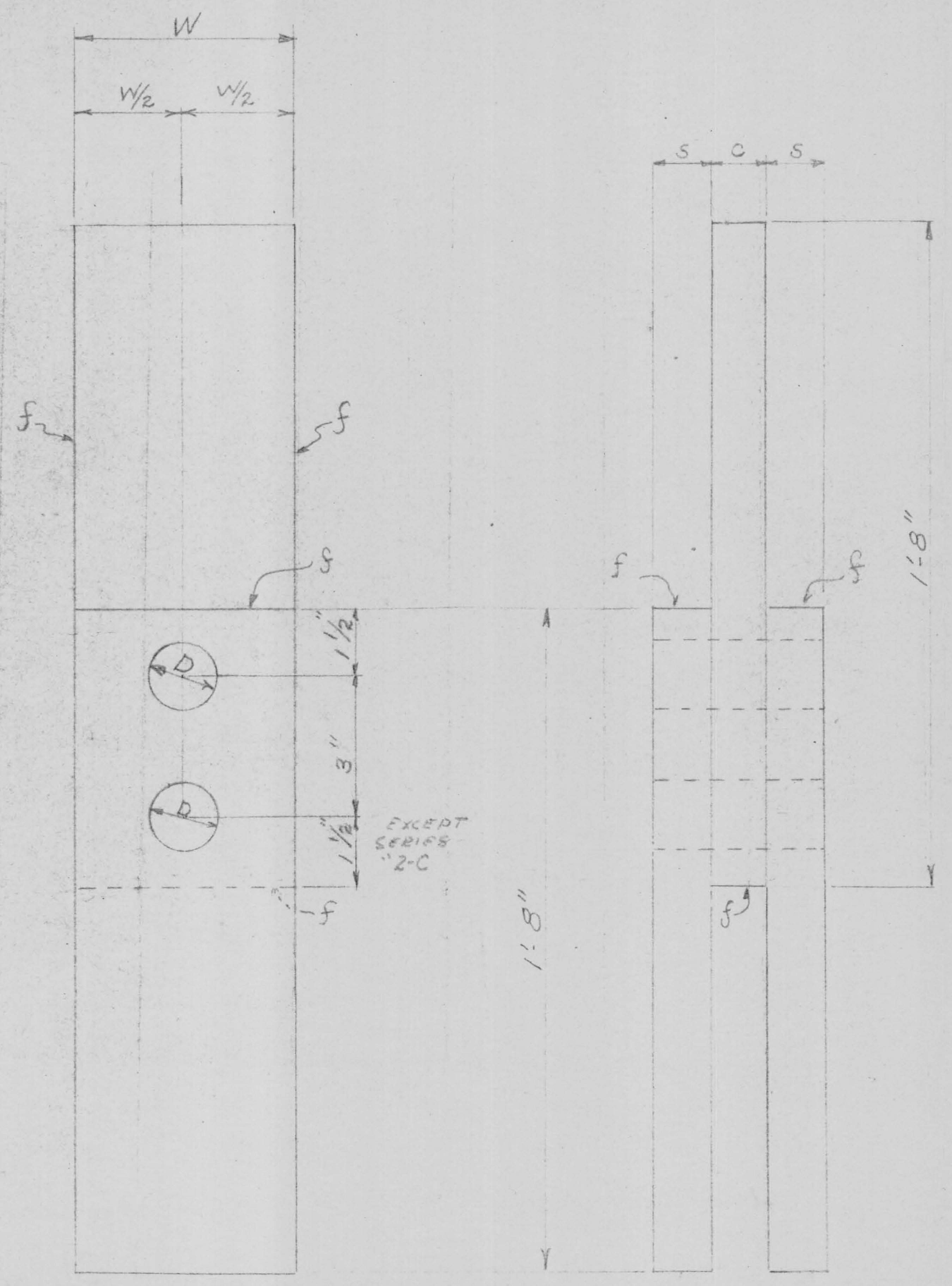
*Shear failure of common bolts.

TABLE IV

Table Comparing Effect of Bolt Tension

on H.T.B. Joint Efficiency

Bolt Tension Kips	T:S:B	Ave. Test Eff.x100 / Ave. Rel. Gage Eff.
0	1:0.98:2.67	99.0%
26.0	1:0.98:2.67	99.0%



SCHEDULE OF DIMENSIONS

JOINT TYPE	No. JOINTS REQ'D	DIMENSIONS (IN INCHES) W	W/2	D	C	S	REMARKS
A	6	3.59	1.785	13/16	7/16	3/8	RIVET 2 JOINTS 3/4"φ
B	2	3.59	1.785	13/16	9/16	3/8	
C	6	4.56	2.280	13/16	7/16	3/8	SERIES "2-C" EDGE DISTANCE MADE 2"
D	2	2.92	1.460	15/16	9/16	3/8	
E	2	4.18	2.090	15/16	5/16	3/8	

NOTE:

1. ALL HOLES DRILLED TO DIAMETERS SHOW ON SCHEDULE.
2. FINISH ALL SURFACES MARKED "f"
3. STEEL SPECIFICATION - A.S.T.M. A7-46
   RIVET SPECIFICATION - A.S.T.M. A141-39
4. ONLY 2 JOINTS MARKED "A" TO BE RIVETED
5. CENTER PLATES TO BE CUT FROM PARENT PLATE AS SHOWN ON DRW'G. Nos J-2 & J-3

LEHIGH UNIVERSITY
DEPARTMENT OF
CIVIL ENGINEERING & MECH.
PROJECT #243
JOINT DETAILS
J-1

DESIGNED	J.R.P. W.H.L.	DATE - 2-28-54
DRAWN BY	J.R.P. W.H.L.	SCALE - NONE
CHECKED	[signature]	APPROVED [signature]

FIG. 1

FIG. 1

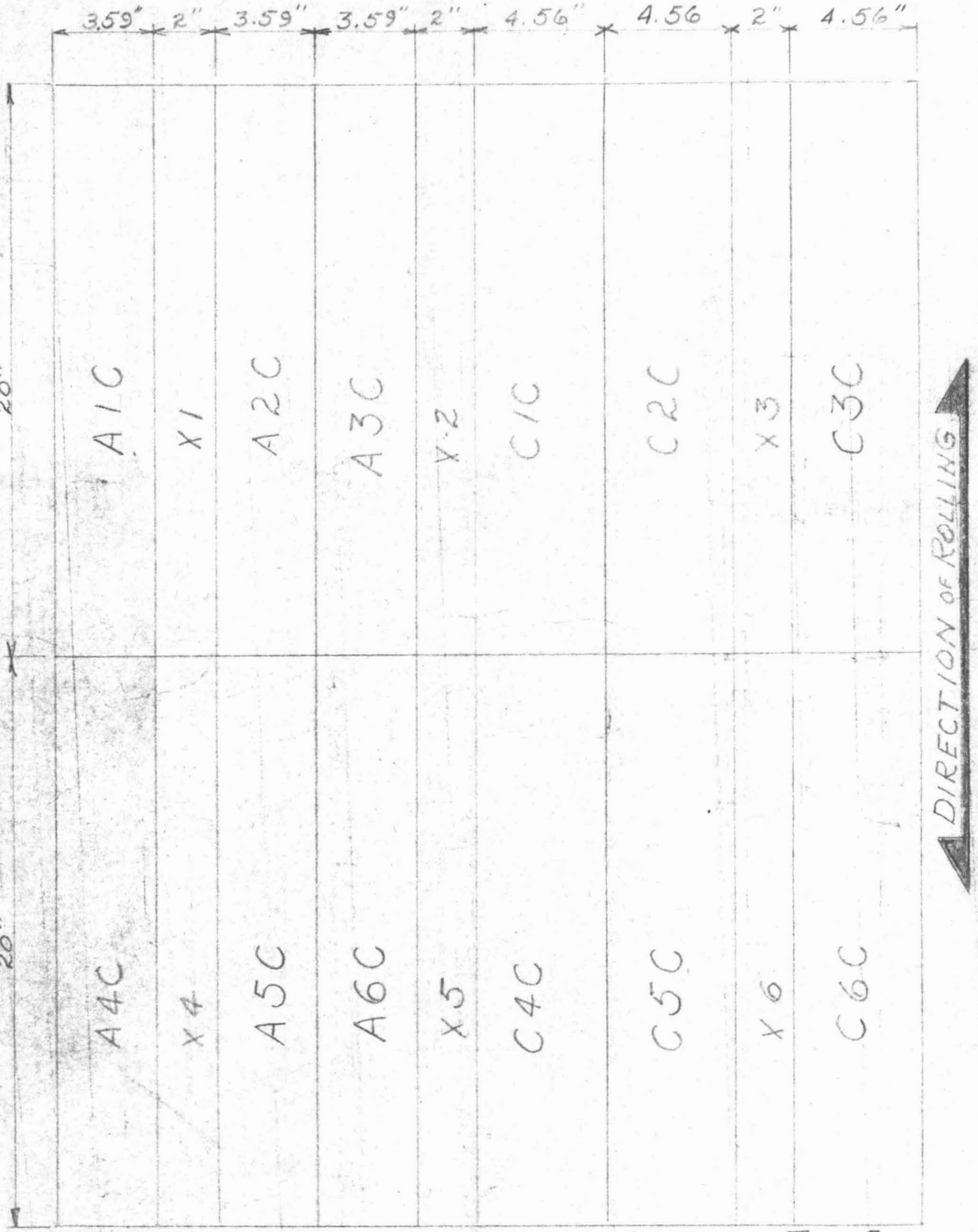


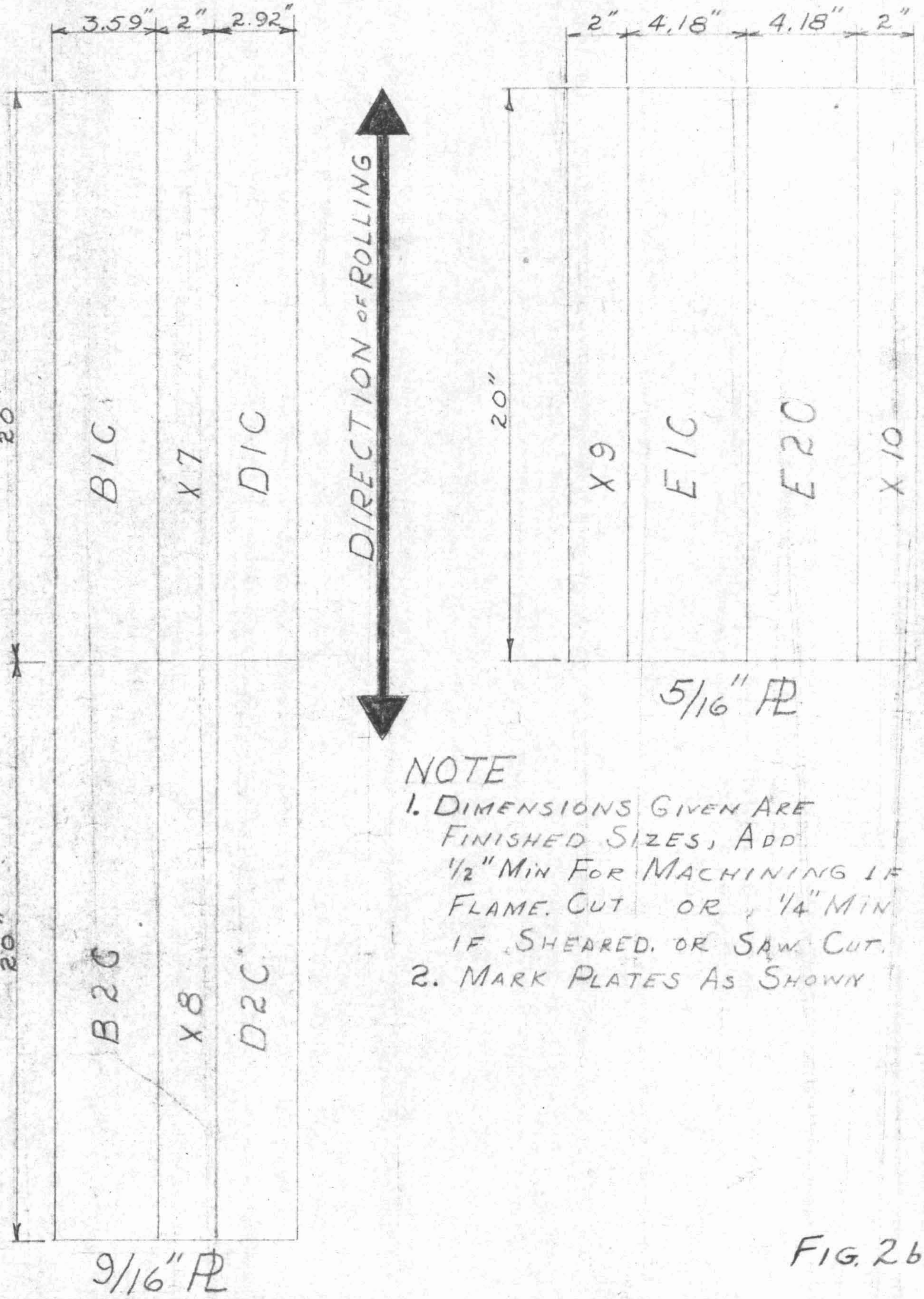
Fig 2a

IMPORTANT- FOR NOTES REFER TO DR'W'G. No J-3

7/16" PLATE LAYOUT
LEHIGH UNIVERSITY PROJECT 243
2-28-54 DRAWN BY - JRP - W.H.L. APPROVED

J-2

FIG. 2a



NOTE

1. DIMENSIONS GIVEN ARE FINISHED SIZES, ADD 1/2" MIN FOR MACHINING IF FLAME CUT OR , 1/4" MIN IF SHEARED OR SAW CUT.
2. MARK PLATES AS SHOWN

FIG. 2b

9/16" & 5/16" PLATE LAYOUT LEHIGH UNIVERSITY PROJECT 243 2-28-54 DRAWN BY-JRP - W.H.L, APPROVED-	J-3

FIG. 2b

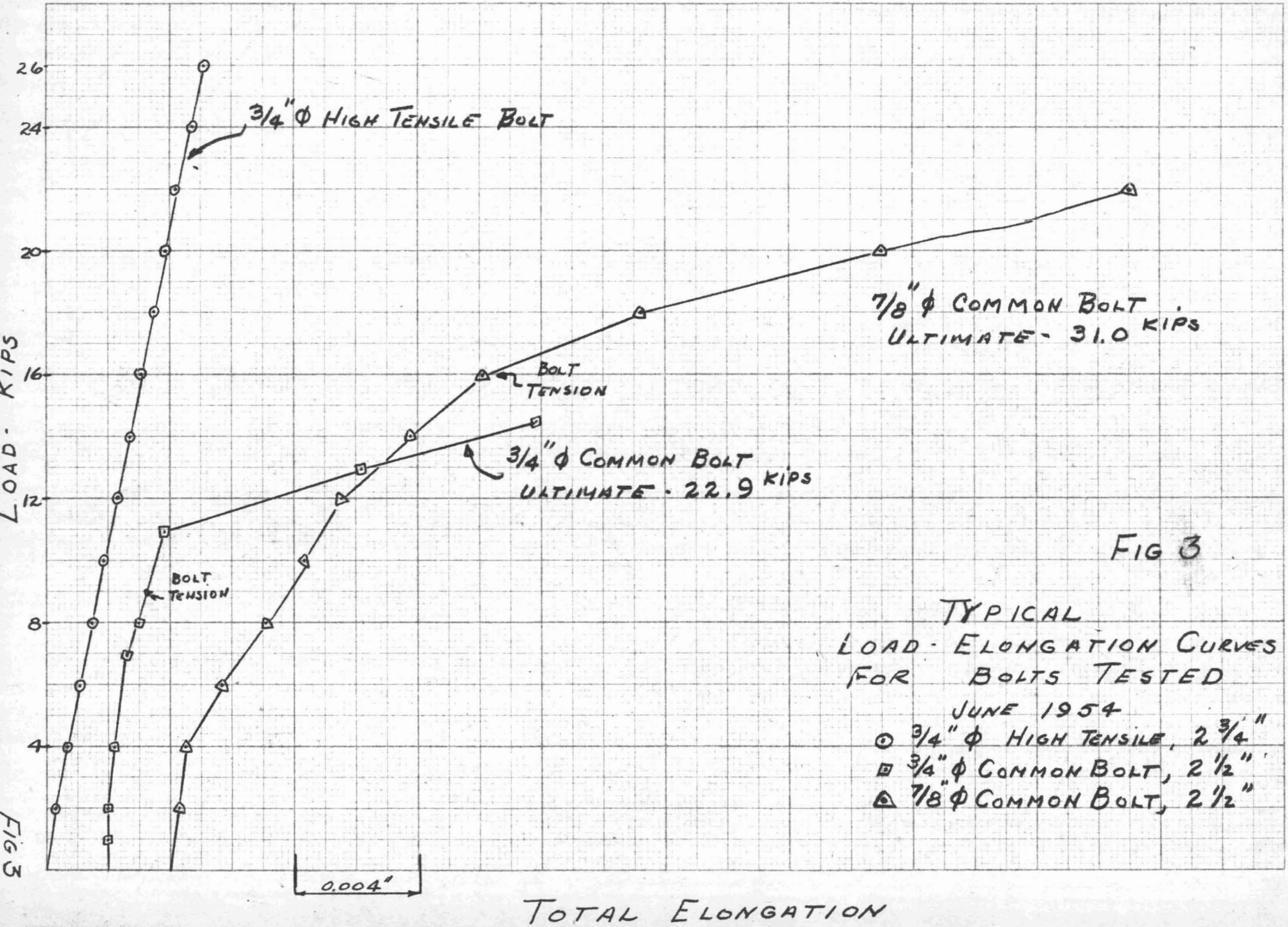

LOAD - KIPS
26
24
20
16
12
8
4
3/4" Φ HIGH TENSILE BOLT
7/8" Φ COMMON BOLT
ULTIMATE - 31.0 KIPS
BOLT TENSION
3/4" Φ COMMON BOLT
ULTIMATE - 22.9 KIPS
BOLT TENSION
0.004"
TOTAL ELONGATION
FIG 3
TYPICAL
LOAD - ELONGATION CURVES
FOR BOLTS TESTED
JUNE 1954
⊙ 3/4" Φ HIGH TENSILE, 2 3/4"
⊡ 3/4" Φ COMMON BOLT, 2 1/2"
△ 7/8" Φ COMMON BOLT, 2 1/2"

FIG 3

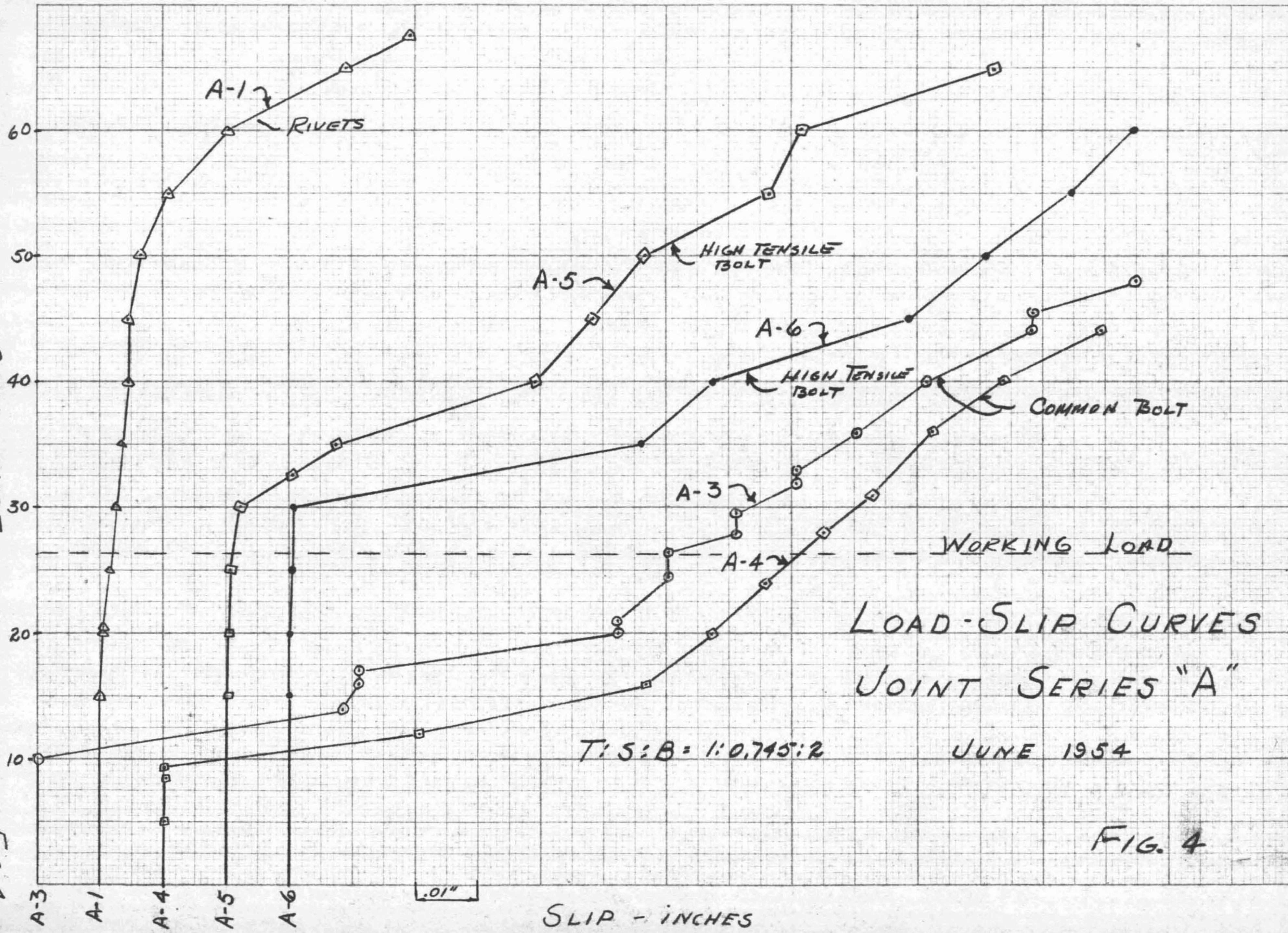

A-1
RIVETS
A-5
HIGH TENSILE BOLT
A-6
HIGH TENSILE BOLT
COMMON BOLT
A-3
A-4
WORKING LOAD
LOAD - KIPS
60
50
40
30
20
10
A-3
A-1
A-4
A-5
A-6
.01"
SLIP - INCHES
LOAD-SLIP CURVES
JOINT SERIES "A"
T: S: B = 1: 0.745: 2
JUNE 1954
FIG. 4

Fig 4

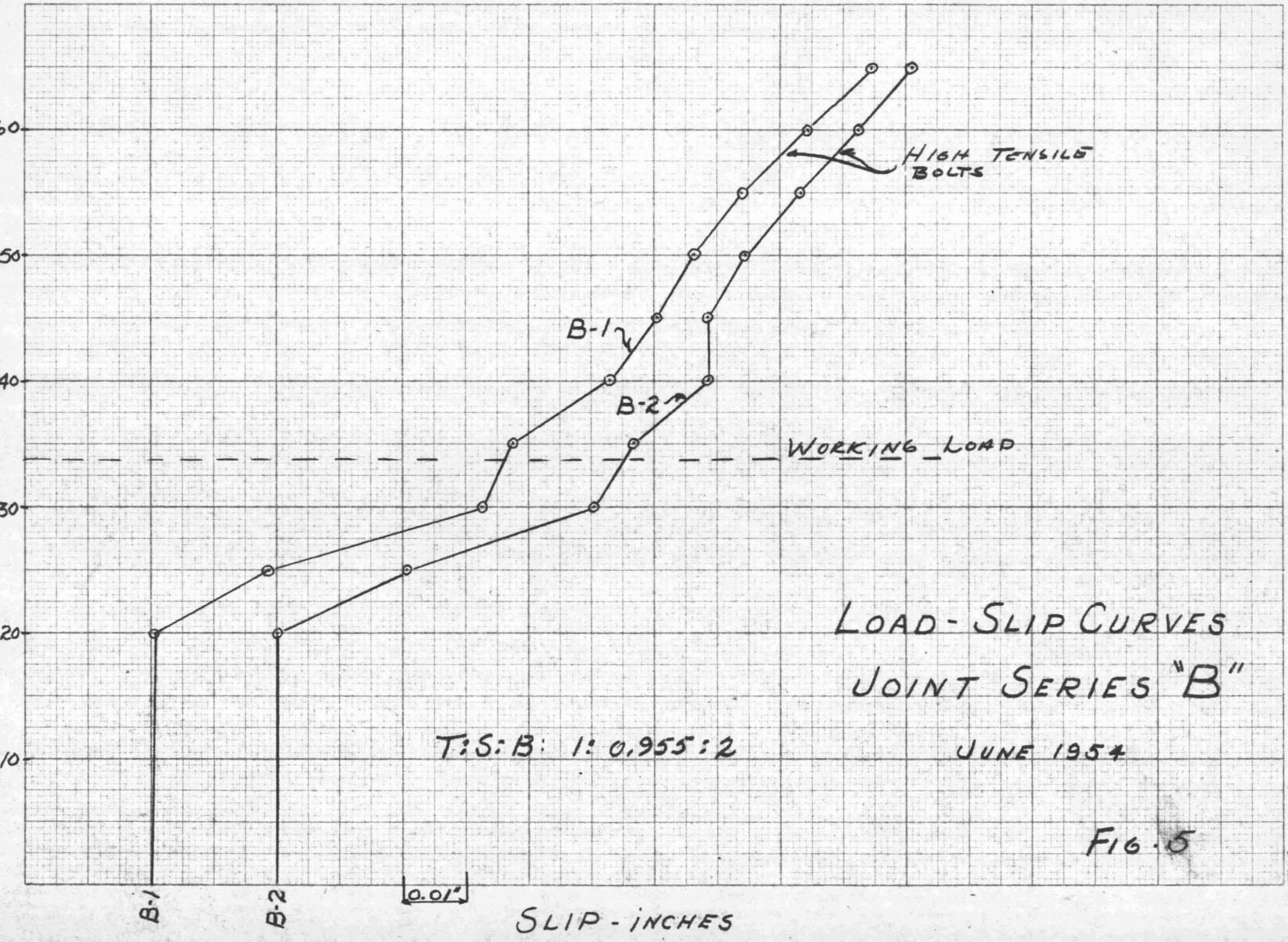

LOAD-SLIP CURVES
JOINT SERIES "B"
JUNE 1954
T:S:B: 1:0.955:2
HIGH TENSILE BOLTS
WORKING LOAD
B-1
B-2
LOAD - KIPS
SLIP - INCHES
0.01"
10
20
30
40
50
60

FIG. 5

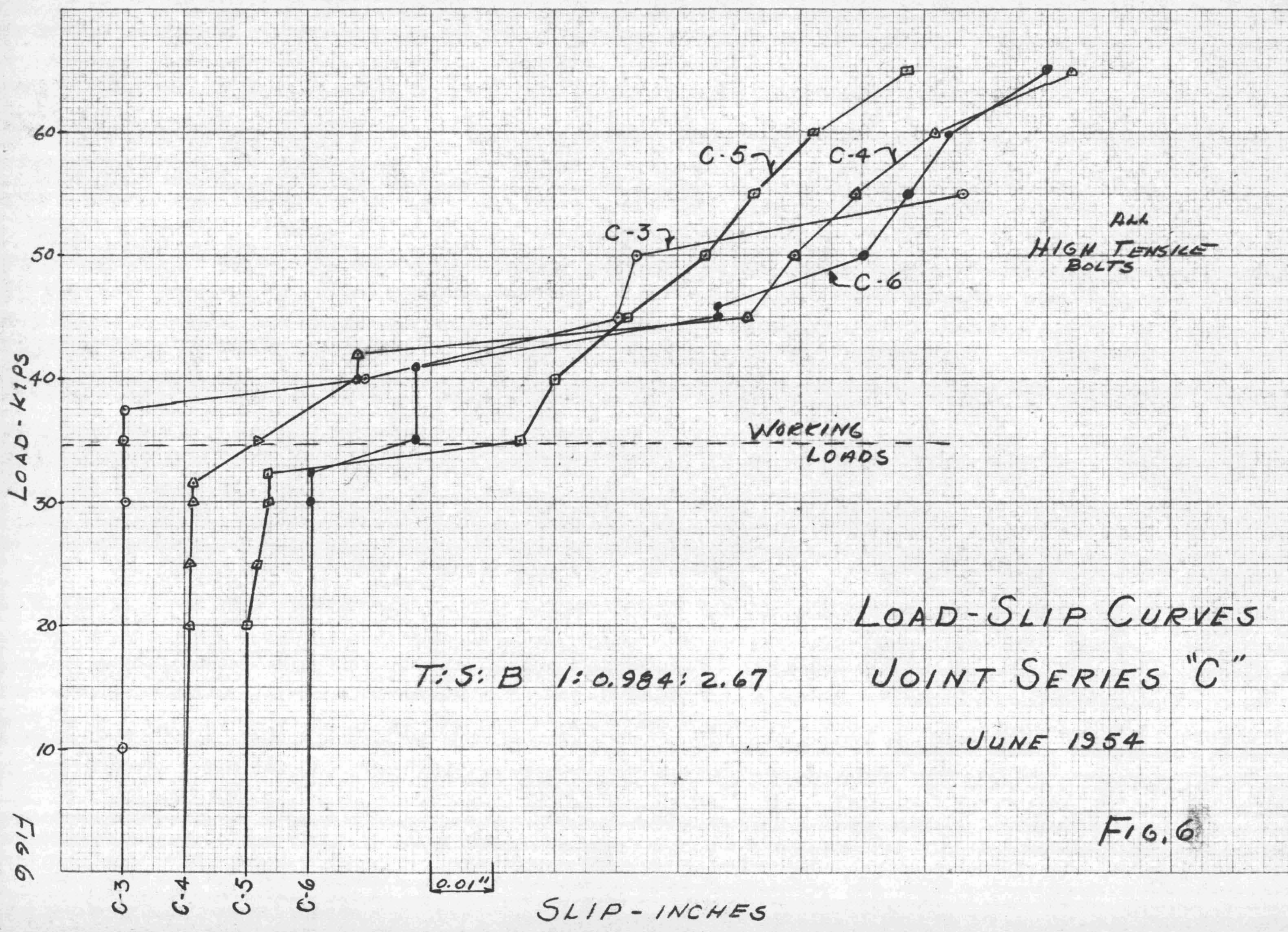

LOAD - KIPS
60
50
40
30
20
10
C-5
C-4
C-3
C-6
ALL
HIGH TENSILE
BOLTS
WORKING
LOADS
LOAD-SLIP CURVES
JOINT SERIES "C"
T:S:B 1:0.984:2.67
JUNE 1954
C-3
C-4
C-5
C-6
0.01"
SLIP - INCHES

FIG. 6

FIG 6

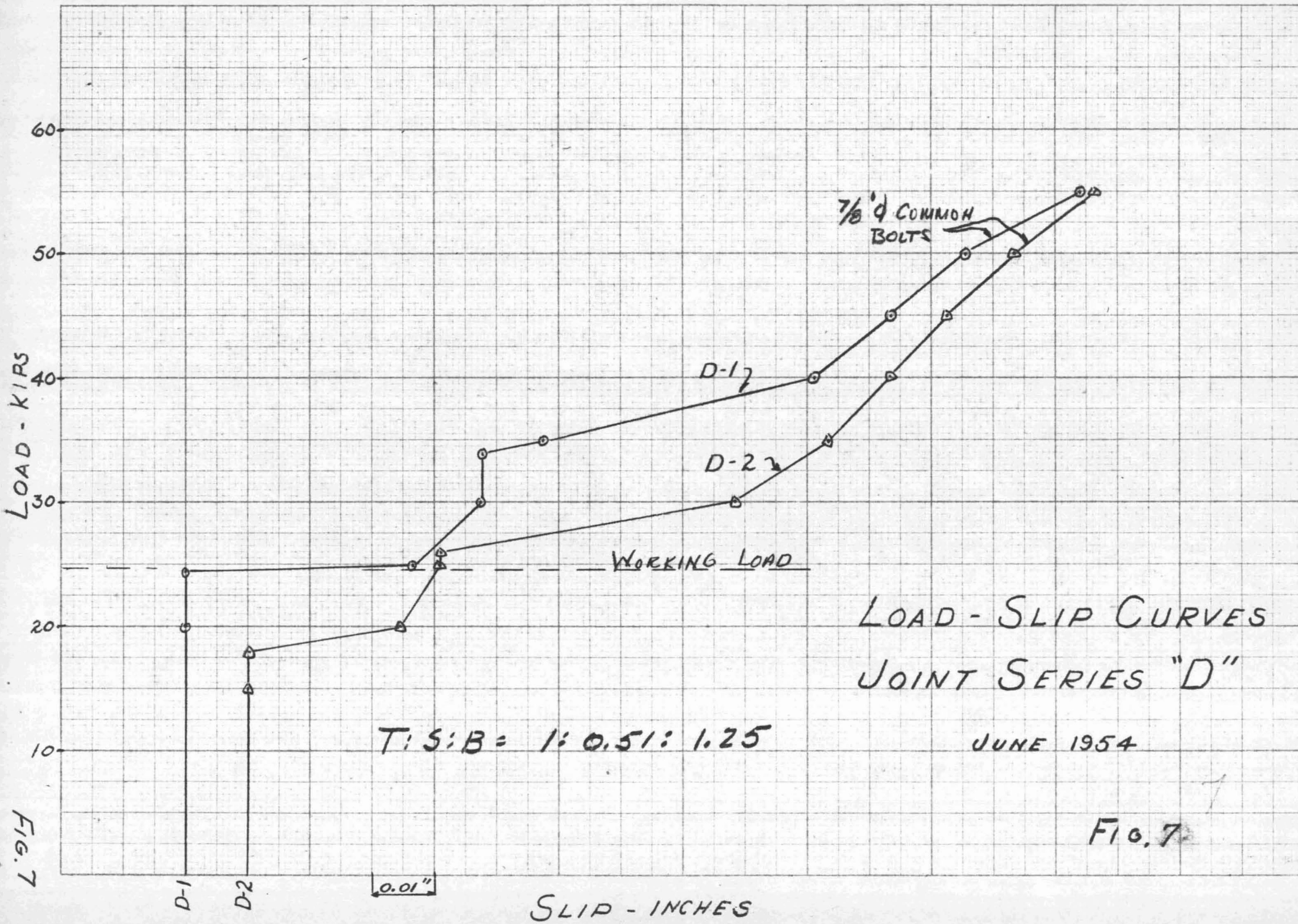
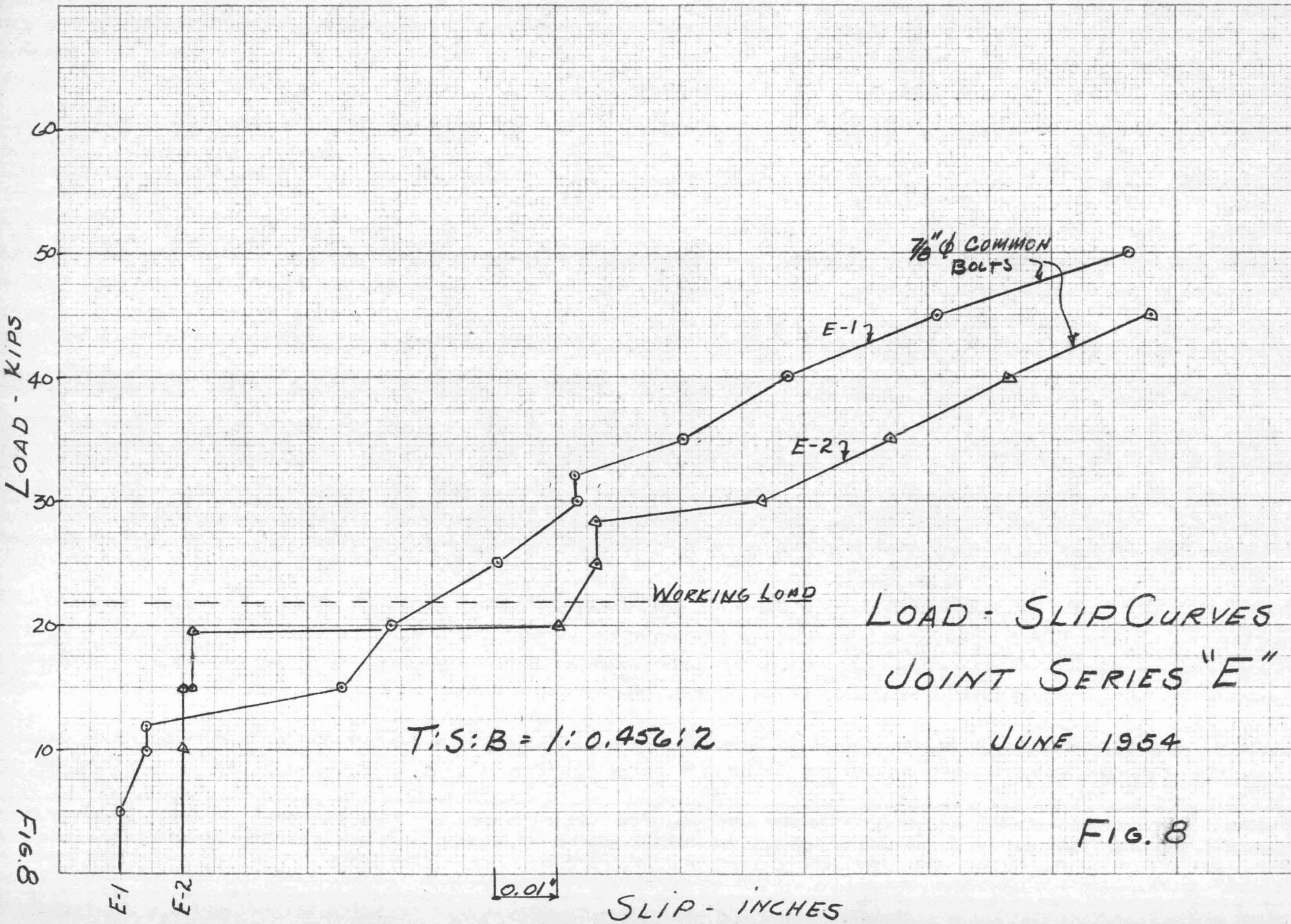
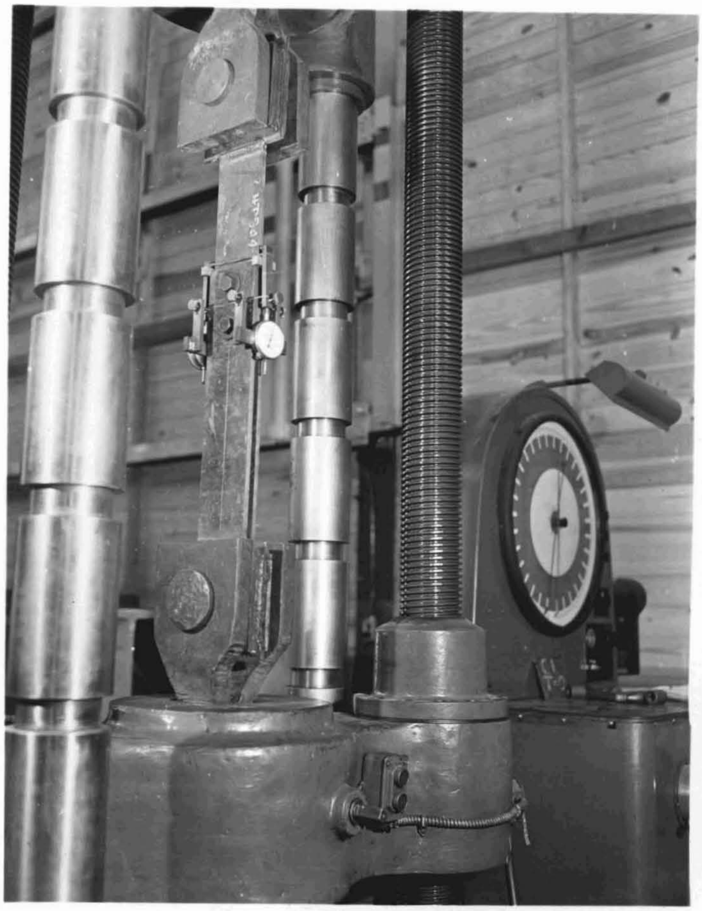

60
50
40
30
20
10
LOAD - KIPS
7/8" ∅ COMMON BOLTS
D-1
D-2
WORKING LOAD
LOAD - SLIP CURVES
JOINT SERIES "D"
T: S: B = 1: 0.51: 1.25
JUNE 1954
D-1
D-2
0.01"
SLIP - INCHES

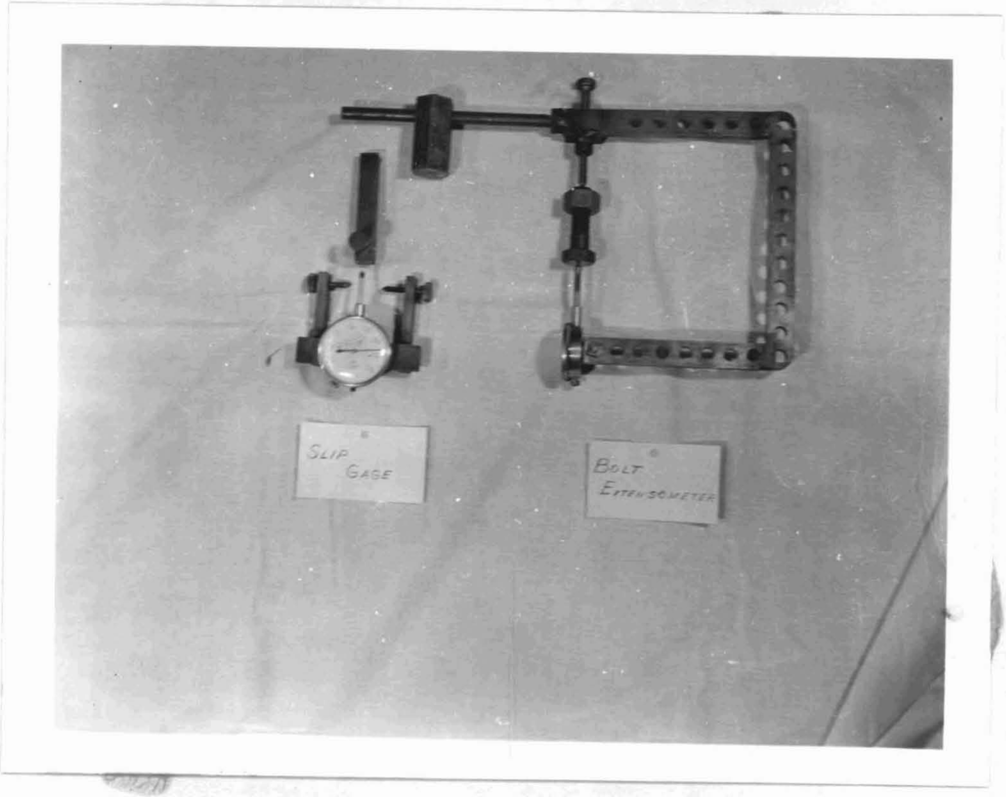
FIG. 7


LOAD - KIPS
60
50
40
30
20
10
7/8" ϕ COMMON BOLTS
E-1
E-2
WORKING LOAD
T:S:B = 1:0.456:2
0.01"
E-1
E-2
SLIP - INCHES
LOAD - SLIP CURVES
JOINT SERIES "E"
JUNE 1954
FIG. 8
FIG. 8



TEST SET-UP WITH SLIP GAGES

PHOTOGRAPH 1

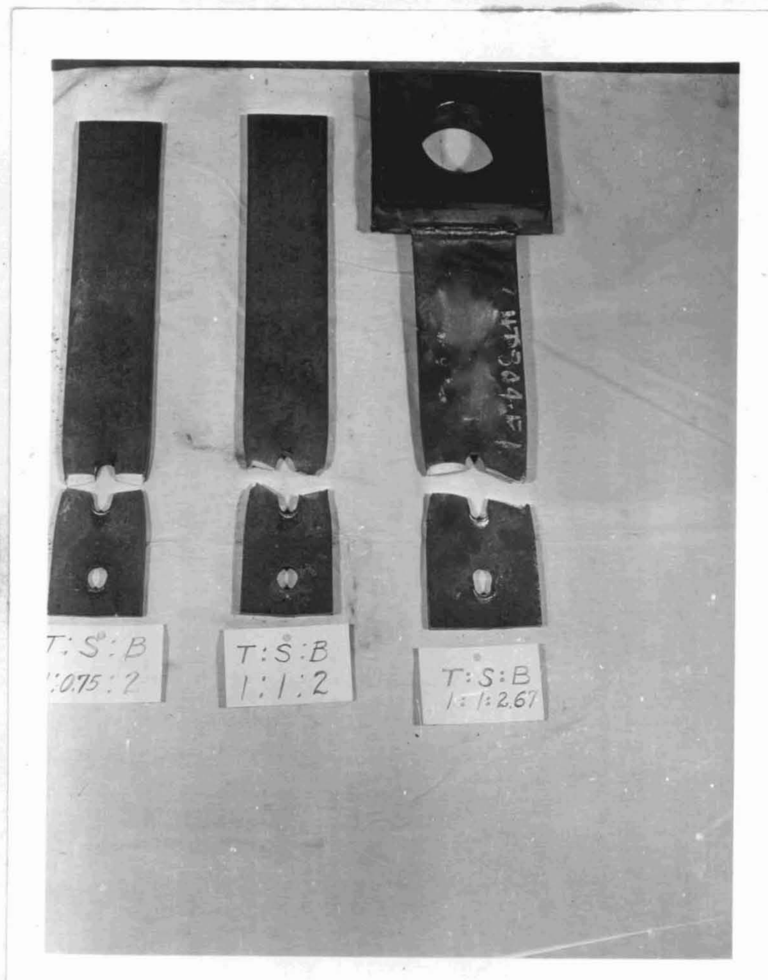


SPECIAL EQUIPMENT

PHOTOGRAPH 2

END TEAR OUT AND FAILURE WITH INCREASED EDGE DISTANCE

PHOTOGRAPH 3



FAILURES WITH VARYING T:S:B

PHOTOGRAPH 4

FAILURES WITH VARYING INITIAL BOLT TENSIONS

PHOTOGRAPH 5