Robert M. Mosborg

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LABORATORY TESTS OF STRUCTURAL JOINTS WITH OVER-STRESSED HIGH TENSILE STEEL BOLTS

By

JAMES R. FULLER and W. H. MUNSE

UNIVERSITY OF ILLINOIS
URBANA, ILLINOIS

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A Progress Report of an Investigation
Conducted by

THE UNIVERSITY OF ILLINOIS ENGINEERING EXPERIMENT STATION

in Cooperation with

THE RESEARCH COUNCIL ON RIVETED AND BOLTED STRUCTURAL JOINTS
THE ILLINOIS DIVISION OF HIGHWAYS
and
THE BUREAU OF PUBLIC ROADS

Project IV

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SYNOPSIS

This report summarizes the results of tests conducted on seven double-strap butt-type joints fastened with high tensile steel bolts. The bolts were torqued far into their plastic range. The joints were then subjected to fatigue and/or static loading to failure. The tests, although few in number, indicate quite clearly that for the type of joint tested, over-stressed high tensile steel bolts are not likely to fail in fatigue: nor is the static strength of the joints affected by the over-stressing of the bolts.

I. INTRODUCTION

In structural joints* fastened with high tensile steel bolts**, the load, in general, is resisted by the friction forces on the contact surfaces of the joints. However, for these joints to perform in this manner, at working loads, it is necessary that the bolts apply sufficient compressive force to the contact surfaces of the members to provide a transfer of load across the joint by friction. If the bolts are to supply these high compressive forces, with the accompanying large frictional resistance, they must be subjected to and maintain high axial tensions. These high initial bolt tensions are mandatory; techniques and devices for controlling them have been worked out in the laboratory and in the field.

On the other hand, what is the capacity of a joint with over-torqued high tensile steel bolts for resisting static or repeated loads? If the bolts are stressed far into their plastic range initially, will they fail in fatigue themselves as a result of repeated reversals of load on the joint?

If during a fatigue test the joint does not slip and the stresses in the bolts remain nearly constant, the bolts certainly would not be

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* Joints assembled in accordance with the specifications, "Assembly of Structural Joints Using High Tensile Steel Bolts", approved by Research Council on Bolted and Riveted Structural Joints of the Engineering Foundation, January 1951 and endorsed by the American Institute of Steel Construction and the Industrial Fasteners Institute.

** Bolts meeting ASTM Designation A325-49T for "Quenched and Tempered Steel Bolts and Studs".

expected to fail in fatigue. If, however, the joint slips such that some or all of the bolts are subjected to repeated bending and the plates to repeated bolt bearing, even though these bearing stresses account for only a fraction of the load applied (a substantial portion of the load will still be resisted by the high frictional resistance), there may be a possibility of failure in the bolts from repeated bending.

These are some of the questions which this series of tests was designed to study.

II. ACKNOWLEDGMENT

The study described in this report is part of an investigation conducted in the Engineering Experiment Station of the University of Illinois in cooperation with the Illinois Division of Highways, the Bureau of Public Roads, and the Research Council on Riveted and Bolted Structural Joints. It is part of the structural research program of the Department of Civil Engineering and is under the general direction of N. M. Newmark, Research Professor of Structural Engineering. The work was carried out by James R. Fuller and F. W. Schutz, Jr.[*], research assistants in Civil Engineering working under the direct supervision of W. H. Munse, Research Associate Professor of Civil Engineering.

The tests described in this report were planned in cooperation with the Project IV Committee of the Research Council on Riveted and Bolted Structural Joints. The members of the Project IV Committee are as follows:

W. C. Stewart, Chairman
Raymond Archibald
Frank Baron
J. S. Davey
R. A. Hechtman
T. R. Higgins
Jonathan Jones
J. J. Kelley
K. H. Lenzen
C. Neufeld
Joseph Matte, Jr.
W. H. Munse
N. M. Newmark
W. R. Penman
W. M. Wilson
L. T. Wyly

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[*] Presently, Assistant Professor of Civil Engineering, Lehigh University, Bethlehem, Pennsylvania.

III. MATERIALS

A. Description of Specimens

Details of the test specimens are shown in Fig. 1. All center plates were 3/4-in. and all side plates were 1/2-in. thick. The width of all joints at the critical section was 6 1/2 in. All plates were cut from the same parent plate of either 3/4 or 1/2-in. thickness. The bolt holes were drilled 15/16 in. in diameter, which was 1/16-in. larger than the nominal bolt diameter.

B. Properties of the Material

The tensile properties of the 3/4-in. plate material did not meet fully the requirements of ASTM Designation A7 for "Steel for Bridges and Buildings". The average tensile properties of the center-plate material as determined from tests of two standard coupons 1 1/2 in. wide were as follows:

Yield Point	30,480 psi
Tensile Strength	54,550 psi
Reduction of Area	61.6 per cent
Elongation in 8-in. gage length	36.1 per cent

C. Description of Bolts

The bolts used in the investigation were of the type furnished under ASTM Designation A325-49T for "Quenched and Tempered Steel Bolts and Studs". All bolts were 7/8-in. nominal diameter, 6-in. long, and had a 1 3/8-in. plain shank. All washers were carburized, had a 2 1/4-in. outside diameter, 15/16-in. inside diameter, and were approximately 0.17-in. thick. A washer was installed under each nut and bolt head.

after torquing is illustrated in the center of Fig. 3. Photographs of a calibration bolt after rupture and an over-torqued bolt assembled with a nut and washer are also shown in Fig. 3. The photograph of the "Bolt Assembly" shows the position of the necked-down section in relation to the washers which are set at the proper grip of 1 3/4 in.

On torquing, the bolt shanks necked down such that the shank threads at the face of the nut were only partly in contact with the first nut threads. Consequently, the threads farther back in the nut resisted most of the bolt tension. The average reduction of area at the necked-down section of the over-stressed bolts was about 10 per cent. This was based on the mean diameter of the threaded section.

V. STATIC TESTS

Two joints of this series, BOS-5 and BOS-6, were tested statically to failure. BOS-5 was tested first in fatigue for 2,000,000 cycles at 0 to 30,000 psi tension without any apparent signs of failure. This specimen had small weld beads which had been placed on the contact surfaces of the side plates 1/4 in. below both rows of holes. The beads extended across the joint, normal to the direction of loading, and to within 1/4 in. of the edges of the joint. The position of the bead indentations on the center plate of BOS-5 are shown in Fig. 4. The results of the fatigue test on this joint will be discussed later; however, it might be mentioned that the slip per cycle was much less than 0.001 in. from the beginning of the fatigue test, in spite of the high value of average applied stress.

The load-slip characteristics of joint BOS-5, in the static test, were as might be expected (See Fig. 5). The hard weld beads prevented sudden slip in the joint because the beads had been embedded in the center-plate during the bolt torquing. This embed~~d~~ment acted as a definite "key", particularly, in the vicinity of the bolts. The first significant slip in this joint occurred at a stress of 34,500 psi on the net section. At this point the specimen continued to take more load but at a much slower rate. Finally, the bolts were eased into bearing, with no apparent discontinuity in the load-slip relationship.

Specimen BOS-5 exhibited general yielding at a load of 159,000 lb. This load corresponds to a nominal unit stress on the net section of 45,000 psi. The maximum load carried by this specimen was 212,800 lb. which corresponds to a stress of 60,400 psi.

Specimen BOS-6 had no previous stress history; it was subjected to static loading only. The contact surfaces were clean mill-scale. First slip in this joint was about 0.002 in. at a load of 95,000 lb. or 26,800 psi. This was followed by a slip of approximately 0.02 in. at a load of 98,500 lb. or 27,900 psi. As more load was imposed on the specimen, the joint slipped again bringing all of the bolts into bearing. It is believed that the bolts were in bearing at a load of 125,000 lb. or 35,400 psi and a total slip of 0.068 in. After the bolts were in bearing, the load on specimen BOS-6 increased continuously until it reached a maximum of 206,500 lb. or 58,300 psi. Thus, the joint with the weld beads, in spite of its previous fatigue testing, exhibited the greater maximum static strength.

VI. FATIGUE TESTS

The fatigue tests were conducted in the 200,000 lb. fatigue testing machines shown in Fig. 6. These machines are of the lever type and are described in University of Illinois Engineering Experiment Station Bulletin 302.

A. Method of Assembly

The joints were assembled prior to their installation in the fatigue machine. They were then properly aligned and each bolt was torqued-up manually with a wrench having a 5-ft. long extension handle. The bolt elongations were measured during the torquing with the gage shown in Fig. 7. The torquing was discontinued after the bolts had shown an elongation of approximately 500 divisions on the gage. This corresponds to an extension of the bolt of approximately 0.104 in. and required about 1 1/2 turns of the nut. As stated previously, something slightly greater than 2 turns of the nut, after it is hand-tight, would be required to break the bolt.

B. Results of Fatigue Tests

The results of the fatigue tests are summarized in the Table 1. Joint BOS-1 was tested on a stress cycle of 22,840 psi tension to an equal compression and failed at 1,206,000 cycles by fracturing across the first row of bolt holes in the center-plate.

Two other specimens, BOS-3 and BOS-4, were also tested on a stress cycle of complete reversal. BOS-4 was tested at 20,000 psi, and did not fail in 2,083,000 cycles. However, BOS-3, tested at the same stress cycle, failed after 4,405,000 cycles.

Specimen BOS-2 was assembled with a thick coating of gun grease (cosmoline) on the contact surfaces. As the bolts were tightened, much of this grease was squeezed out. The specimen was then tested at a number of different stress ranges. It was first subjected to a 0 to 30,000 psi tension cycle for a total of 2,130,000 cycles. The machine was next set to run on a cycle of complete reversal at 20,000 psi. However, while the machine was being turned over by hand during the load setting operations, the specimen slipped back and forth about 0.025 in. The stress cycle was then reduced to ±15,000 psi and maintained for 31,000 cycles. At this point the stress range was increased to ±20,000 psi. After an additional 2,168,000 cycles, or a total of 4,329,000 cycles, the specimen fractured through the first row of bolt holes in the center-plate. This agrees favorably with the results from specimen BOS-3, which failed after 4,405,000 cycles at a stress range of ±20,000 psi. It might be noted that the stress cycle of 0 to 30,000 psi in tension was approximately equal, in its effects, to a stress cycle of ±20,000 psi. This is in agreement with results obtained previously in other investigations.

Specimens BOS-5 and BOS-6 were tested statically and have previously been discussed as such. Specimen BOS-5, however, was first tested in fatigue on a stress cycle of 0 to 30,000 psi tension for 2,000,000 cycles without failure or any visible signs of damage. It was noticed, however, that the elongation of the bolts had increased.

The bolt elongations were not greatly affected during the fatigue tests for the specimens without the weld beads. However, the bolt elongations in BOS-5, the specimen with the weld beads, increased considerably during the fatigue test. The average bolt elongation in BOS-5 after torquing was 0.1150 in., and after the fatigue test it was 0.1257 in. This increase, it is thought, resulted when the joint was loaded in tension and the weld beads slid-up out of the indentations they had produced in the center-plate of the joint.

Specimen BOS-7 was tested initially in fatigue on a cycle of 0 to 30,000 psi tension. It had clean mill-scale contact surfaces. At the end of 1,973,000 cycles the specimen showed no signs of distress. The top edges of the side plates were then covered with a No. 10 cutting oil, so that the oil could seep down between the plates, thus saturating the contact surfaces. The oil pools were held on top of the 1/2-in. side plates by the surface tension of the oil itself, although the pools would disappear after about 2 hours. Insofar as possible, the oil pools were replenished whenever the specimen ran dry. After 364,000 additional cycles on a stress cycle of 0 to 30,000 psi, with oil on the joint, the stress cycle was changed to ±20,000 psi. The specimen was subjected to this stress cycle for an additional 210,000 cycles. The machine was then reset to a cycle of ±30,000 psi. After 17,000 cycles had been accrued at this setting, the specimen failed at the first row of bolt holes in the center plate. During the 0 to ±30,000 psi and the ±20,000 psi testing no significant slip was detectable.

C. Detection of Fatigue Cracks

Figure 8 shows the detectable fatigue damage in some of the specimens of the series. BOS-2 is shown rough-ground only because no cracks other than the final failure crack were detected. BOS-7 showed no signs of fatigue distress and was not photographed. BOS-5 and BOS-6 were static specimens and are shown separately in Fig. 4.

The photograph in the upper left-hand corner of Fig. 8 shows specimen BOS-1 after the surface of the plate at the critical section had been polished. The cracks in this specimen were not discernible until the mill-scale had been removed. However, after polishing, the fine fatigue cracks in front of the bolt holes were visible to the naked eye. The two photographs to the right show both sides of the center-plate of BOS-1; the cracks have been clarified by using "Dy-Chek"*. Both sides of the center-plate of specimen BOS-3 are also shown in Fig. 8 and exhibit pronounced fatigue cracks. Cracks were found only on one side of the center-plate of specimen BOS-4.

It may be noted that the cracks do not have their origin at the bolt holes. The average distance from the midpoints of the small unpropagated cracks to the edge of the bolt holes was determined as 0.58 in. This would indicate that the average crack was about 1/8 in. inside of the outside edge of the washer in the center-plate. The average crack also seemed to lay on a line inclined at about 33° with the vertical from the outside edge of bearing surface of the nut or bolt head.

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* A commercial dye penetrant.

VII. CONCLUSIONS

At no time during any of the fatigue testing was there any signs of impending fatigue failure in the bolts. The bolt elongations, after the fatigue tests, were essentially the same as the initial bolt elongations except in specimen BOS-5. This would indicate that the initial bolt tensions were maintained relatively constant during the fatigue tests.

Under these high bolt tensions, it is very likely that the "interlocking action" of the irregularities of the mill-scale contact surfaces prevented slip from occurring at the test loads even though the contact surfaces, in one case, were greased before assembly. Slip occurred in the greased specimen only after a ±20,000 psi stress cycle had been applied and in an oiled specimen only after a ±30,000 psi stress cycle had been applied.

In the static test of BOS-6, the irregularities in the mill-scale seemed to act as shear connectors. This joint effectively resisted without appreciable slip, one applied load which produced a stress of 26,800 psi on the net section. The weld beads on specimen BOS-5 increased the resistance of the joint to slip such that the initial slip did not occur until the stress on the net section was 34,500 psi.

TABLE 1

RESULTS OF FATIGUE TESTS

Specimen Number	Tensile Stress psi*	Compression Stress psi*	Cycles in 1000's	Total Cumulative Cycles in 1000's	Average Cumulative Slip at Start of Test in.	Average Cumulative Slip During Test in.	Average Cumulative Slip at Finish of Test in.	Condition of Contact Surfaces**
BOS-1	22.8	22.8	1,206	1,206	0	0	0	M.S.
BOS-2	30.0	0	2,130	2,130	.020	0	.020	M.S.G.
	20.0	20.0	0	2,130	.020	.012	.008	M.S.G.
	15.0	15.0	31	2,161	.008	0	.008	M.S.G.
	20.0	20.0	2,168	4,329	.008	.002	.010	M.S.G.
BOS-3	20.0	20.0	4,405	4,405	0	0	0	M.S.
BOS-4	20.0	20.0	2,083	2,083	0	0	0	M.S.
BOS-5	30.0	0	2,000	2,000	0	.001	.001	M.S.W.
BOS-7	30.0	0	1,973	1,973	.001	.009	.005	M.S.
	30.0	0	364	2,337	.005	.001	.004	M.S.O.
	20.0	20.0	210	2,547	.004	0	.004	M.S.O.
	30.0	30.0	17	2,564	.004	.004	0	M.S.O.

* Stresses based on net section of joint.

** M.S. Mill Scale
M.S.G. Mill Scale Greased
M.S.W. Mill Scale with Weld Beads
M.S.O. Mill Scale Oiled

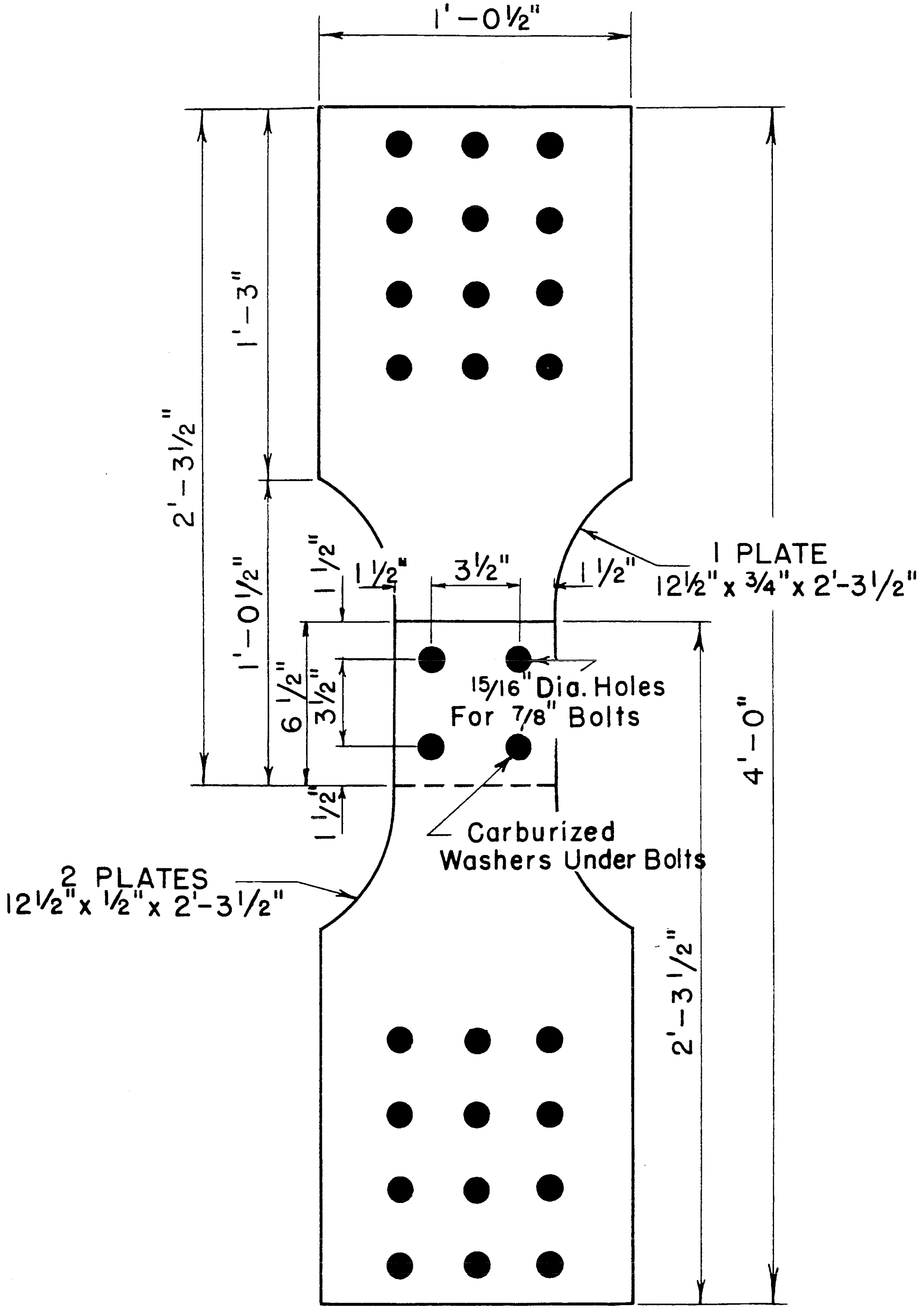


FIG. 1 BOLTED TEST SPECIMENS, BOS SERIES

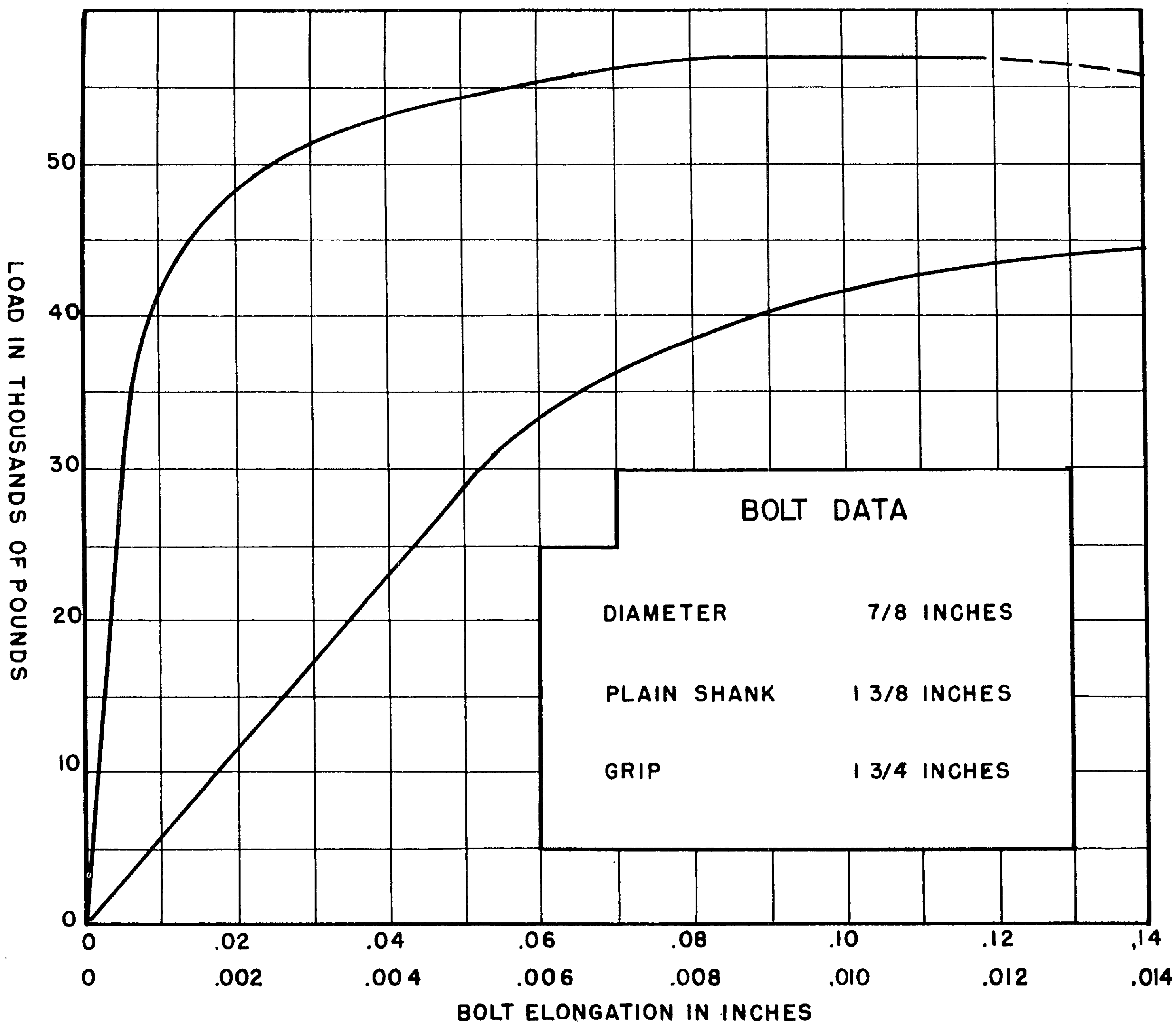
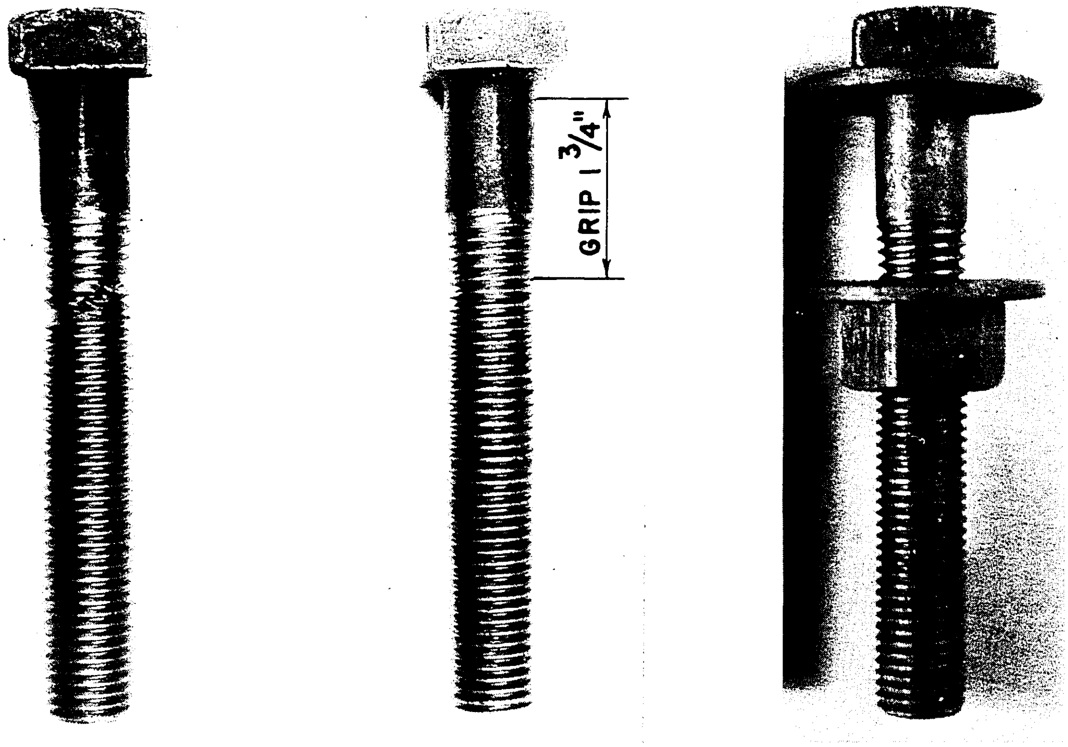


FIG. 2 LOAD-ELONGATION BOLT CALIBRATION CURVE

FOR BOLTS OF BOS SERIES



CALIBRATION
BOLT

BOLT TORQUED IN
SPECIMEN

BOLT
ASSEMBLY

FIG. 3 OVER-STRESSED BOLTS

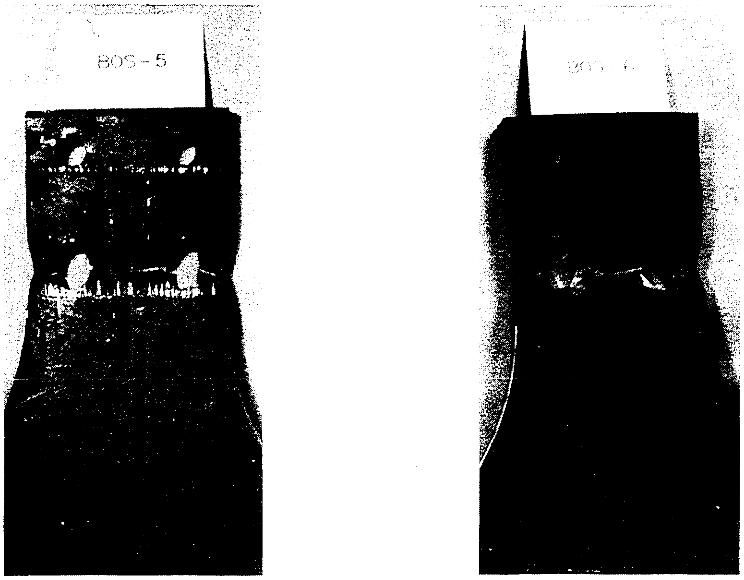
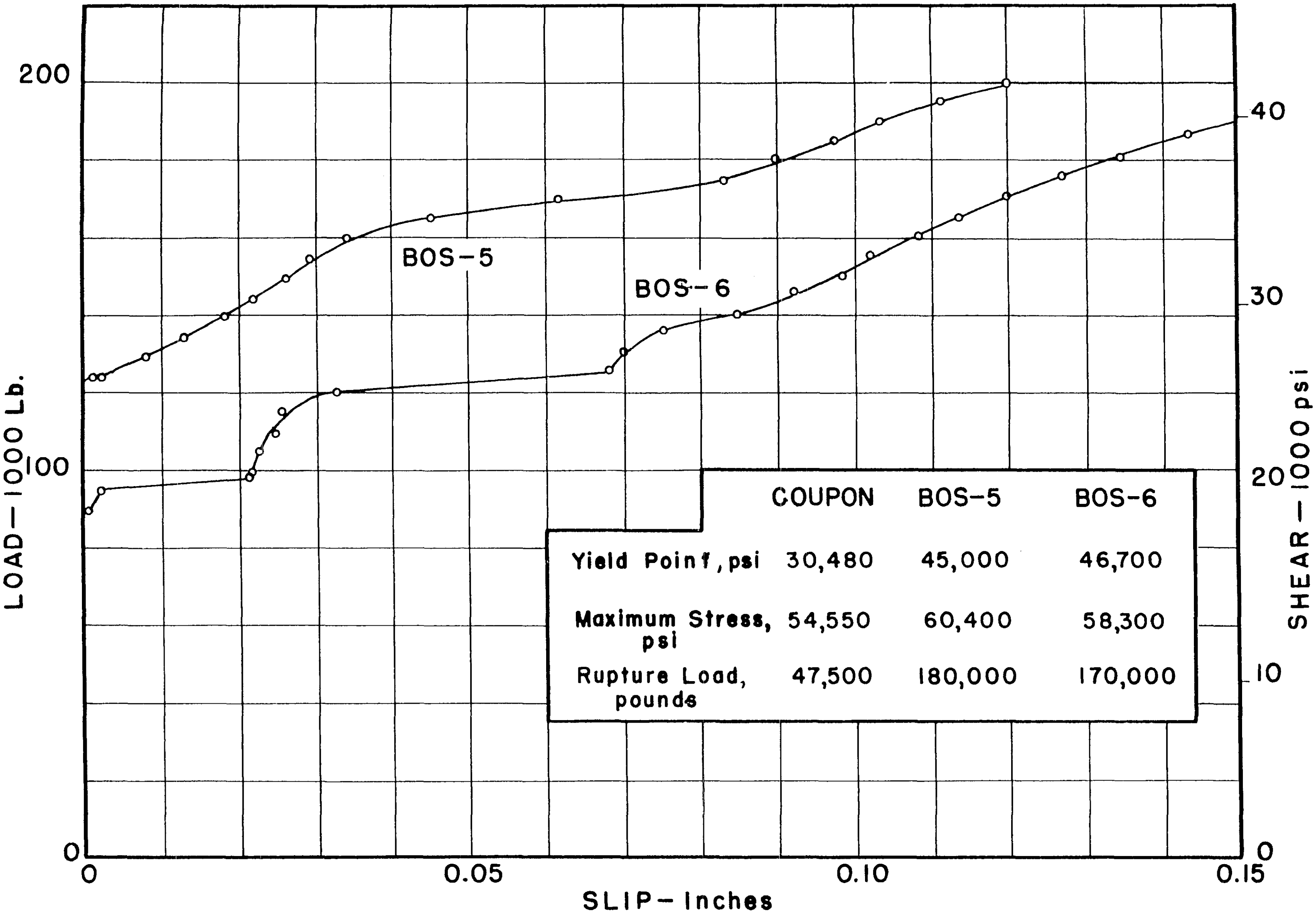


FIG. 4 STATIC TEST SPECIMENS



	COUPON	BOS-5	BOS-6
Yield Point, psi	30,480	45,000	46,700
Maximum Stress, psi	54,550	60,400	58,300
Rupture Load, pounds	47,500	180,000	170,000

FIG. 5 LOAD—SLIP CURVES
FOR STATIC TESTS

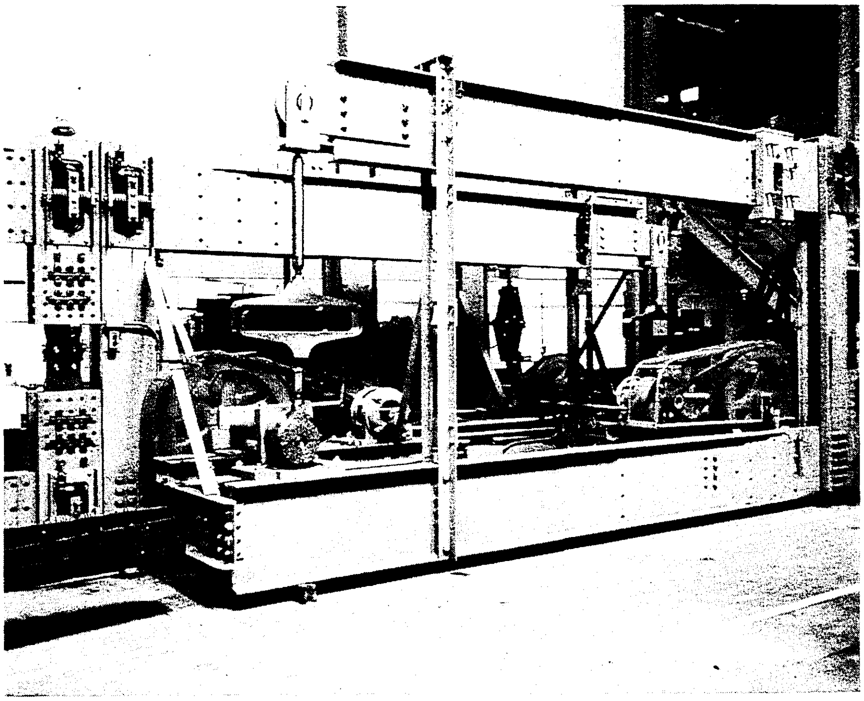


FIG. 6 200,000 FATIGUE TESTING MACHINE

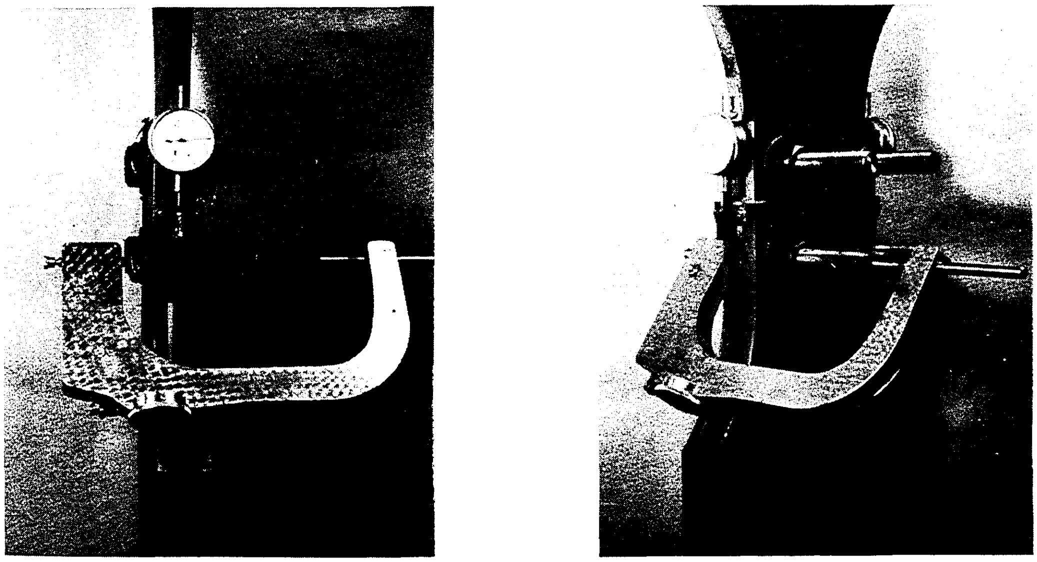


FIG. 7 TEST SET-UP

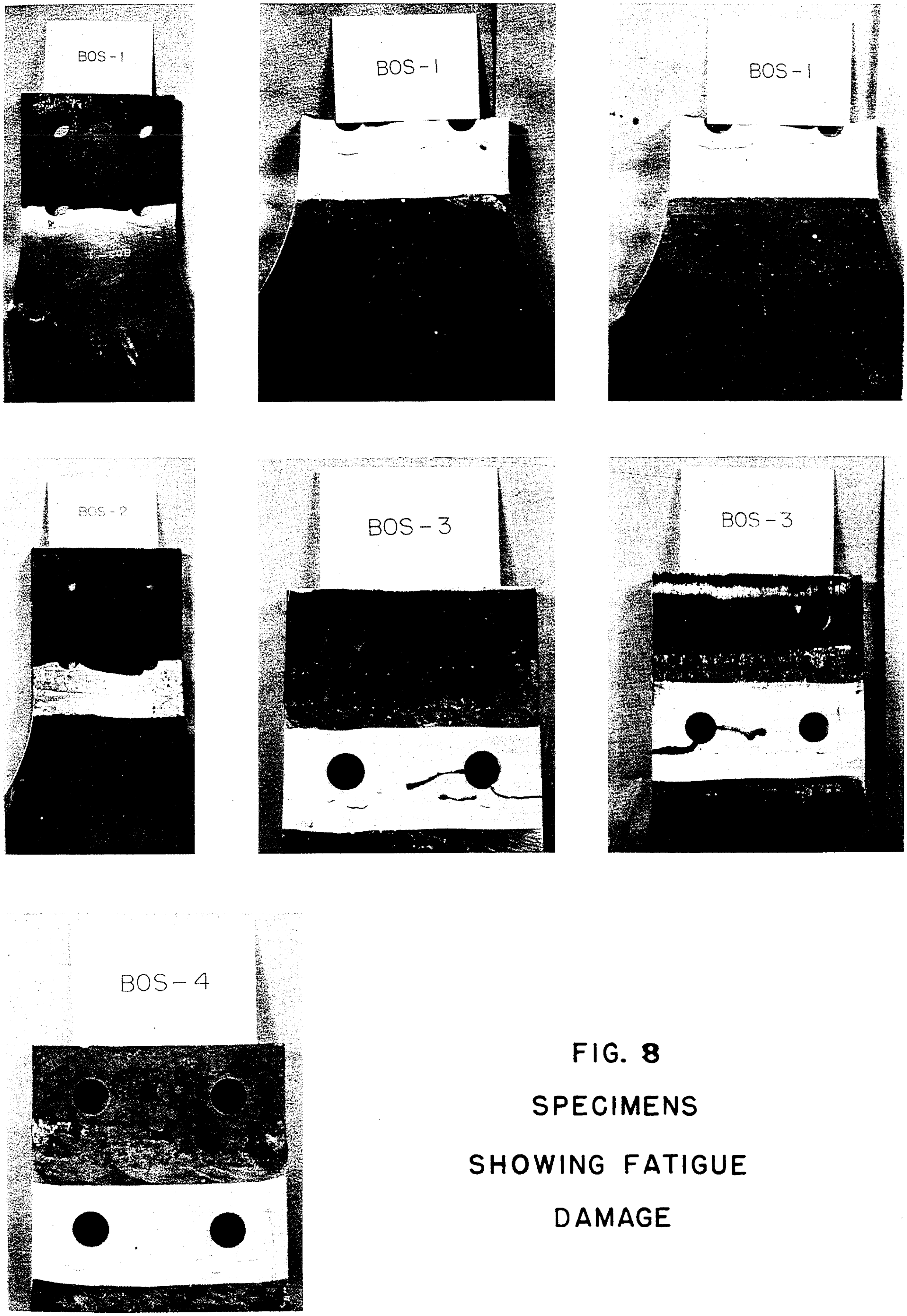


FIG. 8
SPECIMENS
SHOWING FATIGUE
DAMAGE