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# EFFECTS OF REPEATED LOADINGS ON STRUCTURAL CONNECTIONS WITH HIGH-STRENGTH BOLTS

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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 Department of Commerce, Bureau of Public Roads

Project IV

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# SYNOPSIS

The tests reported herein were conducted to study the effects of repeated loadings on structural connections. Two types of specimens were used: 6-in. 12.5-lb. I-sections connected at the flanges to 5/8 in. gusset plates, and T-sections fabricated from 18-in. 54.7 lb. I-sections and connected at the flanges to 1-in. gusset plates. Rivets or high strength bolts were used as the fasteners. It has been found that, in general, the fatigue strength of tension members with bolted connections and flexural members with bolted partial length cover plates may be expected to be somewhat greater than that of similar riveted members.

# I. INTRODUCTION

## 1. Object and Scope of Investigation

The investigation reported herein was conducted to study the behavior of bolted structural connections subjected to repeated loads. To date, many fatigue tests have been conducted on connections fabricated with flat plates, but only a very few have been conducted on connections of rolled structural sections. Therefore, one of the principal objectives of these tests was to study the effect of repeated loads on connections of rolled sections.

If current specifications for the use of high strength bolts* are followed, beveled washers are required for bolted connections of standard I-sections because of the 1:6 slope of the flanges. However, there is little or no data to show that these washers are always necessary. To obtain information concerning the effect of and the need for the beveled washers, part of the specimens of this study were assembled with bolts having only flat washers against the sloping flanges. The balance of the bolted members were assembled with beveled washers in accordance with the present recommended practice. This provides the second major objective of the present study: to study the need for beveled washers in bolted connections of standard I-sections.

Two types of specimens were tested: small 6-in. I-sections, and T-sections cut from 18-in. I-sections. The 6-in. I-section was the

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*"Specifications for Assembly of Structural Joints Using High Strength Bolts" approved February 27, 1954 by Research Council on Riveted and Bolted Structural Joints.

largest that could be accommodated in the fatigue testing machines available for this study. However, in using this type of specimen, a small but complete truss-type connection could be tested. The T-sections were used to study the behavior of a larger section using larger bolts.

Three types of 5/8-in. fasteners were used in the 6-in. I-section specimens: rivets, bolts with plain washers against the sloping flanges, and bolts with beveled washers against the flanges. The larger T-sections were assembled with two types of 7/8-in. fasteners: bolts with plain washers and bolts with beveled washers under the bolt heads. The T-sections, being larger, provided a better opportunity to study the fastener detail and its effect on the fatigue resistance of the section. Also, because of the bending in the T-sections, an indication is obtained of the fatigue resistance one may expect at the end of a cover plate of a flexural member.

## 2. Acknowledgements

The tests described in this report are a part of an investigation resulting from a cooperative agreement between the Engineering Experiment Station of the University of Illinois, the Illinois Division of Highways, the Department of Commerce, Bureau of Public Roads, and the Research Council on Riveted and Bolted Structural Joints. This study is a part of the structural research program of the Department of Civil Engineering under the general direction of N. M. Newmark, Research Professor of Structural Engineering, and was carried out by W. S. Beam, Research Assistant in Civil Engineering, working under the direct supervision of W. H. Munse, Research Associate Professor of Civil Engineering. J. R. Fuller, Research Assistant, and T. F. Leahey, former Research Assistant, conducted the fatigue tests of

the riveted 6-in. I-section specimens and supervised a part of the specimen fabrication. The specimens for this study, except for the riveting, were fabricated by the laboratory mechanics of the Structural Research Laboratory at the University.

The tests described in this report were approved by the Project 4 Committee of the Research Council. This committee is concerned with the "Fatigue Strength of Bolted Structural Joints." The members of the Committee are as follows:

W. C. Stewart, Chairman
Raymond Archibald
E. F. Ball
Frank Baron
J. S. Davey
R. A. Hechtman
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Jonathan Jones
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L. T. Wyly

# II. DESCRIPTION OF SPECIMENS AND TESTS

## 3. I-Sections

Three groups of small truss-type specimens were fabricated from 6-in. 12.5 lb. I-sections. One specimen from each group was tested statically and the remaining four specimens of the group were tested in fatigue. These specimens, having a tension-shear ratio of 1.0:0.75, were designed to fail through the first transverse row of fasteners of the 6-in. I-section.

Figure 1a shows the details of the I-section specimens. The fasteners in the two joints of each specimen were arranged in two lines* on a 2-in. gage and in three rows at a pitch of 2 1/2-in. All holes were drilled 11/16-in. in diameter while the parts were clamped together to ensure good alignment of the holes during final assembly of the members.

The specimens of Series R6** were fabricated with 5/8-in. rivets conforming to ASTM Designation A141, while the specimens of Series B6 and P6 were fabricated with high strength bolts meeting ASTM Designation A-325. The specimens of Series B6 were designed in accordance with the Specification for the Assembly of Bolted Structural Joints as approved by the Research Council on Riveted and Bolted Structural Joints in February 1954. Hardened

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* A line of fasteners is referred to herein as a series of fasteners parallel to the direction of loading, and a row of those fasteners which lie on a line normal to the direction of loading.

**R6, B6, P6 designate specimens of 6-in. I-sections -- riveted, bolted with beveled washers, and bolted with plain washers, respectively. B18 and P18 designate T-sections cut from 18-in. I sections and bolted with beveled washers or with plain washers, respectively.

washers having a 16 2/3 per cent bevel were placed under the bolt head to provide parallel contact surfaces between the bolt head and nut. Specimens of Series P6, however, were assembled with flat, plain hardened washers under the bolt head. Therefore, because of the sloped surface under the heads, the bolts of the series P6 members were forced to bend through an angle of nearly 10 degrees when tightened. A summary of the details of the rivets and bolts for the three types of specimens is given in Table 1.

The mechanical properties of the 6-in. I-sections were determined from standard coupon specimens which were taken from the center of the flanges and the web, and tested in accordance with ASTM Designation E8. The results of these tests are given in Table 2. In general, the material of the I-sections met the requirements of ASTM Designation A7 for structural grade steel. However, it was noted that the flanges were out of square with the web by as much as 3/32 in. This is the maximum allowable out of square rolling tolerance permitted by the AISC Rolling and Cutting Tolerances.*

In addition, the webs of some of the members were found to be located somewhat off the center of the flanges. Consequently, since the rivet and bolt holes were aligned with the webs of the members, some of the connections were not centered on the flanges. This irregularity caused the flange toe area on one side of the flange to be somewhat smaller, in some cases, than that on the opposite edge of the same flange.

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* Page 65, "Rolling Mill Practice," AISC Manual.

## 4. T-Sections

Two groups of T-section specimens were fabricated from 18-in. 54.7 lb. I-sections. One specimen of each group was tested statically and the remaining four specimens of the group were tested in fatigue. Except for specimen P18-2, all of the fatigue specimens were pulled apart statically upon completion of the fatigue test. This was done to examine the static fracture section for possible fatigue cracks and also to obtain further data on the static strength of the members.

Figure 1b shows the details of the T-section specimens. These specimens, having a tension-shear ratio 1.0:0.82, were designed to fail through the T-sections.

The 6-in. I-section was selected for the first part of the study because it was the largest section that could be placed between the pull-heads of the fatigue testing machine. However, it was considered advisable to include in the program a larger specimen, one which would permit the use of larger diameter fasteners. Therefore, a specimen made up of two gusset plates and two T-sections cut from a 18-in. 54.7-lb. I-section was adopted. In fabricating these specimens the center 12 in. of the I-beam web was cut out leaving two sections, each of which contained a standard flange and a 3-in. portion of the web. Two of these T-sections, placed back to back and separated by a 1-in. gusset plate at each end, were used for each of the test specimens. The gusset plate of each joint was connected to the flanges of the T-sections by eight 7/8-in. high-strength bolts arranged in two lines on a 3 1/2-in. gage and in four rows at a 2 5/8-in. pitch. All of the bolt holes were drilled 15/16 in. in diameter while the parts were clamped together to ensure good alignment of the holes.

For convenience in bolting, the connections of rolled section flanges to gusset plates usually are assembled with the bolt heads adjacent to the sloped flange surfaces and the nuts adjacent to the gusset plates. In this way, the nuts always bear on a plane normal to the bolt axis. In order to simulate this arrangement in the present tests, a hardened beveled washer was used under each of the nuts of all T-section specimens. To study the effect of the beveled washers under the heads of the bolts, two groups of specimens were tested: one with and one without a beveled washer under the bolt head.

The specimens of Series B18 were fabricated with a hardened beveled washer under the bolt head. Thus the bearing surfaces for the heads of the bolts and the nuts were parallel. This is in accordance with the present recommendations of the Research Council's specification for the assembly of such connections. The second group of specimens, Series P18, was assembled with plain, flat hardened washers under the bolt head. Because of the slope of the flanges, these bolts were forced to bend through an angle of nearly 10 degrees while being tightened. The details of the two types of bolt assembly are given in Table 1.

The mechanical properties of the material used to fabricate the T-section specimens are given in Table 3. In general, this material met the requirements of ASTM Designation A7 for structural grade steel.

The surface conditions for the component parts of both I-section and T-section specimens were very similar. The gusset plate material had a mill scale surface which was free of rust. All surfaces of the 6-in. 12.5 lb. I-sections and 18-in. 54.7-lb. I-sections, however, were heavily coated with rust. Before assembly of the specimens, the rolled sections were machine-brushed leaving the surfaces relatively clean.

## 5. Description of Tests

Four fatigue specimens were included in each group of I- and T-section tests. Two were tested on a stress cycle of 0 to 18,000 psi tension*, and two were tested on a completely reversed stress cycle of 12,000 psi tension to an equal compression. On the basis of previous fatigue tests, it was assumed that the average fatigue life of these specimens would be at least 1,000,000 cycles.

Each fatigue specimen was equipped with eight mechanical dial indicators** to measure slip between the rolled section and the gusset plates at the first rows of fasteners. Each slip dial was attached to the gusset plate with its plunger bearing on a clip soldered to an extending from the flange toe of the section at the first row of fasteners.

The fatigue tests were performed at room temperature in the 200,000 lb. lever-type fatigue testing machines at the University of Illinois. A general view of these machines is shown in Figure 2a. These machines operate at approximately 180 cycles of loading per minute. The load of the specimen is adjusted by means of a turnbuckle and a variable throw eccentric while a calibrated dynamometer is used to indicate the magnitude of the load applied to the specimen.

All static tests were conducted in the 600,000 lb. Riehle Screw-Type Testing Machine shown in Fig. 2b. The specimens were loaded in axial tension at a rate of 0.05 in. per min. Eight slip dials were used on each

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[*] These are the average intensities of stress which were applied to the net area.

[**] The term "slip dial" will be used herein to replace the term "mechanical dial indicator."

of the static I-section specimens in the same manner as in the fatigue tests. In addition to the eight slip dials, eight SR-4 (type A-7, 1/4 in. gage length) wire resistance strain gages were positioned at the net section of one joint in each of the two T-section specimens. The eight strain gages, four on each T-section, were located parallel to the direction of loading and centered on a plane through the first row of bolts. The gages were positioned on the extreme edges of the flanges, at the center of the flanges and on the milled edges of the webs. The location diagram included in Fig. 15 shows the positions of these gages. Fully instrumented static specimens of each type are shown in Figs. 3a and 3b.

The test of each fatigue specimen was discontinued when the specimen either failed or reached 2,000,000 or more cycles without failing. All of the T-section specimens withstood 2,000,000 cycles or more without any sign of failure. Therefore, upon completion of the fatigue tests, all of these specimens except P18-2 were tested statically to determine whether any damage was incurred during the fatigue tests. Dial indicators were also used to measure slip in these static tests.

## 6. Bolt Calibrations

Load-torque relationships were obtained from calibration tests using a "bolt calibrator" recently developed in the Structural Research Laboratory at the University of Illinois.

Bolt tension was measured with the calibrator and torque was measured with a torque wrench as the nut was tightened. Various adaptors, which provide different grips and bearing conditions, could be used in the calibrator. Therefore, the type of contact or bearing surfaces and proper specimen grip to simulate the conditions in the test specimens could be duplicated in these calibration tests. The individual conditions for each type of bolt detail shown in Table 1, were used in the calibration tests.

The high strength bolts and carburized washers for these tests were supplied by two manufacturers. Because of the small grip of the 6-in. I-section, the 5/8-in. diameter bolts were cut to a 2 1/4-in. length and rethreaded to leave a 1-in. plain shank. The 4-in. long 7/8-in. diameter bolts were used as supplied. To obtain uniform conditions for the bolt threads, all bolts were cleaned with solvent then dried and lightly oiled. All excess oil was then removed leaving only a thin uniform film on all of the bolts. Each nut was then "worked" on the bolt by hand until the nut rotated freely to the thread runout.

The bolts from each manufacturer met the specification requirements, for ASTM A-325 bolts and exhibited similar characteristics in the calibration tests. Therefore, no further distinction will be made as to the bolt manufacturer.

Seven 5/8-in. bolts were calibrated with parallel contact surfaces under each nut and bolt head to obtain the average torque-tension relationship for the bolts. To attain the minimum specified 17,300 lb. bolt tension, a torque of 160 to 215 ft.-lb. was required on the nut. At the specified bolt tension, a scatter of approximately ± 15 per cent (See Fig. 4a) was found in the required torque.

The average torque from these calibration tests was 180 ft.-lb., and is equal to that recommended in the present specifications. However, a torque of only about 150 ft.-lb. was used for the bolts in the B6 series. The bolt tensions for these tests were based on load-elongation rather than torque calibrations. Consequently, a bolt extensometer was used to set the bolt tensions on the basis of the bolt elongations. A later recalibration of this gage showed, however, that the gage constant was in error. Therefore, although somewhat lower than the specified 180 ft.-lb., the bolt torques have been used as a measure of the actual bolt tension in the specimens.

Twenty-six 5/8-in. bolts were calibrated with a 16 2/3 per cent slope under the bolt head. With this beveled surface, a range of 170 to 235 ft.-lb. of torque was obtained at the specified minimum bolt tension of 17,300 lb. The average torque of 200 ft.-lb. obtained in these tests was used in installing the bolts in the specimens of the P6 series. The total scatter in the torque required to obtain the specified bolt tension for this case was approximately ± 16 per cent, (See Fig. 4b).

Three 7/8-in. bolts with parallel contact surfaces under the nut and bolt head were tested. For these calibrations, 470 to 525 ft.-lb. of torque was required to develop the specified 32,400 lb. bolt tension. The average torque was 480 ft.-lb. and the scatter in torque at 32,400 lb. bolt tension was approximately ± 10 per cent, (See Fig. 5a). The bolts were installed in the specimens of series B18 using 475 to 495 ft.-lb. of torque.

Four 7/8-in. bolts were tested with a 16 2/3 per cent slope under the bolt heads. The range of torque at the specified bolt tension of 32,000 lb. varied, in this case, from 415 to 445 ft.-lb. with an average of 435 ft.-lb. (See Plotted Average Load-Torque Curve Fig. 5b.) This curve, however, is somewhat below the 470 ft.-lb. suggested by the present specifications for minimum load and, exhibits an unusual non-linear load-torque relationship.

In addition, an inspection of the bolts tightened to a torque of approximately 430 ft.-lb. showed that the bolt heads were not in complete contact with the sloping surfaces of the flange. Therefore, a torque of 480 ft.-lb., the same as that used for the B18 specimens, was used to install the bolts in the specimens of the P18 series. This torque gave complete contact under the bolt heads.

# III. RESULTS AND ANALYSIS OF TESTS

## 7. Fatigue Tests of I-Sections

The total number of cycles to failure of the 6-in. I-section fatigue specimens varied considerably. Table 4 shows the number of cycles to failure and the stress cycle at which each specimen was tested. Two specimens had a fatigue life between 150,000 and 200,000 cycles, and six between 350,000 and 650,000 cycles. The remaining four specimens ran 2,000,000 or more cycles. Three of these latter specimens showed no signs of failure; the fourth specimen, R6-4, showed the beginning of a fatigue crack after 3,856,000 cycles of loading.

A wide range in the number of cycles for failure was obtained in each series of the three types of specimens. This makes it extremely difficult to interpret the tests and to evaluate the effect that the type of fastener might have had on the fatigue strength of the members. The type of loading, however, did show some effect on the fatigue strength of the specimens. In general, the completely reversed cycle of loading (± 12,000 psi) produced fatigue failures at a somewhat smaller number of cycles than did the zero to tension cycle of loading (+ 18,000 psi).

All twelve I-section fatigue specimens failed through the net section at the first transverse rows of bolts or rivets. The cracks always began in the flange toe area -- that area between the rivet or bolt hole and the extreme edge of the flange. An inspection of the specimens during the tests indicated that the fatigue cracks started initially at the edge of the holes at the first transverse row of fasteners and progressed outwards through the toe.

As a crack propagated through the toe of a 6-in. I-section, neither a drop in load on the member nor an increase in slip could be detected. However, when the crack had broken through the toe and started to progress toward the web-flange junction, enough of the cross section area had been broken that an increase in slip and a decrease in load occurred. Failure was considered to have occurred when the crack had propagated across a flange since, at this stage, the specimen would no longer maintain the desired cyclic load. Figure 6a shows a fatigue crack through a first row flange toe, and Fig. 6b shows fatigue cracks in the flanges of four of the specimens after they had been tested.

Table 4 gives the slip of the joints of each specimen as measured by the slip dials located at the first transverse fastener rows. The maximum slip per cycle of loading ranged between 0.002 in. and 0.008 in. except for specimen P6-1 which had 0.020 in. slip per cycle. During the tests, the specimens accumulated a permanent slip in the joints which ranged between 0.001 in. and 0.016 in. The lack of consistency in slip between the various specimens makes it almost impossible to detect any correlation between the slip and the fatigue strength or life of the specimens.

Figure 7 shows a comparison of the test results for the 6-in. I-sections with the average S-N diagrams of previous tests of flexural and tension specimens. Only the specimens having a loading cycle of zero to 18,000 psi tension have been used in this comparison. There was considerable variation in the number of cycles required to cause failure in the I-sections. However, the average life in the present tests is approximately 900,000 to 1,500,000 cycles at a stress of zero to 18,000 psi tension. This compares with the established S-N diagrams for flexural or tension members assembled with rivets.

It had been expected, on the basis of previous tests, that the bolted members would exhibit a greater resistance to repeated loads than the riveted members but, in these tests, there is little difference between them. The reasons for this unexpected behavior is not known; however, it is believed that the existance of an extremely small edge distance in the flange of the I-section may be the principal factor. Fatigue tests of wide-flange sections would help to answer this question and demonstrate whether the fatigue strengths of bolted connections in plates and I or wide-flange sections are comparable.

## 8. Fatigue Tests of T-Sections

Table 5 lists the stress cycle, number of cycles applied, and the slip of the joint per cycle for the tests of the T-sections. All of the T-sections withstood about 2,000,000 or more cycles without any visible signs of failure. Specimen P18-2, the second T-section specimen tested, ran 2,400,000 cycles at an average stress on the net section of ± 12,000 psi without any sign of failure. The stress level was then changed to a completely reversed stress cycle of 17,200 psi to hasten failure. After an additional 200,000 cycles, a crack became visible and had progressed through one of the first row flange toes. The arrow in Fig. 19 indicates the location of this crack.

To inspect the specimens for possible small fatigue cracks, the remaining fatigue specimens were loaded statically after being tested in fatigue. No indications of fatigue cracks were found on the static fracture sections of specimens P18-1, B18-1 and B18-2. However the static fracture sections of specimens P18-3, P18-4, B18-3, and B18-4 had small areas easily identified as fatigue cracks. These fatigue crack areas began at the bolt holes and extended into the flange toes a short distance. The photographs of Fig. 8a and Fig. 8b show partial cracks of this type in the toes of specimens B18-4 and P18-4. These cracks were all small and impossible to see because of the washers under the heads and nuts of the bolts.

Table 5 shows the slip of each specimen as measured by slip dials located at the first transverse fastener rows. The slip per cycle, ranged consistently between 0.002 in. in 0.004 in. and the permanent slip accumulated during the tests varied between 0.001 in. and 0.006 in. except for P18-1 which had a 0.026 in. accumulated slip.

The fastener details (flat or beveled washers) did not produce any difference in the behavior of the T-sections. The loading cycle was the only factor which had any observable effect on the fatigue strength. Specimens loaded with the completely reversed cycle exhibited more and larger cracks than did the specimens loaded cyclically from zero to tension; the completely reversed stress cycle evidently was more severe than the zero to tension cycle used in these tests.

## 9. Static Tests of I-Sections

Figure 9 shows the average load-slip curves obtained in the static tests of the I-section specimens R6-5, B6-5, and P6-5. None of these specimens experienced sudden slip during testing. Up to a total specimen load of 60,000 lb., the slip in all three specimens increased uniformly to a maximum of .0024 in. Between 60,00 lb. and 110,000 lb. total load, both bolted specimens developed enough slip to bring the bolts into bearing. The riveted specimen, however, continued loading to 130,000 lb. before developing a major change in the rate of increase in slip. This increase in the rate of slip in the riveted specimen is probably an indication of general yielding in the rivets and the I-section. Because of the short grip of the rivets, it is assumed that the fasteners of specimen R6-5 were in bearing in the early stages of the test.

Table 6 shows the maximum loads sustained in the static tests of the I-section specimens. Just prior to reaching the maximum specimen load, failures occurred in a number of the flange toes at the first transverse rows of fasteners. This local failure was preceded by a necking-down in the toes. Failure took place in one of the joints of each specimen through the I-section at the first transverse row of fasteners. Figure 10 shows the failure section for each of the static I-section specimens.

## 10. Static Tests of T-Sections

The load-slip relations for all of the static tests of the T-section specimens, including the static tests of the fatigue specimens after they had been tested in fatigue, are shown in Figs. 11 and 12. Figure 11 includes the specimens (Series B18 with beveled washers) with parallel contact surfaces under the bolt head and nut, and Fig. 12 includes the specimens (Series P18 with flat washers) with non-parallel bolting surfaces.

The load developed just before slip occurred depended primarily upon the initial tension in the bolts and the condition of the contact surfaces of the bolted parts. Specimens P18-1, P18-5, B18-5 had cleaner and smoother contact surfaces than the remaining fatigue specimens, and reached the maximum load carrying capacity of the joint without exhibiting a sudden slip. The remaining members slipped suddenly with an accompanying decrease in the applied load. This is seen as a dotted line on the load-slip diagrams of Figs. 11 and 12. In most cases, the specimens with the rougher contact surfaces developed higher loads at first major slip than the specimens with clean contact surfaces, even though their initial bolt tension may have been lower. The loads on the specimens at first major slip varied from 150,000 lb. to 271,000 lb., as may be noted in Table 6. Lowest of these values are those obtained from the static tests of specimens not tested previously in fatigue. This confirms previous observations that the repeated loadings on the bolted joints, although producing a decrease in the bolt tension, provide an increase in frictional resistance.

The T-sections all fractured at a section through the first transverse row of fasteners of one of the two joints at loads varying from 390,000 to 458,000 lb. Views of the fractures of B18-5 and P18-5 are shown in Figs. 13a and 13b, respectively. Figure 14a is a longitudinal view of one of the T-sections of specimen P18-4 after fracture and shows the "neck down" of the web.

In the process of withstanding the maximum loads, the flange toes at the critical sections in nearly all of the specimens ruptured. This was probably a result of the notch effect of the bolt holes and the fatigue cracks. At least half of the specimens exhibited broken flange toes just before or at maximum load. The remainder of the specimens developed breaks in the toes after the maximum load had been reached but before rupture took place. Figure 14b shows the highly localized necking-down which was typical of a flange toe at a first transverse row of fasteners just before the flange toe fractured.

The load-strain relationships that were obtained at the critical section of the static test specimens, B18-5 and P18-5, indicate that the strains at the center of the flanges were greater than those at the extreme edge of the toes or at the milled edge of the web. The individual load-strain relationships for a given position on both T-sections of the specimens have been averaged. The average load-strain relations are shown in Fig. 15.

At a load of 140,000 lb., an average net-section stress of 18,000 psi, the average measured axial stresses* at the center of flanges, on the milled edges of the webs and at the edges of the flange toes were only 16,600, 11,000, and 12,800 psi, respectively. Consequently, the stresses in the vicinity of the holes certainly were higher than these values and the stress gradients across the flanges, because of the stress concentration at the holes and the clamping at the bolts, must have been large.

A study of the average strains at the center of the flanges and at the edge of the webs shows, at a nominal net stress of 18,000 psi, a variation in strain equal to approximately the variation one would expect at the corresponding locations in a 16 to 20 in beam loaded in flexure. Thus, in the fatigue tests, the T-sections of these tests may be considered as representative of the tension flange of a flexural member, and the resistance to repeated loads as representative of the fatigue strength at the end of a partial length cover plate which is bolted to an 18-in. I-section.

## 11. Residual Bolt Tension

### a) Residual Bolt Tension after Fatigue Tests

The tension remaining in the bolts upon completion of the fatigue tests was measured by the torque required to loosen the nuts. In each case

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* Stresses were computed from the measured strains by assuming a modulus of elasticity = 30,000,000 psi.

the nut was retightened before the torque reading was taken on the adjacent bolts. In this manner the clamping force between the connected parts was maintained and the residual torque unaffected by the measurements on adjacent bolts.

Figure 16 shows the average initial bolt tensions and the residual bolt tensions of the fatigue specimens, series B6, after testing. During the fatigue tests, the average maximum loss in bolt tension was 50 per cent and occurred at the first transverse rows of fasteners; the average minimum loss of tension, 31 per cent, occurred at the second transverse row. Figure 17 shows the average bolt tensions in the specimens of series P6 at various stages of testing. The specimens of the P6 series showed more consistent bolt tensions after the fatigue tests than did the specimens of series B6. The average maximum loss in bolt tension during the fatigue tests of these specimens was 39 per cent at the first transverse rows of fasteners; the average minimum loss was 31 per cent at the third row of fasteners. The average loss in bolt tension for the bolts of each specimen is given in Table 4.

Figure 18 shows the bolt tensions before and after the fatigue tests of the T-section specimens of the B18 and P18 series. The loss in bolt tension during 2,000,000 cycles of loading was in good agreement at each transverse row of fasteners. The average maximum loss of bolt tension, 25 to 36 per cent, occurred at the first transverse rows. The loss in bolt tension at the third row of fasteners was smallest and ranged from 13 to 28 per cent. The average loss in bolt tension for the bolts of each specimen is given in Table 5.

In Fig. 18 the bolts in both series of specimens were assumed to have developed 32,400 lb. initial bolt tension at 470 ft.-lb. of torque. The bolts in the specimens of series B18 were in close agreement with the assumption, but the bolt calibrations for the specimens of series P18 indicated that a torque of 470 ft.-lb. may have developed 37,000 lb. bolt tension. (See Fig. 4b.) However, the average bolt tensions remaining in the two types of specimens after the fatigue tests were in reasonably good agreement -- the average tension in series P18 being only slightly lower than that in series B18. If a smaller torque had been used to tighten the bolts in the Series P18, the residual tension upon completion of the fatigue test would, very likely, have been considerably below that in the bolts of the series B18 members.

A Grinding action took place on the contact surfaces of the specimens during the fatigue tests. Although this grinding existed at many points on the surfaces, it was predominant at the first and fourth transverse rows of fasteners. The grinding pulverized the rust and mill scale, and caused a reseating of the contact surfaces. This action is believed to have reduced the original grip of the bolt slightly and may have been responsible for the loss in tension being largest at the first and fourth rows of fasteners. An example of the areas polished by this grinding action may be seen in Fig. 19.

### b) Risidual Bolt Tension after Static Tests

The tension remaining in the bolts after the static testing was also measured in terms of the torque required to loosen the nuts. Figures 16 and 17 show the residual bolt tensions for specimens B6-5 and P6-5; Fig. 18 shows the bolt tension remaining in the specimens of series B18 and P18.

The bolts in the first transverse rows of specimens B6-5 and P6-5 lost 80 to 90 per cent of their initial tension while those in the third transverse rows lost 40 to 60 per cent. The bolts in the T-section specimens had a 95 to 100 per cent loss in tension at the first transverse rows and a 50 to 60 per cent loss in the third rows. This extreme loss in tension at the first rows was due, of course, to the necking-down and fracture of the connected parts.

Table 6 shows that the initial bolt tension had little or no effect on the maximum static load developed in the T-section specimens. All specimens withstood approximately the same maximum load, although the initial bolt tension varied from 23,600 to 41,400 lb. In addition the tension remaining in the various bolts after failure was within a relatively narrow band for all specimens in spite of the fact that the initial torque applied to the bolts of the specimens varied from 350 to 600 ft.-lb.

### c) Bolts from Fatigue Specimens

An inspection of the bolts from the specimens with plain hardened washers against the sloped (series P6 and P18) flange surfaces showed that both elastic and inelastic bending took place in the bolts during tightening.

Figure 20a shows a 7/8-in. bolt, nut, plain washer and square beveled washer taken from fatigue specimen P18-1 upon completion of the fatigue test. The bolt head produced a localized punching into the flat hardened washer at the point of initial contact. This depression in the washer reduced the angle through which the bolt was bent as it was tightened, by about 2 degrees. Thus, approximately eight degrees of bending remained to be absorbed by the bolt as it was torqued.

The inelastic bending in the 7/8-in. bolt occurred in about one third of the plain shank adjacent to the bolt head. This inelastic bending produced an angle of approximately four degrees between the head and the longitudinal axis of the bolt. The remaining four degrees of bolt bending must have been elastic bending because the bolt heads appeared to be entirely in contact with the washers at 480 ft.-lb. of torque.

Figure 20b shows a 5/8-in. bolt, nut, and plain washer as used in the P6 fatigue specimens. The inelastic bending in this bolt occurred primarily in the last three threads before the thread run-out. The angle formed between the head of the bolt and the longitudinal axis through the threaded portion of the bolt was approximately five degrees. Since only a negligible angle of impression occurred in the washer under the bolt head, and since the bolt heads appeared to be in contact with the washers at 200 ft.-lb. torque, the elastic bending of these bolts must have been about four or five degrees also. Thus, for the 5/8-in. and 7/8-in. bolts torqued to 200 ft.-lb. and 480 ft.-lb. respectively on non-parallel contact surfaces, about 50 per cent of the total bending in the bolt was elastic and about 50 per cent inelastic.

# IV. SUMMARY OF RESULTS AND CONCLUSIONS

## 12. Summary of Results

The results of the tests contained herein may be summarized as follows:

1) The number of cycles to failure at a given stress cycle was erratic for the specimens of 6-in. I-sections. The average number of cycles to failures was 900,000, considering only specimens loaded on a cycle of zero to 18,000 psi tension. This average number of cycles to failure is about the same as the fatigue lives determined by previous studies of riveted members tested in tension and flexure.

2) The fatigue lives of the T-section specimens were greater than 2,000,000 cycles for both the stress cycle of zero to 18,000 psi tension and the stress cycle of 12,000 psi complete reversal.

3) In the tests of I-section specimens, the fatigue cracks originated in the flange toes at the critical or net section of the I-section.

4) During the fatigue tests, the 5/8-in. bolts lost between 28 and 60 per cent of their tension; the 7/8-in. bolts had an average loss of bolt tension ranging from 20 to 30 per cent.

5) The initial bolt tension had little or no effect on the static strength of the specimens.

6) The specimens assembled with plain washers had fatigue strengths comparable to those specimens assembled with beveled washers.

7) The bolts bearing on the sloped surfaces bent through an angle of 8 to 10 degrees as the nuts were torqued. Approximately 50 per cent of the total bending was elastic and 50 per cent inelastic.

## 13. Conclusions

The tests of this study support the following conclusions:

1) A wide variation in the number of cycles to failure for small 6-in. I-section specimens can be expected. The use of larger sections in this type of study might give more consistent and greater fatigue strengths for the bolted members.

2) The use of flat washers instead of beveled washers against the sloped flange surface does not reduce the fatigue or static strength of the connections.

3) The fatigue strength of tension members with bolted connections and flexural members with partial length cover plates bolted in place may be expected to be somewhat greater than that of similar riveted members.

4) Since the very small toe of the standard I-beam flanges is the point at which all of the fractures initiated, greater strengths might be expected if the edge distance of the connections could be increased.

# BIBLIOGRAPHY

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2. Wilson, Wilbur M., "Flexural Fatigue Strength of Steel Beams," Bulletin 377, Engineering Experiment Station, University of Illinois, 1948.

3. Wilson, Wilbur M., and Munse, William H., "Fatigue Strength of Various Details Used for the Repair of Bridge Members," Bulletin 382, Engineering Experiment Station, University of Illinois 1949.

4. Fuller, J. R., Leahey, T. F., and Munse, W. H., "Static Tensile Tests of Large I-Section Connections," Unpublished Progress Report, Engineering Experiment Station, University of Illinois, 1954.

## TABLE 1

## DESCRIPTION OF FASTENERS FOR TEST SPECIMENS

| Specimen Series | Fasteners | | Beveled Washer Under Bolt Head | Grip of Specimen, in. |
|---|---|---|---|---|
| | Dia. in. | Type | | |
| B6 | 5/8 | Bolts | Yes* | 0.94 |
| P6 | 5/8 | Bolts | No* | 0.94 |
| R6 | 5/8 | Rivets | Riveted | 0.94 |
| B18 | 7/8 | Bolts | Yes** | 2.38 |
| P18 | 7/8 | Bolts | No** | 2.38 |

* Plain washers under nut on all bolts, no washers used under rivet heads.

** Beveled washers under nut on all bolts.

## TABLE 2

## MECHANICAL PROPERTIES OF 6-IN. 12.5 LB. I-SECTION MATERIAL

| Coupon | Location in Section | Yield Point, psi | Ultimate Strength, psi | Elong. in 8 in., per cent | Reduction of Area, per cent |
|---|---|---|---|---|---|
| C-1A | Center-Flange | 37,600 | 62,500 | 27.4 | 48.9 |
| C-2A | Center-Flange | 38,700 | 62,000 | 25.8 | 51.8 |
| C-3A | Center-Flange | 37,600 | 62,000 | 24.1 | 35.5 |
| C-1C | Center-Flange | 38,800 | 61,600 | 25.2 | 47.3 |
| C-2C | Center-Flange | 37,800 | 62,400 | 22.6 | 32.9 |
| C-3C | Center-Flange | 39,600 | 61,800 | 28.8 | 49.2 |
| | Average | 38,400 | 62,000 | 25.6 | 44.3 |
| C-1B | Center-Web | 40,000 | 60,900 | 30.4 | 43.2 |
| C-2B | Center-Web | 40,100 | 59,700 | 26.8 | 45.7 |
| C-3B | Center-Web | 41,900 | 60,800 | 30.4 | 50.0 |
| | Average | 40,700 | 60,500 | 29.2 | 46.3 |
| | Grand Average | 39,100 | 61,500 | 26.8 | 44.9 |

## TABLE 3

## MECHANICAL PROPERTIES OF 18-IN. 54.7 LB. I-SECTION MATERIAL

| Coupon | Location in Section | Yield Point, psi | Ultimate Strength, psi | Elong. in 8 in., per cent | Reduction of Area, per cent |
|---|---|---|---|---|---|
| S-A | Toe-Flange | 40,100 | 69,500 | 24.8 | 48.0 |
| S-C | Toe-Flange | 41,400 | 68,950 | 20.6 | 43.4 |
| S-G | Toe-Flange | 38,400 | 68,400 | 28.7 | 47.4 |
| S-I | Toe-Flange | 41,820 | 68,840 | 27.5 | 46.8 |
|  | Average | 40,430 | 68,920 | 25.4 | 46.4 |
| S-B | Center-Flange | 35,700 | 67,700 | 28.8 | 47.1 |
| S-H | Center-Flange | 35,600 | 68,300 | 29.9 | 49.1 |
|  | Average | 35,650 | 68,000 | 29.4 | 48.1 |
| S-D | Web | 41,700 | 75,700 | 27.3 | 41.9 |
| S-E | Web | 41,880 | 74,200 | 26.7 | 42.0 |
| S-F | Web | 41,030 | 73,780 | 25.1 | 42.9 |
|  | Average | 41,540 | 74,560 | 26.4 | 42.3 |
|  | Grand Average | 39,740 | 70,600 | 26.6 | 45.4 |

## TABLE 4

## SUMMARY OF RESULTS OF FATIGUE TESTS OF I-SECTION SPECIMENS

| Spec. No. | Average Initial Bolt Torque, ft.-lb. | Average Initial Bolt Tension, lb. | Average Bolt Tension After Test lb. | Average Loss in Tension During test per cent | Stress Cycle on Net Section Area ksi | Number of Cycles to Failure, in 1000 | Max. Slip Per Cycle During Test in. | Max. Slip Accumulated During Test in. |
|---|---|---|---|---|---|---|---|---|
| B6-1 | 145 | 13,900 | 5,300 | 61.9 | ±12 | 387 | 0.008 | 0.002 |
| B6-2 | 160 | 15,400 | 11,000 | 28.6 | 0 to +18 | 5,398* | 0.003 | 0.016 |
| B6-3 | 135 | 13,000 | 8,100 | 37.7 | ±12 | 286 | 0.005 | 0.001 |
| B6-4 | 140 | 13,500 | 9,500 | 29.6 | 0 to +18 | 608 | 0.007 | 0.008 |
| P6-1 | 200 | 17,300 | 10,800 | 37.6 | 0 to +18 | 653 | 0.020 | 0.010 |
| P6-2 | 200 | 17,300 | 11,200 | 35.3 | ±12 | 2,264* | 0.003 | 0.000 |
| P6-3 | 200 | 17,300 | 11,000 | 35.8 | 0 to +18 | 2,085* | 0.002 | 0.003 |
| P6-4 | 200 | 17,300 | 11,500 | 33.5 | ±12 | 200 | 0.002 | 0.001 |
| R6-1 | --- | ------ | ------ | ---- | ±12 | 491 | 0.003 | 0.002 |
| R6-2 | --- | ------ | ------ | ---- | 0 to +18 | 428 | 0.004 | 0.007 |
| R6-3 | --- | ------ | ------ | ---- | ±12 | 151 | 0.008 | 0.003 |
| R6-4 | --- | ------ | ------ | ---- | 0 to +18 | 3,856 | 0.006 | 0.004 |

*These specimens did not fail

# TABLE 5

# SUMMARY OF RESULTS OF FATIGUE TESTS OF T-SECTION SPECIMENS

| Spec. No. | Average Initial Bolt Torque, ft.-lb. | Average Initial Bolt Tension, lb. | Average Bolt Tension After Test lb. | Average Loss in Tension During Test per cent | Stress Cycle on Net Section Area ksi | Number of Cycles Applied in 1000** | Max. Slip Per Cycle During Test in. | Max. Slip Accumulated During Test in. |
|---|---|---|---|---|---|---|---|---|
| B18-1 | 475 | 32,700 | 25,000 | 23.5 | 0 to +18 | 2,459 | 0.002 | 0.004 |
| B18-2 | 480 | 33,100 | 25,300 | 23.6 | ±12 | 2,177 | 0.002 | 0.002*** |
| B18-3 | 495 | 34,100 | 25,400 | 25.7 | 0 to +18 | 2,235 | 0.004 | 0.004 |
| B18-4 | 490 | 33,800 | 26,800 | 20.5 | ±12 | 1,954 | 0.003 | 0.006*** |
| P18-1 | 480 | 32,400 | 24,200 | 25.3 | 0 to +18 | 2,233 | 0.002 | 0.026 |
| P18-2 | 480 | 32,400 | 22,200 | 31.5 | ±12 | 2,394 | 0.004 | 0.005 |
| P18-3 | 480 | 32,400 | 23,600* | ---- | 0 to +18 | 2,008 | 0.002 | 0.003 |
| P18-4 | 480 | 32,400 | 23,600* | ---- | ±12 | 2,253 | 0.003 | 0.001 |

* Estimated from the tension remaining in P18-1 and P18-2 after fatigue tests.

** None of the specimens failed.

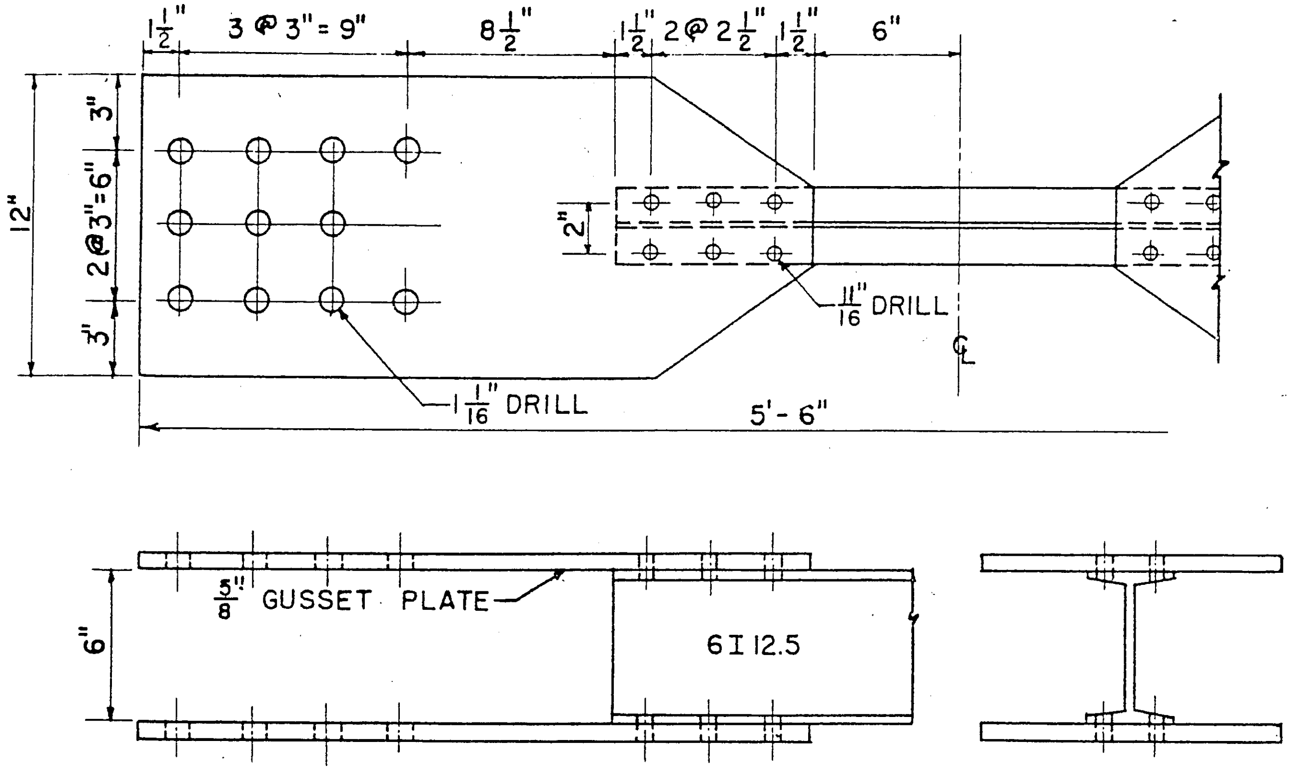
*** Had permanent slip in direction of compression loading, all other specimens had permanent slip in the direction of tension loading.

# TABLE 6

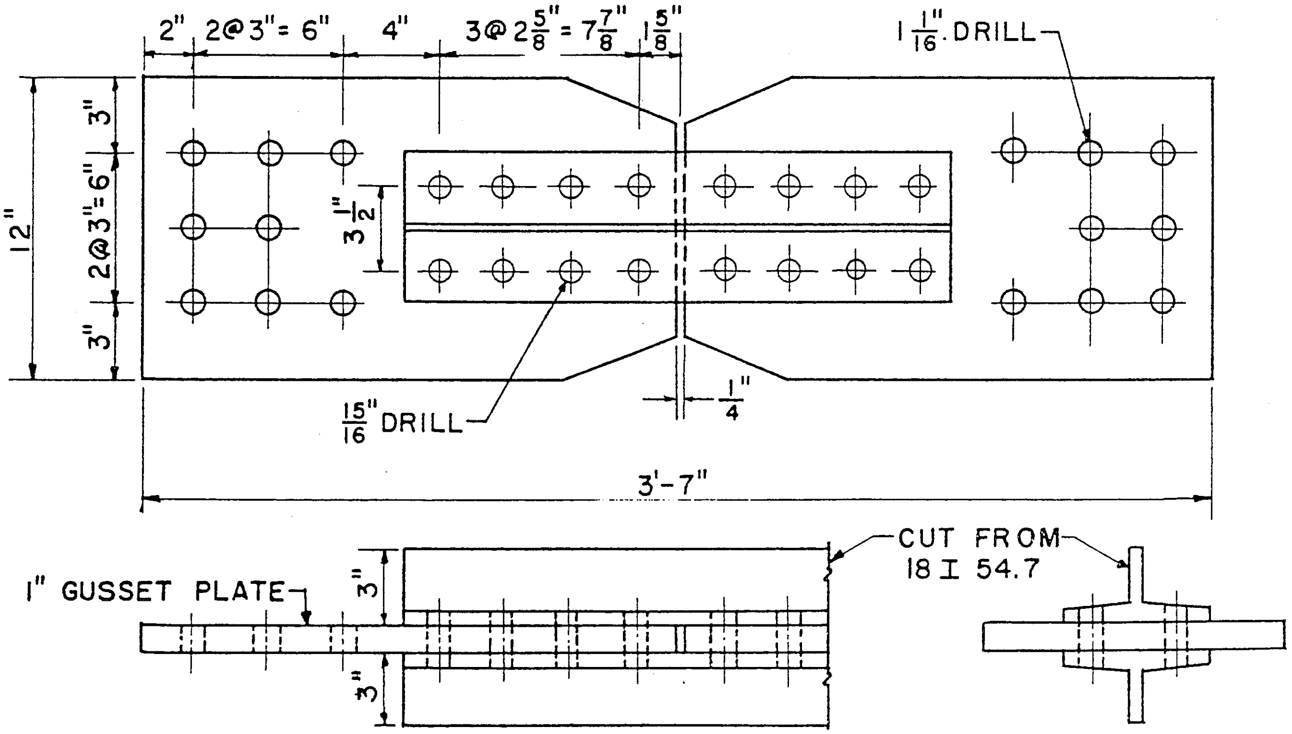
## SUMMARY OF RESULTS OF STATIC TESTS OF I-SECTION AND T-SECTION SPECIMENS

| Spec. No. | Average Initial Bolt Torque, ft.-lb. | Average Initial Bolt Tension, lb. | Load on Specimen at First Major Slip, kips | Maximum Load on Specimen, kips |
|---|---|---|---|---|
| B6-5 | 180 | 17,300 | ---- | 176 |
| P6-5 | 180 | 17,300 | ---- | 170 |
| R6-5 | --- | ---- | ---- | 172 |
| B18-1 | 600 | 41,400 | 271 | 425 |
| B18-2 | 600 | 41,400 | 260 | 429 |
| B18-3 | 400 | 27,500 | 200 | 418 |
| B18-4 | 400 | 27,500 | 243 | 458 |
| B18-5 | 480 | 33,100 | 180 | 414 |
| P18-1 | 600 | 40,600 | 248 | 421 |
| P18-3* | 350 | 23,600 | 185 | 399 |
| P18-4* | 350 | 23,600 | 214 | 391 |
| P18-5 | 480 | 32,400 | 150 | 427 |

[*] The tension in the bolts of this specimen is that tension remaining after fatigue tests.

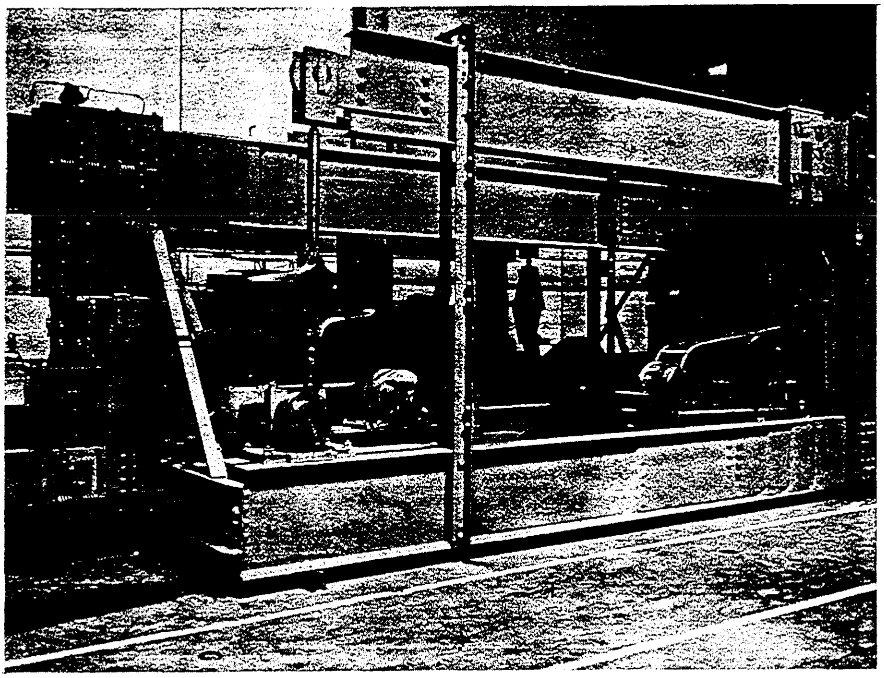


(a) I-SECTIONS

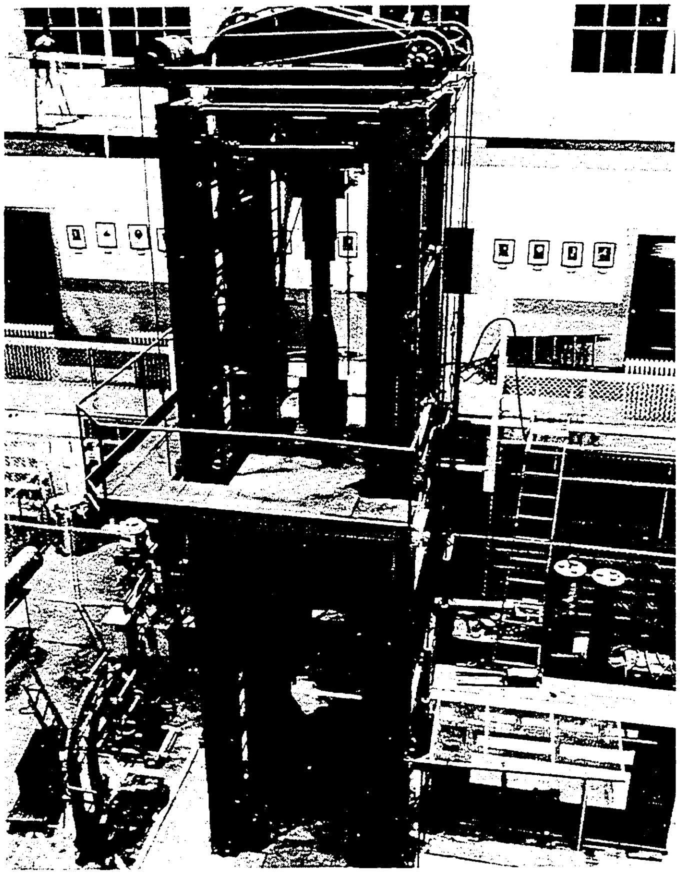


(b) T-SECTIONS CUT FROM 18in. I 54.7lb

FIG. I DETAILS OF TEST SPECIMENS

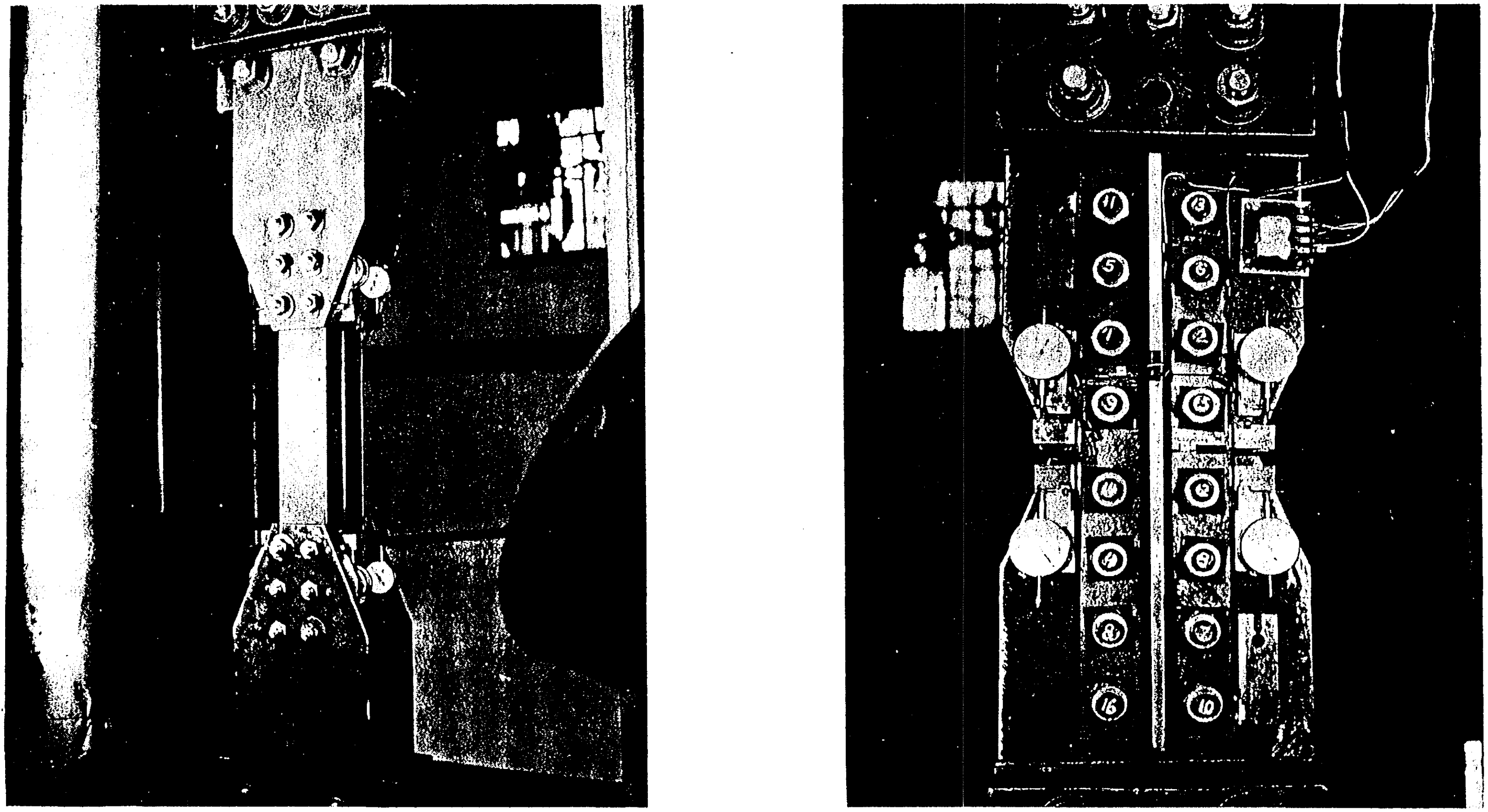


(a) 200,000 LB FATIGUE MACHINE



(b) 600,000 LB STATIC MACHINE

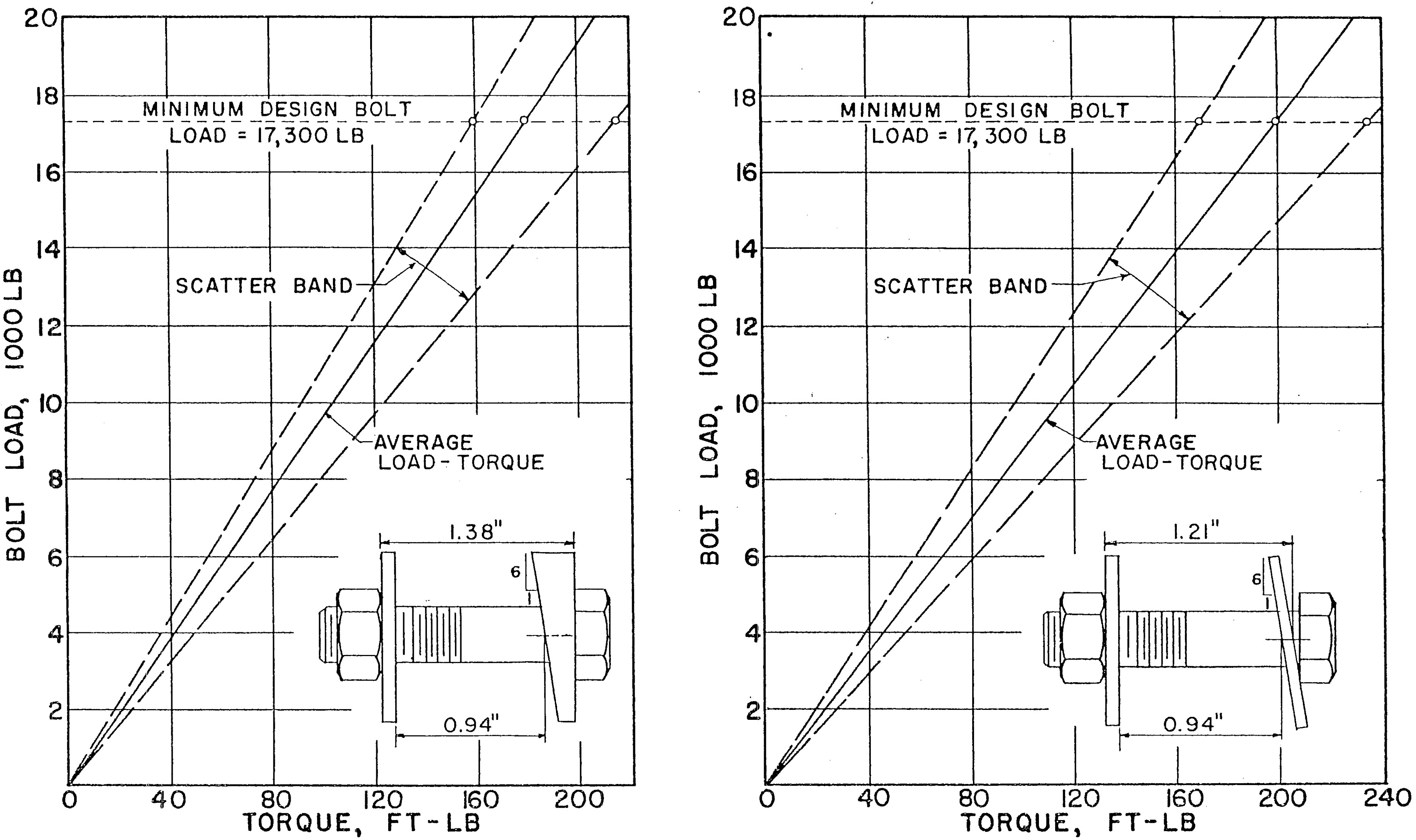
FIG. 2 LABORATORY TESTING MACHINES



(a) I - SECTION SPECIMEN B6 - 5

(b) T - SECTION SPECIMEN P18 - 5

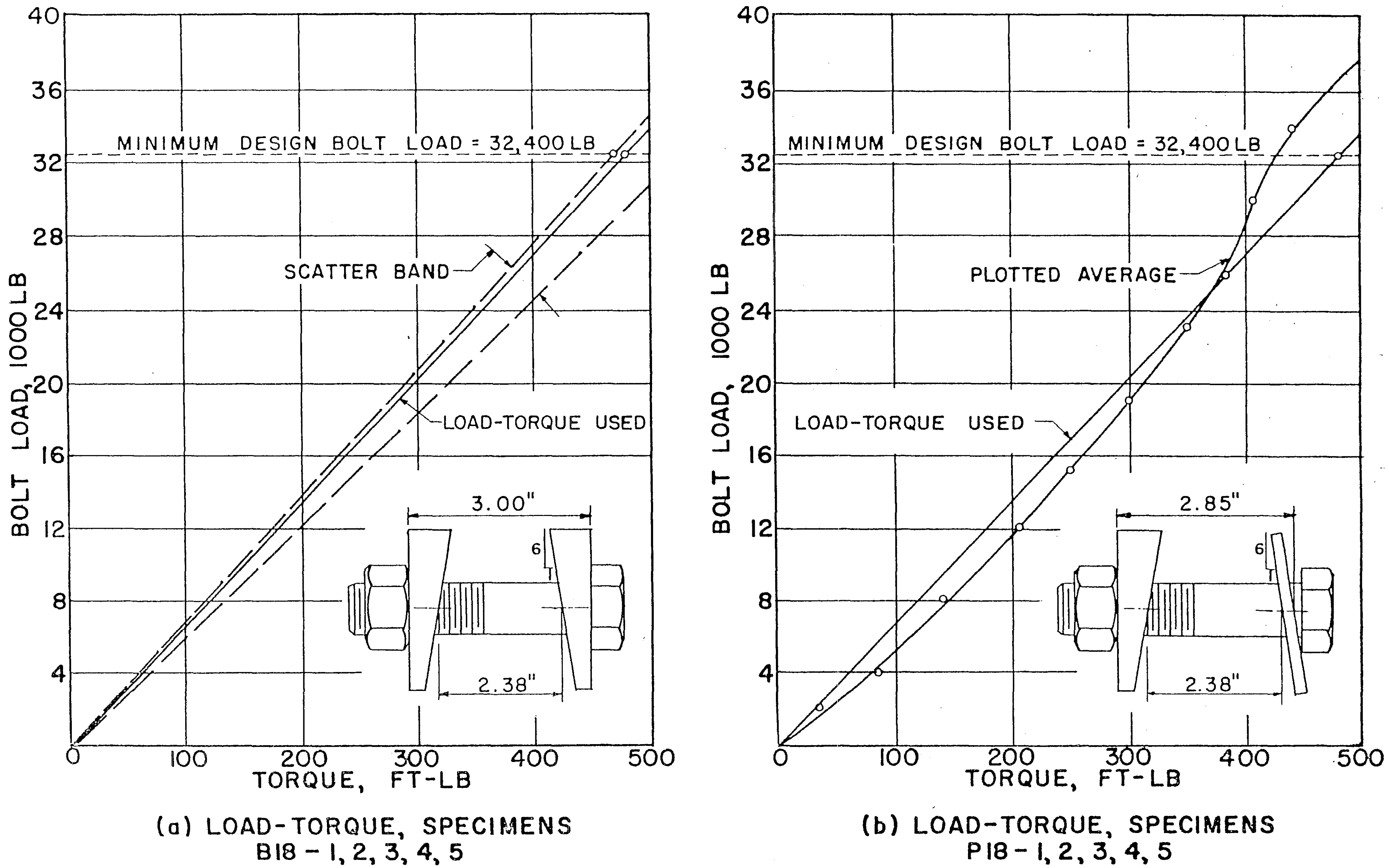
FIG. 3 STATIC SPECIMENS WITH INSTRUMENTATION IN PLACE FOR TESTING



(a) LOAD - TORQUE, SPECIMENS
B6 - 1, 2, 3, 4, 5

(b) LOAD - TORQUE, SPECIMENS
P6 - 1, 2, 3, 4, 5

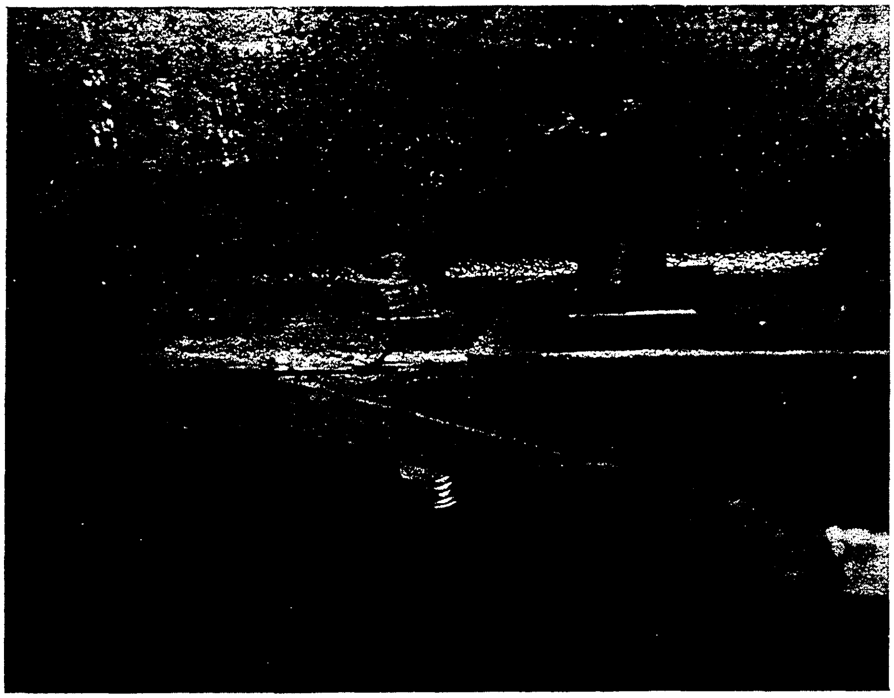
FIG. 4 CALIBRATIONS OF 5/8" BOLTS



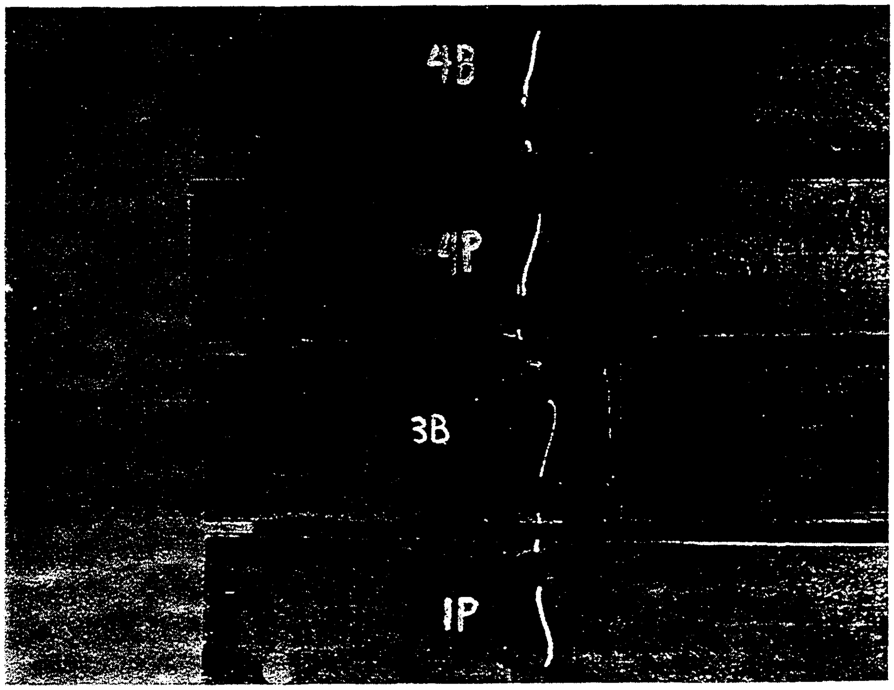
(a) LOAD-TORQUE, SPECIMENS
B18 - 1, 2, 3, 4, 5

(b) LOAD-TORQUE, SPECIMENS
P18 - 1, 2, 3, 4, 5

FIG. 5 CALIBRATIONS OF 7/8" BOLTS



(a) FATIGUE CRACK IN FLANGE TOE OF SPECIMEN B6 - 4



(b) FATIGUE CRACKS IN FLANGES AT FAILURE

FIG. 6 FATIGUE CRACKS IN SMALL I-SECTIONS

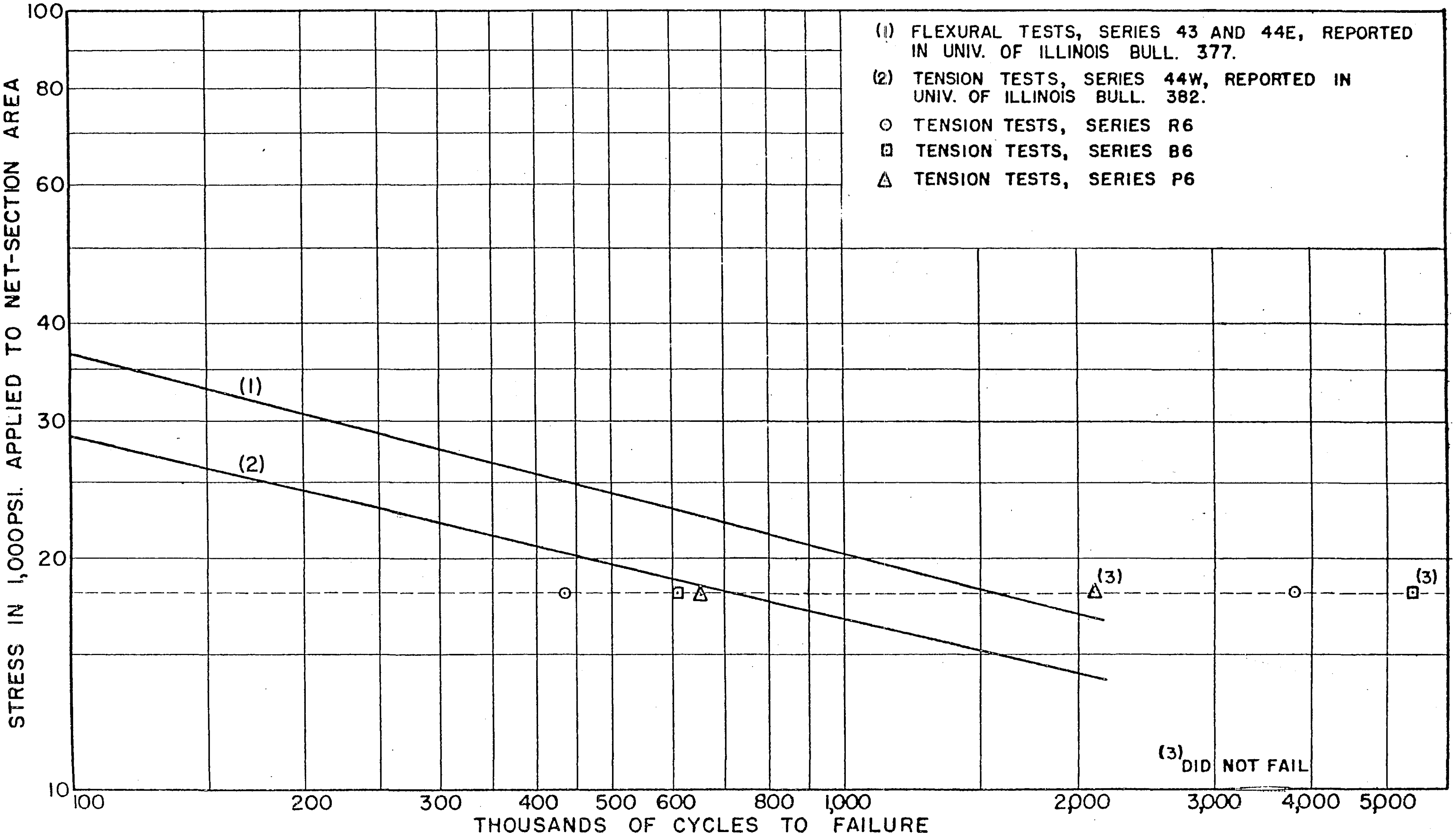
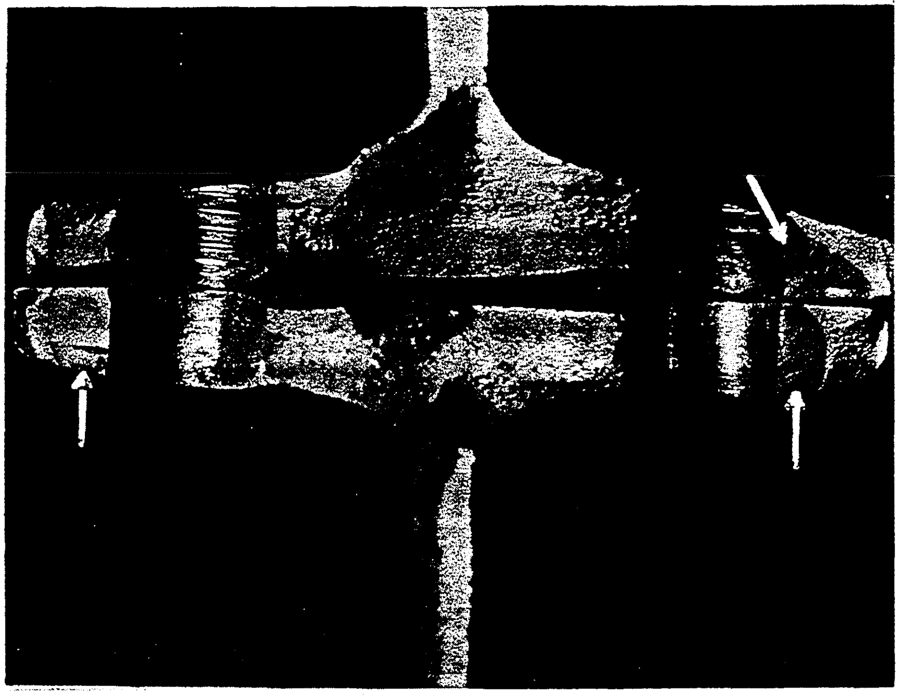
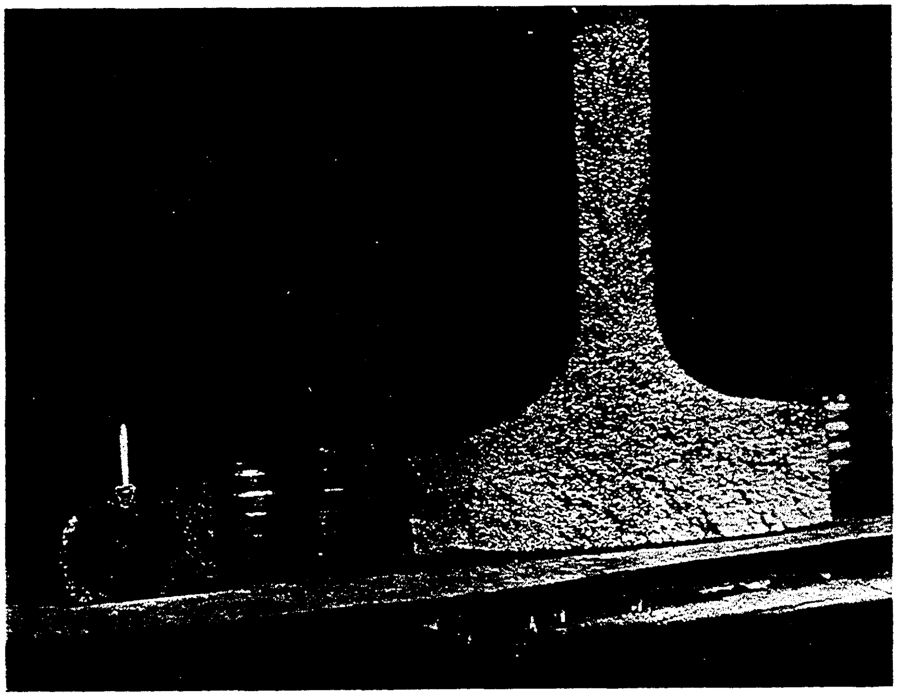


FIG. 7 COMPARISON OF TEST DATA WITH S-N DIAGRAMS ESTABLISHED BY PREVIOUS TESTS



(a) FATIGUE CRACKS VISIBLE IN TOES OF SPECIMEN P18-4 AFTER STATIC TEST



(b) FATIGUE CRACK THROUGH TOE OF SPECIMEN B18-4, AFTER STATIC TEST

FIG 8 FATIGUE CRACKS IN FLANGE TOES OF T-SECTIONS

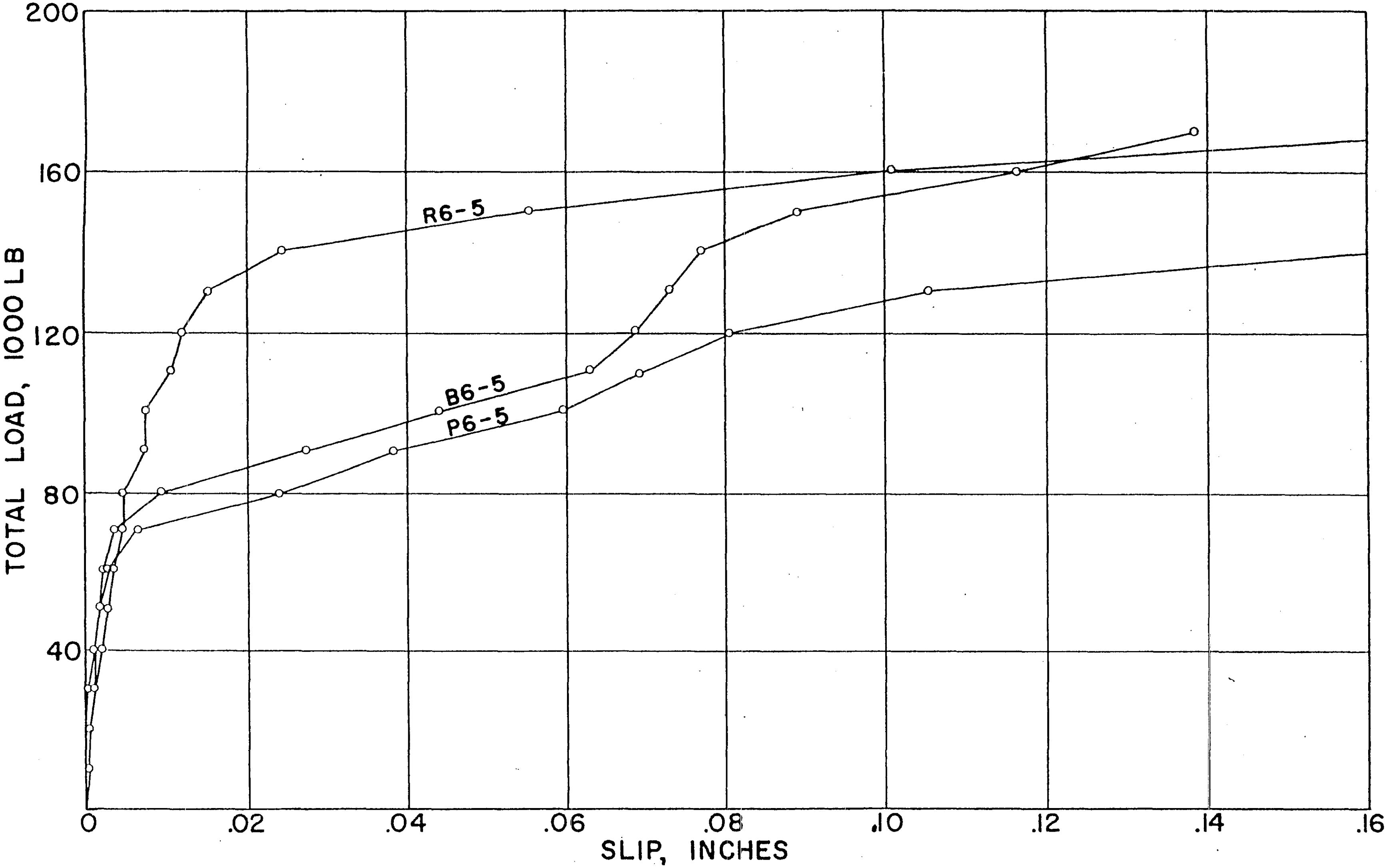
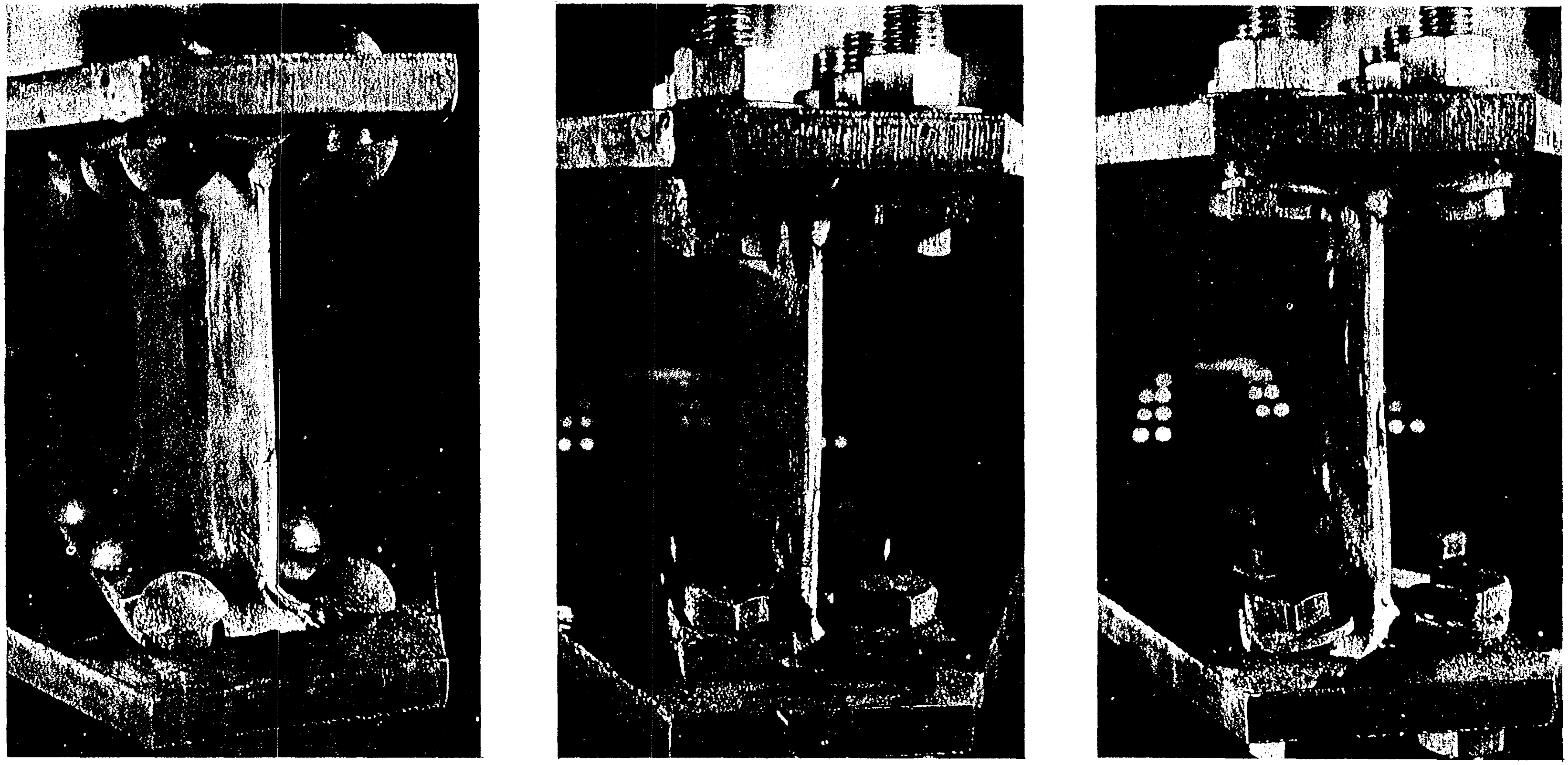


FIG. 9 AVERAGE LOAD-SLIP CURVES FROM STATIC TESTS OF 6in. I-SECTIONS (AT FIRST ROW FASTENERS)



(a) R6 - 5, RIVETED

(b) B6 - 5, BOLTED (WITH BEVELED WASHERS)

(c) P6 - 5, BOLTED (WITH PLAIN WASHERS)

FIG. 10 FRACTURES OBTAINED IN STATIC TESTS OF SMALL I- SECTIONS

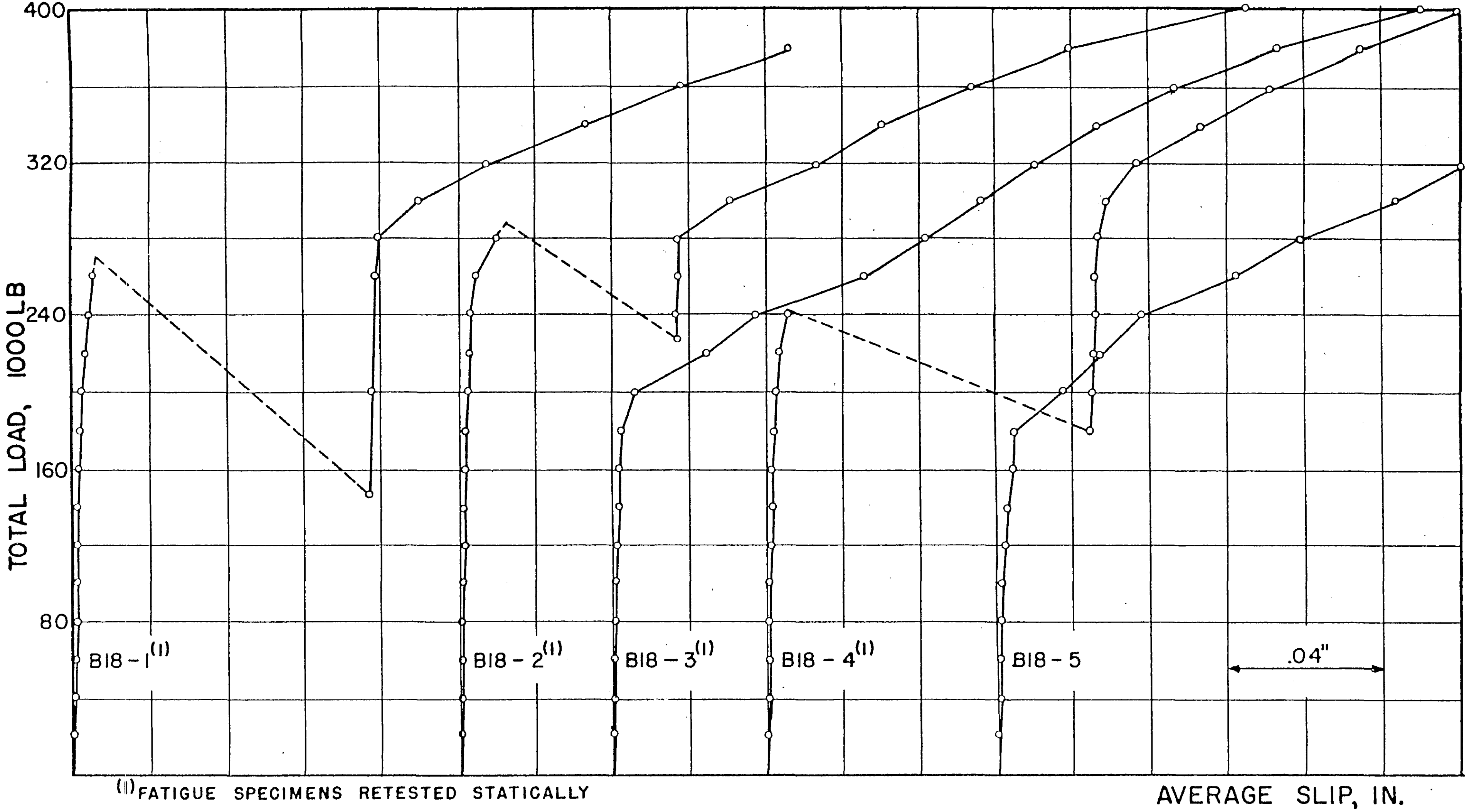


FIG. 11 AVERAGE LOAD-SLIP CURVES FROM STATIC TESTS OF T-SECTIONS
(AT FIRST ROW FASTENERS)

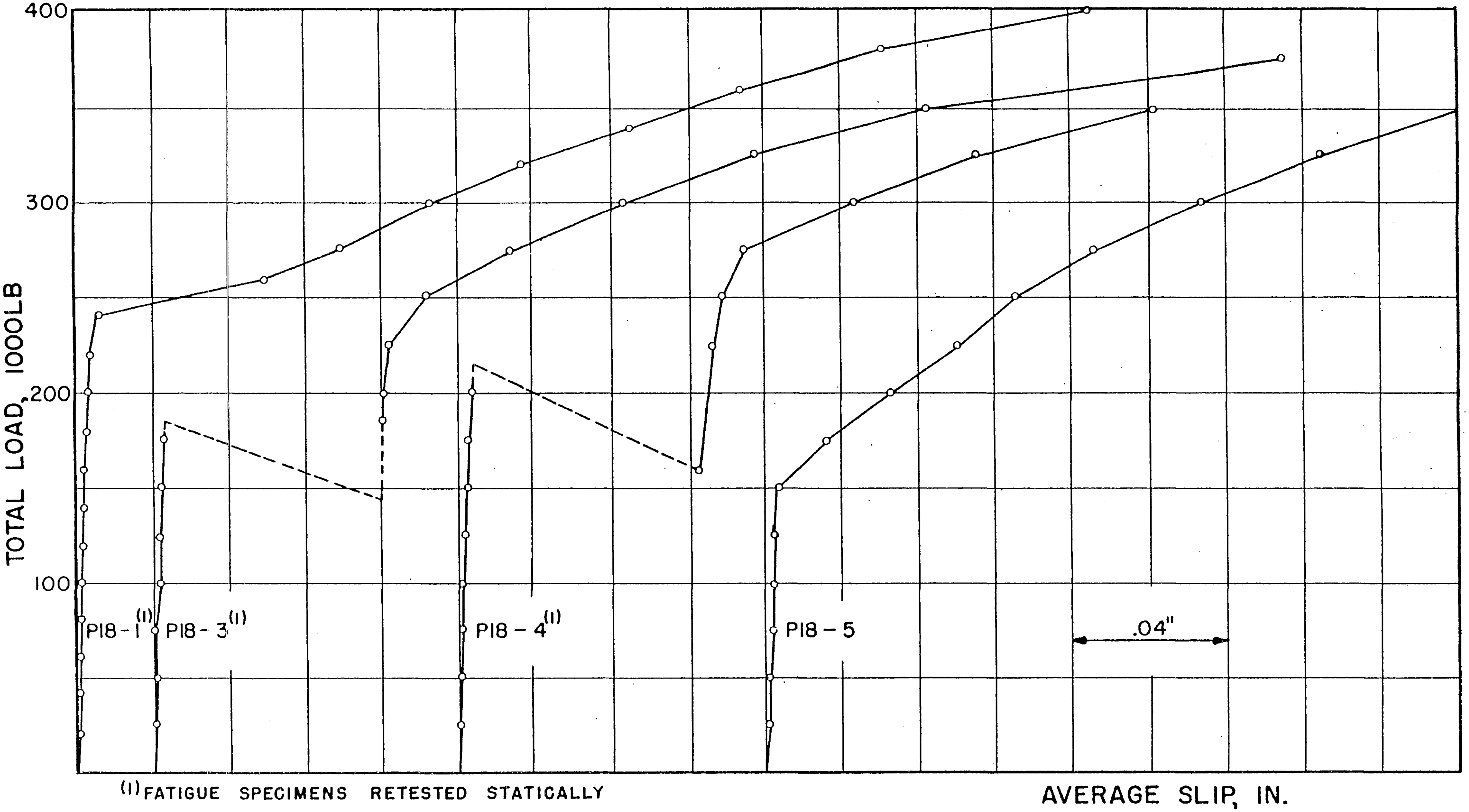
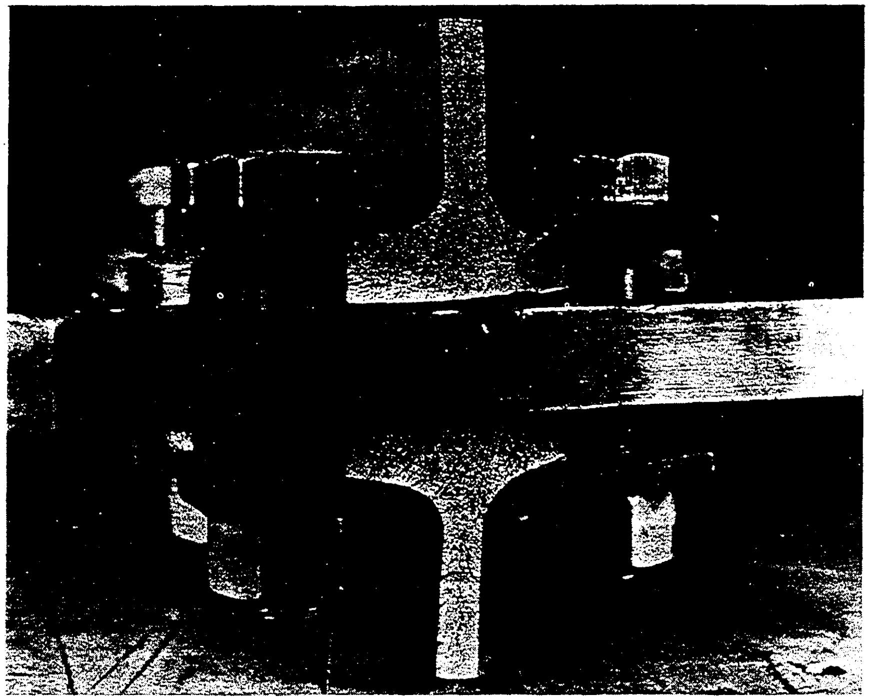
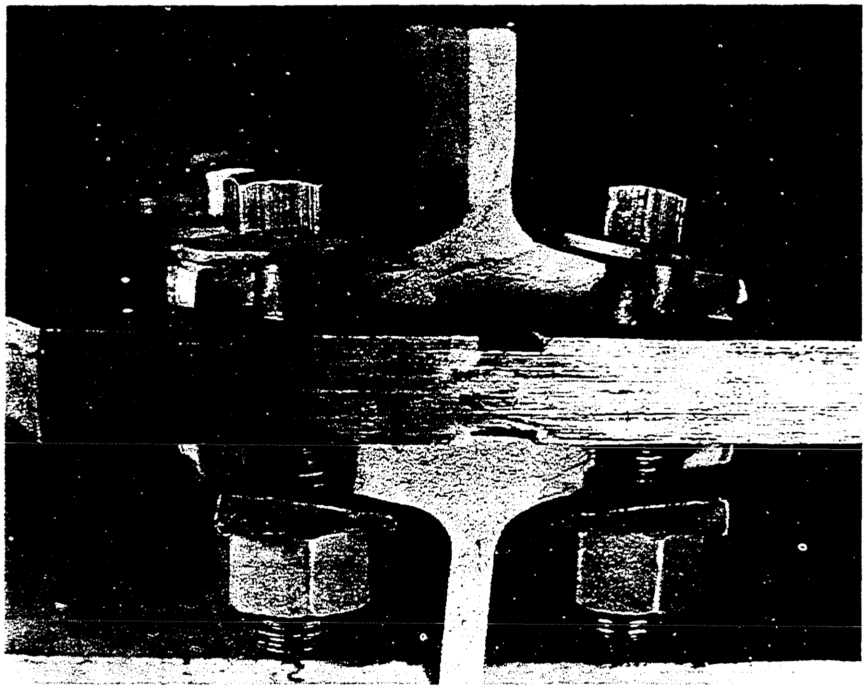


FIG. 12 AVERAGE LOAD-SLIP CURVES FROM STATIC TESTS OF T-SECTIONS (AT FIRST ROW FASTENERS)

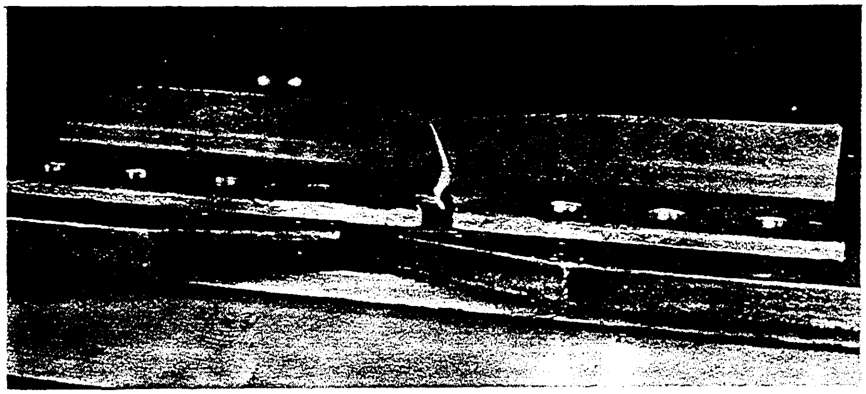


(a) B18-5 BOLTED (WITH BEVELED WASHERS)

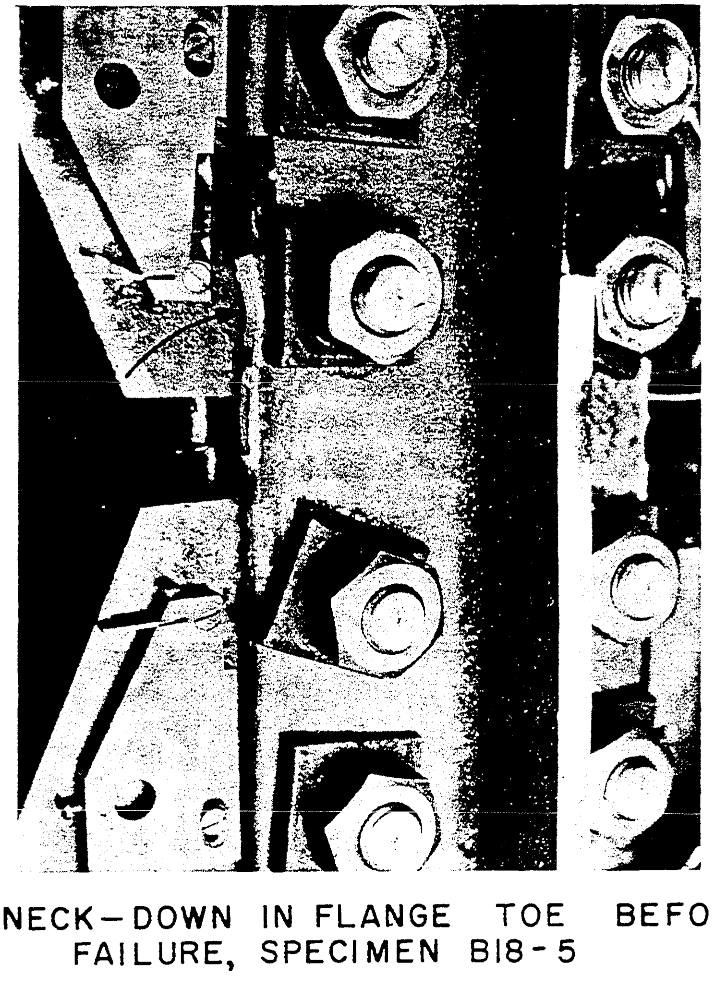


(b) P18-5 BOLTED (WITH PLAIN WASHERS)

FIG. 13 FRACTURES OBTAINED IN STATIC TESTS OF T-SECTIONS



(a) NECK-DOWN IN WEB AT NET SECTION AFTER FAILURE, SPECIMEN P18-4



(b) NECK-DOWN IN FLANGE TOE BEFORE FAILURE, SPECIMEN B18-5

FIG. 14 CRITICAL SECTION OF T-SECTIONS (STATIC TESTS)

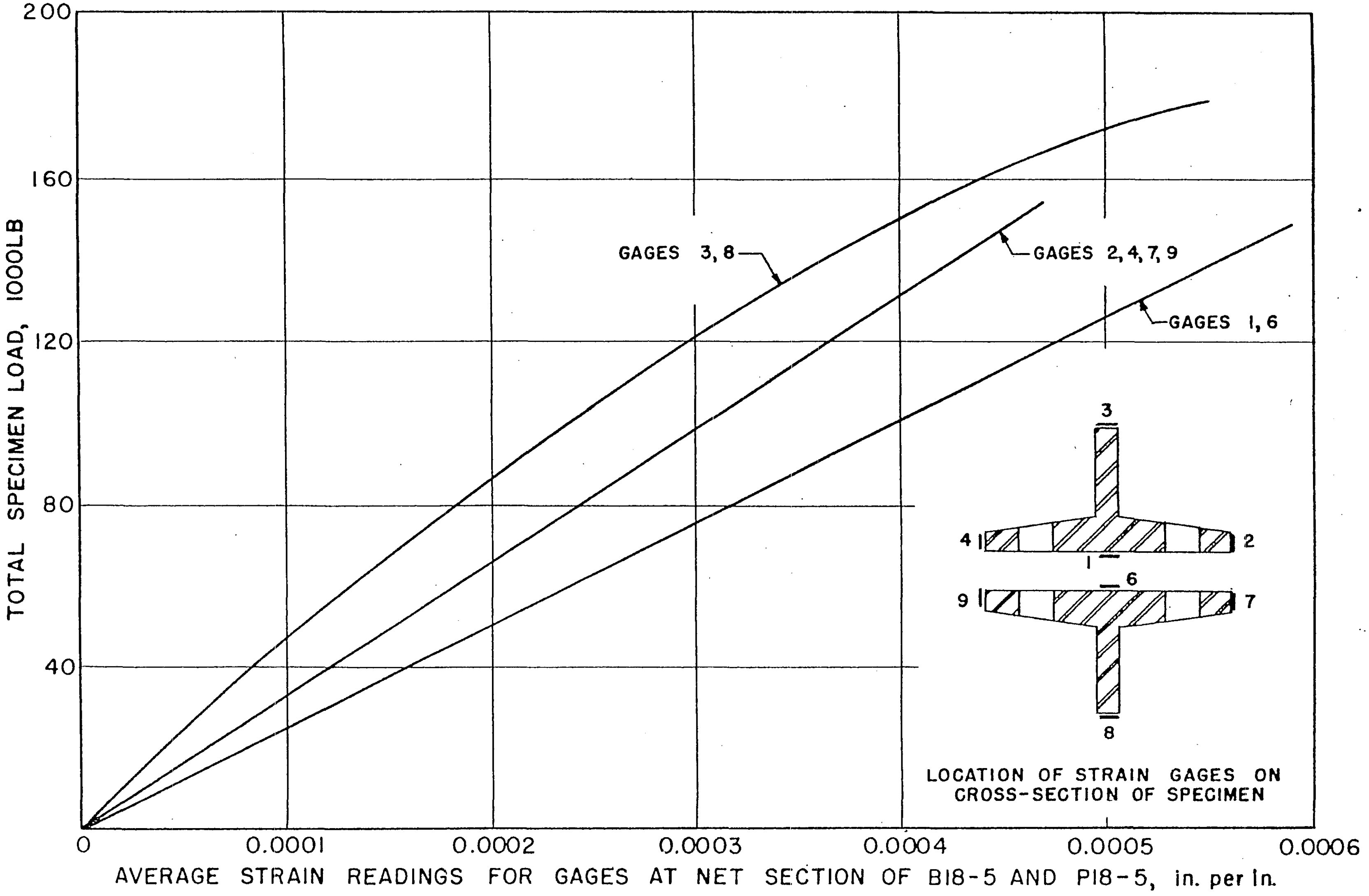


FIG. 15 AVERAGE STRAIN DISTRIBUTION IN T-SECTIONS DURING STATIC TESTS

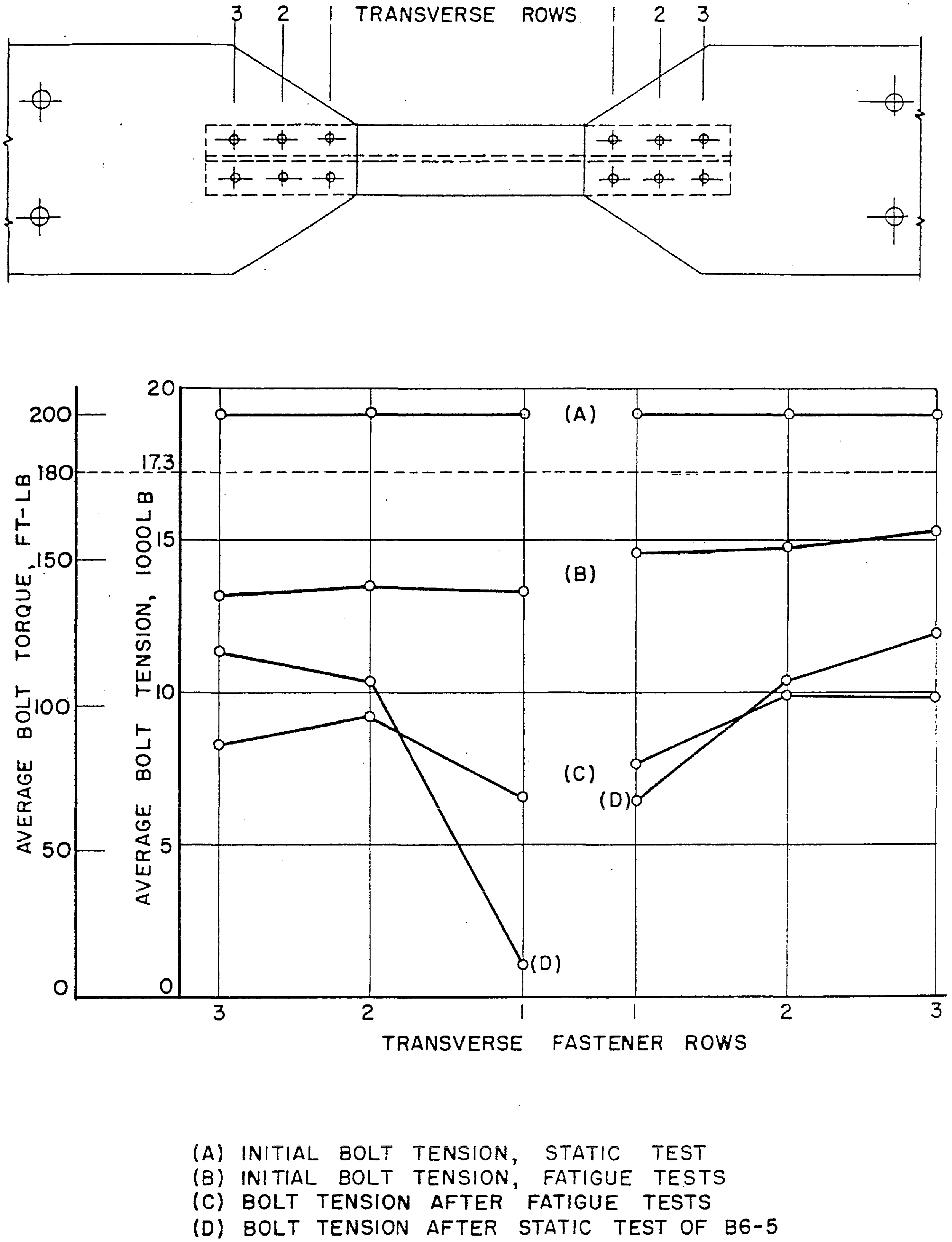
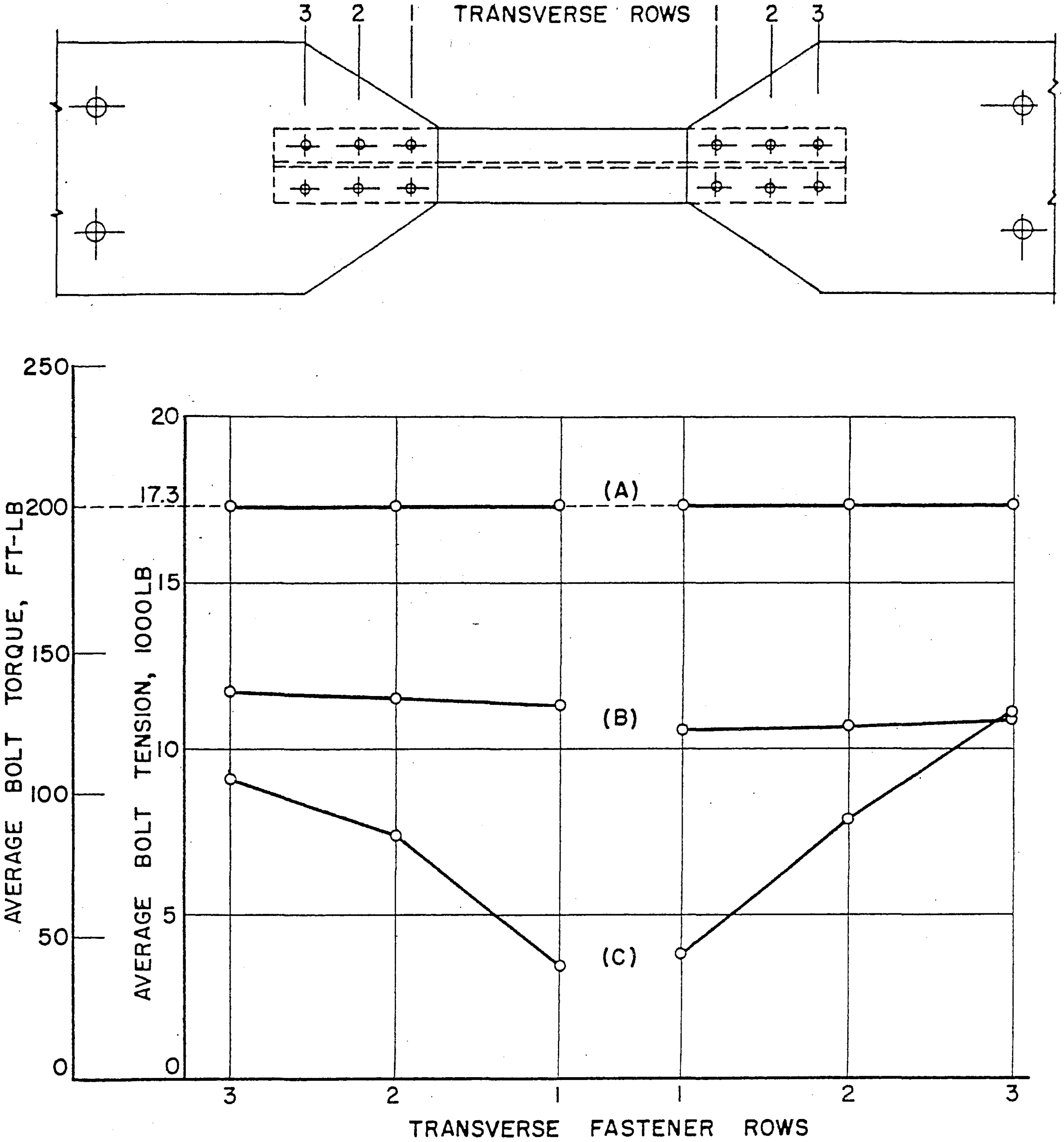


FIG. 16 BOLT TENSIONS AT VARIOUS STAGES DURING TESTING OF SPECIMENS OF SERIES B6



(A) INITIAL BOLT TENSION, STATIC & FATIGUE TESTS
(B) BOLT TENSION AFTER FATIGUE TESTS
(C) BOLT TENSION AFTER STATIC TEST OF P6-5

FIG. 17 BOLT TENSIONS AT VARIOUS STAGES DURING TESTING OF SPECIMENS OF SERIES P6

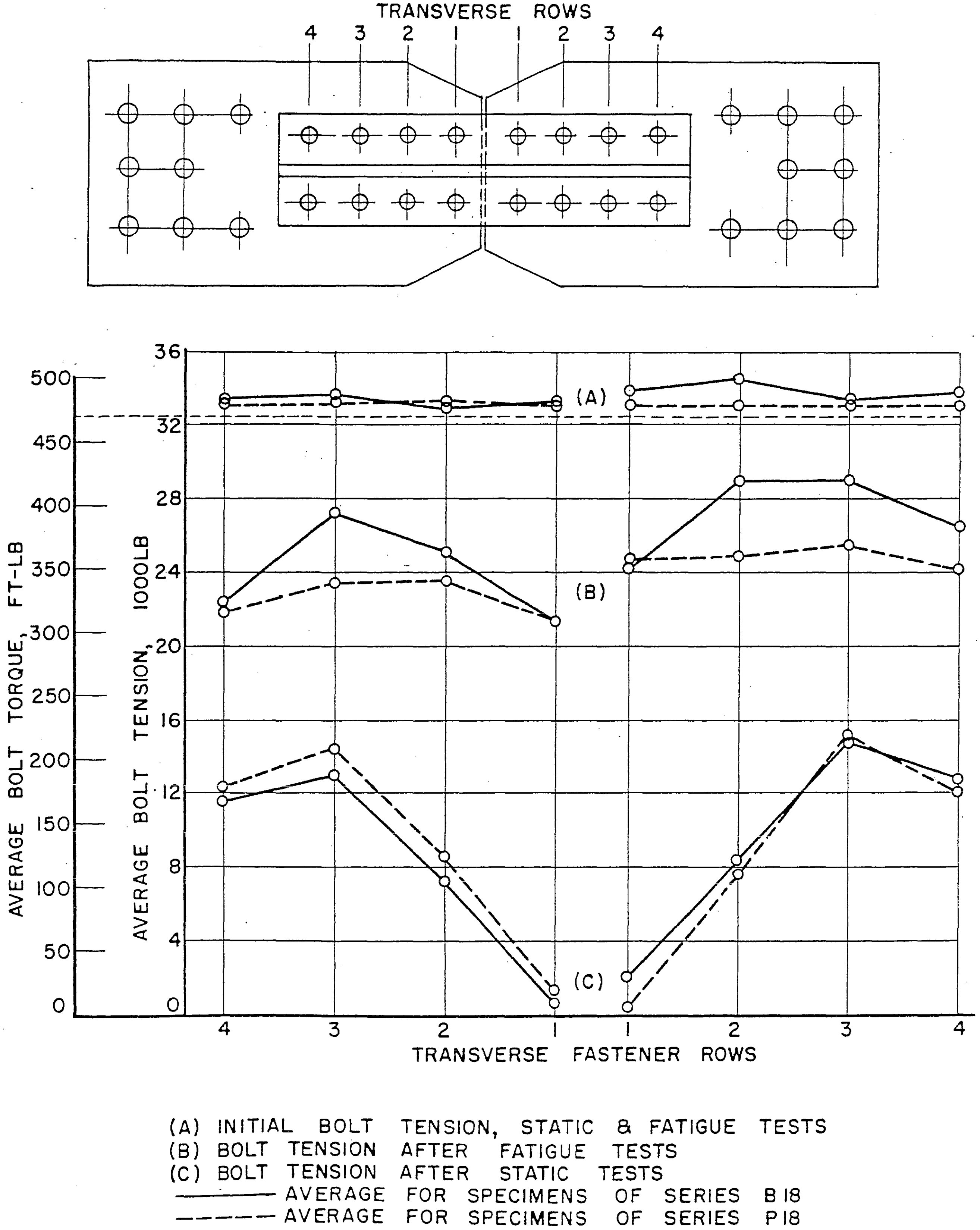


FIG. 18 BOLT TENSIONS AT VARIOUS STAGES DURING TESTING OF SPECIMENS OF SERIES B18 AND P18

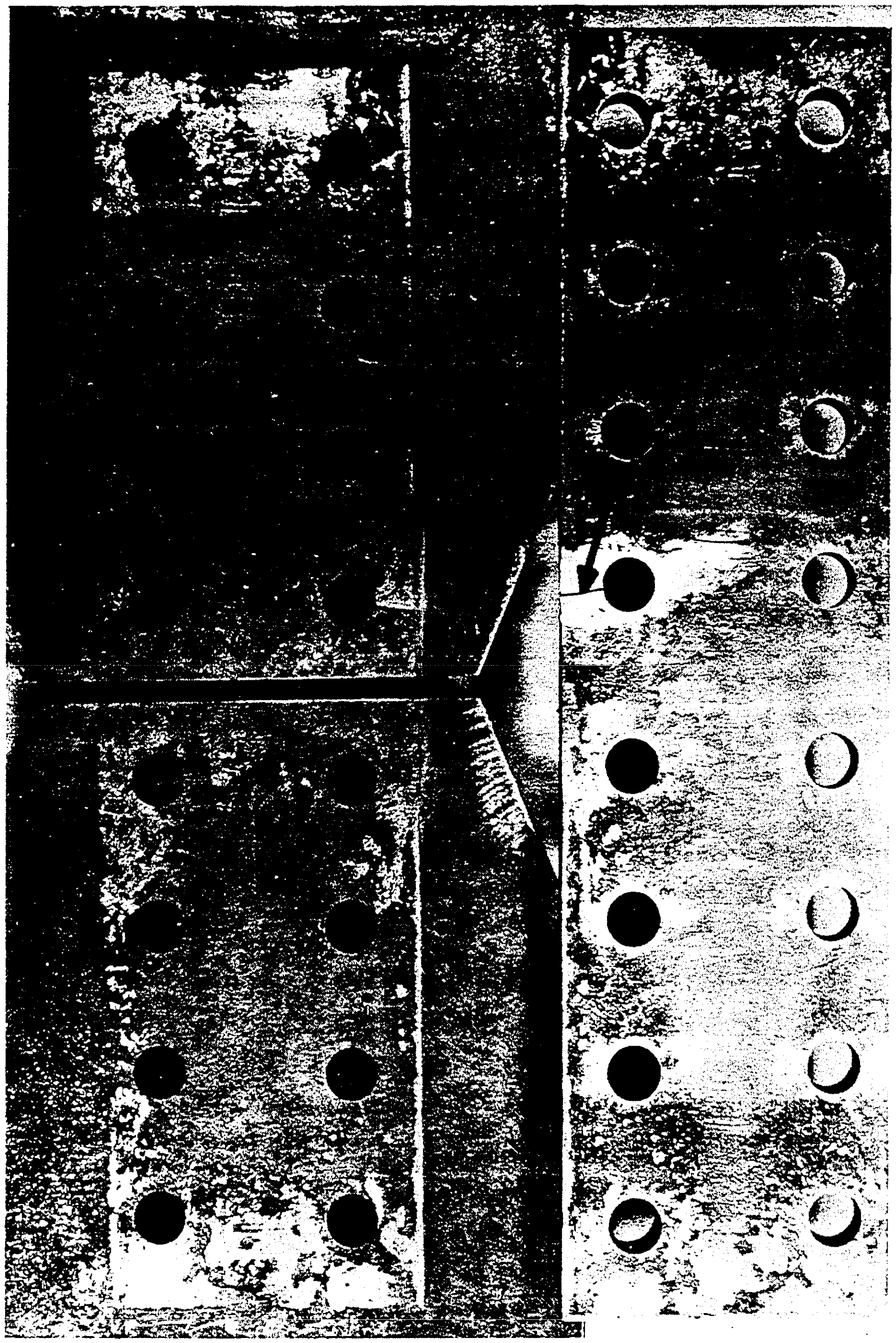
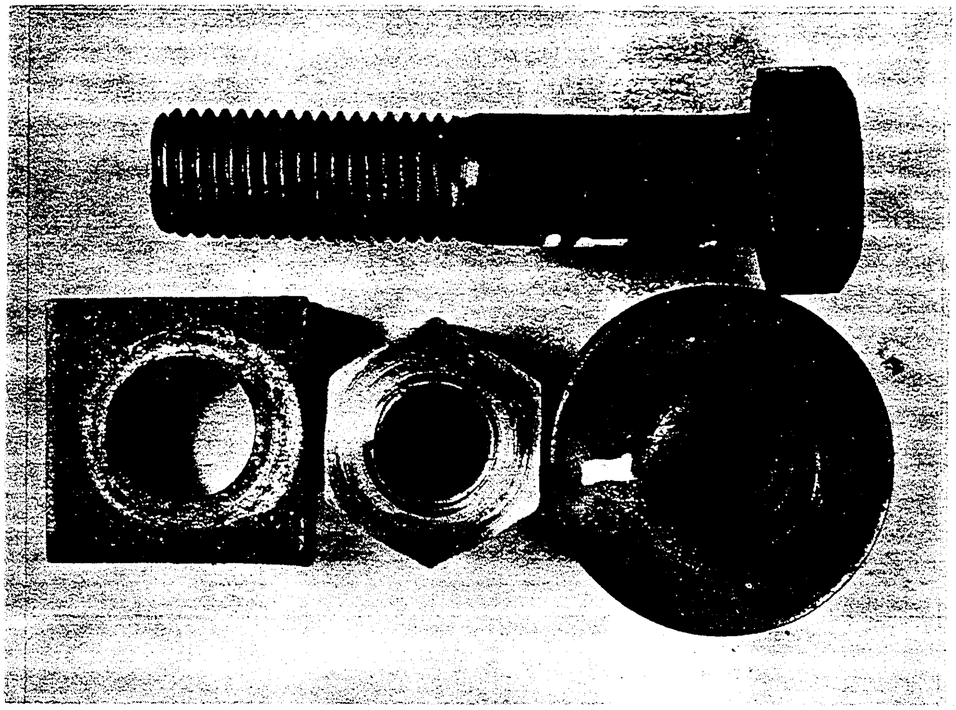
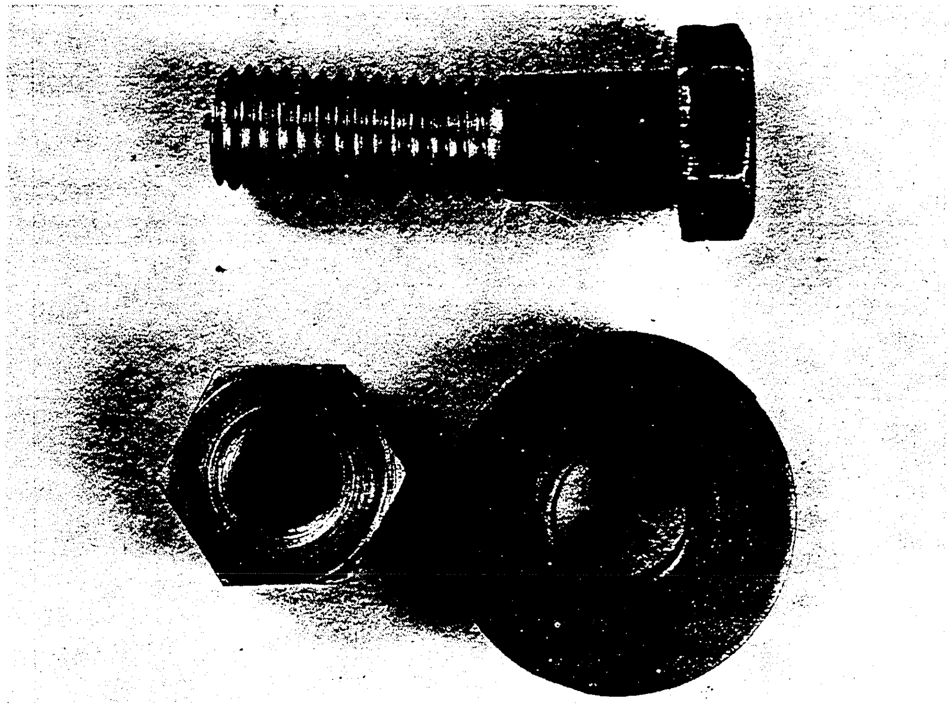


FIG. 19 GRINDING ACTION ON JOINT CONTACT SURFACES OF SPECIMEN P18-2



(a) 7/8 in. BOLT, NUT, & WASHERS
(3/4 ACTUAL SIZE)



(b) 5/8 in. BOLT, NUT, & WASHER
(ACTUAL SIZE)

FIG. 20 BOLTS REMOVED FROM FATIGUE SPECIMENS
(WITH PLAIN WASHERS ON FLANGES)