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HISTORY OF TENSION IN BOLTS CONNECTING LARGE JOINTS

by

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ABSTRACT

This report describes an experimental study of the changes in bolt tension in high-strength A325 and A490 bolts connecting A440 and constructional alloy steel joints.

Until major slip occurred in the large bolted joints, high-strength steel bolts lost only a small amount of their initial tension. This loss was due to the plate contraction caused by the Poisson effect.

After slip the bolts came into bearing, and the variations in bolt tension became more pronounced. For bolts with a 4 in. grip the bolt tension decreased with an increase in joint load beyond the slip load. As the joint load approached its ultimate value, however, the bolts at the lap plate end began to show an increase in tension. This was brought about by the outward prying action of the lap plate. These results showed that the load transferred by friction, at the ultimate joint strength, was negligible.

For bolts with an 8 in. grip the bolt tension increased as the joint was loaded beyond the slip load. This increase was caused by bending of the bolts, and indicated that some load was being transferred by frictional resistance in the interior of the joint. However, because of the lap plate prying phenomenon there was a clear separation of the faying surfaces near the joint end and the bolt tension was not completely indicative of the normal force acting on the faying surface.

For all joints it was found that the bolts at the lap plate ends, being under a higher combined shear and tension loading than the bolts at the main plate end, were usually the first to fail.

1. INTRODUCTION

1.1 SUMMARY OF PREVIOUS STUDIES

Little is known about the variation of internal bolt tension in bolts connecting large joints subjected to static tensile loads, particularly near the ultimate strength of the joint.

Because of the observed behavior of rivets, it has been generally assumed that the initial clamping force has no significant effect on the shear strength of the rivets(1). Yielding of the rivet apparently reduced the clamping force and the shear strength was unaffected.

Several investigators have measured changes in the internal bolt tension up until slip occurs. Lenzen(2) tested several small bolted butt splices connected by 3/4 in. high-strength bolts and found that the measured decrease in bolt tension varied directly with an increase of joint tensile load until major slip occurred. It was apparent that the Poisson effect was the principal cause of the change in bolt tension. The changes in bolt tension were based on measured changes in strain as recorded by strain gages attached to the bolt shank. One test of a single bolt specimen showed a decrease in the clamping force of 7% up to slip, while a 9 bolt specimen showed a decrease of about 13%.

Tests reported by Foreman and Rumpf(3) to determine the basic shear strength of single A325 bolts indicated that bolt tension had no effect on the ultimate shear strength of bolts loaded in double shear. Apparently the inelastic bolt deformation relieved the bolt clamping force in these short bolts in the same manner as that observed in rivets(1).

Shear tests were also conducted with lubricated and non-lubricated faying surfaces[3][4]. Bolts tested in the non-lubricated joints failed at slightly higher loads indicating that friction carried a small but negligible portion of the ultimate load.

During recent studies concerned with the coefficient of friction, the bolt tension was measured with the aid of strain gages attached to the bolt shank[5]. These tests showed that the change in bolt tension was proportional to the applied joint tensile load until slip occurred, as was the case with Lenzen's[2] study. Good agreement was obtained between the measured changes in bolt tension and the computed values based on the Poisson effect.

An investigation of the shear strength of single alloy steel bolts[6] showed that the initial bolt tension had no appreciable effect on the shear strength of A325 and A490 bolts.

Brief mention of the instrumentation for measuring changes in the internal bolt tension for bolts installed in a large joint was given in Ref. 7. However, the results were not presented or discussed and, as a result, that information has been incorporated into this paper.

1.2 PURPOSE AND SCOPE

The purpose of this investigation was to ascertain the magnitude of the internal bolt tension when the ultimate load of large bolted connections had been reached. Since tests of single bolts indicated that the initial preload had a negligible effect on the ultimate shear strength, it was desirable to know whether or not bolt tension provided any frictional load transfer near the ultimate strength of multi-fastener joints.

The agreement between tests of large bolted connections[3][7][8] and theoretical studies[9], which assumed that the frictional forces could be neglected, was good. This implied that bolt tension and the corresponding frictional forces were negligible at the ultimate joint load in large bolted connections. Tests were desirable to further verify this implication.

The results of the measurement of changes in internal bolt tension for bolts installed in seven large joints is reported herein.

2.1 TEST JOINTS AND TESTING PROCEDURES

Table 1 shows the types of butt splice joints which were tested, and the location within the joints of the bolts which had strain gages attached.

Joints E163 and E164 each had a nominal thickness of 8 inches. The main plate was formed by four 1 inch plates. Lap plates, consisting of two 1 inch plates, were bolted to each side of the main plate to form the butt splice.

Each of the remaining five joints had a nominal thickness of 4 inches (two 1 inch plates for the main plate section with one 1 inch lap plate on each side).

Load was applied to the joint continuously until major slip occurred. At increments of 50 or 100 kips the loading was momentarily stopped until all dials and gages could be read. At these loads the change in bolt strain indicated by the SR-4 strain gages was recorded. Beyond the slip load of the joint the strain gage recordings were taken in the same manner. As the predicted joint failure load was approached the readings given by the strain gage attached to the critical fastener at the lap plate end were recorded at intervals of 5 to 10 kips to obtain the change in strain at the failure load.

2.2 BOLT INSTRUMENTATION AND CALIBRATION

The two types of bolts used met the ASTM specification requirements for their particular types[(10)(11)]. The nuts used with the A490 bolts were ASTM A194, grade 2H. Heavy semi-finished nuts were used with the A325 bolts. One hardened washer was provided under the nut of each bolt. Neither the threads nor the thread runout extended into the shear planes.

SR-4 type A7 electric resistance gages were attached to the bolt shanks in the manner shown in Fig. 1. Small areas, approximately 1/2 in. long and 1/16 in. deep were milled just under the bolt head to provide a flat surface on which to mount the gages. These milled areas did not extend into the shear planes. The gages were mounted, one on each side of the bolt, and were wired in series. The bolts were installed so that the gages faced at 90^{o} to the direction of the applied load. These three factors combined to give an average strain reading, and eliminated any effect of lateral bending.

In order to relate the strain readings taken on the SR-4 gages to bolt tension each bolt had to be calibrated in direct tension. Typical calibration curves are shown in Figs. 2 and 3, for the A490 and A325 bolts respectively. Figures 2a and 3a show the elongation of the whole bolt, as measured by a 1/10,000 inch dial gage. Figures 2b and 3b show the strain readings recorded from the SR-4 gages. It is apparent in Fig. 2b that the A490 bolt shanks remained elastic throughout the calibration. However, some permanent deformation occurred in the threads, as is shown by the elongation measurements in Fig. 2a. Figure 3b indicated that the A325 bolt yielded in the shank as well as in the threads.

2.3 INSTALLATION OF BOLTS

Figure 4 is a schematic representation of the method of installing the gaged bolts. A bolt tension, which was usually slightly below the average load of the remaining bolts in the joint, was chosen as the "desired" tension. The strain "required" was determined from the individual calibration curve of each bolt. The bolt was then tightened (by a pneumatic impact wrench) until this strain was achieved.

Each gaged bolt in joints J42b and J42c was installed to an initial load of 75 kips. This was just slightly above the proof load for those bolts. The gaged bolts in K42d were given a preload of about 60 kips each, again just slightly above proof load. The bolts in joints, E163, E164, and E721, were installed at a load of about 40 kips each, as compared to a proof load of 36.05 kips for these bolts.

The A325 bolts used in joint E741, were installed in a different manner from those discussed above. Each bolt was tightened, using an impact wrench, to 1/2 turn from snug and the bolt elongation was recorded by using a C-frame extensometer with a 1/10,000 dial. The load-strain behavior of the bolt was assumed to follow the previously determined calibration curve under further loading. The complete bolting up procedure for joint E741 is given in Ref. 7.

3. TEST RESULTS AND ANALYSIS

The variations of the internal bolt tension with joint load are shown in Figs. 5 to 11 for each joint tested. The change in bolt tension was computed, by using the measured changes in bolt strain, from the calibration curve determined for each bolt. In some cases the internal bolt tension increased beyond the yield strength. In these instances the bolt load was determined from the load-strain relationship of the direct tension tests of the particular bolt lot.

3.1 BEHAVIOR UP TO MAJOR SLIP

The test results plotted in Figs. 5 to 11 show that the bolt tension had decreased from 1% to 8% at the occurrence of major slip. This was expected, and was caused by the Poisson effect.

In most joints major slip occurred suddenly, and all bolts throughout the joint came into complete bearing. At this instant the long (8 in.) bolts showed an increase in load, as is shown in Fig. 5 for joint E163. (Because of the nature of "slip" in joint E164 this effect was not noted). Joints with 4 in. grips showed a decrease in bolt tension at the instant of major slip. This is clearly shown in Figs. 7, 9, 10, and 11.

This sudden increase in bolt tension in joint E163 was probably caused by bending in the long bolts. The reason for the reduction in bolt tension in the shorter grip joints is not readily apparent. A very complex stress condition exists, of course, in the bolt and may have caused the reduction in tension.

3.2 BEHAVIOR AFTER SLIP

Three separate and distinct behavior patterns were noted on the variations in bolt tension, after major slip had occurred.

The first pattern is illustrated in the behavior of the long bolts (8 in. grip) used in joints E163 and E164. (Figs. 5 and 6). As load was applied to the joint after major slip several of the bolts in the interior of the joints indicated an increase in tension, as shown by measured strains. Visual observations of the plate edges indicated a relative movement of the individual plates which would cause the bolt to assume a curved shape. Thus, as load was increased on the joint, tension was introduced into the bolts by this bending action.

The inelastic deformations due to bearing and yielding of the plate material caused a prying action which tended to move the lap plate outward from the main plate. This action was responsible for a further increase in the tensile load of those bolts located near the lap plate end of the joint. This outward movement of the lap plate with respect to the main plate extended some distance from the lap plate end. In joint E163, for example, it was possible to insert an ordinary sheet of paper between the lap plate and the main plate, as far down as the third row, just prior to joint failure. At this same load the separation at the first bolt row was about 1/16 in.

The increase in tension of those bolts in the interior of the joint was apparently caused by the bending effect. The heads of bolts 5 and 6, (Fig. 5) were observed to bear on one edge as the ultimate joint load was approached, and it was obvious that bolt bending was considerable.

Bolt 4 in joint E164, Fig. 6, behaved differently from all other bolts in that joint. No explanation for this behavior is apparent, but it indicated that some of the interior bolts, with 8 in. grips, may have unloaded instead of increasing in tension.

Figures 7, 8, and 9 shows the behavior of the short bolts (4 in. grip) tested in A440 steel joints. As the joint was loaded beyond slip the bolt tensions dropped continuously in all fasteners, until the ultimate load was approached. Near the ultimate load considerable lap plate prying action was present and this caused the bolts near the lap plate end to show an increase in tension. This behavior is apparent in Figs. 8 and 9. An electrical short occurred in bolt No. 1 (see Fig. 7) of joint E721 at a load of 900 kips, and thus prevented the observation of bolt tension beyond that point. However, from the lap plate prying action, which was visually obvious, it was apparent that an increase in bolt tension had occurred. The interior bolts in joints E721, E741, and K42d all showed a continual decrease in tension with joint load.

Joints J42b and J42c were A514 steel plates connected by A490 bolts. These joints were proportioned such that no inelastic deformations had occurred in the plate material at the ultimate joint load. Consequently, there was practically no lap plate prying, and the bolt tension decreased continually with joint load until failure had occurred. This is illustrated in Figs. 10 and 11.

In any symmetrical butt splice the fasteners at each end carry the same amount of load in shear. Consequently one would expect that failure in a joint would be precipitated by failure of one of the end fasteners. Many tests have shown that the bolts at the lap plate end are usually the first to unbutton. Figures 7 and 9 show that the prying action produces a large tensile component in the row of bolts at the end of the lap plates. Since these bolts are under a higher combined shear and tensile stress state than the bolts at the main plate end they would be expected to fail first. (Variations in individual bolt properties may cause initial failure at the main plate end, but in most tests the bolts at the lap plate end fail first).

3.3 LOAD CARRIED BY FRICTION

For the joints with short bolts (4 in. grip) it is obvious that the load carried by friction, near the ultimate joint load, was negligible. The bolts near the lap plate end indicated an increase in tension loading. However, this was caused by the prying apart of the lap plate from the main plate, and this increase in bolt tension did not indicate a force holding the two faying surfaces together.

Present theory assumes that frictional forces can be neglected at ultimate joint load. It is apparent that in joints with long bolts this assumption is not altogether true since there is still very high tension in the bolts in the joint interior at ultimate load. As was pointed out previously, however, the lap plate prying of joint E163 was such that a paper could be inserted between the lap and main plate past the third row of bolts. Hence, the behavior of the joint near the critical areas was as assumed since no frictional forces were involved.

Some load was carried by friction near the main plate end of the joint, and in the joint interior. Neglecting this frictional resistance would lead to a conservative estimate of the ultimate load capacity of the joint. In actual tests it was observed that the maximum variations between the predicted loads (based on "no friction") and the actual loads was about 4% and occurred for long joints[9]. In all cases the predicted load was less than the true load. It is probable that part of this variation was caused by friction forces which were neglected in the analysis.

3.4 SHEAR STRENGTH AND INTERNAL BOLT TENSION

By using the strain energy of distortion theory a quantitative evaluation of the influence of internal bolt tension on the bolt shear strength can be made. The presence of a tensile stress component will cause a decrease in the ultimate bolt shear strength. The ultimate shear strength will be unaffected if the initially induced bolt tension is reduced to zero load under the shearing force. However, the decrease in shear strength is very slight, even when the bolt tension approaches its ultimate tensile value. Both measurements and theory have indicated that bolt failure at the main plate end of the joint was imminent at the failure load, even though the tension in these bolts has been considerably reduced. Subsequent load has caused these fasteners to fail following the failure of the bolts at the lap plate end.

Tests conducted on single A354BD bolts[12] have verified that the ultimate single shear strength is reduced when a bolt is subjected to a combined shear and tensile loading.

4. CONCLUSIONS

1. Until inelastic deformations occur in the fasteners the change in bolt tension is caused by Poisson's effect.

2. For joints with short bolts (4 in. grip) the amount of load transferred by friction at the ultimate joint load is negligible.

3. The bolts with long grips (8 in.) had considerable tension induced by bending action as the joint load approached its ultimate value. Near the critical fasteners the faying surfaces were not in contact and the assumption of no frictional forces was confirmed. However, in the joint interior it was apparent that some friction forces must be present.

5. ACKNOWLEDGEMENTS

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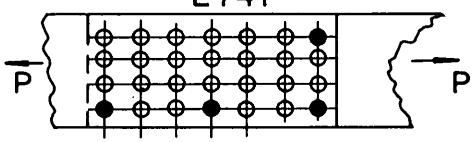
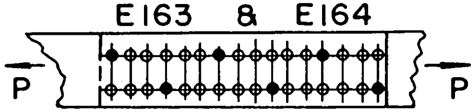
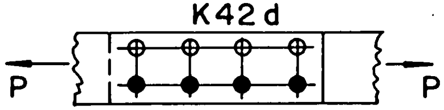
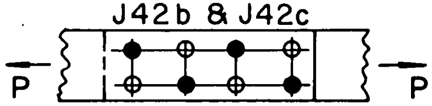
STATIC STRENGTH OF HIGH-STRENGTH BOLTS UNDER COMBINED TENSION AND SHEAR, Bulletin 469, University of Illinois, 1964

TABLE I.

JOINT CONFIGURATION	STEEL TYPE	BOLT TYPE	DIA., IN.	LENGTH UNDER HEAD, IN.	GRIP, IN.
E741 	A440	A325	7/8	5 1/2	4
E721 	A440	A325	7/8	5 1/2	4
E163 & E164 	A440	A325	7/8	9 1/2	8
K42d 	A440	A490	7/8	5 1/2	4
J42b & J42c 	A514	A490	1	5 1/2	4

● Bolts with SR-4 Strain Gages

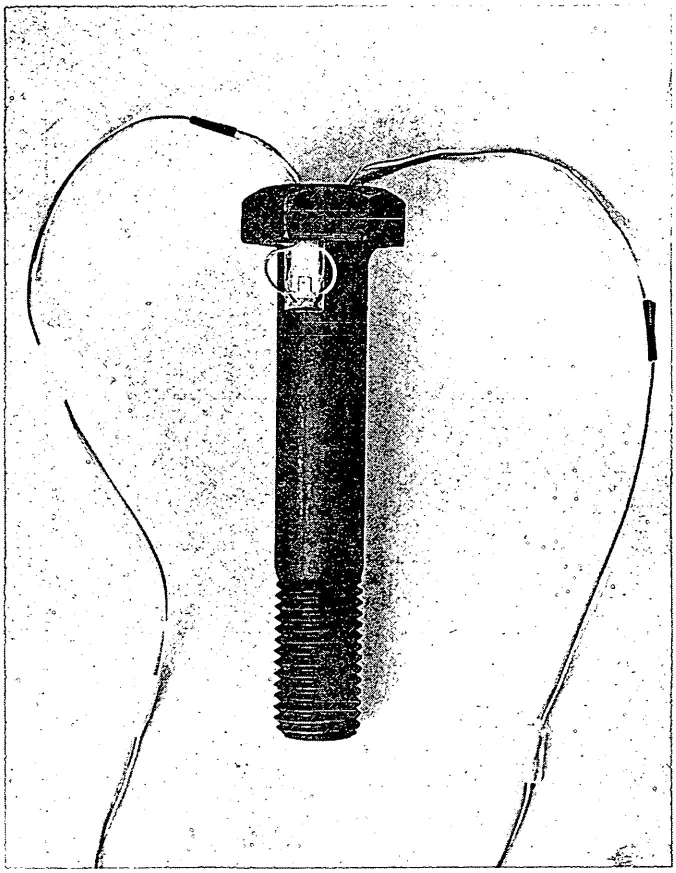


Fig. 1 Strain Gage Instrumentation on the Bolt Shank

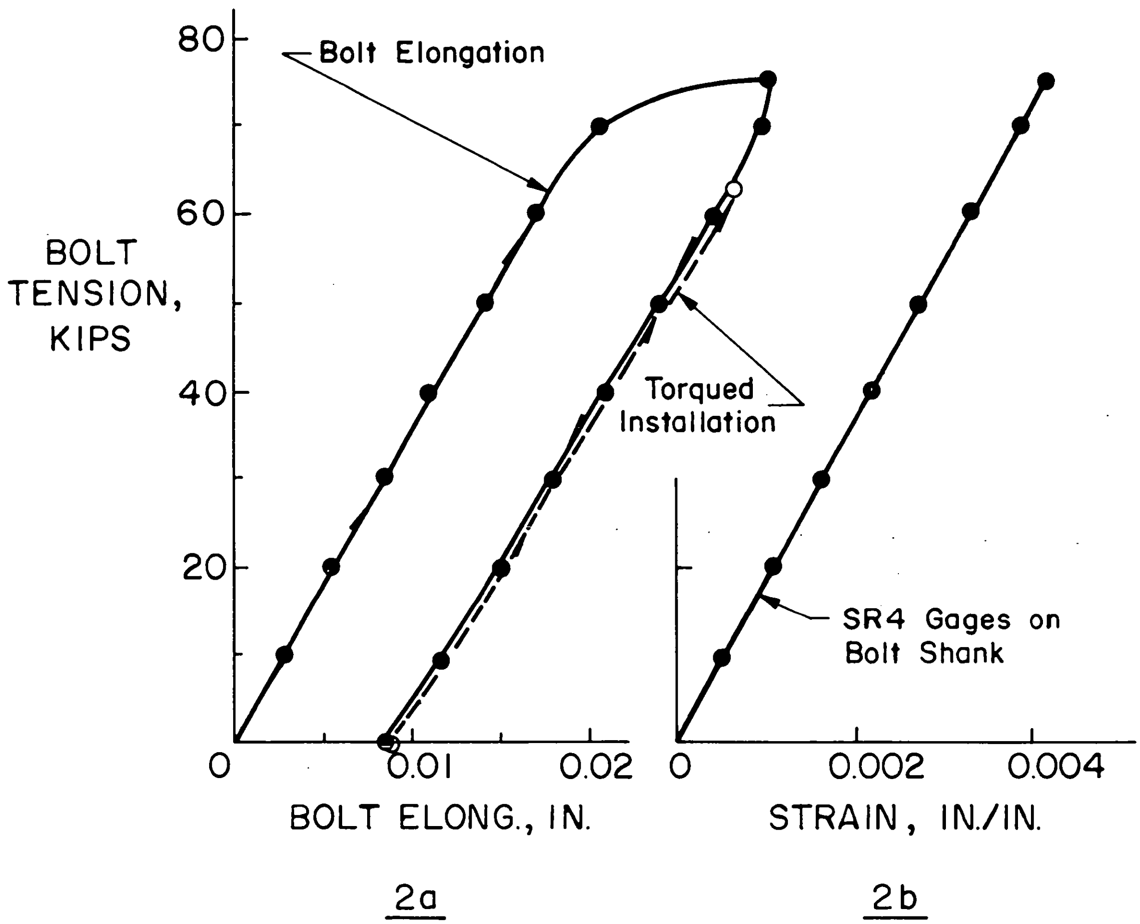


Fig. 2 Typical Calibration Curves for A490 Bolts

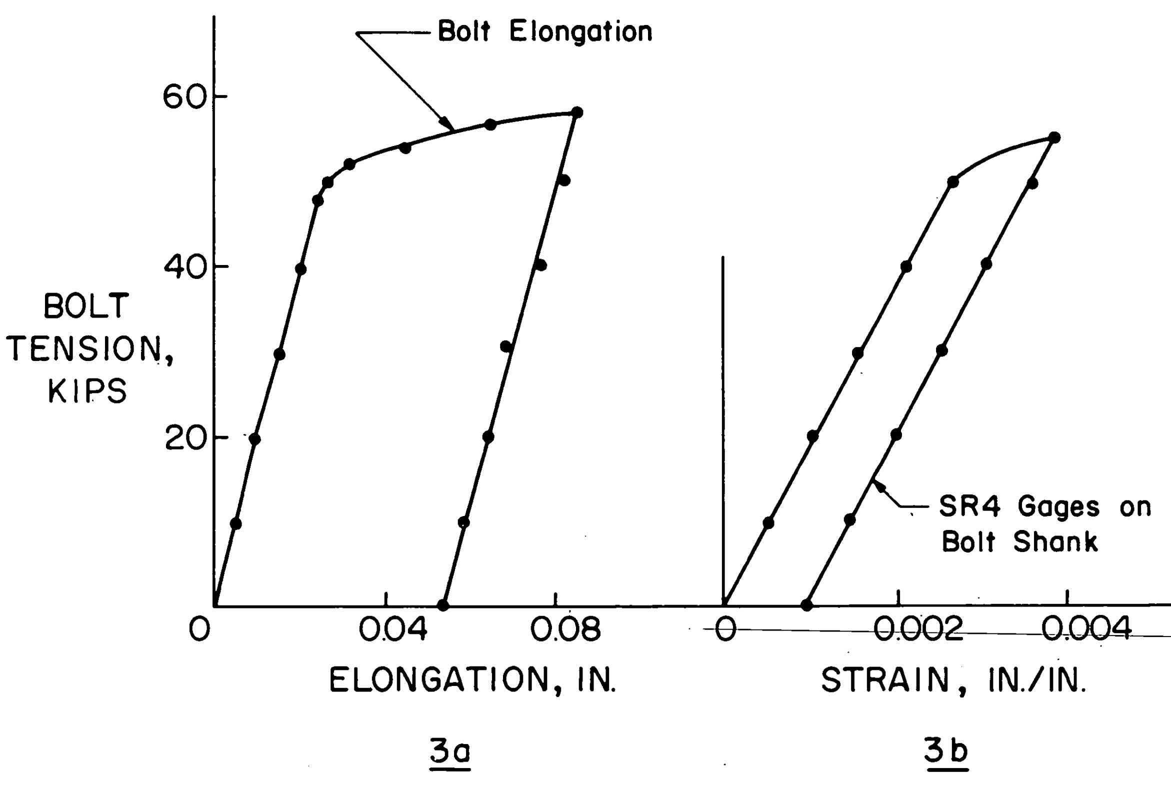


Fig. 3 Typical Calibration Curves for A325 Bolts

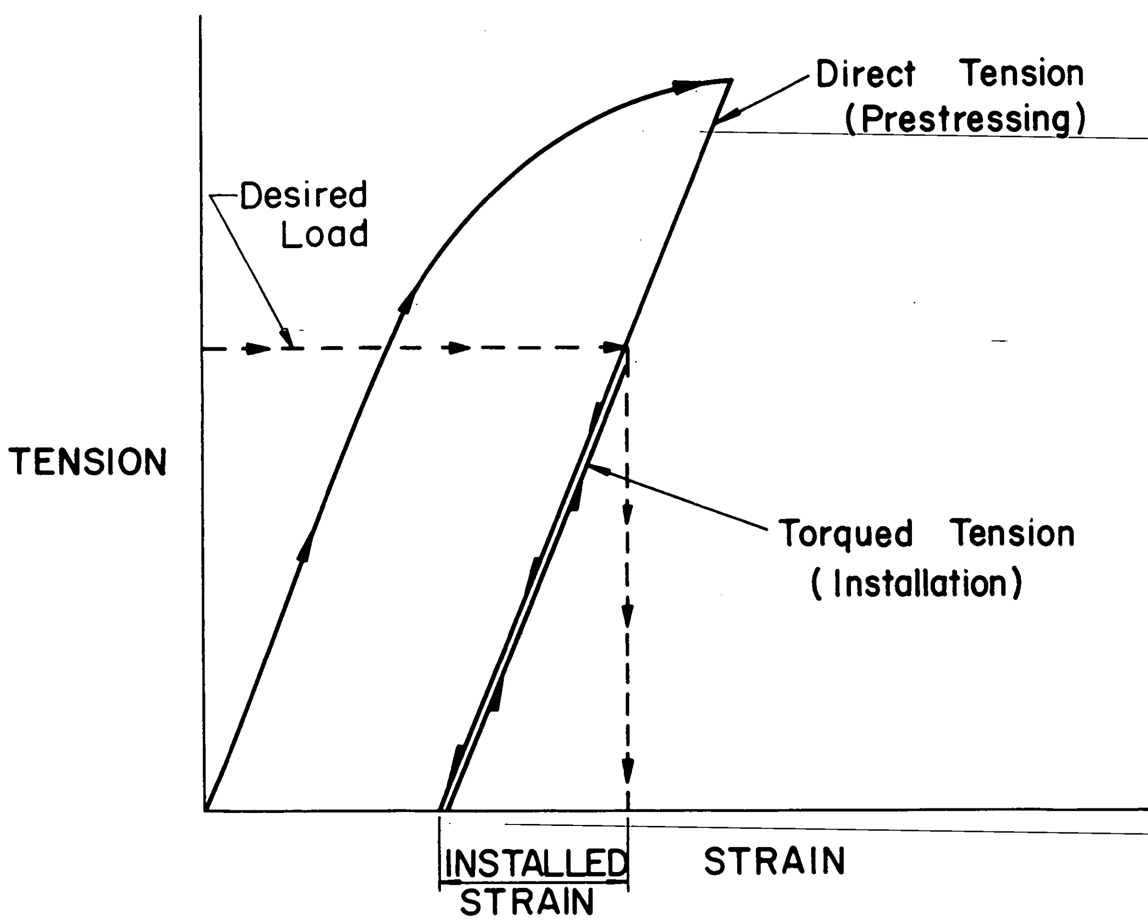


Fig. 4 Strain Required to Achieve Desired Bolt Tension

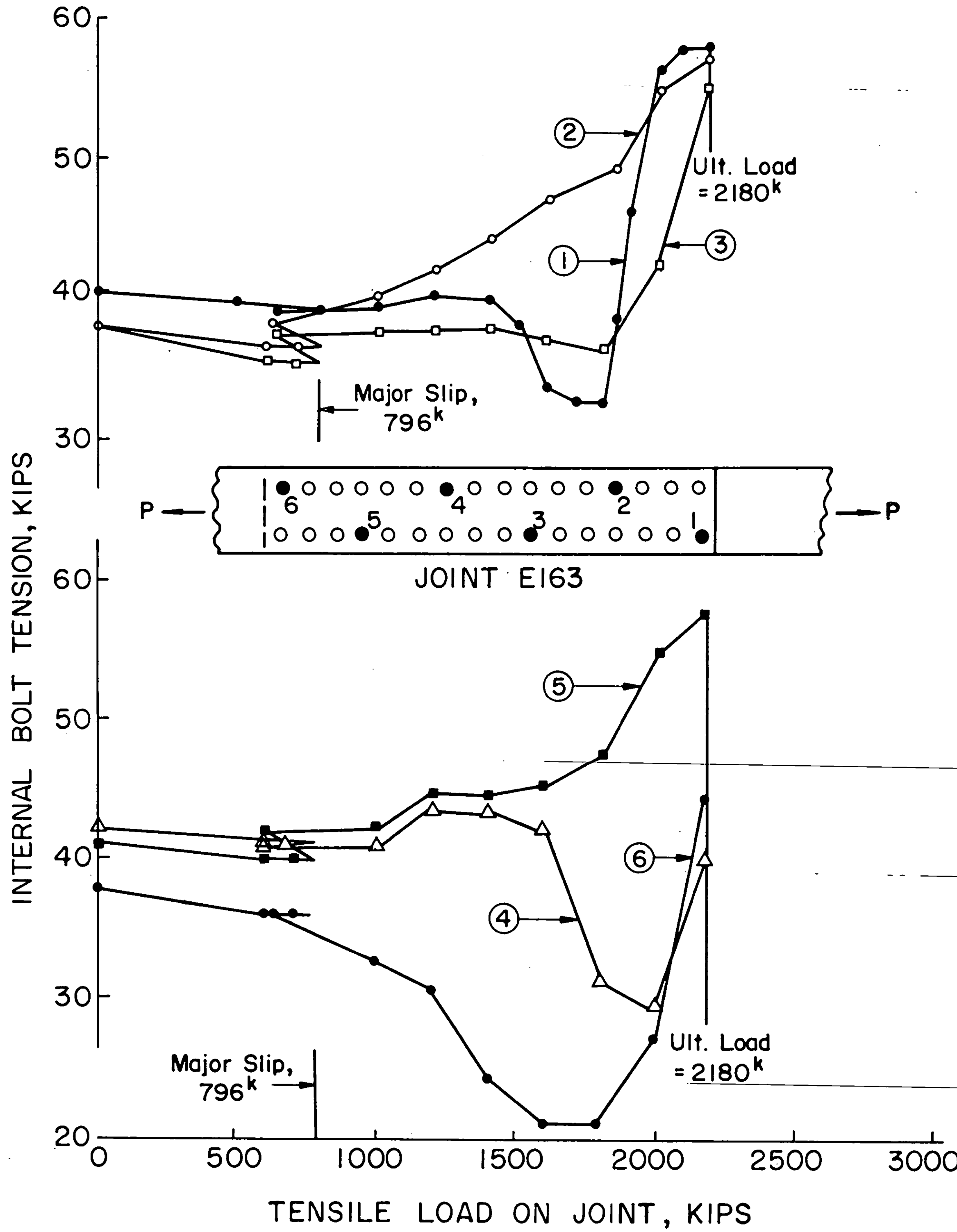


Fig. 5 Bolt Tension - Joint Load Characteristics of Joint E163

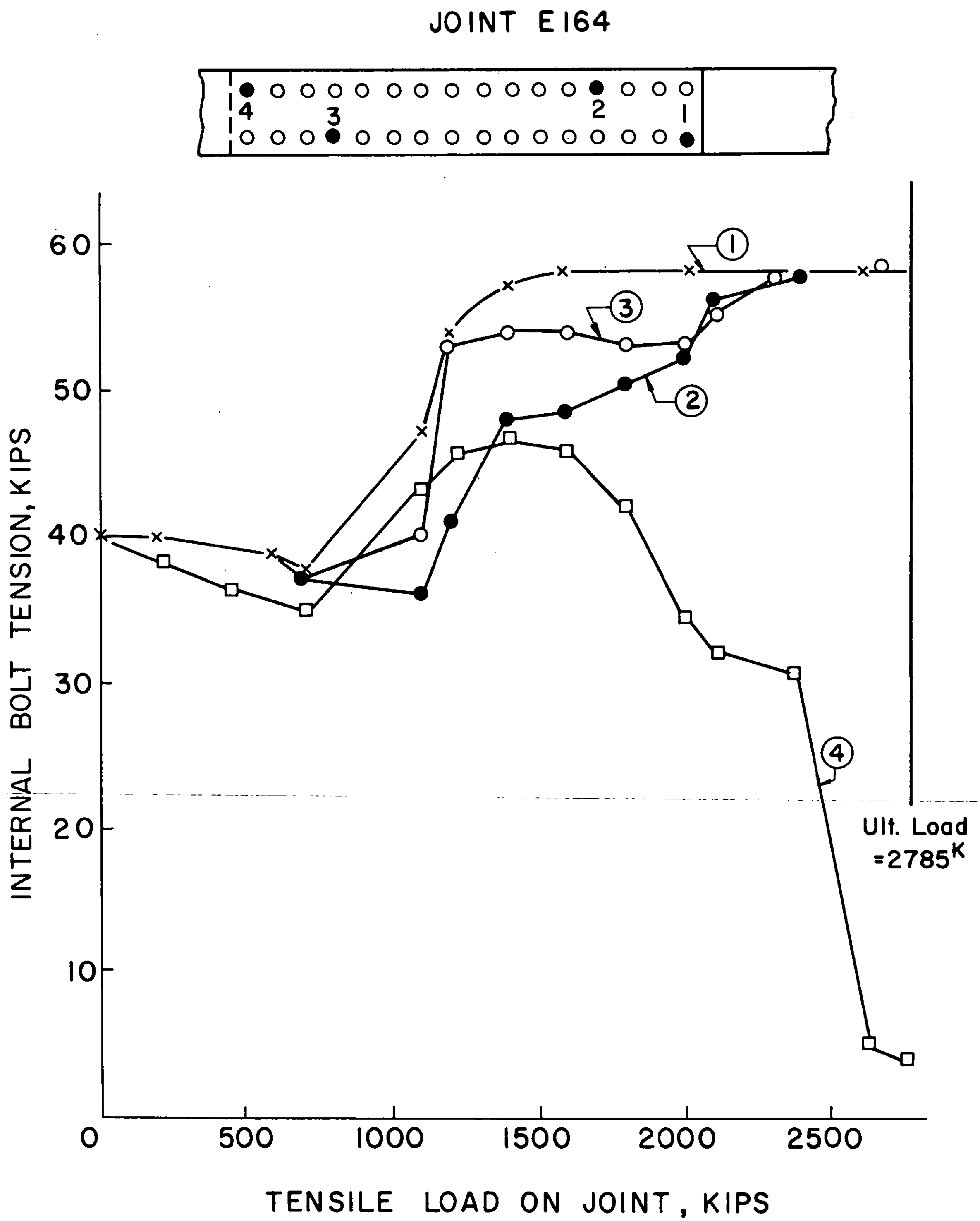


Fig. 6 Bolt Tension - Joint Load Characteristics of Joint E164

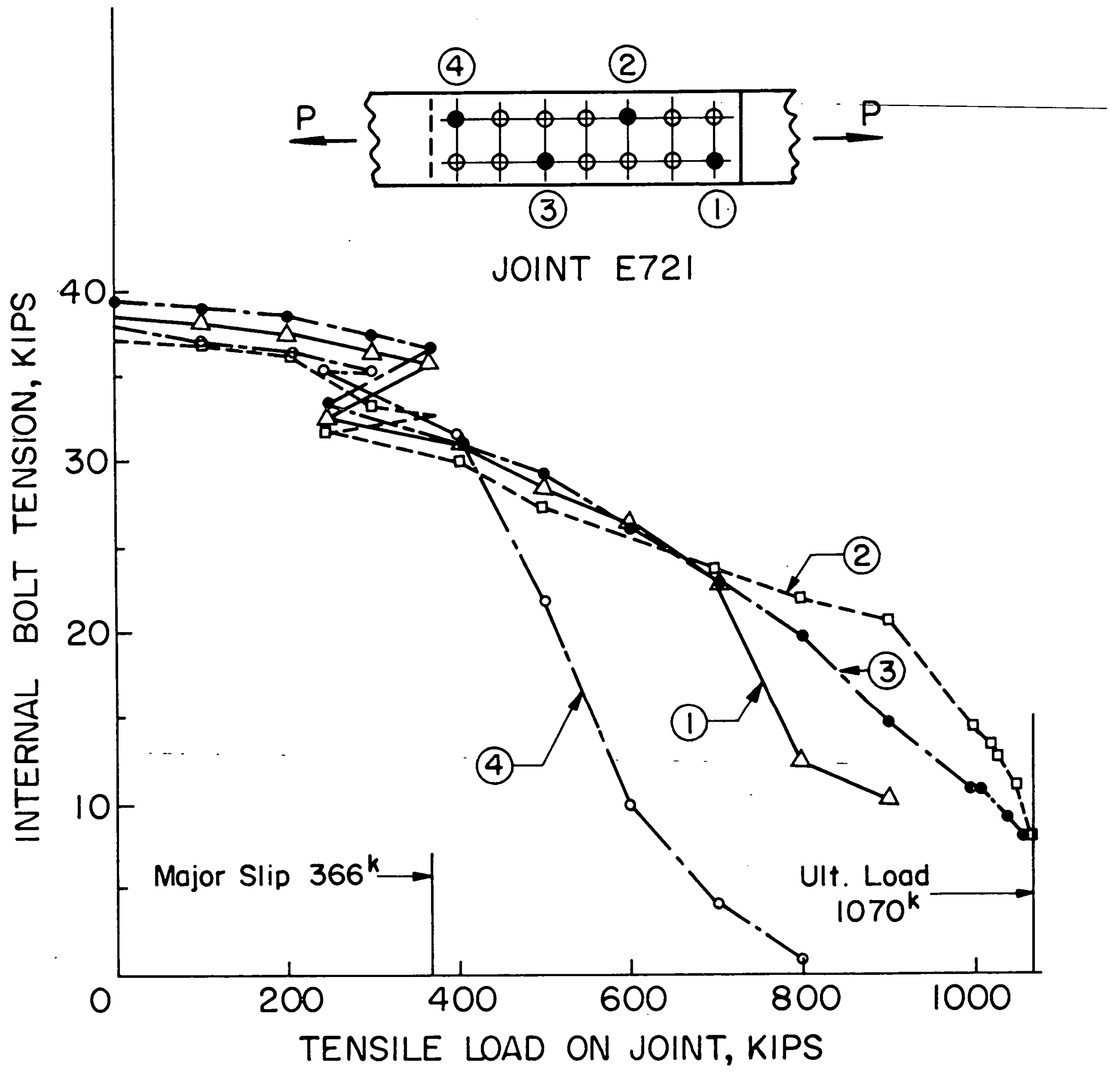


Fig. 7 Bolt Tension - Joint Load Characteristics of Joint E721

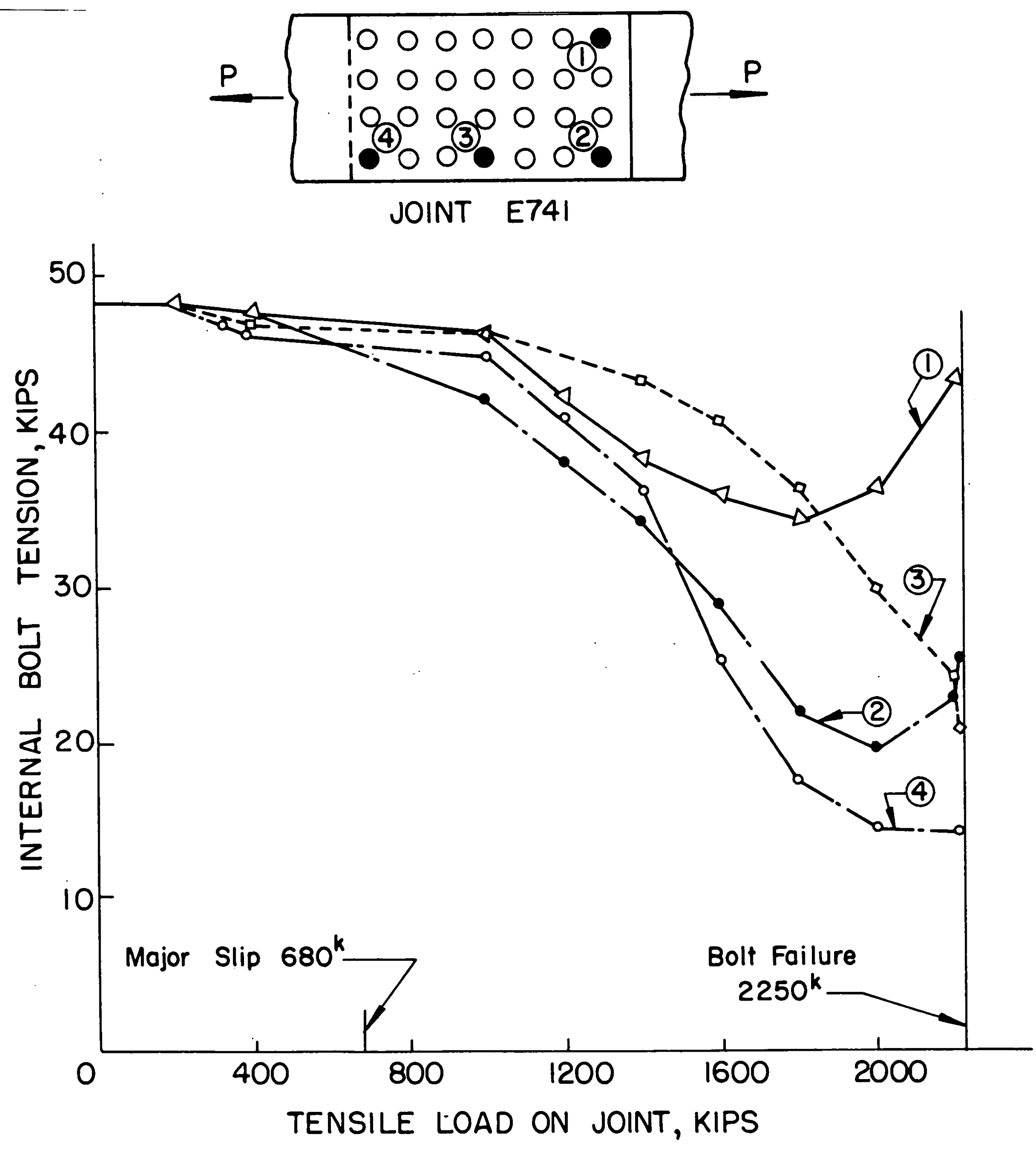


Fig. 8 Bolt Tension - Joint Load Characteristics of Joint E741

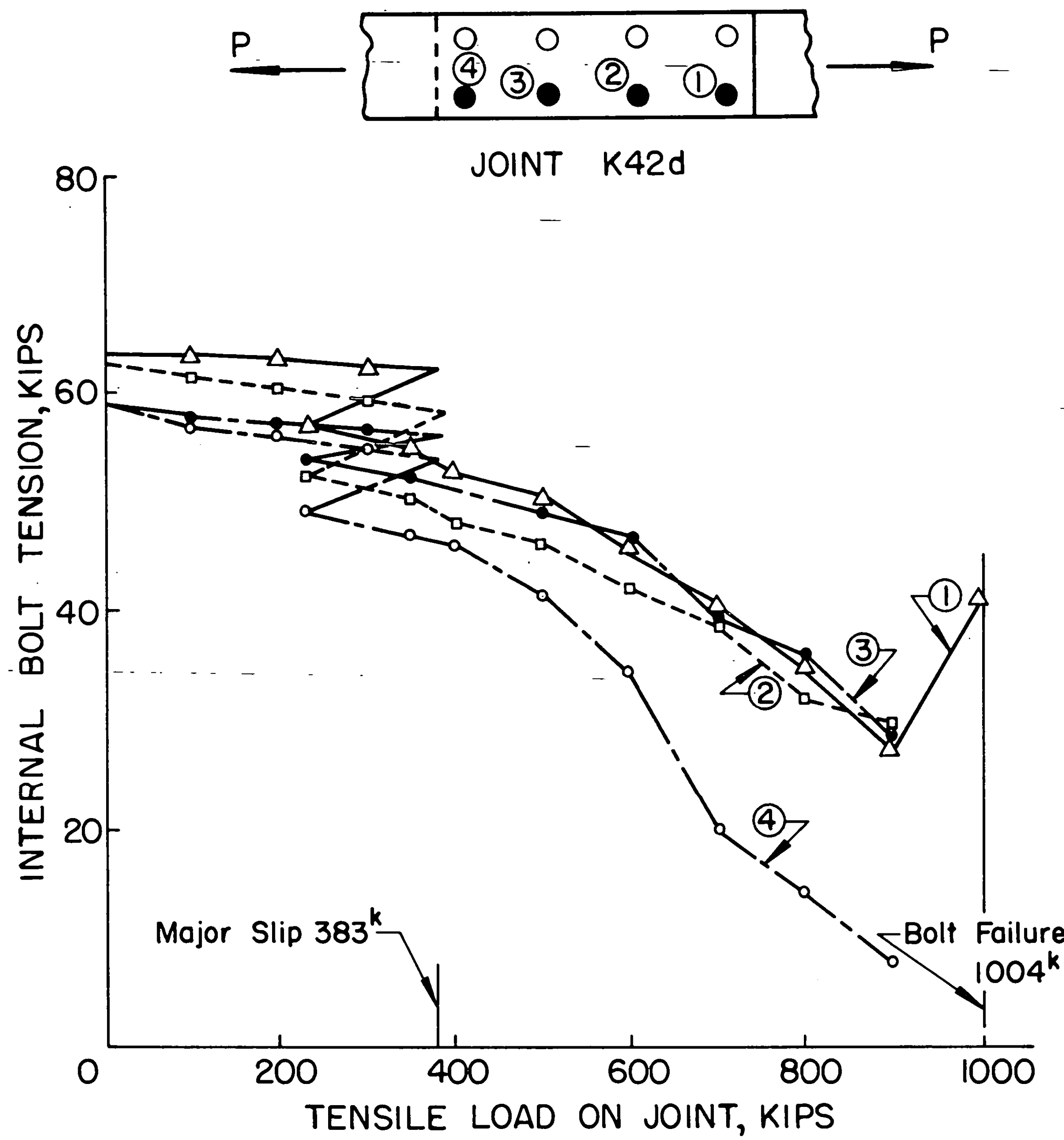


Fig. 9 Bolt Tension - Joint Load Characteristics of Joint K42d

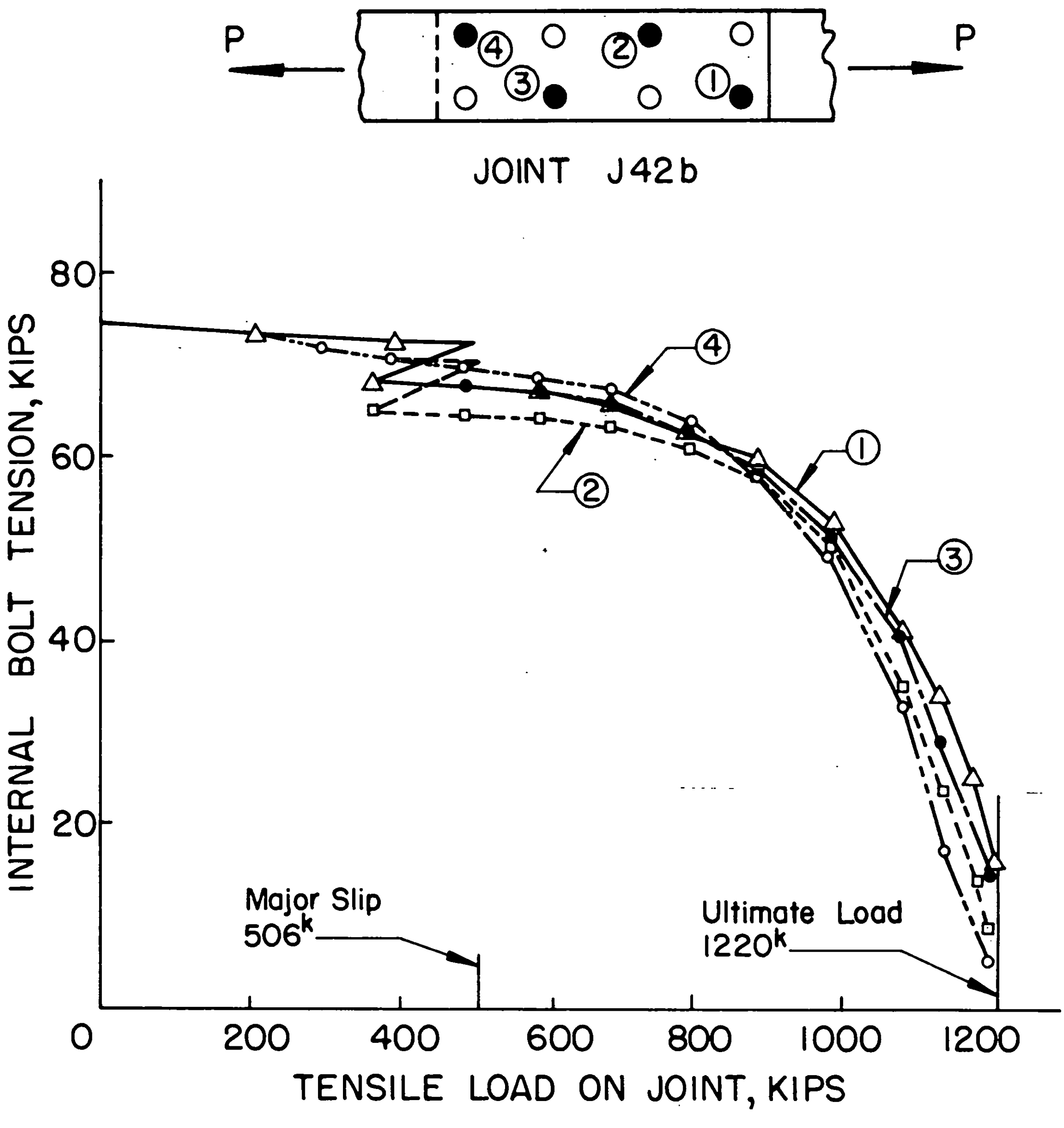


Fig. 10 Bolt Tension - Joint Load Characteristics of Joint J42b

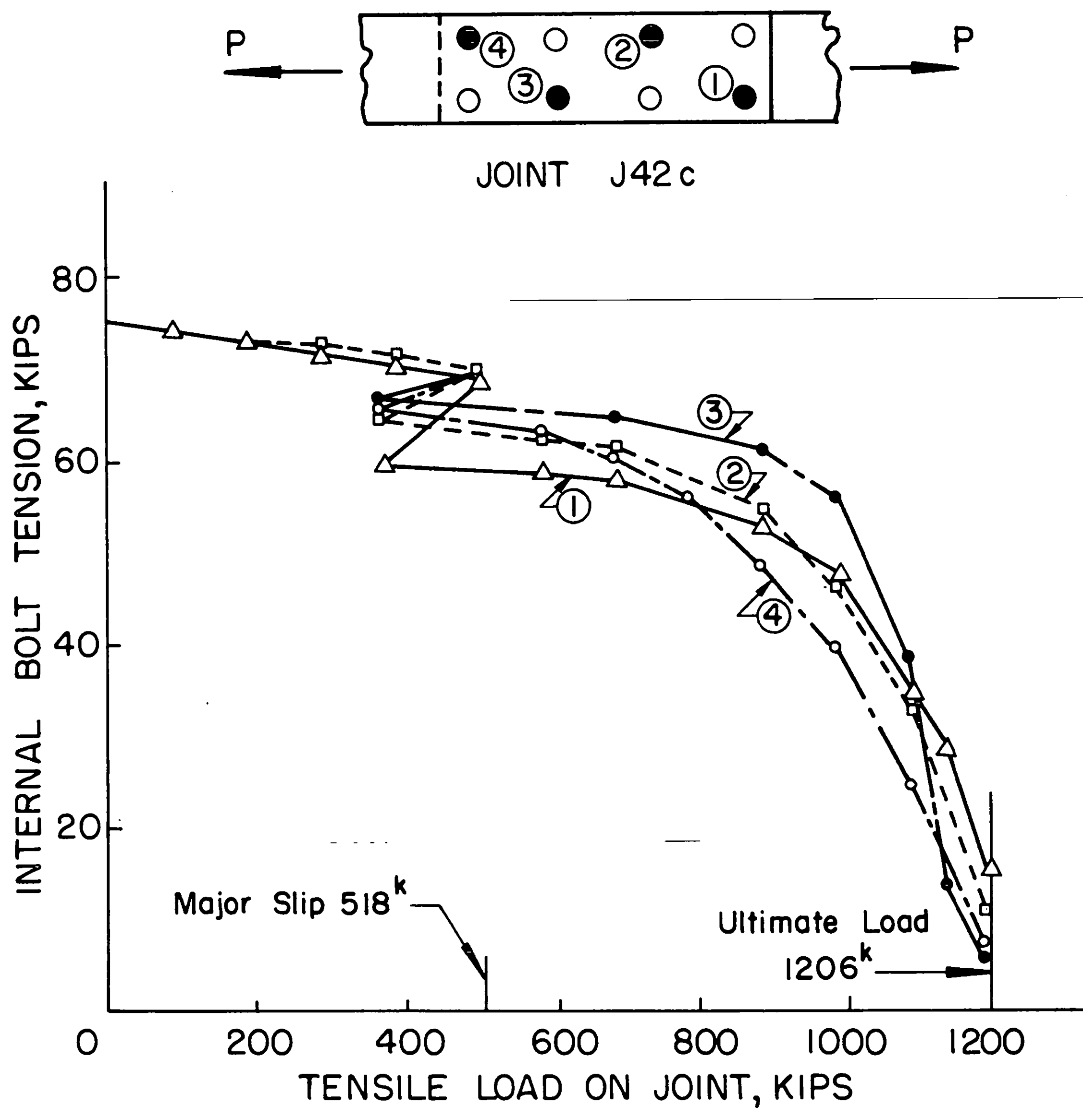


Fig. 11 Bolt Tension - Joint Load Characteristics of Joint J42c