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What Happens to Bolt Tension in Large Joints?

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ABSTRACT

An experimental study was made of the changes in bolt tension in high-strength A325 and A490 bolts connecting A440 (high-strength) and A514 (constructional alloy) steel joints. Until major slip occurred in the large bolted joints, high-strength steel bolts lost little initial tension. The loss was due to plate contraction caused by the Poisson effect.

After major slip, the bolts came into bearing and the variations in bolt tension became more pronounced. For bolts with a 4-in. grip, 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, bolt tension increased as the joint was loaded beyond the slip load. This increase, caused by bending of the bolts, indicated that some load was being transferred by frictional resistance within the joint. However, because of the lap plate prying phenomenon, there was a clear separation of the faying surfaces near the joint end. Therefore, the bolt tension was not indicative of the normal force acting on the faying surface.

For all joints, the bolts at the lap plate ends (under a higher combined shear and tension loading than the bolts at the main plate end) were usually the first to fail.

This work was carried out as part of the Large Bolted Connections Project sponsored financially by the Pennsylvania Department of Highways, the Department of Commerce—Bureau of Public Roads, the American Institute of Steel Construction, and the Research Council on Riveted and Bolted Structural Joints.

INTRODUCTION

Initial clamping force has no significant effect on the shear strength of rivets(1). Yielding of the rivet apparently reduces the clamping force and the shear strength is unaffected. An investigation of the shear strength of single bolts showed that the initial bolt tension had no appreciable effect on the shear strength of A325 and A490 high-strength bolts(2). However, little is known about the variation of internal tension in bolts connecting large joints subjected to static tensile loads, particularly near the ultimate strength of the joint. The agreement between predicted joint strengths and test results of large joints was good when it was assumed that the load transfer was by bearing and shear(3). This also suggested that bolt clamping was negligible at ultimate loads since frictional forces were negligible.

Several investigators have measured changes in bolt tension until slip occurs. Reference (4) reported tests of several small bolted butt splices connected by ¾-in. high-strength bolts and showed that the measured decrease in bolt tension varied directly

(1) Munse, W. H., and Cox, H. L., THE STATIC STRENGTH OF RIVETS SUBJECTED TO COMBINED TENSION AND SHEAR, University of Illinois Engineering Experiment Station Bulletin No. 437, December, 1956.

(2) Wallaert, J. J., and Fisher, J. W., SHEAR STRENGTH OF HIGH STRENGTH BOLTS, Journal of the Structural Division, ASCE, Vol. 91, ST3, 1965.

(3) Fisher, J. W., and Rumpf, J. L., ANALYSIS OF BOLTED BUTT JOINTS, Journal of the Structural Division, ASCE, Vol. 91, ST5, 1965.

(4) Lenzen, K. H., THE EFFECT OF VARIOUS FASTENERS ON THE FATIGUE STRENGTH OF A STRUCTURAL JOINT, Proceedings of the Association of American Railroads, Vol. 51, 1950.

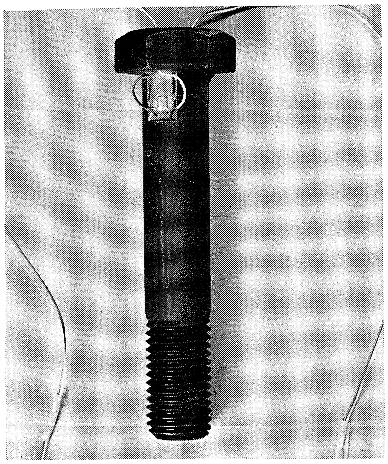

Fig. 1—Strain Gage Instrumentation on the Bolt Shank

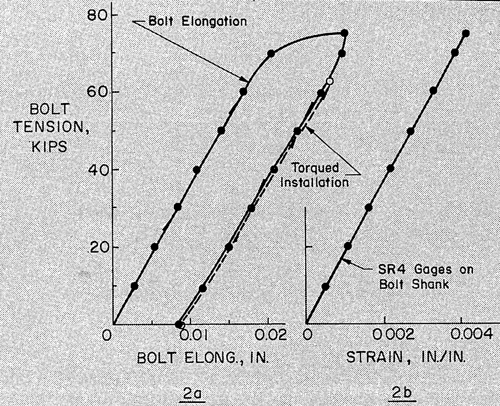

Fig. 2—Typical Calibration Curves for A490 Bolts

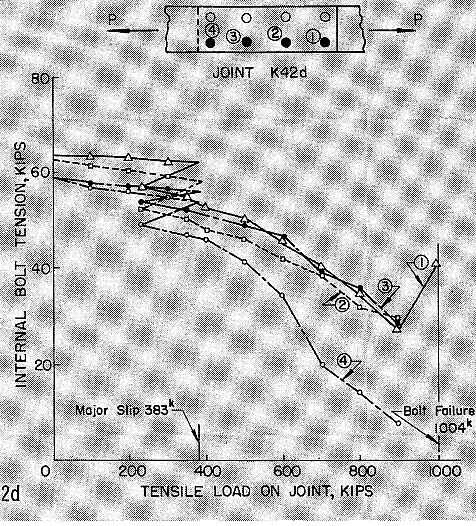

Fig. 3—Bolt Tension-Joint Load Characteristics of Joint K42d

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 tension changes were determined from measured changes in strain 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%.

During recent studies of the coefficient of friction, the bolt tension was measured with the aid of strain gages attached to the bolt shank(5). The measured changes in bolt tension corresponded closely with the computed values based on the Poisson effect.

The purpose of the investigation described in this article was to measure the internal bolt tension as load was applied to large connections to further confirm that frictional load transfer was negligible as the ultimate strength was approached.

DESCRIPTION OF TEST SPECIMENS AND PROCEDURES

Table 1 shows the types of butt splice joints which were tested and the locations within the joints of the bolts where strain gages were attached.

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

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

Load was applied to the joint continuously until major slip occurred. At increments of 50 to 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.

Electric resistance strain gages were attached to the bolt shanks in the manner shown in Fig. 1. Small areas approximately ½ 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 bolts were installed in the test joints with the gages oriented toward the joint edges as indicated in Table 1, in order to minimize the effect of bolt bending.

Each bolt was calibrated in order to relate the strain readings taken on the SR-4 gages to bolt tension. A typical calibration curve is shown in Fig. 2a, which shows the elongation of the whole bolt as measured by a 1/10,000 in. dial gage. Fig. 2b shows the strain readings recorded from the SR-4 gages. Each gaged bolt was installed in the test joints with an initial tension just slightly above its proof load.

Additional details of the joint tests are given in Reference (6).

TEST RESULTS AND ANALYSIS

Variations of the internal bolt tension with joint load in typical joints are shown in Figs. 3, 4, 5. The change in bolt tension was determined from

JOINT CONFIGURATION	STEEL TYPE	BOLT TYPE	DIA., IN.	LENGTH UNDER HEAD, IN.	GRIP, IN.
E741	A440	A325	7/8	5½	4
E721	A440	A325	7/8	5½	4
E163 & E164	A440	A325	7/8	9½	8
K42d	A440	A490	7/8	5½	4
J42b & J42c (SR4 gages)	A514	A490	1	5½	4

● Bolts with SR-4 Strain Gages

(5) Chiang, K. C., and Vasarhelyi, D. D., THE COEFFICIENT OF FRICTION IN BOLTED JOINTS MADE WITH VARIOUS STEELS AND WITH MULTIPLE CONTACT SURFACES, Thirteenth Report on Bolted Joints, University of Washington, 1964.

(6) Fisher, J. W., Ramseier, P. O., and Beedle, L. S., STRENGTH OF A440 STEEL JOINTS FASTENED WITH A325 BOLTS, Publications, IABSE, Vol. 23, 1963.

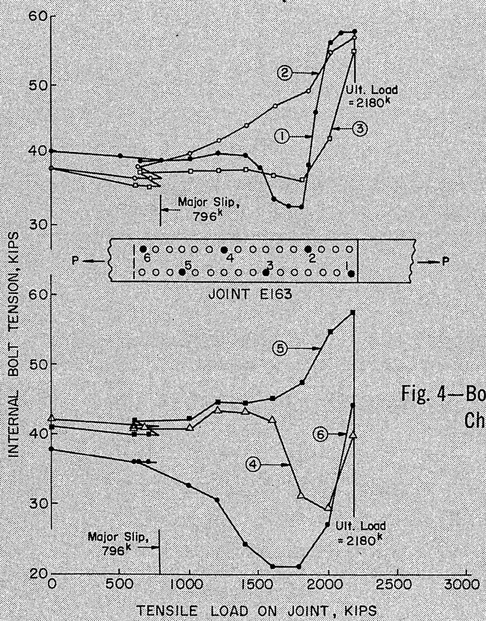

Fig. 4—Bolt Tension-Joint Load Characteristics of Joint E163

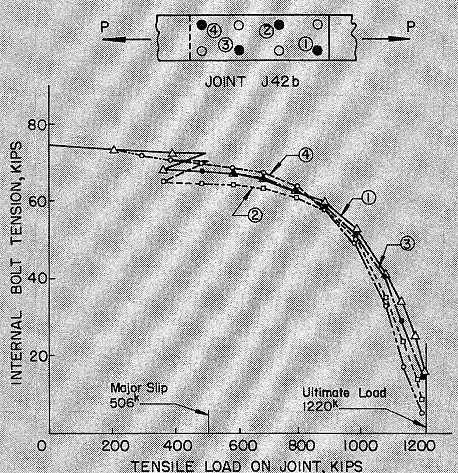

Fig. 5—Bolt Tension-Joint Load Characteristics of Joint J42b

the measured changes in bolt strain and the calibration curves. 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.

Behavior up to Major Slip

The test results plotted in Figs. 3, 4, and 5 show that the bolt tension, as expected, had decreased from 1% to 8% at major slip due to the Poisson effect.

In most joints, major slip occurred suddenly and all bolts throughout the joint came into complete bearing. Joint slip caused a drop in load acting on the joint due to the sudden deformation. This is readily apparent in Figs. 3, 4, and 5. After slip the long (8-in.) bolts showed an increase in load, as shown in Fig. 4 for joint E163. Joints with 4-in. grips showed a decrease in bolt tension after major slip. This is clearly shown in Figs. 3 and 5. The increase in bolt tension in joint E163 was probably due to the catenary effect resulting from bending in the long bolts. Apparently, the shorter bolts show a decrease in tension because the catenary effect is not present and the sudden impact at slip causes a relaxation of clamping force.

Behavior After Slip

Three separate and distinct behavior patterns were noted in the variations in bolt tension after major slip. Two are illustrated in Fig. 4. 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. 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 their catenary action. In addition, inelastic deformations due to bearing and yielding of the A440 steel plate 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 bolts 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 just prior to joint failure, for example, it was possible to insert an ordinary sheet of paper between the lap plate and the main plate down to the third bolt row. The separation at the first bolt row was about 1/16-in.

Figure 6 is a sawed section of a portion of a joint after failure. It is visually evident that tension is being introduced into the long bolts because of the catenary effect. (*continued*)

Fig. 6—Bending of Long Bolts

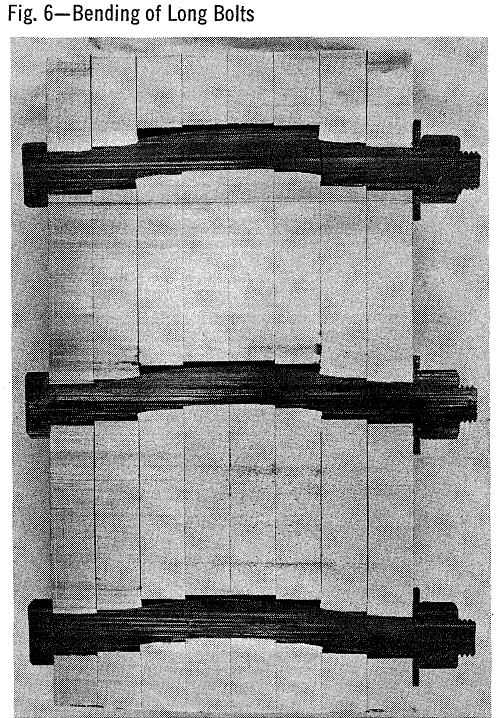

Figure 3 shows the behavior of the short bolts (4-in. grip) tested in A440 steel joints. As the joint was loaded beyond slip, bolt tensions dropped continuously in all fasteners until the ultimate load was approached. Near the ultimate load, considerable lap plate prying action was present causing the bolts near the lap plate end to show an increase in tension (Bolt 1 in Fig. 3). The interior bolts in joints E721, E741, and K42d all showed a continual decrease in tension with joint load and no catenary action was noted.

The third type of behavior is illustrated in Fig. 5 for joint J42b, A514 steel plates connected by A490 bolts. Joints J42b and J42c were proportioned so that small inelastic deformations had occurred in the plate material at the ultimate joint load. Consequently, there was practically no lap plate prying and bolt tension decreased continually with joint load until failure occurred (Fig. 5). The sawed section of joint J42b confirmed that little if any prying or catenary effects were present.

In any symmetrical butt splice, the fasteners at each end carry approximately equal loads 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 of long joints are usually the first to unbutton. Figures 3 and 4 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 usually under a more severe combined shear and tensile condition than the bolts at the main plate end, the failure mode of long joints described above is logical.

Load Carried by Friction

For the joints with short bolts, it was obvious that near ultimate the load carried by friction was negligible. As ultimate load was approached, the bolts near the lap plate ends of A440 steel joints indicated an increase in tension. This was caused by the prying of the lap plate away from the main plate.

In joints with long bolts, there was some load transfer by friction in the joint interior because considerable internal tension remained. However, because of lap plate prying, the behavior of the joint near its end was not affected by frictional forces. Tests have indicated that the load carried by friction near the main plate end of the joint and in the joint interior had only a small influence on the load partition. The maximum variations between the predicted loads neglecting friction and tests were about 4%[3].

CONCLUSIONS

1. Until inelastic deformations occur in the fasteners, the change in bolt tension was caused by the Poisson effect. This caused a decrease in bolt tension of 1 to 8% until major slip.

2. In constructional alloy steel (A514) joints, the internal tension in A325 and A490 bolts decreased continually with increasing joint load. At failure no clamping force remained.

3. In A440 steel joints, the bolt tension usually decreased until the lap plates yielded and introduced prying or the catenary effect. This caused additional tension to be induced into the bolt. This did not affect the joint behavior because the faying surfaces were not in contact near the end fasteners.

4. The load carried by friction on the faying surfaces of joints was negligible near ultimate load. Hence, the bolts were transmitting most of the applied load by bearing and shear as the ultimate strength of the joint was approached.

5. These tests also confirm that initial bolt tension has a negligible influence on the shear strength of the bolts.

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