Top-and-Seat-Angle Connections and End-Plate Connections: Snug vs. Fully Pretensioned Bolts*

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SUMMARY

The effect of partially pretensioned bolts has been examined through research conducted at the ATLSS center of Lehigh University. Extended end-plate and top-and-seat-angle connections incorporating fully pretensioned and snug-tight bolts were tested. Fully pretensioned bolts were tightened to 70% of their ultimate strength (as specified by AISC), and snug bolts were tightened to between 30% and 40% of their ultimate strength.† A W27×94 beam section was connected to a W14×193 column section for the tests considered. All material was 50 ksi steel, and A325 1-in. and 1⅛-in. diameter bolts were used for all connections.

Snug-tightened end-plate connections performed essentially the same as their fully pretensioned counterparts. Snug connections were nearly as stiff as the fully pretensioned connections at moderate loads, and the ultimate strength was the same for either case. Snug-tight connections actually behaved stiffer during the course of reversal loading.

Top-and-seat-angle connections were designed to resist moment by using equally large angles attached at the top and bottom beam flanges. The snug-tight connection for multiple bolt rows behaved stiffer and stronger than its fully pretensioned counterpart. Two modes of behavior are proposed for these cases. The snug-tight connection also reacted less adversely to load reversal, and its load-deformation response remained linear over a larger range of loading.

INTRODUCTION

The performance of tension connections incorporating snug-tight (partially pretensioned) high-strength bolts is of considerable interest to the construction industry. This paper presents results of experiments which compare these connections with their fully pretensioned counterparts. A summary of current practice, background information, and terminology is presented.

Definitions

The following is a list of useful descriptions and definitions of terms used throughout the paper:

- *Slip-Critical Joints*—These are defined by RCSC (AISC, 1986) as joints in which slip would be detrimental to the serviceability of the structure.
- *Shear/Bearing Joint*—Joint in which the loads are carried by bearing of the bolts against the connected elements.
- *Tension Joint*—Joint subjected primarily to tensile loading.
- *Fully Pretensioned Condition*—The tightening level used for slip-critical and tension joints, equal to 70% of the minimum specified tensile strength of the fastener.
- *Snug-Tight Condition*—RCSC defines this as the tightness that exists when all plies in a joint are in firm contact. This level is approximately 50% of the fully pretensioned case. The snug-tight condition is considered sufficient for most shear/bearing joints.

Advantages of Snug-Tight Bolting

Tightening bolts to the snug condition is more attractive than full pretensioning due to the following factors:

- One worker can perform the tightening process with an ordinary "spud" wrench.
- Only a few impacts of an impact wrench are required.
- Visual inspection is adequate.

Because of the minimal worker effort required, these factors lead to savings in money and time. The use of heavy equipment is eliminated and the tightening becomes a safer process.

Current Practice

Current specifications, as defined by RCSC, require fully pretensioned bolts in connections within the tension, slip-critical, and friction type bearing categories. The full tension requirement is imposed for the following reasons:

1. *Tension*—For a group of bolts in tension, the pre-stress enables tensile forces to be distributed evenly. Bolt forces due to tensile loading will increase only a small amount prior to separation of connected elements.

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† Tightening to 30% or 40% of the ultimate strength can be achieved using an ordinary spud wrench.

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2. *Fatigue*—Pretensioning lowers or eliminates the applied stress range induced in the bolts.
3. *Slip*—Pretensioning invokes friction resistance of the connected element's faying surface which is sufficient to avoid bolt slip.

Snug-Tight Applications

Snug-tight bolting may be adequate for certain tension type connections. For connections subject to static loading only or small fatigue stress ranges (wind loading), full pretensioning may not be essential. In some cases the elastic behavior of snug bolts may be favorable, as discussed later. For slip-critical and fatigue loading, full pre-stress should always be incorporated. Due to their inherent lack of ductility, use of A490 bolts in snug-tight applications is discouraged.

General Description of the Studied Connection Types

The research reported here involved testing of extended end-plate and top-and-seat-angle connection types as represented in Fig. 1a and 1b respectively.

Extended End-Plate Connection

End-plate connections are classified as tension-type connections. The applied moments subject the tension region bolts primarily to direct tension, and under current design procedures fully pretensioned bolts are required. Shear-tension interaction is not addressed in current end-plate design procedures. The frictional shear resistance of the compressed portion of the end-plate is increased due to the applied moment, hence minimal shear forces are transferred to the tension bolts.

The tension bolts in an end-plate connection must resist the applied tensile forces, forces due to prying action, and bending forces. Bolt forces will be affected by the end-plate flexibility and bolt placement.

Top-and-Seat-Angle Connection

Current design procedures for the top-and-seat-angle connection consider its response to be simple or unable to transfer any moment. The top angle, used simply for stability of the connected beam, is designed to provide no resistance to the beam's end rotation. Therefore, the bolts in the tension (top) angle are not considered to carry tension. Though the lack of horizontal symmetry about the flange creates a different force and deformation condition than that which occurs in the end-plate connection, the bolts in top-and-seat-angle connections experience similar forces (shear, tension, bending, prying).

Experimental Program

The experimental program consisted of a series of tests on extended end-plate and top-and-seat-angle connections. Loading of the connections was static in nature, and a number of tests involved reversal loading (Chasten, et al., 1989). Bolt pretension and plate thickness were varied for the end-plate connection tests, while bolt pretension and the number of bolt rows were varied for the top-and-seat-angle connection tests.

BOLT MECHANICS IN TENSION CONNECTIONS

The forces and the resulting response of a bolt group are a function of many parameters including the bolt's diameter and pretension, the gage and pitch, number of bolt rows, flexibility of the detail element, contact surface condition, etc. This section discusses tension, bending, and prying forces in the bolts of tension connections.

Forces

Tension connections require bolt groups to transmit predominantly tensile forces. However, the tensile force applied to the bolt may be amplified by prying action, and bolt bending stresses will exist. In beam-to-column connections, a lateral component of shear also acts on the bolt. However, in many cases, the shear in a connection is assumed to be carried by contact friction in the compression portion of the connection.

Tension

When components of a connection are bolted, the bolt pretension will affect the overall response to external tensile loading; however, the ultimate strength is unaffected (Kulak, Fisher, and Struik, 1987). Until the external load overcomes the pretension, the assemblage of bolts and connected plies acts as one, resulting in an overall increase in stiffness. After the pretension is overcome (plate separation), the bolt force is simply equal to the external load, regardless of the original magnitude of bolt pretension.

Prying Action

Bolt groups in tension connections are susceptible to prying action. Consider the free-body diagram of a simple tee-hanger connection as shown in Fig. 2. The applied load T

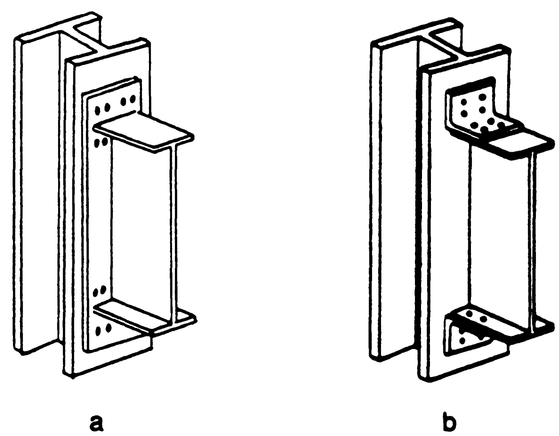

Fig. 1. Connection types: (a) Extended end-plate, (b) Top-and-seat-angle.

must be transferred through the hanger by the two rows of bolts located symmetrically about the tee stem. Prying forces must develop to resist the tee flange bending moment, i.e., $Q = f(M_b)$. Therefore, the bolt forces will include force components from both the applied load and additional forces due to prying action. For n bolts acting to resist the applied load T, the following relationship is obtained:

$$\sum_{i=1}^{n} B = T + Q$$

Since the prying forces are a function of M_b, their magnitude depends on an interaction of the flexural rigidity of the flange and the connector's pretension as discussed in the following paragraphs.

Flexural Rigidity—If the tee-flange is sufficiently rigid, bending deformations and resulting flange moments will be minimal. Conversely, if the flange is relatively flexible, the external loading will induce large bending deformations in the tee-flange and M_b will be significant.

Pretension—Separation of bolted elements is dependent on the value of the bolt pretension. Until the pretension is overcome, M_b will be insignificant since the flange will remain undeformed. Therefore, assuming that the tee-flange is flexible, lowering the pretension will result in prying action at a lower value of external load. Test results show that initial clamping force does not influence the magnitude of prying forces at the ultimate loading conditions (Kulak, Fisher, and Struik, 1987). The tests reported herein confirm this observation.

Bending

The bending relationship will be developed for the case of a tension angle within a connection; a similar relationship can be derived for other connections. Figure 3 shows the free body of the angle member. As the applied load T works to overcome the contact forces at the bolt line, a moment initiates which tends to increase the contact force (prying) at the far side of the bolt line and decrease contact on the near side. The bolt pretension is gradually overcome as the contact surface recedes. In addition to the tensile force T and the prying force Q, moment M_a from the angle curvature and a proportion (α) of the total connection shear V_{conn} exist.

The relative effect of the bending force M_b is rather large. Employ the following assumptions: (1) Small deflection theory; (2) M_a, the angle moment due to the outstanding leg's forced curvature, is an order of magnitude lower; (3) the moment arms a, b, and g are approximately equal to the usual bolt spacing, six times the bolt radius, r; and (4) in the most extreme case, the summation of the prying and shear component, $Q + \alpha V_{conn} \approx T/2$. The equilibrium equation for moments about the bolt shank is

$$M_b = T6r - T\sin\theta 6r - \alpha V_{conn} 6r - Q6r$$

$$M_b = T6r - T\sin\theta 6r - T/2\ 6r$$

$$M_b = 6r(T/2 - T\sin\theta)$$

Then, the axial and flexural stresses on the bolt are respectively:

$$\sigma_{ax} = \frac{P}{A} = \frac{T}{\pi r^2}$$

$$\sigma_{bnd} = \frac{M_b c}{I} = \frac{6r^2(T - T/2)}{\frac{1}{4}\pi r^4} = \frac{12T}{\pi r^2}$$

This approximate bending stress was derived for the case of a tension angle. For other connections, such as the end-plate, this stress can be even more significant.

The bending effects are considerable, and portions of the bolt should yield well before the axial value reaches the yield load of a bolt subjected to direct tension. Furthermore, the bending stresses cause the extreme fibers of a bolt to experience a large stress range when subjected to load reversals. Fatigue cracks can originate from this region and propagate across the bolt cross-section as the neutral axis migrates. Therefore, bending stresses can have a pronounced effect on the behavior and useful life of a bolt.

Current Practice

The current editions of AISC's LRFD (1986) and ASD (1990) steel design manuals have a number of conditions concerning bolt design. These include the limited use of snug-tight

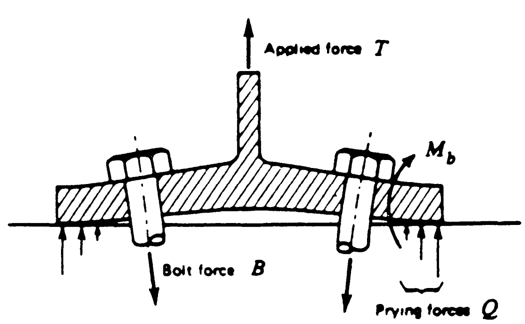

Fig. 2. Free-body diagram of a Tee-hanger connection.

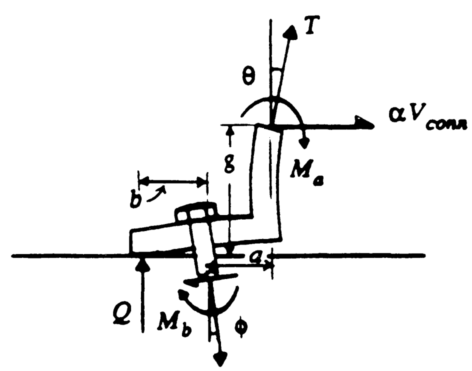

Fig. 3. Tension angle free-body diagram.

bolts in certain types of connections. This section focuses on the code's handling of bolt bending and prying action.

Bolt Bending

Although this condition is not directly mentioned in the specifications or the commentary of AISC's steel construction manuals (AISC, 1990; AISC, 1986), potentially dangerous bending situations are handled concurrently with prying. The main detrimental effect of bending is fatigue related. The code does not allow any bending (i.e., pretension being overcome) in connections undergoing fatigue loading. If the application of snug-tightening is expanded, further research on bolt bending is needed, and results must be implemented into the code.

Prying

AISC's steel design manuals present prying force formulas for tee-hanger connections. The formulas are to be used in the design of tee-stub and top-and-seat angle moment connections (including double web angles for shear). AISC's design procedure for the end-plate connection, however, does not include prying action. The procedure was developed by Krishnamurthy in 1978.

Concerning the experimental cases studied by Krishnamurthy (configurations in which the bolt diameter to end-plate thickness ratio is relatively large), prying forces will be minimal due to the dominant effect of the bolts' pretension. However, for situations in which the bolt diameters are smaller, the pretension effects will be reduced and substantial prying forces may develop.

Bolt Instrumentation

Strain gages were placed on bolts at opposite sides of the shank as shown in Fig. 4. A number of gaged bolts were included for each connection test. A calibration of the bolts to determine the external load versus internal strain readings was required. The calibration data was used to evaluate forces in the bolts from given strain readings as each test progressed. The bolts were oriented in such a manner that the strain gages would give readings to indicate the moment gradient across the bolt. Combinations of dial gages and LVDTs were placed across the bolt line to measure global axial deformations of each bolt. The above strain and displacement measurements were useful in three ways: force paths could be determined using the calibration data; the limits of pretension and elasticity could be bench-marked; and comparisons, such as relative bending between bolt lines, could be monitored.

EXTENDED END-PLATE CONNECTION TEST RESULTS AND DISCUSSION

Test Program

The research reported here examines end-plate connections that consist of a pattern with eight 1-in. bolts placed in four rows across the tension region of the end plate (see Fig. 1a). The testing program included three sets of tests†† (1SNR–1TR; 34SNR–34TR; and 1SNM–1TM) that were detailed identically with the exception that each set included a snug-tightened and a fully pretensioned counterpart.

Bolt Behavior

Force Distribution

Consider the force distribution within the bolt group in the tension region as connection moment is applied. The bolts that are closer to the beam web are surrounded by a stiffer region and will carry most of the external force as the connection is initially loaded. However, as higher loads are applied, the external load will be distributed more evenly.

Bolt forces across the end plate are more evenly distributed for the snug-tight configurations due to their lower pretension. As the contact pressure at the inner bolts is relieved, the outer bolts begin to carry a larger portion of the external load. The snug configurations allow this to happen at a lower load, resulting in a more uniform distribution of forces. This situation is similar to that of the top-and-seat-angle connections that incorporate two bolt rows on the vertical leg of the top angle.

†† 1 and 34 denote 1- and ¾-in. end plates; SN and T denote snug and fully pretensioned bolts; R and M denote reversal and monotonic loading, respectively.

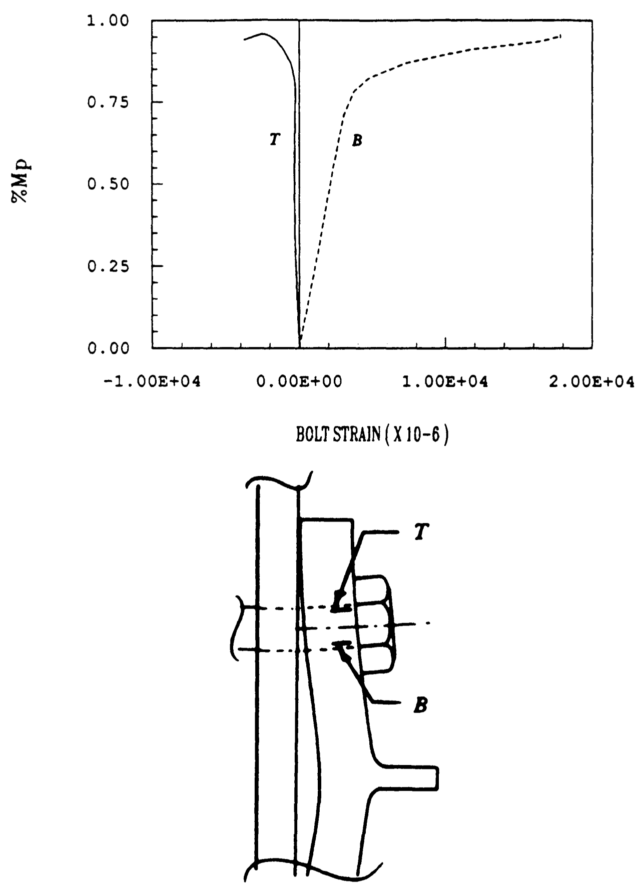

Fig. 4. Strain components of bolts under bending.

Bolt Bending Forces

Substantial bolt bending forces were present in each of the six experiments. Figure 4 shows the strain at the extreme fibers of a typical bolt in the outer row for 1TR. The figure shows that there is a marked difference in the measured strain, indicating that bolt bending forces are present. The stress distribution across the bolt is a superposition of axial and bending stress. Therefore, the portion of the bolt *T* under the compressive component of bending is actually unstressed throughout most of the loading range and goes into compression at extreme loads. The portion of the bolt *B* subject to a tensile bending component of stress will yield at a lower external load than for a case of pure tension. The following paragraphs discuss the effects of bolt pretension and plate thickness (i.e., flexural rigidity) on bolt bending.

Bolt Pretension—The magnitude of bolt pretension affects the amount of bolt bending that may exist in tension connections. As an end-plate connection is loaded, the bolts on the outstanding leg will experience bending forces as the contact pressure due to bolt pretension is relieved. Bolt bending will occur in snug-tight connections at a lower value of external load, since the initial contact force is lower. Test results confirm that slightly more bending is present in the bolts of the snug-tight configurations when compared to their fully pretensioned counterparts. Figure 5 is a plot that compares the bending of a similar bolt of the ¾-in. snug-tight and fully pretensioned conditions. The figure indicates that higher bolt bending forces are present in the snug-tight configuration at loads below 50% M_p. However, the differences are minimal, and near the ultimate load the values are approximately the same.

Plate Flexural Rigidity—Bolt bending forces are also influenced by the flexural rigidity of the end plate. For example, the bolts of a connection with rigid flanges will not experience bending stresses. As the rigid portion is pulled away from its base, it will remain undeformed and the bolts will carry purely axial forces. The bolts of the ¾-in. end-plate connections exhibit higher bending forces than the bolts of the 1-in. end-plate connections (see Fig. 6). The bolt bending force is plotted for a bolt of 34TR and the corresponding bolt of 1TR. The thinner end plate causes a higher bending force to occur in the bolt. This is a result of the lower flexural rigidity of the ¾-in. end plate.

Prying Action

Results from each end-plate connection indicate that the bolts included dominant prying forces. The bolt group of the tension region was subjected to forces approximately 1.2 to 1.3 times the amount of force required to maintain moment equilibrium (*M/d*).

Considering the discussion of prying action in the section on bolt mechanics, larger prying forces should occur for the snug-tight configuration at low values of external load. Figure 7††† compares the prying action of a typical bolt for the 1-in. snug and fully pretensioned cases. In the figure, the contribution of prying action is indicated by a jump in the bolt force. For the snug-tight configuration, prying effects are substantial at a value of 20% M_p, while for the fully pretensioned case, substantial prying effects begin at 40% M_p. The prying force at loads near the ultimate, however, are the same for both cases.

Connection Behavior

Strength Characteristics

The ultimate strength of the connections was not affected by snug-tightening. The ultimate strength of each connection with a 1-in. end plate was approximately 100% M_p.†††† Both ¾-in. end-plate connections attained approximately 90% M_p.†††††

††† The solid lines of the figure represent the value of bolt force that would be present if prying action did not exist.

†††† The test 1SNR was terminated due to excessive column web yielding. However, at the time the test was discontinued, the connection had attained 94% M_p.

††††† 34SNR: M_u = 86% M_p; 34TR: M_u = 88% M_p.

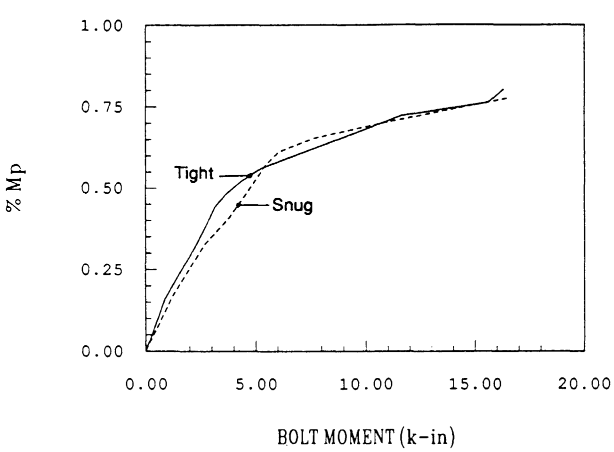

Fig. 5. Snug and fully pretensioned bolt bending forces.

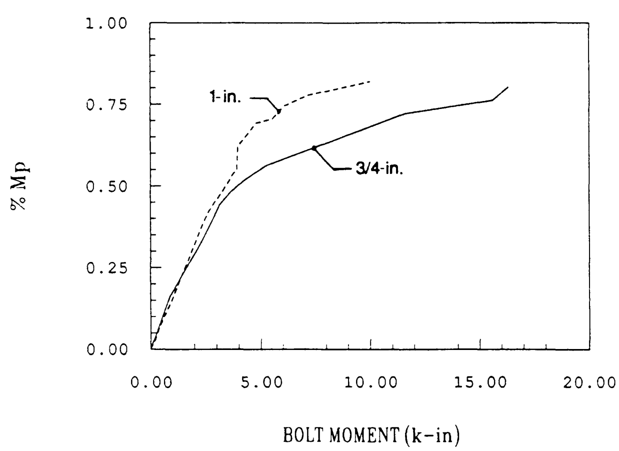

Fig. 6. Plate thickness effect on bolt bending.

Stiffness Characteristics

Generally, as the external load of an end-plate connection is increased, the end-plate and column flange contact forces are relieved and the connection's stiffness is gradually reduced. The stiffness of two connections detailed identically will be exactly the same as long as contact pressure is present between the connected plies. Snug-tightening simply allows the contact pressure to be overcome earlier. As the contact pressure due to pretensioning is relieved, the deformation of the connection is more dependent on the restraint offered by the bolts. However, as an end-plate connection is loaded, the stiffness depends on bolt restraint and plate deformation.

The connection's stiffness is also affected by yielding of the end-plate material and its connecting bolts. As loads of large magnitudes are applied to a connection, its stiffness will decrease due to yielding of its elements. When elements begin to yield, they no longer have the capacity to resist increases of external load. Deformation occurs as load increases are redistributed to unyielded portions of the connection. For an end-plate connection, the portion of the end plate that will experience yielding first will be at its juncture with the beam flange. Depending on the restraining capacity of the bolt, a second position of yielding may occur at the bolt line.

Consider the effects of end-plate yielding during reversal loading. If the end plate has yielded, permanent deformations result and the connection's geometry is changed. At the time that the load is reversed, the connection's stiffness will decrease due to this change of geometry (Chasten, 1988).

The following paragraphs discuss the effects of snug-tightening bolts on connection stiffness for monotonic and reversal loading.

Monotonic Loading—The influence of tightening procedures on connection stiffness is most clearly represented by the moment-rotation†††††† characteristics of the monotonically loaded connections (1SNM and 1TM). Figure 8 shows the variation in connection stiffness throughout a complete loading history.

At low values of connection moment, the two connections represented in Fig. 8 display identical stiffnesses. At moments above approximately 20% M_p, the snug configuration is somewhat more flexible since the contact forces are relieved at a lower moment. However, near the connection's ultimate capacity, the two configurations exhibit identical characteristics.

Reversal Loading—For the set of ¾-in. tests that included reversal loading (34SNR and 34TR), yielding of the end-plate material occurred in the fully pretensioned connection at a lower load. The first plastic hinge formed at 67% M_p for 34TR (tight) and 73% M_p for 34SNR (snug). The end plate of the fully pretensioned configuration is subjected to a stiffer boundary condition at the bolt line due to the larger bolt clamping force. Therefore, it will attract a higher bending moment at the bolt line, and yielding of the plate will occur at a lower value of external load. Figure 9 shows the moment-rotation response of the two connections. The first (left-to-right) two lines of the figure represent the initial response,

†††††† Rotation is determined as the relative deflection of the top and bottom beam flanges divided by the beam length.

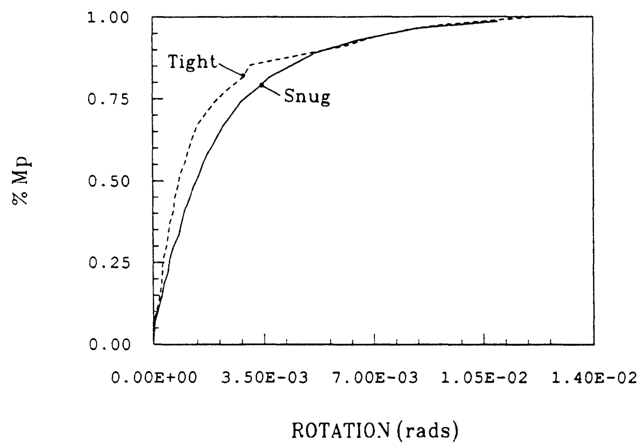

Fig. 8. Snug-tight effects on connection stiffness.

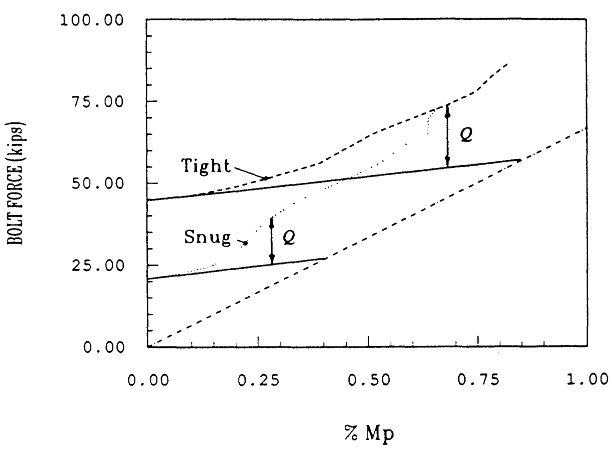

Fig. 7. Snug-tight effects on prying action.

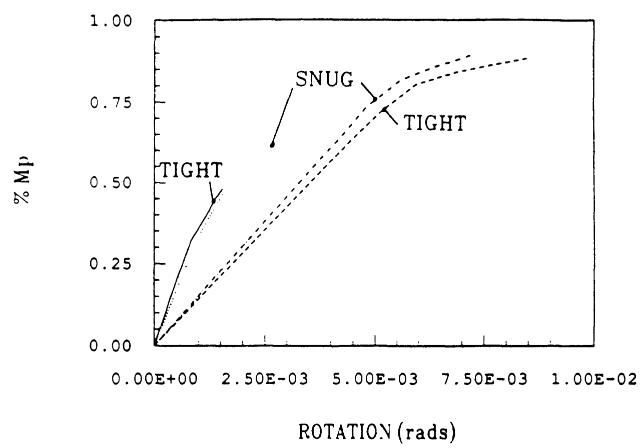

Fig. 9. ¾-in. snug-tight stiffness after reversal loading.

and the remaining two lines represent the response after a number of load reversals for each connection. Initially, the fully pretensioned (tight) condition is stiffer, while the snug case is stiffer during the final (fifth) cycle.

In the final cycle, the fully pretensioned case is less stiff because of its larger compression flange deformation (change in the connection's geometry due to yielding) at the time of load reversal. The tight condition is always stiffer until yielding of the end plate occurs; however, as yielding begins the snug configuration may be stiffer. The 1-in. end-plate connections exhibit the same response at high load values.

Summary

The snug-tight connections performed adequately. When the connections were subjected to moderate loads, there was less stiffness, higher bolt bending forces, and earlier indications of prying action. However, none of the above were significantly different from the fully pretensioned condition, and in all cases the connections performed the same at high loads. Snug-tight connections actually exhibited higher stiffnesses after a number of reversal load cycles had been applied (see Fig. 9).

Substantial increases of bolt force due to prying action developed during the course of loading. Other researchers have also indicated that large prying forces can develop in end-plate connections (Agerskov, 1976; Mann, 1979). Prying action needs to be addressed in design procedures of end-plate connections.

TOP-AND-SEAT-ANGLE CONNECTION TEST RESULTS AND DISCUSSION

This section contains information about the behavior and effects of bolts in top-and-seat-angle connections. The experimental work was performed at Lehigh University in 1988. The full details of this study are contained within another report (Fleischman, 1988).

Testing Program

For each pair of experiments in the testing program of top-and-seat-angle connections, the individual tests were identical in detail with the exception of the degree to which the bolts were tightened. In each series, the first experiment contained bolts which were pretensioned to full pretension ($0.7F_u$), while the second experiment contained snug bolts (0.3–$0.4F_u$). The bolts were tightened using a two-pass, inner-to-outer pattern. The first series was monotonically loaded; the second series was loaded in seven cycles apiece, incrementing the peak load at a constant rate so as to reach the beam's plastic moment at midspan of the final cycle.

The flush leg of the top (tension) angle is referred to as the critical leg. The bolt lines on this face will be referred to as the critical (inner) and secondary (outer) bolt line (see Fig. 1b). In the first series (two experiments), the critical leg only contained one bolt line.

First Series—One Bolt Row

Full Pretension vs. Snug-Tight Bolt Behavior

The bolts in this experiment were 1⅛-in. A325. The tightening condition was 61 kips ($0.7F_u$) for the fully tightened and 27 kips ($0.3F_u$) for the snug-tight condition. Monotonic loading was applied.

The bolt load increments††††††† for both cases were practically the same at higher loads. At low loading, the snug-tight experiment responded earlier due to its lesser pretension. The bolt moment relationships of the two tightening cases are almost identical; however, in the snug case, bending is initiated at a lower flange force. Once the pretension is overcome in the full case, the curves are almost identical. Figure 10 visually details the prying action per bolt in the two tests. The value of the prying force is the vertical distance between the curve and the straight line. The bolts of the snug test exhibit prying action almost immediately. When pretension is overcome for the full case, the two curves join together as was the case with the bolt bending.

Bolt Effect on Connections with One Bolt Row

The connections with one bolt row acted independently of degree of pretension. There were only subtle differences in response, and the connections both developed the same ultimate moment and rotation. The snug test was slightly more susceptible to bending and prying at early loads.

Failure Mode

In both the fully pretensioned and snug-tightened cases the failure was the same. At approximately the same load, the bolt heads broke off the critical line bolts. From the strain gage readings and the sounds at bolt fracture, it seems that one bolt broke and the second bolt followed almost immediately. The fracture surface in both cases was ductile.

††††††† "Increment" refers to the amount of bolt force above the initial pretension.

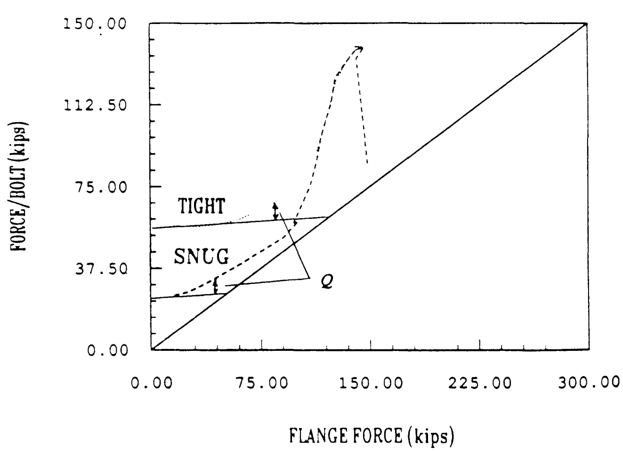

Fig. 10. One bolt row: Bolt prying.

Second Series—Two Bolt Rows

This section will examine the behavior of bolts in the critical and secondary bolt line of the top-and-seat-angle connection with two bolt rows. The bolts were 1-in. diameter, A325 high-strength. The cycling of loads created hysteresis curves for the bolt load increment plots. Instead of plotting bolt response versus load or end moment, this section will usually present bolt data versus flange force, where flange force is taken as the end moment divided by the nominal beam depth, (M/d).

Full Pretension

The full pretension condition was 50 kips ($0.7F_u$) for these tests.

Bolt Strain Increment—Figure 11 shows the average strain increment of bolts from the critical and secondary bolt line. The critical bolts carry a disproportionate amount of the load. In fact, during the early cycles, the secondary bolt line feels none of the tensile force. The critical bolt's response is similar to an ordinary tensile coupon test with periods of unloading. The unloading in the actual experiment occurs when the load is reversed. On full load reversal, the original critical (tension) leg under consideration becomes the compression angle. Since there is no physical connection between the bolt head and the angle, a progressive permanent set occurs in each cycle.

Bolt Bending—From tensile and torque-tension tests it was determined that the yield strain of the bolts was approximately 2600 microstrains. Examining the strain gages on the tension side of the bending separately, it was found that the critical line bolts began to yield at a flange force of 105 kips or 88% of the axial load that would yield the bolt line. This 12% reduction shows the significant effects of bending forces in bolts.

Prying—Figure 12 shows a plot of force per bolt versus flange force for both the full pretension and the snug-tight case. The vertical difference between the plot and the solid line represents the prying force, which is considerable for the full pretension. This prying force takes place at a contact surface between the bolt lines as will be explained.

Snug-Tight Bolts

The snug-tight condition was 25 kips ($0.35F_u$) for these tests.

Bolt Load Increment—Figure 13 shows a plot of critical and secondary line bolt load versus flange force. In the zone for positive flange force, nearly equal values of bolt force indicate that both bolt rows share the tensile flange force, as opposed to the full pretension case. In contrast, the secondary bolt loses almost all of its initial tightening during compressive loading. This is a result of an imperfect fit, a situation more prevalent in the snug-tight condition. On load reversal, the angle flattens against the column and the bolts lose a portion of their pretension.

Bending and Prying—With the exception of the initial portion, the snug-tight prying force in Fig. 12 is considerably smaller than the prying on the fully pretensioned connection. Both bolt rows bend more evenly and less severely than the corresponding fully pretensioned connection. Figure 14 shows the bending of the two bolt rows in opposite direc-

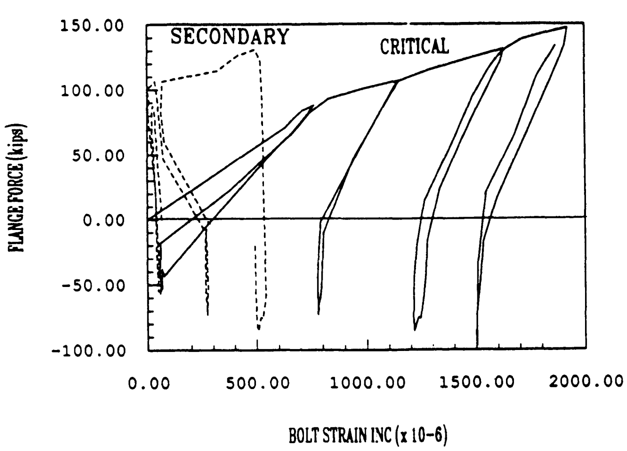

Fig. 11. Two bolt row, tight: Bolt strain increment.

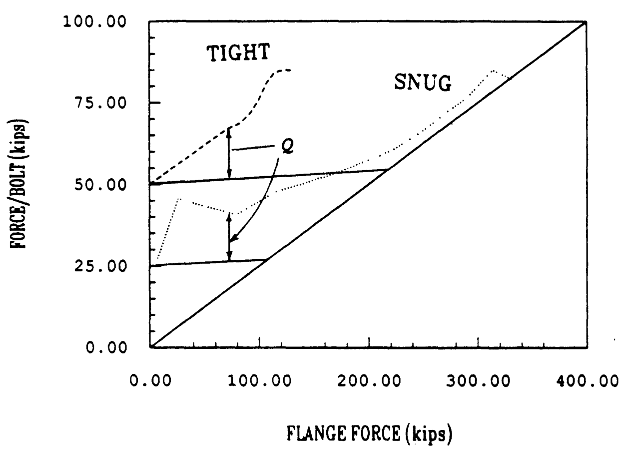

Fig. 12. Two bolt row: Bolt prying.

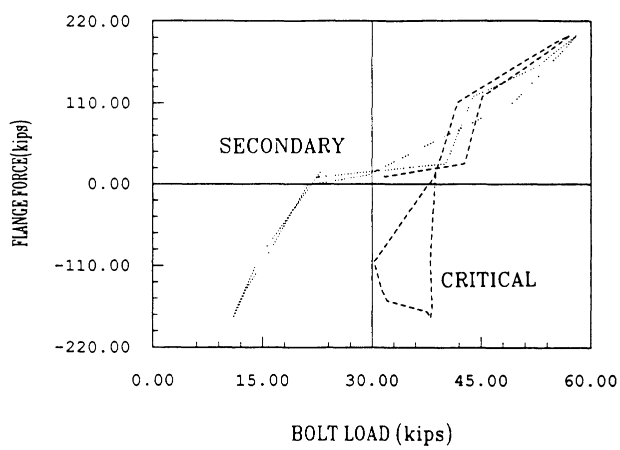

Fig. 13. Two bolt row, snug: Bolt load increment.

tions during an early cycle. Opposite curvatures and the initially high prying force are believed to be a result of a dishing effect of the angle under low pretension and imperfect fit. The lower prying forces for the snug-tight experiment are a result of a different mode of behavior that a multiple-bolt-row tension connection experiences for snug-tight bolts. Both the dishing effect and the snug-tight mode are described in the next section.

Bolt Effect on Connections with Two Bolt Rows

As described in the previous two sections, the bolt groups under full pretension acted quite differently than those under snug-tightening. In fact, two modes of bolt-induced connection behavior exist. In the case of fully pretensioned bolts, the first bolt row becomes inelastic quite early. A progressive softening of the connection occurs on reversal. The response of snug-tight bolts remains linear until near the maximum connection capacity.

Full Pretension Mode—In the case of fully pretensioned bolts, ideally there exists a perfect contact surface from the second to the first bolt row. Figure 15 shows the load-deformation curve for a high-strength A325 bolt. For a

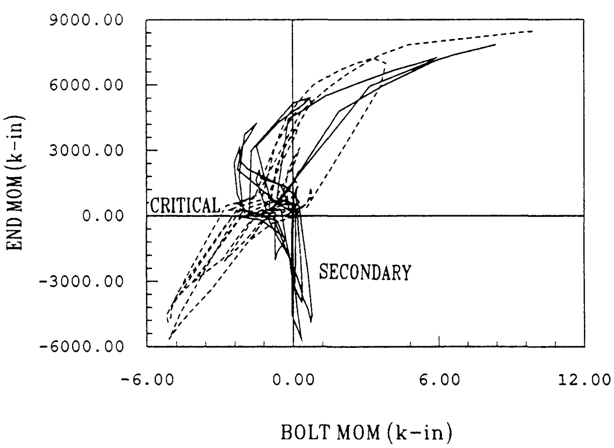

Fig. 14. Two bolt row, snug: Bolt bending.

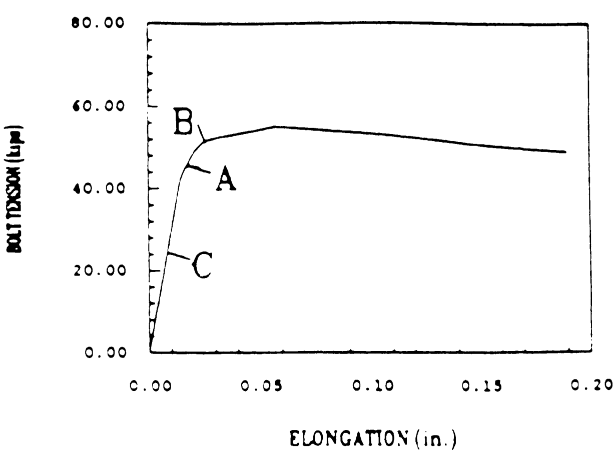

Fig. 15. A325 bolt load-deformation curve.

pretension of F_{pr} and N bolts per row, when the flange force (P_f) reaches a value of

$$P_f = N \times F_{pr}$$

the first row of bolts is engaged, and their subsequent deflection is described by the force-elongation curve beginning at point A. Concurrently, the contact surface travels toward the second bolt row. Because the proportional limit (Point B) of the bolt is near its pretension value (Point A), the first row of bolts yields before the contact surface reaches the second row, i.e., before the second row of bolts begins to assist in carrying the tensile force. Thus, the Full Pretension Mode of multiple bolt row connections is one in which the inner bolt row deforms excessively due to an eccentric tensile force, while the remaining bolt rows do not participate (see Fig. 16a). This results in a much more flexible connection and the tendency of an early yield line between the bolts.

Snug-Tight Mode—In the case of snug-tight bolts, the pretension is overcome at a much lower load, but, as the contact surface is traveling toward the second bolt row, the critical bolts are deflecting along the path beginning at C. This allows the first bolt line to act elastically while the small amount of pretension is overcome in the secondary row. The second bolt line becomes useful and with four unyielded bolts a force of

$$P_f = 2 \times N \times F_y$$

is required to put any bolt into yield, where

$$F_y \approx F_{pr} = \text{yield load for the bolt.}$$

The deflected shape of the angle under moderate loads is dependent on the initial fit. In this test, it was close to what is depicted in Fig. 16b. The prying force actually occurs between the bolt lines and affects both rows. This is the dishing effect which caused the reverse curvature discussed in the section on snug-tight bolts.

Verification—Figure 17 shows the elongation of the critical bolt line versus load step for this series of experiments. A full pretension mode of yielding requires a flange force of $P_f = N \times F_{pr}$ and, in turn, an end moment of $M = P_f \times d$. Data presented in another report (Fleischman, 1988) indicates that an end moment of this value occurs at load step 105. Figure 17 shows this step to be the location of the first excessive deflection of the bolt line for the full

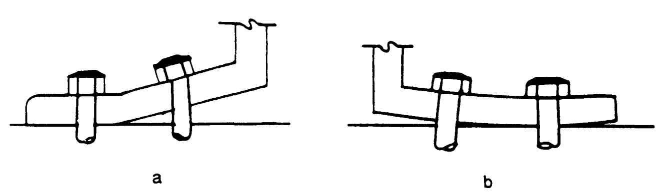

Fig. 16. Full pretension and snug-tight modes.

pretension case. Similarly, the load required for a Snug-Tight Mode of yield is $P_f = 2 \times N \times F_y$. The report indicates a flange force of this magnitude does not occur in the snug-tight test until load step 170, near the experiment's conclusion. (See Fig. 17, snug case.)

The above supports the postulation that the secondary bolt line of fully pretensioned bolts does not participate, while in the snug-tight case it does. Furthermore, in Fig. 17, the inelastic elongation of the fully pretensioned bolt line never returns to its original position despite load reversal. Conversely, for the snug-tight case, though the bolt line had minor deformations almost immediately (due to the low pretension), it returned to near its original position until the critical load. At this point, all the bolts yield at once and the elongation propagates to the ultimate condition.

Modal Effect on the Connection—The connection with snug bolts was approximately 25% stronger than the connection with fully pretensioned bolts. The full pretension test began with a slightly higher rotational stiffness. However, with each load reversal the connection softened considerably (see Fig. 18). While beginning at only 75% stiffness of its fully pretensioned counterpart, the snug test remained at that stiffness until the last cycle of loading (see Fig. 19). The lower strength and stiffness for the fully pretensioned case can be attributed to the full pretension mode of yielding of the critical bolt line and the progressive migration of the yield lines in the angle toward the secondary bolt row. This migration, caused by the excessive elongations of the critical bolt line, causes the moment arm of the angle flush leg to increase. Though only of small length, this arm holds tremendous leverage over the rotation and hence the stiffness of the joint.

Failure Mode

As might be expected, the critical bolts in the full pretension case both fractured at the ultimate condition. The snug-tight test was concluded with the bolts intact; however, the critical bolts plastically elongated to the extent that they could be spun by hand while remaining in the unloaded frame.

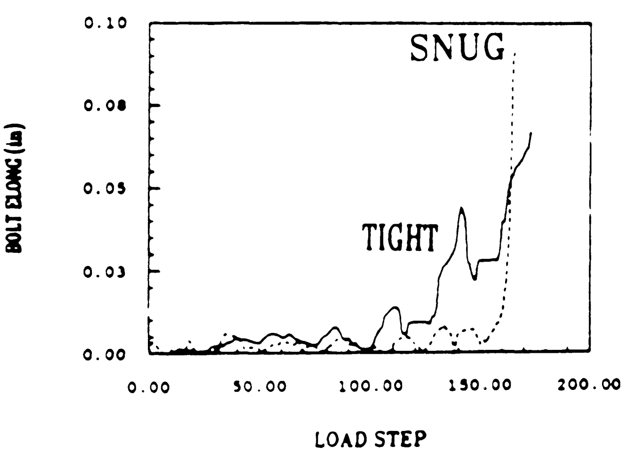

Fig. 17. Two bolt row: Bolt line elongation.

CONCLUSIONS

End-Plate Connections

- Snug-tight applications may exhibit a more favorable response to external loading for situations in which static reversal loads are present.
- For both the 1-in. and ¾-in. end-plate connections, substantial bending forces were present. Both cases incorporating snug-tightened bolts exhibited higher bending forces. However, the difference of the magnitudes of bolt bending forces between the snug and fully pretensioned counterparts is negligible. Therefore, there is not a significant effect on bolt moments when snug-tightened configurations are incorporated.
- Snug-tight bolts will be adequate for most static loading conditions of thin end plates if the bolts are sized to resist the additional bending and prying forces. Bolts must be designed conservatively to account for these forces.
- Snug-tight bolting actually gives a more uniform distribution of bolt forces in multiple bolt groups. (If multi-

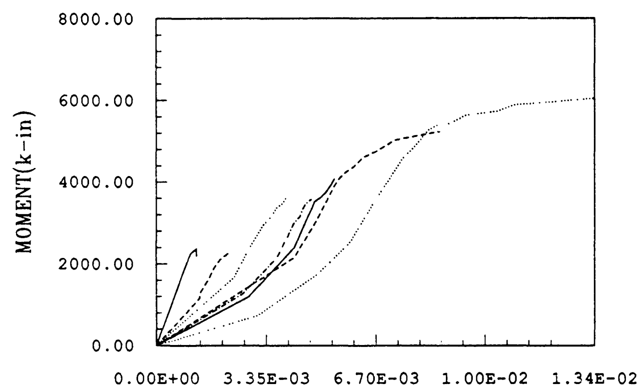

Fig. 18. Progressive softening of fully tight connection.

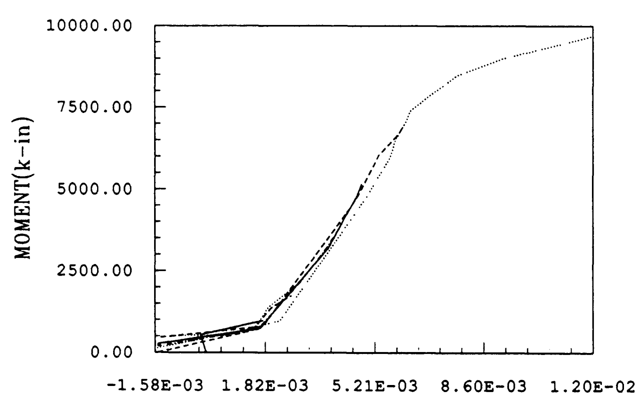

Fig. 19. Stable stiffness of snug tight connection.

ple bolt rows are used, then snug bolts are actually better because forces are distributed to the outer bolts more easily.)

Top-and-Seat-Angle Connections

Multiple Bolt Row

- The connection with the snug bolts achieved more strength while actually behaving stiffer for the majority of the experiment. This can be attributed to their lower (elastic) pretension.
- The snug connection reacted less adversely to load (wind) reversal and remained linear longer.
- The snug connection developed 50% of the beam's plastic moment, while the fully pretensioned connection achieved 40%.
- In the fully pretensioned experiment, only the inner bolt row participated in carrying the tensile force, while all bolts participated in the snug-tight test. This different mode of behavior caused higher bending and prying forces in the fully pretensioned case.

Single Bolt Row

The connections behaved almost identically, independent of pretensioning level.

General Observation

In the experimental work performed for this paper, the top-and-seat-angle connection's behavior as a structural component is primarily dependent on the bolts of the critical line in the tension angle. The number of bolt rows and the degree to which they are tightened control the behavior of this connection. It has been determined in these experiments that the yield lines in the tension angle are responses to the deformation that the bolts are permitting the beam to impose on the angle.

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