7-1-1989

Top and Seat Angle Connections and End Plate Connections: Snug vs Fully Pre-Tensioned Bolts

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ADVANCED TECHNOLOGY FOR
LARGE
STRUCTURAL SYSTEMS

Lehigh University

TOP-AND-SEAT-ANGLE CONNECTIONS AND END-PLATE CONNECTIONS:
Snug vs. Fully Pre-Tensioned Bolts

by

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ATLSS Report No. 89-06

July 1989

An NSF Sponsored Engineering Research Center

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Abstract

The effect of partially pre-tensioned 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 pre-tensioned and snug-tight bolts were tested. Fully pre-tensioned 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 X 94 beam section was connected to a W14 X 193 column section for the tests considered. All material was 50 ksi steel and A325 1-inch and 1-1/8-inch diameter bolts were used for all connections.

Snug-tightened end-plate connections performed essentially the same as their fully pre-tensioned counter parts. Snug connections were nearly as stiff as the fully pre-tensioned 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 pre-tensioned 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.

1 Introduction

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

1.1 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*[1] 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 Pre-tensioned 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 pre-tensioned case. The snug-tight condition is considered sufficient for most shear/bearing joints.

1.2 Advantages of Snug-Tight Bolting

Tightening bolts to the snug condition is more attractive than full pre-tensioning due to the following factors:

- One man 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.

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*Research Council on Structural Connections of the Engineering Foundation

1.3 Current Practice

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

1. *Tension* -- For a group of bolts in tension, the pre-tension enables tensile forces to be distributed evenly prior to pre-tension being overcome. Bolt forces due to tensile loading will increase only a small amount prior to separation of connected elements.
2. *Fatigue* -- Full pre-tensioning lowers or eliminates the applied stress range induced in the bolts.
3. *Slip* -- Full pre-tensioning invokes friction resistance of the connected element's faying surface which is sufficient to avoid bolt slip.

1.4 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 pre-tensioning may not be essential. In some cases the elastic behavior of snug bolts may be favorable as discussed in Sections 3 and 4. For slip-critical and fatigue loading, full pre-tension should always be incorporated. Due to their inherent lack of ductility, use of A490 bolts in snug-tight applications is discouraged.

1.5 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 Figures 1 and 2 respectively.

1.5.1 Extended End-Plate Connection

End-plate connections are classified as tension-type connections. The applied beam moment subjects the tension region bolts primarily to direct tension, and under current design procedures fully pre-tensioned 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.

1.5.2 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 load. In fact, these bolts experience similar forces (shear, tension, bending, prying) as bolts in the end-plate connection.

1.6 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. Bolt pre-tension and plate thickness were varied for the end-plate connection tests, while bolt pre-tension and the number of bolt rows were varied for the top-and-seat-angle connection tests. The experimental program is described in detail elsewhere[2].

2 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 pre-tension, 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.

2.1 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.

2.1.1 Tension

When components of a connection are bolted, the bolt pre-tension will affect the overall response to external tensile loading; however, the ultimate strength is unaffected[3]. Until the external load overcomes the pre-tension, the assemblage of bolts and connected plies acts as one, resulting in an overall increase in stiffness. After the pre-tension is overcome (plate separation), the bolt force is simply equal to the external load (assuming no prying action), regardless of the original magnitude of bolt pre-tension.

2.1.2 Bending

Figure 3-a shows the contact force distribution for a portion of a connection under bolt pre-tension. As the applied load T works to overcome the contact forces at the bolt line (Figure 3-b), a moment initiates which tends to increase the contact force at the far side of the bolt line, and decrease contact on the near side. The bolt pre-tension is gradually overcome as the contact surface recedes.

The bending effects are considerable and portions of the bolt should yield well before the axial value reaches the bolt's direct tensile yield load. 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.

2.1.3 Prying Action

Bolt groups in tension connections are susceptible to prying action. Consider the diagram of a simple tee-hanger connection as shown in Figure 4. This is simply an extension of Figure 3, with a higher external load being applied. The applied load T 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 the tee flange bending moment M_b, their magnitude depends on an interaction of the flexural rigidity of the flange and the connector's pre-tension 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.

Pre-Tension

Separation of bolted elements is dependent on the value of the bolt pre-tension. Until the pre-tension is overcome, M_b will be insignificant since the flange will remain undeformed. Therefore, assuming that the tee-flange is flexible, lowering the pre-tension 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[3]. The tests reported herein confirm this observation.

2.2 Current Practice

The current editions of AISC's LRFD[1] and ASD[4] steel design manuals have a number of restrictions related to bolt design. These include the limited use of *snug-tight* bolts in certain types of connections. This section focuses on the code's handling of bolt bending and prying action.

2.2.1 Bolt Bending

Although this condition is not directly mentioned in the specifications or the commentary of AISC's steel construction manuals, 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. pre-tension 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.

2.2.2 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[5].

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' pre-tension. However, for situations with smaller ratios (bolt diameter/plate thickness), the pre-tension effects will be reduced and substantial prying forces may develop.

2.3 Bolt Instrumentation

Strain gages were placed on bolts at opposite sides of the shank as shown in Figure 5. 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 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 pre-tension and elasticity could be bench-marked; and comparisons, such as relative bending between bolt lines, could be monitored.

3 Extended End-Plate Connection Test Results and Discussion

3.1 Test Program

The research reported here examines end-plate connections that consist of a pattern with eight, one-inch bolts placed in two rows across the tension region of the end-plate (See Figure 1). 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 pre-tensioned experiment.

3.2 Bolt Behavior

3.2.1 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 pre-tension. 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 each angle (See Section 4.3.4).

3.2.2 Bolt Bending Forces

Substantial bolt bending forces were present in each of the six experiments. Figure 5 shows the bolt strain increment due to external load at the extreme fibers of a typical bolt of an end-plate connection. The figure shows that there is a marked difference in the measured strains, 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 actually remains at the

*1 and 34 denotes 1- and 3/4-inch end-plates; SN and T denote snug and fully pre-tensioned "tight" bolts; R and M denote reversal and monotonic loading respectively.

pre-tension value throughout most of the loading range, and its strain decreases 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 (80–85 % P_y). The following paragraphs discuss the effects of bolt pre-tension and plate thickness (flexural rigidity) on bolt bending.

Bolt Pre-Tension

The magnitude of bolt pre-tension 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 pre-tension is relieved. Bolt bending will occur in snug-tight connections at a lower value of external load, since the initial contact force is lower (See Section 2.1.2). Test results confirm that slightly more bending is present in the bolts of the snug-tight configurations when compared to their fully pre-tensioned counterparts. Figure 6 is a plot that compares the bending of a similar bolt of the 3/4-inch, snug-tight and fully pre-tensioned conditions. The figure indicates that higher bolt bending forces are present in the snug-tight configuration at connection moments 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. The bolts of the 3/4-inch end-plate connections exhibit higher bending forces than the bolts of the 1-inch end-plate connections (See Figure 7). 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 3/4-inch end-plate.

3.2.3 Prying Action

Results from each end-plate connection test indicate that the bolts were subjected to dominant prying forces. The bolt group of the tension region was subjected to forces approximately 1.2 - 1.3 times the amount of force required to maintain moment equilibrium ($\frac{M}{d}$).

Considering the discussion of prying action in Section 2.1.3, larger prying forces should occur for the snug-tight configuration at low values of external load. Figure 8 compares the prying action of a typical bolt for the 1-inch snug and fully pre-tensioned cases. In the figure, the contribution of prying action is denoted by Q. For the snug-tight configuration, prying effects are substantial at a value of 20% M_p, while for the fully pre-tensioned case, substantial prying effects begin at 40% M_p. The prying force at loads near the ultimate, however, are the same for both cases.

3.3 Connection Behavior

3.3.1 Strength Characteristics

The ultimate strength of the connections was not affected by snug-tightening. The ultimate strength of each connection with a one-inch end-plate was approximately 100% M_p. Both 3/4-inch end-plate connections attained approximately 90% M_p.

3.3.2 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. Snug-tightening simply allows the contact pressure to be overcome earlier. As the contact pressure due to pre-tensioning is relieved, the deformation of the connection is more dependent on the restraint offered by the bolts. Then, as the 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 additional load is redistributed to un-yielded portions of the connection. For a typical 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[6].

The following paragraphs discuss the effects of snug-tightened 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 9 shows the variation in connection stiffness throughout a complete loading history.

At low values of connection moment, the two connections represented in Figure 9 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.

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

Reversal Loading

For the set of 3/4-inch tests that included reversal loading (34SNR and 34TR), yielding of the end-plate material occured in the fully pre-tensioned 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 with fully pre-tensioned bolts was subjected to a stiffer boundary condition at the bolt line due to the larger bolt clamping force. Therefore, it attracted a higher bending moment at the bolt line, and yielding of the plate occurred at a lower value of external load. Figure 10 shows the moment-rotation response of the two connections. The first (left-to-right) two lines of the figure represent the initial response, and the remaining two lines represent the response after a number of load reversals for each connection. Initially, the fully pre-tensioned (tight) condition is stiffer, while the snug case is stiffer during the final (fifth) cycle.

In the final cycle, the fully pre-tensioned 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-inch end-plate connections exhibit the same response at high load values.

3.4 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 pre-tensioned 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 Figure 10).

Substantial increases of bolt force due to prying action developed during the course of loading (See Section 3.2.3). Other researchers have also indicated that large prying forces can develop in end-plate connections[7, 8]. Prying action needs to be addressed in design procedures of end-plate connections.

4 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 full details of this study are contained within another report[9].

4.1 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 fully pre-tensioned ($0.7F_u$), 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 monitonically 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 during 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 Figure 2-b). In the first series (two experiments), the critical leg only contained one bolt line (See Figure 2-a).

4.2 First Series -- One Bolt Row

The bolts in these experiments were 1-1/8", A325. The tightening condition was 61 kips ($0.7F_u$) for the fully pre-tensioned and 27 kips ($0.3F_u$) for the snug-tight condition. Monotonic loading was applied.

4.2.1 Full Pre-Tension vs. Snug-Tight Bolt Behavior

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 pre-tension. 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 pre-tension is overcome in the full case, the curves are almost identical. Figure 11 visually details the prying action per bolt in the two tests. The prying force is the vertical distance between the curve and the straight line, denoted as Q. The bolts of the snug test exhibit prying action almost immediately. When pre-tension is overcome for the full case, the two curves join together as was the case with the bolt bending.

4.2.2 Bolt Pre-Tension Effect on Connections with One Bolt Row

The connections with one bolt row acted independently of degree of pre-tension, as is seen in the similar moment-rotation curves of Figure 12. 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 bolt bending and prying at early loads.

4.2.3 Failure Mode

In both the fully pre-tensioned 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.

4.3 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-inch diameter, A325 high-strength. 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, ($\frac{M}{d}$).

4.3.1 Two-Bolt-Row Connection Behavior

The connection with snug bolts was approximately 25% stronger than the connection with fully pre-tensioned bolts as shown in Figure 13. The full pre-tension test began with a slightly higher rotational stiffness. However, with each load reversal the connection softened considerably (See Figure 14). While beginning at only 75% stiffness of its fully pre-tensioned counterpart, the snug test remained at that stiffness until the last cycle of loading (See Figure 15). The lower strength and stiffness for the fully pre-tensioned case can be attributed to the full pre-tension mode of yielding of the critical bolt line, described in Section 4.3.4.

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*Increment refers to the amount of bolt force above the initial pre-tension.

4.3.2 Full Pre-Tension Bolt Behavior

The full pre-tension condition was 50 kips ($0.7 F_u$) for these two-bolt-row tests.

Bolt Bending and Prying

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.

Figure 16 shows a plot of force per bolt versus flange force for both the full pre-tension and the snug-tight case. The vertical difference between the plot and the solid line, denoted as Q, represents the prying force, which is considerable for the full pre-tension. This prying force takes place at a contact surface *between* the bolt lines.

Bolt Strain Increment

Figure 17 shows the average strain increment of bolts from the critical and secondary bolt line. The critical bolts carry a disproportionate amount of the strain, i.e., external load. In fact, the critical bolts begin to yield before the secondary bolt line feels any of the external tensile force.

4.3.3 Snug-Tight Bolt Behavior

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

Bolt Load Increment

Figure 18 shows a plot of critical and secondary line bolt load versus flange force. Nearly equal values of bolt force indicate that both bolt rows share the tensile flange force, as opposed to the full pre-tension case.

Bolt Bending and Prying

Both bolt rows bended more evenly and less severely than the corresponding fully pre-tensioned connection. With the exception of the initial portion, the snug-tight prying force in Figure 16 is considerably smaller than the prying on the fully pre-tensioned connection. 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 which will be described in the next section.

4.3.4 Bolt Pre-Tension Effect on Connections with Two Bolt Rows

As described in Sections 4.3.2 and 4.3.3, the bolt groups under full pre-tension acted quite differently than those under snug-tightening. In fact, two modes of bolt-induced connection behavior exist. In the case of fully pre-tensioned bolts, the critical (inner) row is required to carry most of the external force, while the connection with snug-tightened bolts shares the load among both rows. This occurs because of a more efficient redistribution of forces by the snug-tightened bolts after pre-tension is overcome.

Full Pre-Tension Mode

In the case of fully pre-tensioned bolts, ideally there exists a perfect contact surface from the second to the first bolt row. Figure 19 shows the load-deformation curve for a high-strength (A325) bolt. Please refer to this figure for the next two paragraphs. For a pre-tension of F_{fpr} and N bolts per row, when the flange force (P_f) reaches a value of

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

the first row of bolts becomes useful in resisting the additional external tensile force and their subsequent deflection is described by the force-elongation curve beginning at the point indicated in Figure 19 by *Tight*. Concurrently, the contact surface travels toward the second bolt row. Because the proportional limit of the bolt, indicated by *Yield* in the figure, is near its pre-tension value (*Tight*), 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 external tensile force. Thus, the *Full Pre-Tension 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 Figure 20-a). 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 pre-tension is overcome at a much lower load, but, as the contact surface recedes toward the second bolt row, the critical bolts are deflecting along the curve in Figure 19 beginning at the point indicated by *Snug*. The large elastic reserve (the distance along the curve from the point *Snug* to the point *Yield*), allows the first bolt line to act elastically while the small amount of pre-tension 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 $F_y \approx F_{fpr} = \textit{yield load for the bolt.}$ Therefore, with both bolt rows active and elastic, the angle is forced to assume the shape shown in Figure 20-b. Note that with a shorter moment arm (l_{cr}) the angle will not yield until a much higher load than the fully pre-tensioned case. In general, the yield lines in the tension angle are *responses* to the deformation that the bolts are *permitting* (full pre-tension), or *restricting* (snug case) the beam to impose on the angle.

4.3.5 Load Reversal Effects

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 permanent set remains in a yielded bolt on reversal. In the fully pre-tensioned case, the critical bolt line never returns to its original position despite load reversal, and a progressive migration of the yield lines occurs 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. Conversely, for the snug-tight case, though the bolt line had minor deformations almost immediately (due to the low pre-tension), it returned to near its original postion

5 Conclusions

5.1 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-inch and 3/4-inch end-plate connections, substantial bolt 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 pre-tensioned counter-parts is negligible. Therefore, there is not a significant effect on bolt moments due to the pre-tension level.
- Snug-tight bolts will be adequate for most static loading conditions of thin end-plates if the bolts are sized conservatively to resist the additional bending and prying forces.
- Snug-tight bolting actually gives a more uniform distribution of bolt forces to outer bolts in multiple bolt groups after pre-tension is overcome.

5.2 Top-and-Seat-Angle Connections

5.2.1 Single Bolt Row

The connections behaved almost identically, independent of pre-tensioning level.

5.2.2 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) pre-tension.
- 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 pre-tensioned connection achieved 40%.
- In the fully pre-tensioned 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 induced higher bolt bending and prying forces in the fully pre-tensioned case.

5.3 General Observations

- The deficiencies associated with snug bolts did exist (earlier prying and bolt bending, less initial stiffness), however they had a minor effect on the connection's behavior.
- In the experimental work performed for this paper, full-scale large-sized connections, the connections' behavior as a structural component is primarily dependent on the bolts of the tension region.

Acknowledgements

The studies reported here were conducted in the Engineering Research Center for Advanced Technology for Large Structural Systems (ATLSS) at Lehigh University. The ATLSS Center was created by a grant from the National Science Foundation. Dr. John W. Fisher is the Director of ATLSS.

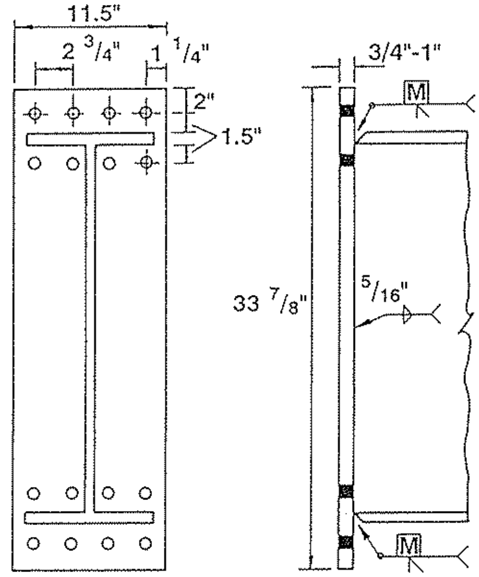
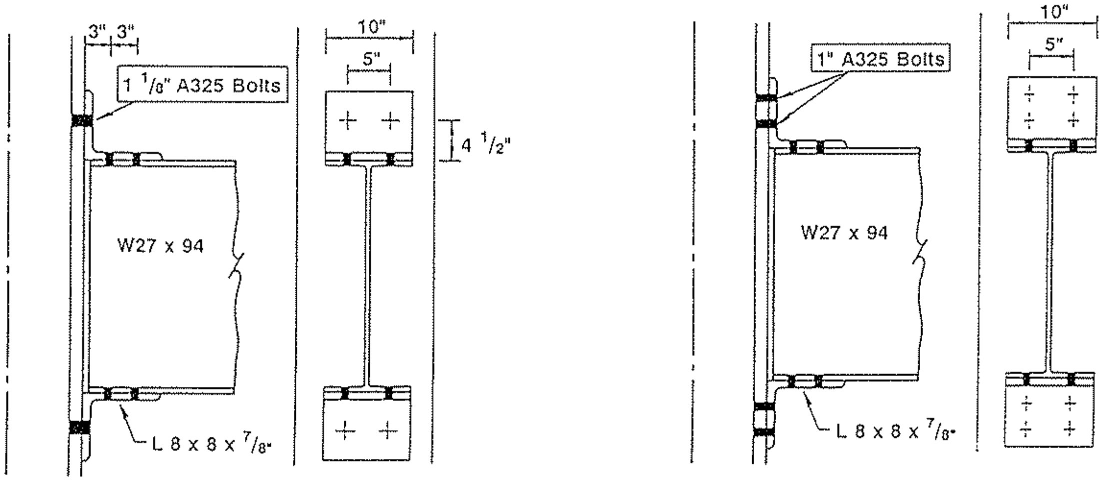


Figure 1: Extended End-Plate Test Specimen.



(a) *(b)*

Figure 2: Top-and-Seat-Angle Test Specimens; a: One Bolt Row, b: Two Bolt Rows

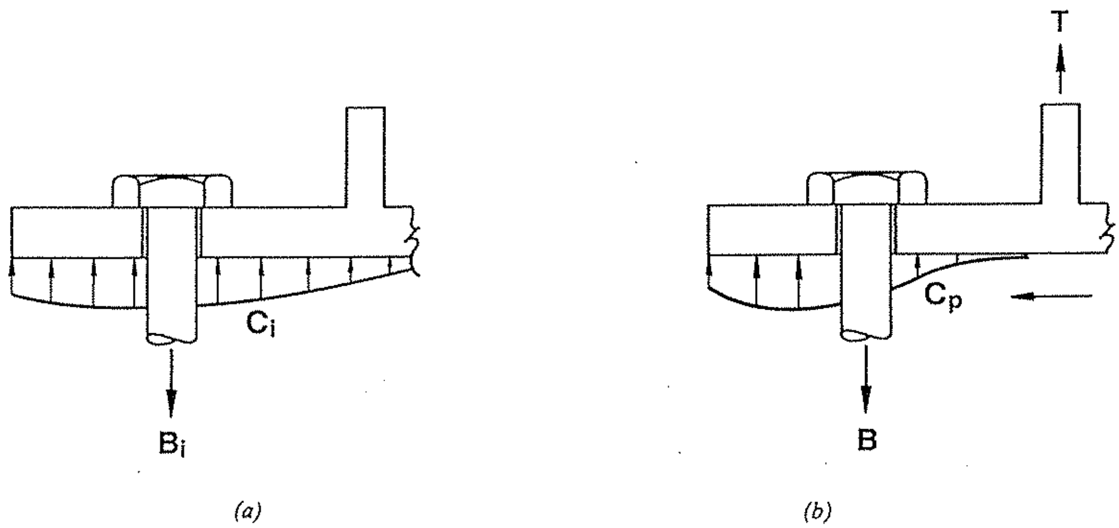


Figure 3: Contact Surface; a: Undisturbed, b: Receding.

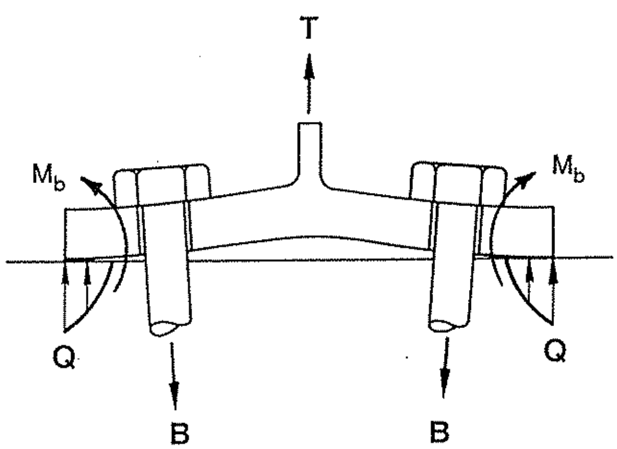


Figure 4: Tee-Hanger Connection under External Tensile Load.

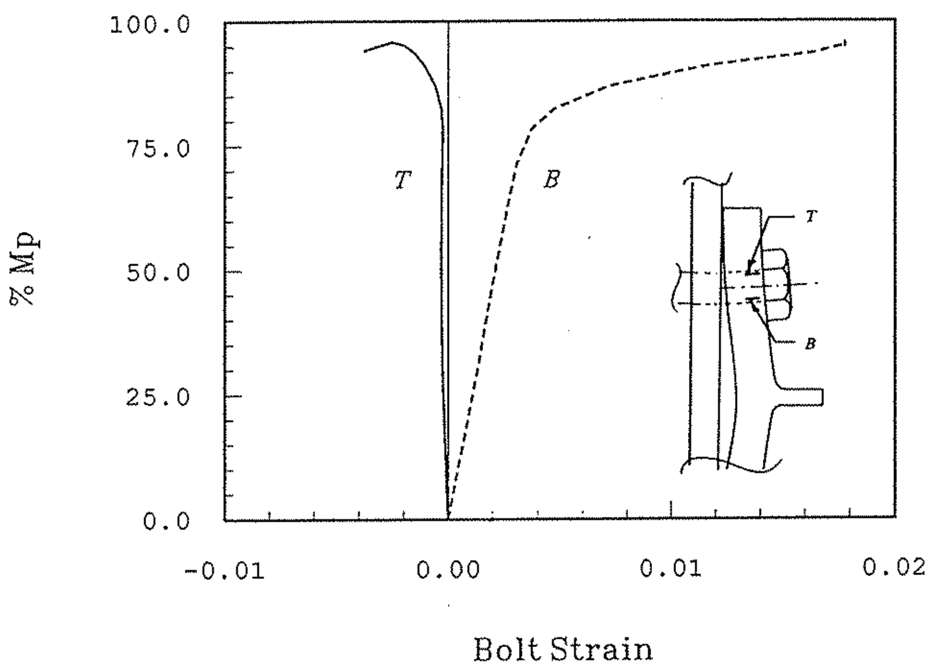


Figure 5: Strain Components of a Bolt Under Bending.

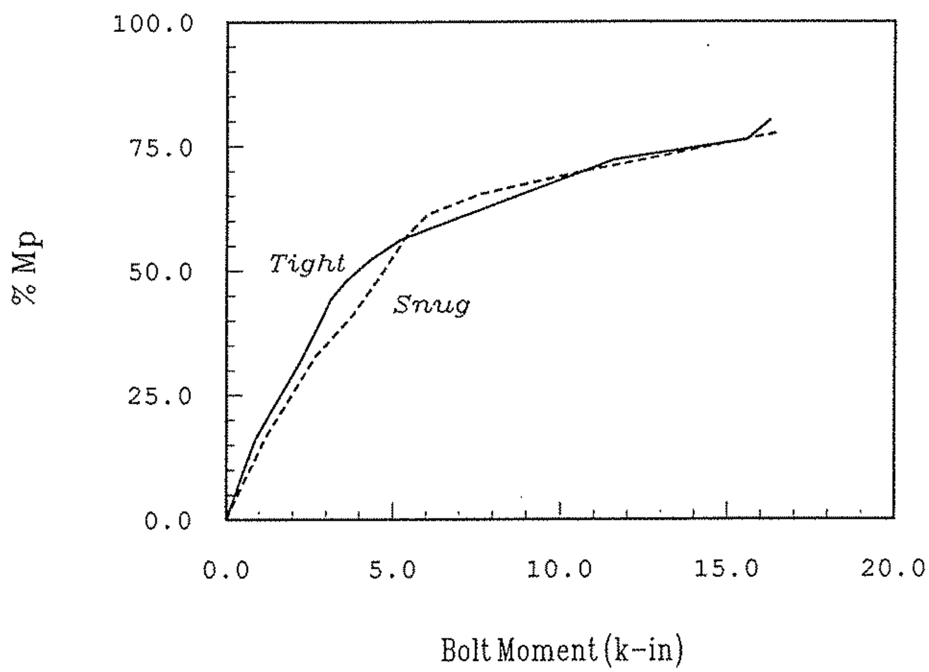


Figure 6: Snug and Fully Pre-Tensioned Bolt Bending Forces, End-Plate.

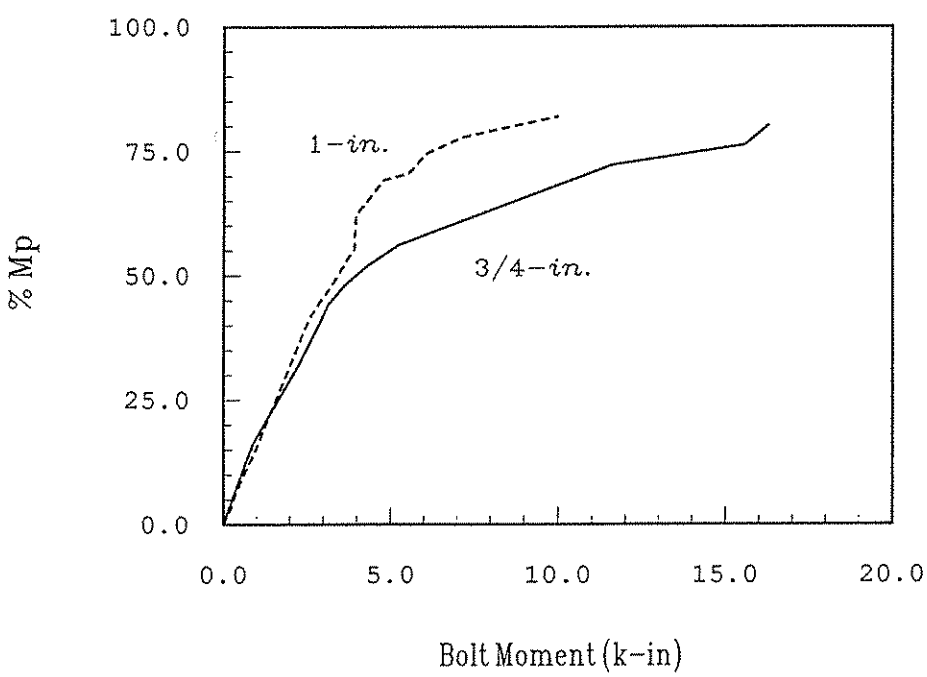
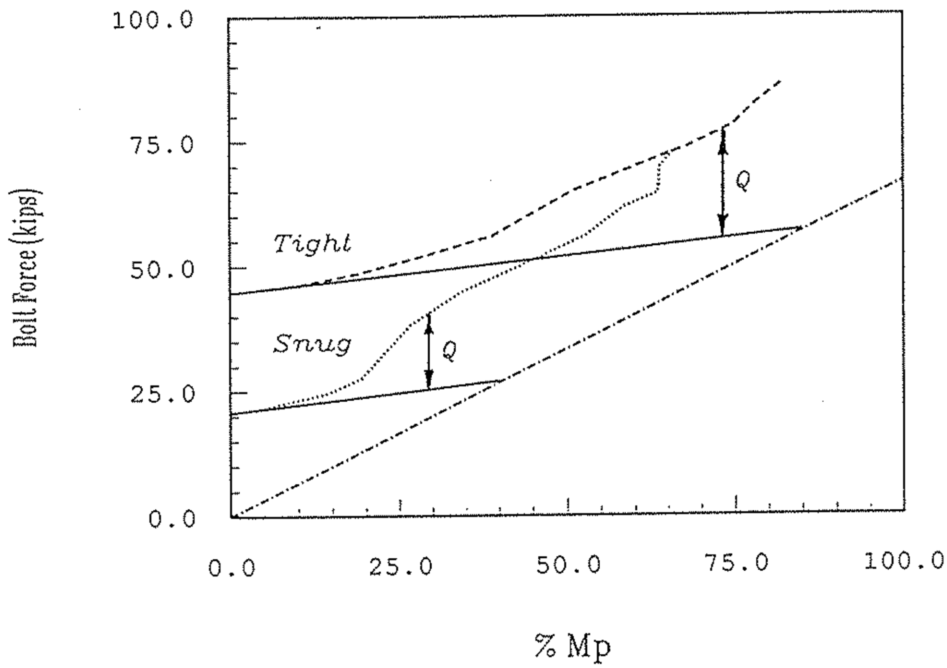


Figure 7: End-Plate Thickness Effect on Bolt Bending.



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

Figure 8: Snug-Tight Effects on Prying Action, End-Plate.

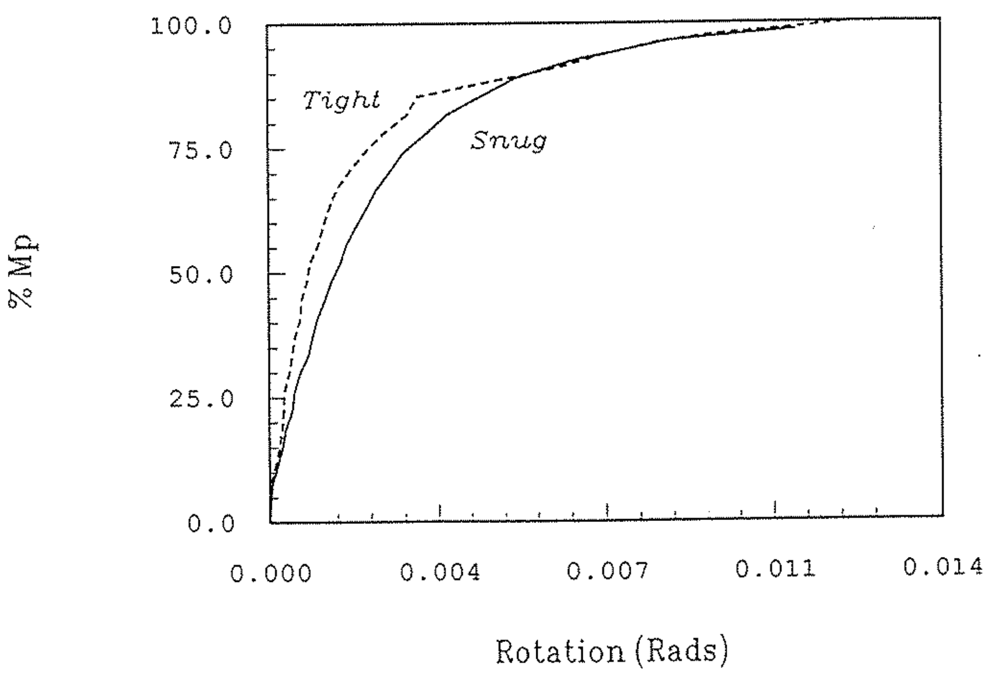


Figure 9: Snug-Tight Effects on Connection Stiffness, End-Plate.

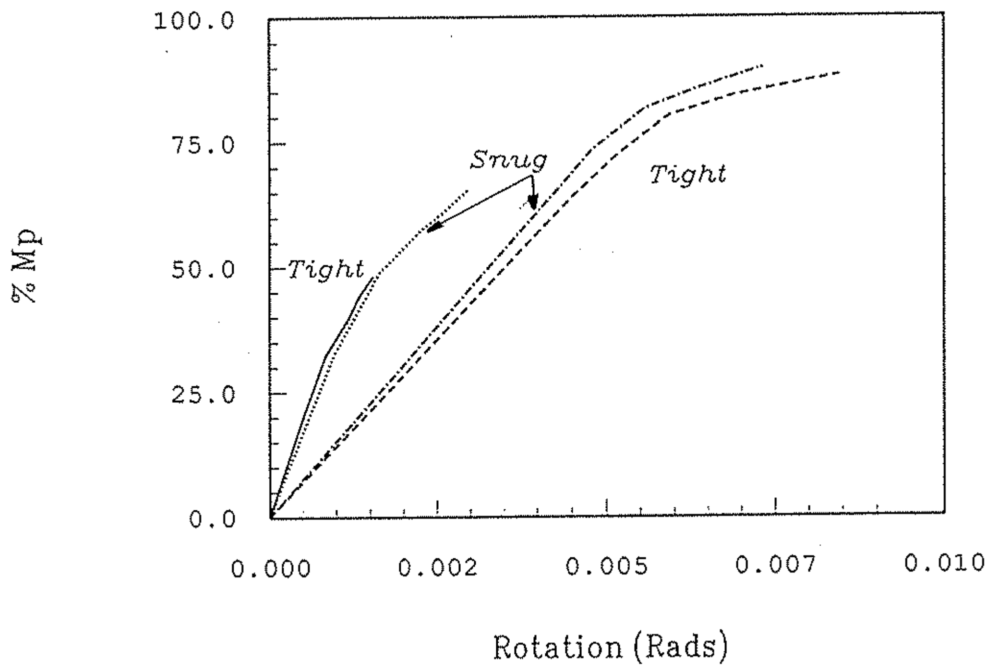


Figure 10: 3/4-inch End-Plate Stiffness After Reversal Loading.

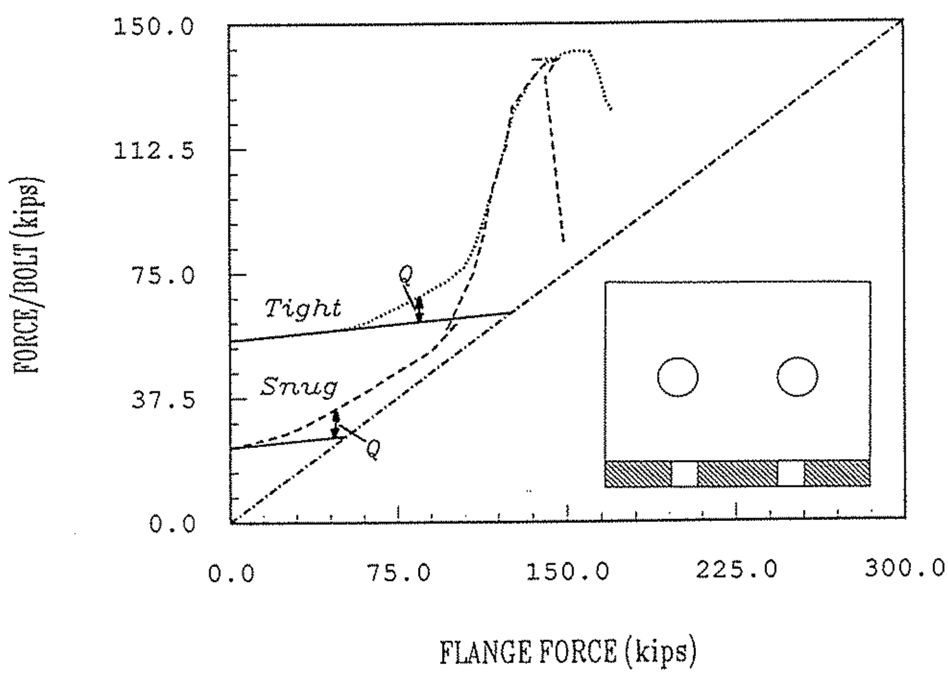


Figure 11: Top-and-Seat, One Bolt Row - Bolt Prying.

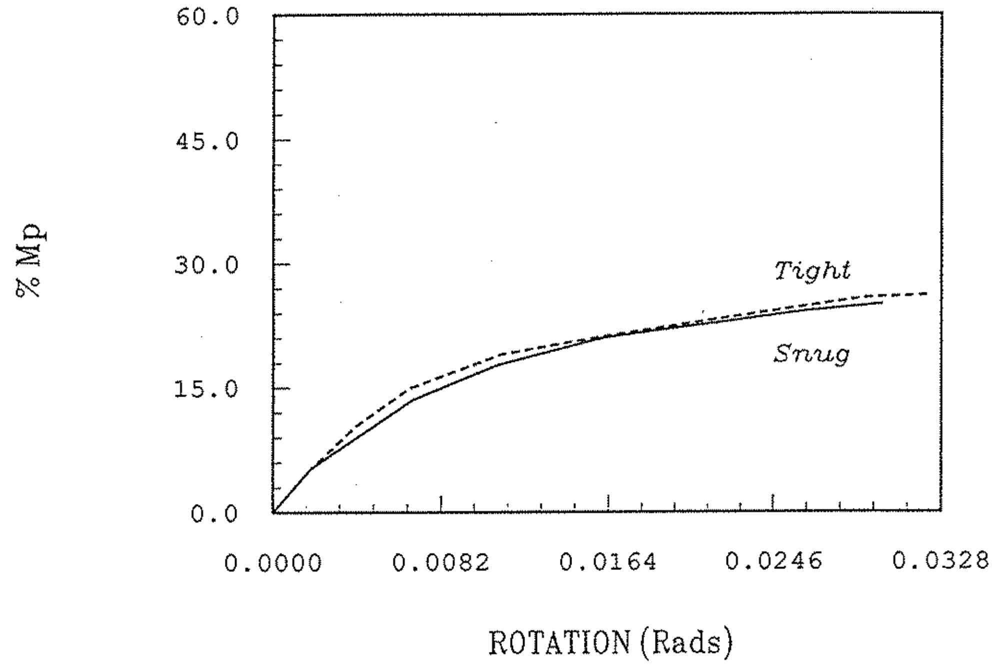


Figure 12: Top-and-Seat, One Bolt Row - Moment-Rotation.

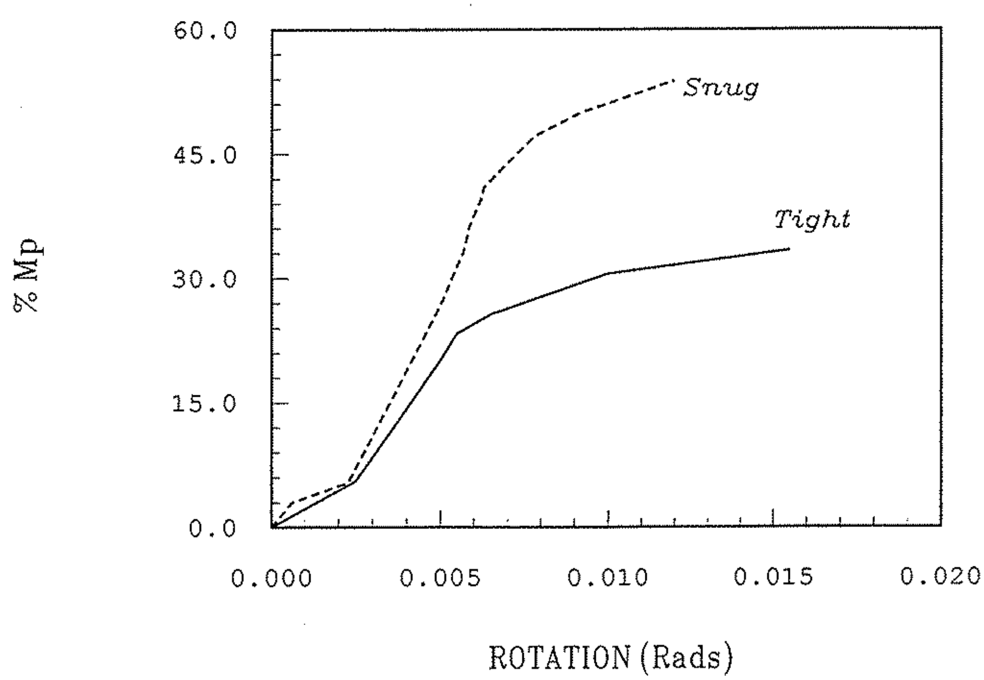


Figure 13: Top-and-Seat, Two Bolt Row - Moment-Rotation.

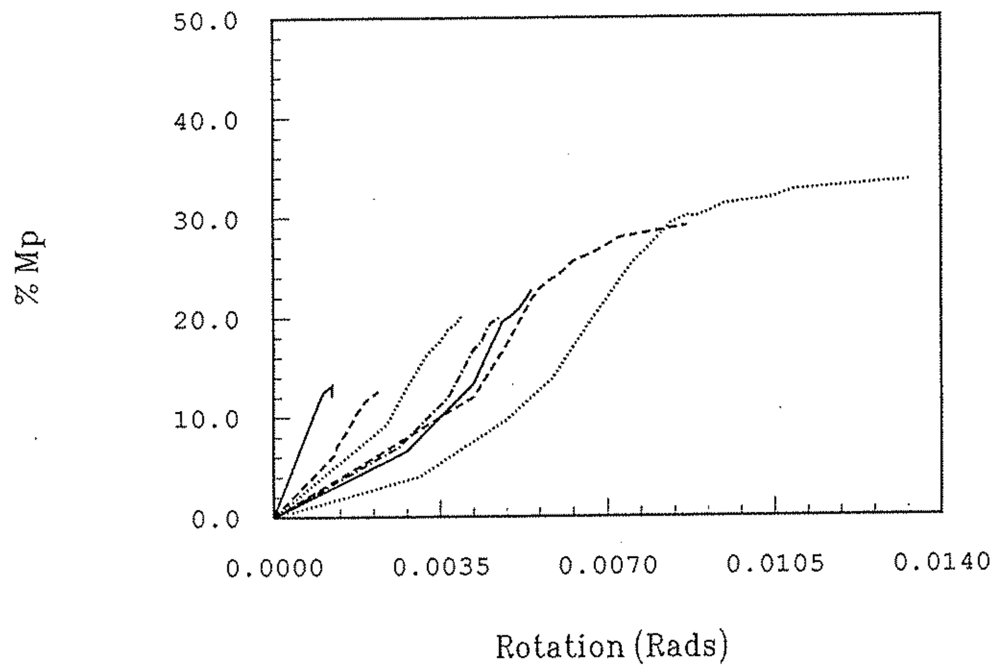


Figure 14: Progressive Softening of a Fully Pre-Tensioned Connection.

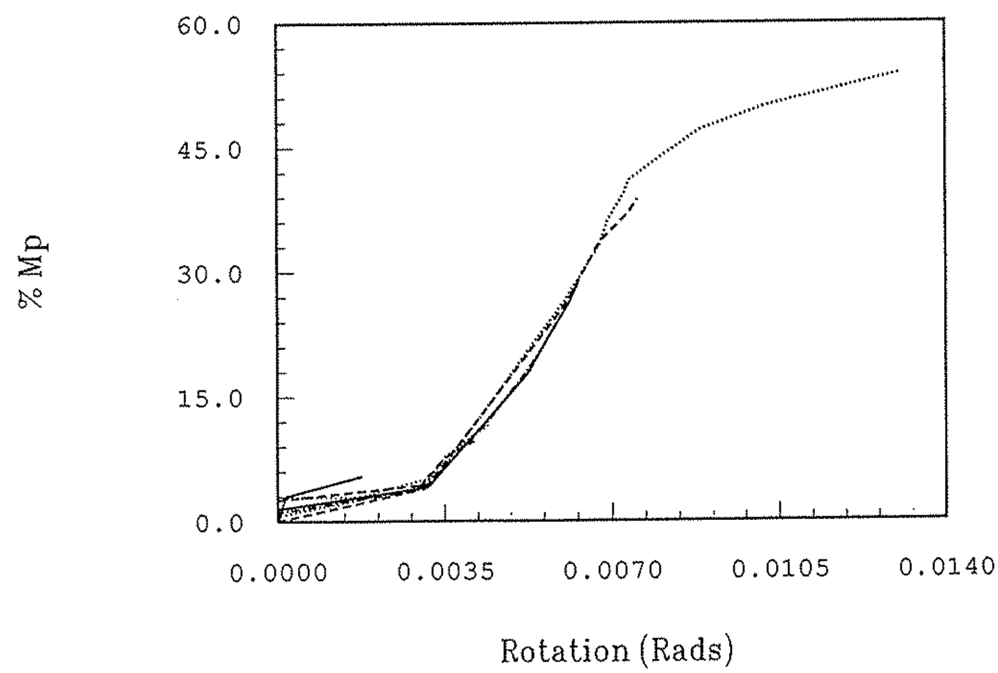


Figure 15: Stable Stiffness of Snug-Tight Connection.

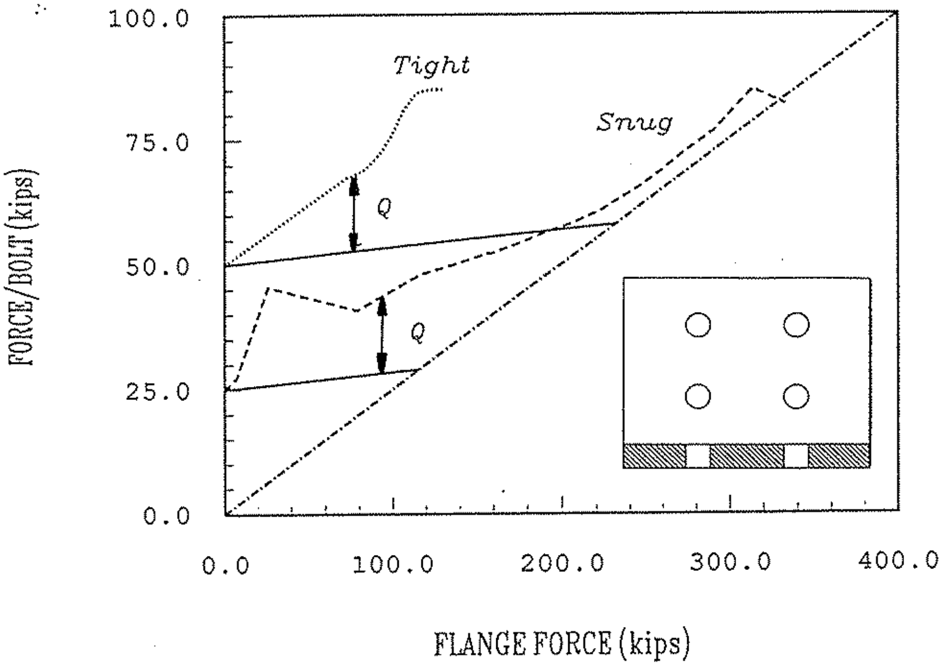


Figure 16: Top-and-Seat, Two Bolt Row - Bolt Prying.

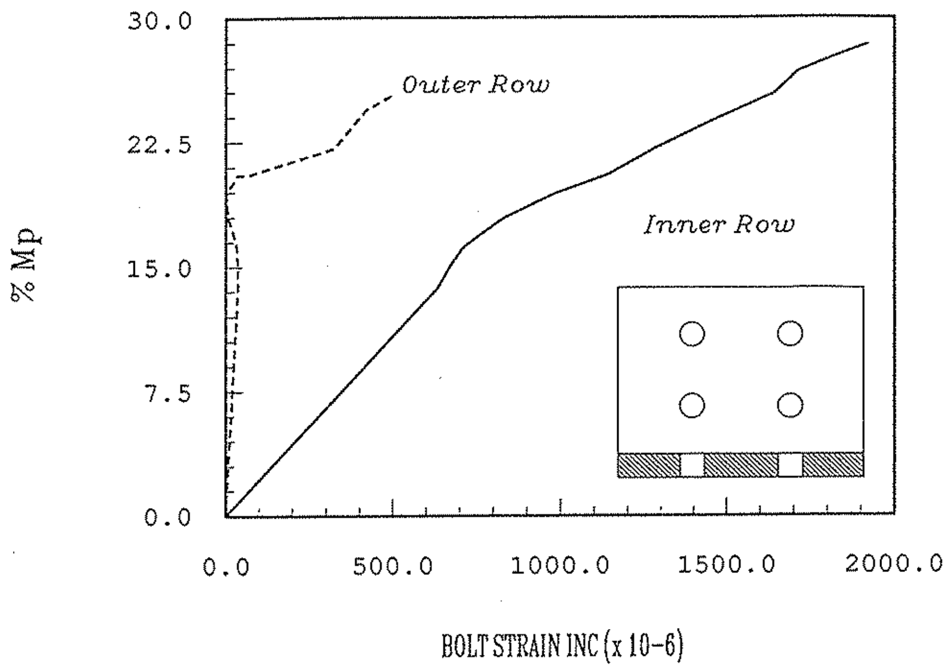


Figure 17: Two Bolt Row, Tight - Bolt Strain Increment.

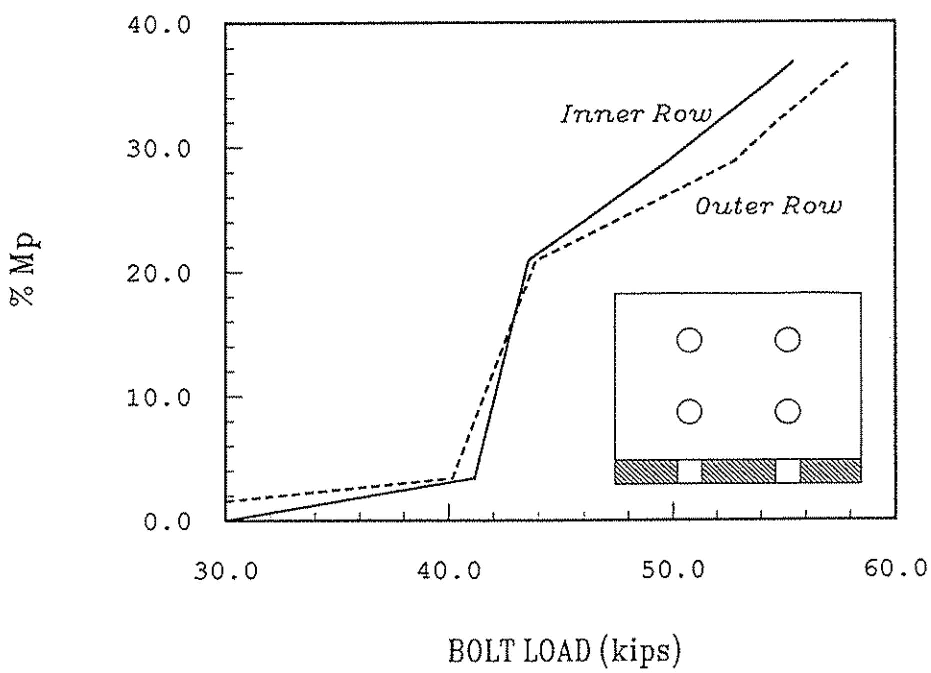


Figure 18: Two Bolt Row, Snug - Bolt Load Increment.

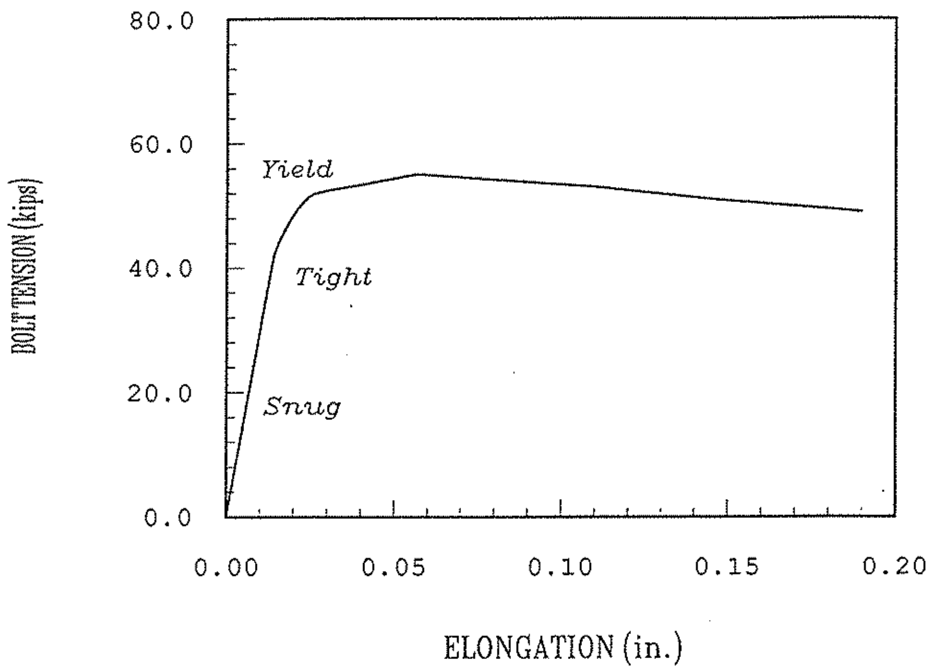


Figure 19: A325 Bolt Load-Deformation Curve.

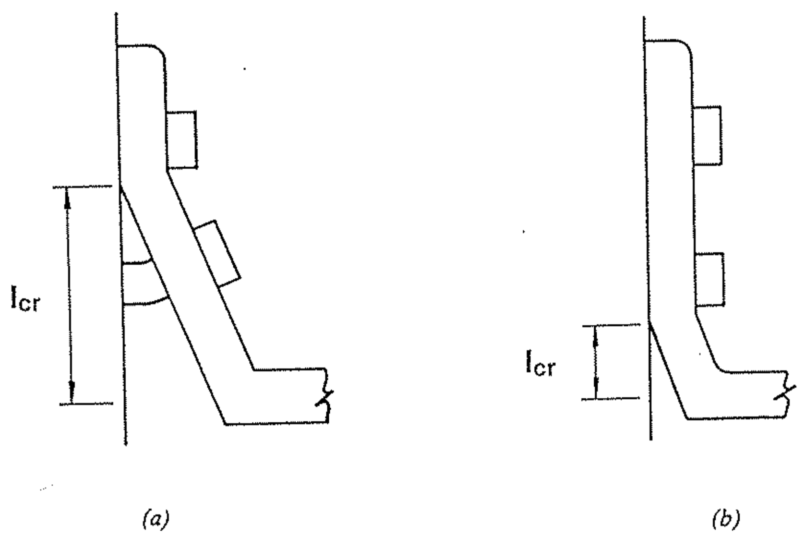


Figure 20: Full Pre-Tension and Snug-Tight Modes.

References

1. AISC, MANUAL OF STEEL CONSTRUCTION: LOAD AND RESISTANCE FACTOR DESIGN, 1st Edition, American Institute of Steel Construction, Chicago, Illinois, 1986.

2. Chasten, C. P., Fleischman, R. B., Driscoll, G. C., Lu, Le-Wu, "TOP-AND-SEAT-ANGLE CONNECTIONS AND END-PLATE CONNECTIONS: BEHAVIOR AND STRENGTH UNDER MONOTONIC AND CYCLIC LOADING", *Fabricators & Engineers, Working Together*, American Institute of Steel Construction, Nashville, Tennessee, June 1989.

3. Kulak, G. L., Fisher, J. W., Struik, J. H. A.,, *GUIDE TO DESIGN CRITERIA FOR BOLTED AND RIVETED JOINTS*, John Wiley & Sons, New York, 1987, Second Edition

4. AISC,. MANUAL OF STEEL CONSTRUCTION, Eighth Edition, American Institute of Steel Construction, Chicago, IL, 1980.

5. Krishnamurthy, N.,, "A FRESH LOOK AT BOLTED END-PLATE BEHAVIOR AND DESIGN", *Engineering Journal, AISC*, Vol. 15, No. 2, 1978, pp. 39-49.

6. Chasten, C. P.,, "THEORETICAL MODELING AND TESTING OF 8-BOLT EXTENDED END-PLATE CONNECTIONS", Master's thesis, Lehigh University, October 1988, ATLSS Project A3.1

7. Agerskov, H.,, "HIGH-STRENGTH BOLTED CONNECTIONS SUBJECT TO PRYING", *Journal of the Structural Division, ASCE*, Vol. 102, No. ST1, Jan. 1976, pp. 161-175.

8. Mann, A. P., Morris, L. J.,, "LIMIT DESIGN OF EXTENDED END-PLATE CONNECTIONS", *Journal of the Structural Division, ASCE*, Vol. 105, No. ST3, March 1979, pp. 511-526.

9. Fleischman, Robert B., "EXPERIMENTAL AND THEORETICAL ANALYSIS OF COMPONENT BEHAVIOR IN TOP-AND-SEAT-ANGLE CONNECTIONS", Master's thesis, Lehigh University, September 1988, ATLSS Project A3.1