

ADDIS ABABA UNIVERSITY
ADDIS ABABA INSTITUTE OF TECHNOLOGY
SCHOOL OF CIVIL AND ENVIRONMENTAL ENGINEERING



**A Study on The Effect of Prying Action on the
Tension Resistance of Beam-to-Column
Connections**

A Thesis in Structural Engineering

By Mihret Moges

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A Thesis

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UNDERTAKING

I certify that research work titled “**A Study on the Effect of Prying Action on the Tension Resistance of Beam-to-Column Connections**” is my own work. The work has not been presented elsewhere for assessment. Where material has been used from other sources it has been properly acknowledged / referred.

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List of Symbols

The following symbols are used in this paper.

α_i = Sensitivity factor

A_s = Tensile stress area

B = Bolt force

B_o = Additional bolt force due to prying force

C.V = Coefficient of variation

$F_{t,Rd}$ = Tensile strength of a single bolt

$F_{T,Rd}$ = design tension resistance of a T-stub flange

f_{yb} = yield strength of the bolt

f_{yp} = yield strength of the end-plate

l_{eff} = effective length

m = distance between bolt axis and root of the profile

n = distance between bolt axis and edge of the end-plate

Q = Prying Force

Q_{all} = Allowable prying Force

t_f = thickness of the flange

T = Applied Tension force

U_i = Uncertainty coefficient

ABSTRACT

The effect of prying action in endplates tends to increase the tensile load that is transferred to the bolts and therefore its effect should be evaluated. The aim of this thesis is to study the effect of prying action on the tension resistance of beam-to-column connections and the scope was restricted to end plate connections for which the collapse was governed by the tension zone idealized by T-stubs. Where there is deformation, no matter how small, there is bound to be a prying force created. The question is whether or not the connection fails because of it. And this is based on the capacity of the bolts to carry the additional force and the capacity of the flange to not form a mechanism and fail. 30 finite element models were modeled and studied to study the effects of four variables on the generation and amount of prying force. From this analysis, it was found that the thickness of the flange, yield strength of the bolt, yield strength of the flange and the distance between the bolt axis and the root of the profile have a -43%, 37%, -4% and 16% contributions to the prying force generated. It was found that for thin flanges, using low yield strength bolts resulted in lower prying force than using high yield strength bolts and for thick flanges, using high yield strength bolts resulted in higher prying force generation than those with lower yield strength bolts whose prying forces were minimums, even zero. The studies also revealed that the best and optional combination to yield a minimum, even nonexistent, prying force and minimum deformation were thick flanges with low yield strength bolts.

Key Words: T-stub, Tension Resistance, Prying Force

1. INTRODUCTION

1.1 Background Information

Steel has become one of the most popular construction materials for both low and high rise buildings and for truss structures, and its structural properties such as high strength-to-weight ratio and ductility, offer distinct advantages when compared to concrete. Fast erection speed, long spans, elegance and adaptability are other features which makes steel a popular structural material.

The behavior of a structure is influenced as much by the behavior of its joints as by the behavior of its individual members. One of the design requirements aside from its effectiveness and economy is the harmony within the structure which is affected by the relationships between the different systems of the structure. This leads to the question of the effectiveness of the connections and their load carrying capacity. ES EN 1993-1-8:2013 hereafter referred to as ES EN 3:1-8, provides the necessary procedures for the design of these connections. This code along with others considers the effect of prying forces, which is the force within a connection which is resulted from the deformation of the connected parts, when designing bolts.

Bolted connections under tensile force are liable to be fractured under strength lower than the estimated design strength due to prying action between members. Thus, there have been many studies on estimating such prying forces between members. Prying action is a phenomenon that results in an additional tension on fasteners due to the deformation of t-stub flanges when loaded. Extensive studies on the subject of prying action have been carried out and they all have concluded that there can exist a failure in the flange, plastic hinge formations, in addition to a failure in the bolts and that the stiffness properties of both the flange and the fasteners are significant determinants of this effect.

This research paper studied the effect of prying action on the tensile resistance of an end-plate beam-to-column connection varying the thickness of the flange, the distance between bolt axis and root of the profile, yield strength of the plate, and yield strength of the bolt.

1.2 Objective of the Research

General objective: to study the prying forces generated and failure mechanisms of connections.

Specific objectives:

- To study the effect of thickness of the flange, the distance between bolt axis and root of the profile, yield strength of the plate, and yield strength of the bolt on prying action.
- To evaluate the performance of the design tension resistance of a t-stub flange given in ES EN 3:1-8, 6.2.4.1 (5)

1.3 Statement of the Problem

ES EN 3:1-8, 6.2.4 has given the design tension resistance of a t-stub flange. However, the effect of prying force on the behavior of the flange is not clearly outlined in the article. Moreover, the design industry is not giving attention to the effect of prying action on bolts and plates which could lead the connection to failure. Generally, the fact that prying force can drastically increase the amount of tensile stress produced in the bolt, and possibly cause failure in the flange plate itself is the driving force for this research in studying the various variables affecting this action.

1.4 Scope of the Research

This research is limited to the study of prying action on the tensile resistance of beam-to-column connections when subjected to a tensile load. In this research, the effect of bolt pre-loading, bolt position and spacing on prying action are not considered.

1.5 Research Methodology

Dependent variables: prying force

Independent variables: thickness of the flange, t_f , the distance between bolt axis and root of the profile, m , yield strength of the plate, f_{yp} and yield strength of the bolt, f_{yb}

Extraneous variables: bolt diameter, effective length of the flange, thickness of the web of the flange, number of bolts.

The following procedures were followed:

1. A beam-to-column connection and a tension member connection were modeled and simulated using available simulation software, ABAQUS
2. The failure of the connection in each simulation were studied based on failure mechanism and value of prying force generated,
3. The effect of the independent variables on the prying action were thoroughly investigated,
4. The design tension resistance of a t-stub flange was checked.

1.6 Organization of the Thesis

The thesis consists of an introduction, four chapters and general conclusions. A general introduction, scope and objective of the research are discussed in the first chapter. The second chapter provides a review of relevant literatures on prying action. Furthermore previous studies and existing expressions for prying forces are reviewed.

The third chapter presents the mechanical properties of materials used in the calculations and for the finite element models as well as the sampling technique used. The fourth chapter presents the method of analysis which involves the validation of the finite element models, and the method of analysis used.

The fifth chapter presents the results and discussion of the results obtained from the models. Whereas the sixth chapter presents the general conclusion and recommendations made for future works.

2. LITRATURE REVIEW

2.1. Prying Action

Depending on the direction of the bending moment, either the top or bottom flange T-stub in a beam-to-column connection is stressed in tension. The flexural deformation of the connected plates due to the exerted tension force results in an increased fastener/bolt forces. Depending on the flexural rigidity of the T-stub, additional forces may be developed near the flange tip; this phenomenon is referred as prying action and is illustrated in Figure 2.1[4].

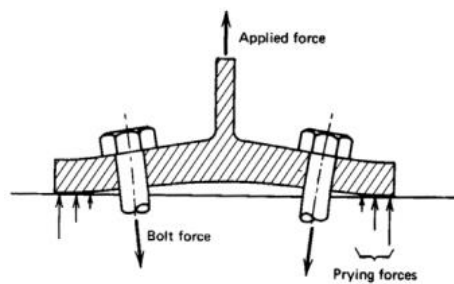


Figure 2-1 Schematic of joint deformation

An applied load of $2T$ on the less complicated and simplified connection in Figure 2.2 is to be transmitted. At first glance it might seem that each bolt in this connection will transmit a load $2T/2=T$ but in practice, the applied external load will bend the T-stub flange (see Figure 2.3). This deflection will cause the flanges to exert pressure on each other. The result is that the bolts must not only transmit the external load $2T$ but also the internal loads Q which develop due to the deflection of the flanges, as illustrated in Figure 2.4 [10].

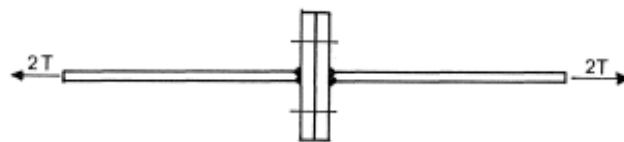


Figure 2-2 T-stub connection

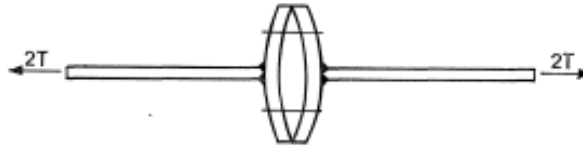


Figure 2-3 Bending of the T-stub flange

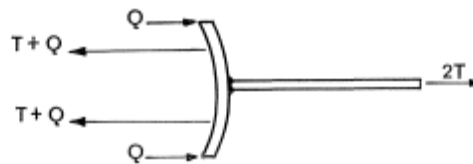


Figure 2-4 Force distribution in the T-stub

Initially, the external load reduces the contact pressure between the flanges until separation at the bolt line occurs. Bending in the outer portion of the flanges develops prying forces acting between the bolt line and the edge of the flanges. These forces will develop only when the ends of the flanges are in contact due to the external load [4].

2.1.1. Factors Affecting Prying Action

Although every component has an effect on the strength and stiffness of a connection, different researchers have studied specific components to evaluate their effect on the overall resistance.

Munse, Peterson and Chesson studied the effect of tee-section flange thickness and the grip length of the bolts and found that changes in the flanges thickness resulted in a range of bolt efficiency of 30% in the connections tested, connections with thicker flanges yielding higher efficiency. The effect of grip length was found to be small [11].

Douty and McGuire varied the flange thickness, the edge distance and the bolt diameter and came up with a semi-empirical equation to calculate the prying force created. While Leahey and Munse studied the effect of bolt pretension the behavior of the connection and found that changes in bolt pretension has little effect on the ultimate load of the connection when subjected to a static load [11].

Surtees and Mann also concluded that the bolt pretension has little effect on the connection stiffness and suggested an increase of 33% in the direct bolt tensile force to account for the prying forces. Salem, Sayed-Ahmed and Samaan studied the effect of bolt diameter, bolt end distance and end plate thickness and concluded that large edge distances decrease the bending moment capacity, and prying force to tensile bolt force ratio decreases by the increase in head plate thickness. For specimens with thick head plates, the prying force vanishes completely [1].

In this research, the effect of the end plate thickness, the distance between bolt axis and root of the profile, yield strength of the plate, and yield strength of the bolt are studied.

2.2. Previous Studies Done on Prying Action

Many researches are based on an analogy between the extended region of the endplate and tee-stubs, since it is easier to conceptualize and estimate prying action with tee-stubs. Previous investigations done on prying action on Beam-to-column and t-stub connections are reviewed in this section.

The tension region of a beam-column connection can be idealized as a tee-stub. Figure 2.5 show the enlarged view of the tee-stub in flexure under load where $2F$ is the flange force, Q is the prying force, and P is the bolt force. The extended region of the endplate, or/and the column flange in the tension region, is considered to behave like a tee profile with bolts placed around the stem [6].

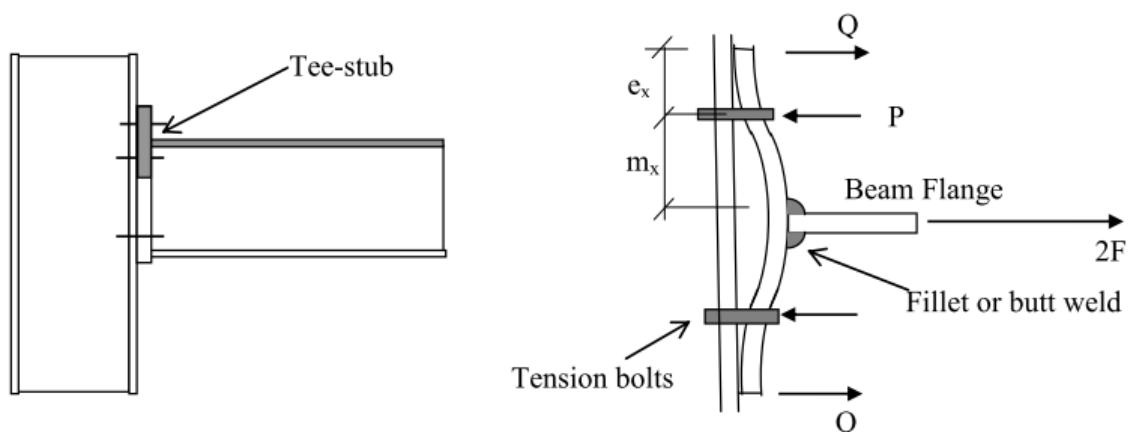


Figure 2-5 T-stub analogy for extended endplates

There were researchers like Surtees and Mann who tried to model endplate connections directly, and who conceptualized the extended regions of the endplate as half of a fixed ended beam terminating at the bolt line. On the other hand, there were researchers like Nair, Birkemoe and Munse, who concentrated more on tee-stubs and the tee-stub analogy, and who tended to conceptualize this as a simply supported beam extended to the edge of the plate. The former group of researchers tended to ignore prying forces or to assess them using simple rule of thumbs, while the latter group went to considerable trouble to calculate the prying forces on tee-stubs. The prying action assumptions for tee-stubs were then 'extrapolated' to extended endplates [6].

Douty and McGuire

Douty and McGuire's prying force derivation was involved, based on the initial elastic deformation of the endplate around the bolts due to the bolt pretension, and also including the initial bolt elongations. Their analytical model was derived from the assumption that the tee flange behaves as a simply supported elastic beam, spanning across the flange ends. The development of the prying force equation, relating the prying force Q to the ultimate load of the connection, was based on both equilibrium and compatibility conditions. The semi-empirical equation developed by Douty and McGuire that is based on the assumption that prying forces act at the tip of the flange is:

$$Q = \left[\frac{\frac{6Tt^4}{2} + \left[\frac{wt^4}{30ab^2A_b} \right]}{\frac{a}{b} \left[\left(\frac{a}{3b} \right) + 1 \right] + \left[\frac{wt^4}{6ab^2A_b} \right]} \right] T$$

(2-1)

Where: w = width of the flange,

t = thickness of the flange,

a = distance from face of the stem to the centerline of the bolt,

b = distance from the centerline of the bolt to the edge of the flange,

A_b = area of the bolt,

Q = prying force, and

T = external applied force.

However, the above equation is based on a specific combination of the bolt and plate material, different formulas maybe required for different bolt and plate combinations.

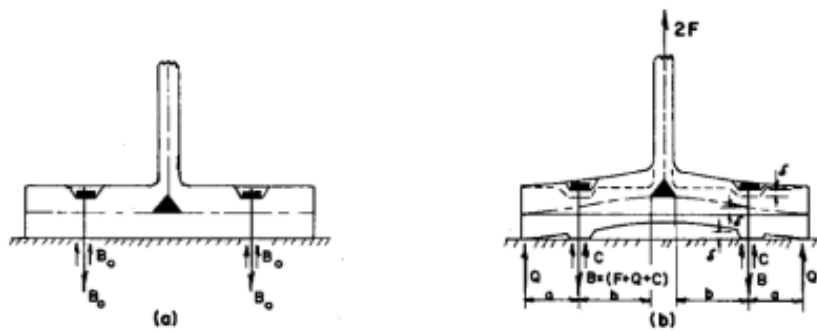


Figure 2-6 Simplified prying model of Douty and McGuire [9]

Surtees and Mann

Surtees and Mann tested six single-sided extended endplate connections with variable endplate thickness and proposed equations for obtaining the endplate thickness and the bolt sizes. The resulting equation for the endplate thickness is:

$$t_p = \sqrt{16d_f \left(\frac{2b_p}{p_1} + \frac{d_f}{p_2} \right)} \tag{2-2}$$

Where d_f is the depth between centers of the beam flanges, p_2 is the bolt gauge distance, p_1 is the bolt pitch distance, and b_p is the endplate width. They considered the possibility of prying action, catering for this with an empirical 30% increase in the bolt load. Thus, the bolts are to be sized for a force P, where: [6]

$$P = \frac{M_p}{4d_f} * 1.3 \approx \frac{M_p}{3d_f} \tag{2-3}$$

Nair, Birkemoe and Munse

In their study to determine the behavior of high strength bolts loaded in direct tension in tee-connections, Nair, Birkemoe and Munse concluded that the geometry of the tee-sections, the size of the bolts and the bolt type, in their case ASTM A325 & A490, govern the magnitude of the prying force. This study is based on bolt failure as the critical failure

mode. The ratio of the prying force, Q , to the externally applied load, p , in a bolted tee-connection at the point of failure of the bolts can be accurately determined by means of the equations shown below [11].

For connections with A325 bolts

$$\left(\frac{Q}{P}\right)_u = \frac{100bd^2 - 18wt^2}{70ad^2 + 21wt^2} \geq 0 \quad (2-4)$$

For connections with A490 bolts

$$\left(\frac{Q}{P}\right)_u = \frac{100bd^2 - 14wt^2}{62ad^2 + 21wt^2} \geq 0 \quad (2-5)$$

Where: d = nominal bolt diameter,
 t = thickness of the tee-section flange,
 w = length of flange tributary to each bolt,
 b = distance from the bolt line to the face of the web minus 1/16 inch,
 a = distance from the bolt line to the edge of the flange ($a \leq 2t$)

The ultimate load, P_u , of a tee-connection which fails by bolt fracture may be determined from the equation,

$$P_u = \frac{nT_u}{1 + \left(\frac{Q}{P}\right)_u} \quad (2-6)$$

Where: n = number of bolts in the connection,
 T_u = tensile strength of each bolt

Yield line theory can be used to determine the capacity of a connection as well as the force that can be exerted on a bolt. However, yield line theory does not provide bolt force predictions that include prying action forces. Hence, Kennedy, et al. (1981) suggested a method to predict the bolt forces as a function of the applied flange force. [12]

The Kennedy method is based on the split-tee analogy and three stages of plate behavior. He considered a split-tee model, Figure 2.7, consisting of a flange bolted to a rigid support and attached to a web through which a tension load is applied.



Figure 2-7 Kennedy's split-tee model

At the lower levels of the applied loads, the flange behavior is termed as “thick plate behavior”, as plastic hinges have not formed in the split-tee flange, Figure 2.8a. As the applied load is increased, two plastic hinges form at the centerline of the flange and each web face intersection, Figure 2.8b. This yielding marks the “thick plate limit” and the transition to the second stage of plate behavior termed as “intermediate plate behavior”. At a greater applied load level, two additional plastic hinges form at the centerline of the flange and each bolt, Figure 2.8c. The formation of this second set of plastic hinges marks the “thin plate limit” and the transition to the third stage of plate behavior termed as “thin plate behavior”.

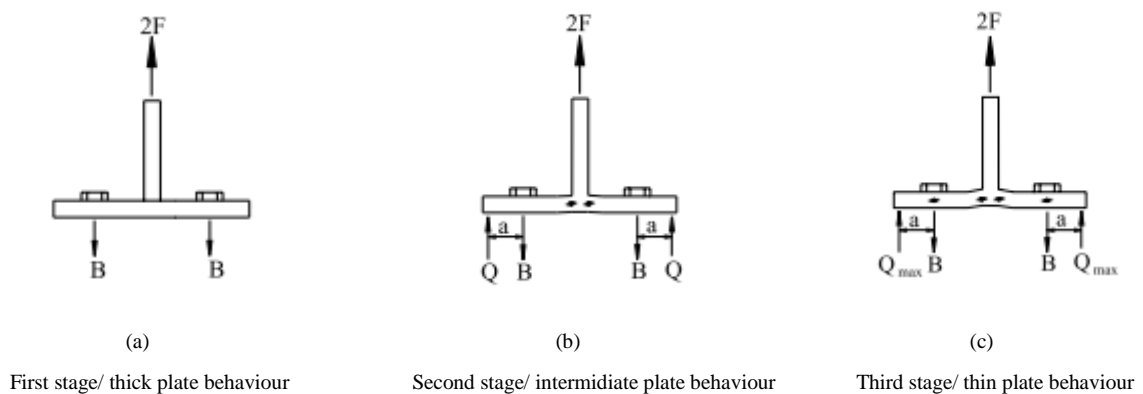


Figure 2-8 Flange behavior models

Bruhn and Niu

Both Bruhn and Niu studied the effect of prying on tension clips from aeronautical engineering point of view. However since tension clips used on aircraft assemblies and T-stub connections have similar characteristics in terms of prying action, the concept applies for both.

Bruhn presented a simple analytical approach by using static equilibrium.

$$\frac{Q}{F} = \frac{b}{a} \quad (2-7)$$

Where, Q is prying force

F is the applied load

a is distance between the bolt axis and the edge

b is the distances between the bolt axis and the root radius

Whereas Niu emphasized the impossibility of having an exact calculation for prying effect due to plenty of dependent variables like: [9]

- Geometry of the connection
- Type, material and location of the fastener
- Preload in fastener
- Distribution shape of contact forces forming the prying load
- Thickness ratio of flange and web

Kristian Ydstebo

Kristian Ydstebo, by using H. Ersland's prying force model, calculated the prying force by modeling the T-stub shown in Figure 2.9, where the bolt and the prying force are modeled as roller support and the distance between bolt axis and edge of the end-plate taken as the maximum distance provided by ES EN 3:1-8, n is 1.25m. Since the system is statically indeterminate, the unit load method was used to determine the prying force, Q.

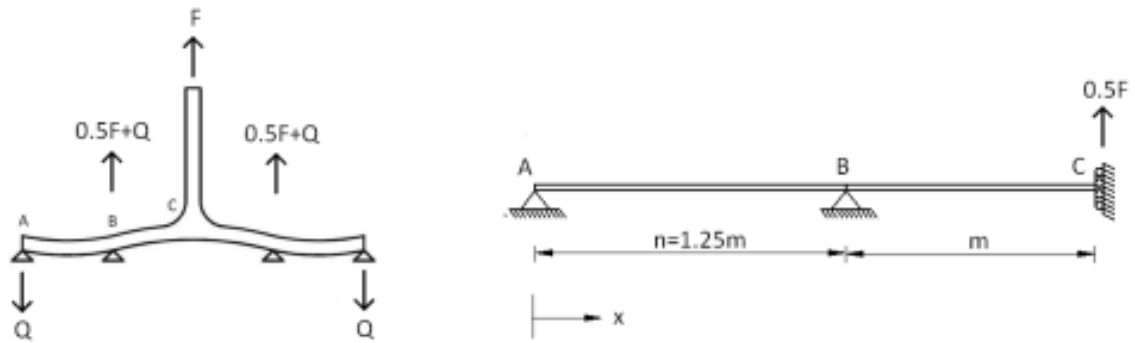


Figure 2-9 Model for determining the prying force, Q

Using the unit load method, Kristian Ydstebo determined the bolt force as $0.64F$ and the prying force as $0.14F$ meaning the prying force exerts an additional 28% of the load applied. [8]

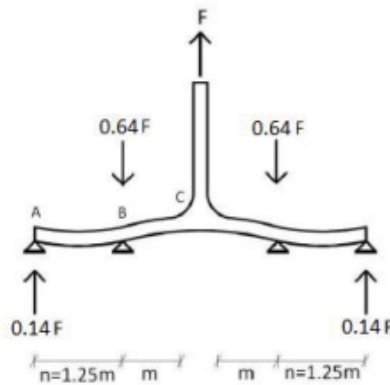


Figure 2-10 Prying force on a T-stub

However, this model only focused on the equilibrium condition of the system and doesn't consider the contribution of the thickness or the material property of the flange.

2.3. Existing Expressions for Prying Action

Different codes and standards define prying action a little differently and consider its effects in different ways. Even though they all consider this effect in the design of connections, some codes consider it implicitly by calculating the amount of prying force created while others consider the effect explicitly by calculating the resistance of the connection to take this effect in to consideration.

Load and Resistance Factor Design, LRFD and ASD

The *Load and Resistance Factor Design* specification for structural steel buildings, *LRFD*, defines prying action as a lever action that exists in connections in which the line of application of the applied load is eccentric to the axis of the bolt, causing deformation of the fitting and an amplification of the axial force in the bolt.

The *LRFD* specification states that the required tensile strength shall include any tension resulting from prying action produced by deformation of the connected parts.

Even though, *LRFD* and *ASD* vary by the factor of safety they use for the calculation of the design resistance of flanges, the concept behind prying action is the same.

Chinese code

The *code of practice for the structural use of steel 2011, Hong Kong*, states that

- a) Design against prying force is not required provided that all the following conditions are satisfied.
 - i. Bolt tension capacity P_t is reduced to

$$P_{nom} = 0.8A_tP_t \quad (2-8)$$

In which P_{nom} is the nominal tension capacity of the bolt and A_t is the tensile stress area of a bolt

- ii. The bolt gauge G on the flange of UB, UC and T sections does not exceed $0.55B$, in which B is total width of the flange, see figure 3.1

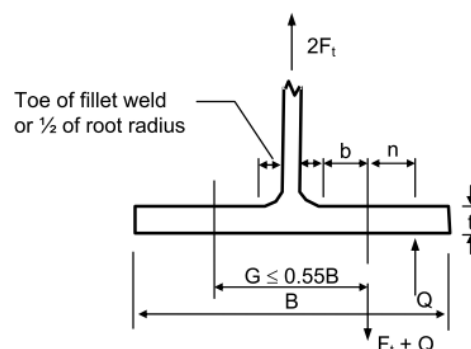


Figure 2-11 Prying Force according to the Chinese code

- b) If the conditions described in (a) above cannot be satisfied, the prying force Q should be calculated and taken into account and F_{tot} should be calculated as follows:

$$F_{tot} = F_t + Q < P_t \quad (2-9)$$

F_{tot} is the total applied tension in the bolt including the prying force, and F_t is the tension force in the bolt.

Even though the Chinese code recommends taking prying force in to account when calculating the total applied tension force in bolts, it doesn't state a way to calculate this prying force.

Indian Standard

The *Indian Standard, IS 800: 2007* defines prying force as an additional force developed in a bolt as a result of the flexing of a connection component such as a beam end plate or leg of angle.

IS 800:2007 states that if the prying force, Q is significant, it shall be calculated as given below and added to the tension in the bolt.

$$Q = \frac{l_v}{2l_e} \left(T_e - \frac{\beta \eta f_o b_e t^4}{27l_e l_v^2} \right) \quad (2-10)$$

Where

l_v = distance from the bolt centerline to the toe of the fillet weld or to half the root radius of a rolled section

l_e = distance between prying force and bolt centerline and is the minimum of either the end distance or the value given by:

$$l_e = 1.1t \sqrt{\frac{B T_e}{f_y}} \quad (2-11)$$

Where: $B = 2$ for non pre-tensioned bolt and 1 for pre-tensioned bolt,

$\eta = 1.5$,

b_e = effective width of flange per pair of bolts,

f_o = proof stress in consistent units, and

t = thickNess of the end plate.

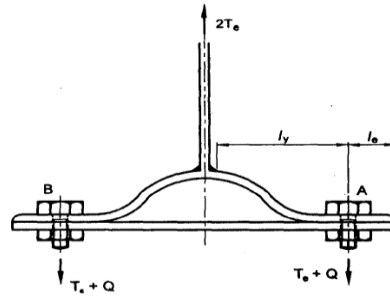


Figure 2-12 Combined prying force and tension according to the Indian standard

Ethiopian Building Code and Standard

The Ethiopian Building Code and Standard, Design of Steel Structures, ES EN 1993-1-8:2013 implicitly takes prying effects into consideration when determining the design tension resistance of a T-stub flange. It also states when fasteners are required to carry an applied tensile force, they should be designed to resist the additional force due to prying action. However, it doesn't state how to calculate these additional forces.

Prying forces may develop if $L_b \leq L_b^*$

Where; L_b is the bolt elongation length, taken equal to the grip length (total thickness of material and washers), plus half the sum of the height of the bolt head and the height of the nut.

$$L_b^* = \frac{8.8 \cdot m^3 \cdot A_s}{\sum l_{eff} t_f^3} \quad (2-12)$$

ES EN like Eurocode3 divides the possible failures into three modes. Mode 1 is the complete yielding of the flange; Mode 2 is the combination of bolt failure with yielding of the flange while Mode 3 is bolt failure.

In cases where prying forces may develop, the design tension resistance of a T-stub flange $F_{T,Rd}$ should be taken as the smallest value for the three possible failure modes 1, 2, and 3.

Mode 1: connections with thin end-plate

In connections where thin end-plate relative to tensile bolt resistance is used, complete yield of the plate flange is observed. Design resistance of the t-stub can be obtained from the equation:

$$F_{T,Rd} = \frac{4M_{pl,1,Rd}}{m} \quad (2-13)$$

where: $M_{pl,Rd}$ is the yielding moment of the end-plate

m is the distance between bolt axis and weld or root of I or H profile.

Mode 2: connections with medium thickness end-plate

In connections where the thickness of the end-plate is greater than in above, a partial plasticization of the end-plate is observed. Deformations of the end-plate cause the increase in force in the bolts and finally leading them to failure. Tensile resistance of the connection can be obtained from the equation:

$$F_{T,Rd} = \frac{2M_{pl,2,Rd} + n \sum F_{t,Rd}}{m + n} \quad (2-14)$$

Where: $M_{pl,Rd}$ is the yielding moment of the end-plate

$F_{t,Rd}$ is the design tension resistance of a bolt

m is the distance between bolt axis and weld or root of I or H profile.

n is the distance between bolt axis and edge of the end-plate, but $n \leq 1.25m$.

Mode 3: connections with thick end-plate

In connection where a thick end-plate is used, the deformation of the plate is very small and the failure will be a bolt failure. Design resistance of the t-stub can be obtained from the equation:

$$F_{T,Rd} = \sum F_{t,Rd} \quad (2-15)$$

Where: $F_{t,Rd}$ is the design tension resistance of a bolt

Yielding moment of the end-plate can be obtained from the equation:

$$M_{pl,1,Rd} = \frac{0.25 \sum l_{eff,1} t_f^2 f_y}{\gamma_{Mo}} \quad (2-16)$$

$$M_{pl,2,Rd} = \frac{0.25 \sum l_{eff,2} t_f^2 f_y}{\gamma_{Mo}} \quad (2-17)$$

The fact that this standard doesn't explicitly consider the effect of prying force on the calculation of the design resistance of flanges is the main reason for this research.

2.4. Equivalent T-stub

According to ES EN 3:1-8 [3], it is possible to use an equivalent T-stub in bolted connections for modeling the design resistance of the following basic components:

- Column flange in bending
- End-plate in bending
- Flange cleat in bending
- Base plate in bending under torsion

From the four basic components stated in the standard, only end-plates in bending were considered for this research.

The equivalent T-stub model is a geometrical idealization of the tension zone where as the name indicates, is a T profile made of web in tension and a flange in bending. The equivalence will be reached through the definition of an appropriate length of the equivalent T-stubs called effective length, l_{eff} [7].

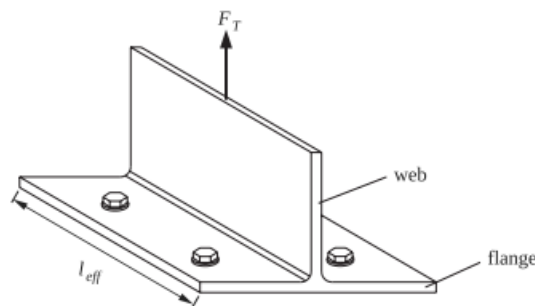


Figure 2-13 T-stub geometry

The effective length of an equivalent T-stub, a notional length which doesn't necessarily correspond to the physical length of the basic joint component that it represents, should be such that the design resistance of its flange is equivalent to that of the basic joint component that it represents [3].

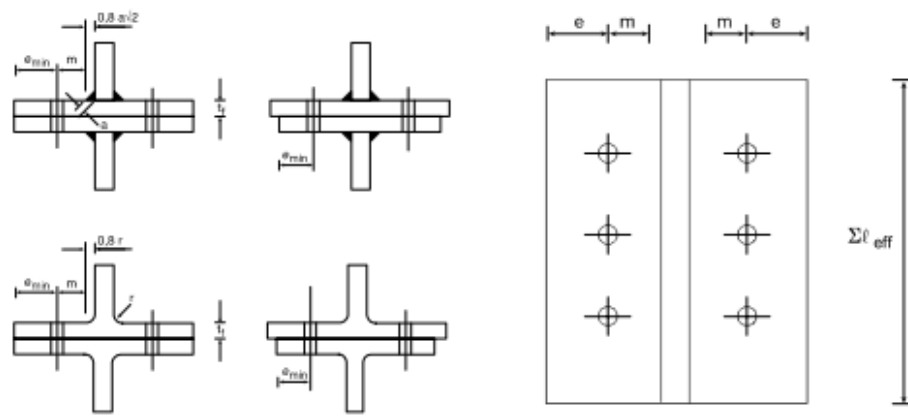


Figure 2-14 Dimensions of an equivalent T-stub flange

When determining the design resistance of a T-stub flange, one of the three different failure modes will be the dominant failure mode. For failure mode 1 and 2, the plastic moment must be known. The effective length is then necessary to know when calculating the plastic moments, see Equation 2.16 and 2.17. The effective length depends on the positioning of the bolts and whether the column flange is stiffened, unstiffened or if it is an end-plate. The standard also divided the failure yield patterns in to circular and non-circular patterns as well as individual bolt-rows and part of a group of bolt-rows.

The formation of non-circular yield patterns requires the development of prying forces in the T-stub, while the formation of circular yield patterns doesn't require the development of prying forces [3]. Hence, this paper only considered the formation of non-circular yield patterns and calculated the effective lengths accordingly. It should also be noted that since the design resistance formulae in equations 2-13, 2-14, and 2-15 are only valid for a T-stub with two bolts per row [7].

3. MATERIALS AND METHOD OF ANALYSIS

3.1. Study Parameters

The effect of prying action on the tensile resistance of a column flange and an end-plate in bending are studied by varying the following study parameters;

- Thickness of the flange (t_f),
- Distance between bolt axis and root of the profile (m),
- Yield strength of the plate (f_{yp}), and
- Yield strength of the bolt (f_{yb}).

The studied T-stub is an IPE500 section cut in the middle in to two T-stubs and is bolted together using two bolt-rows (a total of four bolts). M16 bolts were used for the simulation process.

Taking availability of material properties in the Ethiopian market for practical consideration, the yield strengths of the flange were taken as S235H, S275H, and S355H.

Table 3-1 Mechanical properties of flange

Material Type	Yield Stress (N/mm ²)	Ultimate Stress (N/mm ²)	Density (kg/m ³)	Young's Modulus(kN/mm ²)	Poisson Ratio
S 235H	235	360	7850	210	0.3
S 275H	275	430	7850	210	0.3
S 355H	355	510	7850	210	0.3

The bolt grades were chosen arbitrarily, taking the two smallest grade and the two highest grades stated in ES EN 1993-1-8, table 3.1.

Table 3-2 Mechanical properties of bolt

Material Type	Yield Stress (N/mm ²)	Ultimate Stress (N/mm ²)	Density (kg/m ³)	Young's Modulus(kN/mm ²)	Poisson Ratio
4.6 Bolt	240	400	7850	210	0.3
5.6 Bolt	300	500	7850	210	0.3
8.8 Bolt	640	800	7850	210	0.3
10.9 Bolt	900	1000	7850	210	0.3

ES EN 3:1-8 recommends the use of the material types in Table 3.1 for steel thickness ≤ 40 mm. however, since plate thicknesses above 25mm are seldom used, the range of the plate thickness used are as follows;

Table 3-3 End plate thickness

Material Type	Thickness(mm)				
	S 235H	5	10	15	20
S 275H	5	10	15	20	25
S 355H	5	10	15	20	25

The distances between the bolt axis and the root radius are chosen by calculating the maximum distances allowed by the standard for an IPE500 section and taking that as a mean value. According to ES EN 3:1-8, in order to avoid prying action, the distance between the bolt axis and the edge, n , has to be less than or equal to 1.25 times the distances between the bolt axis and the root radius, m . The calculation for the maximum distances allowed by the standard to avoid prying action is as follows:

$$b = n + m + 0.8r + t_w + 0.8r + n + m$$

$$200 = n + m + (0.8 * 21) + 10.2 + (0.8 * 21) + n + m$$

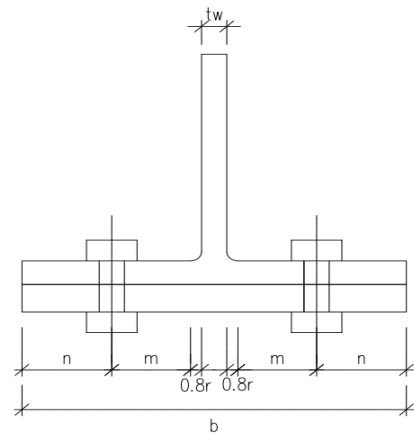
$$200 = 2n + 2m + 43.8$$

$$200 - 43.8 = 2n + 2m, n \leq 1.25m$$

$$156.2 = 2(1.25m) + 2m$$

$$m_{\max} = \frac{156.2}{4.5} = 34.71\text{mm}$$

$$n_{\max} = 1.25 * m = 43.39\text{mm}$$

**Table 3-4 Values for n and m**

m(mm)	15	25	34.71	45	55	65	70
n(mm)	18.75	31.25	43.39	56.25	68.75	81.25	87.5

Therefore, the values of m were taken as shown in Table 3.4 by taking the minimum as an approximation of half of the mean and the maximum as double of the mean. For every configuration, the values of n were calculated by taking the maximum limit of $n = 1.25m$

Table 3-5 Values of the independent variables

m (mm)	15	25	34.71	45	55	65	70
t_f (mm)	5	10	15	20	25		
f_{yb} (MPa)	240	300	640	900			
f_{yp} (MPa)	235	275	355				

3.2. Finite Element Model

Finite element model of the T-stub connections have been created using the finite element program, Abaqus version 6.13. The true stresses and strains, calculated from the engineering stresses and strains, were used for the constitutive models of the T-stubs and the bolts. Figure 3-1 shows models for S 235H steel and bolt grade 5.6.

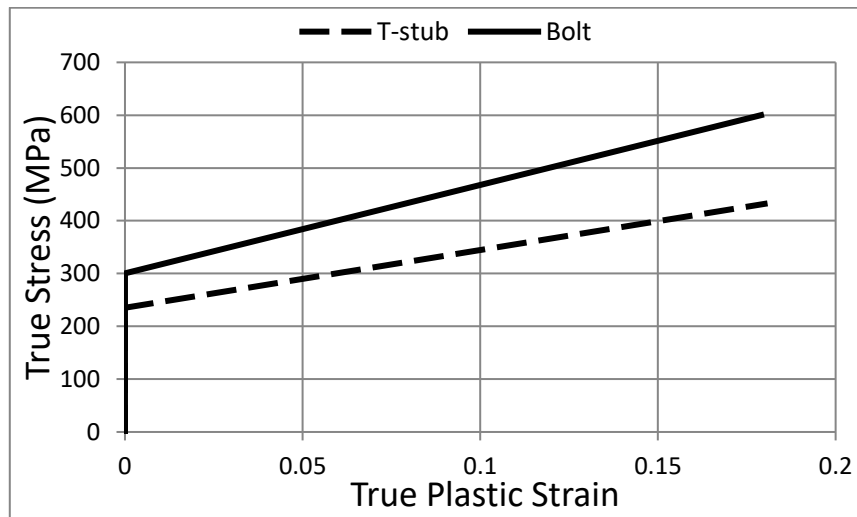


Figure 3-1 Constitutive model for T-stub and bolt

The models analyzed were the assemblies of subcomponents which were modeled separately. The assembled model consists of four bolts, a supporting plate, and two T-stubs. However, to minimize the computational time, the T-stubs were cut in to two symmetrical parts and one was used for the simulations. The final assembled model, Figure 3.2, consists of two bolts, a supporting plate and two T-stubs.

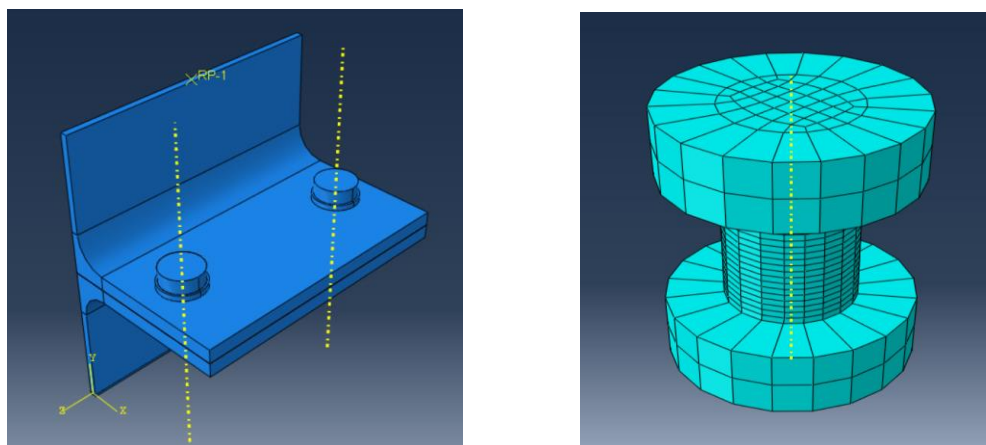


Figure 3-2 Assembled model and simplified bolt

3.2.1. Simplified Bolt

A simplified element model of the bolt without threads has been used. Because the threads on the bolts have been ignored, the tensile area of the bolt was used to calculate the diameter. For M16 bolts with a tensile area A_s of 157mm^2 , the diameter is 14.14mm. The grip length for every configuration was taken as the sum of the thicknesses of the two T-stubs and the washer. The grip length, therefore the length of the bolt differs for every flange thickness used. The bolt and nut were modeled as one part; however, the washer was modeled independently and assembled.

3.2.2. Material data

The materials are assumed to behave elastically until they reach their true yield stress and plastically until an ultimate stress is reached. The plastic strain is taken as zero at yielding and true plastic strain is taken as the corresponding strain to the ultimate stress. Elastic and plastic material properties used in the finite element analysis for the bolts, flanges and webs are as follows. For detailed calculations, see Appendix B.

Table 3-6 Material data for FEM

Material	Elastic Properties		Plastic Properties	
	Young's Modulus(MPa)	Poisson's Ration	Yield Stress(MPa)	Plastic Strain
S 235H	210000	0.3	235.26	0
			435.6	0.189
S 275H	210000	0.3	275.36	0
			516	0.18
S 355H	210000	0.3	355.6	0
			601.8	0.163
Bolt class 4.6	210000	0.3	240.27	0
			488	0.197
Bolt class 5.6	210000	0.3	300.43	0
			600	0.179
Bolt class 8.8	210000	0.3	641.95	0
			896	0.109
Bolt class 10.9	210000	0.3	903.86	0
			1100	0.09

3.3. Sampling Technique

The independent variables under considerations; thickness of the flange, t_f , the distance between bolt axis and root of the profile, m , yield strength of the plate, f_{yp} , and yield strength of the bolt, f_{yb} when combined result in 360 combinations. Out of these combinations, Latin hypercube sampling method, LHS, was used to select 32 representative combinations.

Table 3-7 Statistical variation of random variables

variable	unit	\bar{x}_i	σ_i
m	mm	17.101	12.873
t_f	mm	10	6.455
f_{yb}	MPa	288.333	61.101
f_{yp}	MPa	520	308.545

Table 3-8 Configurations used

Configurations	m (mm)	t_f (mm)	f_{yb} (MPa)	f_{yp} (MPa)
1	35	5	300	355
2	45	15	640	235
3	35	25	900	235
4	65	10	900	355
5	65	10	240	235
6	35	15	640	355
7	55	25	240	275
8	55	20	300	235
9	55	20	640	235
10	45	10	900	355
12	45	10	300	275
13	70	25	900	275
14	70	5	640	355
15	25	15	900	235
16	45	5	300	355
17	25	15	640	355
19	35	20	240	235
20	55	25	640	275
21	55	5	640	275
22	35	20	300	355
23	65	20	640	275
24	55	10	640	275
25	25	15	240	235
26	65	10	300	275
27	45	25	640	355
28	55	15	900	355
29	45	20	240	355
30	70	15	900	355
31	35	25	300	355
32	45	15	240	235

Out of these 32 combinations/ configurations, configuration 11 was eliminated as it doesn't satisfy the minimum end distance requirement stated in ES EN 3:1-8, 3.5, Table 3.3. And configuration 18 was eliminated because the configuration is the same as configuration 2. Therefore 30 configurations were used to best represent the possible combinations of the random variables.

3.3.1. Sensitivity Analysis

Sensitivity analysis is the analysis of the effect of input quantity variability on the output quantity variability. It answers the question as to which quantities are dominant, and therefore they have to be paid particular attention to when (i) preparing the input values; (ii) considering and deciding on improvement of technological procedures; (iii) conceiving and organizing the control activities. Also, economic criteria are usually included into cases (ii) and (iii). Moreover, it is possible to distinguish by means of the sensitivity analysis which quantities are in a rather low influential position; therefore they can be considered only in a deterministic way (as non-random ones). This can contribute to simplification and acceleration both of the calculations and modeling [13]. Although range is the simplest measure of spread for a given data, it is not considered a very reliable measure because it is highly sensitive to the sample size and is very sensitive to the extreme values. Hence, coefficient of variation, CoV, is used to quantify the spread of the data points. This statistic is the ratio of the standard deviation to the mean. As such, it provides a normalized measure of the spread. It is often expressed in the form of a percent.

Coefficient of variation (CoV)

$$CoV_i = \frac{\overline{x_i}}{\sigma_i} * 100\% \quad (3-1)$$

Sensitivity factor

$$\alpha_i = \frac{\partial F_{T,Rd}}{\partial_i} * \frac{\overline{x_i}}{F_{T,Rd}} \quad (3-2)$$

Uncertainty Analysis

$$U_i = CoV_i * \alpha_i \quad , i = \text{random variable index} \quad (3-3)$$

The uncertainty coefficients were calculated by multiplying the coefficient of variation and the sensitivity factor. The uncertainty analysis states the percentage contribution of the variables. If the U_i value is positive then the variable has a positive contribution which means increasing those particular variable results in an increased value of the dependent variable and if it is negative it has a negative contribution which means decreasing those particular variable results in an increased value of the dependent variable.

4. ANALYSIS

4.1. Validation of the Finite Element Model

As experiments were not performed in this study, the use of simulation software, ABAQUS, was necessary. The test performed by Kristian Ydstebo[8] at the University of Stavanger, Norway where the t-stubs were tested by clamping the web of the bottom t-stub and pulling the web of the top t-stub with a constant velocity are used to check the reliability of the simulations done in ABAQUS.

Table 4-1 Material data for validation

Material	Young's Modulus(MPa)	Poisson's Ratio	Stress(MPa)		Plastic Strain
			f_y	f_u	
S 355H	210000	0.3	f_y	355.6	0
			f_u	601.8	0.163
Bolt class 8.8	210000	0.3	f_y	641.95	0
			f_u	896	0.109

From the experiment, it was found that the failure load was 177.4kN with 29.6mm deflection and from the finite element model, it was found that the failure load was 191.22kN with 29.03mm deflection, measured at the center of the flange, which has a 7.7% error. Both samples showed bolt fracture as the failure mode with their edges still in contact. It can be observed that the finite element model result is in good agreement with the experimental result. The similarity of failures can be seen in Figure 4-1.

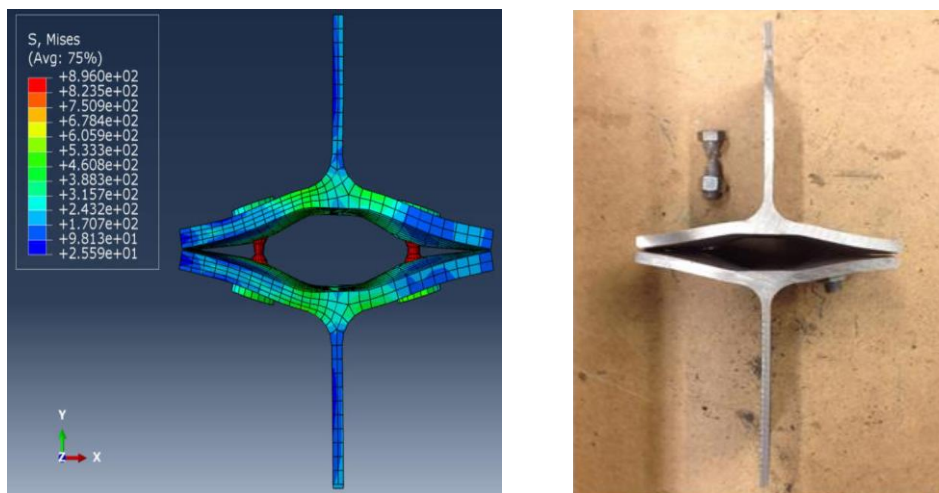


Figure 4-1 Comparison of FEM and experimental result

4.2. Analytical Study of the Finite Element Model

Step

The model had an initial increments size of 0.001. The total time was set to 1. Each increment was limited by the minimum size of $1e-30$ and maximum size of 1. Total allowed increments were 100000. If the analysis required either more increments or increment size beyond the limitations, the analysis would be cancelled. The limitations were set to prevent the analysis to run for long period of time without significant progress.

Interaction

Two types of interactions were used. A General contact with an 'All* with self' surface pair and a Surface-to-surface contact with a specified master and slave surfaces were used. For both interactions, a contact property of tangential behavior with a friction coefficient of 0.8 was used.

The bottom T-stub and the support plate were tied together using the 'Tie' constraint. And the loading point and the top T-stub were constrained together using a 'Kinematic Coupling' constraint with all the DoFs constrained.

Load

Tension load was applied by adding displacement in the Y-direction on the top web as a boundary condition. This displacement was increased uniformly using amplitude. The remaining degrees of freedom were set to be zero.

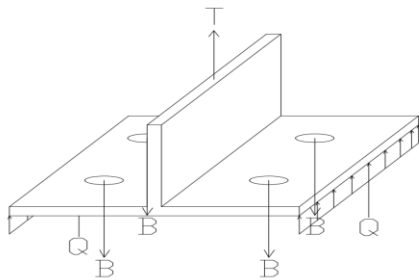
Mesh

Three-dimensional hexahedral elements with eight nodes at each corner, C3D8R, are used. The element sizes differ, as part that are not prioritized for investigation, like the nut and head of the bolt, and the support plate, have coarse meshes while those that are prioritized have finer meshes. This was done to reduce the computational time.

4.3. Prying Force Calculation

The prying force, Q , for the finite element models is calculated as the resulting bolt force, B , minus the applied tension force, T . where the applied tension force is taken as the failure load of the T-stub.

Since prying action occurs as the reaction of the pressing force that occurs because of the pulling force created by the deformation of the flange, there has to be a contact between the two T-stub flanges. Therefore, the prying forces are calculated for those configurations whose flanges edges are still in contact at failure.



The total bolt force on the system is the summation of the applied force and the prying force, on both sides.

$$T + (2 * Q) = (4 * B)$$

$$Q = \frac{(4 * B) - T}{2} \quad (4-1)$$

The allowable prying force, Q_{all} , on a single bolt can be calculated as the difference of the tensile strength of a single bolt, $F_{t,Rd}$ and the portion of the tension load applied on one bolt, $T/4$.

$$Q_{all} = F_{t,Rd} - \frac{T}{4} \quad (4-2)$$

Hence, the additional force the bolts are subjected to is the difference between the allowable and the applied prying forces. This allowable force is the reserve capacity the bolts have in case of a prying action and if the existing prying force is less than this value, the bolts can carry the additional loads. However, if the prying force is greater than the allowable, then the bolts will have to carry additional loads.

$$B_o = Q - Q_{all} \quad (4-3)$$

This is the case for all configurations except those with no prying force generated, whose tension capacity can't carry the applied tension load and doesn't have an allowable prying force.

4.4. Design Resistance According to ES EN 1993-1-8:2013

The design tension resistance of the different T-stub configurations based on the calculations given in ES EN 3:1-8 has been calculated. In order to achieve the best basis for comparing the load capacity calculations with the results obtained from the finite element analysis, the partial safety factors are set equal to 1.0. Since the factor is used as a safety for failure, the capacity is meant to have a lower value than the actual capacity; the best assessment of the regulations is without the partial safety factor.

Effective length, l_{eff}

According to ES EN 3:1-8, the effective length shall be determined using one of the three tables given in the standard; effective length for an unstiffened column flange, effective length for a stiffened column flange and effective length for an end-plate [3]. Out of the different bolt-row locations, the one used for this computation is the end bolt-row location.

Table 4-2 Effective length calculations

	Bolt-row Location	Bolt-row considered as part of a group of bolt-rows
End-plate	end bolt-row	$2m + 0.625e + 0.5p$
	Mode 1	$\sum l_{eff,1} = \sum l_{eff,nc}$
	Mode 2	$\sum l_{eff,2} = \sum l_{eff,nc}$

Since the effective length of a T-stub is a function of edge distance, distance between bolts and the distance between the bolt axis and the root radius, for every configuration the effective length varies. For every configuration, the effective length is calculated by considering the bolt rows as a part of a group.

Since the formation of circular yield patterns doesn't require the development of prying forces but the formation of non-circular yield patterns does, the effective length is also calculated for the non-circular yield pattern cases only. As the mode of failure is the same whether the bolt-rows are considered individually or as part of a group, only one is considered; the bolt-rows are considered as a part of a group.

5. RESULTS AND DISCUSSION

The results obtained from the finite element models are discussed in terms of the tension capacities and the prying forces generated. Also, by using sensitivity/ uncertainty analysis, the percentage contribution of the different variables; m , t_f , f_{yb} , and f_{yp} were obtained. This process is done for both the results obtained from the formula provided by ES 3:1-8 for the calculation of tension resistance of T-stubs and from the results obtained from the finite element models.

5.1. Evaluation of the Finite Element Models

From the 30 configurations, the detailed discussions of three representative configurations are presented as follows:

Configuration 4

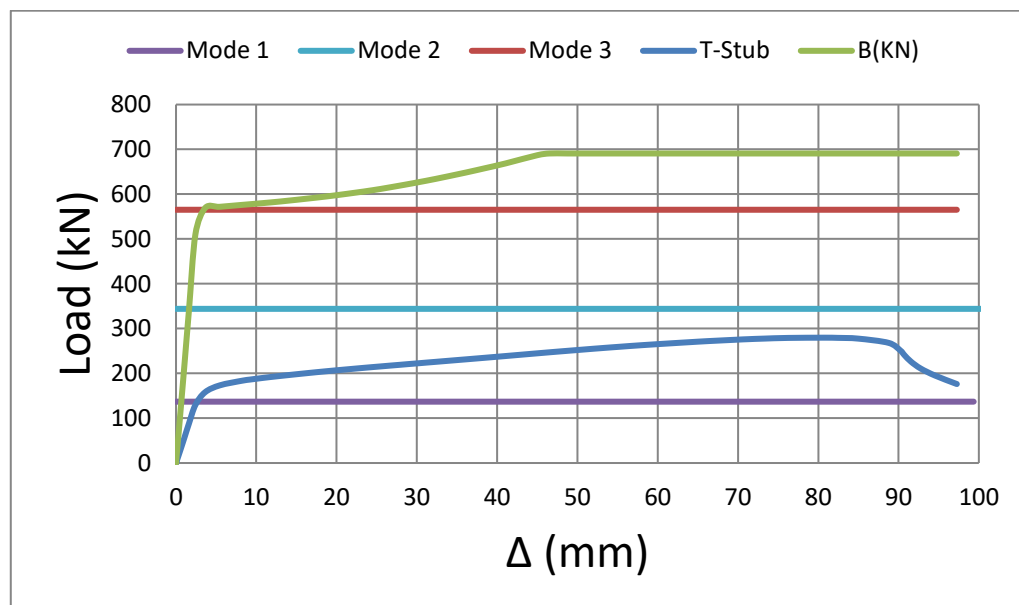


Figure 5-1 Load-deflection curve of configuration 4

The load-deflection curves of the T-stub and the bolt show elastic-plastic behavior until ultimate failure. The governing failure mode for configuration 4 is mode 1 indicating the yielding of the flange at an applied failure load of 136.9kN. It can be seen from the curve that the T-stub flange yields at a load of 129.6kN which is only slightly lower than the load predicted by the analytical formula in the code. However, the failure load of the T-stub is 279.7kN which means mode 1 shows a large reserve capacity beyond the failure criterion of the code.

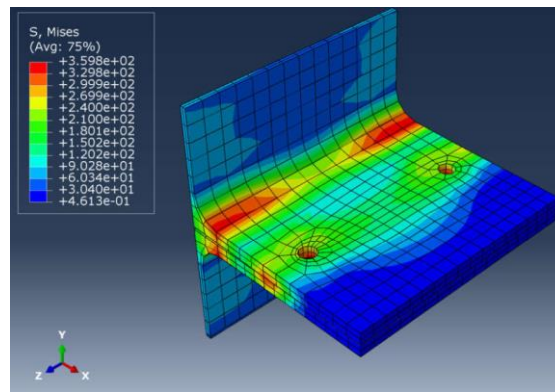


Figure 5-2 T-stub stress at 129.6kN

The T-stub flange yielded first at the root of the profile at an applied load of 129.6kN with a deflection of 2.4mm but the ultimate tensile capacity of the system is 279.7kN with a deflection of 80.74mm.

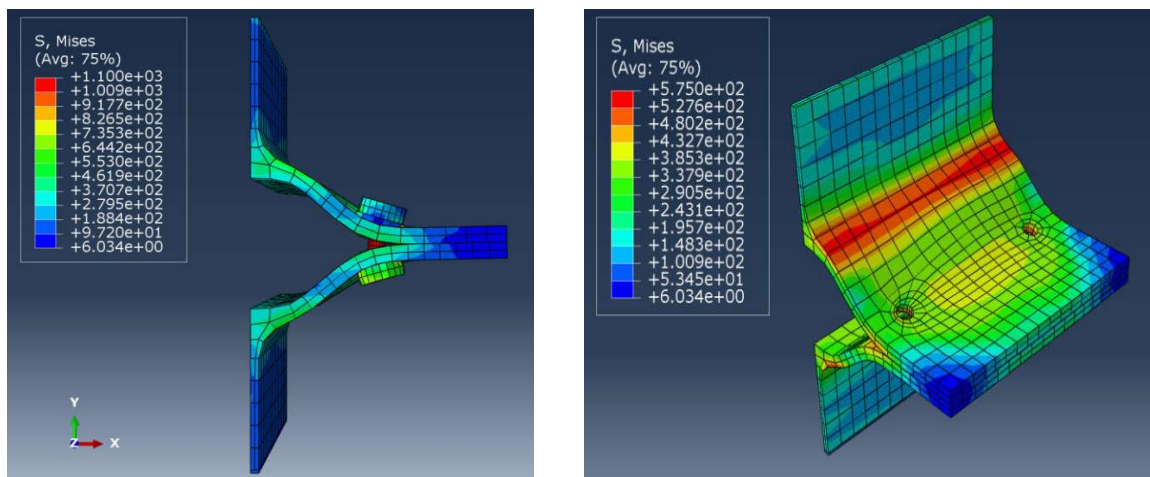


Figure 5-3 Bolt and T-stub stresses at 279.9kN

The curve also shows the tension forces in the bolts are much higher than the applied force because of the presence of prying action in the T-stub. The ultimate failure of the T-stub occurs when the forces on the bolts reach 690.8kN which is more than the applied tension load, 279.7kN. This indicates prying force, 205.55kN, is generated on each edge and there are additional forces, 31.4.kN, induced on the bolts due to this action. This can be seen in figure 5.4 where the bolt force versus applied force is plotted to show how much the forces on the bolts deviated from the forces they should have had if there was no prying action.

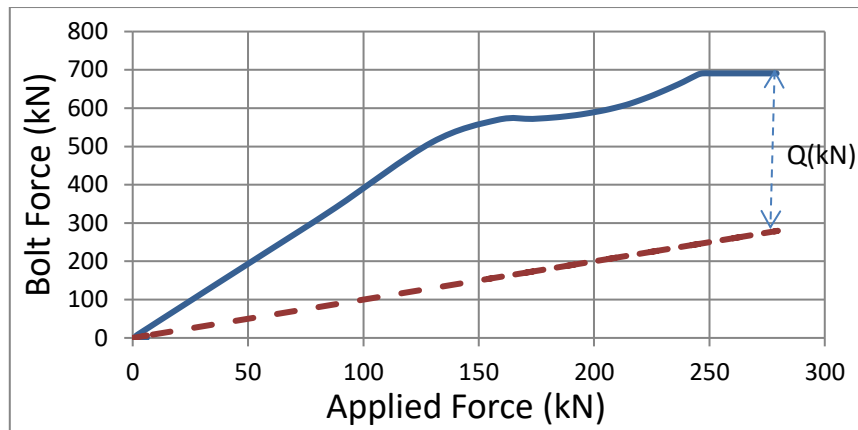


Figure 5-4 Bolt Vs. Applied force for configuration 4

Configuration 8

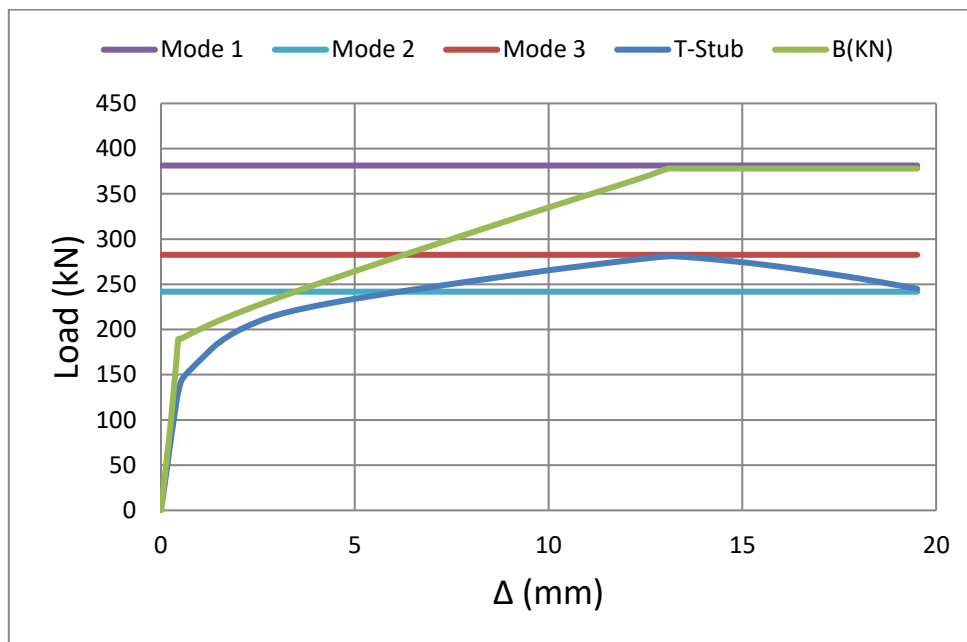


Figure 5-5 Load-deflection curve of configuration 8

The code predicts the failure of the configuration 8 by yielding of the flange with bolt failure at an applied force of 241.825kN after removing the safety factors in the calculations. The finite element model shows the T-stub fails by bolt failure at an applied load of 280.8kN. Here, it can be seen that mode 3, 282.6kN, predicts the failure more than mode 2, 241.825kN, this is because since the yield strength of the bolt is small, the bolt yields at an applied load of 131.098kN before the flange yielded. The flange yielded but never reached the ultimate stress because the bolt fractured.

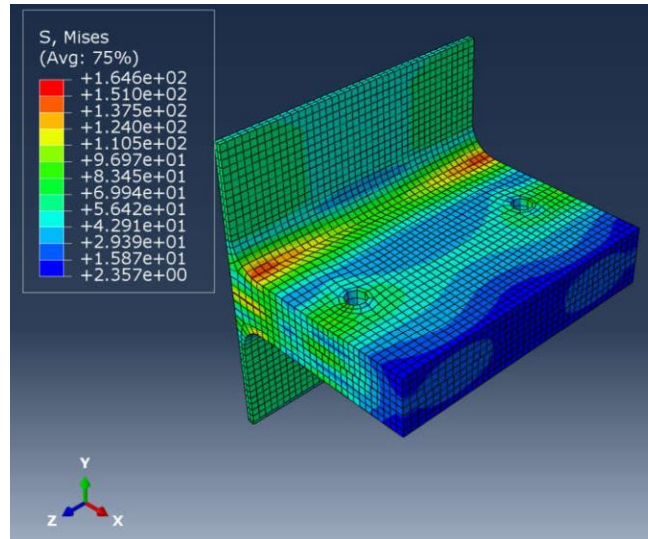


Figure 5-6 T-stub stress at 131.098kN

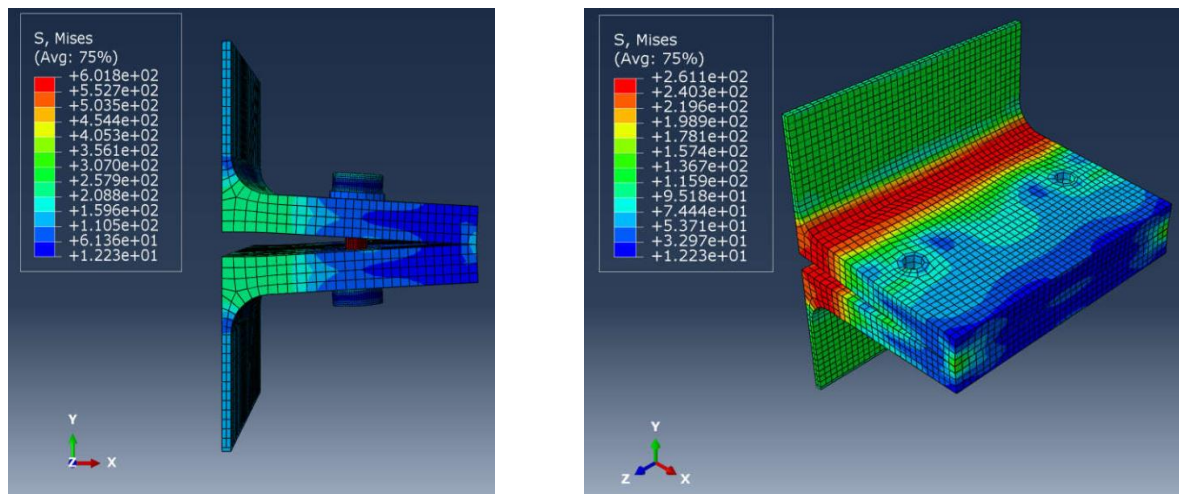


Figure 5-7 Bolt and T-stub stresses at 280.8kN

It can be seen that the tension forces in the bolts are much higher than the applied force because of the presence of prying action in the T-stub. The ultimate failure of the T-stub occurs when the forces on the bolts reach 377.4kN which is more than 280.8kN, the ultimate axial capacity. This indicates prying force, 48.6kN, is generated on each edge and there are additional forces, 23.8kN, induced on the bolts due to this action. This can be seen in figure 5.8 where the bolt force versus applied force is plotted to show how much the forces on the bolts deviated from the forces they should have had if there was no prying action, although the decrease of loads after yield cannot be explained. Configuration 8 has the smallest prying force than the rest of the configurations. This is because the T-stub flange is thick, 20mm, and the yield strength of the bolt is small, 300MPa.

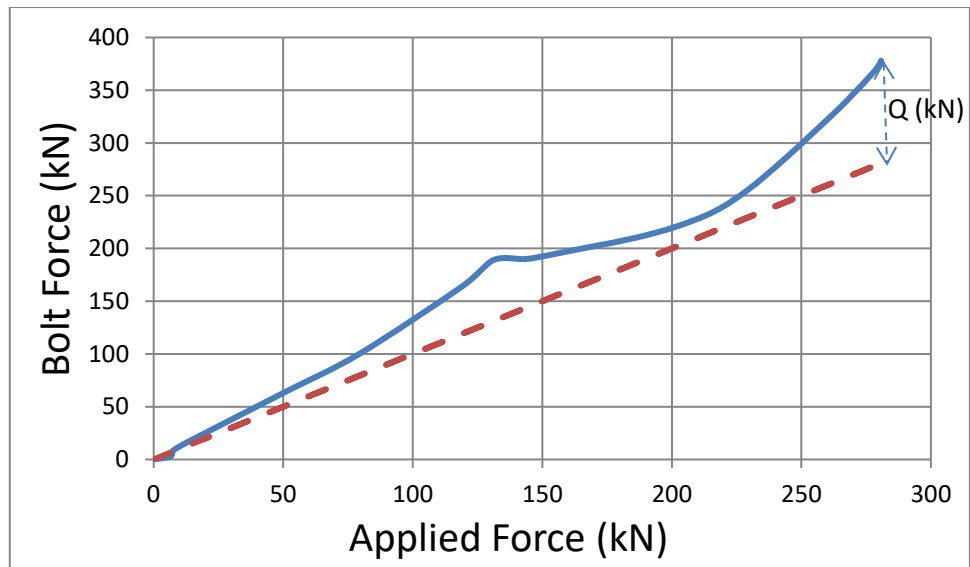


Figure 5-8 Bolt Vs. Applied force for configuration 8

Configuration 13

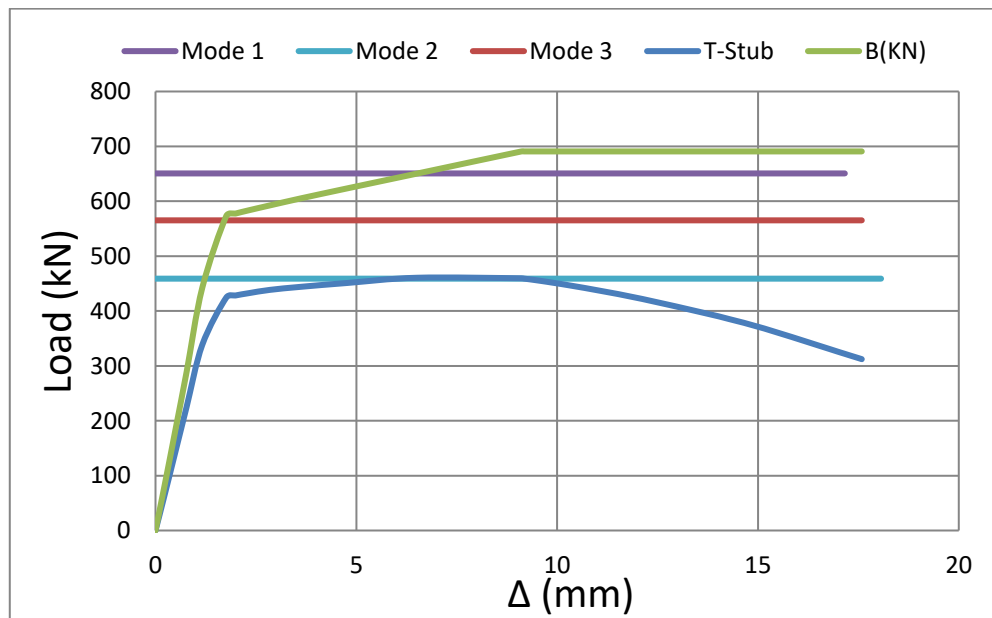


Figure 5-9 Load-deflection curve of configuration 13

The governing failure mode for configuration 13 is mode 2 indicating a bolt failure with yielding of the flange at an applied failure load of 458.9kN and it can be seen from the curve that the T-stub failed at a load of 460.614kN which is only slightly higher than the load predicted by the analytical formula in the code.

Both the flange and the bolts yielded at the same time at an applied load of 424.5kN and the system fails at an applied load of 460.614kN. This shows there is no reserve capacity in the failure mode which is not a desirable condition.

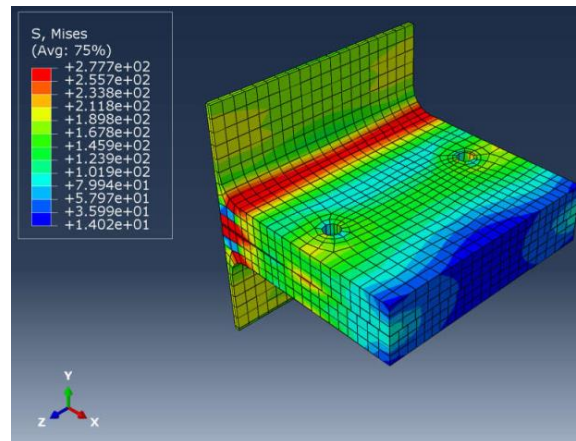


Figure 5-10 T-stub stress at 424.5kN

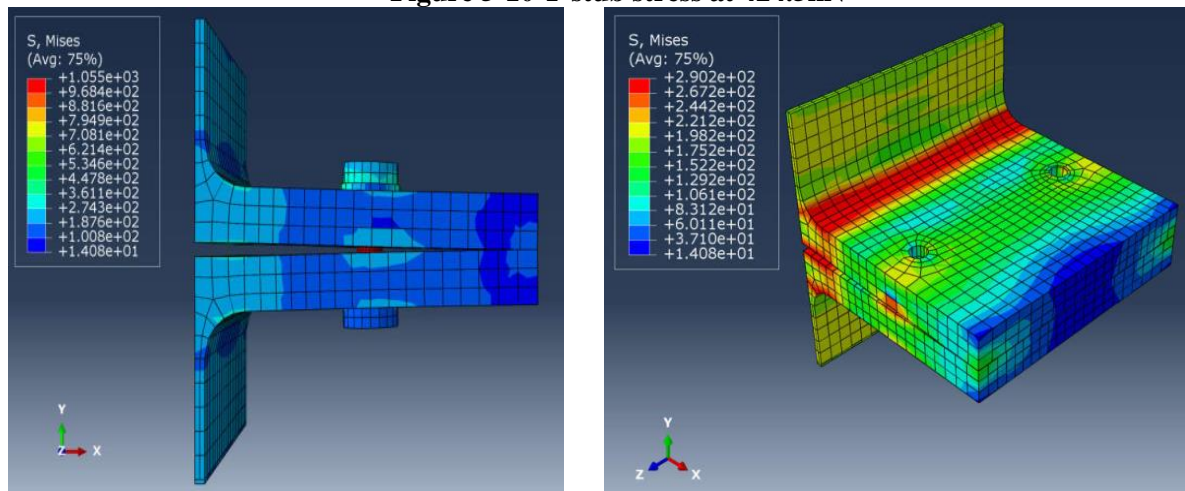


Figure 5-11 Bolt and T-stub stresses at 460.614kN

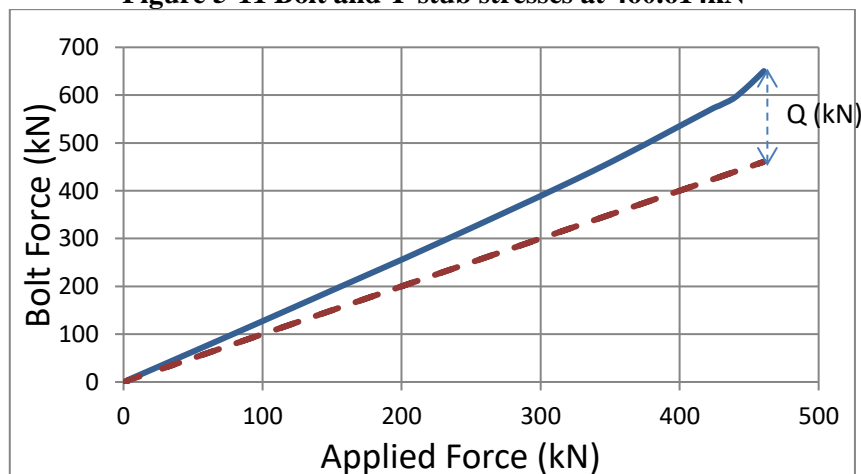


Figure 5-12 Bolt Vs. Applied force for configuration 13

The curve shows the tension forces in the bolts are much higher than the applied force because of the presence of prying action in the T-stub. The ultimate failure of the T-stub occurs when the forces on the bolts reach 650.325kN which is more than 460.614kN, the applied tension load. This indicates prying force, 94.867kN, is generated on each edge and there are additional forces, 21.3kN, induced on the bolts due to this action. This can be seen in Figure 5.12 where the bolt force versus applied force is plotted to show how much the forces on the bolts deviated from the forces they should have had if there was no prying action.

The summary output of the finite element models for the 30 combinations is shown in Table 5-4.

Table 5-1 Prying force calculation

Configuration	B (kN)	T (kN)	Q (kN)	Q _{all} (kN)	B _o (kN)	Failure Mode
1	376.8	145.18	115.81	34.35	23.55	Both
2	562.68	334.704	113.99	29.36	27.63	Bolt Failure
3	690.8	565.004	62.89	0.05	31.4	Flange Yielding
4	690.8	283.60	203.59	71.37	31.4	Flange Yielding
5	306.46	144.19	81.13	20.47	20.09	Bolt Failure
6	562.68	393.90	84.39	14.56	27.63	Bolt Failure
7	302.51	245.29	0	0	0	Bolt Failure
8	377.93	280.75	48.58	0.45	23.83	Bolt Failure
9	562.688	362.22	100.23	22.48	27.63	Both
10	690.8	319.56	185.62	61.41	31.4	Flange Yielding
12	376.8	204.09	86.35	19.63	23.55	Bolt Failure
13	650.32	460.61	94.85	26.15	21.28	Both
14	562.68	185.03	188.83	66.78	27.63	Flange Yielding
15	690.8	438.61	126.09	31.65	31.4	Flange Yielding
16	376.8	134.94	120.93	36.92	23.55	Bolt Failure
17	562.68	442.94	59.87	2.31	27.63	Bolt Failure
19	306.46	245.06	0	0	0	Bolt Failure
20	562.68	454.37	54.16	0	27.63	Bolt Failure
21	562.68	207.96	177.36	61.05	27.63	Flange Yielding
22	376.8	306.97	0	0	0	Bolt Failure
23	562.16	362.47	99.85	22.42	27.50	Both
24	562.68	242.84	159.92	52.33	27.63	Flange Yielding
25	306.46	245.65	0	0	0	Bolt Failure
26	376.8	175.54	100.63	26.76	23.55	Bolt Failure
27	562.688	487.31	0	0	0	Bolt Failure
28	690.8	413.49	138.65	37.93	31.4	Flange Yielding
29	306.46	245.21	0	0	0	Bolt Failure
30	690.8	382.83	153.98	45.59	31.4	Both
31	373.86	307.59	0	0	0	Bolt Failure
32	306.46	201.44	52.51	6.159	20.09	Bolt Failure

According to ES 3:1-8, prying forces may develop if $L_b \leq L_b^*$. By calculating the equivalent L_b and L_b^* values for all configurations, it was found that configurations 3, 19, 22, 27 & 31 have not developed prying forces while the remaining 25 configurations have. Prying forces only develop when the ends of the flanges are in contact due to the applied load. Taking this in to consideration, configurations 19, 22, 27 & 31 indeed haven't developed prying forces. However that is not the case for configuration 3, which developed a prying force of 62.898kN. In this configuration, the contribution of the yield strength of the bolt can be observed. Even though the thickness of the flange is large, which have a negative contribution to the prying force, since the yield strength of the bolt is large; prying force was developed at the edges. Figure 5-4(a) shows how the edges of the flanges in configuration 3 are still in contact at failure and (b) shows those of configuration 19 are not.

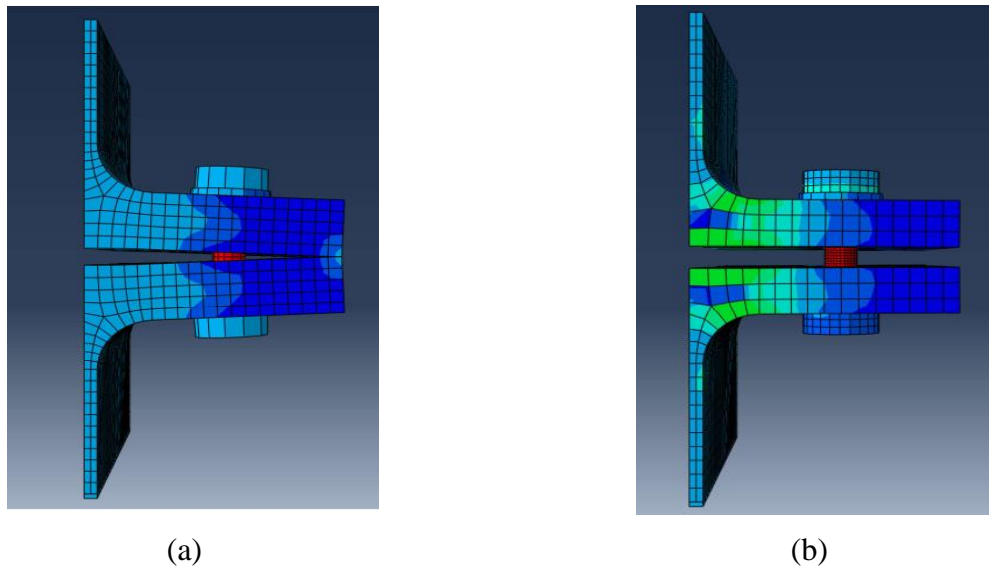


Figure 5-13 Contact criteria for prying action

From table 5-1, it can be seen that there is an average 30% increase in bolt force due to the presence of prying force. It can also be seen that all configurations with low yield strength bolts, except configuration 1, failed by bolt failure, mode 3. Configuration 1 had a mode 2 failure because the thickness of the flange is thin.

Sensitivity Analysis – Tension Capacity

Using Equations 3-1, 3-2 and 3-3, the sensitivity factors and uncertainty are obtained. From this it can be seen that the thickness of the T-stub flange and the yield strength of bolts govern the tension resistance of the T-stub more than m and f_{yp} .

Table 5-2 Sensitivity Analysis parameters for FEM

	α_i	CoV _i	U _i	%
m	-0.32378	29%	-0.09283	-14%
t_f	0.529325	43%	0.22505	35%
f_{yb}	0.560595	48%	0.26856	42%
f_{yp}	0.310197	18%	0.055476	9%

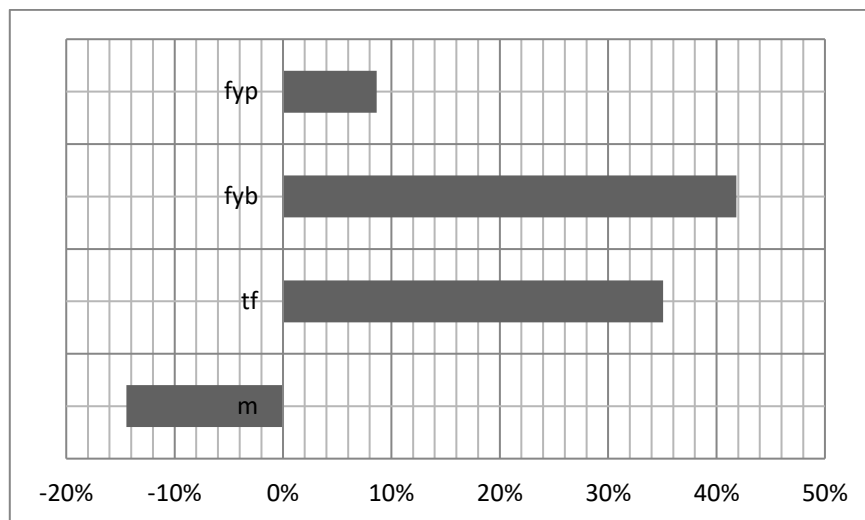


Figure 5-14 Sensitivity analysis for the finite element model

Sensitivity Analysis – Prying Force

Using Equations 3-1, 3-2 and 3-3, the sensitivity factors and uncertainty are obtained. From this it can be seen that t_f and f_{yb} govern the prying force created at the edges of the T-stub more than m and f_{yp} .

Table 5-3 Sensitivity Analysis parameters for prying action

	α_i	CoV _i	U _i	%
m	0.484768	29%	0.182854	16%
t_f	-0.90923	43%	-0.50963	-43%
f_{yb}	0.681353	48%	0.437812	37%
f_{yp}	0.661165	18%	-0.0428	-4%

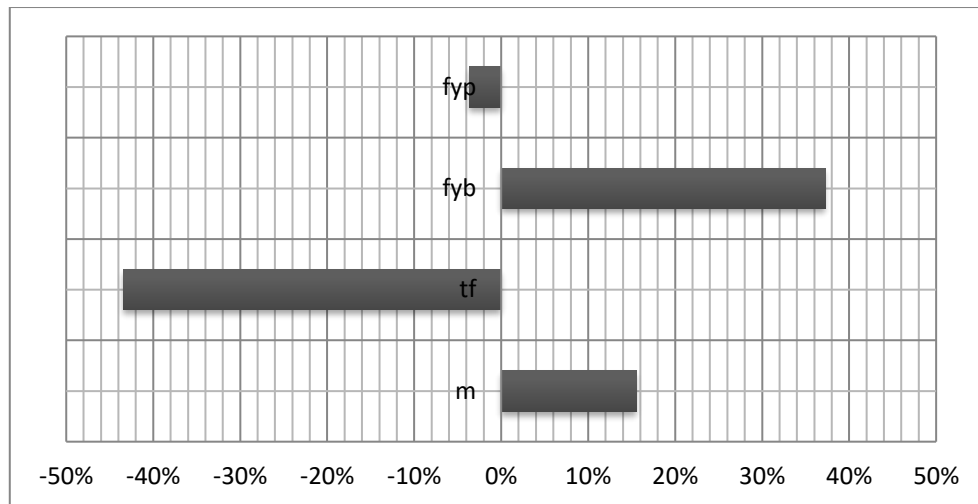


Figure 5-15 Sensitivity Analysis for prying force

From the sensitivity analysis, it can be seen that the thickness of the flange has a negative contribution which means increasing the thickness will significantly decrease the prying force created, while the yield strength of the bolt has a positive contribution.

The distance between the bolt axis and the root and the yield strength of the flange also has positive and negative contributions, respectively, even though their contributions are not as much as the formers. This can be seen in configurations 1 and 16. For these configurations, the role of m comes to play. These two configurations are the same except for the values of m . now, since m has a 16% contribution to the magnitude of the prying force, the one with the higher value of m has the larger Q , 120.93kN. But since m has a -14% contribution to the tensile capacity, the one with the smaller m has the larger T , 145.18kN.

5.2. Evaluation of the Design Tension Resistance in ES EN 1993-1-8:2013

Using Equations 3-1, 3-2 and 3-3, the sensitivity factors and uncertainty are obtained. From this it can be seen that the thickness of the T-stub flange and the yield strength of bolts govern the tension resistance of the T-stub more than m and f_{yp} .

Table 5-4 Sensitivity Analysis parameters for ES EN 3:1-8

	α_i	CoV _i	U _i	%
m	-0.19066	29%	-0.05466	-7%
t_f	1.068731	43%	0.454387	60%
f_{yb}	0.42373	48%	0.202993	27%
f_{yp}	0.24206	18%	0.043291	6%

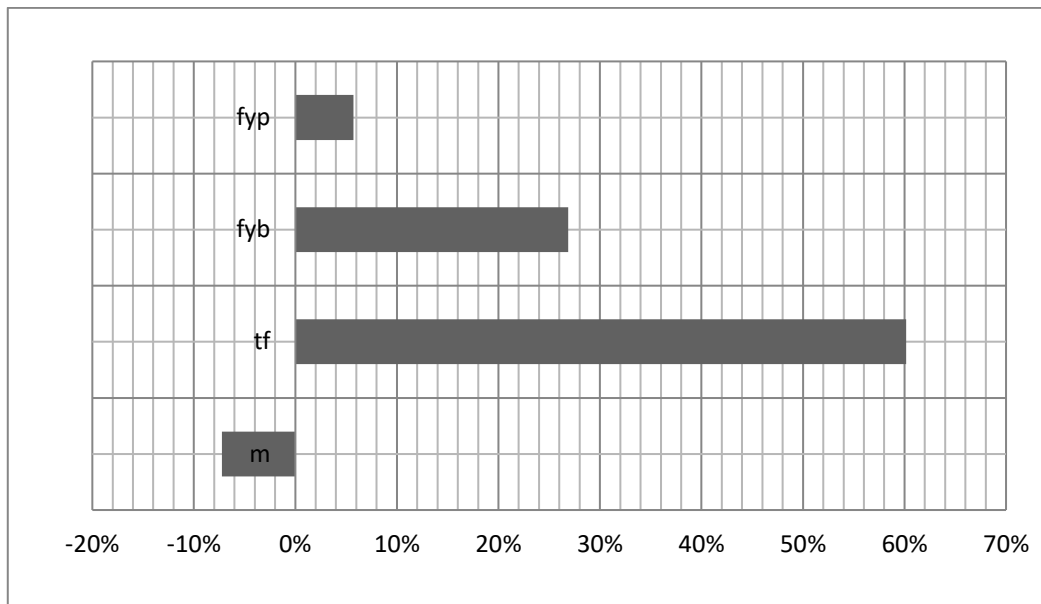


Figure 5-16 Sensitivity analysis for ES EN 3:1-8

Even though the positive and negative contributions of the variables are the same for both cases; the tensile resistances from the finite element models and code, there seems to be a contradiction between which variable contribute more to the tension resistance. According to the finite element models, the yield strength of the bolt contributes 42% while the thickness of the flange contributes 35% but according to the analytical formula given in the code, the yield strength of the bolt contributes 27% while the thickness of the flange contributes 60%. This is because aside from mode 3, the formula provided in the code for both modes 1 and 2 are predominantly influenced by the thickness of the T-stub flange.

However, since the presence of prying action induces additional loads on the bolts, there is a chance of more bolt failures, mode 3, than modes 1 and 2. Therefore the tensile resistance of the T-stub can also be influenced by the tension resistance of the bolts hence the yield strength of the bolts.

6. CONCLUSION AND RECOMMENDATIONS

6.1. Conclusion

Where there is deformation/deflection, no matter how small, there is bound to be a prying force created. The question is whether or not the connection fails because of it. And this is based on the capacity of the bolts to carry the additional force and the capacity of the flange to not form a mechanism and fail. The aim of this thesis was to study the effect of prying action on the tension resistance of beam-to-column connections and the scope of was restricted to end plate connections for which the collapse was governed by the tension zone idealized by T-stubs. After examining the finite element models, the following conclusions are drawn:

- The thickness of the flange and the yield strength of the bolts contribute to the development of larger prying forces than the yield strength of the flange and the distance between the bolt axis and the root do.
- For thin flanges (5 and 10mm), even though the deformations are higher, the tensile capacities are lower. But this is the case for those whose bolts have lower yield strengths. For thin flanges, as the yield strength of the bolts increase, the tensile capacity and the prying force generated also increase.
- For thick flanges (15, 20 and 25mm), with lower deformations, the tensile capacities are higher. Again for thicker flanges, as the yield strength of the bolts increase, the tensile capacity and the prying force generated also increase.
- For thin flanges, using low yield strength bolts results in lower prying force generation with bolt fracture as the failure mode than using high yield strength bolts with flange yielding as the failure mode.
- For thick flanges, using high yield strength bolts results in higher prying force generation than those with lower yield strength bolts whose prying forces are minimums, even zero.
- The best and optional combination to yield a minimum, even nonexistent, prying force and minimum deformation is thick flanges with low yield strength bolts.
- The finite element models revealed reserve capacities in terms of ductility and ultimate capacity for ductile failure mode 1.

6.2. Recommendation

The following recommendations are given for future works:

- An equation for the calculation of prying force should be given in the code.
- The requirement for the development of prying should be revised.
- In the finite element models, bolt preloading should be investigated to see its effect on the tension resistance of connections.
- The effect of change of bolt position as well as the effect of bolt spacing should be investigated.
- Since prying action bends bolts, increasing the stress on one side than the other, this should also be investigated as to how much it affects the capacity of the bolts.

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APPENDICES

Appendix A

Result output values using Latin hypercube sampling method

Con.	Result Output Values				Corrected Values			
	m(mm)	t _f (mm)	f _{yb} (MPa)	f _{yp} (MPa)	m(mm)	t _f (mm)	f _{yb} (MPa)	f _{yp} (MPa)
1	32.13	5.28	296.45	339.08	35	5	300	355
2	44.15	16.56	713.18	237.59	45	15	640	235
3	39.85	26.21	812.12	230.48	35	25	900	235
4	63.67	8.43	899.47	300.38	65	10	900	355
5	68.55	9.27	227.88	222.50	65	10	240	235
6	39.38	15.93	507.91	326.59	35	15	640	355
7	55.19	22.48	187.54	295.53	55	25	240	275
8	51.63	19.95	459.19	213.19	55	20	300	235
9	55.05	20.73	580.81	250.08	55	20	640	235
10	41.83	11.48	1184.57	332.60	45	10	900	355
11	0.04	3.79	263.75	266.33	15	5	240	275
12	40.20	10.05	434.32	281.14	45	10	300	275
13	78.64	24.72	1037.10	285.94	70	25	900	275
14	73.34	1.75	483.66	419.94	70	5	640	355
15	25.11	14.07	852.46	156.73	25	15	900	235
16	46.66	6.48	355.42	310.34	45	5	300	355
17	19.01	14.69	605.68	354.17	25	15	640	355
18	43.30	15.31	532.09	244.06	45	15	640	235
19	37.20	18.52	82.55	185.93	35	20	240	235
20	53.38	32.03	743.55	261.14	55	25	640	275
21	59.11	-2.03	631.12	305.30	55	5	640	275
22	34.82	19.22	326.82	315.53	35	20	300	355
23	61.29	17.85	556.34	271.37	65	20	640	275
24	58.29	10.78	657.33	290.73	55	10	640	275
25	29.48	12.15	2.90	201.70	25	15	240	235
26	66.36	7.52	408.88	276.29	65	10	300	275
27	46.85	23.52	684.58	346.18	45	25	640	355
28	57.09	17.20	776.25	363.48	55	15	900	355
29	43.44	21.57	140.53	374.96	45	20	240	355
30	88.44	12.80	957.45	390.73	70	15	900	355
31	31.40	28.25	382.67	320.93	35	25	300	355
32	49.94	13.44	144.57	255.74	45	15	240	235

Configurations 2 and 18 have the same combinations, hence, one needed to be removed to avoid redundancy. Configuration 11 had to be removed because it does not satisfy the edge distance requirement given in EC3:1-8.

Appendix B

Material Data

Calculations of the material data of a bolt, bolt class 5.6

Yield strength, $f_{yb} = 300\text{MPa}$

Ultimate tensile strength, $f_{ub} = 500\text{MPa}$

Young's Modulus, $E = 210\text{GPa}$

Elongation after fracture, $\delta = 20\%$

Engineering elastic strain:

$$\varepsilon_{eng,el} = \frac{f_y}{E} = \frac{300\text{MPa}}{210\text{GPa}} = \frac{300}{210000} = \underline{\underline{0.001429}}$$

True elastic strain:

$$\varepsilon_{true,el} = \ln(1 + \varepsilon_{eng,el}) - \varepsilon_{eng,el} = \ln(1 + 0.001429) - 0.001429 \approx \underline{\underline{0}}$$

Engineering plastic strain:

$$\varepsilon_{eng,pl} = \delta - \varepsilon_{eng,el} = 0.2 - 0.001429 = 0.1986 \approx \underline{\underline{0.2}}$$

True yield stress:

$$\sigma_{true} = f_y(1 + \varepsilon_{eng,el}) = 300\text{MPa}(1 + 0.001429) = \underline{\underline{300.43\text{MPa}}}$$

True ultimate stress, plastic:

$$\sigma_{true,pl} = f_u(1 + \varepsilon_{eng,pl}) = 500\text{MPa}(1 + 0.2) = \underline{\underline{600\text{MPa}}}$$

True plastic strain:

$$\varepsilon_{true,pl} = \ln(1 + \varepsilon_{eng,pl}) - \frac{\sigma_{true}}{E} = \ln(1 + 0.2) - \frac{300.43\text{MPa}}{210\text{GPa}} = \underline{\underline{0.179}}$$

Appendix C

Design Tension Resistance of a T-stub flange According to ES EN 1993-1-8:2013

Given:

Yield strength of the bolt, $f_{yb} = 240\text{MPa}$

Ultimate tensile strength of the bolt, $f_{ub} = 400\text{MPa}$

Yield strength of the flange plate, $f_{yp} = 235\text{MPa}$

Bolt diameter, M16

Distance between the bolt axis and the root radius, $m = 30\text{mm}$

Distance between the bolt axis and the edge, $n = 37.5\text{mm}$

Thickness of flange, $t_f = 10\text{mm}$

Effective Length calculations

$$2m + 0.625e + 0.5p = 2 * 30 + 0.625 * 37.5 + 0.5 * 140 = \underline{\underline{153.4375\text{mm}}}$$

Design resistance calculation

$$M_{pl,1,Rd} = \frac{0.25 \sum l_{eff} t_f^2 f_y}{\gamma_{Mo}} = \frac{0.25 * 153.4375\text{mm} * (10\text{mm})^2 * 235\text{N/mm}}{1} = \underline{\underline{901445.3125\text{N} - \text{mm}}}$$

Failure Mode – 1:

$$F_{T,Rd} = \frac{4M_{pl,1,Rd}}{m} = \frac{4 * 901445.3125\text{N} - \text{mm}}{30\text{mm}} = \underline{\underline{120192.7083\text{N}}}$$

Failure Mode – 2:

$$F_{T,Rd} = \frac{2M_{pl,2,Rd} + n \sum F_{t,Rd}}{m + n} = \frac{2 * 901445.3125\text{N} - \text{mm} + 37.5\text{mm} * 180864\text{N}}{30\text{mm} + 37.5\text{mm}} = \underline{\underline{127189.4907\text{N}}}$$

Failure Mode – 3:

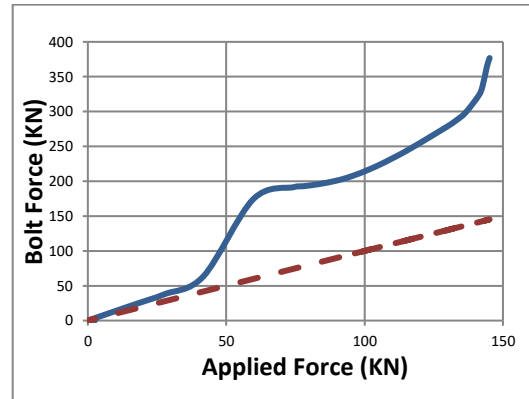
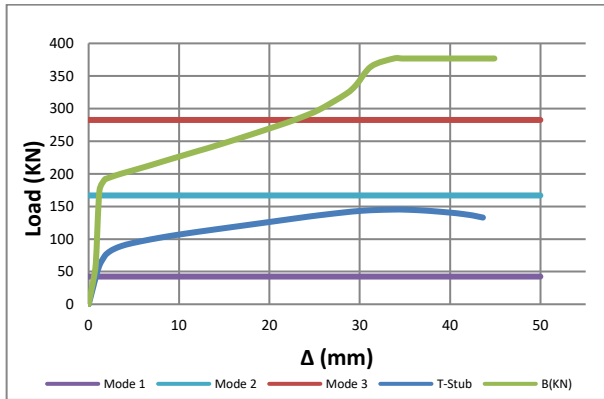
$$F_{T,Rd} = \sum F_{t,Rd} = 180864\text{N}$$

$$F_{T,Rd} = \text{Min} \left\{ \begin{array}{l} F_{T,1,Rd} \\ F_{T,2,Rd} \\ F_{T,3,Rd} \end{array} \right\} = \text{Min} \left\{ \begin{array}{l} 120192.7083 \\ 127189.4907\text{N} \\ 180864\text{N} \end{array} \right\} = \underline{\underline{120192.7083\text{N}}} = \underline{\underline{120.193\text{KN}}}$$

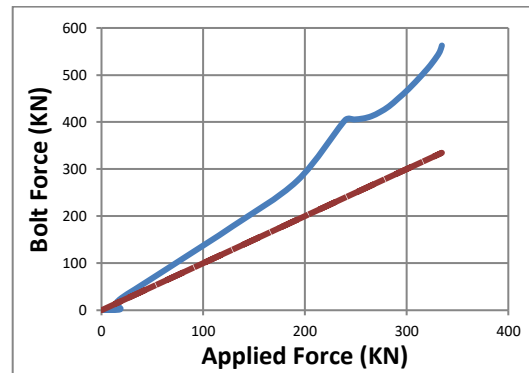
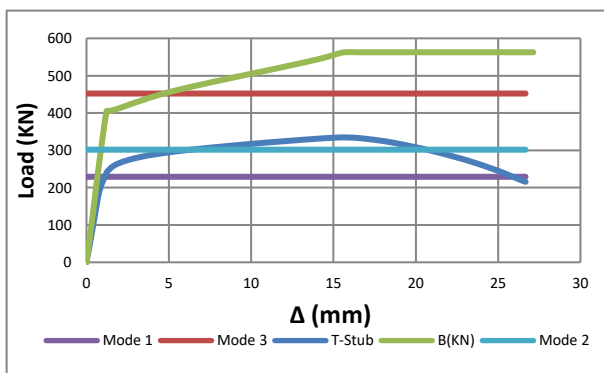
Appendix D

Load-Deflection and Bolt vs. Applied force charts for all configurations

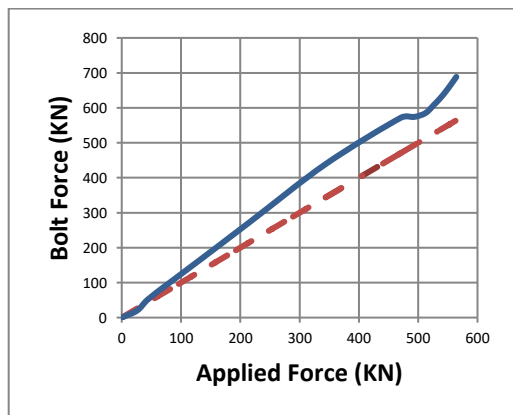
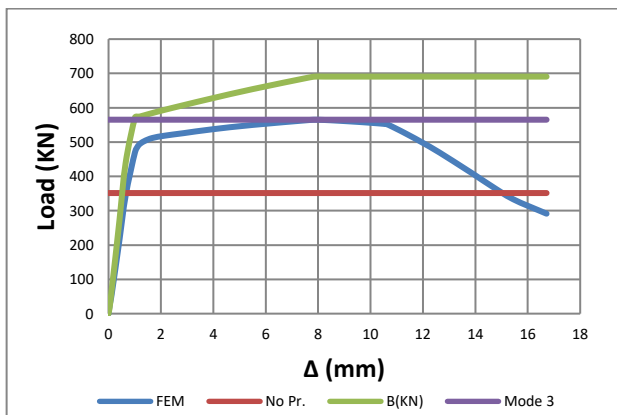
Configuration 1



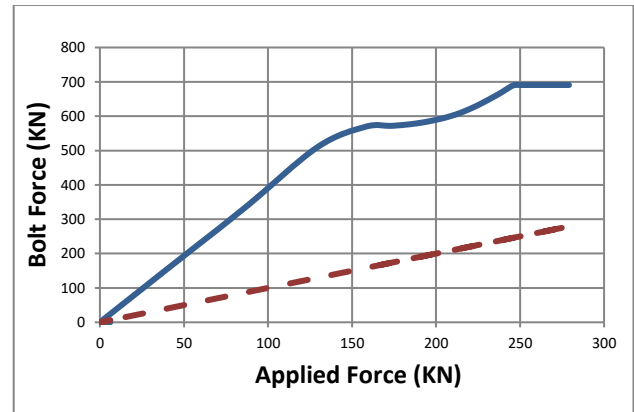
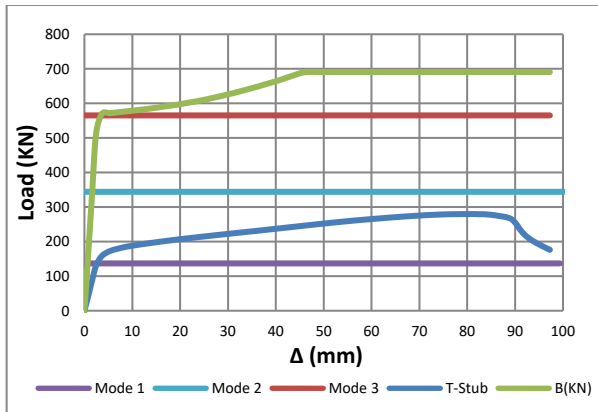
Configuration 2



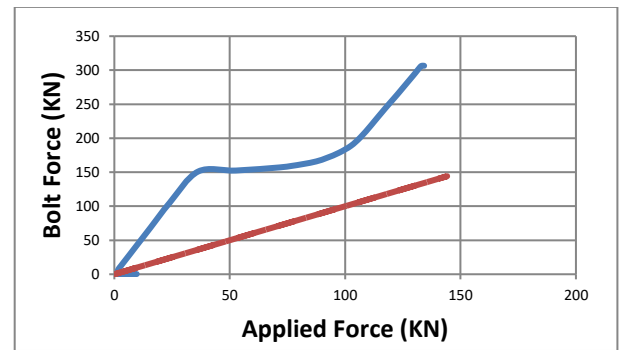
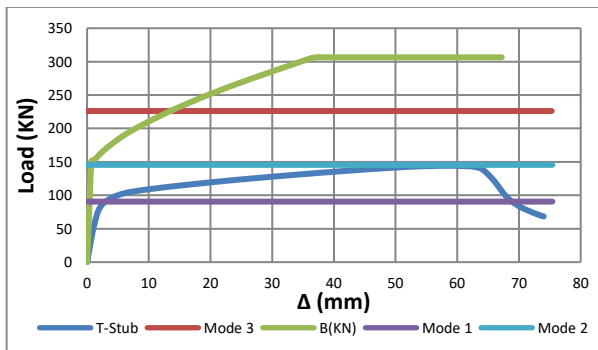
Configuration 3



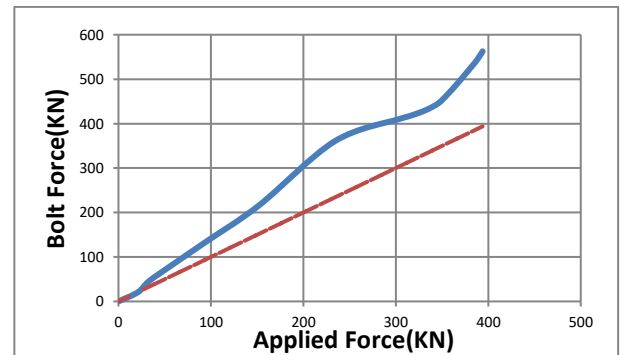
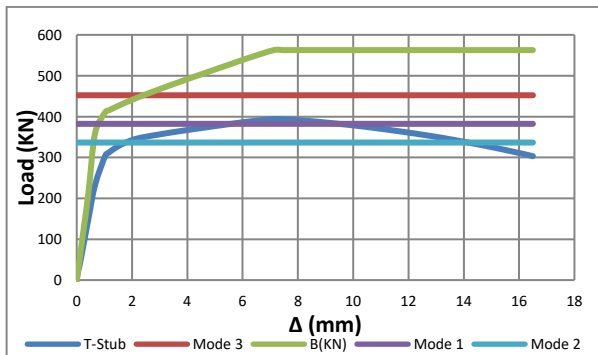
Configuration 4



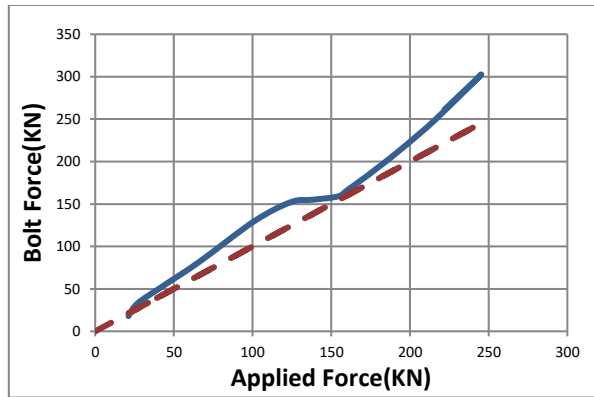
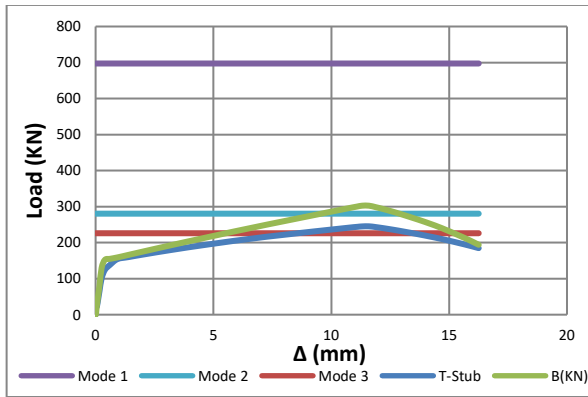
Configuration 5



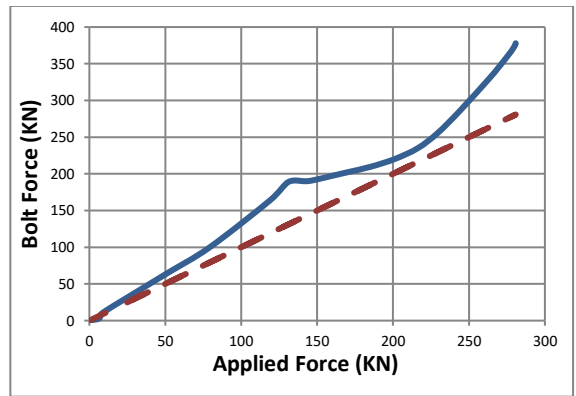
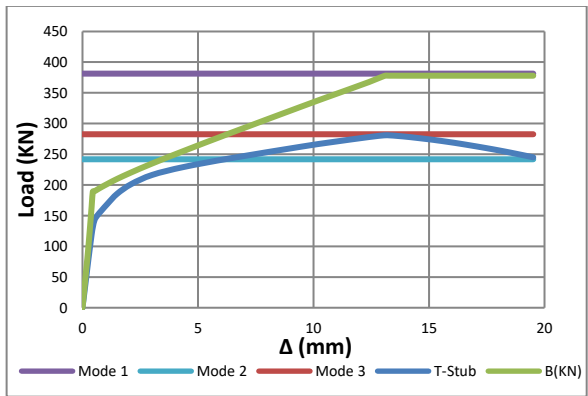
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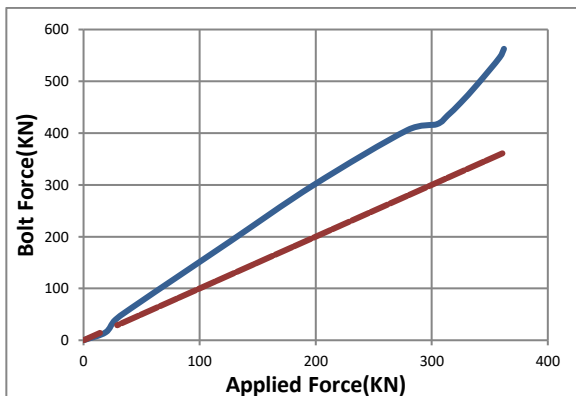
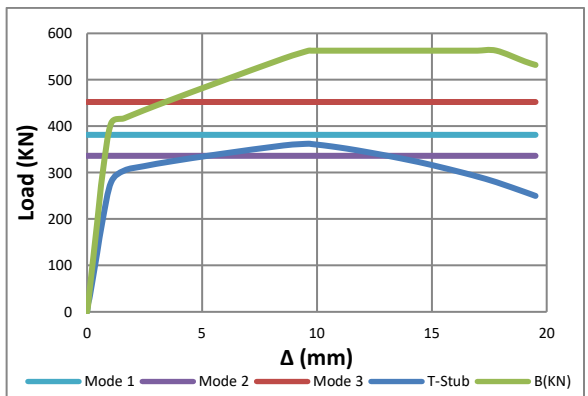
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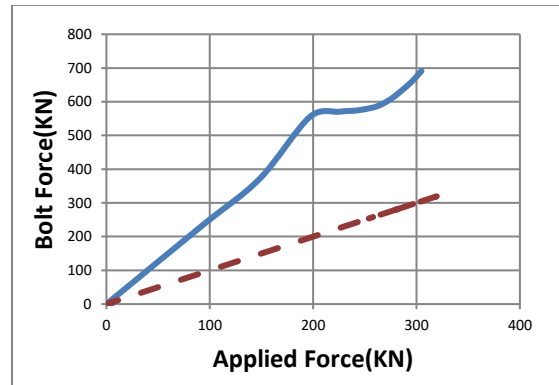
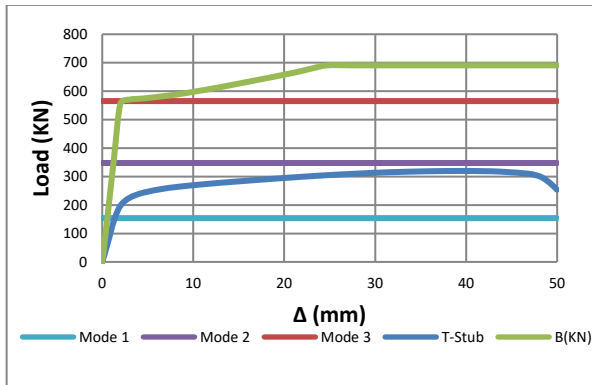
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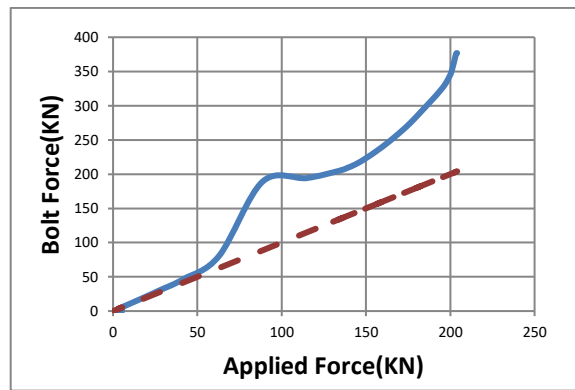
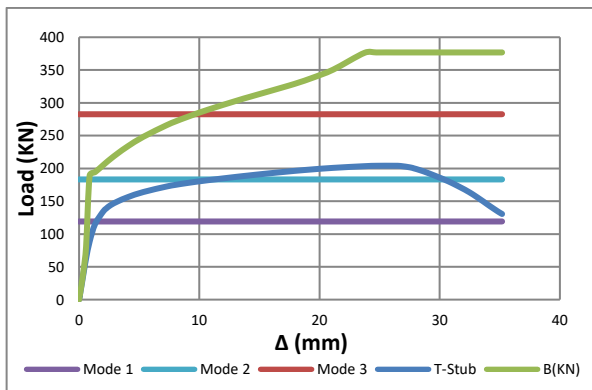
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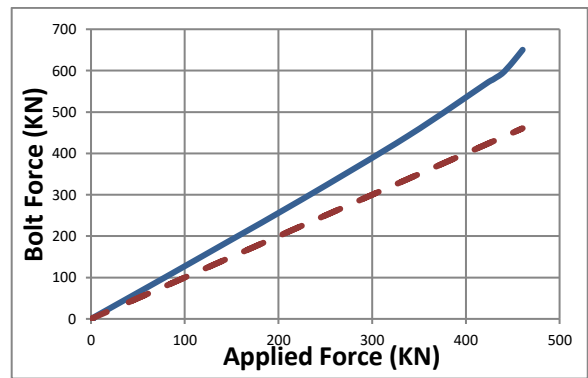
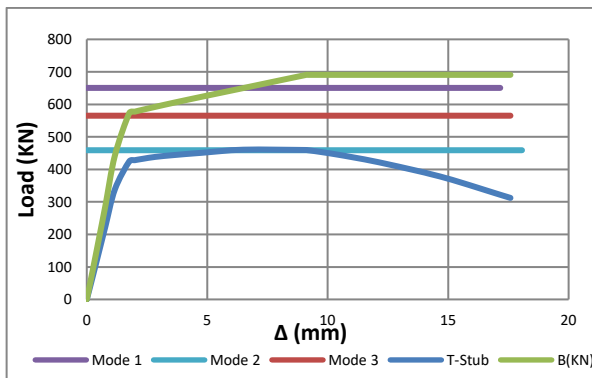
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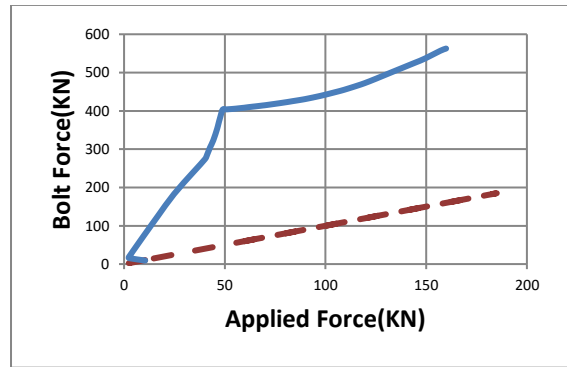
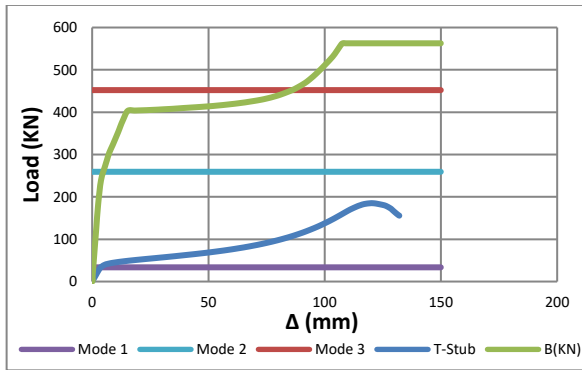
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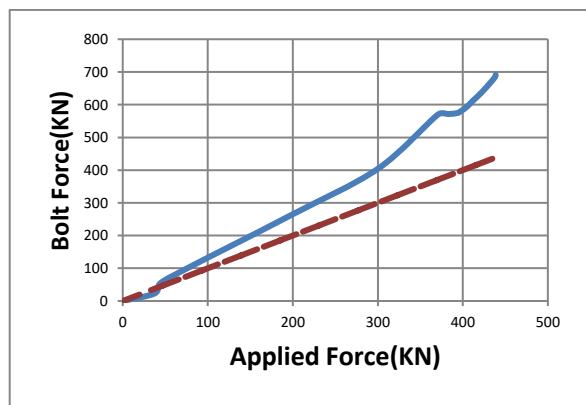
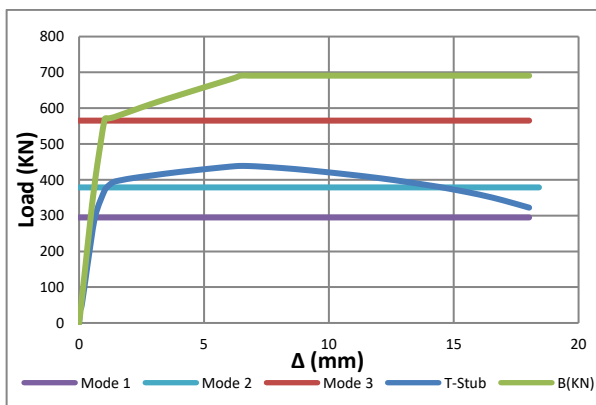
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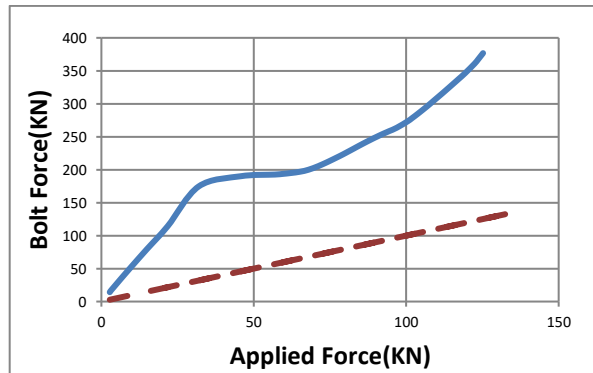
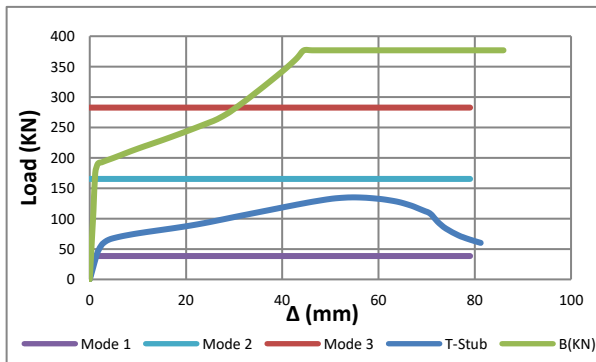
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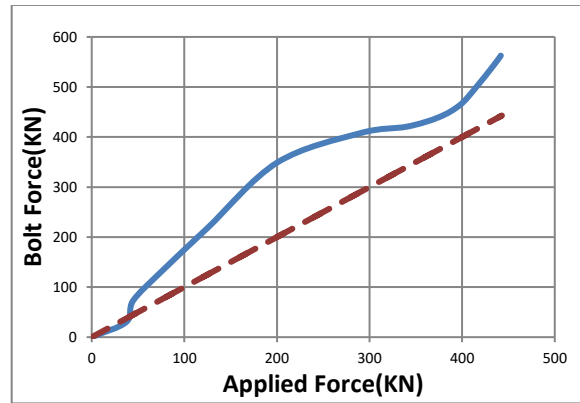
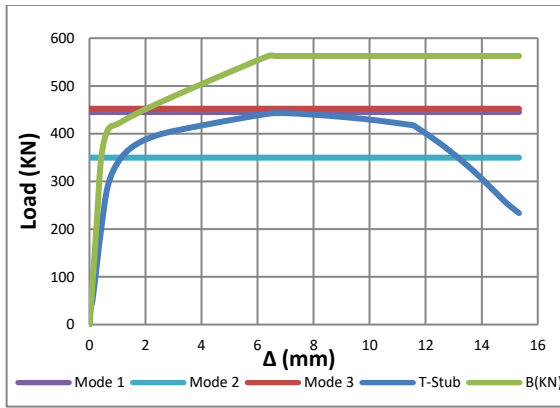
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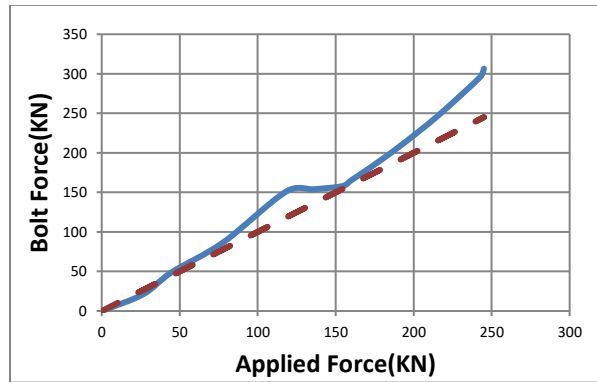
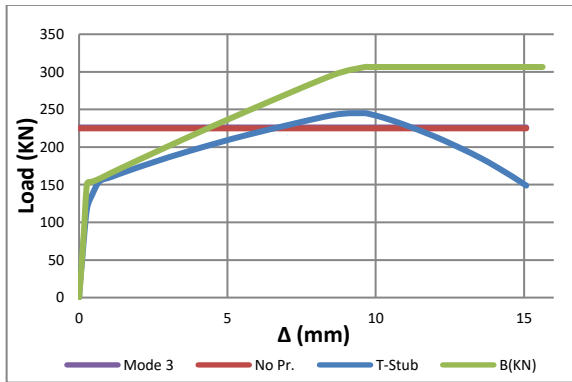
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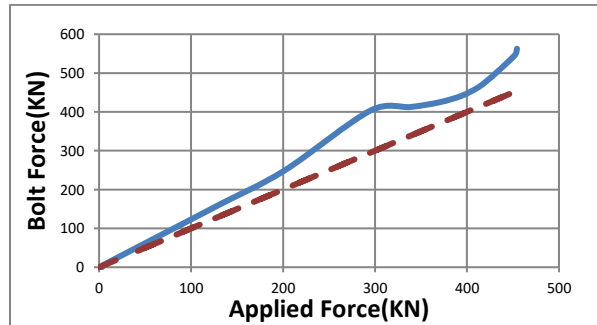
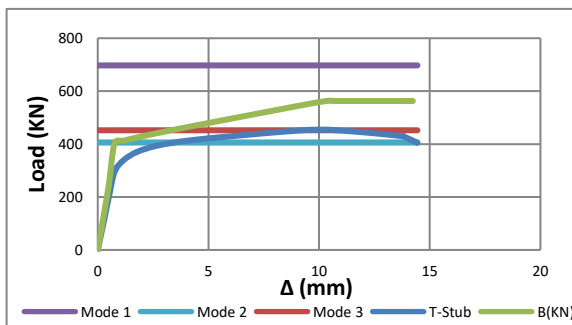
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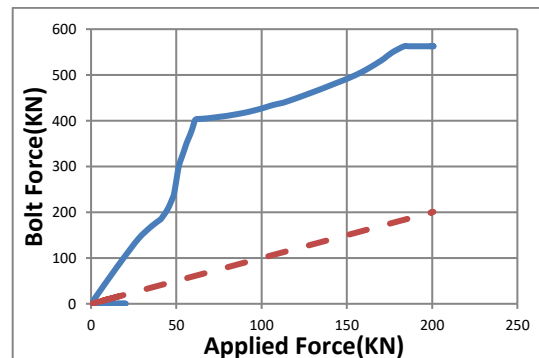
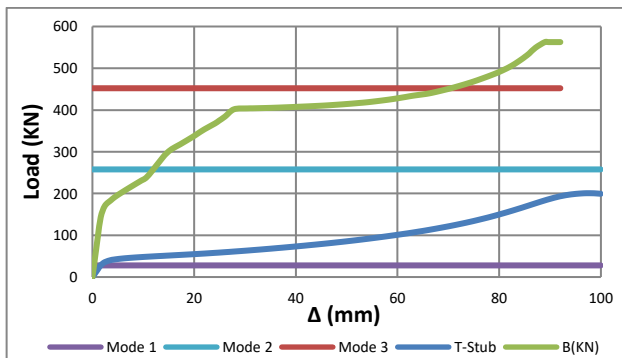
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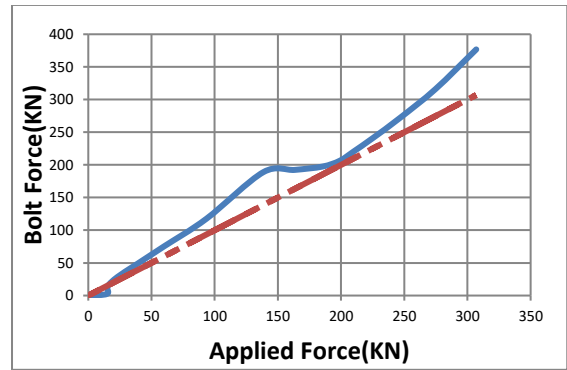
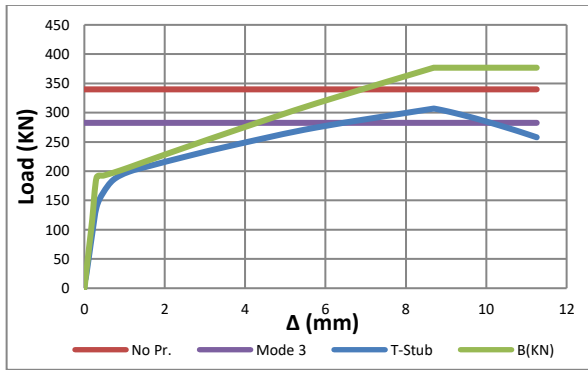
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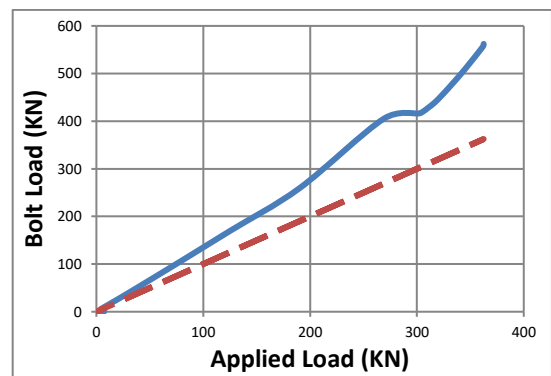
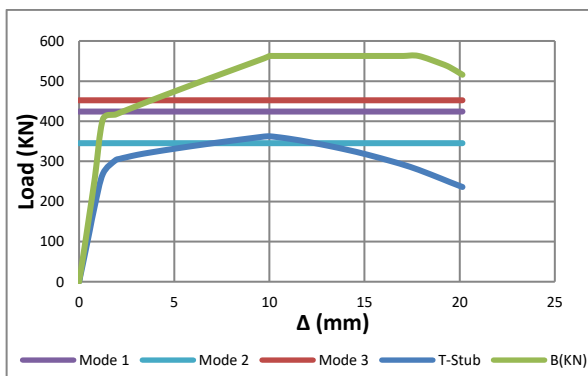
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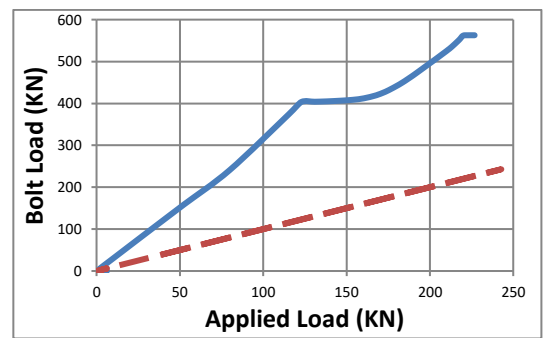
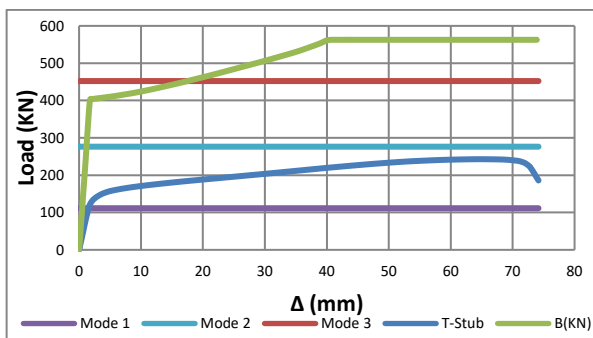
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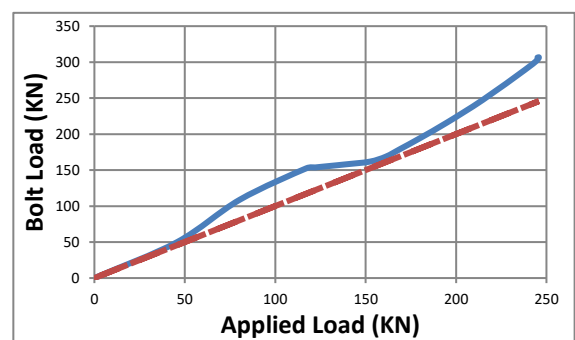
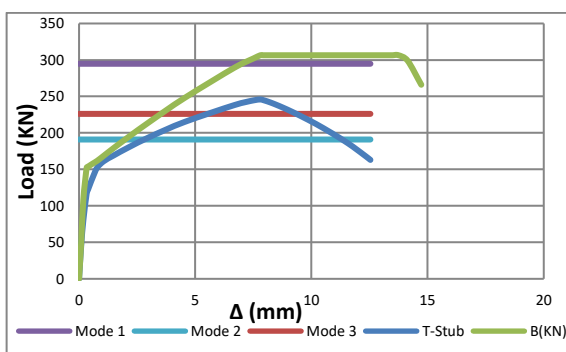
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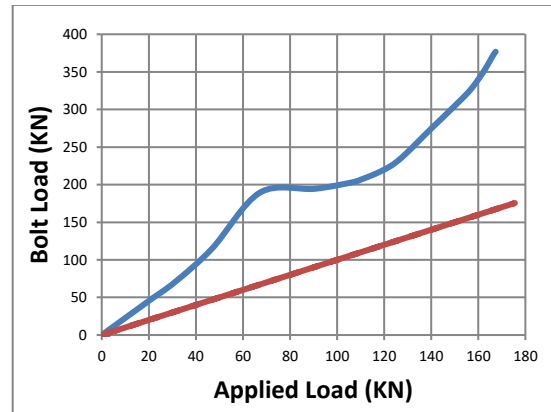
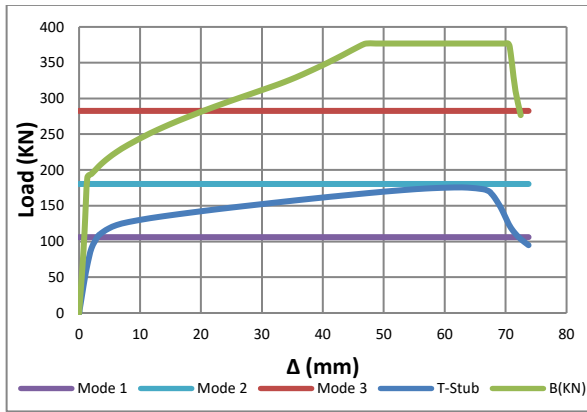
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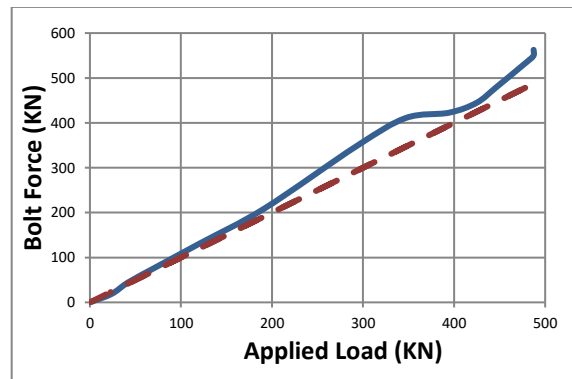
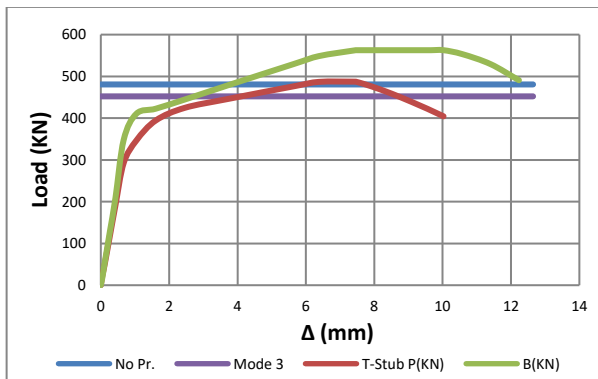
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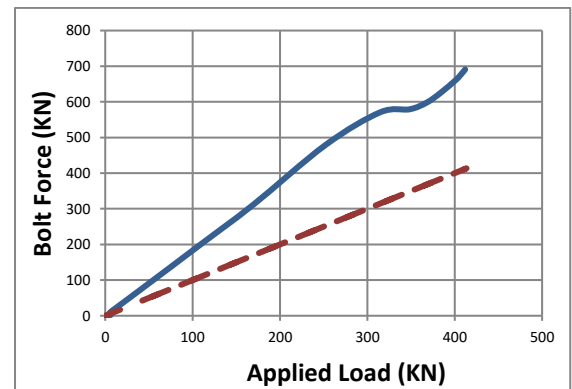
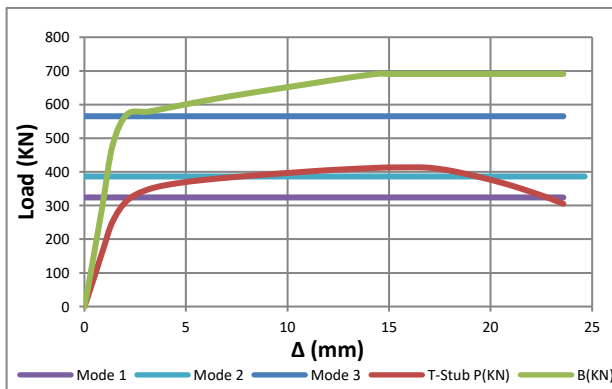
Configuration 26



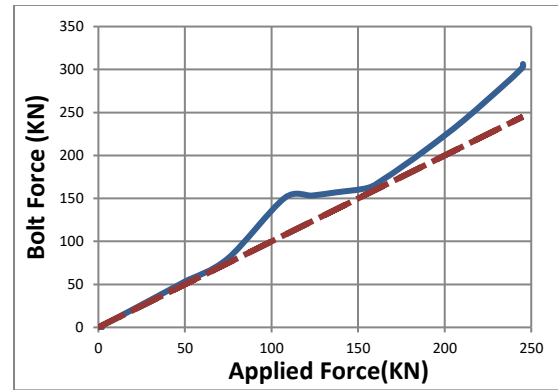
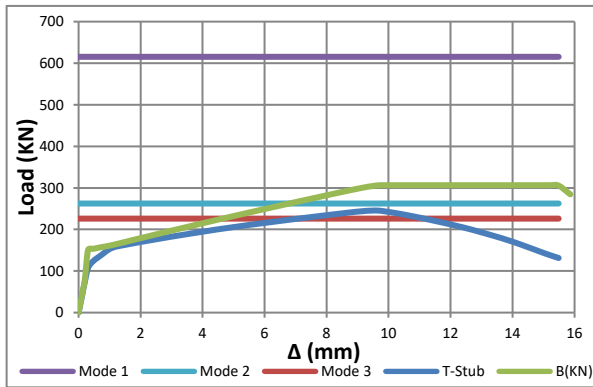
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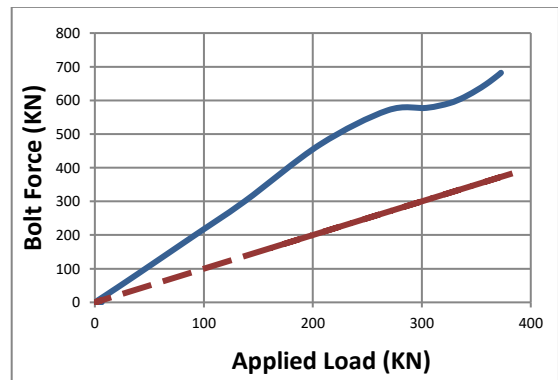
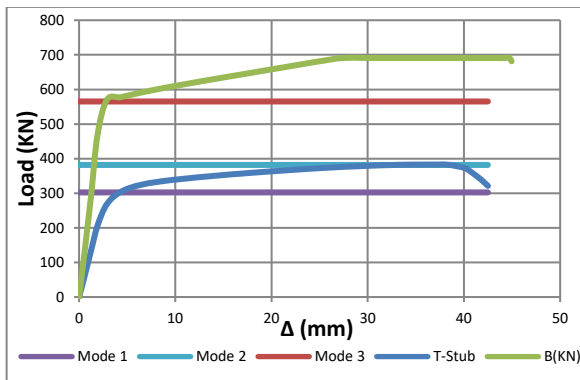
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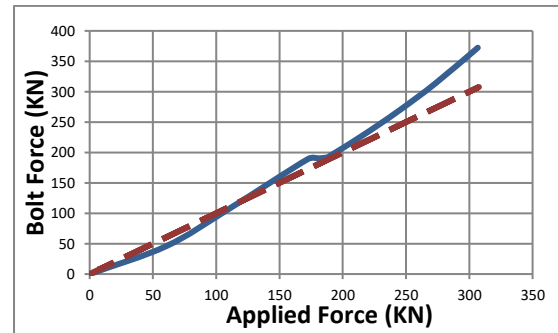
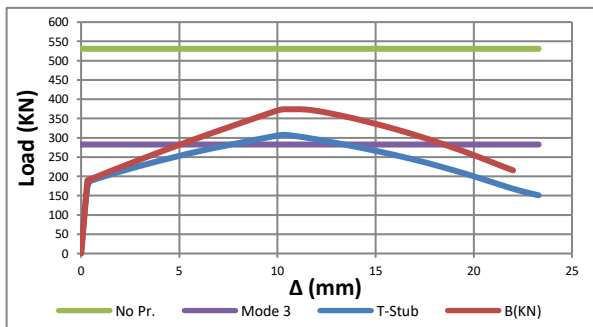
Configuration 29



Configuration 30



Configuration 31



Configuration 32

