Investigation on bolt tension of flanged pipe joint subjected to bending

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ABSTRACT: This paper presents an investigation on bolt tension of a flanged pipe joint subjected to bending. A finite element model to analyze the flanged pipe joint has been developed by using finite element software ANSYS. The pipe in the model has been subjected to yield moment of pipe and a non-linear finite element analysis has been performed. After that, an extensive parametric study has been carried out on the pipe joint to understand the effect of various parameters (i.e. diameter of pipe, flange width, flange thickness, number of bolts, and diameter of bolt) on bolt tension. Then a comparative study of the maximum bolt tension obtained from conventional method and finite element analysis method has been performed under certain range of parametric conditions. From the study, it has been found that some parameters have significant effect on bolt tension. For example, it has been observed that the bolt tension varies with the change in dimension of flange thickness, flange width and diameter of bolt. Actually, the present study gives us a better understanding of the behavior of flanged pipe joint subjected to bending and also helps us in evaluating the bolt tension value that is structurally effective for a flanged pipe joint.

1 INTRODUCTION

Pipe or tube or circular hollow section (CHS) is one of the most widely used structural steel sections. It is found in every modern home for plumbing and heating, in industrial building, into cross-country oil lines, in water and gas systems, in transmission towers and in countless other places. It is also used as a structural frame member in different structures all over the world. Some of the most widely used examples where pipes are used as structural frame members with bolted joint connections are buildings, foot over bridges, structures in entertainment parks, water tanks, bill board columns, steel pipe piles, TV masts, transmission towers etc. Most importantly, these structural pipes offer better resistance to torsional stresses and sagging. Moreover, their comparatively small exterior surface area, without sharp angles, ensures ease of maintenance.

Such an example can be observed at the foot over bridge near BUET campus (figure 1a) in Dhaka, Bangladesh which is supported by steel pipe columns. Another example can be seen in Fantasy Kingdom Entertainment Park, Ashulia (figure1b), Dhaka, Bangladesh where the track of the roller coaster is supported by some steel pipe columns.

Figure 1a. Foot over bridge at BUET campus, Dhaka

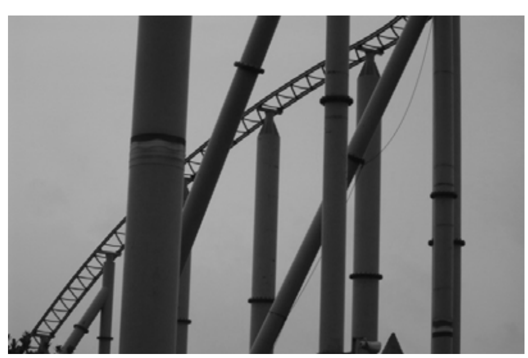

Figure 1b. Roller coaster at fantasy kingdom park, Ashulia

Wide application of pipes for structural purposes requires reliable and economical methods of determining bolt tension at pipe joints. Bolts usually connect two flanges in a pipe joint and are subjected to bending along with axial forces. Hence it is very necessary to determine the maximum bolt tension for the design of flanged pipe joint. Conventionally, due to the absence of specific guideline or code provisions, a method similar to the flexural stress distribution across a beam section is used for determining bolt tension. But this method may not always give the accurate result since the assumptions made are not practically valid. In the previous study (Waters and Taylor, 1927), the stress conditions on flange of a pipe joint were explored along three principal directions (i.e. tangential, radial and axial) with the object of determining the location and magnitude of maximum stress acted on the flange. Another study on this was carried out (Hwang and Stallings, 1994) where a 2-D axisymmetric finite element model and a 3-D solid finite element model of a high pressure bolted flange joint were generated to investigate the stress behaviors. More recently, a research study was conducted (Choudhury *et. al*., 2008) where nonlinear finite element analysis was performed on a flanged pipe joint subjected to bending to determine the maximum bolt tension. But the effect of initially applied clamping forces on the bolts was not taken into consideration in that analysis. In addition to that, no bolt hole, bolt head and bolt shank were created for the bolt modeling. As a result it could not reliably simulate the actual behavior of the bolted joint. In spite of such drawbacks, the research work is a significant one which is related to the bolt tension evaluation of a flanged pipe joint. Moreover, this study gives a thorough insight into the behavior of flanged pipe joint subjected to bending. In another research work (Azim, 2010) done very recently, a nonlinear finite element analysis was performed on flanged pipe joint under bending. The effect of various parameters had been observed on the bolt tension. An important aspect of this study is that, bolt holes were included the flange in the FE model. However, no bolt head and bolt shanks were created for the bolt modeling. As a result, it also could not reliably represent the actual behavior of the bolted joint. In spite of having such a drawback, this research work is a significant one since some drawbacks of Chowdhury (2006) had been tried out to minimize in a rational way.

Although all the previous studies mentioned so far contributes in understanding the behavior of flanged pipe joint subjected to bending, no definite guideline is available to assist the designer to make a decisive guideline in case of flanged pipe joint design. Due to the complexity of the moment-transfer mechanism between the flange and the bolt under loading and lacking of assumptions that may lead to a correct prediction of the flanged pipe joint response, there is a significant scope to investigate this matter. The proposed investigation is intended to estimate the effective bolt tension of the flanged pipe joint subjected to bending.

2 SCOPES AND OBJECTIVE

The objective of this present study is to investigate the behavior of flanged pipe joint under bending and to determine the effective bolt tension for a flanged pipe joint structure under various parametric conditions. The pipe joint with bolted flange connection, subjected to yield moment of steel pipe, has been considered. For this purpose, a typical problem has been studied under various parametric conditions that influence the bolt tension. A flanged pipe joint is modeled using finite element method, which also includes contact simulation at the pipe joint. After that the effect of various parameters (i.e. flange width, flange thickness, bolt diameter and number of bolt) on bolt tension of the pipe joint has been observed under certain range of parametric conditions.

3 GEOMETRY AND PROPERTIES OF FLANGED PIPE JOINT

A three dimensional isometric view and front view of a typical flanged pipe joint has been shown in the following figures 2a and 2b respectively.

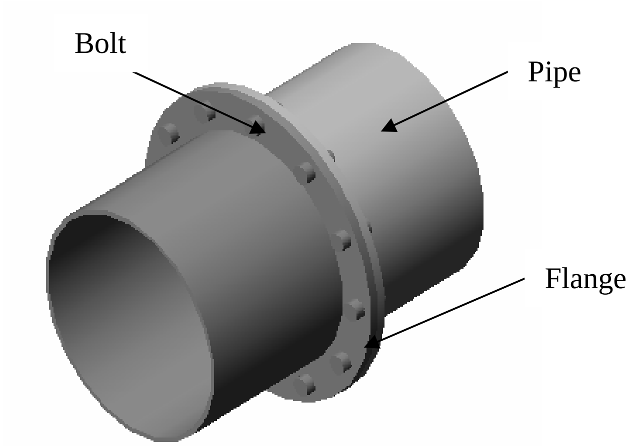

Figure 2a. 3-D isometric view of a typical Flanged pipe Joint

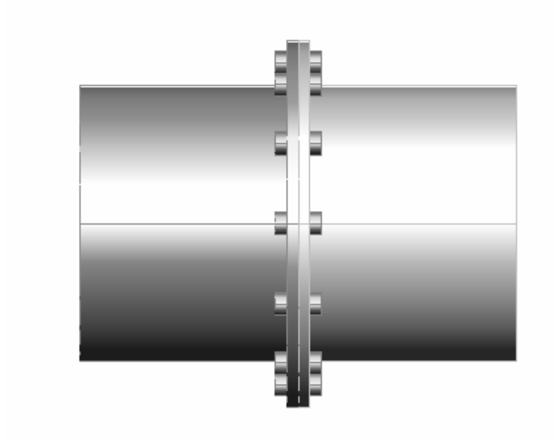

Figure 2b. Front view of a typical Flanged pipe Joint

In this analysis, small deflection and plastic material properties (material nonlinearity) are considered. The material properties of the pipe joint structure are given in table 1. In addition, various parameters of flanged pipe joint which have been used to conduct the parametric study have been shown in table 2.

Table 1. Material properties of flanged pipe joint

Properties	Unit	Value
Poisson's ratio	------	0.25
Modulus of Elasticity of steel	ksi or MPa	30,000 or 206,820
Yield strength of AISC steel pipe and flange	ksi or MPa	40 or 275.76
Yield strength of A325 steel bolt	ksi or MPa	90 or 620.7
Applied Moment	N-mm	Yield Moment

Table 2. Various Parameters of the flanged pipe joint

Parameter	Symbol	Variable Data
Nominal diameter of pipe	d_p	*50mm, 78.588mm, 102.26mm, 128.194mm, 158.78mm, 202.717mm, 254mm, 304.8mm
Pipe wall thickness	p_t	*4.775mm, 5.156mm, 6.02mm, 6.553mm, 7.925mm, 8.179mm, 9.525mm, 9.525mm
Pipe length	l_p	2 times of nominal diameter of pipe ($l_p=2d_p$)
Flange thickness	f_t	1 to 4 times of the pipe wall thickness [$f_t = p_t$; $f_t = 2p_t$; $f_t = 3p_t$; $f_t = 4p_t$]
Flange Width	f_w	50mm, 60mm, 70mm, 80mm, 90mm, 100mm, 110mm, 120mm
Nominal Bolt Diameter	d_b	**12.7mm, 15.875mm, 19.05mm, 22.225mm, 25.4mm, 28.575mm, 31.75mm, 34.925mm
Thickness of bolt head	bh_t	**7.94mm, 9.92mm, 11.01mm, 13.89mm, 15.48mm, 17.46mm, 19.84mm, 21.43mm
Number of bolts	n	4, 6, 8, 10, 12

*AISC (American Institute of Steel Construction) specified nominal diameter of pipes and corresponding pipe thickness
**RCSC (Research Council on Structural Connections) specified bolt diameter and bolt head thickness for ASTM A325 bolts

4 DIFFERENT METHODS FOR DETERMINING BOLT TENSION

4.1 *Conventional Method*

Bolt tension of a flanged pipe joint can be calculated by using the conventional method. This linear force distribution method is similar to the flexural stress distribution across a beam section subjected to bending. In fact, when a beam is subjected to positive bending, flexural stress generally develops along the axis of the beam which is normal to the plane section. Actually the tensile stress develops at the lower half of the plane and compressive stress develops at the upper half of the plane section. In addition, the stress is developed zero at the midlevel but it tends to increase towards the extreme fiber of the beam section. This similar phenomenon also happens in the flanged pipe joint when it is subjected to bending.

Bolt tension of a flanged pipe joint can be calculated by using the conventional linear force distribution method. This can be demonstrated by the following example.

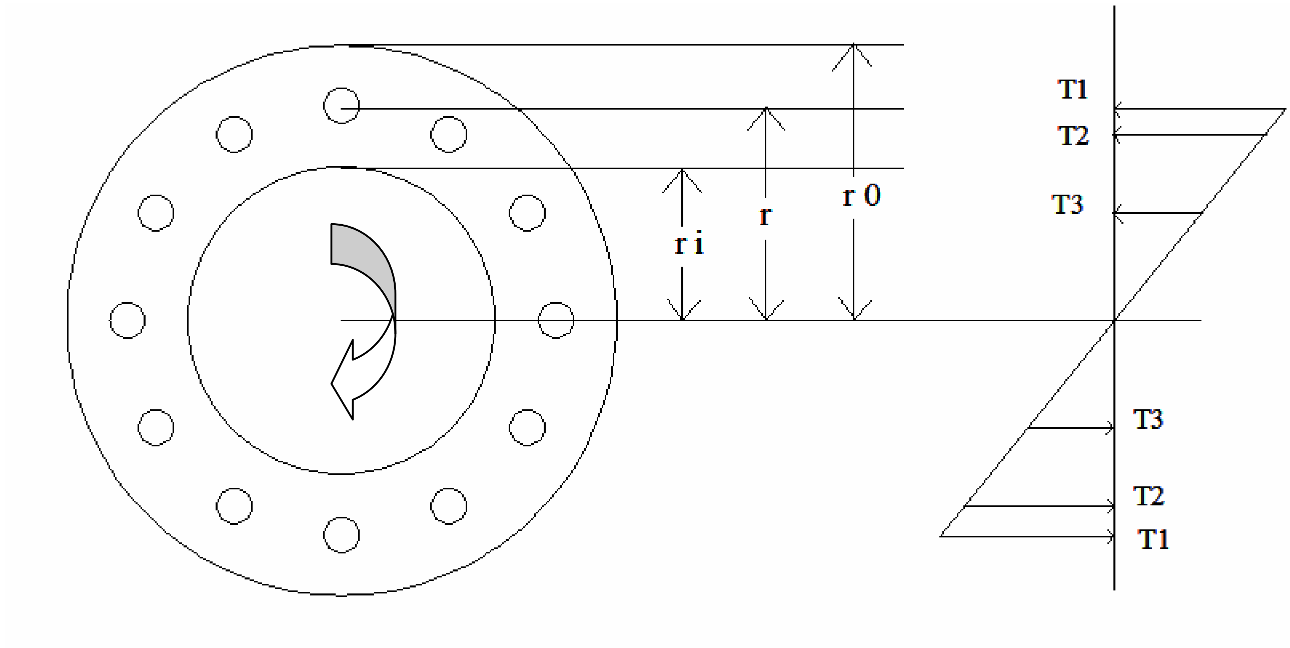

Figure 3. Plan and force distribution of a typical flanged pipe joint with 12 bolts

$$T_1 = \frac{M}{2r + 4r\sin^2 60^\circ + 4r\sin^2 30^\circ} \qquad (1)$$

where, r_i = pipe radius; r_o = outer radius of flange; r = distance from the center of the pipe to the center of the bolt; T_1 = bolt tension of the furthest bolt; M = applied moment.

By using this type of above equation (1), the maximum bolt tension can be determined which is furthest from the center of the pipe for various pipe diameter and for different number of bolts. When a flanged pipe joint is subjected to bending, the reaction force normally develops on the bolts. Figure 3 shows the plan and linear force distribution system of the flanged pipe joint and it is observed here that the tensile reaction force develops on the upper bolts and compressive force develops on the lower bolts whose phenomenon is almost similar to the flexural stress distribution across the beam section mentioned earlier.

4.2 *Finite Element Method*

The flanged pipe joint has been modeled by using the finite element analysis software ANSYS v.10. Due to symmetry, only one side of the joint has been modeled with appropriate boundary conditions. For the modeling of pipe, flange, contact surface, bolts and stiffening ring, separate elements have been used. For the pipe and flange modeling SHELL43 8-nodded structural shell element, for the bolt shanks COMBIN39 linear spring element (resists both tension and compression), for contact surface COMBIN39 nonlinear spring element (resists compression well but very much weak in tension) and for the stiffening ring BEAM4 3D elastic beam element has been used.

After modeling the flanged pipe joint structure, some boundary conditions are applied at the pipe joint structure. The free ends of the combin39 link element, which simulate the contact, are restrained in all directions. Apart from that, all peripheral nodes of the flange are also restrained in horizontal direction to resist against sliding. In addition to that, the vertical and translational movements are also restrained on all bolt heads to simulate the actual condition in pipe joint structure.

In case of application of load, total load is applied to the pipe joint in two consecutive load steps. In the first load step, the initial clamping force has been applied at the bottom of all bolt shanks in order to simulate the actual condition. Then in the second load step, the model is subjected to yield moment of steel pipe. In this model, the moment is applied by a pair of parallel and opposite forces representing a couple. Figure 4 shows the finite element mesh of the flanged pipe joint with boundary conditions and applied loading. After the load application, a nonlinear static analysis has been performed. The deflected shape and stress contour of the pipe joint has also been shown in figure 5 and 6 respectively.

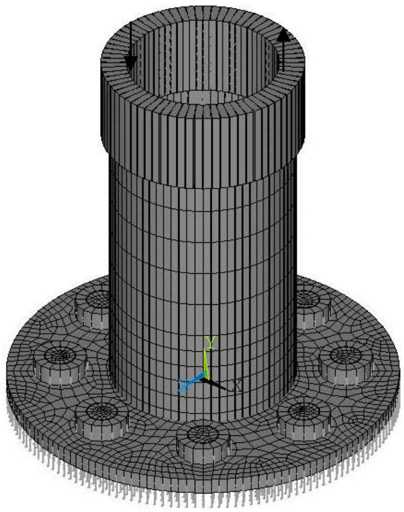

Figure 4. Flanged pipe joint with boundary conditions and applied loading

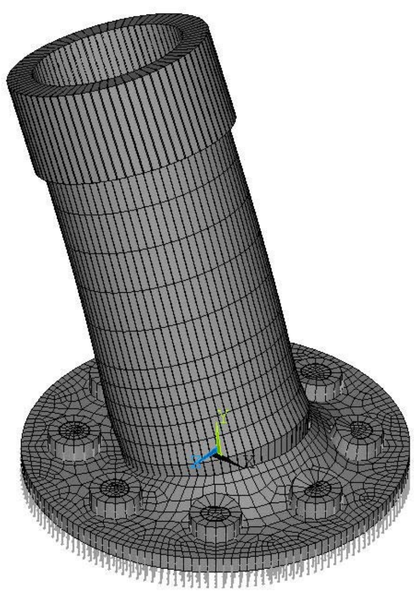

Figure 5: Deformed shape of the flanged pipe joint

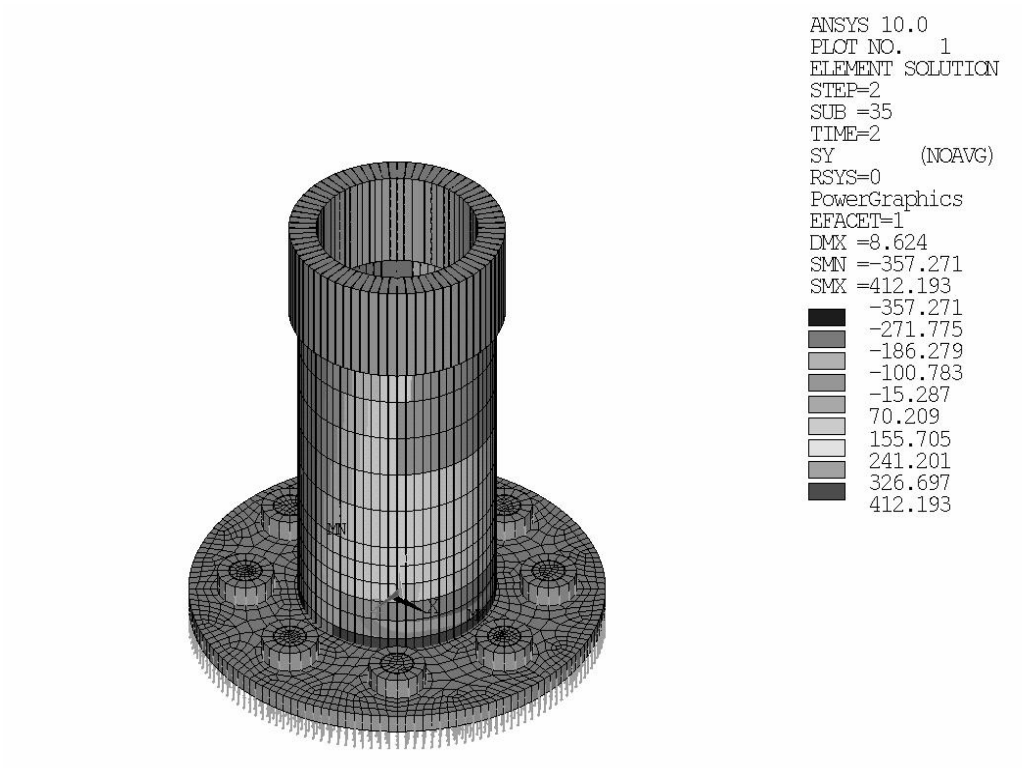

Figure 6: Flexural Stress contour of the pipe joint along the axis of the pipe

This analysis has been done on eight AISC standard structural steel pipe sections of 40ksi yield strength within a certain range of some parameters like flange width, diameter of bolt, number of bolts and flange to pipe thickness ratio. Finally, the reaction forces of all bolts are obtained to get the value of maximum bolt tension. It is to be noted here that the maximum bolt tension exceeding the yield strength of A325 bolt (90 ksi or 620.7 N/mm^2) is not taken into account.

5 EFFECTS OF VARIOUS PARAMETERS ON BOLT TENSION

The results obtained from conventional method do not vary with the flange thickness. But in finite element method, the bolt tension values depend on flange thickness which has been shown in the following graphs by giving proper symbols for different flange thicknesses ($f_t = p_t$, $f_t = 2p_t$, $f_t = 3p_t$ and $f_t = 4p_t$). The effect of number of bolts, diameter of bolt, flange thickness and flange width on maximum bolt tension of the pipe joint has been shown in the following graphs from 7a to 7f.

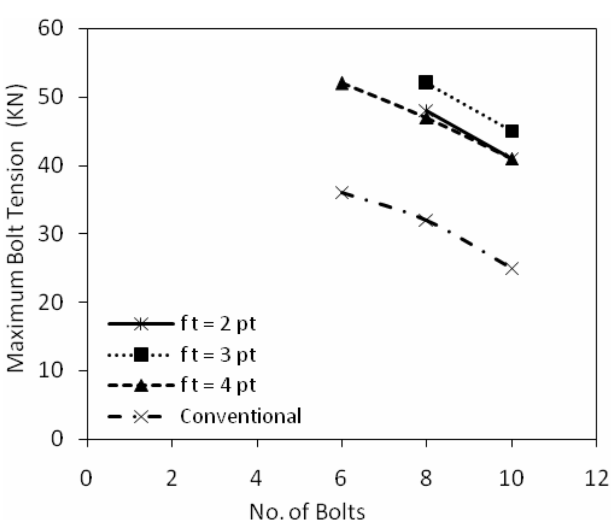

Figure 7a. For d_p = 78.588 mm, f_w = 50mm, d_b = 12.7mm

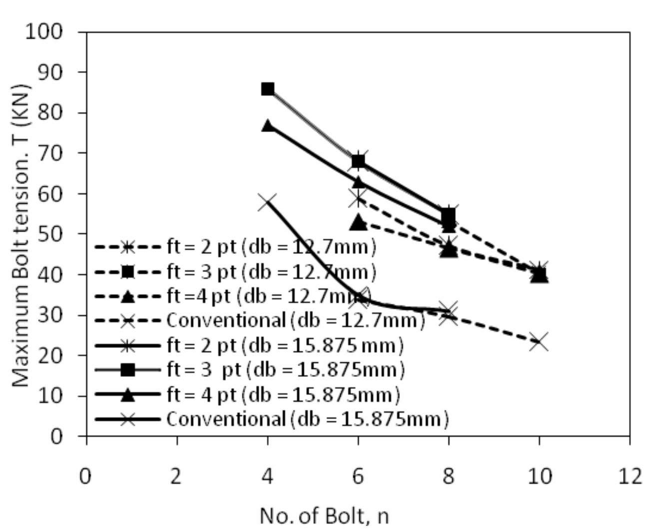

Figure 7b. For d_p = 78.588 mm, f_w = 60mm, d_b = 12.7and 15.875mm

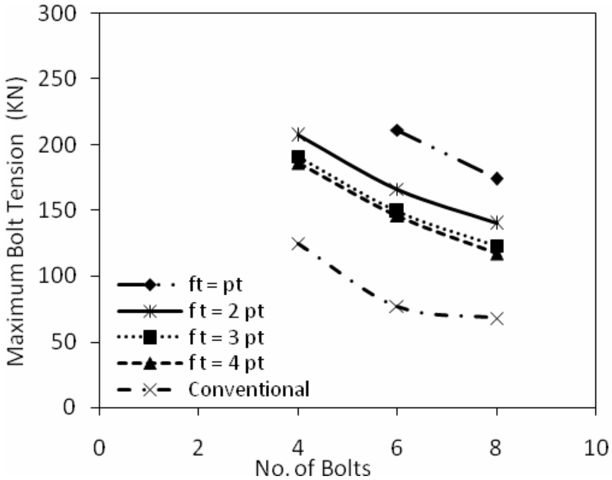

Figure 7c. For d_p = 128.194 mm, f_w = 90mm, d_b = 25.4mm

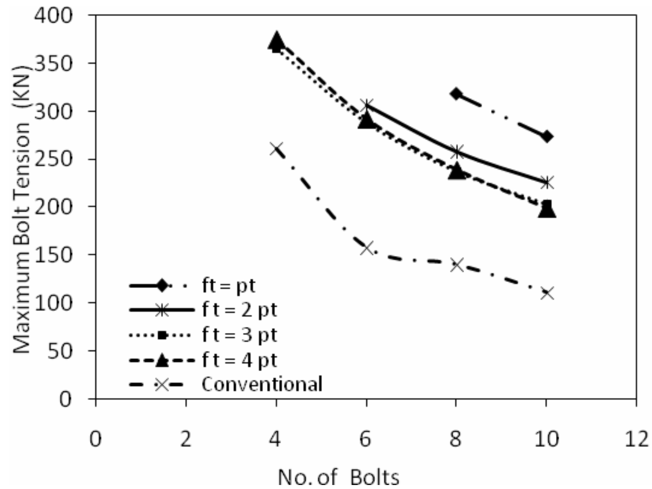

Figure 7d. For d_p = 202.717 mm, f_w = 110mm, d_b = 31.75mm

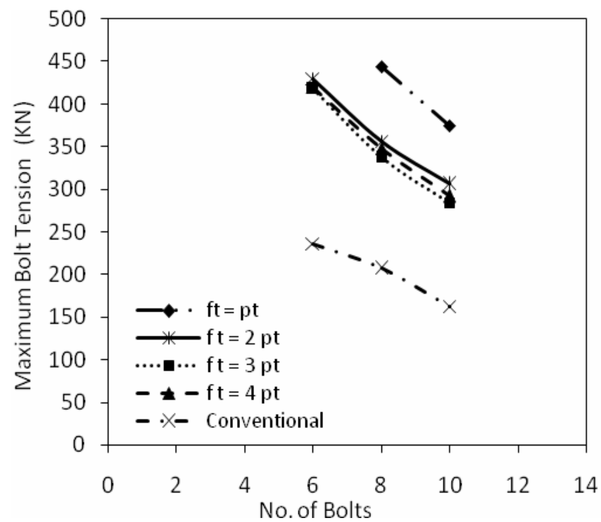

Figure 7e. For d_p = 254 mm, f_w = 120mm, d_b = 34.925mm

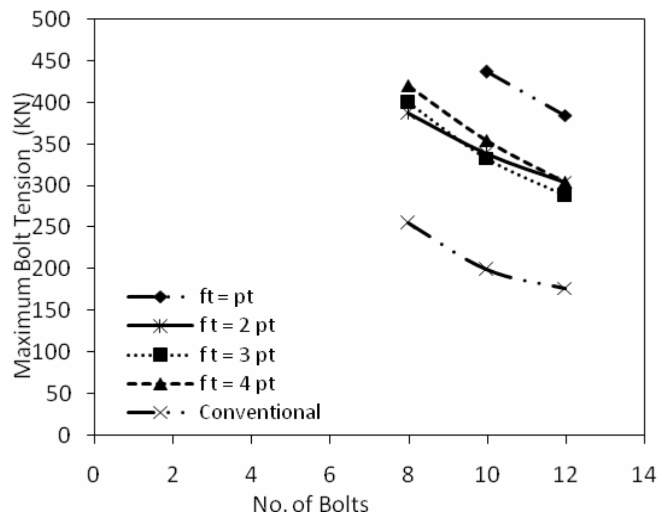

Figure 7f. For d_p = 304.8 mm, f_w = 120mm, d_b = 34.925mm

Figure 7. Effect of number of bolts , diameter of bolt, flange thickness on bolt tension for different diameter pipes
(Pipe diameter = d_p, pipe thickness = p_t, flange width = f_w, flange thickness = f_t, diameter of bolt = d_b)

5.1 *Effect of number of bolts on bolt tension*

The curves, generated for bolt tension against number of bolts from the respective finite element analysis results and conventional calculations, are presented in figure 7a through 7f. The trend lines of the curves are demonstrated a downtrend with a parabolic nature for increasing number of bolt under the study parameters. It is evident from the figures that bolt tension decreases with the increasing number of bolts. This implies that, increasing number of bolts results in decreasing bolt tension as logically expected. In fact, if only the number of bolt increases for a particular case of other parameters, the total effective tensile stress area of bolts will also increase. As a result the tensile reactive force per bolt will decrease for the same applied moment in pipe joint structure.

5.2 *Effect of diameter of bolt on bolt tension*

As the diameter of bolt increases the developed bolt tension value also increases for any particular case of diameter of pipe, number of bolt, flange width and flange thickness. This occurs mainly due to the fact that if the diameter of bolt increases, the stiffness of the bolt generally increases. As a result, large tension value develops on greater diameter bolts.

5.3 *Effect of flange thickness on bolt tension*

With reference to figure 7a through 7f, it may be inferred that, bolt tension also depends on flange thickness. But it does not follow any particular trend. From the presented graphs, both increase and decrease in tension value have been observed in an irregular pattern when flange thickness is increased or decreased in case of finite element method. Apart from that it is also observed that, the band width of bolt tension values (ranging from $f_t = 2p_t$, $f_t = 3p_t$ to $f_t = 4p_t$) tends to decrease as the pipe diameter increases. This clearly indicates that the effect of flange thickness on bolt tension is reducing with the increase in pipe diameter. This is probably due to the fact that if the flange thickness is relatively small (that is if the flange is less stiff) then considerable bending will occur on the flange and at the same time connected bolts to the flange will tend to be elongated. As a consequence the contact area between two flanges will be reduced and the developed prying force near the edge of the flange will increase. Therefore in case of thin flanges the bolt tension value is comparatively large. On the other hand, in case of thick flange, the flange is stiffer to resist the applied loading and the contact area between two flanges does not get more reduced due to applied load. In addition, the prying force develops small in comparison with the thin flange. Hence the bolt tension value develops relatively small in case of thick flange.

5.4 *Effect of flange width on bolt tension*

As the flange width increases, the prying force developed near the edge of the flange generally decreases. As a result the bolt tension value decreases with the increase in flange width.

6 CONCLUSIONS

The important conclusions derived from the study of the flanged pipe joint are summarized as follows:

- The research study provided us with an opportunity to understand the behavior of a bolted flanged pipe connection subjected to bending.
- The effect of various parameters on the bolt tension is reflected in this research work.
  - Flange thickness affects bolt tension which the conventional analysis method cannot account for. The variation of bolt tension with flange thickness does not follow any particular pattern and further study is needed to establish the effect of this parameter in a definitive manner.
  - The maximum bolt tension decreases as flange width increases for any particular case of diameter of pipe, number of bolt, diameter of bolt and flange thickness.
  - The maximum bolt tension increases as diameter of bolt increases for any particular case of diameter of pipe, number of bolt, flange width and flange thickness.
- The bolt tension values obtained from conventional method are not accurate as the effect of variation in flange thickness and flange width is not incorporated in this method which is not justifiable from the rational point of view. On the other hand the effect of variation in flange thickness and width has been clearly demonstrated by FE analyses. Therefore, any rational guideline to determine bolt tension in flanged pipe joint must include the effect of flange thickness and flange width.

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