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Finite element investigation on the behavior of bolted flanged steel pipe joint subject to bending

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Abstract

In this paper a Finite Element (FE) procedure is described for simulating the behavior of bolted flanged steel pipe joint subject to bending. The FE model of the pipe joint has been subjected to yield moment of steel pipe and the maximum bolt tension has been determined under that moment. FE models presented in this paper incorporate nonlinear material properties and simulation of contact between flanges as well as between bolt-head and flange. An extensive numerical study has been carried out to find out the effect of various parameters on bolt tension. The study reveals that flange thickness and diameter of bolt have predominant effect on bolt tension forces. The study presented here provides us with an opportunity to better understand the behavior of flanged pipe joint subjected to bending.

Keywords: Fertilizer, nutrient load, rice cultivation, agricultural return flow, nonpoint-source pollution

1. Introduction

Different types of structures are built all over the world. Pipe, tube or circular hollow section (CHS) is one of the most common structural sections which is widely used in many types of structural steel constructions. It is used as a structural frame member in 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.

Structural pipes are generally connected at joints with each other. Flanged joint is one of the common types of pipe joints. In bolted flanged pipe joint, pipes are connected with flanges which are then bolted together in order to make a strong connection. When a flanged pipe joint is subjected to bending, the whole structure tends to bend and some tensile forces are developed on the bolts. In many cases the pipe joint may fail due to over loading. Therefore in order to ensure the safety of pipe joint structure, the maximum bolt tension needs to be known. Bolt force is needed to be properly determined for safe design of the joint.

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. A three dimensional isometric view and front view of a typical bolted flanged pipe joint have been shown in the following figure 2. The usual deflected shape of the flanged pipe joint subjected to bending has been shown in figure 3.

(a)

Fig. 1. (a) Foot over bridge at BUET campus

(b)

Fig. 1. (b) Roller coaster at Fantasy Kingdom park, Ashulia

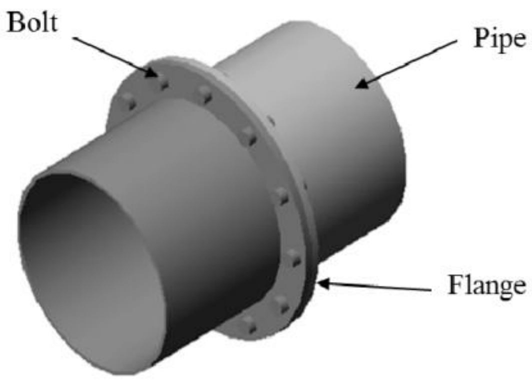


Fig. 2. 3-D isometric view of a typical flanged pipe joint

Analysis of a flanged pipe joint subjected to bending and determination of maximum bolt tension is a rather difficult task due to absence of a rational method of analysis. Conventionally, in absence of specific guideline or code provisions, a method analogous to beam flexure is generally adopted to determine bolt reaction forces. It is assumed that bolt force (tension or compression) is linearly proportional to the distance from the neutral axis. But this method may not always give the accurate result since the assumptions made are not practically valid. In a study (Waters and Taylor, 1927), the stress conditions on flange of a pipe joint have been 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 has been 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 have been modeled to investigate the stress behaviors.

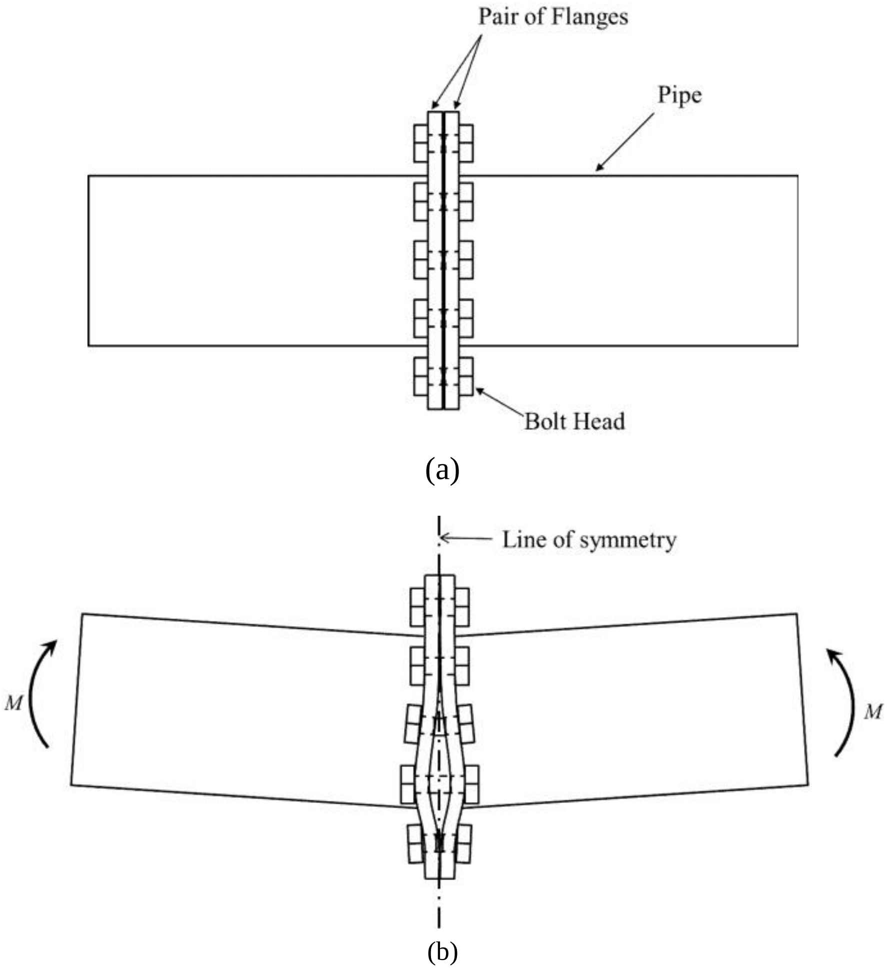


Fig. 3. (a) Front view of a typical bolted flanged pipe joint (b) Deflected shape of flanged pipe joint subjected to bending

More recently, a research study was conducted by Choudhury *et. al.* (2008) where nonlinear finite element analysis has been performed on a flanged pipe joint subjected to bending to determine the maximum bolt reaction forces. But the initially applied clamping forces on the bolts have not been taken into account in that analysis. Besides that, some components like bolt hole, bolt head and bolt shank have not been included in bolt modeling. In another research work (Azim, 2010), bolt holes have been modeled on the flange of the FE model though no bolt head and bolt shanks are created in bolt modeling. In spite of having such drawbacks, these research works are significant since some limitations of Chowdhury *et. al.* (2008) has been tried out to minimize in a rational way. In a research work done very recently (Tafheem, 2012), a FE model of flanged pipe joint has been subjected to yield moment of steel pipe and then nonlinear finite element analysis has been performed. Here almost all necessary components including bolt heads, bolt holes, bolt shanks, contact elements have been modeled to simulate the actual behavior of the pipe joint and the initial clamping force has also been applied at the bottom of all bolt shanks. In addition to that, a comparative study for the maximum bolt force obtained from conventional linear force distribution method which is analogous to beam flexure theory and finite element analysis has also been carried out. The effect of various parameters on maximum bolt tension has been investigated on flanged pipe joint under certain range of different parameters (Tafheem and Amanat, 2011).

Although all the previous works mentioned so far contributes in understanding the behavior of flanged pipe joint subjected to bending, no definite guideline is available to assist. 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 reaction forces of the flanged pipe joint subject to bending.

The objective of the present study is to investigate the behavior of flanged pipe joint subjected to bending. A bolted flanged pipe joint is modeled using finite element method, which also includes contact simulation at the pipe joint. The pipe joint, subjected to yield moment of steel pipe, has been considered. After that, the effect of various parameters such as flange width, flange thickness, bolt diameter on bolt tension has been investigated under certain range of various parameters.

2. Details of Material properties and geometric dimensions

In this FE analysis, small deflection and material nonlinearity have been considered. The material properties of the pipe joint are given in Table 1 and various parameters of flanged pipe joint 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	MPa	206.82
Yield strength of AISC steel pipe and flange	MPa	275.76
Yield strength of A325 steel bolt	MPa	620.7

Table 2
Various Parameters of the flanged pipe joint

Parameter	Symbol	Variable Data
Nominal diameter of pipe, mm	d_p	*50, 78.588, 102.26, 128.194, 158.78, 202.717, 254, 304.8
Pipe wall thickness, mm	p_t	*4.775, 5.156, 6.02, 6.553, 7.925, 8.179, 9.525, 9.525
Flange thickness, mm	f_t	2 to 4 times of pipe wall thickness [$f_t = 2\,p_t$; $f_t = 3\,p_t$; $f_t = 4\,p_t$]
Flange Width, mm	f_w	50, 70, 90, 110, 130, 150
Nominal Bolt Diameter, mm	d_b	**12.7, 15.875, 19.05, 22.225, 25.4
Number of bolts	n	4, 6, 8, 10, 12,14, 16, 18, 20, 22

**AISC (American Institute of Steel Construction) specified nominal diameter of pipe and corresponding pipe thickness*
***RCSC (Research Council on Structural Connections) specified bolt diam*

The necessary dimensions of the pipe joint are schematically shown in the following figure 4. In FE model the distance from the centre of a bolt to the centre of the adjacent bolt is not allowed greater than three times of bolt diameter ($3d_b$) and the distance from the centre of the bolt to the edge of the flange is always maintained greater than 1.5 times of bolt diameter ($1.5d_b$) as it should be followed according to RCSC.

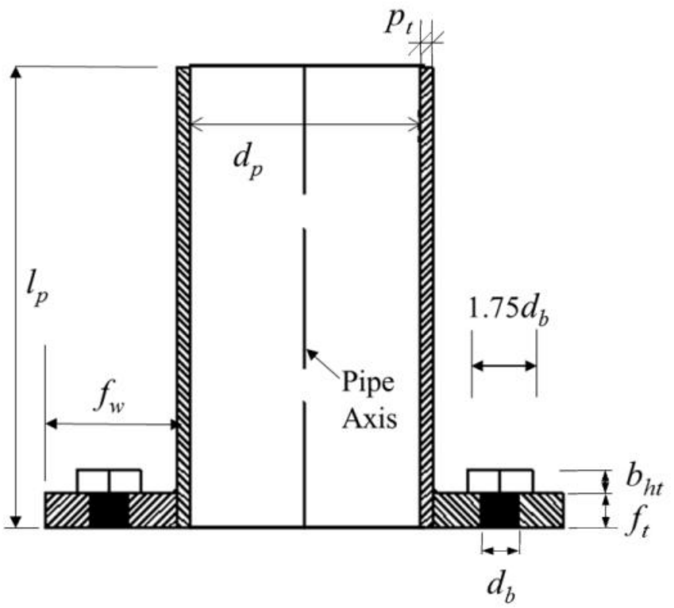


Fig. 4. Elevation of the upper part of the pipe joint with necessary dimensions

3. Conventional Method

Bolt reaction forces of a flanged pipe joint under bending can be calculated by using conventional linear force distribution method which is similar to the flexural stress distribution across a beam section subjected to bending. The following figure 5 shows the plan and linear force distribution system of a flanged pipe joint under bending.

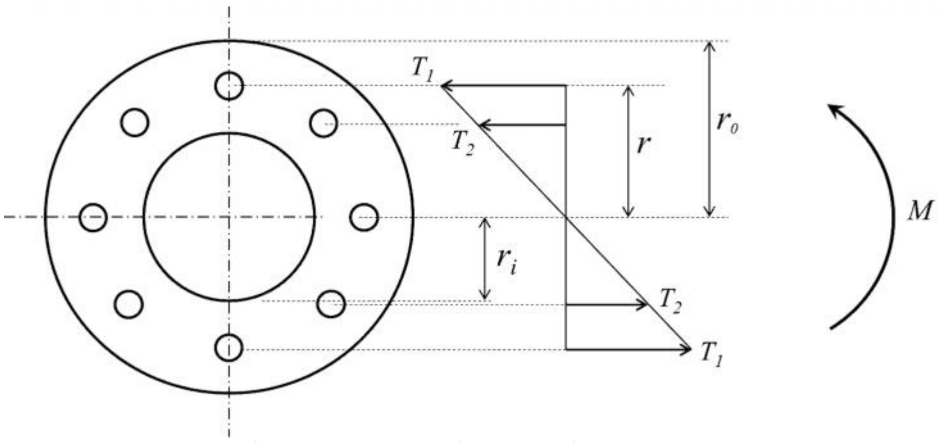


Fig. 5. Plan and force distribution of a typical flanged pipe joint with 8 bolts

When a flanged pipe joint is subjected to bending, the reaction forces generally develop on the bolts. From figure 5, it has been observed that tensile forces are developed on the upper bolts and compressive forces on the lower bolts whose phenomenon is almost similar to the flexural stress distribution across a beam section mentioned earlier. Here, 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 reaction of the furthest bolt, M = applied moment. The expressions for the bolt forces are given in equation (1) and (2).

$$T_2 = T_1 \times \sin 45° \tag{1}$$

For 8-bolt configuration, the general expression for the furthest bolt force T_1 is found in equation (2) which is given as follows:

$$T_1 = \frac{M}{\left(2r + 4r\sin^2 45°\right)} \tag{2}$$

The bolt reaction forces obtained from conventional method may not be realistic as the effect of variation in flange thickness and diameter of bolt are not incorporated which is not justifiable from the rational point of view.

4. Details of Finite Element Method

4.1 Modeling Methodology

The typical configuration of the pipe joint is shown with different components labeled in figure 6. Due to symmetry of the pipe joint as shown in figure 6, only one side of the pipe joint has been modeled with appropriate boundary conditions. The flanged pipe joint is modeled using a finite element analysis software package ANSYS v.10. For the modeling of pipe, flange, contact surface, bolt; separate element has been used. For the pipe and flange modeling 8-nodded structural shell element, for the bolt shank linear spring element (resists both tension and compression equally), for contact surface nonlinear spring element (resists compression well but very much weak in tension) has been used. The following figure 7 shows the stress-strain behavior of contact springs and bolt shanks.

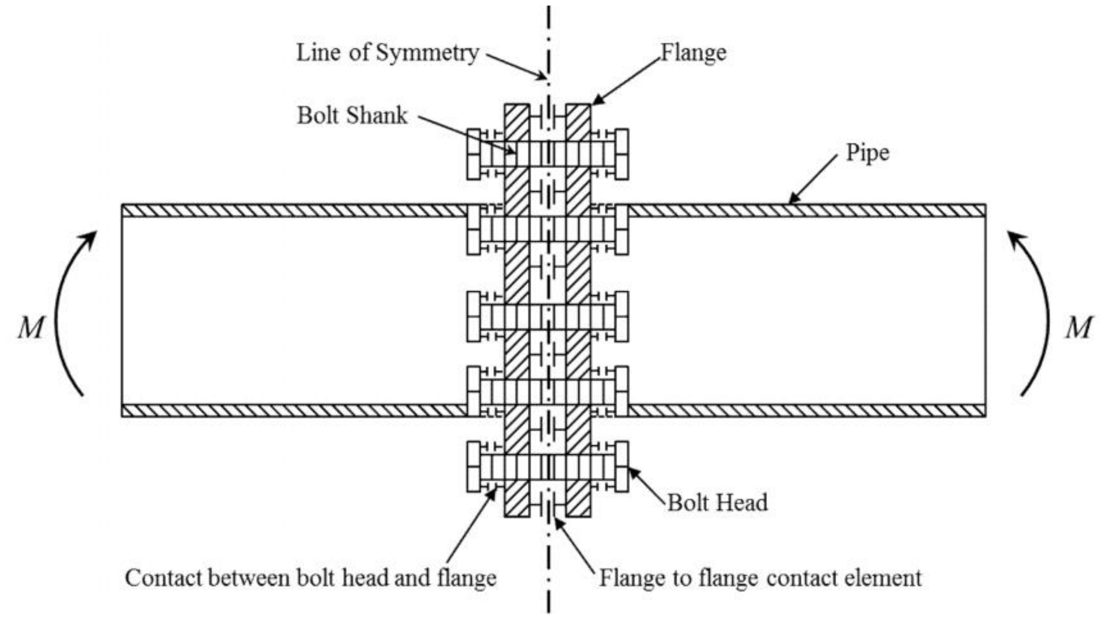


Fig. 6. Typical Configuration of 3D finite element model

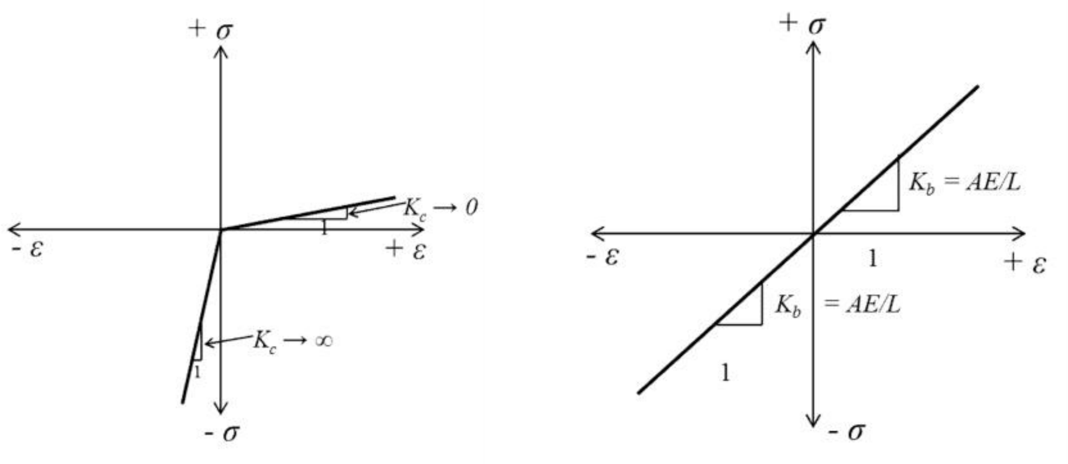
In bolted flanged pipe connection, the flanges are in contact with each other through a contact surface. When the flanged pipe joint is subjected to flexure, one side of the neutral axis is in compression causing bearing stress on the flange faces. Portion of the flange on the other side of neutral axis tends to move apart from each other since no tension can be developed between contact surfaces. This behavior is numerically simulated in FE analysis with the help of contact spring elements. These elements are assigned high stiffness in compression to simulate the bearing and very low stiffness in tension to simulate the separation of surfaces without requiring any force. Nonlinear spring element has been developed to generate similar type of contact in this model. On the other hand, linear spring elements are used to simulate the behavior of bolt shanks. The stiffness of the spring elements for bolts are taken as AE/L (where A is the bolts area, E is the Young's modulus and L is the bolt length) which is same both in tension and in compression (figure 7).

4.2 Meshing

For obtaining an optimal solution, a fine mesh in areas of high stress gradient and a coarser mesh in the remaining areas have to be used. Hence in this FE model, denser meshing has been done at pipe region near the flange which can be seen in the following figure 6.

4.3 Boundary Conditions

After modeling the flanged pipe joint structure, some boundary conditions are applied in the pipe joint. The free ends of the nonlinear spring elements, 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 horizontal movements are also obstructed on all bolt heads to simulate the actual condition in flanged pipe joint.



(a) (b)

Fig. 7. Stress- strain behaviour of (a) Contact Springs and (b) Bolt shanks

4.4 Loading

In case of application of load, the 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. In 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. The following figure 8 shows the finite element mesh of the flanged pipe joint with applied loading. After the load application, a nonlinear static analysis has been performed. The typical deflected shape of the pipe joint due to bending is shown in figure 9.

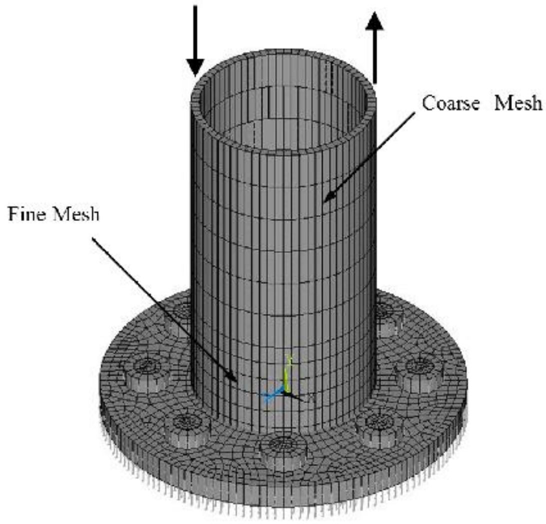


Fig. 8. Meshing of flanged pipe joint with applied loading

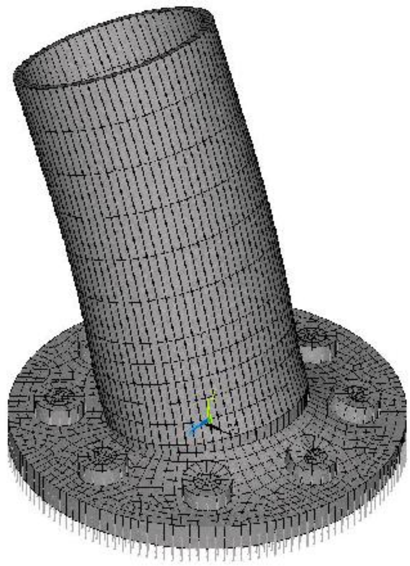


Fig. 9. Typical deformed shape of the flanged pipe joint due to bending

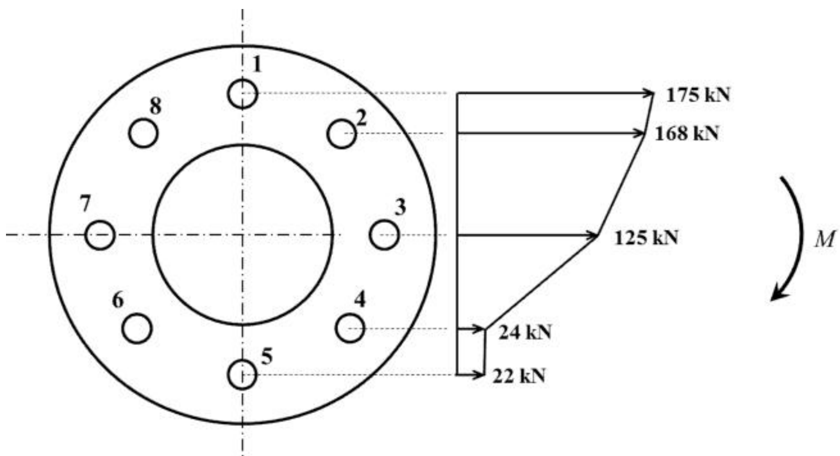


Fig. 10. Graphical representation of bolt forces of a pipe joint from FE analysis results

4.5 Distribution of Bolt reaction forces

This analysis has been done on eight AISC standard structural steel pipe sections of 275 MPa yield strength within a certain range of various parameters. The bolt reaction forces developed, due to initially applied clamping forces and bending, are obtained to get the value of maximum bolt force. Here all the parameters are limited to yield strength of A325 steel bolt that is 620.7 N/mm^2. The distribution of bolt reaction forces in flanged pipe joint (for pipe diameter = 158.78 mm, flange width = 90 mm, bolt diameter = 25.4 mm, flange thickness = 3 × pipe thickness, number of bolt = 8) has been shown in figure 10. From the following figure, it is clearly observed that the bolt reactions on bolt no. 4, 5 and 6 are tensile which are developed due to the initially applied clamping forces that induce tensile forces on those bolts.

From figure 10, it has been observed that maximum bolt force develops on bolt number 1. Apart from that, the same bolt reaction force has been developed on bolt no. 2 and 8 bolt no. 3 and 7, bolt no.4 and 6. It is to be noted here that minimum bolt tension develops on bolt no.5. More importantly, the maximum bolt force developed on bolt no. 1 is needed to be known for the safety of the pipe joint.

5. Comparison of Conventional and FEA method

A comparative study for maximum bolt reaction forces obtained from conventional method and finite element analysis (FEA) is shown graphically in figure 11 arranged according to various pipe diameters.

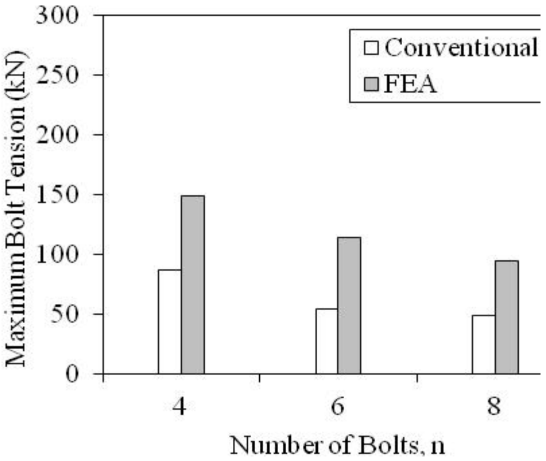
After observing the bar graphs of figure 11, it can be said that conventional method yields bolt tension values very small compared to the results found from FE analysis. It is also found that finite element results are about 1.2 to 2.4 times the bolt reaction forces predicted by conventional method. The conventional analysis formula, mentioned in equation (2), does not incorporate the effect of flange thickness and bolt diameter. It shows only the effect of diameter of pipe, flange width and number of bolts on bolt tension. Conventional analysis results can be used with certainty provided that flange thickness and pipe thickness are almost equal. For higher flange thicknesses, conventional analysis results are not reliable and may result in unsafe design. On the other hand, the effect of variation in flange thickness and bolt diameter has been incorporated in finite element analyses. The bolt reaction forces do not vary linearly from the centre of the pipe to the bolt location in finite element analysis which has been shown in figure 10. But in conventional method, the bolt reactions vary linearly which has been illustrated in figure 5.

6. Effects of different parameters on bolt force

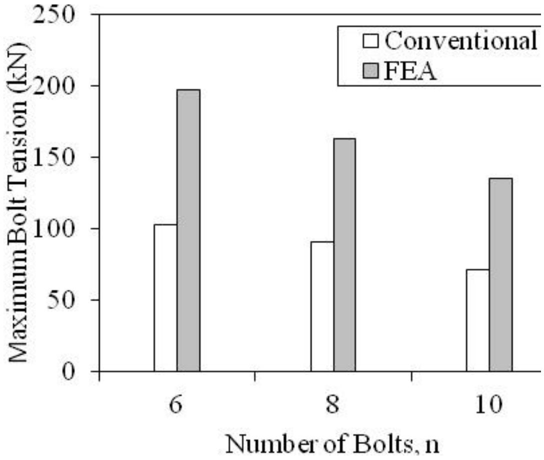
The results obtained from conventional method do not vary with flange thickness. But in finite element method, the bolt tension values depend on flange thickness, flange width, diameter of bolt which has been shown in the following graphs. The effect of number of bolts and flange thickness on maximum bolt reaction force has been shown in the following figure 12.

6.1 Effect of number of bolts

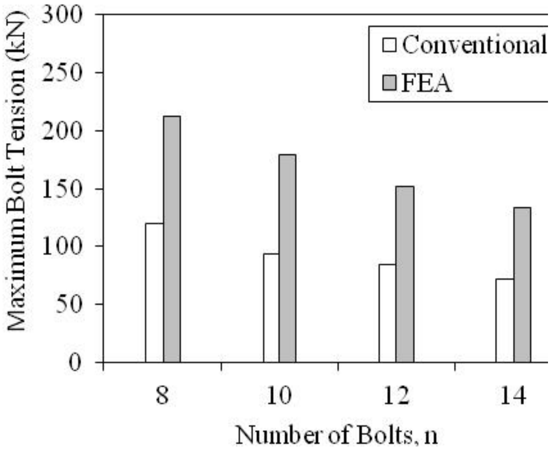
The curves, generated for maximum bolt force against number of bolts from the respective finite element analysis results and conventional calculations, are presented in figure 12. The trend lines of the curves are demonstrated a downtrend with a parabolic nature for increasing number of bolt under the study parameters. It is evident from the figures that bolt tension decreases with the increasing number of bolts as logically expected.



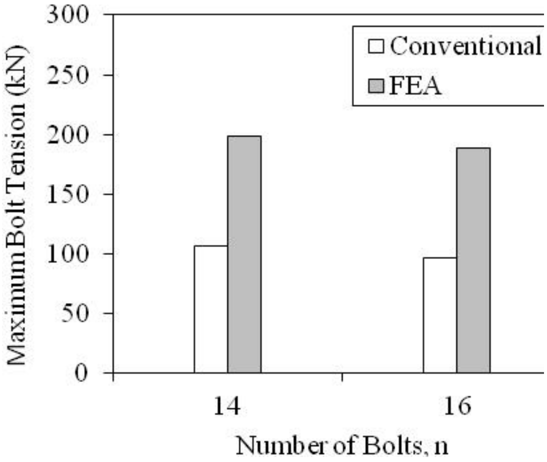
(a) For d_p = 102.26 mm, f_w = 90 mm, f_t / p_t = 3



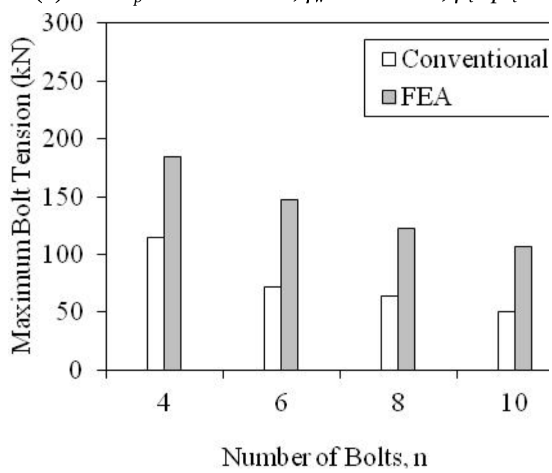
(b) For d_p = 128.194 mm, f_w = 110 mm, f_t / p_t = 3



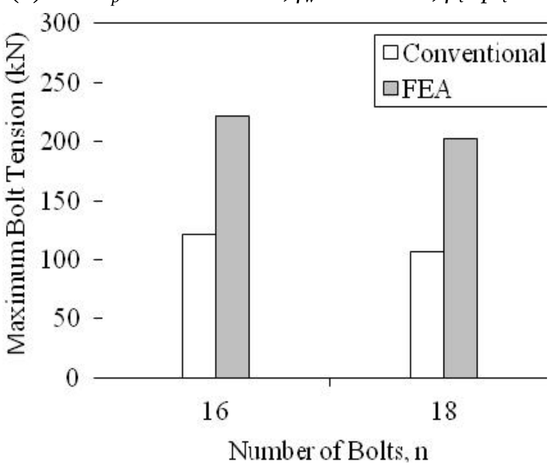
(c) For d_p = 158.78 mm, f_w = 130 mm, f_t / p_t = 4



(d) For d_p = 202.714 mm, f_w = 150 mm, f_t / p_t = 4

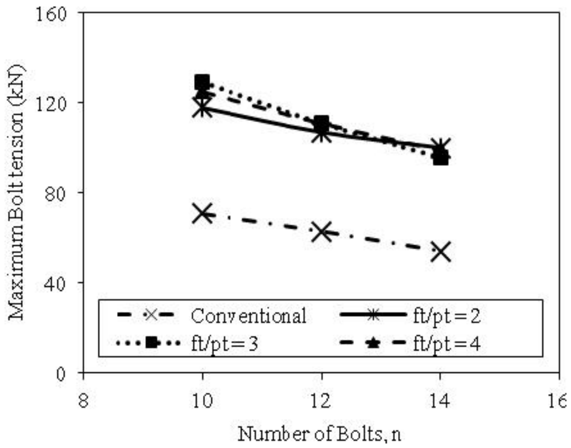


(e) For d_p = 254 mm, f_w = 150 mm, f_t / p_t = 2

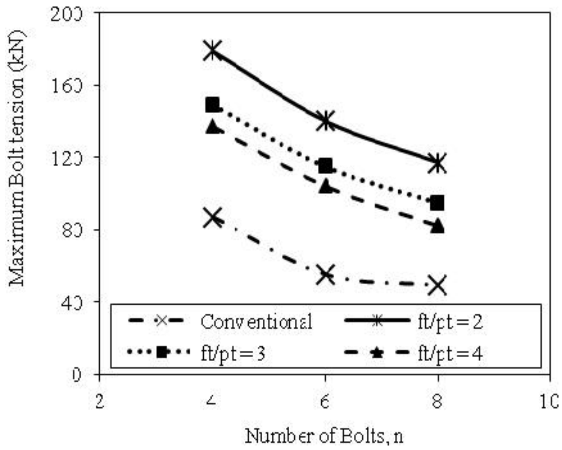


(f) For d_p = 304.8 mm, f_w = 150 mm, f_t / p_t = 2

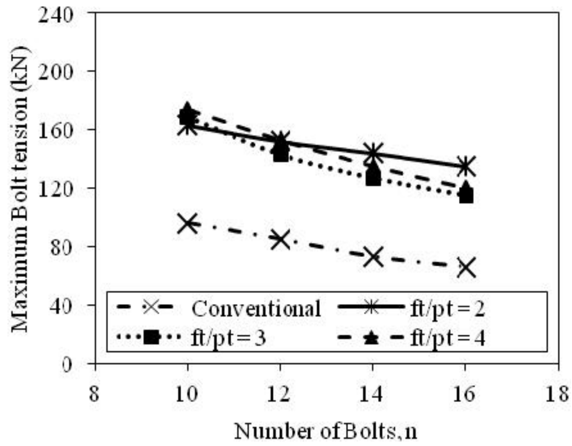
Fig. 11. Comparison for maximum bolt force using bolt diameter of 25.4 mm



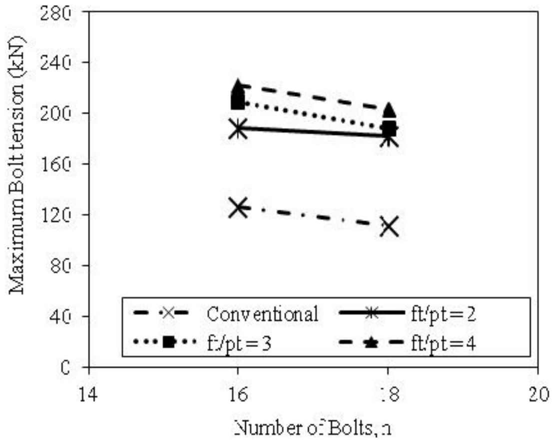
(a) For d_p = 102.26 mm, f_w = 90 mm, d_b = 25.4 mm



(b) For d_p = 158.78 mm, f_w = 110 mm, d_b = 19.05 mm



(c) For d_p = 202.717 mm, f_w = 130 mm, d_b = 22.225 mm

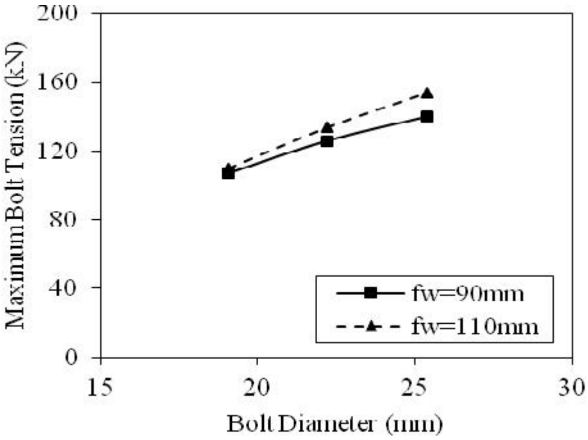


(d) For d_p = 304.8 mm, f_w = 130 mm, d_b = 25.4 mm

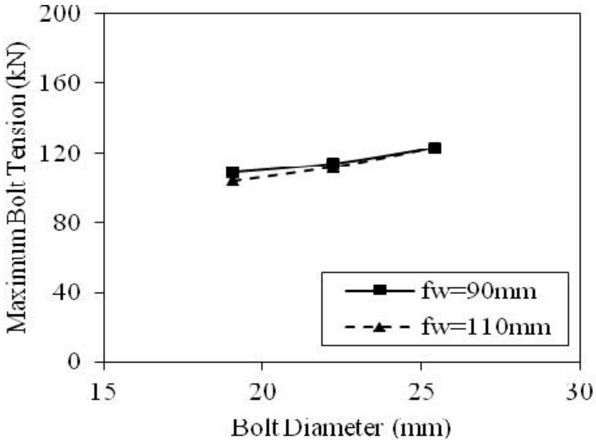
Fig. 12. Effect of number of bolts and flange thickness on bolt force for different diameter pipes.

6.2 *Effect of flange thickness*

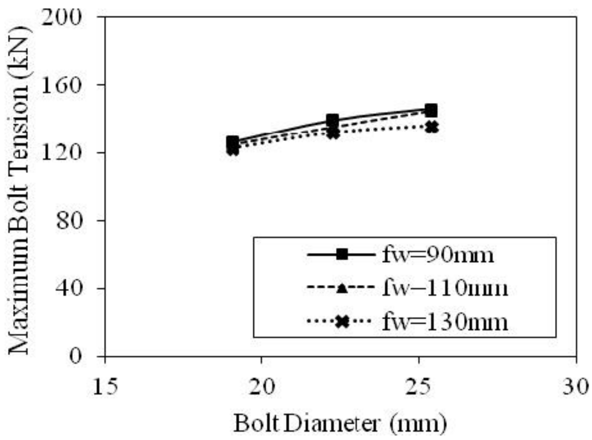
With reference to figure 12, it can be said that, bolt reaction force also depends on flange thickness. But it does not follow any particular trend. From the presented graphs, both increase and decrease in tension value have been observed in an irregular pattern when flange thickness is increased or 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. Generally, from the theoretical point of view, 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 forces are 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 developed bolt reaction forces are relatively small in case of thick flange. Moreover, the effect of diameter of bolt and flange width on maximum bolt force has also been shown in the following figure 13.



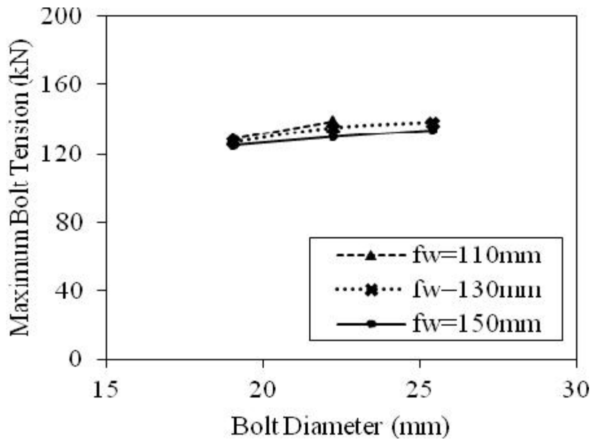
(a) For d_p = 128.194 mm, f_t / p_t = 2, n = 8



(b) For d_p = 128.194 mm, f_t / p_t = 3, n = 8



(c) For d_p = 158.78 mm, f_t / p_t = 4, n = 10



(d) For d_p = 202.717 mm, f_t / p_t = 4, n = 14

Fig. 13. Effect of flange width and diameter of bolt on maximum bolt force

6.3 Effect of diameter of bolt

With reference to figure 13, as the diameter of bolt increases, the developed bolt tension value also increases for any particular case of other parameters. This occurs mainly due to the fact that if the diameter of bolt increases, the stiffness of the bolt generally increases. As a result, a little more tension value develops on greater diameter bolts.

6.4 Effect of flange width

With reference to figure 13, it has been observed that bolt reaction force decreases with the increase in flange width in most of the cases. 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 in most of the cases. It has been noted here that there is a very small variation in bolt tension with the change in dimension of flange width. As a result it can be said that the flange width has a very small effect on bolt tension.

7. Conclusions

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

- The present study provides us with an opportunity to understand the behavior of a bolted flanged pipe joint subjected to bending.
- The effect of various parameters on the maximum bolt reaction force has been reflected in this study.
    a) Flange thickness affects bolt force in finite element analysis which the conventional analysis method cannot account for. The variation of maximum bolt force 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.
    b) In most of the cases, maximum bolt force decreases as flange width increases for any particular case of other parameters.
    c) The maximum bolt force increases as diameter of bolt increases for any particular case of other parameters.
- The bolt reaction forces obtained from conventional method are not practically suitable as the effects of variation in flange thickness and diameter of bolt are 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 bolt diameter 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 bolt diameter.
- Finally, it can be concluded that the research work is successful and helpful in obtaining the maximum bolt reaction force of flanged pipe joint which is subjected to bending.

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