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AN ANALYTICAL INVESTIGATION ON BOLT TENSION OF A FLANGED STEEL PIPE JOINT SUBJECTED TO BENDING MOMENTS

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ABSTRACT: *Apparently no analytical method is available to analyze the bolt tension in a flanged pipe joint subjected to flexure taking into account the actual stress distribution at the joint. Conventionally, a method similar to the flexural analysis of beam is sometimes applied on the assumption that bolt tension is proportional to the distance from neutral axis which is far from the actual stress condition. In this paper, an investigation has been carried out to find the effects of various parameters relating to flanged pipe joint connection, so that a definite guideline on determining the bolt tension can be developed. In addition, results are compared with the conventional analysis. To carry out the investigation, a flanged pipe joint subjected to bending has been modeled using finite element method, which also includes contact simulation. In this analysis, shell element has been used for the modeling of pipe and flange. Non-linear spring has been used to model contact surface and bolt. Non-linear finite element method has been used to find out results till failure by yielding of pipe. Joint has been subjected to ultimate moment and under this moment; the maximum bolt tension has been evaluated. Based on the study, an attempt has been made to present a guideline to find out bolt tension that is structurally effective for a flanged pipe joint. The whole process is carried out under various parametric conditions within certain range. It has been found that some parameters like flange thickness, width of flange and numbers of bolts have significant effect on effective bolt tension. Based on the results of the analysis, an empirical equation has been developed to determine the bolt tension for different number of bolts and flange thickness for different pipe diameter. It has been shown that, the suggested empirical equation is useful in structural analysis for calculating the effective bolt tension with reasonable degree of accuracy when the flanged pipe joint is subjected to external bending moment.*

KEY-WORDS: *Flanged Pipe Joint, Bending Moment, Bolt Tension, Conventional Analysis, Finite Element Modeling, Meshing.*

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1.0 INTRODUCTION:

Steel pipes are used in different structures as structural frame members. Pipes are usually connected through flanges using bolts. The joints are the weakest element in most structures. This is where the product leaks, wears, slips or tears apart. In spite of their importance, bolted flanged joints are not well understood. There are widely used design theories and equations for liquid transmission pipe joints, but these are not applicable in the design and construction of the pipe frame systems. When a pipe joint is subjected to bending or a moment acts on the pipe, tension is produced in the bolts. It is very important to determine the tension value of the bolt. Accuracy in determining the maximum bolt tension is a pre-requisite for the safe designing of structures having bolted flanged pipe joint.

The earliest method of calculation to receive wide attention was the so-called "*Locomotive*" method, (*The Locomotive*) generally credited to the late Dr. A.D. Risteen [1] (1905). Crocker and Sanford developed a method (Taylor-Waters, 1927; Discussion of paper by Waters and Taylor, 1927) whereby the flange is analyzed as a beam.

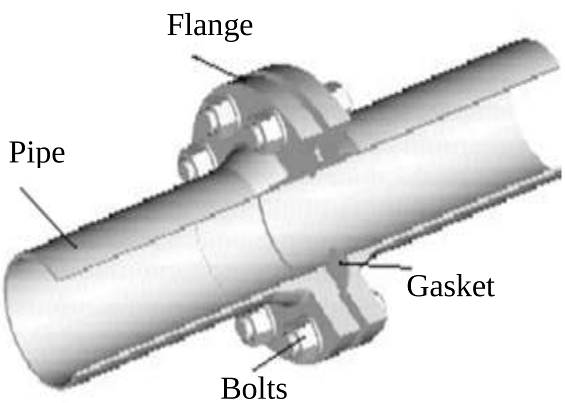

Figure 1: *A flanged pipe joint with different components.*

Waters and Taylor [2] (1927), in order to determine the location and magnitude of the maximum stress explored the stress conditions in a flange in the three principal directions - tangential, radial, and axial based on a combination of the flat plate and the elastically supported beam theories. In 1931, Holmberg and Axelson [3] wrote a paper in which they used the flat-plate theory in developing formulas for stresses in loose-ring flanges and in flanges made integral with the wall of a pressure vessel or pipe.

The above works however, are a number of decades old. It appears that, no significant work on this problem of flanged pipe joint is undertaken during the last few decades. Not much study had been conducted on this matter until study on this was carried out by Hwang and Stallings[4] in 1994.In their paper, 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. Very recently work of Choudhury [5] in 2006 and Choudhury et al [6] in 2008. Finite element analysis was performed for bolt tension in a flanged pipe joint varying parameters like pipe diameter, pipe wall thickness, flange thickness and flange width and then compared with conventional analysis procedure. But the analysis results have limited practical applicability because of not using standard pipe specifications for the analysis. Still, this work is a very important contribution since it is the first significant research which is directly related to bolt tension evaluation in a flanged pipe joint.

The aim of this paper, therefore, is to develop an appropriate 3D modeling of a flanged pipe joint and to investigate its behavior under appropriate geometric dimensions so as to ensure practical applicability.

2.0 CONVENTIONAL ANALYSIS

Bolt tension of a flanged pipe joint can be calculated by using the conventional linear distribution method based on the assumptions that bolt force vary linearly from the centroid of the flange which is analogous to the flexural stress calculation of beam section and force transfer occurs only through the bolts in the form of tension and compression. Force transmitted through the flange contact surface is assumed to be zero. Let us consider an example having 12 bolts in a joint as shown in figure 2.

Let us assume,

The pipe radius = r_i

The outer radius of flange = r_o

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The distance from the center of the pipe to the center of the bolt = r

If the flanged pipe joint is subjected to a moment M, then maximum bolt tension of the flanged pipe joint can be found by taking moment at the center of the pipe which gives the equation for maximum bolt tension as shown in equation 1:

$$T_1 = \frac{M}{2r + 4r\,(sin60°)^2 + 4r\,(sin30°)^2} - - - (1)$$

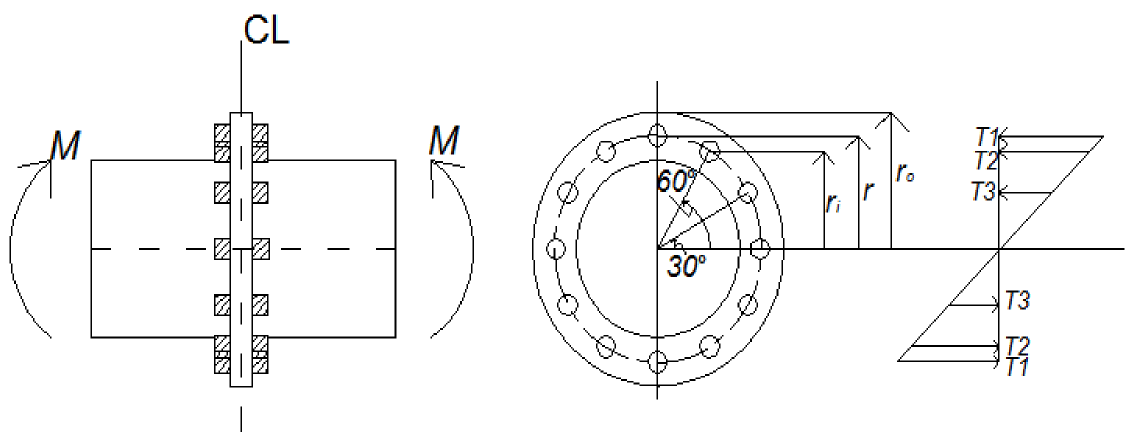

Figure 2: *Front & plan view with force distribution of a typical flanged pipe joint with 12 bolts*

By using this method, the maximum tension in a bolt can be determined for various pipe diameters and for different number of bolts. According to this procedure, maximum tension occurs in the bolt which is farthest from the center of the pipe. This equation (Eq. 1) has been derived assuming the number of bolts to be 12. For other number of bolts, similar equations can be derived.

The limitation of the conventional analysis lies in the fact that the effect of flange thickness cannot be incorporated in the equation. Also the assumption of transfer of compressive force through bolts is not a good one, since the sides of the pipe wall and contact surfaces of the flanges take bulk of the compression.

3.0 COMPUTATIONAL MODELING

For nonlinear analysis of flanged pipe joint, elasto-plastic material property is used. Though it costs more time, it gives more realistic results.

3.1 Finite Element Modeling

A schematic diagram explaining the configuration of flanged pipe joint for FE modeling with the bolt and contact surface is shown in figure 3.

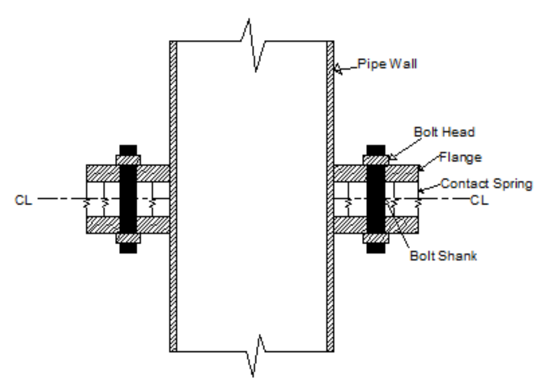

Figure 3: *A schematic diagram explaining the configuration of flanged pipe joint*

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Figure 4 shows a general sketch of the simplified model of flanged pipe joint that is used in the FE software. Due to symmetry, only one side of the joint is modeled with appropriate boundary conditions.

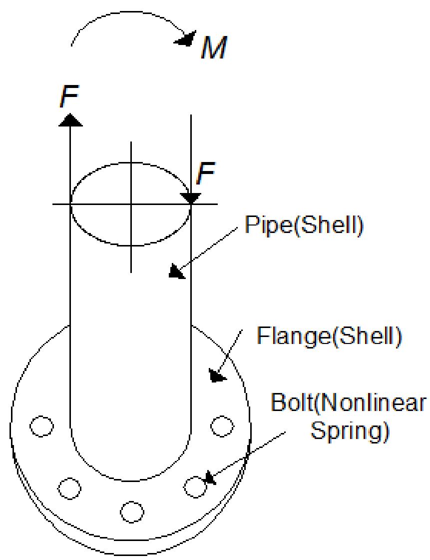

Figure 4: *General Sketch of the Flanged Pipe Joint Studied in this Paper*

3.1.1 Modeling of the Flanged Pipe Joint

For the modeling of pipe, flange, contact surface and bolts, separate elements have been used as outlined below.

3.1.2 Meshing of the Pipe and Flange

8-node structural shell elements have been selected for the meshing of pipe & flange. Pipe is divided along length and along periphery. Individual division is rectangular. Number of division is chosen in such a way that the aspect ratio of the element is reasonable. Mesh size is set as half of bolt diameter for flange & two-thirds the diameter of bolt for pipe. Smaller mesh size is used here to better represent the contact surfaces between flange and pipe as well as flange and bolt. For the mesh size chosen here, the solution converged at reasonable pace and results were consistent.

3.1.3 Properties of Contact Element

In the flanged bolted connection, the flanges are in contact with each other. Nonlinear contact element has been used in this model. Each node of the flange was extruded along the axis of the pipe, to generate contact element. Here the properties of the link element were such that they can resist compression and very weak in tension. This element develops compression normal to the plane of the flange.

Figure 5 shows the force - deflection behavior of contact springs. The value of K_c. is high and the value of K_t is very low. Here, K_c and K_t represents axial stiffness factor *(AE/L)* in compression and tension respectively.

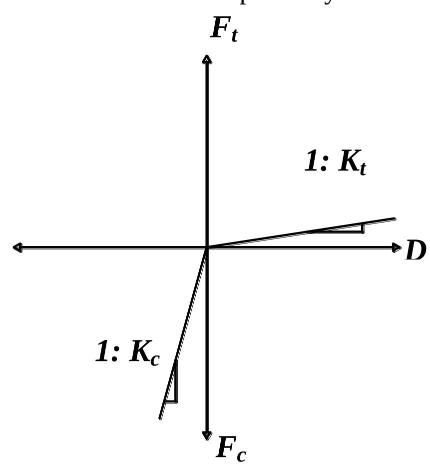

Figure 5: *Force - deflection behavior of contact springs.*

3.1.4 Modeling of Bolts

Spring elements were used to simulate the behavior of bolts. In this model, the link elements in position of bolts were assigned bolt properties. That is, these elements, representing the bolts, can resist both tension and compression. Figure 6 shows the force-deflection behavior of bolts. The value of both K_c and K_t are equal here. Here K_c and K_t represents axial stiffness factor *(AE/L)* in compression & tension respectively.

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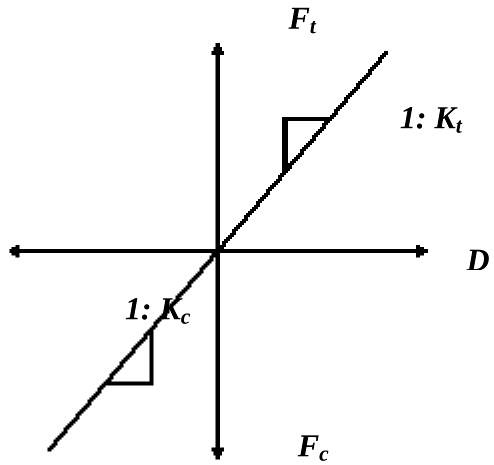

Figure 6: *Force – deflection behavior of bolts.*

3.1.5 Restraint:

The free ends of the contact element were restrained in all directions. This element does not have any bending capability. Therefore, to protect against sliding, the peripheral nodes of the flange were also restrained in horizontal direction. After meshing, the finite element model is shown in figure 7.

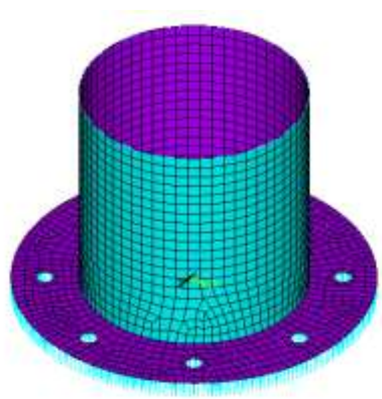

Figure 7: *Finite element mesh of a flanged pipe joint.*

3.1.6 Loading:

The joint is subjected to moment. In this model, the moment is applied by a pair of parallel and opposite forces representing a couple. The value of the coupling force gradually increased with each load step to reach the ultimate moment capacity of the steel pipe section.

3.1.7 Study Parameters:

The sample problems under investigation with the variable data within certain range are described in the table 1.

In the following figures (8,9,10 &11) some FEA results showing nodal strain & the three principal stresses are shown. It can be seen that stress concentration occurs in the location of bolt holes and also along the line of flange-pipe joint.

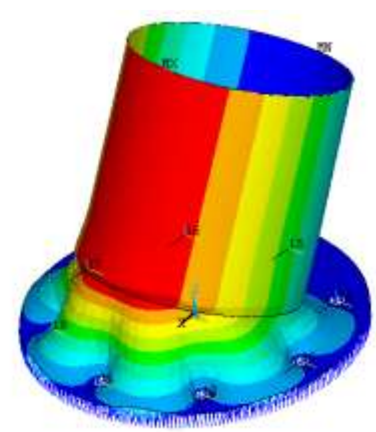

Figure 8*: Contour depicting nodal strain along with deformed shape*

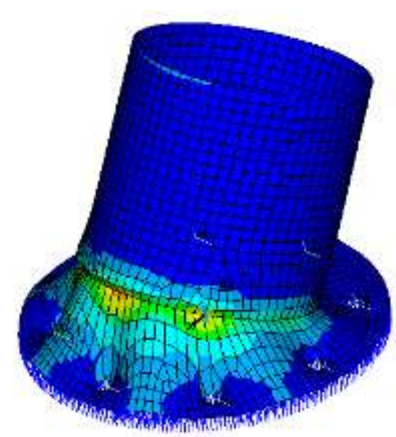

Figure 9: *Contour of 1st Principal Stress*

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Table 1: *Study Parameters [7, 8]*

Parameter	Reference Value
Pipe length(mm)	250
Pipe Sections (US Standard Weight Pipe)	AISC Standard Pipe Sections of 125,150,200,250&300mm nominal diameters
Flange width(mm)	75, 100 and 125
Number of bolts	4,6,8,10,12,14 & 16
Bolt diameter(mm)	20
Flange thickness	1 to 3 times of the pipe wall thickness
Poisson's ratio	0.30
Yield Strength (MPa)	275
Applied Moment	Ultimate Moment

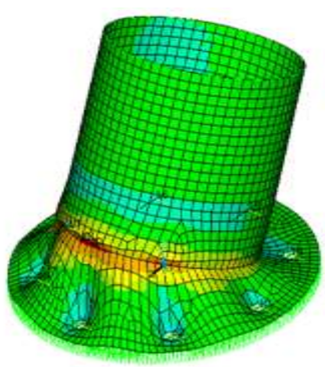

Figure 10: *Contour of 2nd Principal Stress*

4.0 RESULTS & DISCUSSION:

In the following graphs some of the FE Analysis results and corresponding conventional analysis results are shown. The legends *ft* and *pt* stands for flange thickness and pipe wall thickness respectively.

Figure 11: *Contour of 3rd Principal Stress*

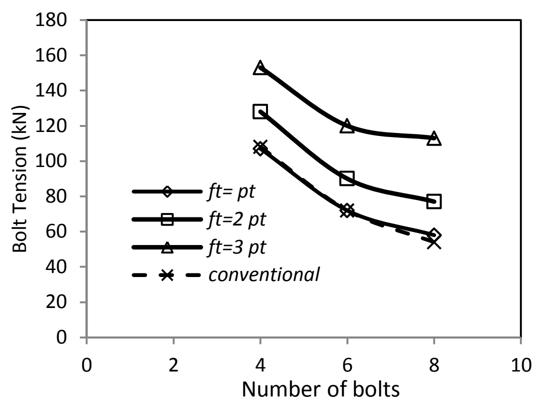

Figure 12: *Effect of number of bolts on bolt tension for 125 mm diameter pipe and 100 mm flange width.*

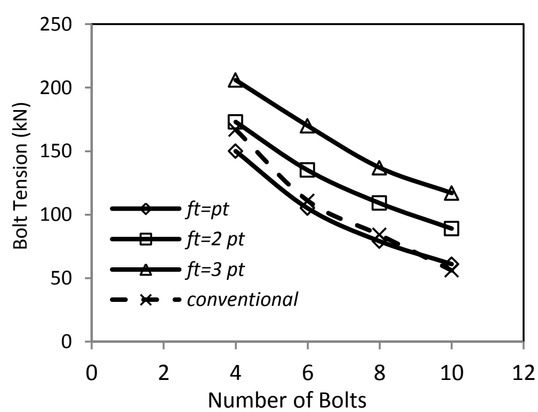

Figure 13: *Effect of number of bolts on bolt tension for 150 mm diameter pipe and 75 mm flange width.*

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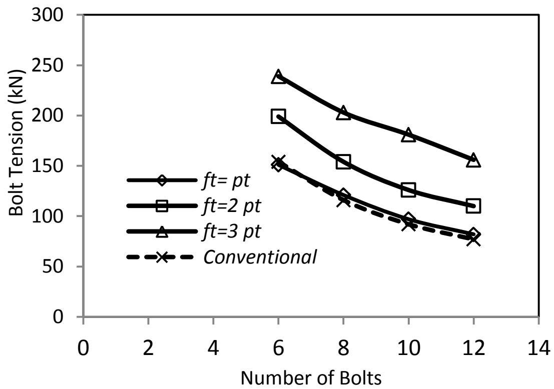

Figure 14: *Effect of number of bolts on bolt tension for 200 mm diameter pipe and 125 mm flange width.*

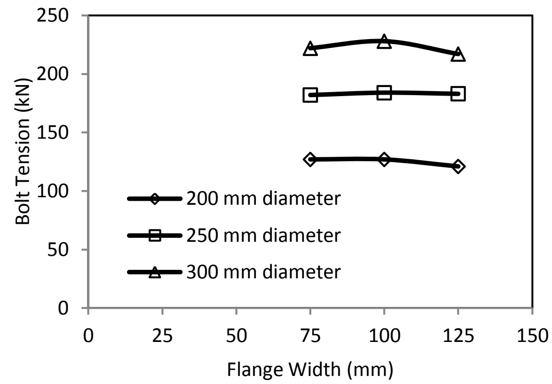

Figure 17*: Effect of flange width on bolt tension when number of bolts is 8 and* $f_t = p_t$.

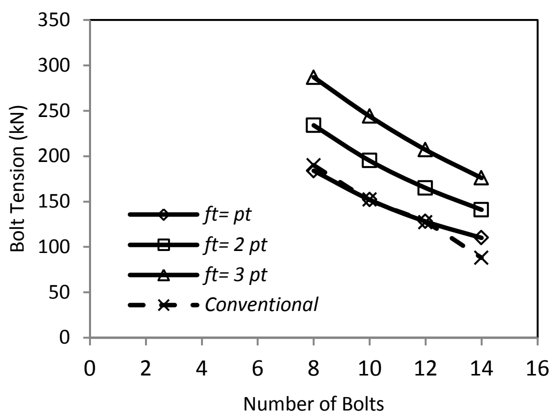

Figure 15: *Effect of number of bolts on bolt tension for 250 mm diameter pipe and 100 mm flange width*

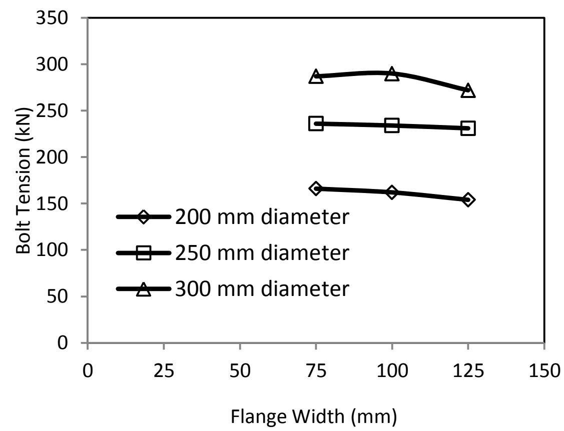

Figure 18*: Effect of flange width on bolt tension when number of bolts is 8 and* $f_t = 2p_t$

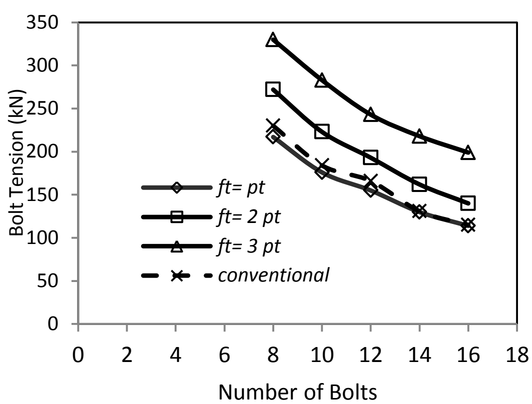

Figure 16*: Effect of number of bolts on bolt tension for 300 mm diameter pipe and 125 mm flange width.*

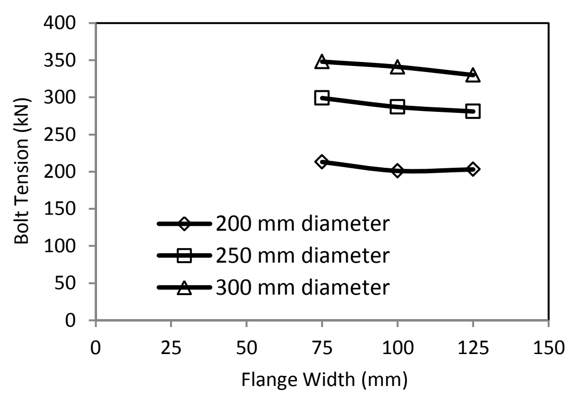

Figure 19*: Effect of flange width on bolt tension when number of bolts is 8 and* $f_t = 3p_t$

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4.1 Effect of Number of Bolts

For a flanged pipe joint, the effective bolt tension obtained for different number of bolts, pipe diameters (i.e. 125, 150, 200, 250 & 300 mm) and flange thicknesses have been investigated for flange width of 75 mm, 100 mm and 125 mm. The curves are generated for bolt tension against number of bolts obtained from respective finite element analysis results and conventional calculations. The trend lines of the curves demonstrated a downward trend with a parabolic nature for increasing number of bolts under the study parameters. It is evident from the figures (figure 12 to 16) that bolt tension decreases with the increasing number of bolts. This implies that, increasing number of bolts results in decreasing bolt tension as normally expected.

4.2 Effect of Flange Thickness and Flange Width

Flange thickness has significant effect on bolt tension. There is an upward shift in the bolt tension against the number of bolts curves with increase in flange thickness. That is, the bolt tension increases with the increase in flange thickness.

Bolt tension also depends on flange width. But the effect of flange width is not as pronounced as that of flange thickness in case of FE analysis as can be seen from figure 17, 18 & 19. Both increase and decrease in tension value have been observed at random when flange width is increased or decreased. This is observed in all cases of flange thickness to pipe wall thickness ratio.

4.3 Comparison between FE Analysis & Conventional Analysis

Number of bolts has significant effect upon bolt tension in case of a flanged pipe joint and it us observed that bolt tension decreases with increasing number of bolts. This fact is observed both in case of conventional and FE analysis.

But major deviation occurs from conventional to FE analysis when the effect of flange thickness is taken into account. When the flange thickness and pipe thickness are equal, the results are almost similar for both types of analysis with little discrepancies. But when flange thickness is greater than pipe thickness, FE analysis shows increasing trend of tension values. The conventional analysis formula cannot take into account the influence of flange thickness. It only shows the effect of number of bolts and flange width. As a result, considerable variation in bolt tension value occurs when flange thickness is much higher than pipe wall thickness. In fact when flange thickness is three times pipe thickness, sometimes the FE analysis value exceeds twice that of conventional analysis value.

The increase in flange width for a particular case of pipe diameter and bolt number causes reduction in bolt tension according to the conventional analysis. However, as stated in the previous article, FE analysis shows random increase and decrease in bolt tension with increasing flange width and generally the effect of flange width on bolt tension is not that pronounced in FE analysis.

Summing up the study results, it is conclusive that, number of bolts, flange thickness and flange width are the three parameters, which influence bolt tension for a flanged pipe joint. 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. The bolts subjected to maximum tension may fail due to overstress long before the pipe section reaches its ultimate moment, it is designed to resist. For example, 20 mm diameter A325 structural bolts have ultimate tensile capacity of 194 kN. It becomes quite apparent that on a number of occasions especially, for higher flange thicknesses, the pipe may not be able to reach its ultimate capacity because of bolt failure in tension. In these cases either number of bolts or the diameter of the bolts needs to be increased.

5.0 DEVELOPMENT OF A PROCEDURE FOR DETERMINING BOLT TENSION

Since the fact that, conventional method for evaluating bolt tension is not reliable when flange thickness is greater than pipe wall thickness, hence the significance for development of a procedure for determining bolt tension which will predict the maximum bolt tension with reliability.

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An equation (Eq. 2) is developed that evaluates the maximum bolt tension due to bending in a flanged pipe joint. This equation is obtained by rigorous hand trials and also by using statistical software. The trends of the analysis results were observed meticulously to figure out the parameters of major influence. The equation is thus developed to simulate the FE results. Variables of this equation are taken as pipe nominal diameter, flange thickness, pipe wall thickness, flange width and number of bolts. This equation is based on analysis results of steel pipe with 275MPa yield stress and 20 mm bolt diameter. The equation is suggested as follows:

$$T = \frac{1}{2}d^2 + \frac{300}{d} f_t^{\,2} f_w + 3000\, b^k ----(2)$$

Where,

T = Maximum Bolt tension in Newton.

f_w = Flange width, $(75 \le f_w \le 125)$, mm.

d = Nominal Pipe diameter $(125 \le d \le 300)$, mm.

n = Number of bolts $(4 \le n \le 16)$.

f_t = Flange thickness (1-3 times pipe wall thickness)

p_t = pipe wall thickness

$$b = \frac{\sqrt{f_t}\, p_t^{\,1.5}}{n}$$

k= refer to table 2.

5.1 Comparison of Bolt Tension Values

In the following graphs (figure 20 through 24) comparison between bolt tension values obtained by conventional analysis, FE analysis and the suggested equation is depicted according to various pipe diameter and flange width.

Table 2: *Values of k to be used in the above proposed equation*

f_w (mm)	f_t /p_t	k				
		d=125mm	d=150mm	d=200mm	d=250 mm	d=300 mm
75	1	1.51	1.55	1.62	1.65	1.68
	2	1.30	1.21	1.47	1.45	1.49
	3	1.10	1.02	1.40	1.31	1.39
100	1	1.45	1.46	1.61	1.64	1.53
	2	1.20	1.28	1.44	1.51	1.51
	3	0.97	1.10	1.31	1.43	1.49
125	1	*	*	1.57	1.64	1.53
	2	*	*	1.40	1.48	1.49
	3	*	*	1.20	1.35	1.39

*these combinations of parameters were not considered for study

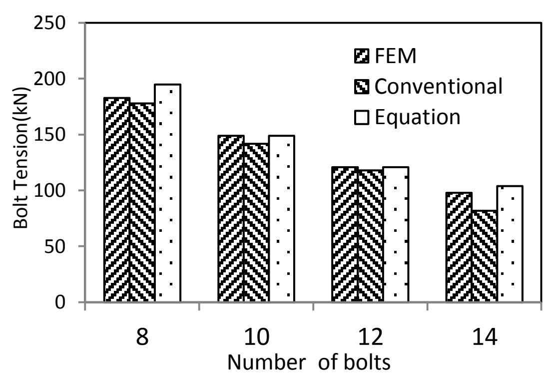

Figure 20: *Bolt Tension in 250 mm diameter pipe when flange width is 125 mm* ($f_t = p_t$).

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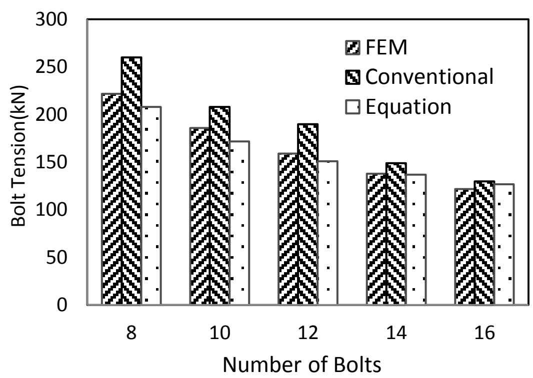

Figure 21: *Bolt Tension in 300 mm diameter pipe when flange width is 100 mm ($f_t = p_t$).*

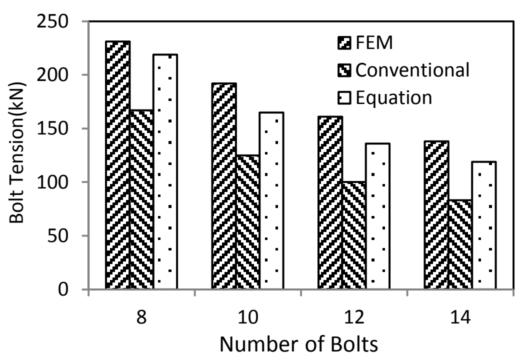

Figure 22: *Bolt Tension in 250 mm diameter pipe when flange width is 125 mm ($f_t = 2p_t$).*

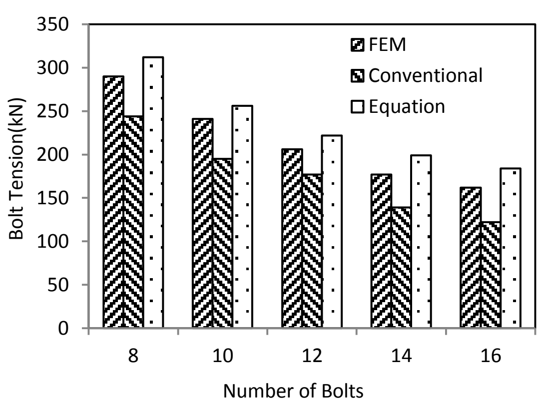

Figure 23: *Bolt Tension in 300 mm diameter pipe when flange width is 100 mm ($f_t = 2p_t$).*

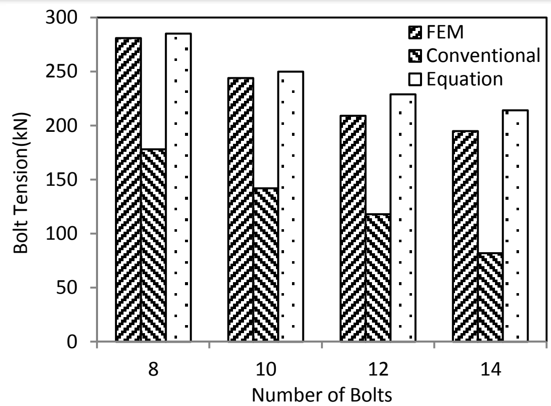

Figure 24: *Bolt Tension for 250 mm diameter pipe when flange width is 125mm ($f_t = 3p_t$).*

From the graphs (figure 20 through to 24), it is observable that the values obtained by the proposed equation are in good agreement with the corresponding FE analysis results with minor discrepancies. Hence this equation can be used with reliability when the parameter values are within the specified limit.

6.0 CONCLUSION

The aim of this study is to investigate the behavior of steel flanged pipe joint with bolted connection in bending. It has been found that, bolt tension decreases with increasing number of bolts. With increasing pipe diameter the bolt tension (for any particular case of flange width, number of bolts and flange thickness) increases. The variation of bolt tension with flange width does not follow any particular pattern. Bolt tension increases with increase in flange thickness and this increase is significant when flange thickness is 2-3 times of pipe wall thickness. In these cases, the tension values obtained by conventional analysis may result in unsafe design of flanged pipe joint.

Based on the analysis results an empirical equation has been developed to conveniently determine the maximum bolt tension in a bolted flanged pipe joint. For the values of various parameters within the range specified in article 5, this empirical equation is concordant with the FEA results.

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