Analysis of Bolted Joints with Different Bolt Patterns Using Non Linear Finite Element Analysis

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Abstract

In this paper the numbers of bolt patterns were designed and analyzed by using non linear finite element method. The advantages of replacement of welded joints by bolted joint in supporting structure of pressure vessel were also explained. On bolted joints axial or tensile load is acting. Numerical study was conducted on several T-Stub connections to study the effect of the bolt pattern configuration on performance of the connection. The various types of bolt patterns such as circular, rectangular, inline were designed and analyzed with careful FEA. For bolting design the requirement of material and structural strength was according to ASTM. After successful completion of FE analysis the most appropriate bolt pattern was that safe in axial load condition. Numerical results of the rectangular bolt pattern connection were compared with remaining bolt pattern connections. The outcomes of this study show that the rectangular bolt pattern can improve the moment capacity, minimize the stress and plate separation of the end plate connections. This shows that failure is minimum for rectangular bolt pattern connection. The experimental results were compared with FEA results. The result achieved from the FE analysis and experimental shows close agreement.

Keywords – *End plate connections, bolt spread pattenrs.*

1. Introduction

Typically in pressure vessels, Welded joint is preferred for connections in the support structures. However significant events like northridge earthquake demonstrated that many unexpected failures occurs on numerous fully-welded beam-to-column connections as shown in Figure 1.1. Lot of welded steel moment frame structures sustained brittle fractures in their welded moment connections, which demonstrated in no uncertain terms the vulnerability of welded connections to seismic loading. Brittle fracture in column webs, column flanges, welds and shear tabs were reported. Cracks were initiated at welding roots and then extended into the column web and/or flange. The welding of stiffeners is very expensive. Therefore, unbraced connections are applied to an increasing degree. Unfortunately, they have the property of being much more deformable than stiffened connections. These deformations can affect the load-carrying behaviour of frames significantly. As a consequence, the deformability has to be taken into consideration as pointed out. Also the welded connections cannot be dismantaled. Hence it is not feasible to use them in portable pressure vessels. However the bolted endplate connections offer these flexibilities and they can withstand the local buckling also. Also it is compulsory to use them in portable pressure vessels because they can be dismantled. Hence there is need of replacing welded joints by the bolted joints for the supporting structure of pressure vessels.

In frame analysis, the physical model of a connection in the sense of a macro element can be a spring representing a bending moment. Its properties are given by the moment versus rotation curves of the connection. The analysis of the nonlinear load-carrying behaviour of structures with respect to the design process is feasible only when the finite element method is applied. Consequently, it is logically consistent to apply this powerful tool for the investigation of all members of a structure in order to develop a conclusive design method

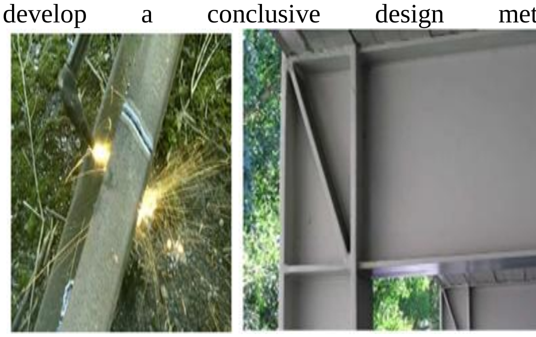

Fig.1.1 Welded Joints in Supporting Structures

Among the moment resisting bolted connections, the extended end-plate connections with the available beam sections are the most popular types of the bolted connections because of its fabrication simplicity, good overall performance and cost effectiveness compared with other connection type. The extended end plate moment connection presents a number of advantages over the more conventional welded flange moment connection. Although numerous studies have been conducted on the behavior of these connections and only the limited attention has been drawn towards the configuration of the bolt patterns, end-plate deformation, and their effect on the bolt-force distribution and overall connection performance. On bolted joints and flanges tensile or axial load is acting due to wind, internal pressure and self weight including all piping connections and vessel weight. This will be a critical phenomenon and will need careful FEA for determining safety of the bolted joint.

2. Literature Review

A detailed review of the literature on the analysis of bolt pattern and its significance on strength characteristics of supports is presented below.

Maggi et.al [1] presented and discussed results of parametric analyses on the behavior of bolted extended end plate connections using Finite Element (FE) modeling tools. Comparisons between numerical and experimental data for moment-rotation curves, displacements of the end plate, and forces on bolts showed satisfactory agreement. The results presented herein show that failures associated with either formation of yield lines in the plate or bolt tension failure are well-defined, while failures due to combinations of these mechanisms represent levels of interaction between the end plate and bolts that are difficult to predict accurately.

Shi et al. [2] studied eight full-scale structural steel beam-to-column end-plate moment connection under earthquake loading in order to investigate the influences on the connection moment capacity, rotational stiffness, rotational capacity and hysteretic curves. He concluded the end-plate connection extended on both sides can improved the strength, joint rotational stiffness, ductility and energy dissipation capacity required for use in seismic force moment resisting frames.

Chasten et al. [3] conducted seven tests on large extended unstiffened end-plate connection with eight bolts placed in two rows across the end-plate at the tension flange (four bolts wide). In this study, the end-plate connections were designed to resist 50-70% of the beam plastic moment capacity. Both snug and fully tensioned bolts were used in the testing. At least one connection failed by bolt fracture, weld fracture, or plate shear fraction. The experimental results led to concerns for bolt prying forces and end-plate shear forces. Finite element analysis was used to predict the bolt forces and to predict the magnitude and location of the prying forces.

Sumner [4] investigated the performance of eleven cyclically loaded extended end-plate bolted connection. The experimental results demonstrate that a properly designed and detailed extended end plate moment connection can be use in seismic force resisting moment frames. He suggested a strong column, strong connection and weak beam design philosophy should be utilized.

Fleischman et al. [5] studied the effect of partially (snug-tight) and fully pre-tensioned bolts on the performance of the top-and-seat-angle and extended end-plate connections. They concluded that the snug-tight connection for multiple bolt rows behaved similar at moderate loads, and ultimate strength was the same for either cases. Snug –tight connections actually behaved stiffer during the course of reversal loading.

Piluso and Rizzano [6] studied the behavior of the 28 T-stubs with two high strength bolts. The scope of their research was to extend the design method so called component approach presented in Eurocode 3 and develop a numerical method for modeling and analyzing the T-stubs under monotonic and cyclic loading. The displacement control load was applied to the specimens with both constant and increasing amplitude. The degree of accuracy of the proposed models showed a good agreement with the experimental results in terms of energy dissipation capacity.

Grundy et al. [7] conducted two experimental tests on the extended end-plate connections. They used two rows of four bolts (eight total) to design an end-plate and bolt system that provides a moment capacity greater than the plastic moment capacity of the beam being connected. They concluded that the end-plate bolted connections are prone to non-ductile failure, whether the end-plate is thick or thin, and regardless of the available theory used in design.

Kukreti et al. [8] presented the results of their investigation conducted on the behavior of the stiffened moment end-plate with two rows of bolts inside and outside the beam tension flange. Finite element was used to model the tension flange. For

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simplification, the tension flange and the end-pate at the tension flange was assumed to have similar behavior as a stiffened T-Stub (tee-hanger). They also conducted a parametric analysis to develop an empirical equation to predict the behavior of the endplate connections.

3. Design and Finite Element Analysis

3.1 Types of bolt patterns

Here the several bolt pattern configurations were proposed and finite element models were developed and analyzed using ANSYS software within the range of force 100 KN to 300 KN by varying the parameters like distance between the bolts and angle between the bolts. Until now it is seen that no studies have been conducted on the effect of the configuration of the bolt pattern on overall connection behavior. The focus is to investigate the behavior of the extended end-plate bolted connections with inline, rectangular and circular bolt patters and to find out the most suitable bolt pattern. The bolt patterns are produced on the tension flanges and two such tension flanges are joined with the bolts to create physical model of bolted end plate connection. The plate separation and stress produced due to applied load has to study.

The bolt pattern was selected from regular geometric shapes to simplify the design as well as fabrication process. Figure 3-1shows the regular geometric shapes that were proposed, modeled, analyzed and tested in this study.

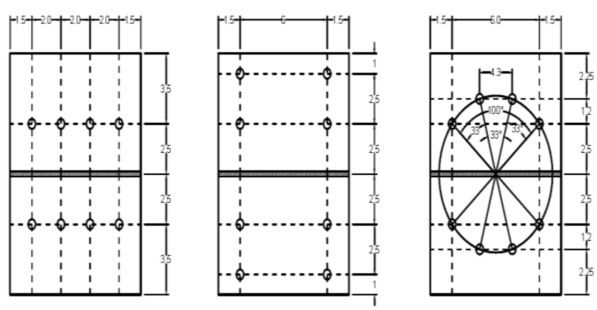

Figure 3-1 Bolt Pattern Configurations, (a) Inline, (b) Rectangular, (c) Circular.
(All dimensions are in centimeters)

Figure 3-1(a) inline bolt pattern, Figure 3-1(b) shows the connection with the traditional rectangular bolt pattern, Figure 3-1(c) shows the circular bolt pattern.

3.2 Meshing

Finite element method reduces degrees of freedom from infinite to finite with the help of Discretization or meshing of entire domain or physical model. Meshing is an integral part of the computer-aided engineering simulation process. The mesh influences the accuracy, convergence and speed of the solution. Various types of elements like 1D, 2D, 3D, mass, spring, damper, gap etc. are available for meshing, one has to select them depending upon the geometry, size and shape of the component, type of the analysis to be carried out and time availability for completion of project and the results were compared with experimental values for convergence requirements. Figure 3.2 shows meshed model of in line pattern.

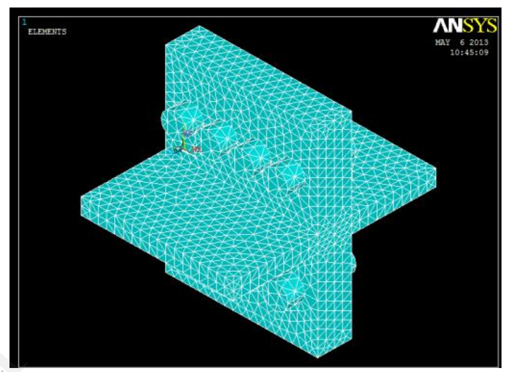

Figure 3.2 Meshed Model of Inline Pattern

3.3. Analysis Approach

Here in this analysis approach only the tensile load is applied on the connections. Total 45 analyses has been done for this approach, out of that 15 analyses for inline bolt pattern, 15 analyses for rectangular bolt pattern and 15 analyses for circular bolt pattern were carried out. The tensile load acting on the connection is varied between 100KN to 300KN.

1. Model

The three types of models which are used for tensile load analysis are as follows,

a) Bolted End Plate Connection with Inline Bolt Pattern

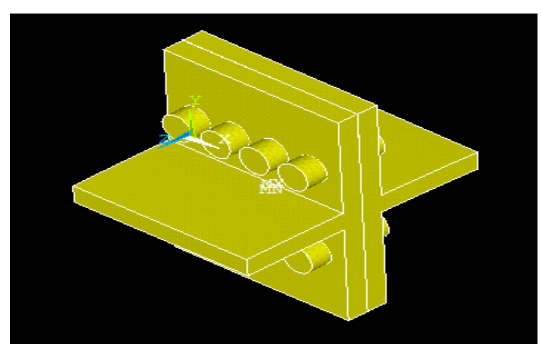

Figure 3.3 Bolted End Plate Connection with Inline Bolt Pattern for Tensile Load Analysis

Figure 3.3 shows the model of inline bolt pattern which is used for analysis. Total 15 analyses have been carried out on this model by changing the position of bolts with reference to horizontal axis and by changing the load from 100KN to 300 KN with the sub step of 50 KN. Initially the vertical distance of these bolts from the horizontal axis is 25 mm which changes to 30 mm and 35 mm.

b) Bolted End Plate Connection with Rectangular Bolt Pattern

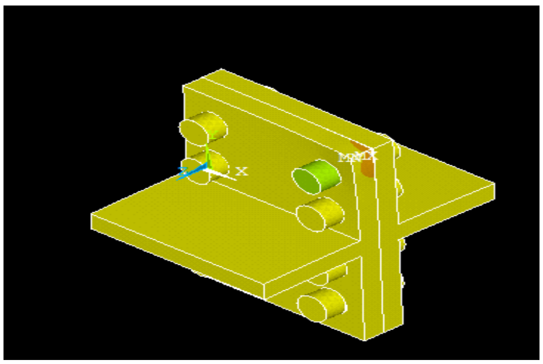

Figure 3.4 Bolted End Plate Connection with Rectangular Bolt Pattern for Tensile Load Analysis

Figure 3.4 shows the model of rectangular bolt pattern which is used for analysis. Total 15 analyses have been carried out on this model by changing the horizontal distance between the bolts and by changing the load from 100KN to 300 KN with the sub step of 50 KN. Initially the horizontal distance between the bolts is 60 mm which changes to 40 mm and 25 mm.

c) Bolted End Plate Connection with Circular Bolt Pattern

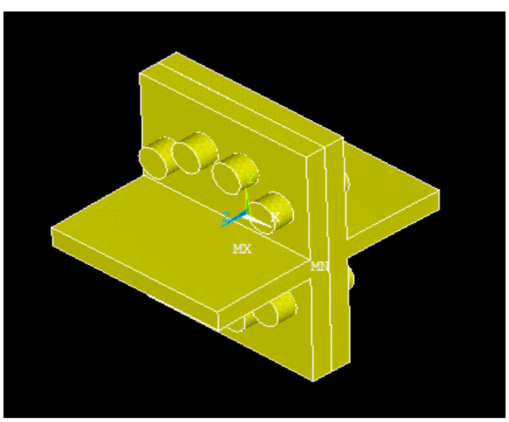

Figure 3.5 Bolted End Plate Connection with Circular Bolt Pattern for Tensile Load Analysis

Figure 3.5 shows the model of circular bolt pattern which is used for analysis. Total 15 analyses have been carried out on this model by changing the angle between the bolts and by changing the load from 100 KN to 300 KN with the sub step of 50 KN. Initially the angle between the bolts is 32^0 which changes to 33^0 and 34^0.

3.4 Boundary Condition

On the physical model of end plate bolted connection, the tensile load is acting due to self weight of pressure vessel including all piping connections. So that it is required to fix the one end of web of the model and apply the load on the other web which is opposite to fixed one as shown in figure 3.6. The maximum load acting on the connection is 300 KN. For analysis purpose the load acting on the connection is varied between 100 KN to 300KN with the sub step of 50 KN for doing the iterations for accuracy in the results. Same boundary conditions are applied for inline, rectangular and circular bolt patterns.

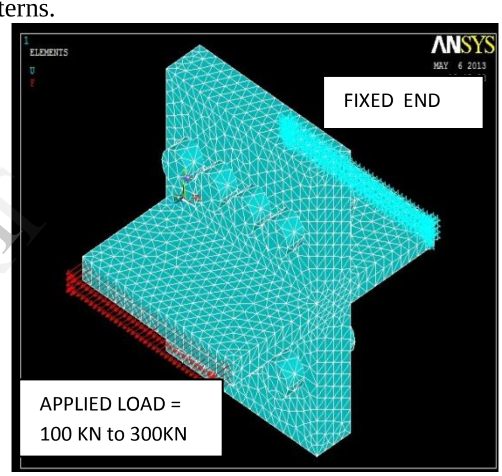

Figure 3.6 Boundary Conditions for Tensile Load Analysis

3.5 Result figures

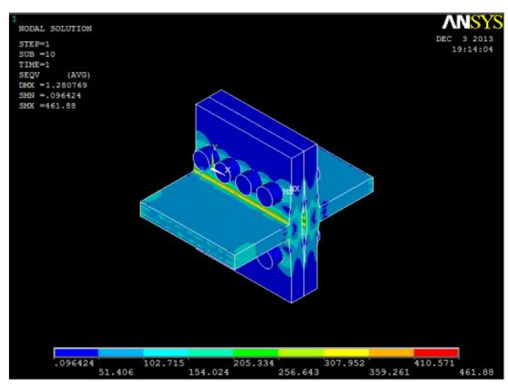

Figure 3.7 Equivalent Stress and Deformation for the Inline Bolt Pattern for the Vertical Distance of 25 mm and Load of 300 KN for Tensile Load

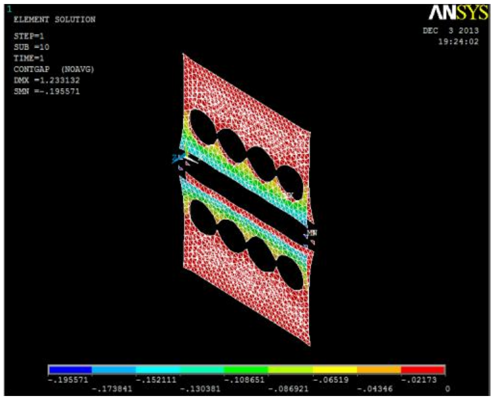

Figure 3.8 Plate Separation for the Inline Bolt Pattern for the Vertical Distance of 25 Mm and Load of 300 KN for Tensile Load

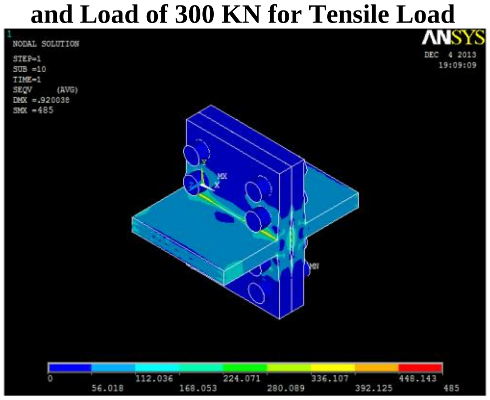

Figure 3.9 Equivalent Stress and Deformation for the Rectangular Bolt Pattern for the Horizontal Distance of 60 mm and Load of 300 KN for Tensile Load

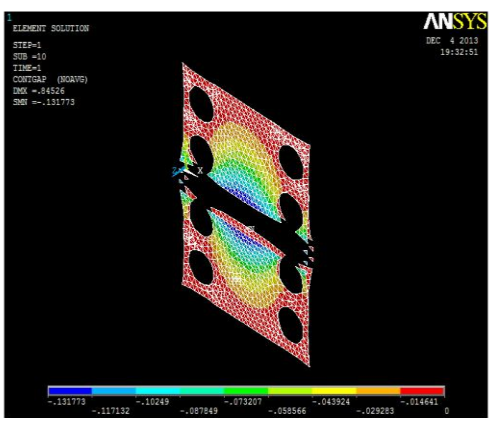

Figure 3.10 Plate Separation for the Rectangular Bolt Pattern for the Horizontal Distance of 60 mm and Load of 300 KN for Tensile Load

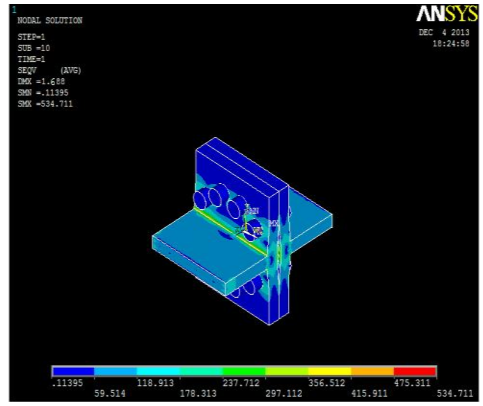

Figure 3.10 Equivalent Stress and Deformation for the Circular Bolt Pattern with Angle Between Bolts 34^0 and Load of 300 KN for Tensile Load

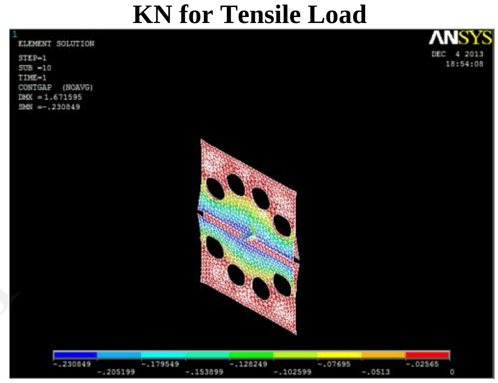

Figure 3.12 Plate Separation for the Circular Bolt Pattern with Angle Between Bolts 34^0 and Load of 300 KN for Tensile Load

4. Results and plots

Total 45 analyses has been done for the tensile load. Out of which the 15 analyses were done for inline bolt pattern, 15 analyses were done for rectangular bolt pattern, 15 analyses were done for circular bolt pattern. Here the main objective in the analyses is to find out the contact gap distance i.e. the plate separation and maximum equivalent stress. The results of these analyses are explained below.

1. In Line Patterns

Table 4.1 Results of Inline Bolt Pattern Analyses for Tensile Load

	IN LINE L1=25		IN LINE L2=30		IN LINE L3=35	
Load (KN)	**Plate separation (mm)**	**Max Stress (MPa)**	**Plate separation (mm)**	**Max Stress (MPa)**	**Plate separation (mm)**	**Max Stress (MPa)**
100	0.3174	150	0.4806	166.5	0.6927	193.6
150	0.4949	205	0.7766	249	0.9931	302
200	0.6988	270.46	1.122	323	1.3267	357
250	0.9393	343.2	1.5300	413	1.7412	491
300	**1.2331**	**461.88**	**1.9830**	**510**	**2.1987**	**608**

Table 4.1 shows the plate separation and equivalent stress for the inline bolt pattern for the vertical distance of the bolts of 25 mm, 30 mm and 35 mm for the load of 100 KN to 300KN. The minimum plate separation = 1.2331 mm and stress = 464.8 MPa for the maximum load of 300 KN is obtained for bolt pattern with the vertical distance of 25 mm.

2. Rectangular Patterns

Table 4.2 Results of Rectangular bolt pattern analyses for Tensile Load

	R1=60		R2=40		R3=25	
Load (KN)	**Plate separation (mm)**	**Max Stress (MPa)**	**Plate separation (mm)**	**Max Stress (MPa)**	**Plate separation (mm)**	**Max Stress (MPa)**
100	0.2275	164	0.2423	168	0.3233	171
150	0.3547	235.2	0.3738	237	0.5088	246
200	0.4988	312.9	0.5270	325	0.7180	329
250	0.6640	396	0.6966	397	0.9644	420
300	**0.8452**	**485**	**0.8952**	**489**	**1.26**	**499**

Table 4.2 shows the plate separation and equivalent stress for the rectangular bolt pattern for the horizontal distance between the bolts of 60 mm, 40 mm and 25 mm for the load of 100 KN to 300KN. The minimum plate separation 0.8452 mm and stress = 485 MPa for the maximum load of 300 KN is obtained for bolt pattern with the horizontal distance of 60 mm between the bolts.

3. Circular Patterns

Table 4.3 Results of Circular bolt pattern analyses for Tensile Load

	C1=32		C2=33		C3=34	
Load (KN)	**Plate separation (mm)**	**Max Stress (MPa)**	**Plate separation (mm)**	**Max Stress (MPa)**	**Plate separation (mm)**	**Max Stress (MPa)**
100	0.4230	192	0.3939	177	0.3725	161
150	0.6735	282.3	0.6238	256	0.5868	253
200	0.9732	384.3	0.898	342	0.8421	337.24
250	1.3280	509	1.125	439.41	1.4170	431
300	**1.7910**	**549**	**1.585**	**544**	**1.6715**	**534.711**

Table47.3 shows the plate separation and equivalent stress for the circular bolt pattern for the angle between the bolts of $32^{0,}$ 33^{0} and 34^{0} for the load of 100 KN to 300KN. The minimum plate separation is 1.585 mm at the maximum load of 300 KN is obtained for bolt pattern with the angle between the bolts 33^{0}. The minimum stress is 534.711 MPa at the maximum load of 300 KN is obtained for bolt pattern with the angle between the bolts 34^{0}.

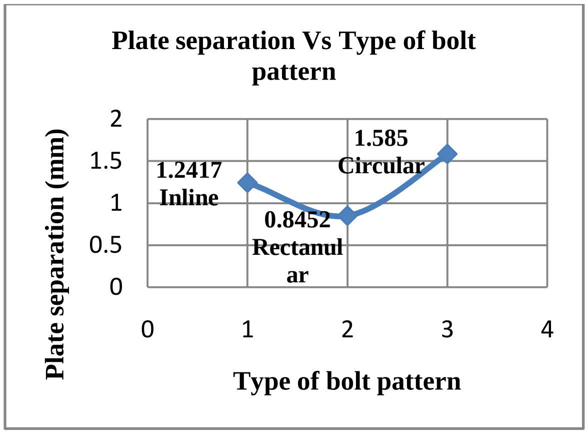

Figure 4.1 Graph of Plate separation Vs Type of Bolt pattern for Tensile Load

Figure 4.1 shows the graph of minimum plate separation in bolted end plate connection against the types of bolt pattern in the bolted end plate connection for the tensile loading. The values of plate separation on vertical axis are the minimum plate separations for that particular bolt pattern. Out of those minimum plate separations for the particular bolt patterns, the minimum plate separation is achieved for the rectangular bolt pattern as shown in figure. So from all the bolt pattern analyses in tensile loading it is clear that the minimum plate separation is obtained for the rectangular bolt pattern (0.8483 mm).

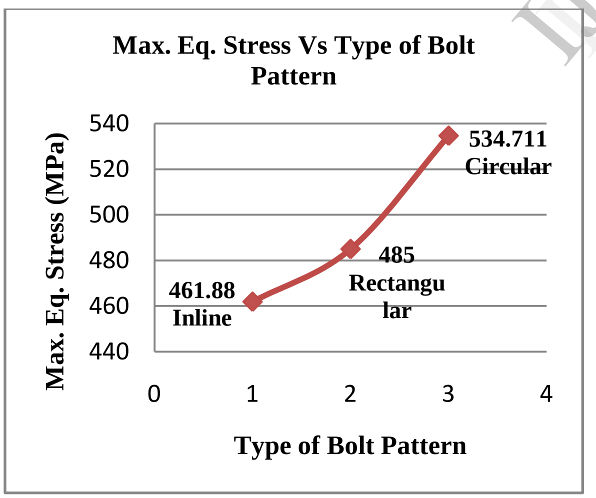

Figure 4.2 Graph of Maximum Equivalent Stress Vs Type of Bolt Pattern in Tensile Load

Figure 4.2 shows the graph of maximum equivalent stress in bolted end plate connection against the types of bolt pattern in the bolted end plate connection for the tensile loading. The values of stresses on vertical axis are the minimum equivalent stresses for that particular bolt pattern. Out of those minimum equivalent stresses for the particular bolt patterns, the minimum equivalent stress is achieved for the inline bolt pattern as shown in figure. The stress value for the rectangular bolt pattern is slightly more than inline bolt pattern but it is in the acceptable limit of stress.

5. Conclusion

In this paper, the both tensile load is acting on the bolted end plate connection and the analyses were carried out. For tensile load analysis the minimum plate separation of 0.8452 mm and equivalent stress of 485 MPa was obtained for the rectangular bolt pattern with the horizontal distance between the bolts of 60 mm for the maximum load of 300 KN. Hence from the results of FE analysis it is concluded that the rectangular bolt pattern is more suitable over inline and circular bolt patterns for tensile load conditions. The close correlations between the FE analysis and experimental results sufficiently demonstrate that good strength can be obtained by using rectangular bolt pattern for the supporting structure of pressure vessels. FE analysis gives finer results as compared to experimental analyses.

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