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Analysis Of Bolt Pattern And Its Significance On Strength Characteristics Of Support

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ABSTRACT

Primarily welded connections are used in structural connections for the pressure vessel, however they probability tend to buckle because of their rigid nature. So it is not preferred in case of extended connections. Welded connection shows brittle fracture in column webs, column flanges, welds and shear tabs. Mostly bottom of the beam flange damaged during the use of welded connection. Alternative method to avoid such type of failures is use of bolted connections. Bolted connections offer flexibilities and they can withstand the local buckling. This work presents the comparison study of the T-stub, bolted together in different patterns. Finite element analysis is done to verify the best pattern among line, rectangular and circular pattern using ANSYS software. Tensile load is applied on one face of T-stub varying from 100kN to 300kN with the step of 50kN with other side fixed. Analysis revealed that, circular pattern is showing significant results than line and rectangular pattern.

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I. INTRODUCTION

Structural connections for the pressure vessel can be designed primarily as welded connections, however their stability is greatly affected in case of moment loading and they tend to buckle because of their rigid nature. Hence it is not feasible to use them in portable pressure vessels also. Brittle fracture in column webs, column flanges, welds and shear tabs were reported. Most of the reported damage was located within the bottom of the beam flange. Cracks were initiated at welding roots and then extended into the column web and/or flange. The tragedy created the initiative of testing and studying the response of the steel beam-to-column connections. However the bolted endplate connections offer these flexibilities and they can withstand the local buckling. Also it is compulsory to use them in portable pressure vessels because they can be dismantled. With regards to bolt connected structure, the key aspect is design of the bolt pattern. This pattern has a direct impact on the strength of the structure. The objective of this paper is to form certain set of guidelines or set of formulations which will serve as a guideline for bolt pattern in bolted endplate connections of Pressure Vessels.

Due to the similarity between the behaviour of the T-Stubs and the tension flange of the end-plate bolted connection, many past researchers used T-Stubs to simplify the behaviour of the connection.

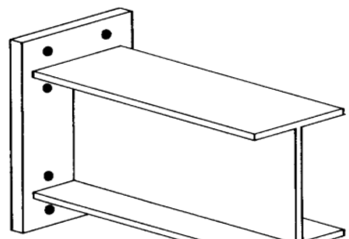


Figure 1. Typical configuration of end-plate connection

The distribution of the bolt forces and the resulting responses of the bolt group in the T-Stubs connection is a function of many parameters including bolt diameter and pretension, the gage and pitch, number of bolt rows flexibility of the detailed element, contact surface condition, etc. Fleischman [11] et al. discussed in "Top-and-Seat Angles Connection and End-Plate Connection: Snug vs. Fully Pre-Tensioned Bolts," the effect of the tension, bending, and prying forces in the overall behaviour of the T-Stub connection. Although the bolts are implemented to transfer the tensile force through the elements in the structures, this tensile force may be amplified by prying action. However, the bending of the bolt induces an additional bending force to the bolt shank, which is increasing the tensile force in the bolt. In beam-to- column connection, a lateral component of shear is also act on the bolt. However, in many cases, the shear in the connection is assumed to be carried by friction in the compression portion of the connection.

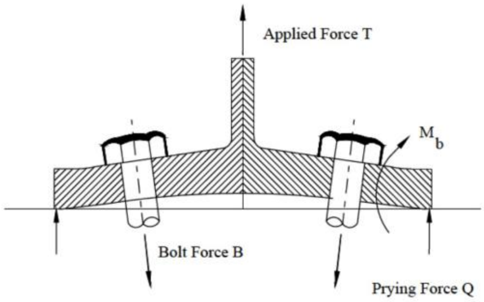


Figure 2. Typical configuration of end-plate connection

A. Tension

When components of the connection are bolted, the bolt pretension will affect the overall response to external tensile loading; however, the ultimate strength is unaffected. Until the external load overcomes the pretension forces, the assemblage of the bolts and connected plies acts as one, resulting in an overall increase in stiffness. After pretension is overcome (plate separation), the bolt forces are simply equal to the external load, regardless of the original magnitude of the bolt pretension.

B. Prying Action

Bolt groups in tension are susceptible to prying action. The applied tensile load T must be transfer through the connection, two rows of bolts presented in Figure2. The bending moment developed in the connection flange must be resisted by the point load $Q=f(M_b)$ at the edge of the flange. This force developed due the bending of the flange is called prying force. If can be seen from the Figure 1.2, that the bolt forces in the connection will include force component from both the applied load and additional forces due to prying action. For n bolts acting to resist the applied load T, the following is obtained:

C. Flexural Rigidity

If the T-Stubs flange is significantly rigid, the bending deformation and consequently resulting flange moments will be minimal. However, if the flange is relatively flexible, the bending deformation of the flange will induce significantly large moment, thus the value of Mb will be trivial.

D. Pretension

In the pretension connections, the flange separation occurs when the applied force overcome the pretension forces. Since the development of Mb requires the flange separation, the value of Mb will remain insignificant while the flange remains un-deformed. Therefore, Assuming the T-Stubs flange is flexible; lowering the pretension will result in prying action at a lower value of the external load. Test results show that initial clamping force does not influence the magnitude of prying forces at the ultimate loading condition.

I. LITERATURE SURVEY

A great deal of research on the behaviour and design of the end-plate moment connection has been conducted over the past several years and are available in the literature. Much research has been conducted since the early 1950s to develop a refined design procedure for both flush and extended end-plate connections. The earlier design methods were based on the static forces and simplified assumptions were made to consider the prying action in the connection. These methods in general resulted in a thick end-plate and large diameter bolts. Many of the recent studies are based on the yield line theory, the finite element method, and the finite element method together with regression analysis to develop equations suitable for design use.

Early experimental studies were done on bolted rigid connections by Douty and McGuire [1] (1963) 'Research on Bolted Connections –A Progress Report'. They investigated the increase in bolt tensile forces caused by prying effects in the end-plate of eight ASTM A7 W16x36 beams and compared theoretical and experimental results. They reported a significant increase in bolt tension when a thinner end-plate was used. Semi-empirical equations were developed to predict the prying force ratio.

Douty and McGuire [2] (1965) conducted full-scale testing on 27 T-Stubs specimens and seven extended end-plate moment resisting connections in "High Strength Bolted Moment Connection". The prying force induced by the tension flange force at the edge of the specimen was studied for both types of connections. Since the extent of the results was not adequate to develop a design procedure for end-plate connection, the bolt forces were assumed to be related to a linear strain model assuming a rigid end-plate, i.e. the prying forces were neglected.

Srouji et al. [3] conducted an experimental study on the two-bolt and four-bolt flush end-plate connections in "Yield-Line Analysis of End-Plate Connections with Bolt Force Predictions". They noted that the strength yield-line analysis accurately predicts the strength of the endplate, and the modified Kennedy [4] method can adequately predict the bolt forces for the flush endplate. Also it was noted that with a few discrepancies, the strength of the end-plates tested by Krishnamurthy [5] can adequately be predicted by using strength yield-line theory.

Grundy et al. [6] conducted two experimental tests on the extended end-plate connections in "Beam-to-Column Moment connection". They used two rows of four bolts (eight totals) 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. A detailed procedure for the design of the beam to column connection is elaborated in the paper. In this approach, the bolt forces were subjected to a 20 per cent increase in the direct force to account for the prying action.

Murray [7] presented "AISC Design Guide Series 4, Extended End-Plate Moment Connections," an overview of the design procedure for the four-bolt un-stiffened, four-bolt wide un-stiffened and eight-bolt extended stiffened end-plate moment connection. The end-plate design procedures were based on the work of Krishnamurthy [5], Ghassemieh et al. [8], and Murray and Kukreti [9].

Graham [10] reviewed “Observation from the Behaviour of Bolted Beam to Unstiffened Column Rigid Connections,” existing design methods and recommended a limit-state design method for the design of rigid beam-to-unstiffened column extended end-plate connections.

The bending relation will be developed for the cases of a tension angle within a connection; a similar relationship can be derived for other connections. As the applied force T works to overcome the contact forces at the bolt line, a moment initiates which tends to increase the contact force (prying) at the far side of the bolt line and decreases contact on the near side. The bolt pretension gradually overcome as the contact surface recedes. In addition to the tensile force T and the prying force Q, moment Ma from the angle curvature and a proportion (α) of the total connection shear Vconn exist. The details of these analyses are presented in research paper by Fleischman et al. [11].

Kennedy et al. [4][12]was a pioneer to develop a unified method for predicting the additional bolt forces due to the prying action in the T-Stubs connection. They assumed that a T-Stubs or a bolted end- plate goes through three stages of behaviour. They presented equations which identifies the thin and thick plate limits based on the geometric properties of the connection, yield stress value of the plate, and applied flange force. Ultimately, the prying forces in the bolts are calculated for each type of plate behaviour determined.

The European structure code [13] introduces the philosophy of the component-based design methods. In this procedure, the connection is divided into several basic T-stubs and the behaviour of an isolated T-stub is related to its actual position in the connection.

II. Methodology

A. T-Stub Testing Program

Due to similarity between the behaviour of the T-Stubs under tension, and tension flange of the extended end-plate connection, numerical analysis of T-Stub models is done. Several bolt pattern configurations were proposed and finite element models were developed and analysed with various bolt size, plate thickness, pitch sizes (P_f), and gage lengths (g). The scope of this phase of the study was to study the potential performance enhancement of the T-Stubs due to various bolt pattern configuration.

B. Bolt Pattern Configuration

Several bolt patterns were selected and a testing matrix was developed. The bolt pattern was selected from regular geometric shapes to simplify the design as well as fabrication process. Figure3 illustrated the regular geometric shapes that were proposed and tested in this study.

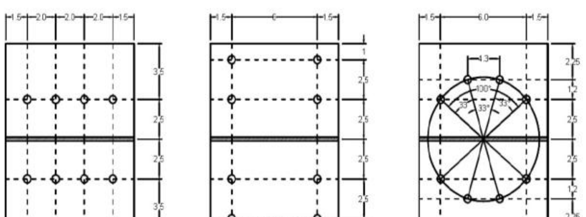


Figure 3 Bolt Pattern Configurations, (a) Line, (b) Square and (c) Circular.

Figure3(a) shows the bolt pattern configuration in which all the bolts are located at the same distance with respect to the stem. The designation name “Line” is assigned to this bolt configuration. Figure3(b) shows the connection with the traditional square bolt pattern. This pattern has been widely used in the industry with various gage, and pitch spacing. Figure3(c) illustrates the proposed circular bolt pattern. The designated name for each test is tabulated in Table 1.

Table 1. T-Stubs Test Matrix

Specimen ID	Bolt Diameter	Bolt Pattern
TS-L	½”	
TS-S		*Square*
TS-C		*Circular*

To validate the numerical results obtained from the finite element analysis, three models with different bolt pattern configurations were selected and tested experimentally, and the results were compared with results collected from finite element models. The detail and results of this study are elaborated in detail in the following sections.

III. Numerical approach

II. Nonlinear 3-D finite element models were developed to simulate the response of the T-Stubs connections under tensile and bending loading. The results obtained from the numerical analyses will compare with the results collected from the experimental testing to verify the accuracy of the numerical results.

A. Material Modelling

It involves assigning material properties. For analysis carried out ASTM A193 GR 50 was taken as BOLT, BOLT HEAD, and END PLATE material. Mechanical properties for forged steel are as shown in table 2 below.

Table 2. Mechanical properties of ASTM A193 GR 50

Properties	Values
Young’s Modulus	200 GPa
Poisson ratio	0.3
Yield strength	250 MPa
Ultimate tensile Strength	460 MPa

The Bilinear combined hardening plasticity model was used in order to model the material behaviour during the loading. Bilinear Isotropic hardening was used to model the material properties of the high strength steel bolts with a material constitutive law as shown in Figure

B. *Modelling*

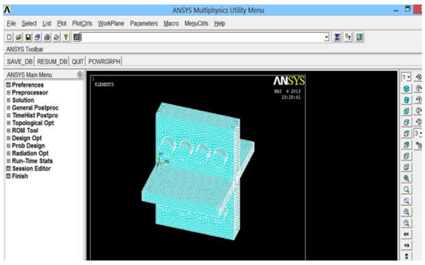


Figure 4 Project window of ANSYS Classic

In geometry modelling, total no. of patterns to be model is 09. Total modelling has done in ANSYS APDL Program.Basically three Programs for In-line, Rectangular and Circular pattern has written in macro file with using parameters.Variations in Geometry are easily achieved by defining Parameters. By just changing the input value of parameters macro file code will generate geometry in ANSYS Classic.

C. *Meshing*

Meshing is an integral part of the computer-aided engineering simulation process. The mesh influences the accuracy, convergence and speed of the solution. The models were meshed in one, two and three layers and the results were compared with experimental values for convergence requirements. The best results were obtained from the models with 3D 10-Node tetrahedral structural solid.

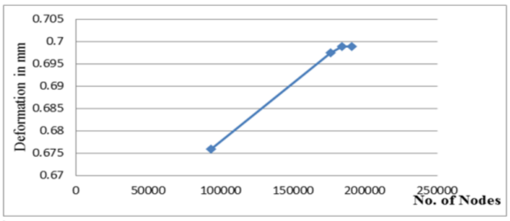


Figure 5. Deformation convergence along element size

Finite element mesh was generated using solid tetrahedral elements with various element lengths. The deformation was checked for convergence. Von-mises stress cannot be checked for convergence because stress concentration occurred at the contact surfaces of the bolt.

Figure5 above shown is deformation versus element size using for checking convergence. Thus element size was found out to be 2.85mm for working in convergence zone.

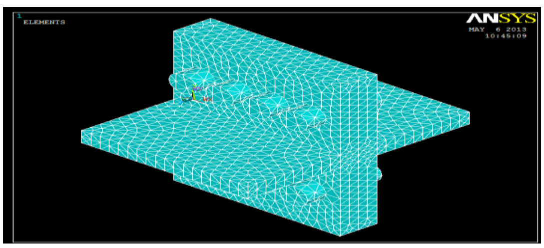


Figure 6Meshed model of inline pattern

Therefore, a finite element mesh was generated with a uniform global element length of 2.85 mm for In line pattern 2.75 mm for Rectangular Pattern(286259 nodes)2.85mm for circular patterns (174588). Fig. 6 shows meshed model of in line pattern.

D. *Element type: SOLID 187*

SOLID187 element is a higher order 3-D, 10-node element. SOLID187 has quadratic displacement behaviour and is well suited to modelling irregular meshes (such as those produced from various CAD/CAM systems).

The element is defined by 10 nodes having three degrees of freedom at each node: translations in the nodal x, y, and z directions. The element has plasticity, hyperelasticity, creep, stress stiffening, large deflection, and large strain capabilities. It also has mixed formulation capability for simulating deformations of nearly incompressible elastoplastic materials, and fully incompressible hyper elastic materials.

E. *Element type: CONTACT 174*

This is a 3-D, 8-node, higher order quadrilateral element that can be located on the surfaces of 3-D solid or shell elements with midside nodes (such as SOLID92, SOLID95, or SHELL281). It can be degenerated to 3-node to 7-node quadrilateral/triangular shapes. CONTA174 supports isotropic and orthotropic Coulomb friction.

F. *Contact Modelling*

The numerical results are highly sensitive to the contact properties between the components of the model. In the bolted connections, the forces are transferred through friction. Surface-to-surface was considered for all the contacts. The surface contact between the end-plate and column was modelled by standard contact which allows deformation. Besides this contact all other contact surfaces of the contacts pair represent the surface of column flange, T-stubs flange, and bolt-shank are bonded (always) with Multi-Point Constraint (MPC) which is also known as rigid contact. The target surface is defined as the surface interfacing with the contact surface. The contact surface in general should have finer mesh.

G. *Boundary Conditions*

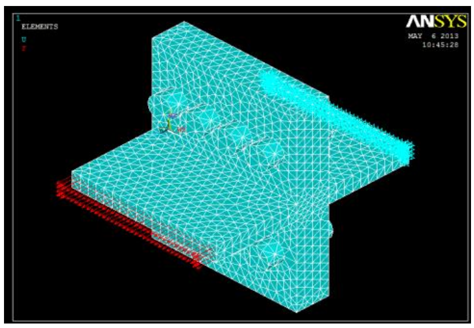
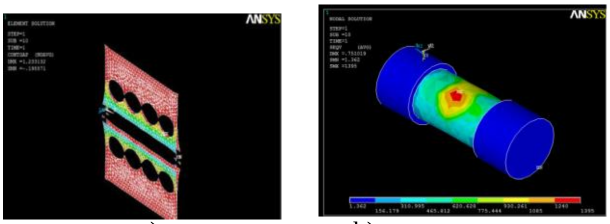


Figure 7 Boundary conditions applied on T Stub

Figure 7 shows boundary conditions applied on the T stub. One face of the T-stub is fixed and on other face tensile load is applied. Load is varying from 100kN to 300kN with the step 50kN

IV. RESULTS AND DISCUSSIONS

Equivalent Von-Mises stress and deformation in all patterns were obtained tensile loading condition using static structural analysis in ANSYS Classic. Maximum stress occurred in the transition area bolt surface as shown in Fig shows stress distribution for tensile loading at bolt surface. In this case maximum stress occurred at bolt surface and end plate hole due stress concentration. Fig 8 shows a) deformation and b) stress distribution for tensile loading.



a) b)

Figure 8a) deformation and b)Stress (σ) distributions for tensile loading at bolt surface

Overall results for line, rectangular and circular pattern for various loading are tabulated in table 3, 4 and 5 respectively.

Table 3. Result of Line Pattern

	IN LINE L1=2"		IN LINE L2=2.5"		IN LINE L3=3"	
LOAD (KN)	δ (mm)	σ (MPa)	δ (mm)	σ (MPa)	δ (mm)	σ (MPa)
100	0.3174	150	0.2039	138.87	0.4806	166.5
150	0.4949	205	0.3174	179	0.7766	249
200	0.6988	270.46	0.4380	231.18	1.122	323
250	0.9393	343.2	0.5742	288.12	1.53	413
300	1.2417	421.8	0.7326	350.45	1.983	510

Table 4. Result of Rectangular Pattern

RECTANGULAR						
	R1=6"		R2=4"		R3=2"	
LOAD (KN)	δ (mm)	σ (MPa)	δ (mm)	σ(MPa)	δ (mm)	σ (MPa)
100	0.2275	164	0.2423	151	0.3233	171
150	0.3547	235.2	0.3738	217	0.5088	246
200	0.4988	312.9	0.5270	285	0.718	329
250	0.664	396	0.6966	357	0.9699	420
300	0.8483	485	0.8952	439	1.26	499

Table 5. Result of Circular Pattern

CIRCULARPATTERNS						
	C1=32		C2=33		C3=34	
LOAD (KN)	δ (mm)	σ (MPa)	δ (mm)	σ(MPa)	δ (mm)	σ (MPa)
100	0.3939	177	0.42305	192	0.3725	161
150	0.6238	256	0.6735	282.3	0.5868	253
200	0.898	342	0.97328	384.3	0.8421	337
250	1.125	439	1.328	509	1.417	431
300	1.585	544	1.791	549	1.6518	519.9

V. Experimental Result

As mentioned before, the main scope of this experimental study was to investigate the behavior of the T-Stubs under various bolt pattern configuration. In addition, the data collected in this section was used to validate the results. Fig.9 show The T-Stubs test setup used for Specimens. The 400K compression/tension testing machine was used to apply a monotonic load to the T-Stubs and Table 6 shows the summary of the test results.Experimental results sufficiently demonstrate that good strength can be obtained by using rectangular bolt pattern for the supporting structure of pressure vessels.

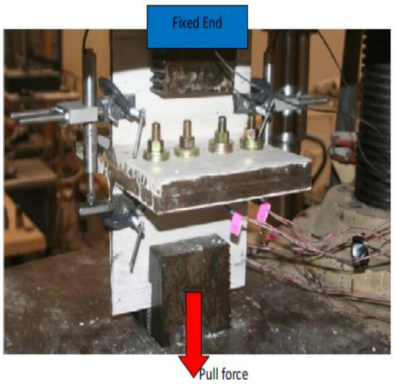


Figure 9 T-Stubs Test Setup

Table 6 Specimens TS-L,TS-S and TS-C

Specimen	Yielding Tensile Force (kN)	Plate Separation in (mm)
TS –L (Inline)	100	0.3872
TS-(Rectangular)	100	0.236
TS-(Circular)	100	0.41

VI. Conclusions

This research paper investigated End plate separation for various bolt spread patterns. Load analysis was performed based on the inputs, which comprised of the bolt radius, bolt spacing, to find out the tensile and compressive stresses acting on T-stub. FEA was carried out with computer aided simulation tool ANSYS in Classic environment. Based on stress observations in all loading conditions scope for plate separation was studied. The following conclusions can be drawn from this study:

1. 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.
2. Deformation in plates is equal to 90% of total deformation in T-stub so we can conclude that plate separations should be controlled on bolt spread patterns.
3. As far tensile loading concern , results show that the increase in separation of the connection is a function of both distance and/or spacing bolts from end plate and load
4. The variation of maximum vonmises stresses for each loading conditions in standard patterns with comparison to different model is very less and it was found to be well below the limit of allowable stress.
5. For tensile loading rectangular patterns shows less deformations compared to all other patterns
6. For tensile loading In Line patterns shows less deformations maximum stress compared to all other patterns and for rectangular patterns no significant rise in maximum vonmises stresses compared to in line patterns,
7. FEA software ANSYS is good design analysis tool which can be used for carrying out optimization by studying stress distributions or by design optimization module.

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