Finite element analysis of bolt pattern and its significance on strength characteristics of support

A.M.Sanas, Prof. N.V.Lakal

amolsanas88@gmail.com
nvlakal.sit@sindhgad.edu

1, 2 Mechanical Engineering department, Sinhgad Institute of Technology, Lonavala, India

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.

Keywords— Bolted connection, FEA, T-Stub design, 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.

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.

II. 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 overcomes 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.

III. 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 (Pₘ), 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. Figure 3 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.

Figure 3(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. Figure 3(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. Figure 3(c) illustrates the proposed circular bolt pattern. The designated name for each test is tabulated in Table 1.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Bolt</th>
<th>Pattern</th>
</tr>
</thead>
<tbody>
<tr>
<td>TS-L</td>
<td>½”</td>
<td>Line</td>
</tr>
<tr>
<td>TS-S</td>
<td>½”</td>
<td>Square</td>
</tr>
<tr>
<td>TS-C</td>
<td>½”</td>
<td>Circular</td>
</tr>
</tbody>
</table>

Table 1. T-Stubs Test Matrix

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.

IV. NUMERICAL APPROACH

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

<table>
<thead>
<tr>
<th>Properties</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young’s Modulus</td>
<td>200 GPa</td>
</tr>
<tr>
<td>Poisson ratio</td>
<td>0.3</td>
</tr>
<tr>
<td>Yield strength</td>
<td>250 MPa</td>
</tr>
<tr>
<td>Ultimate tensile</td>
<td>460 MPa</td>
</tr>
</tbody>
</table>

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.

B. Modelling

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.

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.

Figure 5 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.

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.

V. RESULTS AND DISCUSSION

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.

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

VI. 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](image)
TS-(Circular) & 100 & 0.41 \\

VII. 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, and for rectangular patterns no deformations maximum stress compared to all other patterns

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, 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.

REFERENCES