www.ijecs.in
International Journal Of Engineering And Computer Science ISSN:2319-7242
Volume 4 Issue 5 May 2015, Page No. 12200-12204

Finite Element Analysis on the Structural Behaviour of Bolted Joints

***Naveenkumar P*[1] *Dr. Manivannan A*[2]**
[1]PG Scholar, Department of Mechanical
Regional office Anna University
Tirunelveli Region, India
naveenkumarp54@gmail.com

[2]Head of the department, Assistant Professor
Department of Mechanical
Regional office Anna University
Tirunelveli Region, India

Abstract— **Bolted joints are one of the most common elements in construction and machine design. A finite element model with three-dimensional solid elements was taken to investigate the bearing failure of stainless steel bolted connections under shear. This paper presents an extension of the finite element investigation onto the structural behaviour of stainless steel bolted connections, and three distinctive failure modes as observed in single lap and double lap shear tests are successfully modeled: bearing failure; shear-out failure; and net-section failure. Determine the material analysis of lap joints of the plates in accordance with the parametric optimization technique. Parametric optimization can be engaged by making a hole over the plate with several parameters. By analyzing the parametric study the net-section and shear-out failure are eliminated effectively. In bearing failure material optimization can be engaged by using stainless steel in accordance with the variation of loading conditions and parameters respectively.**

Keywords— **Bolted lap Joints, Failure Modes, Optimization Technics etc.**

1. Introduction

The threaded fastener (nut and bolt) has played a significant role in the industrial revolution even though the exact date of its conception is not known. Threaded fasteners are probably the best choice to apply a desired clamp load to assemble a joint, at a low cost, with the option to disassemble if and when necessary. Furthermore, the simplicity of its mechanism of developing and maintaining the desired clamp force made it very popular and it has become one of the most accepted engineering products. In a negative sense, this simplicity may have made some users complacent.

Based on the service loads there are two types of bolted joints. In tensile joints the bolts are loaded parallel to the bolt axis while in shear joints the bolts are loaded predominantly perpendicular to the bolt axis. For example the connection of two flanges of a pressure vessel constitutes a tensile joint while the connection of a beam to a column can be considered as a shear joint. In a typical shear joint the bolt acts as a shear pin. The analysis of a shear joint is quite straightforward. The bolt does not need to maintain a specific tensile load. In this case the tensile load is applied only to prevent the nut from loosening. When the shear load on the joint changes the corresponding stress field in the bolt also changes. Under dynamic loading this can lead to possible fatigue failure of the bolts.

The most common mode of failure is overloading: Operating forces of the application produce loads that exceed the clamp load, causing the joint to loosen over time or fail catastrophically. Over torqueing might cause failure by damaging the threads and deforming the fastener, though this can happen over a very long time. Under torquing can cause failures by allowing a joint to come loose, and it may also allow the joint to flex and thus fail under fatigue. Brinelling may occur with poor quality washers, leading to a loss of clamp load and subsequent failure of the joint. Other modes of failure include corrosion, embedment, and exceeding the shear stress limit. Bolted joints may be used intentionally as sacrificial parts, which are intended to fail before other parts, as in a shear pin.

At present, many design recommendations for stainless steel connections may be found in the literature which give design rules for the load carrying capacities of fasteners such as bolts, screws and rivets against bearing failure. However, they are empirical expressions developed from test data of specific ranges of material properties such as steel strength and ductility, and of geometrical dimensions such as steel thickness and bolt diameter. Most of the test data are derived from lap shear tests where deformations in the form of axial extensions are large, typically in the range of 3–10 mm, depending on deformation limits adopted during data analysis. These design rules are primarily developed for simple connections under lateral loads, and tension connections under axial forces where connection deformation is not critical to the structural performance of connected members. However, for bolted connections under moment, the bearing resistances of the connected parts in stainless steel sections may only be fully mobilized at large extensions together with large rotation, leading to moment connections of low stiffness and strength. In general, moment connections between stainless steel members are not commonly used in practice due to the lack of information on their structural behaviour and appropriate design guidance.

2. Scope of Work

Based on the finite element model recognized in Ref. [4], this paper presents an extension of the finite element investigation of the structural behaviour of stainless steel bolted connections, in particular, the three distinctive failure modes [2,3] as observed in lap shear tests:

1. bearing failure;
2. shear-out failure; and
3. Net-section failure.

After calibrating against a number of test specimens with different steel grades, thicknesses, breath, loading condition, hole size and hole position in plate with hole. The material analysis of lap joints of the plates in accordance with the parametric optimization technique. Parametric optimization can be engaged by making a hole over the plate with several parameters. A parametric study over a practical range of connection configurations is also performed to reveal the effects of steel strengths and ductility limits on the bearing resistances of the connections. In order to allow for reduced ductility in high strength steels is proposed against the finite element results.

The proposed rule relates the bearing resistances of bolted connections directly with both the yield and the tensile strengths of steel strips through a strength coefficient. It should be noted that for all the connections reported in this paper, the bolts are 18 mm, 22 mm and 26 mm in diameter, and the design yield strengths of the steel strips are between 280 and 600 N/mm^2 while the steel thickness ranges from 2.5 to 5.0 mm.

3. Design on stainless steel connections

3.1 Material Used

There are many situations in engineering where no single material will be suitable to meet a particular design constraint. For example aerospace applications need materials that should have low densities, high strength and stiffness. Such a combination of characteristics is not met by conventional metals, alloys, ceramics and polymeric metals. Frequently strong materials are relatively thick; also, increasing the strength or stiffness generally results in a decrease in impact strength.

Properties of the stainless steel used in this work are shown in Table 1

Table 1
Properties of Stainless Steel

Material	Young modulus (Pa)	Poison ratio	Density (Kg/m^3)
410	2e11	0.3	7740
501	1.9e11	0.28	8030
304	1.93e11	0.29	8030

3.2 Modelling of lap joint with Stainless steel bolt connection

The parametric selection is given below,

Steel strip 304

Length = 150mm Breath = 78mm

Table 2
Naming values of SS bolt connection

		Levels		
		1	2	3
Factors	Material	SS304	SS 410	SS 501
	Bolt size	18	22	26
	Load	70	80	90
	Thickness	3	4	5

The above table shows the parameter used in both single and double lap joints. But in the double lap joints the load used in 100, 200 and 300 KN.

There has been much research work reported in the literature about the development of moment connections between steel in modern roof systems. A number of various connection configurations with sleeves or overlaps were found in various proprietary systems which offered partial continuity along the purlins. Bolted moment connections between steel sections with connection configuration suitable for general application [7–10] were also proposed and tested. Moreover, finite element modeling using three-dimensional solid elements through material, geometrical and boundary non-linearities were also reported in the literature [1, 5-7].

4. Finite element modeling

4.1 Element selection

Three dimensional eight-node iso-parametric solid elements SOLID45 are employed to model all the components of a typical bolted connection, namely, the steel strip, the bolt and also the nut, in order to capture material yielding throughout the steel thickness. Furthermore, the normal stresses acting on the steel strip due to the clamping force developed in the bolt shank and also the tangential stresses due to the frictional forces between contact interfaces may also be incorporated. Based on the results of coupon tests, a true stress–strain curve with reduced strength at large strain after yielding, that is, strength degradation, is adopted.

Contact interfaces between the steel strip, the bolt and the nut are modelled by contact elements CONTAC49 so that intuitive assumption on the position and the size of contact area are not required. Shear force is applied to the finite element model by imposing incremental displacements to the end of the steel strip along the longitudinal direction of the specimen while the steel plate and the root of the bolt are fixed in space throughout the course of loading application. As the finite element model incorporates material, geometrical and contact non-linearity, the full Newton–Raphson nonlinear analysis procedure is employed to obtain the solution after each displacement increment. In a typical finite element model, there are over 8481 nodes, 2563 solid elements and 1000 contact elements.

4.2 Meshing

ANSYS 14.0 is the software used for the pre and post processing. This lap joint is meshed with different elements and different meshing types. At first the joint was meshed with element SOLID 45. This element is a higher order 3-dimentional, 10- node element. SOLID 45 is a quadratic displacement behavior. Meshing is performed on the FE model to ensure sufficiently fine sizes are employed for accuracy of calculated results but at competitive cost.

After testing the joint model for different element sizes with above elements SOLID 45 and CONTAC49 one by one it was seen that smaller mesh size captures the higher stress value. The element SOLID 45 is the test Mesh. But smaller element size is less than 1 mm for both the types of elements was it implemented.

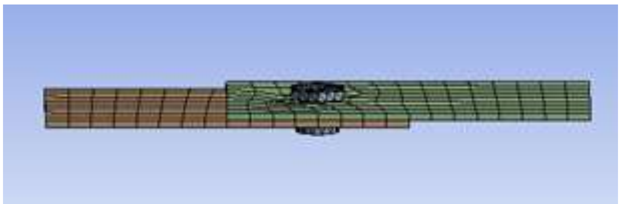

Fig 1 Meshed view of a single lap stainless steel bolted connection.

4.3 Optimization of Single lap Stainless steel bolt connections

The selection of parameters having 4×3 matrix. Each parameter having 3 variables

As per the selected values, Minitab generates the following set of values which is to be modified accordingly. It is based on four parameters and three levels. Nine sets of proceedings generated.

Thus the nine different types of model have chosen for the analysis. In this paper the main aim is to improve the strength of the bolted joints by reducing stress developed in the joints, so each model has been analyzed for its stress. The model with the lowest stress is selected for the optimum values.

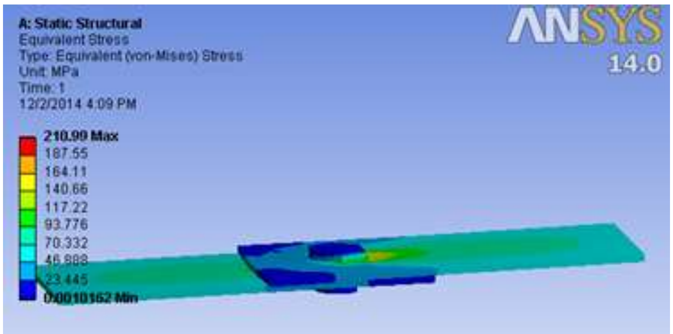

Fig 2 Finite element model of a single lap bolted connection.

It is obvious that maximum stress developed is at edges of the hole section i.e. the red color indicates maximum stress, because the constraints applied at the pressure in both the ends with fixed both and nut. Since hole edges are subjected to maximum stress, care must be taken in bolt design and material selection. The material must have good ductility, resilience and toughness to avoid sudden fracture.

Table 3 L9 Orthogonal Array with Data for Equivalent Stress (For Single lap Joints)

Experiments	**A**	**B**	**C**	**D**	**Stress(Y_1) N/mm^2**
1	SS 304	18	70	3	210.99
2	SS 304	22	80	4	615.15
3	SS 304	26	90	5	745.8
4	SS 410	18	80	5	554.87
5	SS 410	22	90	3	685.54
6	SS 410	26	70	4	663.87
7	SS 501	18	90	4	508.44
8	SS 501	22	70	5	482.26
9	SS 501	26	80	3	657.91

Tabie 4

ANOVA Calculations for Single lap SS bolt connections

Sum of variance	**Sum of Square**	**Degree of freedom**	**Mean sum of square**	**F_{cal}**	**F_{table} at $\alpha = 0.1$**	**Remarks**
A	20188.37	2	10094.19	77.6	99	Insignificant
B	107670.25	2	53835.12	414.1	99	**Significant**
C	63740.57	2	31870.29	245.2	99	**Significant**
D	11836.28	2	5918.14	45.5	99	Insignificant
Error	130	1	130			
Total	203435.47	9				

In factor ‘B & C’ $F_{cal} > F_{table}$ i.e. It is clear that the factor B & C have significant effect on the stress on single lap shear joints. Since F_{cal} for the factor B & C is greater than F_{table}. Hence factor B & C is the best factor among the four factors available to us. So on considering the value of factor B & C i.e. bolt size and load increases the stress in plate increases on the same time while reducing the value the stress in plate decreases.

Table 5 Response Table for Equivalent Stress (For Single Lap Joints)

Level	A	B	C	D
1	549.54	424.77	609.31	594.31
2	634.76	594.32	452.37	518.15
3	523.98	689.19	646.59	595.82
Delta	**110.78**	**264.42**	**194.22**	**77.67**
Rank	**3**	**1**	**2**	**4**

Selected parameter - $A_3B_1C_2D_2$

A_3 → Stainless steel 501 B_1 → 18 mm
C_2 → 80 KN D_2 → 4mm
Where,
A – Material (Stainless Steel series)
B – Bolt Size (in mm)
C – Load (in KN)
D– Thickness (in mm)
Y_1- Equivalent Stress (in N/mm^2)

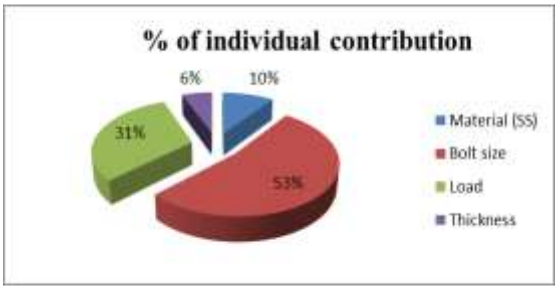

Fig 3 Pie chart for individual contribution of Single lap joints

4.4 Optimization of Double lap Stainless steel bolt connections

The selection of parameters having 4×3 matrix. Each parameter having 3 variables

As per the selected values, Minitab generates the following set of values which is to be modified accordingly. It is based on four parameters and three levels. Nine sets of proceedings generated.

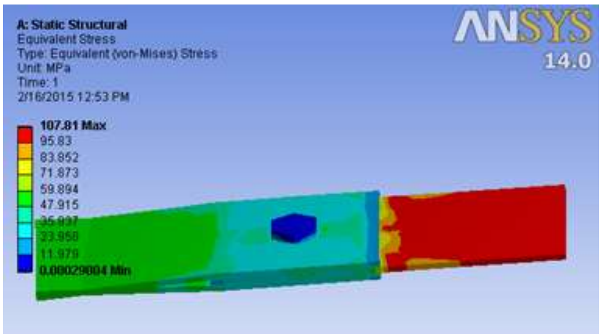

Fig 4 Finite element model of a Double lap bolted connection.

Table 6 L9 Orthogonal Array with Data for Equivalent Stress (For Double lap Joints)

Experiments	E	F	G	H	Stress(Y_2) N/mm^2
1	SS 304	18	100	3	107.38
2	SS 304	22	200	4	213.74
3	SS 304	26	300	5	329.36
4	SS 410	18	200	5	211.65
5	SS 410	22	300	3	679.03
6	SS 410	26	100	4	109.55
7	SS 501	18	300	4	318.94
8	SS 501	22	100	5	241.13
9	SS 501	26	200	3	233.20

Tabie 7

ANOVA Calculations for Double lap SS bolt connections

Sum of variance	Sum of Square	Degree of freedom	Mean sum of square	F_{cal}	F_{table} at $\alpha = 0.1$	Remarks
E	20616.27	2	1030.81	40.88	99	Insignificant
F	51151.34	2	2557.57	99.71	99	**Significant**
G	138091.68	2	6904.58	269.18	99	**Significant**
H	24264.71	2	1213.23	47.30	99	Insignificant
Error	25.65	1	25.65			
Total	234149.65	9				

In factor 'F & G' $F_{cal} > F_{table}$ i.e. It is clear that the factor F & G have significant effect on the stress on double lap shear joints. Since F_{cal} for the factor F & G is greater than F_{table}. Hence factor F & G is the best factor among the four factors available to us. So on considering the value of factor F & G i.e. bolt size and load increases the stress in plate increases on the same time while reducing the value the stress in plate decreases.

Table 8 Response Table for Equivalent Stress (For Double Lap Joints)

Level	E	F	G	H
1	216.83	212.66	152.69	339.87
2	333.41	198.97	219.53	214.07
3	264.42	324.04	442.44	260.71
Delta	**116.58**	**165.31**	**289.75**	**125.80**
Rank	**4**	**2**	**1**	**3**

Selected parameter – $E_1F_2G_1H_2$

E_1 → Stainless steel 304 F_2 → 22 mm
G_1 → 100 KN H_2 → 4 mm

Where,

E – Material (Stainless Steel series)
F – Bolt Size (in mm)
G – Load (in KN)
H– Thickness (in mm)
Y_2- Equivalent Stress (in N/mm^2)

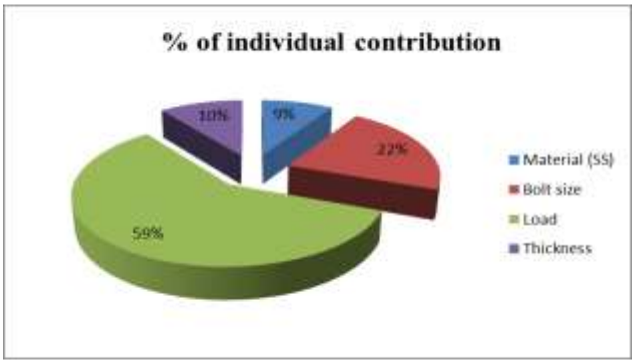

Fig 5 Pie chart for individual contribution of Double lap joints

5 Conclusions

A finite element model is established to investigate the structural behaviour of bolted connections between steel strips under shear. By incorporating both solid and contact elements, the model is able to capture non-linearities associated with geometry, materials and boundary conditions. It is demonstrated that the finite element model may predict successfully the three typical modes of failure in steel bolted connections, namely: bearing failure; shear-out failure; and net section failure.

A calibration exercise on the finite element model against bearing failure is carried out and a number of lap shear tests with steel strips and bolt of different thicknesses were conducted. By varying the material, thicknesses, forces and the bolt size, the bearing resistances of bolted connections at specific extensions with various configurations may be assessed readily.

5.1 For Single lap SS Bolt connection

Individually the parameters that contribute towards decreasing the stress proportionally developed in the lap joints in decreasing order are

- Material (SS) - 9.92 %
- Bolt size (mm) - 52.93 %
- Load (KN) - 31.34 %
- Thickness (mm) - 5.82 %

5.2 For Double lap SS Bolt connection

Individually the parameters that contribute towards decreasing the stress proportionally developed in the lap joints in decreasing order are

- Material (SS) - 8.94 %
- Bolt size (mm) - 21.81 %
- Load (KN) - 58.90 %
- Thickness (mm) - 10.35 %

By applying these values in the design criteria best result than compared to the existing, can be attained.

REFERENCES

[1] Aceti R, Ballio A, Capsoni A , Corradi L, A limit analysis study to interpret the ultimate behavior of bolted joints, Journal of Constructional Steel Research 60 (2004) 1333-1351.

[2] Bayan Anwer Ali, Finite Element Analysis of Cold-formed Steel Connections, International Journal of Engineering (IJE), and Volume (5): Issue (2): 2011.

[3] Bouchair A , Averseng J, Abidelah A, Analysis of the behaviour of stainless steel bolted connections, Journal of Constructional Steel Research 64 (2008)1264-1274.

[4] Chung K.F and Ip K.H, Finite element investigation on the structural behavior of cold formed steel bolted connections, Engineering Structures 23 (2001) 1115- 1125.

[5] Deepak S. Somasundaram, Mohamed B. Trabia, Brendan J. O Toole, A methodology for predicting high impact shock propagation within bolted-joint structures, International Journal of Impact Engineering 73 (2014) 30-42.

[6] Draganic H, Doksanovic T, Markulak D, Investigation of bearing failure in steel single bolt lap connections, Journal of Constructional Steel Research 98 (2014) 59-72.

[7] Ibrahima R.A, Pettit R.L, Uncertainties and dynamic problems of bolted joints and other fasteners, Journal of Sound and Vibration 279 (2005) 857-936.

[8] Jam J.E, Ghaziani N.O, Numerical and experimental investigation of bolted joints, International Journal of Engineering, Science and Technology Vol. 3, No. 8, 2011 285-296.

[9] Jong Hwa Yun, Jin Ho Choi , Jin Hwe Kweon, A study on the strength improvement of the multi-bolted joint, Composite Structures 108 (2014) 409-416.

[10] Ju S.H, Fan C.Y, Wu G.H, Three-dimensional finite elements of steel bolted connections, Engineering Structures 26 (2004) 403-413.