Study of Interfacial Pressure Distribution for Preloaded Bolted Connection

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Abstract: Analysis of double strap bolted lap joint was carried out using Finite Element Method (FEM). Angle of interfacial pressure distributionbetween the plates to be joined usingpreloaded bolted connection has been a debatable point though widely researched. Shigale's Pressure cone approach for the determination of the stiffness of the joint material had been used by many designers with fixed cone angle 30^0. This angle of interfacial pressure distribution is affected by many factors including the plate thicknesses, bolt head diameter, plate material etc. Numerical modelling has been carried outon models with 8mm, 12 mm and 16mm thick cover platespre-compressed using M16 bolts. The results emphasize significance of the half cone angle in the calculation of stiffness of the cover plate in the bolted connection.

Keywords: *Angle of interfacial pressure distribution, Finite Element analysis, Double strap bolted connection*

1 Introduction

Structural joints are essential and critical elements of a structural assembly. But determination of joint stiffness has not been satisfactorily treated analytically until now, therefore, forcing many designers to handle it experimentally. The initial magnitude of bolt preload is the only parameter that can be controlled once the joint is subjected to the service load. There are several parameters like stiffness of connecting material, slip factor, bolt head radius, thickness ratios of plates etc which affect the behaviour of bolted connection.The angle of interfacial pressure distribution or half cone angle has been approximated by many designers since long. The studies have suggested different values of half cone angle obtained from different methods including experimental and numerical analysis. In this work, an attempt has been made to numerically simulate and study the effect of the above factors on the angle of interfacial pressure distribution i.e. half cone angle and contact pressure distribution.

1.1 Bolt pretension

The purpose of bolt preload is to place the bolted components in compression for improved resistance to either static or cyclic external loads. Therefore, the integrity of bolted joints depends on quantitative representation of the contact pressure distribution at the interface during design [1].IS 4000:1992 specifies the minimum bolt pretension for different bolt sizes. (Clause 7.2.1, B-1.2 and D-2.2).

1.2 Contact pressure distribution in the connecting plates

Distribution of the pressureat the connecting plate surfaces(Refer Fig. 1) has been studied through numerical and analytical studies.Analytical models have been developed to predict pressure distribution in bolted joints as a function of the contact radius. FernlundRotscher was one of the early researchers to calculate the spread of stress in a bolted joint [1].
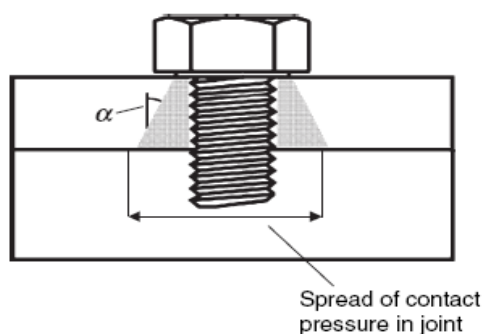
ATLANTIS
PRESS

Spread of contact
pressure in joint

Fig. 1. Shigale's Pressure Cone approach [2]

Shigale [2] stated that half cone angle should be between 25^0 and 33^0 (assuming a washer is used).Marshal et al[3] applied an ultrasonic technique in their investigation to study bolted surfaces with no washer and with plain and spring washers using two different interfaces (turned and ground). It was found out that surface profile and washers affect spread of the contact pressure at bolted interface. Consequently, it was shown that it is inappropriate to use a fixed contact spread angle, as suggested by some other studies, to determine joint stiffness for bolted joints with different contact surface profiles.

1.3Stiffness of the members in the bolted connections

Lehnhoff et al [4] emphasized that the pressure angle of 45^0 proposed by Rotscher overestimates the clamping zone. They proposed an analytical model to calculate the member stiffness and the stress distribution of bolted joints for various bolt sizes, thicknesses and materials of the members. It was assumed that there was a uniform pressure within a frustum cone envelope under bolt head. They recommended a fixed standard pressure angle of 30^0 as a better value for calculating the joint material stiffness:

$$Km = \frac{(\pi E d \tan\alpha)}{2 \ln[(l\tan\alpha + dw - d) (dw + d) / (l\tan\alpha + dw + d)(dw - d)]} \qquad (1)$$

Where$d_w$isdiameter of the contact under the bolt head and$l$ iseffective grip.

Marshall et al [3]in his earlier study had mentioned that the angle of interfacial pressure distribution makes a great difference in the determination of the stiffness of the joint.

2 Finite Element Modelling

The experimental method becomes difficult to comprehend when the measurement of interfacial pressure distribution is of main concern. Thus numerical modelling technique i.e. Finite Element modelling was adopted.The model geometry adopted was conforming to the laboratory standards. These standards are compared with the IS 4000:1992 standards test specimen requirement (Refer Table 1).The model of double cover strap joint with M16 bolt was studied(Refer Fig.2). The holes were oversized holes (d+3).

The study was restricted to linear material model. However, contact non-linearity has been considered in the modeling.Out of several methods available for modeling bolt pre-tension, the method adopted herewas to define the pretension load at the center of the shank by virtually cutting it into the two halves.

8 Noded brick element was used in the FE modelling because of its accuracy and suitability for contact problems.No special elements were required to define contact between the surfaces. The two types of contacts defined were- Normal contact accounts for the hard contact to avoid the penetration of the parts into each other and transfer the normal load and the other- tangential contact which accounts for frictional load transfer between the surfaces. The model was fixed at one end (Refer Fig.2 b).

Table 1

Sr. No.	Parameter	IS	Lab standards
1	Length of cover plate	10d=160mm	166mm
2	Width of cover plate	6d=96mm	80mm
3	Cover plate thickness	$(\frac{d}{-}+3)=11$mm	12mm
4	c/c distance of bolt holes	6d=96mm	86mm (5d min)
5	Edge distance	3d=48mm	40mm
6	End distance	2d= 32mm	40mm

Test

specimen dimension from IS 4000:1992 and Lab standards

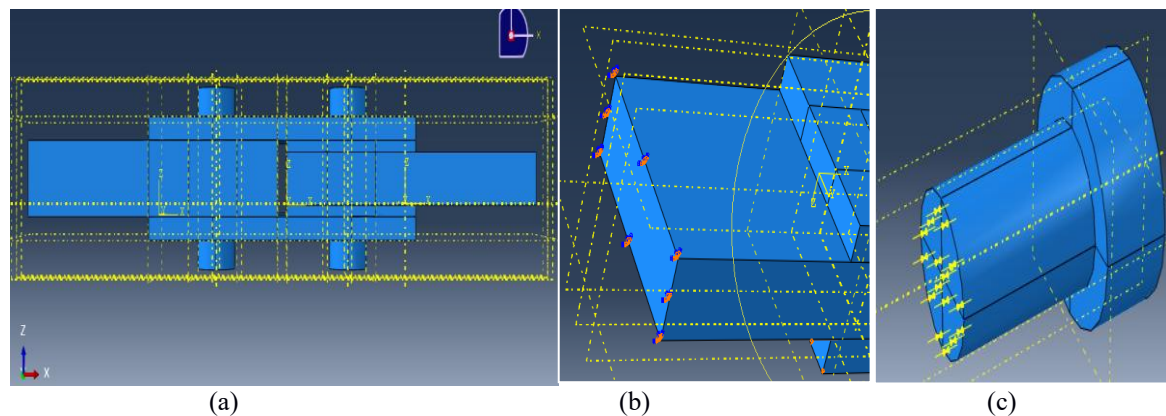|		
(a)	(b)	(c)

Fig. 2. a) Model geometry b) BC-fixed and c) Bolt load at centre of shank

3 Results and Discussion

Effect of different parameter on the interfacial pressure distribution was studied. There was no external load in the first stage of analysis, where the angle of interfacial pressure distribution onlydue to the bolt preload was analysed. In later stage, external shear load was applied and failure of the model was checked. The high strength material used for the metal plates in the analysisprevented their yielding.

3.1 Effect of bolt preload magnitude on interfacial pressure distribution

Bolt pre-tension increasing from 80 kN to 130 kN was applied on M16 bolt. The Interfacial pressure distribution was plotted on the top of the cover plate and on the top of the friction plate. (Refer Fig. 2).

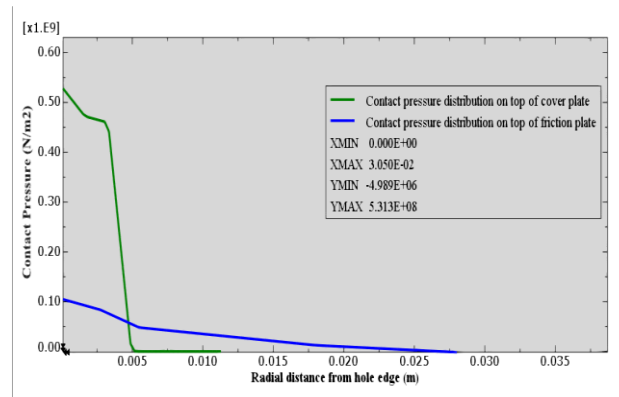| Magnitude of Bolt Preload (kN)	80	100	110	130
Radius of separation (from hole edge) mm	26.26	26.5	26.6	26.8

Fig. 3. Interfacial pressure distributions for 80kN bolt load on 8mm cover plate model

Table 2 shows the effect of bolt preload magnitude on the distribution of the interfacial pressure. It can be seen that radius of separation is not much affected by the bolt preload magnitude.

Table 2 Radius of separation with the different bolt preloads on 8mm cover plate model

3.2Effect of plate thickness on interfacial pressure distribution

The models with the 12mm and 16 mm thick cover plate were studied to know the effect of the cover plate thickness on the interfacial pressure distribution. Width of the plate required to dissipate the contact pressure completely is found insufficient in case of the 16mm thick cover plate model. Table 3shows radii of separations for 8mm and 12mm cover plates. It is observed that radius of separation increases with the increase in the plate thickness.

Table 3 Radius of separation for different plate thicknesses

Plate Thickness	Bolt Preload (kN)	Radius of separation from hole edge (mm)
8mm	80	26.26
	130	26.83
12mm	80	30.02
	130	30.04

The angle of interfacial pressure distribution has been calculated by connecting the two points of zero contact pressure on the cover plate and top of middle plate respectively. Table 4 shows angles of interfacial pressure distributionfor different cover plate thicknesses.

Table4 Angle of interfacial pressure distribution (in degrees) for different steel cover plate thicknesses

Plate thickness	8 mm		12 mm		16 mm	
Bolt load kN	80	130	80	130	80	130

For 0 MPa	69.42	69.91	64.84	64.42	-	-
For 10 MPa	61.62	65.72	56.17	61.55	53.3	57.79

3.3 Effect of material and coefficient of friction on angle of interfacial pressure distribution

Contact pressure distribution on top of 12 mm Aluminium cover plate was found out from the numerical simulation. The radius of separation was 29.28mmfor this model. It was found that there is a minor effect of the material and the coefficient of friction of the surfaces on interfacial pressure distribution.

3.4 Effect of angle of interfacial pressure distribution on the stiffness of the joint

As it is seen from the Table 5, the dimensionless stiffness is highly dependent on the half-apex angle. The dimensionless stiffness jumps from 0.77 to 2.6for the 8mm cover plate for half cone angles 30^0 and 70^0 degrees respectively.

Table 5 Dimensionless stiffness for different values of half apex angle

α (Degrees)	Dimensionlessstiffnessfor used cover plate thicknesses	
	12mm	**8mm**
30	0.73	0.77
40	0.95	1.00
50	1.25	1.301
60	1.706	1.75
70	2.55	2.603

3.5 Effect of meshing on the interfacial pressure distribution:

One of the observations in the study was change in the location of the maximum contact pressure on the cover plate with the meshing. As the mesh is made finer, the maximum contact pressure on the cover plate moves towards the hole edge (ref Fig.4).Ziada (1980) [7] observed that the peak pressure occurs as a ring under the edge of the bole head. The behaviour observed in this study might be related to the use of finite elements in the analysis which needs further investigation.
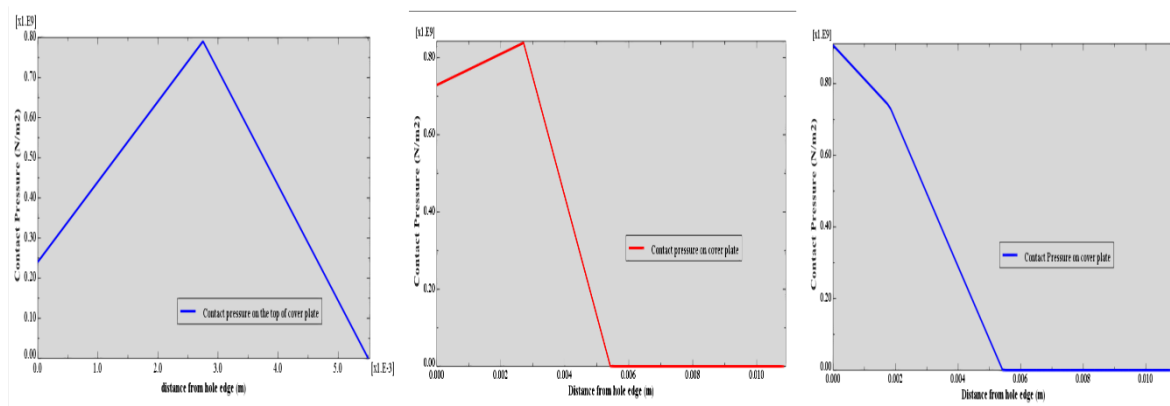

Fig. 4. Location of maximum contact pressure on cover plate (mesh getting finer from left to right)

4 Conclusions

This study underlines importance of determination of accurate angle of interfacial pressure distribution in connecting plates in the bolted connection for calculation of joint-member stiffness. The values of angle of interfacial pressure distribution for cover plates observed are 64^0 and 69^0 for model of double cover strap joint. Also it is was observed that angle of interfacial pressure distribution in metal cover plate of double cover strap joint is affected more by the cover plate thickness than due to its material and coefficient of friction. The important observation in this numerical study was that the finite element mesh size affects the location of the maximum contact pressure on the cover plate.

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