Influence of Loading Condition on Stress Intensity Factor Determination of Threaded Bolt

K.S. Jayakumar*, S. Suresh Kumar and M. Mohamed Niwas
Department of Mechanical Engineering, SSN college of engineering, Chennai – 603 110
***Corresponding author: E-Mail: jayakumarks@ssn.edu.in**

ABSTRACT

Generally cracks initiate at the free surface, at points of high stress concentration such as, root of the thread, thread to shank run out region, tool mark on the surface and at locations and there is sharp change in shape and size of the bolt. Thus there is need to evaluate the stresses in the crack tip to determine the bolt's residual life. The crack-tip stress fields are determined by stress intensity factor (SIF). The present work aims to determine the effect of loading condition on SIF determination of inclined crack at the root of the thread using numerical method. Crack depth ratio of 0.1 to 0.5 and crack inclination angle varying between 0^0 to 67.5^0 was considered. Loading conditions such as, far field loading, nut loading and thread face loading was considered. The crack region was divided from the geometry to apply fine mesh around the crack tip and a 20 node quadratic brick element was used to mesh the crack region. Mixed mode SIF was determined for various values of crack inclination angles and crack depth ratios. The magnitude of the load applied was kept constant (100 MPa) in all the cases. Lower values of SIF is observed for straight cracks subjected to thread face loading compared to other two loading conditions. SIF values estimated for a direct nut loading condition is lower at short crack depth due to higher stress concentration at the thread root region whereas SIF values of far field loading condition increases with crack depth ratio. As the angle of inclination increases, SIF values found to be decreased which may be due to reduction of crack opening displacement with inclination.

KEY WORDS: Stress Intensity Factor (SIF), Crack depth ratio, Geometry correction factor

1. INTRODUCTION

In our daily life, we use nuts and bolts to tighten the components of a machine or structure. It is generally done by placing washers below the nuts. Depending on the working conditions, the stresses could be due to load at the nut face, far field loading and load at the thread face. It has been found out that load at the first thread face will be maximum (P), and subsequently P/2, P/4, etc. for the other thread faces following the first one. Generally, cracks initiate due to various reasons like porosity, inclusions, improper casting technique, presence of foreign (non-homogenous) materials etc. The structural integrity of the threaded joint in service depends on the magnitude of the stresses and the severity of the stresses along the crack front. These crack tip stresses are defined by Stress Intensity Factor (SIF). The Geometry Correction Factor ($Y=K/\sigma\sqrt{\pi a}$) which is used in SIF calculations depends on the crack depth ratio (a/t), crack angle, and the points considered along the crack front. Many researchers have made an effect by analytical and numerical methods to determine the influence of crack plane inclination on SIF of single crack on threaded bolt and nut. Mixed mode of stress filed in the crack tip strength evaluation and its growth was studied and crack path tracking techniques were developed (Yates, 2008).

Yukitaka (2013), determined the threshold SIF for small cracks in high strength steels under hydrogen environment by studying the failure of hydrogenpre-charged cylindrical specimens loaded in uni-axial tension (Yukitaka, 2013). The intensity of threshold stress decreases as the size of inclusion decreases. Koa et al elucidated the effect of load history omission on fatigue crack growth behavior from experimental determinations of opening loads (Koa, 2005; Sallam, 2011), evaluated on SIF of cracked lapped joints using 3D finite element method (FEM) and a group of 3D finite element models for steel lapped joint was constructed (Sallam, 2011). They assumed different clamping forces and co-efficient of friction (Nicoletto, 1986 & Barsom, 1971).

Available SIF solution of threaded fasteners is limited to mode I loading condition and the effect of mode II and mode III fracture has been neglected. Limited work has been carried out to determine SIF of inclined cracks in a threaded bolt. The important objectives of the present paper are

- To determine the influence of different types of loading such as nut loading, far field loading and thread face loading on SIF.
- Understanding the effect of crack depth ratio (a/t) and crack inclination angle on SIF.

In the present work, an attempt has been made to determine the effect of loading conditions and inclination angle on SIF of a bolt. Aluminum bolt was considered with different crack inclinations and crack depth ratios. Crack depth ratio ranging between 0.1 and 0.4 and crack angles ranging between 0^0 and 67.5^0 was considered.

Description of the Finite Element Model: SIF for crack in a bolt and is estimated using ABAQUS finite element software. 2-D Finite Element model of the bolt and nut assembly is shown in fig.2. Single bolt and nut thread has been considered for far field loading condition while multiple threads are considered for other loading conditions. As the effect of helix angle has been neglected, symmetric bolt model has been considered for various crack inclination angles. The line crack is introduced at the thread root region due to severe stress concentration. Different crack angles and crack depth ratios were considered to study the effect of their influence on SIF. Aluminum bolt and nut has been considered in the present work and their corresponding material properties are given in table 1.

Table.1. Mechanical Pro

	Material	Young' Modulus (GPa)	Poisson's Ratio
Nut	Aluminium	76	0.3
Bolt	Aluminium	76	0.3

Perties of the base materials:

(a) (b)

Figure.1. FE model of the bolt and nut assembly

Fig.1, shows the fine element model of the bolt and nut assembly considered for the present study. The region around the crack tip is partitioned to apply fine mesh around it.

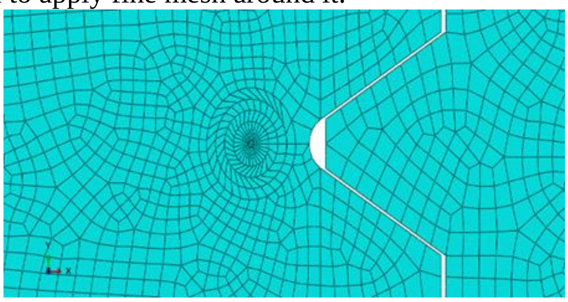
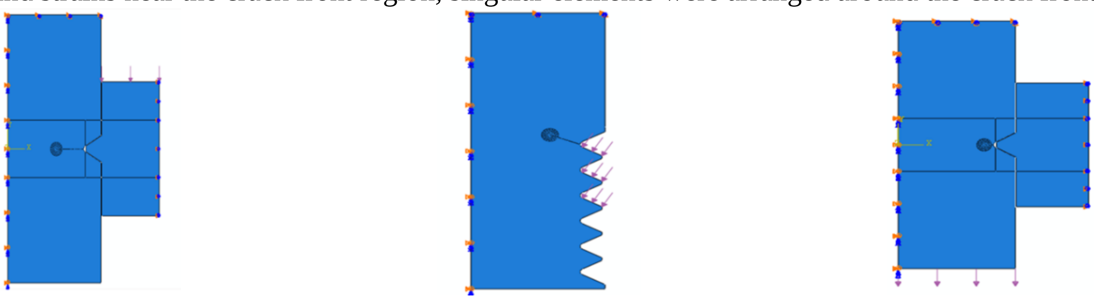


Figure.2. Mesh region around the crack tip

Fig.2, shows the mesh around the crack tip region. To simulate the theoretical inverse square root singularity of stresses and strains near the crack front region, singular elements were arranged around the crack front.



(a) (b) (c)

Figure.3. Various loading methods of bolt

If all the midrace nodes of the brick elements are moved to their quarter points closest to the crack line, the variations in the local stress and strain fields can be reduced. Due to 3-D nature of the crack advancement, crack propagation direction cannot be predicted and hence 'crack plane normal' approach was used to define the crack propagation direction.

To study the effect of loading on SIF of cracked bolt three different loading conditions such as (i) nut loading, (ii) direct thread face loading and (iii) far field loading conditions were considered as shown in fig. 3. Under nut loading condition, the pressure load was applied at the nut surface which is in contact with the bolt thread whereas the pressure load (P) is applied directly over the thread face for thread face loading. As the load distribution between the bolt and nut is not uniform, half of the total magnitude was applied at the second thread and quarter portion of the load was applied at the third thread. Under far field loading, the pressure load was applied at the bottom of the bolt as shown in fig. 3c.

2. METHOD OF ESTIMATING MIXED MODE SIF

When the nut and bolt joint is mechanically loaded, the crack may concurrent open and slide relative to each other. The mixed mode fracture is formed in a joint due to complex loading condition or crack location. When the load reaches a critical value, the crack starts to grow and usually kinks into a new direction. The various modes of fracture for a growing crack are mode-I, mode-II and mode-III. In mode-I fracture the crack surfaces separate directly apart from each other and therefore it is designated as opening mode fracture. Mode II fracture makes the crack surfaces to slide over one another perpendicular to the leading edge of the crack and designated as edge sliding mode. In mode-III fracture the crack surfaces slide with respect to each other parallel to the leading edge of the crack and therefore it is termed as tearing mode. In this work, the mixed SIF is calculated for the crack located in the nut and bolt joint using FEM. The stresses due to three types of loading were considered, namely nut loading, far field tensile loading and thread face loading. Due to these stresses, the mechanical joint experiences a mixed mode fracture. These stresses are responsible for the opening of the crack and therefore the Stress Intensity Factor (SIF) values for different modes are calculated along the crack front. The mixed SIF and Geometry Correction Factor are calculated using the following relations.

$= K_I^2 + K_{II}^2$ (1)

Where $K_{I,}$ K_{II} are mode I and mode II stress intensity factors,

The geometry correction factor (Y) under mixed mode condition is determined from the following equation.

$Kmix = Y\sigma \sqrt{\pi a}$ (2)

Where Y- geometry correction factor

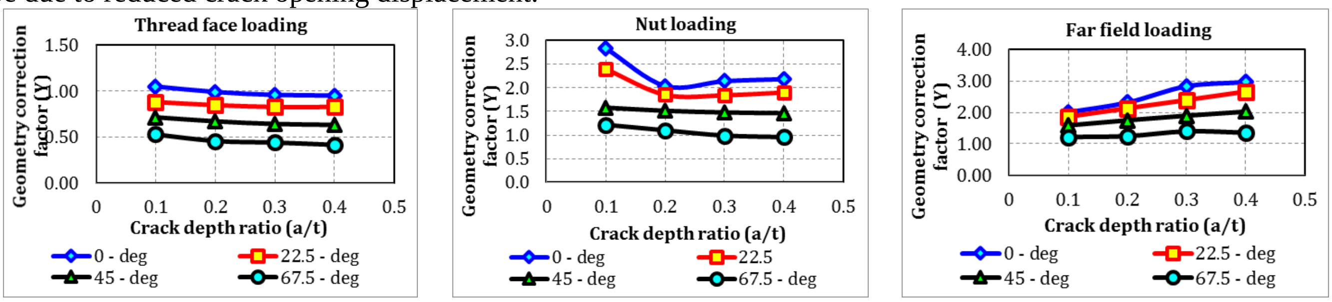
a - crack length (mm)

σ -far field stress (MPa)

3. RESULTS AND DISCUSSIONS

The present work describes the influence of stresses due to different types of loading on SIF determination of inclined crack in a bolt. Bolt with different crack inclination angle was considered for different crack lengths. Variation of SIF with crack depth ratios was studied for all the three types of loading. Normalized coordinate system was used to represent the points along the crack front. The geometry correction factor (Y) was calculated with consideration of mode II fracture which will increase with crack plane inclination angle.

Effect of crack inclination angle on Geometry Correction Factor (Y): Figure 4 shows the effect of bolt loading condition on geometry correction factor (Y). For straight cracks ($\theta = 0^0$) SIF solutions of far field loading condition over estimates the SIF values compared to nut loading condition. Contact constraints (surface to surface) were applied at the bolt and nut interface. As the angle of inclination increases SIF observed to be decreased which may be due to reduced crack opening displacement.

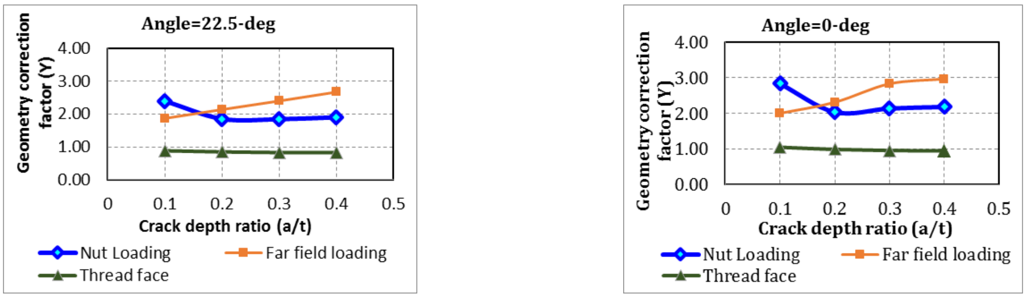


(a) **(b)** **(c)**

Figure.4. Effect of crack plane inclination on SIF

Irrespective of the crack plane inclination angles, direct thread face loading SIF values are observed to be less than other two loading conditions. It is also noted that, SIF values of nut loading condition are higher than far field loading and direct thread face loading which is due to higher stress concentration factor of thread root region.

Effect of loading condition of on Geometry Correction Factor(Y): Figure.5, shows the effect of bolt loading condition on geometry correction factor (Y). For straight cracks ($\theta = 0^0$) SIF solutions of far field loading condition over estimates the SIF values compared to nut loading condition. Contact constraints (surface to surface) were applied at the bolt and nut interface. As the angle of inclination increases SIF observed to be decreased which may be due to reduced crack opening displacement. Irrespective of the crack plane inclination angles, direct thread face loading SIF values are observed to be less than other two loading conditions. It is also noted that, SIF values of nut loading condition are higher than far field loading and direct thread face loading which is due to higher stress concentration factor of thread root region.



(a) **(b)**

Figure.5. Effect of crack inclination angle on SIF

4. CONCLUSION

Mixed mode SIF solution of inclined cracks in a bolt subjected to different loading conditions is presented. The following conclusions are obtained from the numerical analysis.

- As the crack depth ratio increases, SIF values of nut loading and thread face loading decreases while SIF of far field loading increases.
- Irrespective of the crack angle, SIF estimated under far field loading condition over estimates the correction factor compared to other two loading conditions.
- Higher SIF of bolt under nut loading condition mainly due to higher stress concentration at the thread root region.
- As the crack angle increases, mode I SIF decreases as the simultaneous increase of mode II fracture.

REFERENCES

Barsom JM, Imhof EJ, Rolfe ST, Fatigue-crack propagation in high yield-strength steels Engineering Fracture Mechanics, 2 (4), 1971, 301-306.

Guagliano M, Pau M, Analysis of internal cracks in railway wheels under experimentally determined pressure distributions, Journal of Tribology International, 40, 2007, 1147-1160

Korin I, PerezIpina J, Experimental evaluation of fatigue life and fatigue crack growth in a tension bolt–nut threaded connection, International Journal of Fatigue, 33, 2011, 166-175

Mohamed Ferjani, Daniel Averbuch, Andrei Constantinescu, A computational approach for the fatigue design of threaded connections, International Journal of Fatigue, 33, 2011, 610-623

Nicoletto G, Experimental crack tip displacement analysis under small-scale yielding conditions, International journal of fatigue, 8 (2), 1986, 83-89.

Sallam H.E.M, El-Sisi A.E.A, Matar E.B, El-Hussieny O.M, Effect of clamping force and friction coefficient on stress intensity factor of cracked lapped joints, Engineering Failure Analysis, 18, 2011, 1550-1558.

Soon-Gyu Koa, Chung-Seog Ohb, Byung-Ik Choi, The elucidation of load history editing effect on fatigue crack growth by crack closure concept, International Journal of fatigue, 27, 2005, 255-262.

Yates JR, Zanganeh M, Tomlinson R.A, Brown M.W, Diaz Garrido F.A, Crack paths under mixed mode load, Journal of Engineering fracture mechanics, 75, 2008, 319-330.

Yukitaka Murakami, Toshihiko Kanezaki, Petros Sofronis, Hydrogen embrittlement of high strength steels, Determination of the threshold stress intensity for small cracks nucleating at non-metallic inclusions, Journal of Engineering Fracture Mechanics, 97, 2013, 227-243.