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Stress Intensity Factor Determination of Multiple Straight and Oblique Cracks in Double Cover Butt Riveted Joint

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ABSTRACT—In real life, components are subjected to cracking at many vulnerable locations such as the rivet holes. However, we do not consider for the presence of multiple cracks. Unlike components with a single crack, the behavior of these components under tension cannot be predicted. When two cracks approach one another, their stress fields influence each other and produce enhancing or shielding effect depending on the position of the cracks. In the present work, stress intensity factor (SIF) solution of multiple straight and oblique cracks in a rivet hole is considered. Crack depth ratios (a/t) of 0.1, 0.15 and 0.2 have been considered for both straight and inclined cracks. SIF solution of single and multiple cracks were compared for different crack depth ratios. It is noted that as the crack depth ratio increases, SIF decreases significantly irrespective of the points along the crack front. At lower crack depths, the dominant mode of fracture is mode I. As the crack depth ratio increases, it is noted that, the effect of mode II and mode III fracture increases.

KEYWORDS—stress intensity factor, multiple cracks, failure of riveted joints.

I. INTRODUCTION

Riveted joints play an important role in structural members used in automobile, shipping and aviation industry. Rivets are used to fasten metal plates and steel section in structural works such as bridges and roof trusses and in the construction of pressure vessels such as storage tanks and boilers. Riveted joints are very effective in designs subjected to pronounced vibration loads where welded joints are less reliable. Riveted joints may also be employed to connect metals which are difficult to weld together and in the joints which permit no heating welded due to possible tempering or warping of the finished machine parts. Riveting is the process of forming a well-shaped concentric head from the projecting tail end of the shank rivets inserted in the holes previously drilled in the plates to be fastened, without allowing it to develop an initial stress so that it can take up the designed working shear load. A riveted joint may fail in the following ways: a)Tearing of the plate at an edge, b)Tearing of plates across row of rivets, c) Double Shear of rivets, d)Crushing of rivets. By allowing a minimum margin(m=1.5d) the first kind of failure can be avoided. When rivets in a row are separated by a sufficient distance so that load applied is less than tearing resistance, tearing of plates across rivets can be avoided. In the following model double shear of rivets is the main reason for failure. Presence of structural defects like cracks are present, the stresses at the crack tips are greatly increased. Depending on the geometry, size and position of these defects, the joint gets weaker. Generally, cracks initiate at the rivet hole due to stress concentration. The structural integrity of the riveted joint with multiple cracks depends on the length of each crack, its orientation with respect to the other and the distance between cracks and the severity of stresses at the crack tips. These crack tip stresses are defined by Stress Intensity Factor (SIF).The geometry correction factor ($Y=K/\sigma\sqrt{\pi a}$) is used in SIF calculations. Many researchers have studied the various modes of failure in riveted joints numerically and experimentally. Galatolo and Karl-Frederick [1] combined experimental and computational study of the residual strength of a butt joint panel with multiple site damage (MSD).The authors had computed loads for crack initiation propagation and subsequent crack link up and panel failure. They quantified geometric non-linear effects and the sensitivity to variations in fracture parameters and found an excellent overall agreement between experimental and numerical values. Keçelioğlu, Galip[2]studied and analyzed a three dimensional model of single riveted lap joint (with and without a crack). By using finite element method, stress and fracture analyses were carried out under both the residual stress field and external tensile loading. The stress intensity factor solutions obtained could be useful for correlating fatigue crack growth rates, fracture toughness computation, and multiple site damage (MSD) analysis in aircraft bodies. C. Cali` and Citarella[3] summarized a numerical procedure aimed at the residual strength assessment of a cracked butt-joint, based on R-curve analysis and plastic collapse prediction. In a linear elastic fracture analysis, the Stress Intensity Factors evaluation was based on the use of the Dual Boundary Element Method. Experimental joint collapse load was available for comparison with numerical results, in order to validate the procedure. Langrand.B, Deletombe.E, Markiewicz.E, Drazetic.P[4] (2001) used Arcan experimental tools to measure the tensile strength of riveted joints. The rods of rivets broke in their study and the corresponding simulations were developed in FEM software. Gurson damage criterion was utilized to depict the fracture process of the riveted rod. However, a systematic and comprehensive investigation of the failure modes of riveted joints is very scarce. The main objectives of this study are:

1. Numerical SIF determination of multiple straight and inclined cracks in a butt riveted joint.
2. To understand the effect of crack (a/d) depth ratio ratios in SIF
3. To investigate the effect of crack inclinations with respect to load on SIF.

In the present work, the SIF has been evaluated for models with (a/d) ratios of 0.1,0.15 and 0.2. These ratios were also modeled with an inclination of 20^{o} to the normal to the load. Loads were reduced as the ratios increased. The top and front views of one model is shown in Fig.1. The nomenclature of various symbols is given in Table 1.

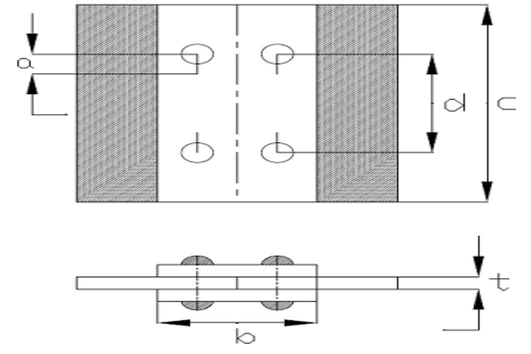

Fig. 1. Top and Front views of the riveted joints

Table 1. Nomenclature

Variable	What it denotes
r	radius of rivet (mm)
d	distance between rivet centres measured along the length (mm)
a	crack length (mm)
t	thickness of plate (mm)
c	length of plate (mm)
b	width of plate (mm)

II. FINITE ELEMENT MODELING OF DOUBLE COVER BUTT RIVETED JOINT

The double cover butt joint was modeled and analyzed using Abaqus. The 3-D model was drawn with dimensions of each plate being 80 mm x 40 mm. Snap head rivets of shank diameter 6 mm were used. The cover plates had 4 holes of diameter 6 mm at a distance of 10 mm from the longer side on either side and a distance of 20 mm from the shorter side on either side. The plates to be fastened have 2 holes each of the same diameter as the cover plate. The rivets were then assembled into the holes. The assembled model is shown in Fig. 2. The plates and the rivets are made of Aluminium 6061-T651. The properties are mentioned in Table 2. Cracks were introduced at the rivet holes at various (a/d) ratios (0.1, 0.15, and 0.2) so that they were normal to applied load in one case and inclined at 20^{o} to the normal in the other. Three models with only two cracks at opposite end of the plates were also modeled. In all, nine different conditions were analyzed. Tensile loads were applied to these models to determine SIF at the crack front. Boundary conditions were chosen and applied to facilitate mixed mode fracture. Hex meshes were used for all plates. Tet meshes were used for rivets. The meshed model is shown in Fig 3. The output was obtained after analysis and the value of the geometric correction factor was calculated.

Table 2. Mechanical properties of base metal

Properties	Plates and Rivets
Material	Aluminium (AA6061-T6)
Young's Modulus	68900 MPa
Poisson's ratio	0.33

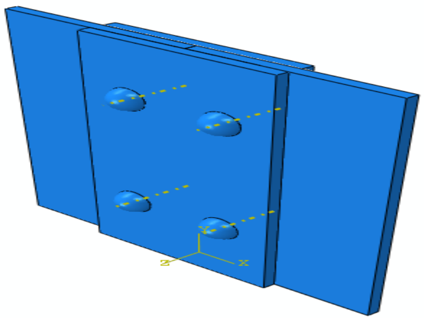

Fig. 2. Assembled model of the joint to be tested

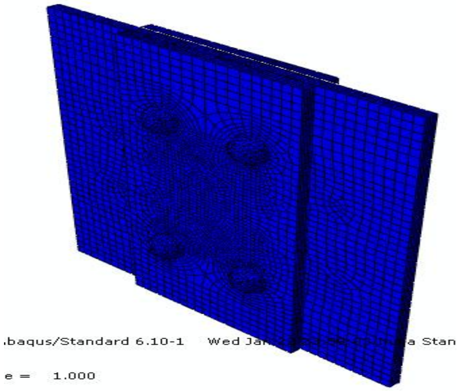

Fig. 3. Model after meshing

A. Modeling of cracks

To determine the effect of multiple crack SIF of riveted joint, four surface cracks were introduced at in the model, one at each of the rivet hole. The cracks were so modeled, such that they were present in all the 3 layers i.e., the 2 cover plates and the plate in between. 4 circular contours were introduced around the crack front to get a more accurate value of stress intensity factor for mixed modes. Partitions were made as necessary to mark crack fronts and seams. Surface-to-Surface interactions between the shank and the inside of the rivet hole in the plate were assigned to ensure opening of crack under applied tensile load. A 3-D meshed crack front and contours in shown in Fig. 4.

Fig. 4. Meshed crack region

B. Estimation of mixed mode SIF

When the riveted joint is mechanically loaded, the cracks may simultaneously open and slide relative to each other. Fig. 5 shows the stresses at the cracks due to mixed mode fracture. 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 different 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 causes 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 designated as tearing mode.

In the present work, mixed mode SIF is calculated for opposite cracks located in a riveted joint using FEM. Transverse cracks are introduced at the centerline of the weld region opposite to each other. The cracks in the riveted joint experience mixed mode fracture due to the formation of non uniform residual stresses during. Far field tensile load is applied to the joint which causes the cracks to open and SIF values are calculated along the crack front. Currently the geometric correction factor (Y) is calculated from mixed mode fracture which includes the additional effect of mode II and mode III fracture. The mixed mode SIF is calculated from the following relation.

$$K^2_{mix} = K_I^2 + K_{II}^2 + \frac{K_{III}^2}{(1-\nu)} \qquad (1)$$

Where $K_{I,}$ $K_{II,}$ K_{III} are mode I, mode II and mode III stress intensity factors,The geometry correction factor (Y) under mixed mode condition is determined from the following equation.

$$K_{mix} = Y\sigma\sqrt{\pi a}$$

Therefore,

$$Y = \frac{K_{mix}}{\sigma\sqrt{\pi a}} \qquad (2)$$

Where Y- geometry correction factor
a - crack length (mm)
σ -far field stress (MPa)

The fatigue crack growth rate and residual life of the joint can be calculated from Paris equation

C. Results and discussions – SIF solution of multiple straight cracks.

SIF solutions of multiple straight and inclined cracks in a butt riveted joint has been attempted. Normalized coordinate system was considered to represent the points along the crack front. $[P/P_0 = \pm 1]$ represents the left and right edge of the crack front and $[P/P_0 = \pm 0]$ represents middle of the crack front. Figure 5 shows the effect of crack depth ratio on SIF of multiple straight cracks in a double cover butt joint. It is noted that, as the crack depth ratio increases, SIF decreases considerably and the SIF values are higher at the crack surface region compared to crack middle region. It is also observed that, the dominant mode of fracture is mode-I at lower crack depths and the effect reduces with increase of crack depth ratio (Fig. 5b). This is due to the fact that, as the crack depth ratio increases additional effect of mode II and mode III fracture increases considerably.

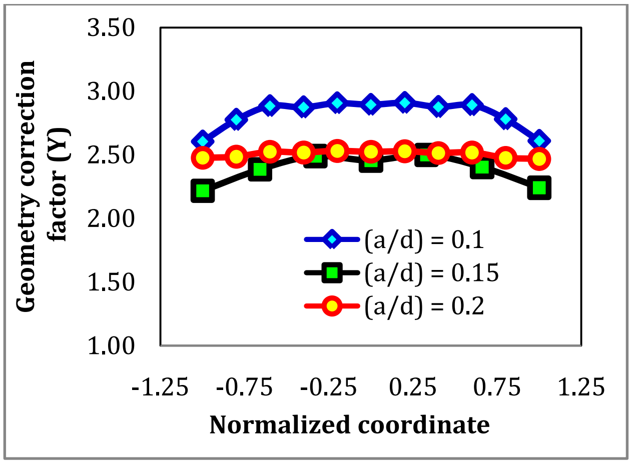

Fig. 5(a)

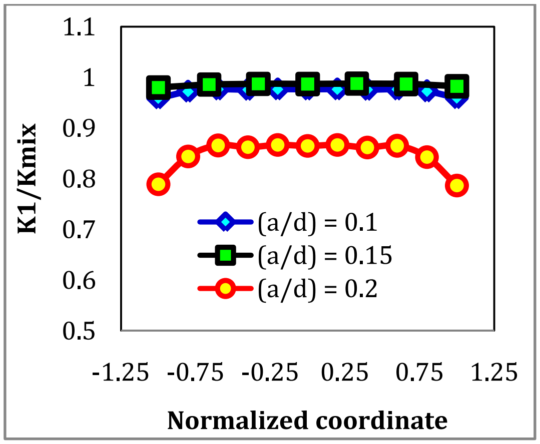

Fig. 5(b)

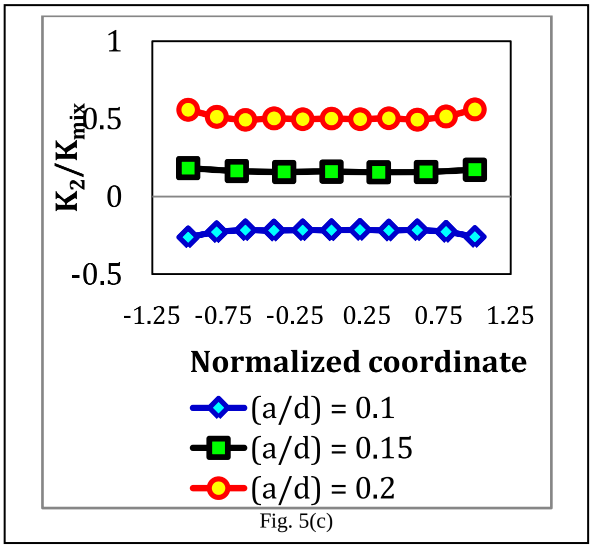

Fig. 5(c)

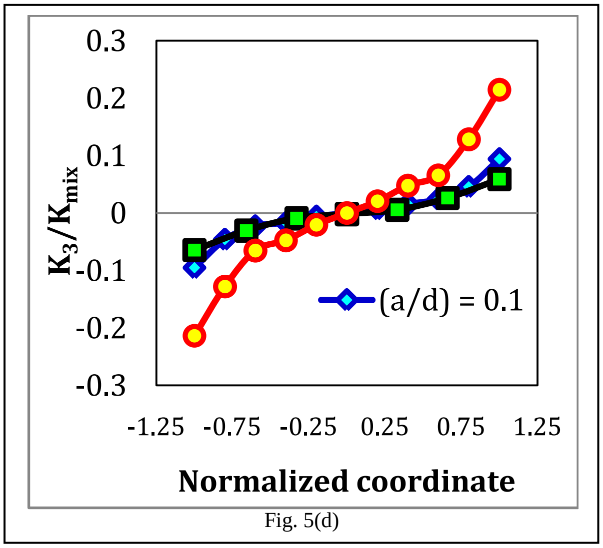

Fig. 5(d)

Fig. 5. Multiple straight crack SIF variation with crack depth ratio

D. Effect of number of cracks on SIF

Figure 6 (a to d) shows the SIF variation of reduced cracks in which number of cracks at the rivet hole region is reduced to two. In this condition also, SIF values are higher at the crack middle region compared to crack surface region. As the crack depth ratio increases, SIF of multiple cracks also increases and a significant variation is observed for the reduced number of cracks compared to four cracks. As the number of cracks reduces, SIF values decreases considerably. This is due to increased stiffness of the joint compared to four cracked model.

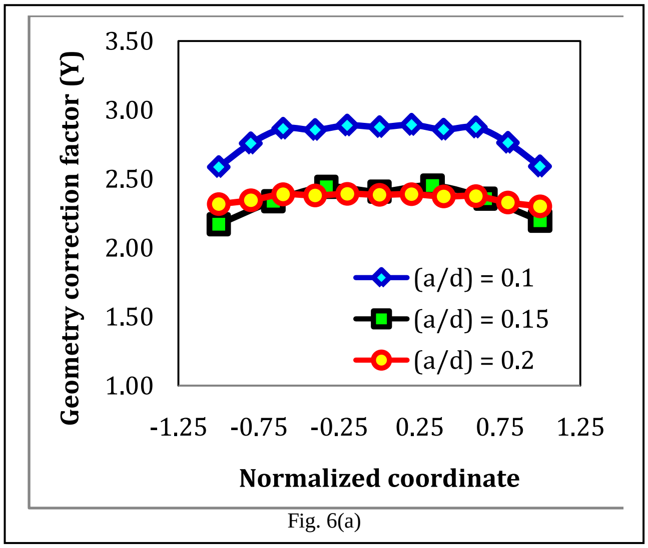

Fig. 6(a)

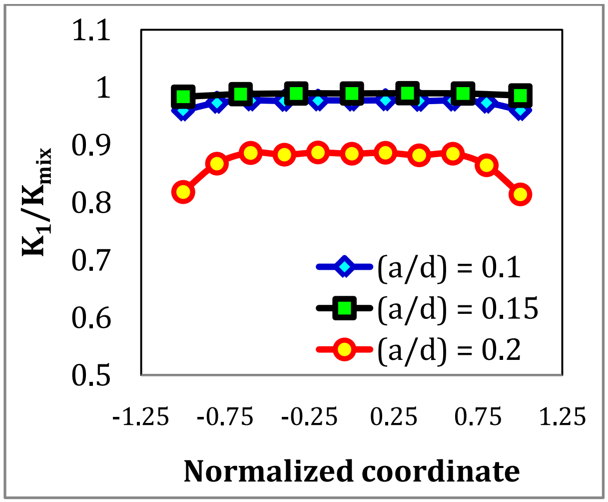

Fig. 6(b)

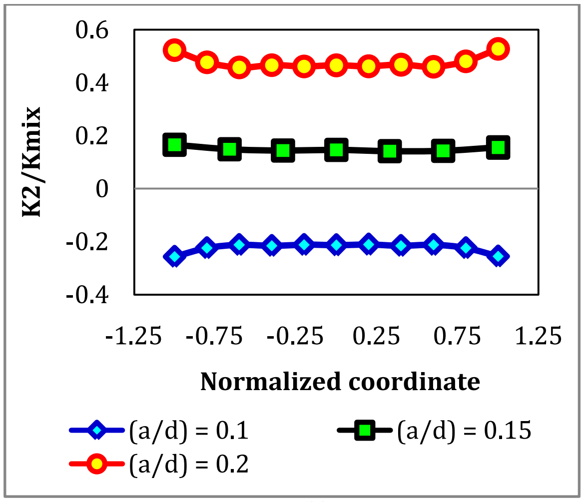

Fig. 6(c)

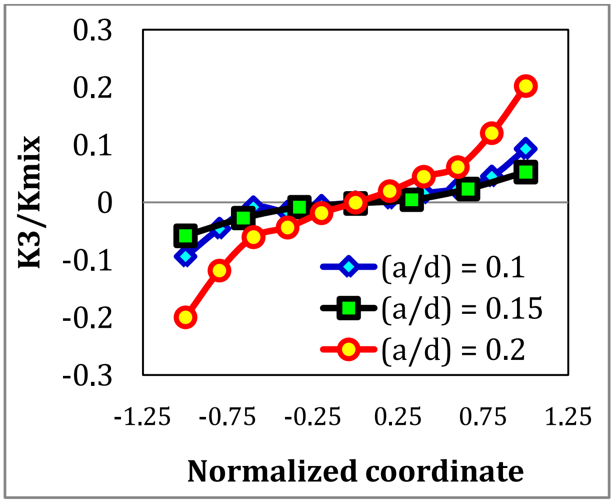

Fig. 6(d)

Fig. 6.Multiple straight crack SIF variation with crack depth ratio

E. Effect of crack inclination angle

Figure 7 (a to d) shows the SIF solution of multiple inclined cracks in a riveted joint hole subjected to far field loading condition. In contrast to straight crack models, SIF solution of inclined cracks increases with crack depth ratio as shown. At lower crack depths, the dominant mode of fracture is mode-I. As the crack depth ratio increases, the effect of mode II and mode III fracture increases considerably. Figure 8 shows the deformed shape of the riveted joint due to multiple inclined cracks at the rivet hole. It is noted that the additional influence of mode II and mode III fracture cannot be neglected though the far field loading is perpendicular to the crack plane.

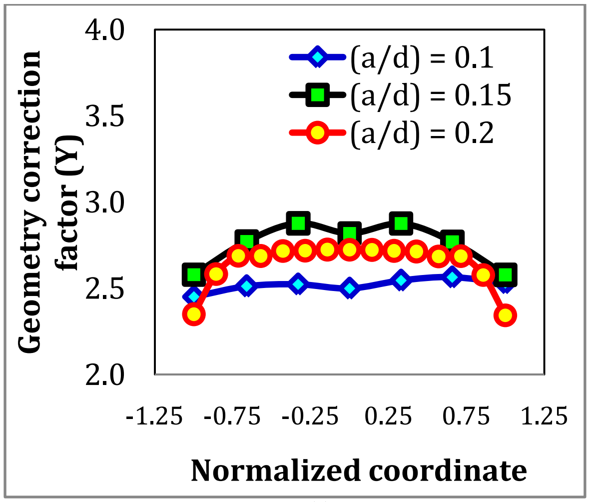

Fig. 7(a)

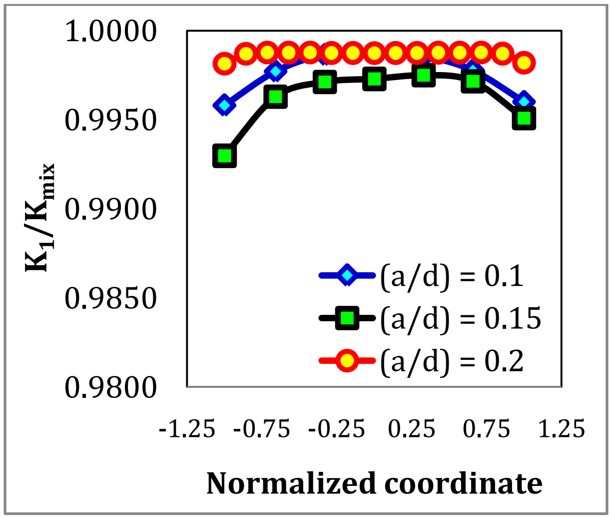

Fig. 7(b)

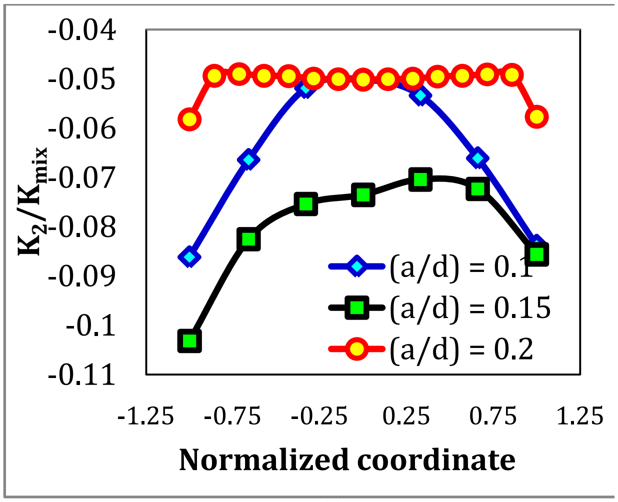

Fig. 7(c)

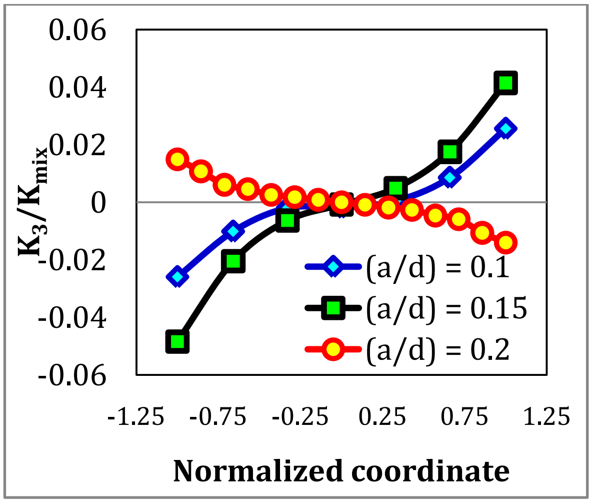

Fig. 7(d)

Fig. 7. Multiple inclined cracks SIF variation with crack depth ratio

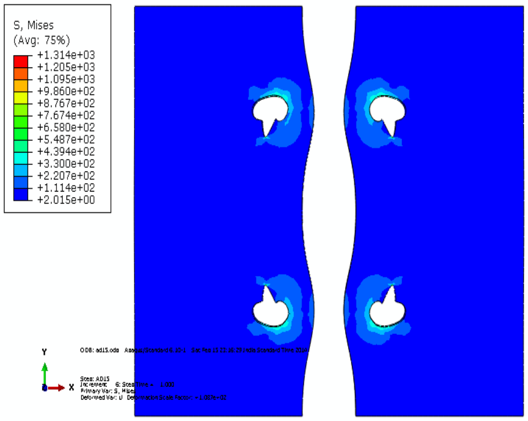

Fig. 8. Deformed riveted joint due to multiple inclined cracks

F. Conclusion

SIF solution of multiple straight and inclined cracks in a double cover butt joint has been determined numerically for different crack depth ratios. Comparison of straight and inclined crack SIF values reveals the following conclusions

1) As the crack depth ratio increases SIF solution of straight cracks decreases considerably. The geometry correction factor is high at the crack middle region irrespective of the crack depth ratios considered in the present work.
2) Significant variation in SIF solution of four and double cracked model was observed which indicates that number of cracks in a structure has an important role on structural integrity assessment of structures.
3) The effect of mode II and mode III fracture increases with inclined crack model compared with straight cracked model. Thus one cannot neglect the effect of mode II and mode III fracture even though the loading is perpendicular to the crack plane.

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