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Fatigue life and reliability assessment of metal structures

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ABSTRACT

This work focusses on the crack growth behaviour of the compact tension specimen under mixed-mode loading, and numerical investigation using ANSYS Mechanical APDL 19.2 extended finite element software with different loading angles. The fatigue life is predicted under-constant amplitude fatigue loading using the Paris' law. The predicted values of the fatigue life in the present study provide consistency with the experimental and numerical results. In addition, the study showed that the direction of crack growth follows the same literature trend of experimental results. According to the results of the crack growth path, there is no effect of changing the geometries thicknesses on the crack growth trajectory. Its only effect is the resistance to higher plastic deformation which decreases as the thickness increases.

1. Introduction

Structural life assessment and performance monitoring are linked and complemented with the goal of maintaining structural mechanisms to operate effectively in the light of eventual aging and degradation arising from operating conditions. The existence of a fatigue crack can cause a structural element to lose its overall effectiveness once the crack reached a critical length. Therefore the net portion resistant to longitudinal loads is minimized. In simple or complex modes there are many different mechanical failures. Due to fatigue deterioration of engineering structures has been a challenging problem facing engineers for many decades. Between 50 and 90 percent of these failures are estimated to be due to fatigue (Solanki, 2002). Structural life assessment regularly assesses the nature and functionality of a structural structure and proposes potential repair steps or the end of structural operational life. This essentially relies on the fracture mechanics theory and the durability theory. Fracture mechanics addresses the analysis of crack growth in a structural element . It aims at determining the local stress and strain fields around a crack tip in terms of local variables such as loading and structural geometry. Furthermore, the reliability theory defines a structure's possibility of completing its anticipated function over a time interval (Ibrahim, 2015). (Stephens, Fatemi, Stephens, & Fuchs, 2000) reported that the total cost to the US economy due to fatigue and fracture is about 4 percent of the total national products, i.e. US$ 356 billion. They asserted that proper design and maintenance could substantially reduce these costs. Components in engineering are almost always subject to complicated variable amplitude loading.

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Although the effectiveness of fatigue within multiaxial nonproportional arbitrary loading has been identified in past few years and extensive investigations have been carried out, even though, studies of the constant amplitude of multiaxial fatigue have been conducted for quite a long time (X. Chen, Jin, & Kim, 2006). As environmental loads are also multi-directional in nature, the fatigue cracks may propagate under mixed-mode conditions (He, Liu, & Xie, 2014; Rege & Pavlou, 2019; Rhee, 1989; Riahi, Bressolette, Chateauneuf, Bouraoui, & Fathallah, 2011). The majority of failures in service is of mixed-mode type, where the cracks do not propagate in the direction normal to the applied load. In reality also mixed mode can be observed, e.g. in turbine shafts or railway tracks by a sudden change of the loading direction. Normally the amount of energy available for fracture depends on the stress field around the crack, which is determined by the stress intensity factor. Different methods developed by many researchers evaluate the value of the stress intensity factor, which depends on the loading mode. If the inertia of relatively wide pieces of a structure is sufficiently large to allow the inclusion of kinetic energy to correctly balance the fracture strength, then the dynamic nature of the fracture dominates the assessment. For a crack that is already propagating, the inertial effects are important when the crack tip speed is small compared with the stress wave velocities. This fact has been realized in the theory of fracture mechanics under the name of dynamic fracture and peridynamic. To perform the numerical analysis for fatigue and failure prediction, there are many finite element programs such as ANSYS, ABAQUS, NASTRAN, etc. which proved to give an accurate results. Various problems concerning fatigue crack growth can be found in the literature using different approaches for simple and complex geometries in two and three dimensions (Abdulnaser M Alshoaibi, 2010, 2015; Abdulnaser Mohammed Alshoaibi, 2019; Abdulnaser M Alshoaibi & Fageehi, 2020). The aim of this paper is to use the extended finite element method implemented by ANSYS APDL 19.2 to investigate the effect of the loading angle for the CTS specimen with different initial cracks.

2. Numerical Predication of Mixed Mode Fatigue Life

Mainly, three methods were widely used to demonstrate the fatigue evaluation of materials, the fracture mechanics method (Paris & Erdogan, 1963), the strain-life method originally developed by (Coffin, 1963) and the stress-life approach introduced by (Wöhler, 1860).

In this research, the first approach was used to predict fatigue life by which the SIFs would identify the crack tip individually. Therefore, an accurate determination of the direction of fatigue crack is essential in order to predict the assessment of fatigue life. The maximum tangential stress criterion theory was used to estimate the angle of crack deflection (Alegre, Preciado, & Ferreño, 2007; H. Chen et al., 2019; Sajith, Murthy, & Robi, 2019) as:

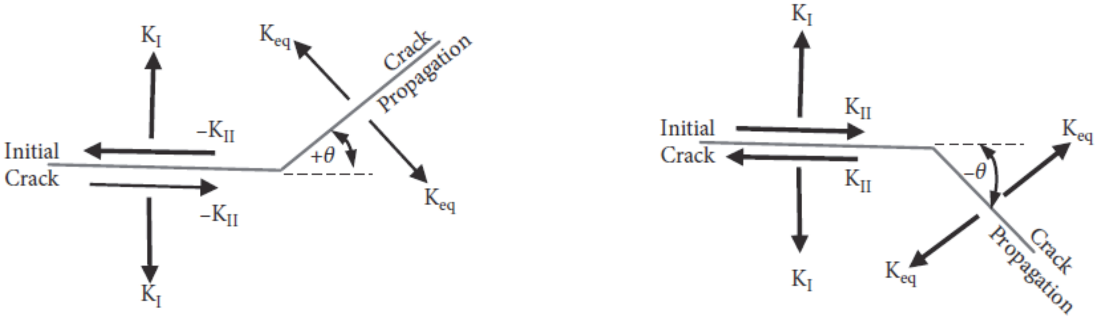
$$\theta = 2\arctan\left(\frac{1}{4}\frac{K_I}{K_{II}} + \frac{1}{4}\sqrt{\left(\frac{K_I}{K_{II}}\right)^2 + 8}\right) \qquad \text{for } K_{II} < 0 \tag{1}$$

$$\theta = 2\arctan\left(\frac{1}{4}\frac{K_I}{K_{II}} - \frac{1}{4}\sqrt{\left(\frac{K_I}{K_{II}}\right)^2 + 8}\right) \qquad \text{for } K_{II} > 0 \tag{2}$$

The two possibilities for the crack growth direction are showed in Fig. 1. Prediction of fatigue crack growth using the corresponding stress intensity factor is the most commonly used approach for structures with complex loading under mixed mode.

Using a modified formula of Paris law, a researcher (Tanaka, 1974) proposed a power law for the fatigue crack growth relationship with ΔK_{eq}, which is specified as:

$$\frac{da}{dN} = C(\Delta K_{eq})^m . \tag{3}$$



(a) (b)

Fig. 1. Crack growth angle (a) $K_{II} > 0$ (b) $K_{II} < 0$

From Eq. (3), for a crack increment, the number of life cycles of fatigue may be predicted as:

$$\int_0^{\Delta a} \frac{da}{C(\Delta K_{eq})^m} = \int_0^{\Delta N} dN = \Delta N \tag{4}$$

Fig. 2 shows the forces distribution according to the loading angles used in ANSYS. Based on the following formulas (Richard 1985), the uniaxial load F is compared to the corresponding loads acting on various holes of the six holes:

$$F_1 = F_6 = F(0.5\cos\alpha + \frac{c}{b}\sin\alpha) \tag{5}$$

$$F_2 = F_5 = F\sin\alpha \tag{6}$$

$$F_3 = F_4 = F(0.5 * \cos\alpha - (c/b)\sin\alpha) \tag{7}$$

where α is the loading angles, *c* and *b* are length parameter shown by Fig. 2 (*c* = *b* = 54 mm). Table 1 displays final values of all loading forces with different loading angle.

Table 1

Values of forces F1 to F6 according to load angle α

α	**F_2=F_5**	**F_1=F_6**	**F_3=F_4**
15	0.259 F	0.742 F	0.224 F
30	0.5 F	0.933 F	-0.067 F
45	0.707 F	1.061 F	-0.354 F
60	0.866 F	1.116 F	-0.616 F
75	0.966 F	1.095 F	-0.837 F
90	F	F	-F

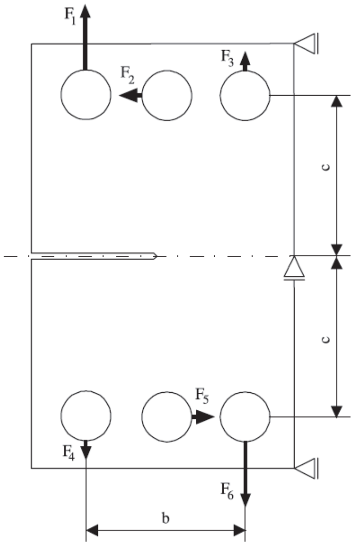
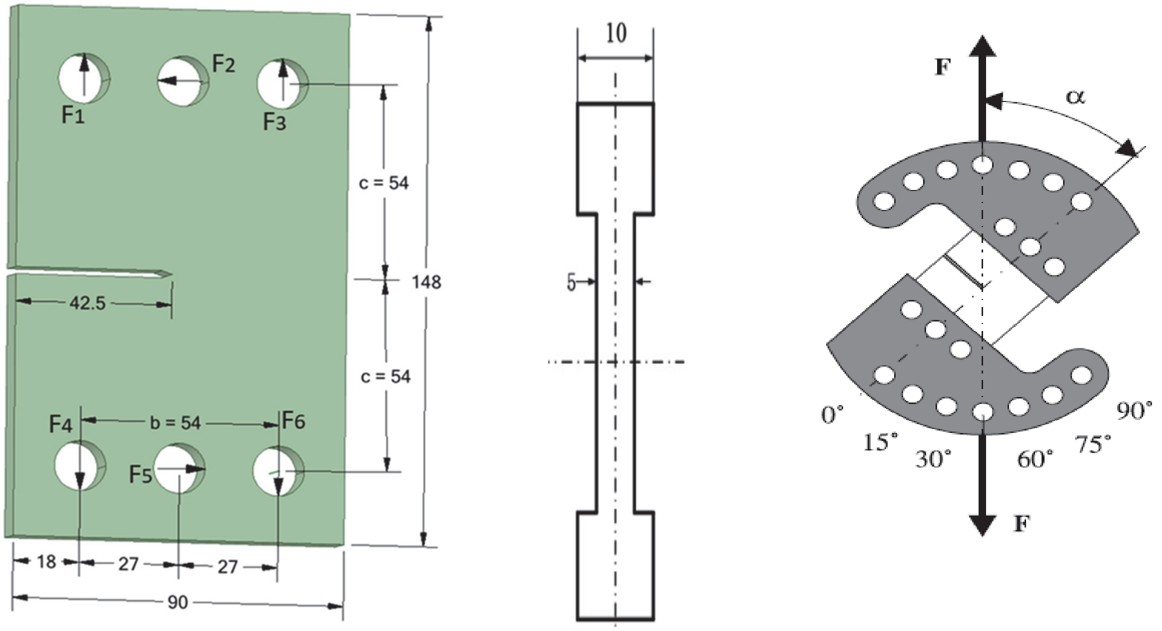


Fig. 2. loading and boundary condition for CTS

3. Results and Discussion

Extended finite element software ANSYS Mechanical APDL 19.2 is introduced to simulate the fatigue crack growth for different type of loading angle of the compact tension specimen (CTS). Fig. 3a displays the CTS geometry, and Fig. 3b shows its proposed loading angles. Fig. 4 shows the 3D finite element mesh for the CTS geometry, with number of nodes = 201567 and number of element = 132525.



(a) (b)

Fig. 3. CTS-geometry (a) dimensions and (b) loading angles

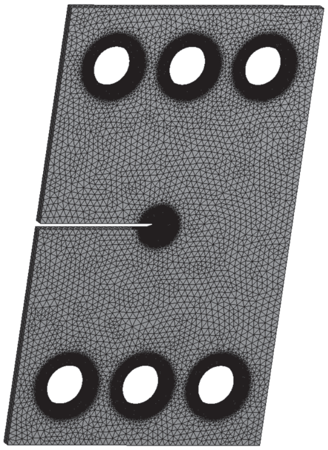


Fig. 4. 3D mesh for CTS specimen (No. of nodes = 201567 and No. of elements = 132525)

According to the values of the loading angle (α), which can be changed in stages of 15° from 30° to 60°, the modes of loading will change to mixed mode. The considered material was aluminium alloy having an elasticity module of $E = 74$ GPa, ν=0.33, $\sigma_Y = 517$ MPa, Tensile strength = 579 MPa, Fracture toughness $K_{IC} = 32.95$ MPa $\sqrt{m}$, threshold SIF $K_{th} = 3.15$ MPa $\sqrt{m}$, Paris constant C=4.3378×10^{-7} ^{7} (mm/cycle)/(MPa $\sqrt{m}$) and Paris exponent, m= 2.6183. For this specimen two parameters have been studied which are:

- The thickness of the specimen and its influence on the crack path, von-Mises stresses and strains, and the first mode stress intensity factor.
- The loading angle θ and its influence on the crack path, along with an estimation of the fatigue lifetime at different applied load F.

3.1 Crack growth path

The SpaceClaim program is used to model the geometry of four specimens with different thicknesses of 3 mm, 6 mm, 9 mm and 12 mm each.. The simulation is performed under fatigue loading with an applied load F = 14 kN, initial crack length (a/W =0.5) and the load ratio R=0.1 ($R=F_{min}/F_{max}$). The ANSYS finite element model shown in Figure 3 is entirely consistent with the state of experimental research conducted by by (Antunes, Branco, Ferreira, & Borrego, 2019; Demir, Ayhan, & İriç, 2017; DEMIR, Ayhan, Sedat, & LEKESIZ, 2018; Sajith, Murthy, & Robi, 2020). In the present simulation, the CTS geometries are loaded in various angles 30°, 45°, 60° and 75° in the original direction of cracking to compare the crack growth direction and fatigue life number of cycles. Different thicknesses of 3 mm, 6 mm, 9 mm and 12 mm were analyzed to show the influence of the thickness on the direction of crack growth as shown in Fig 5.

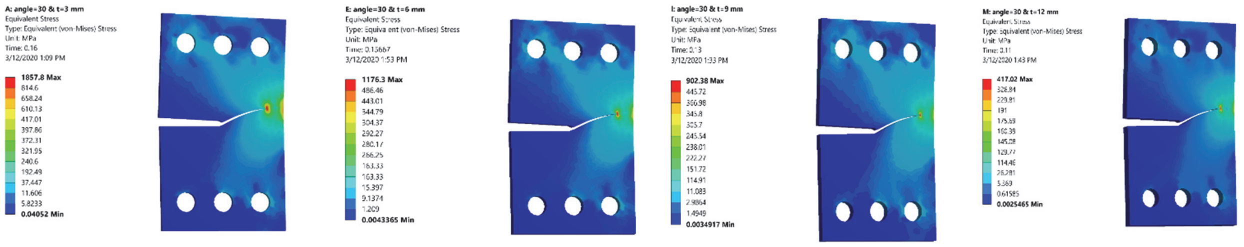
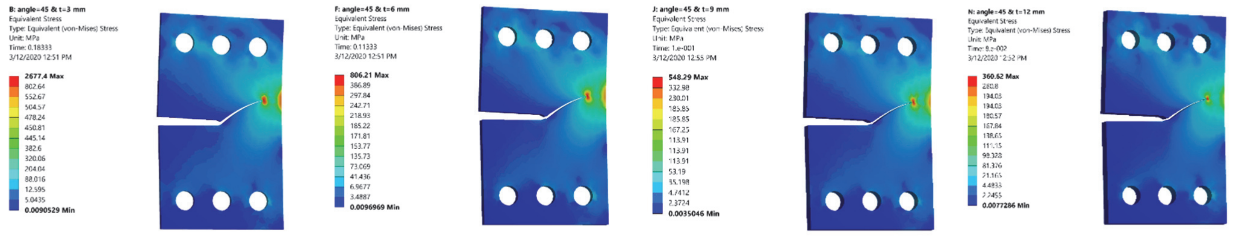


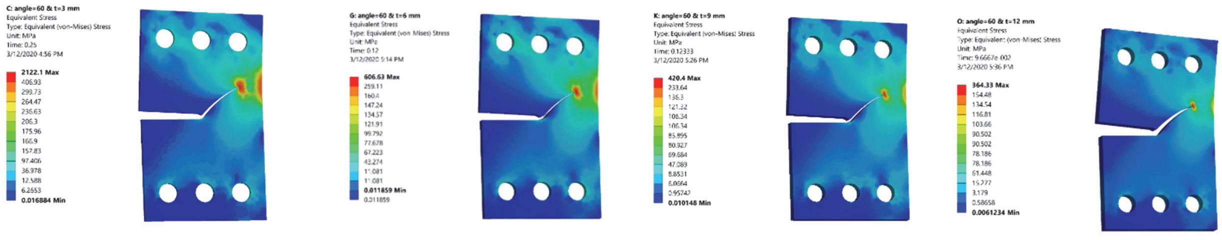
Fig. 5. Predicted crack growth path for CTS at different thicknesses and loading angle 30°

As can be seen in this figure, the expected crack paths of the four geometries are nearly identical, and the specimen's thickness has no significant influence on the crack direction. This statement is only valid under the assumption of small-scale yielding, because, in fact, the lower-thick specimen would be more resistant to higher plastic deformation resulting in sharp lips along the cracked surface, accordingly changing the crack direction.



a) CTS at thickness = 3 mm b) CTS at thickness = 6 mm c) CTS at thickness = 9 mm d) CTS at thickness = 12 mm

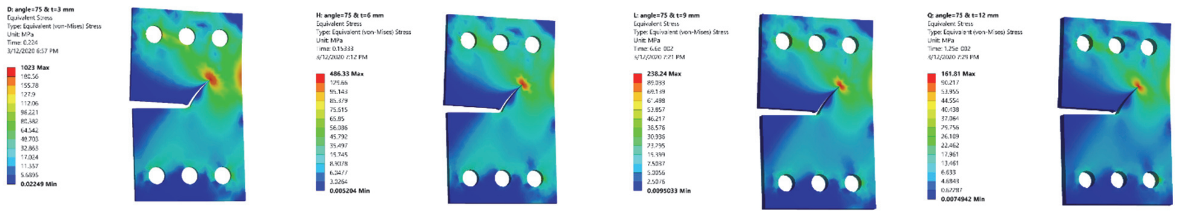
Fig. 6. Predicted crack growth path for CTS at different thicknesses and loading angle 45°



a) CTS at thickness = 3 mm b) CTS at thickness = 6 mm c) CTS at thickness = 9 mm d) CTS at thickness = 12 mm

Fig. 7. Predicted crack growth path for CTS at different thicknesses and loading angle 60°

In addition, there is a higher influence of changing the the thicknesses on the resistance to higher plastic deformation which are clairly shown on the Von-mises stress and strain distribution shown in Figs. 5-8 for the thicknesses of 3 mm, 6 mm, 9 mm and 12 mm and different loading angles of 30°, 45°60° and 75° respectively. For further clarity, the zoom out for the crack tip including the shape of plastic zone around the crack tip which estimated based on the Von Mises yield criterion are shown in Fig. 9 and Fig. 10. For this particular case, therefore, it may be reported that the crack tends to propagate in the direction of K_I once it reaches a sufficient length.



a) CTS at thickness = 3 mm b) CTS at thickness = 6 mm c) CTS at thickness = 9 mm d) CTS at thickness = 12 mm

Fig. 8. Predicted crack growth path for CTS at different thicknesses and loading angle 75°

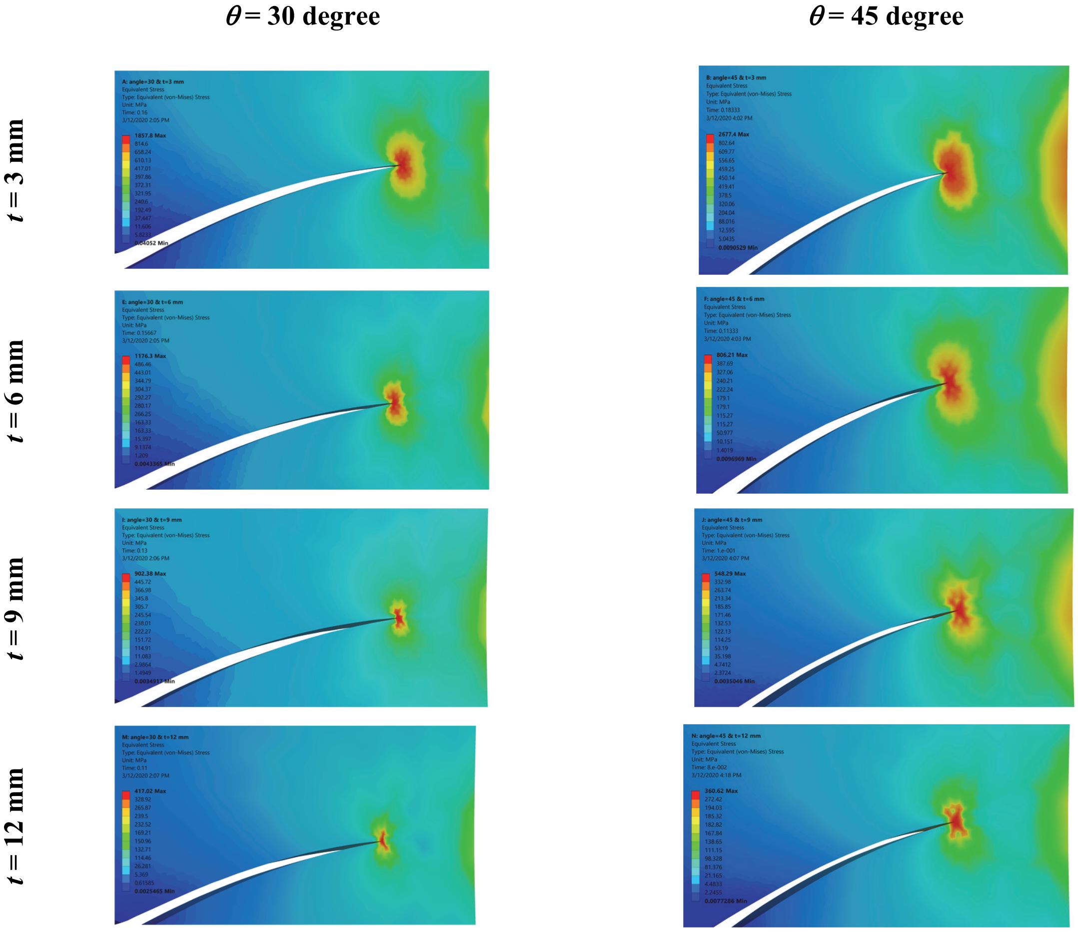


Fig. 9. Von Mises stress distribution with different thicknesses and loading angles 30°, 45°

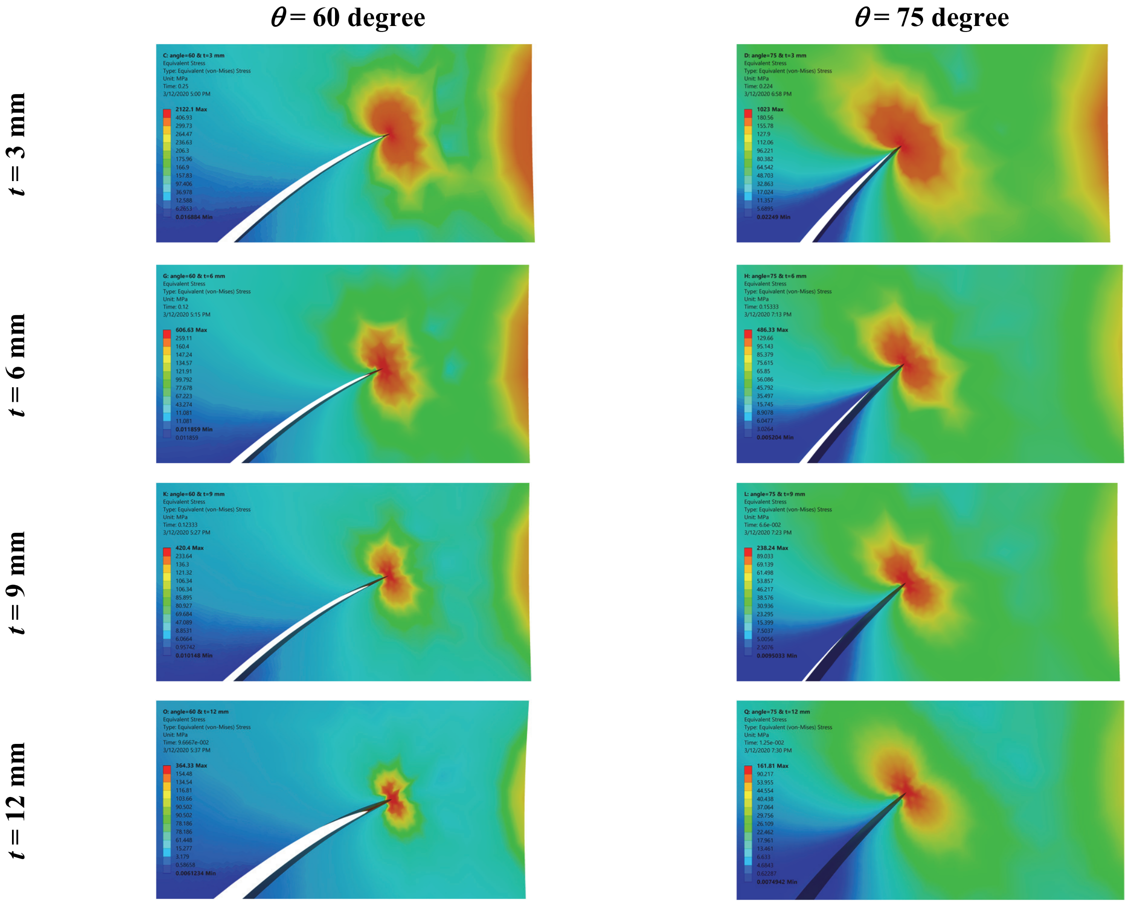


Fig. 10. Von Mises stress distribution with different thicknesses and loading angles 60°, 75°

3.2 Fatigue life estimation

To predict the fatigue life, the number of cycles versus the the crack length calculted in this study for different load angles of 30°, 45°,60° and 75° are compared with the experimental and numerical results performed by (DEMIR et al., 2018; Erdogan & Sih, 1963; Pook, 1989; Richard, Schramm, & Schirmeisen, 2014; Tanaka, 1974) as shown in Fig. 11 to Fig. 16. As shown in these figures, the present study results presents a good agreement with experimental and numerical data for different loading angles and loading values.

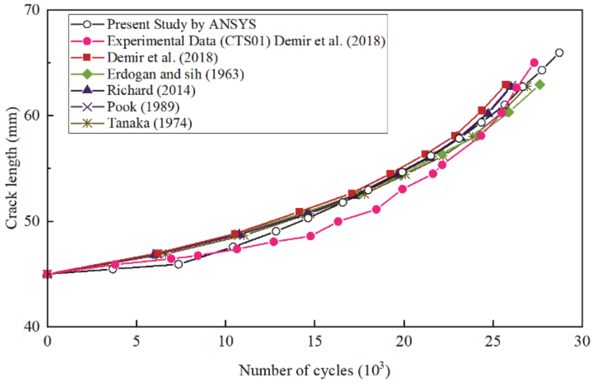


Fig. 11. Comparison of simulated and experimental and numerical data for loading angle 30° and F=8.8 kN

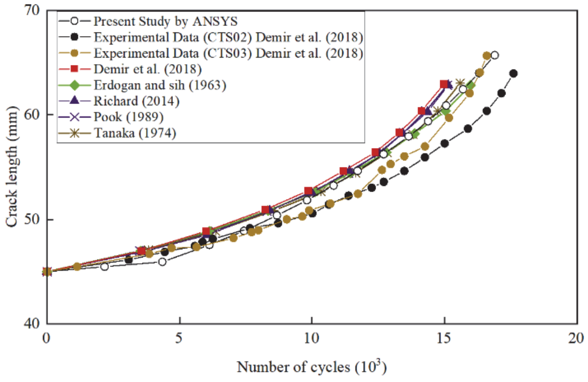
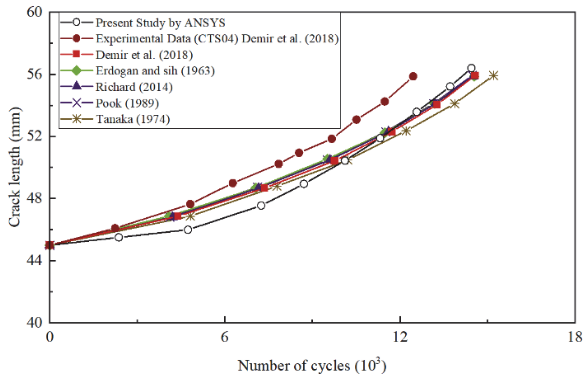


Fig. 12. Comparison of simulated and experimental and numerical data for loading angle 30° and F=11 kN



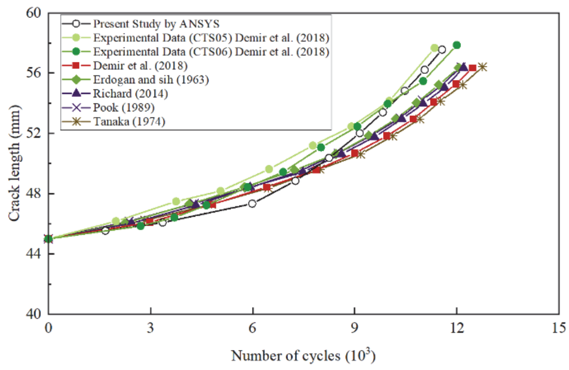
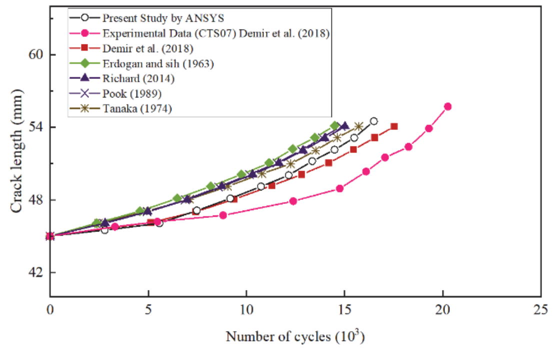


Fig. 13. Comparison of simulated and experimental and numerical data for loading angle 45° and F=11.4 kN

Fig. 14. Comparison of simulated and experimental and numerical data for loading angle 60° and F=13.65 kN



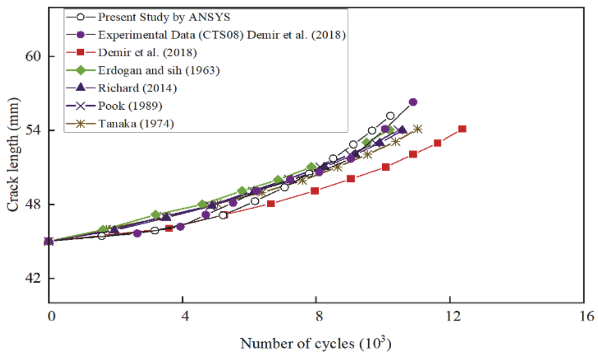


Fig. 15. Comparison of simulated and experimental and numerical data for loading angle 75° and F=13 kN

Fig. 16. Comparison of simulated and experimental and numerical data for loading angle 75° and F=15 kN

4. Conclusions

The finite element study of the mixed mode fatigue crack propagation was performed using ANSYS Mechanical APDL for the CTS specimen and compared with experimental results for various loading angles. For different loading angles, the mixed-mode fatigue life were predicted and compared with available experimental results with a good agreement. Based on the results of the crack growth path, there is no effects of changing the thicknesses of the geometries on the trajectory of crack growth,. The only consequence is the resistance to higher plastic deformation that decreases with increasing thickness. Interestingly, the predicted trajectories of the crack growth for all specimens in the present study were identical to the experimental determined paths for different loading angles. It can be stated that the structure of specimen geometry and its configuration play an important role in obtaining higher values of mixed mode SIFs values. This happens to be significant in terms of applied loads particularly for higher values of K_{II}.

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