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Fatigue life extension by crack repair using stop-hole technique under pure mode-I and pure mode-II loading conditions

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Abstract

Drilling a hole at the crack tip turns the crack into a notch and diminishes the crack tip stress singularity. In this paper, the crack growth retardation is examined using a numerical study on the efficiency of stop holes. Pure mode-I and pure mode-II loading conditions have been generated by using the mixed mode compact tension specimen made of 6061-T651 aluminum alloy. A fatigue crack growth code developed for two-dimensional elastic problems is used to validate the numerical procedure. The numerical results reveal that the presence of stop holes significantly decreases the stress concentration around the crack tip. The fatigue life extensions and the location of fatigue crack initiation from the hole edge are studied under different loading conditions. A comparison between the reported experimental results and the obtained computational results shows that the fatigue life extension caused by the stop-hole method can be well predicted by the numerical model developed in this study.

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*Keywords:*stop hole, fatigue crack growth, mode-II loading condition, crack growth retardation

1. Introduction

One of the easiest and most accessible crack arresting methods is drilling holes close to the crack tip. The crack tip stop hole is used to diminish stress singularity of the crack tip in order to improve the fatigue life of structure. Song et al. reported that by drilling a hole at the crack tip, larger stop hole diameters resulted in longer fatigue lives [1]. Ghfiri et al. tested some precracked specimens under fatigue loading and studied the effect of hole diameter and cold expansion on the fatigue life improvement [2].

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The aim of present paper is to study the effect of crack tip hole on the fatigue life of cracked specimen under mode-I and mode-II loading conditions. Fatigue life analyses are performed using an APDL (Ansys Parametric Design Language) code based on the classical fracture mechanic models. The hole diameter of stop holes is considered as the main variable for numerical investigations under different loading conditions. The effects of stop hole on the crack tip stress condition, crack initiation life and crack growth life are studied.

Nomenclature	
D	stop hole diameter
K_{II}, K_I	mode-I and mode-II stress intensity factor
K_C	critical value of stress intensity factor
ΔK	SIF range = K_{max} - K_{min}
ΔK_{eff}	equivalent stress intensity factor range ΔK for mixed-mode I and II loading condition
R	stress ratio
x, y	Cartesian coordinate components
Δa	crack growth incremental length
θ	loading angle
θ_c	the angle between the initial direction and the direction of new crack growth increment

2. Computational method for fatigue life prediction

To investigate the effect of stop hole on the fatigue life of cracked components, a numerical methodology is used to estimate the remaining fatigue life of components. For studying the effect of stop hole on the fatigue life of cracked specimens, two kinds of fatigue models can be used; the fatigue crack initiation and fatigue crack propagation models. Various methods have been developed to investigate the fatigue initiation behavior of metals in the presence of mean stress. One of the commonly used categories for fatigue life investigation is the strain based methods. In this paper, the crack initiation life from the hole edge is investigated by using the Morrow model [3]. In the linear elastic fracture mechanic (LEFM), fatigue life is usually estimated for a cracked specimen by using an exponential function of stress intensity factor (SIF). An approach that describes all sections of the *da/dN* diagram is the so-called NASGRO equation [4]. In this paper, the fatigue crack growth life is investigated by using the NASGRO model and for 6061-T651 aluminum alloy, its coefficients of NASGRO equation are given in [1,4].Kitagawa et al. (1981) [5] extended the maximum tangential stress criterion to the fatigue crack propagation. They assumed in this modified criterion that the direction of fatigue crack growth corresponds to that of the maximum tangential stress range $\Delta\sigma_{\theta max}$ at the crack tip. According to the mixed mode condition of the crack growth, the equivalent SIF range ΔK of the mixed-mode I and II crack is assumed as [6]

$$\Delta K_{eff} = \Delta K_I \cos^3\left(\frac{\theta_C}{2}\right) - 3\Delta K_{II} \cos^2\left(\frac{\theta_C}{2}\right)\sin\left(\frac{\theta_C}{2}\right) \tag{1}$$

The value of θ_c in the above equation is obtained from the extended maximum tangential stress criterion.

2.1. Numerical procedures for crack tracking

In the present study, the fatigue crack initiation and growth is simulated by an iterative procedure that is based on the fatigue models described earlier. For this purpose, the finite element software ANSYS is linked to the fatigue code to simulate the initiation and extension of crack. The stress, strain and SIF values required for the fatigue models are calculated automatically by ANSYS and are used as input data for the fatigue crack growth (FCG) code. A constant prespecified incremental length of crack growth is considered in every computation step (Fig. 1).The crack geometry is redefined by the extension of incremental crack segment in every iterative computation step. The FE mesh is modified and the previous computational steps are repeated until the crack length reaches its critical length for which $K = K_C$. The results obtained by the fatigue crack growth code were validated with the experimental results reported in reference [1].

3. Computational model

A mixed mode compact tension specimen with the initial crack length of 35 mm was considered for fatigue analyses with linear elastic properties assumption. One circular hole was considered at the crack tip. Fig. 2 illustrates the geometry of specimen and its finite element model. The specimen was assumed to be made from a 6061-T651 aluminum alloy with the Young's modulus of 68.9 GPa and the Poisson's ratio of 0.33. The fatigue analyses were conducted under constant amplitude fatigue loading at the load ratio of $R = 0.1$. The diameter of stop hole (D) varied as 2mm, 2.5mm and 3mm.Also, the analyses were conducted under pure mode-I ($\theta = 90^o$) and pure mode-II ($\theta = 0$) loading conditions. The maximum level of applied cyclic loading of 4.3kN were considered in the analyses.

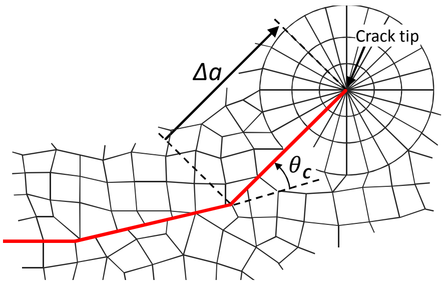

Fig. 1. Incremental fatigue crack growth.

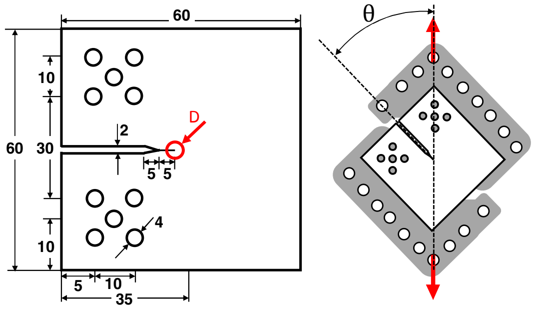

Fig. 2. Geometry of the mixed mode compact tension specimen with stop hole.

The 6-node plane strain elements were used in the finite element models. Higher mesh density was used near the stop hole to improve the accuracy of the results. Besides, the singular elements were used for the first ring of elements around the crack tip. A mesh convergence study was also undertaken to ensure that a proper number of elements was used in fatigue loading modeling. The appropriate values of the crack growth incremental length (Δa) and the crack tip element size were found to be equal to 1mm and 0.1mm, respectively. The element with the lowest fatigue initiation life is where the crack emanates. After crack initiated from the hole edge, the fatigue crack growth was modeled using the NASGRO model. The mode I and mode II loading conditions were modeled using the fixture shown in Fig. 2.

4. Results and Discussion

The FCG code validated previously is now extended to study the effect of stop hole on the retardation of FCG in a the CT specimen under mode I and mode II loading. The diameter of hole was considered as numerical variable in the analyses under different loading conditions. The diameter of stop hole was varied within a specific range as described in section 3. Fig. 3 illustrate the tangential stress distribution around the stop hole for different loading conditions. For mode-I loading condition (Fig. 3a), the maximum stress is located at the direction of the initial crack and for mode-II loading condition, it moves from its initial location to the two sides of the stop hole (Fig. 3b). The higher hole diameter causes lower local stress at the hole edge resulting in a higher fatigue initiation life. Fig. 4 illustrates the schematic location of fatigue crack initiation for the specimen with the 3mm stop hole.

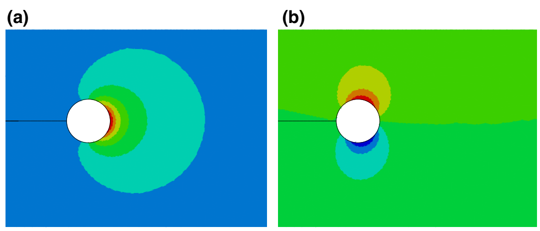

Fig. 3. The tangential stress distribution around the stop hole for the model with 3mm hole diameter under
(a) mode-I, and (b) mode-II loading conditions

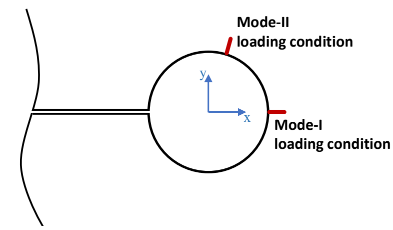

Fig. 4. Location of fatigue crack initiation from the hole edge for different loading conditions (D = 3mm)

The fatigue crack initiation location differs from mode-I loading to mode-II loading. It can be seen that for mode-I loading condition, the fatigue crack is emanated at the direction of the initial crack and for mode-II loading condition, it moves from its initial location to the side of the stop hole that is under tensile tangential stress.

Under pure mode-II loading condition, the fatigue life was higher than the case with mode-I loading condition. Figure5illustrates the fatigue life of the specimens for different values of hole diameter at different loading conditions. It can be seen that for the specimens repaired with 3mm and 2mm diameter stop holes, the highest and the lowest fatigue lives are resulted. This behaviour was observed for different loading conditions. For a constant hole diameter, when the loading condition was changed from mode-I loading towards mode-II loading, the fatigue life improvement was increased. The highest values of the fatigue life improvement was observed for the mode-II loading condition. For the mode-I loading condition, the fatigue life improved about 38.1%, 85.9% and 150.2% for the hole diameters of 2, 2.5 and 3mm. Under pure mode-II loading condition, the fatigue life of CT specimens with the hole diameters of 2, 2.5 and 3 mm was improved about 3.5, 4.4 and 25.1times more than the fatigue life of the plain specimen.

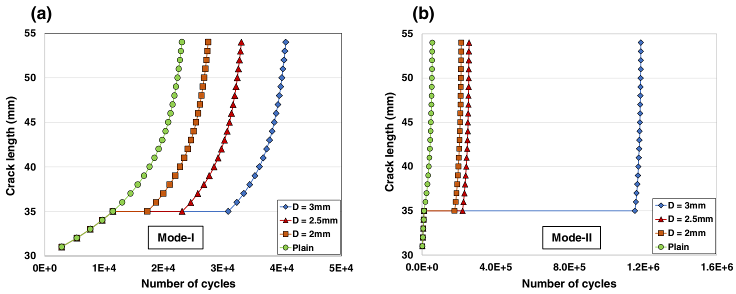

Fig. 5. Fatigue life curves for different stop hole diameters under different loading conditions

5. Conclusion

The effects on crack growth retardation caused by hole drilling at the crack tip were studied numerically in 9.6 mm thick mixed mode CT specimens made of 6061-T651 aluminum alloy. All models with the crack tip holes could provide considerable crack growth retardation and extend the fatigue life successfully. The stress concentration at the stop hole edge was influenced by the loading condition and the hole diameter. Within the scope of results presented in this study, for both loading conditions a higher hole diameter resulted in a higher life extension. The larger hole diameters also resulted in lower stress values at the hole edge causing the fatigue crack to initiate in a longer time. Moreover, for mode-I loading condition, lower fatigue crack initiation and growth lives were observed. The numerical results revealed that the highest and the lowest fatigue life extensions for different hole diameters and loading conditions were 2513% and 38.1%. Although, the related results are obtained for the 6061-T651 aluminum alloy, the same approach can be developed to estimate the fatigue life improvement of other metallic alloys and also other cracked specimens.

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