Stress intensity factors of a crack emanating from a cold expanded hole : Effects of edge distance ratio

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Abstract:

Cold expansion method has beneficial effects on extending the fatigue life of structures containing holes. However, for holes located near the plate edge, there is concern about the residual stress distribution around the hole that associated with beneficial effect of cold expansion process. The purpose of this study is to investigate the influence of edge distance ratio (EDR) on the stress intensity factors of a crack emanating from a cold expanded hole, where EDR is edge distance/hole diameter (or e/D). A 2-D finite element simulation was carried out with various degrees of cold expansion and various EDRs. It was found that the reduction of EDR below e/D=3 has significant effect on the tangential compressive residual stress zone. Furthermore, for a crack considered in the ligament, a significant reduction in the stress intensity factors was found in a cold expanded hole for both small and large EDRs.

Keywords: Cold expansion; Edge distance ratio; Residual stress; Stress intensity factor

1. Introduction

Fatigue cracks often originate in places where tensile stresses are concentrated such as fastener holes. Many attentions are paid on the development of methods to increase the fatigue life of the mechanical components. Cold expansion process which has been used by the aircraft industry for many years, delays the initiation and propagation of fatigue cracks around fastener holes in metal structures. The system consists of pulling a tapered mandrel through the hole and expanding it. The plastic flow of material caused by drawing the mandrel creates an annular zone of residual compressive tangential stresses near the hole edge. The zone of residual compressive stresses decreases the effect of the tensile stresses caused by cyclical loading and has proven to extend the fatigue life. Many researches have been conducted for evaluation of residual stress distribution around a cold expanded hole. However, in almost all published papers, only a hole in the center

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of a plate with adequate distance from the plate free edges has been considered and the effects of free plate edge have been ignored [1-5]. Since in many practical cases, the holes have to be near the edge of a sheet, there are concerns about the residual stress distribution around such a hole and its effects on the cold expansion results. For holes with small EDRs, unconstrained plastic deformation in the ligament near the free edge may relieve the beneficial residual stresses. The purpose of this study is to investigate how a reduction in the EDR may affect the residual stress distribution around a cold expanded hole and presents the results of weight function calculations of the effective stress intensity factors for cracks emanating from the edge of a cold worked hole.

2. Finite element model

The finite element (FE) model used for simulation was a plate assumed to be made from Al 2024-T3 with $E = 71.6 GPa$, $\nu = 0.28$. For an elastic-plastic analysis, the stress-strain relationship was fitted to a bi-linear kinematic hardening behavior. Fig. 1 shows the complete stress-strain curve of the alloy.

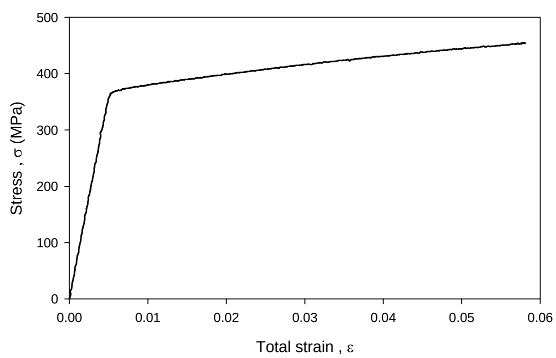

Fig. 1. Stress-strain curve for Al 2024-T3 [2]

The geometry is shown in Fig. 2 with a hole of diameter 6.35mm located in a center distance of e from the plate free edge. The height of the plate h was made large enough, to avoid the effect of second free edge of plate on the results. The FE model used for the analysis is also shown in Fig. 2. Due to symmetry conditions, only one half of plate was simulated. (shaded in Fig. 2a)

The finite element code ABAQUS version 6.6 was employed to determine the residual stresses. Second order isoparametric reduced integration element CPS8R available in the element library of ABAQUS program was used. The mesh was refined close to the hole edge to capture the high stress gradient arising from the cold expansion process. The cold expansion process in this analysis is modeled by applying a uniform expansion to the hole edge.

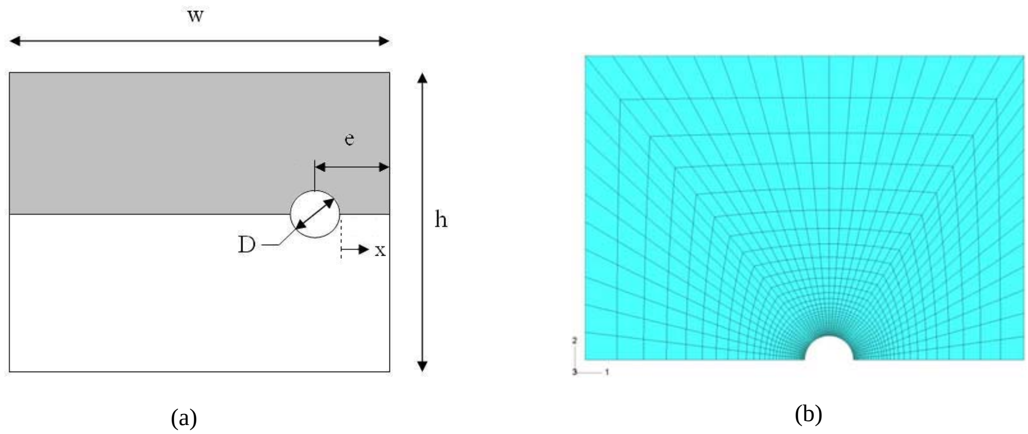

Fig. 2. Fastener hole. (a) geometry details; (b) finite element mesh used for simulation.

3. Residual stress field

In the aerospace industry, typical expansions of 2-5 percent have been used. But a nominal 4% expansion is the most common expansion considered in practice [4]. Fig. 3 shows the variation of the normalized tangential residual stress ($\sigma_{\theta\theta}/\sigma_y$) along the symmetry line versus the normalized distance from the hole edge (x/r). Here, σ_y is yield stress, x is distance from the hole edge and r is the radius of the hole.

Fig. 3 indicates that for edge distance ratios e/D equal to and higher than 3, there is no considerable effect on the residual stress profile for all considered degrees of expansion. For e/D=2, the zone of tangential compressive residual stress (ZCRS) is almost the same as higher e/Ds. But the residual stress profile after compressive part is different from those of higher EDRs.

It also seen from Fig. 3 that for large EDRs and beyond the plastic zone generated by the reverse yielding, the compressive residual stress looses its intensity and becomes tensile due to self-equilibrium far from the hole edge. For small EDRs (e/D≤ 2), this tensile residual stress reaches a maximum value but does not tend to zero when moving towards the free edge of plate. Therefore, a considerable amount of tensile residual stress remains at the plate free edge and it may influence the beneficial effect of the cold expansion process.

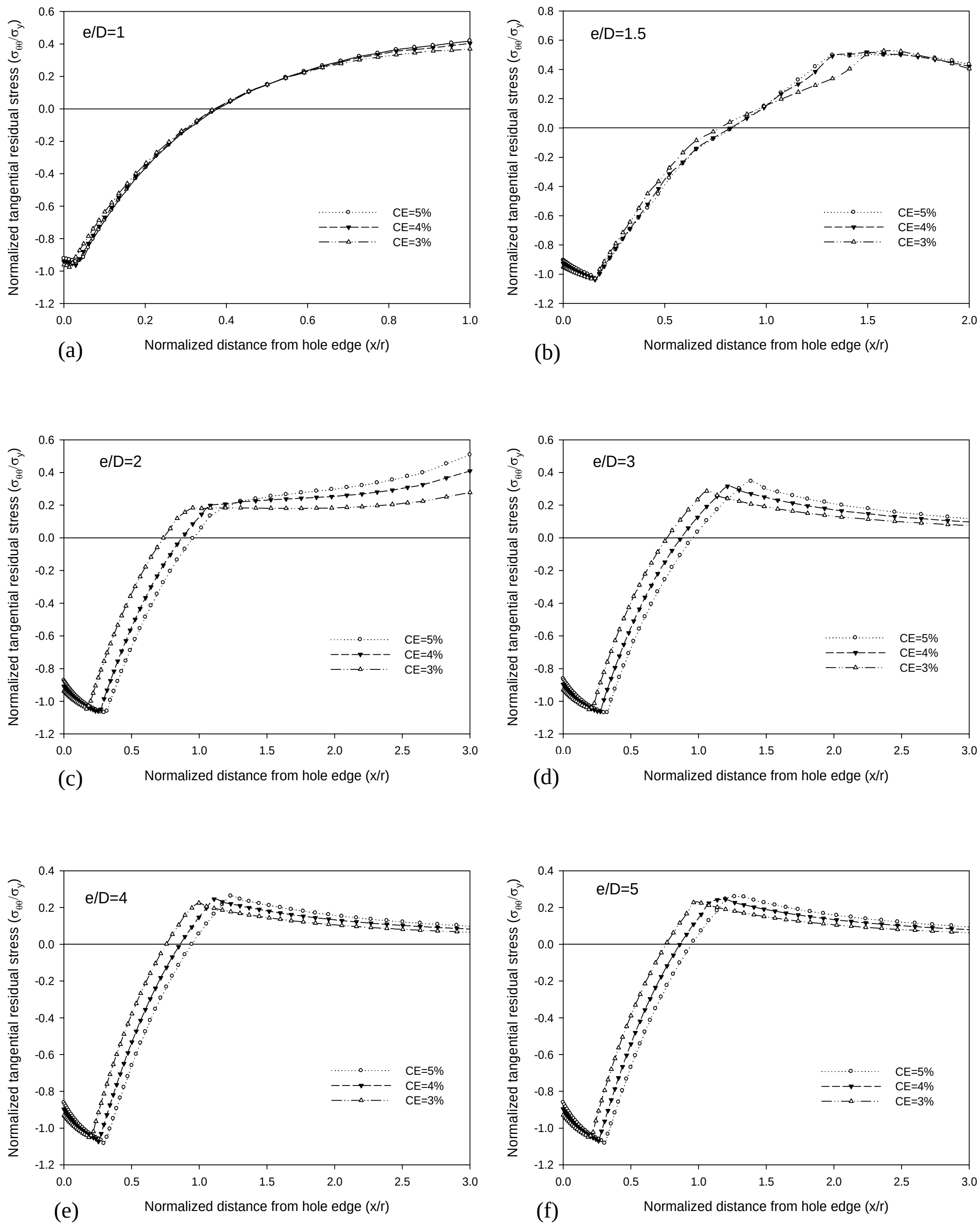

Fig. 3. Variation of normalized residual stress ($\sigma_{\theta\theta}/\sigma_y$) due to different degrees of expansion. (a) for e/D=1; (b) for e/D=1.5; (c) for e/D=2; (d) for e/D=3; (e) for e/D=4; (f) for e/D=5.

Fig. 4 shows the normalized radius of zone of compressive residual stress (x/r) for different EDRs and different degrees of expansion. It was found from this figure that for small EDRs, there is a significant reduction in the compressive residual stress zone. Also Fig. 4 illustrate that for e/D=1, the ZCRS is almost independent of the degree of cold expansion and all considered degrees of expansion result in the same ZCRS around the hole. On the other hand, for a hole with small EDR, the aimed beneficial effect of cold expansion can be obtained with lower degrees of expansion. However, it should be noted that the size of ZCRS for holes with small EDRs are significantly lower than those holes with large EDRs. It can therefore be suggested that the effectiveness of cold expansion process in the life improvement of fastener holes is reduced for small EDRs.

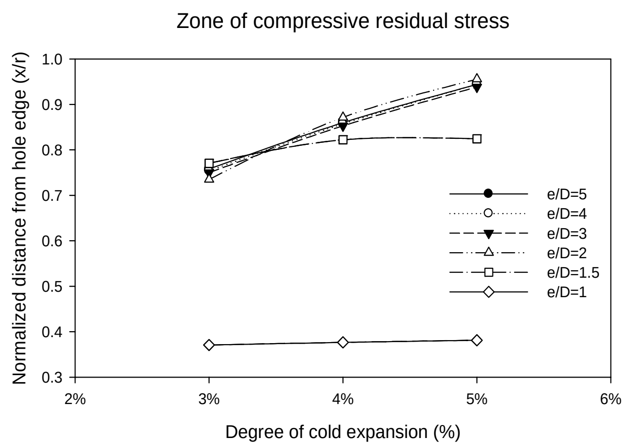

Fig. 4. Variation of radius of zone of compressive residual stress.

4. Stress intensity factor

When a crack lies in a region of compressive residual stress, a tensile applied load must overcome this stress at first, before the crack can propagate. Therefore the compressive residual stress reduces the stress intensity factor (SIF). This stress intensity factor is often called an effective stress intensity factor k_{eff}. A lower fatigue crack growth rate is attributed to a lower k_{eff}.

The weight function method was used to evaluate the effective SIF for cracks in residual stress field. This method allows the effective SIF be determined by a linear superposition of the k solution for residual stress field SIF k_{res}, and that due to external loads applied SIF k_{app} by Eq. (1) [2]:

$$k_{eff} = k_{app} + k_{res} \tag{1}$$

The method proposed by Teh and Brennan was used in this study for determining SIF [6]. Their method expresses the crack opening displacement as an arithmetic series that require three reference solutions. It can consider the effects of finite width between the hole and the plate free edge in determination of weight function. The stress intensity factor K for a given geometry under arbitrary loading is given by Eq. (2):

$$K = \int_0^a \sigma(z) M(a,c) dz \qquad (2)$$

where σ is the stress distribution acting in a direction normal to the crack plane and M is a universal weight function associated with a crack of length a and the coordinate z along the crack faces. The weight function can be given by Eq. (3):

$$m(a,z) = \frac{2\sqrt{\frac{2}{\pi a}}}{Y_{map}} \frac{C_{0sn} + C_{1sn}(1 - \frac{z}{a_n})}{C_{0sn} + C_{1sn}(1 - \left[\frac{z}{a}\right]_P} \times \left[C_{0f} + C_{1f}\left(1 - \left[\frac{z}{a}\right]_P\right) + C_{2f}\left(1 - \left[\frac{z}{a}\right]_P\right)^2 \right] \left(1 - \left[\frac{z}{a}\right]_P\right)^{-\frac{1}{2}} \qquad (3)$$

The detailed procedure for calculating coefficients and validating weight function M can be found in ref. [5].

Because of the complicated geometry, which induces a stress concentration the nominal stress distribution due to the external load and the stress distribution due to the cold expansion process were determined by FE modeling.

A single crack was considered along the symmetry line in the ligament to evaluate the influence of cold expansion for holes with small EDR. The crack was assumed to grow in a radial direction along the symmetry line from the hole edge and in a direction normal to the far-field load, giving pure mode I loading conditions.

Two normalized crack lengths $a/r = 0.2$ and $a/r = 0.8$ were considered. The short crack completely lies in the zone of compressive residual stress but, the tip of longer crack was located out of the zone of compressive residual stress. Fig. 5 compares the effective stress intensity factors for a 4% cold expanded and a non-cold expanded hole under of an external applied load $0.25\sigma_y$. The external applied load was not large in order to avoid full-plasticity in the ligament when EDRs are small.

In Fig. 5 K-NCE refers to the SIF for non-cold expanded hole and K-CE refers to the SIF for a cold expanded hole. Where the weight function approach gives negative value of K_{eff} no singularity is present at the crack tip and it is suggested that K_{eff} is taken zero [2]. Fig. 5 indicates that for e/D>1.5 cold expanding the hole cause the crack tip remains close. For EDRs smaller than e/D=1.5, the crack was opened because of external load, but there is still a significant reduction in the magnitude of SIF for the cold expanded hole in comparison with the non-cold expanded hole. Therefore, the beneficial effect of cold expansion process is clearly seen for small EDRs as well.

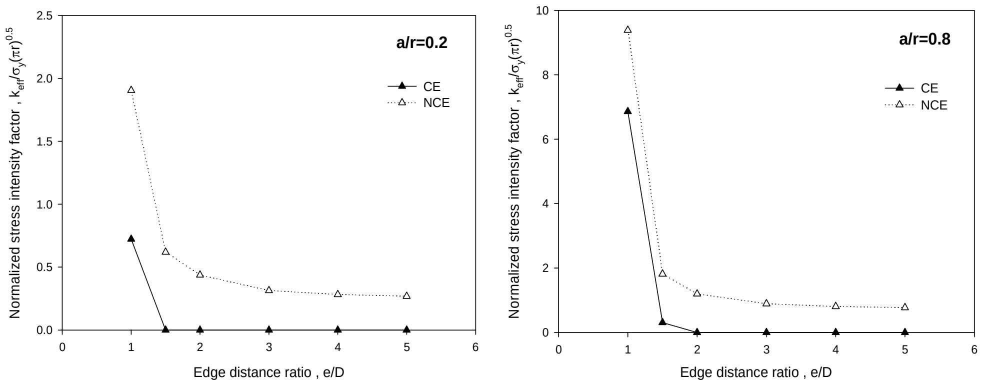

Fig. 5. Comparison of stress intensity factor for a cold expanded and a non-cold expanded hole. (a) normalized crack length a/r=0.2. (b) normalized crack length a/r=0.8.

5. Conclusion

A 2-D finite element simulation was carried out to investigate the influence of the EDR on a cold expanded hole. Several degrees of expansion were applied to holes of different EDRs. The results showed that EDRs higher than e/D=3 have no effect on the residual stress profile generated due to the cold expansion process. For a hole with small EDR, the aimed beneficial effect of cold expansion can be obtained with lower degrees of expansion. However, the ZCRS for holes with small EDRs is significantly lower than holes with large EDRs. The beneficial effect of cold expansion for retarding crack propagation can be obtained for all EDRs due to considerable reduction of SIF for a crack emanating from the edge of a cold expanded hole.

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