Effect of Residual Stresses on Crack Growth from a Hole

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Nomenclature

a = one-half total crack length in a center-cracked specimen, or crack length (or distance) from the edge of a hole, mm
F_{ty} = material tensile yield strength, MPa
K = stress intensity factor, $MN/m^{3/2}$
K_T = stress concentration factor (dimensionless)
ΔK = $K_{max} - K_{min}$, $MN/m^{3/2}$
R = $\sigma_{min}/\sigma_{max}$ or K_{min}/K_{max}
t = thickness, mm
W = specimen width, mm
σ = stress, based on gross area away from the hole, MPa
$\Delta\sigma$ = $\sigma_{max} - \sigma_{min}$, MPa

Abstract

THIS paper employs a "variable stress intensity ratio" concept to elucidate the mechanics of a crack growing through a superimposed stress field (i.e., combining the residual stresses around a hole and the subsequently applied cyclic stresses). The validity of this concept is supported by experimental results generated from specimens containing residual stresses.

Contents

When a crack in a structure is subjected to cyclic loads, the material at the crack tip may undergo plastic yielding during the upward excursion of each loading. Upon unloading, the local nonlinear stresses within a short distance ahead of the crack tip are unloaded linearly; thus, a residual stress field will be developed in front of the crack. The subsequent crack growth behavior may be affected by the presence of residual stresses.

In the areas of high-stress concentrations, such as cutouts and holes, when an elastic material containing a circular hole is subjected to uniform far-field tension, the local stress distribution in the neighborhood of the hole is given by the classical Kirsch solution.[1] Thus, whenever the far-field stress is greater than F_{ty}/K_T, local plastic deformation will occur. Similar to the case of a crack, the plastically deformed material at the hole edge will be subjected to restoring forces by the surrounding elastic material during unloading. This gives rise to a residual stress field.

Consider now the subsequent reloading of the material. The resulting stress field in the vicinity of the hole will be some combination of the residual and applied stresses. If the stress field that would exist due to the new applied stress acting alone is elastic, i.e., when the subsequently applied stress level is low enough, then the resulting stress field may be determined by superposition. For the case of a very small crack at the edge of a hole, the large yielded zone due to the hole will overshadow the smaller crack tip plastic zone. Therefore, the behavior of crack growth at subsequent lower loads will be dominated primarily by the residual stress distribution associated with the hole.

With the assumption that cyclic stresses do not alter the state of residual stress significantly during crack propagation, the mechanics of crack propagation can be conceptually elucidated as follows.

For the case of crack propagation without residual stress, the crack driving force ΔK is a function of $\Delta\sigma$. For a crack propagating inside a superimposed stress field, which combines the pre-existing residual stresses and the applied constant amplitude stresses, the distribution of tangential stress $\Delta\sigma_\theta$ along the crack plane for the superimposed stress field is arithmetically the same as those for the applied stress alone. Therefore, the crack driving force ΔK will be the same for both cases (i.e., with and without residual stresses). However, the resultant stress intensity ratio will not be the same as the applied constant amplitude stress ratio. It also changes along the crack propagation path. Therefore, the effective R ratio that is experienced by the crack is not a constant. The crack behaves as if it were propagating under a sequence of applied elastic stress cycles having R ratios modified by the residual stresses.

In the remainder of this synoptic, the foregoing hypothetical considerations will be referred to as the "variable stress intensity ratio" concept. An experimental program was designed to generate cyclic crack growth rate data to test the hypothesis. The test matrix consisted of specimens with and without a hole. The center-cracked specimens (CCT specimens, 2024-T351, LT, $t = 6.53$ mm, $W = 152.4$ mm) were tested under constant amplitude cyclic stresses to develop baseline crack growth rate curves at seven R ratios ($-2.0 \leq R \leq 0.7$). Cyclic crack propagation tests also were conducted on eight specimens of the same material and dimensions with a circular hole at the center. The hole size was either 12.7 or 19.05 mm in diameter. Five of these specimens were preloaded to a gross area stress level of 248 MPa ($\frac{2}{3}F_{ty}$). Following the removal of this load, an elox cut (a through-crack starter) was made at one side of the hole, then the specimen was precracked by applying fatigue cycling. The other three specimens were also subjected to a 248 MPa preload; however, the high load was applied after precracking (simulating the classic crack growth retardation testing). In the remainder of this synoptic, the former will be referred to as the preyielded hole and the latter will be referred to as the overloaded hole. The term cracked hole or yielded hole will be applied to either type of these specimens. All eight specimens were then subjected to crack propagation testing at constant amplitude stress cycles ($\sigma_{max} = 103.35$ or 124.03 MPa with $R = 0.1$).

All experimental crack growth rate data were reduced to the da/dN vs ΔK format. The K values were computed based on the applied far-field stress. The independent variable, ΔK, was defined to be the full stress intensity range, i.e., $\Delta K \neq K_{max}$, for $R < 0$. The secant expression used in ASTM

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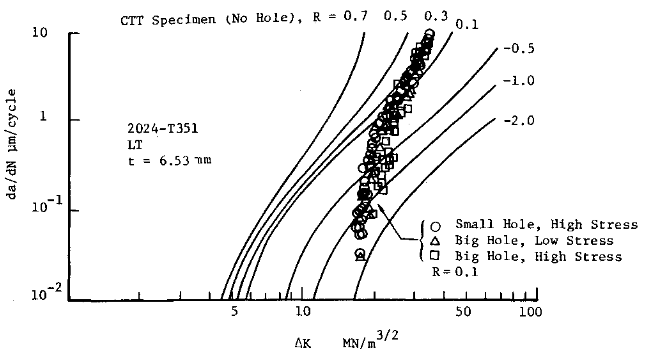

Fig. 1 Crack growth rate behavior of specimens containing a preyielded hole.

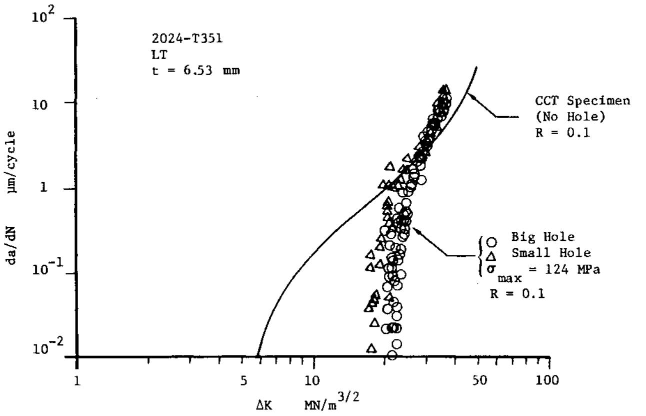

Fig. 2 Crack growth rate behavior of specimens containing an overloaded hole.

Standard E561-76T was used to compute stress intensity factors for the CCT specimens. The stress intensity factor used for the cracked-hole specimens was a compounded factor,[2] which was a product of Bowie's classical solution,[3] and the K expression for the CCT specimen.

The crack growth rate vs ΔK data points for the preyielded hole and the overloaded hole specimens are presented in Figs. 1 and 2, respectively. The curves that fit through the material baseline data points, for each R ratio, are superimposed to these figures for comparison.

Examining all of the data presented, comments on the crack growth rate behavior of the cracked-hole specimens are in order.

1) It is apparent that the crack growth rate behavior for the cracked-hole specimens did not resemble those crack growth rates for the CCT specimens. The da/dN data points for the cracked-hole specimens at $R = 0.1$ behaved as if the crack was propagating under a series of variable R ratios (the effective R ratio changed from -2.0 to $+0.3$), as it had been hypothesized.

2) As opposed to conventional theories for crack growth retardation, which only project retardation, the experimental data in Figs. 1 and 2 also indicate that the cracks were initially retarded but subsequently accelerated (the test data points are below and above the $R = 0.1$ curve for the CCT specimens). The acceleration was attributed to the tensile residual stresses immediately in front of the crack. The acceleration phenomenon was also due, in part, to the possibility of residual stress relaxation (i.e., change of residual stress pattern during crack propagation). It might also be attributed to a similar problem discussed previously,[2] i.e., the actual K value for a long crack having a high a/W ratio could have been higher than those calculated from an analytic solution. Further investigation is required to pin down these variables.

3) Some of the cracked-hole specimens had been precracked at a stress level lower than that for crack growth studies for a long period of time. Some other specimens were subjected to a single stress level for both precracking and crack growth. Despite these differences, consistency in crack growth rate behavior exhibited in all eight cracked-hole specimens suggests that the test results were independent of precracking conditions and that the effect of relaxation in residual stress, if it ever occurred during the test, was not a function of precracking cycles. Since stress relaxation could play a vital role in crack propagation in a residual stress field, a thorough investigation would be required to further identify such a mechanism.

4) The variation of test data points shown in Figs. 1 and 2 was basically due to the effects of specimen geometry (hole size, crack size, etc.) and cyclic stress level on ΔK; it does not represent experimental crack growth rate scatter.

5) Laboratory records[4] indicate that the crack growth lives for the overloaded hole specimens were consistently longer than the preyielded hole specimens (by approximately 200%) whenever the hole diameter and the cyclic stress level in these specimens were compatible. This phenomenon is explicable because the higher geometric K_T in the overloaded hole specimen would have caused more residual stresses along the crack plane. Therefore, it can be said that crack growth rate behavior in both types of these specimens was the same (i.e., retarded and then accelerated). The degree of retardation and acceleration would depend on the magnitude of the residual stresses.

In summary, applying a high load to a specimen containing a hole (with or without a crack initially) may cause yielding of the area adjacent to the hole and thereby induce residual stresses around the hole. Subsequent crack growth at lower loads would be affected significantly by those pre-existing residual stresses. It has been demonstrated that applying the "variable stress intensity ratio" approach to crack growth analysis can adequately account for the influence of residual stresses on constant amplitude crack growth. This approach permits one to use the unadjusted elastic stress intensity factors to perform crack growth life predictions.

Since most structural components are subjected to variable amplitude loading, the high loads in a spectrum can realistically cause yielding and residual stresses. The result of this investigation strongly suggests that analytical modeling for predicting crack growth rate behavior under variable amplitude loading can be achieved by determining the residual stress field (as functions of loading profile) and the material constant amplitude crack growth rates at various R ratios.

It should be noted that this approach is directly applicable to practical applications, such as the coldworked hole and interference fitted hole. It is equally applicable to areas other than holes as long as a residual stress field is present, e.g., the residual stress in a weld, etc.

Acknowledgment

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