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The compressive stress effect on fatigue crack growth under tension–compression loading

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ABSTRACT

Elastic–plastic finite element analyses have been performed to study the compressive stress effect on fatigue crack growth under applied tension–compression loading. The near crack tip stress, displacement and plastic zone size were obtained for a kinematic hardening material. The results have shown that the near crack tip local stress, displacement and reverse plastic zone size continue to change with the change of the applied compressive stress. Based on the finite element analysis results, a fatigue crack propagation model has been developed. Predictions of fatigue crack propagation behaviour under tension–compression loading agreed well with experimental observations.

1. Introduction

It is well known that under tension–tension constant amplitude fatigue loading, the fatigue crack propagation rate, da/dN, can be correlated by the stress intensity factor range, ΔK, and the applied stress ratio R. This approach was first suggested by Paris and Erdogan [1] as follows:

$$da/dN = C(\Delta k)^m \tag{1}$$

where C and m are dependent on material and R. For positive R, this equation has been verified by numerous test results.

Under tension–compression constant amplitude fatigue loading, the calculation of ΔK is usually based on the stress range in the tensile load part of the fatigue load cycle and the contribution of the compressive load part of the fatigue load cycle is ignored as recommended by the ASTM E647-95a. Therefore in a tension–compression fatigue loading, ΔK is equal to $K_{\max}$. This is based on the assumption that under applied compression load the fatigue crack tip is closed and no stress intensity factor is associated with the crack. The plastic damage generated during the compression part of a load cycle is also assumed to be very small, since there is no stress concentration around the closed fatigue crack tip. This indicates that the compression part of an applied fatigue load cycle has little contribution towards the fatigue crack propagation process.

Fatigue crack propagation test performed under tension–compression fatigue loading indicated that the effect of compressive load on fatigue crack propagation rate was strongly material dependent. Test results obtained by Silva [2] showed that for Ti6Al4V and Al7175 the compressive load part of the fatigue load cycle had little effect on fatigue crack propagation rate, and therefore supported the assumption to ignore the compressive load in the calculation process of the fatigue crack propagation driving force.

However, test results obtained by Yu et al. [3], Silva [2] and Pommier and Bompard [4] showed that for Al 2024-T351, ck45 and 0.4% mild steel the compressive load part of the fatigue load cycle had a significant effect on fatigue propagation behaviour. Therefore, the compressive load in the fatigue load cycle cannot be ignored and should be included in the calculation process of the fatigue crack propagation driving force.

Based on the test results, Silva [2,5] found that materials exhibiting strong cyclic hardening and a high Bauschinger effect (such as Al 2024-T351, ck45, 0.4% mild steel) were strongly affected by the applied compressive load while materials exhibiting no cyclic hardening (such as Ti6Al4V and Al7175) were relatively insensitive to applied compressive load.

In order to predict fatigue crack propagation behaviour under applied tension–compression loading, the driving forces need to be identified and a proper fatigue crack propagation model should be developed.

Silva [2,5] evaluated different fatigue crack propagation models [6–8]. He concluded that models based on fatigue crack closure concept were not suitable and models based on material's cyclic plastic properties should be developed to describe the fatigue crack propagation behaviour under applied tension–compression fatigue loading.

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Nomenclature

da/dN	fatigue crack propagation rate per stress cycle
C	constant
COD	crack opening displacement
m	constant
$K_{\max}$	maximum applied stress intensity factor
R	applied stress ratio
R_{pr}	reverse plastic zone size
R_{pr0}	reverse plastic zone size at zero applied stress
α	constant
β	constant
γ	constant
ΔK	stress intensity factor range
ΔK_{th}	threshold stress intensity factor range
σ_0	the applied stress level when the crack tip stress returns to zero from compressive stress
σ_{com}	applied compressive stress
$\sigma_{\max}$	maximum applied tensile stress
σ_{maxcom}	maximum applied compressive stress
σ_{ys}	material' yield stress

The objective of this paper is to identify the internal and external parameters which control fatigue crack growth behaviour and develop a model to describe fatigue crack propagation rate under applied tension–compression loading.

2. Finite element analysis

The specimens used in this analysis were centre cracked panels (CCPs) with four different crack lengths. Specimens were 44.55 mm wide, 116.84 mm long and 2.54 mm thick. These specimen dimensions were the same as those used in the fatigue crack propagation test of 2024-T351 aluminium alloy [3]. The crack lengths, 2a, were 1, 2, 5 and 10 mm, respectively.

This finite element analysis program used in this analysis has been developed based on the work of Rowe et al. [9], which is suitable for general elastic–plastic large strain problems. The suitability for using this program to analyse the near crack tip stress–strain field under elastic–plastic loading has been verified through previous publications [10,11].

Because of symmetry, only one quarter of each specimen was modelled in the current finite element analysis as shown in Fig. 1a. A representation of the finite element mesh around the crack tip is shown in Fig. 1b. The smallest element length near the crack tip was 0.0001 mm and which was only 1/10,000 of the shortest crack length of 1 mm. A interface element for contact between a single crack surface node and a rigid body was used to monitor the contact between a single crack surface node and the plane of symmetry (which was represented by introducing a rigid surface).

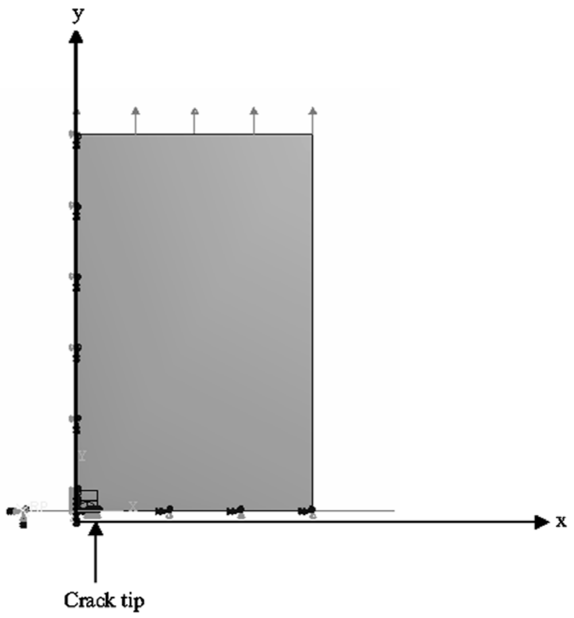

Fig. 1a. A quarter of the specimen representing the area where the finite element model is created.

The mechanical properties used in this analysis were based on the test results of 2024-T351 aliminium alloy [3]. The elastic modulus and Poisson's ratio used in this analysis were 70 GPa and 0.3, respectively.

The 0.2% yield stress was 353 MPa. The material model used in this analysis was based on the concept of incremental, rate-independent classical plasticity. The von Mises criterion was used to identify the initial yield surface and the bilinear kinematic strain hardening rule was used to reflect the Bauschinger effect. The stress–strain

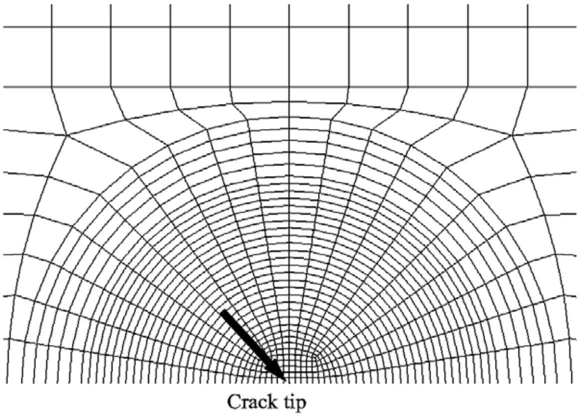

Fig. 1b. A typical finite element mesh near the crack tip.

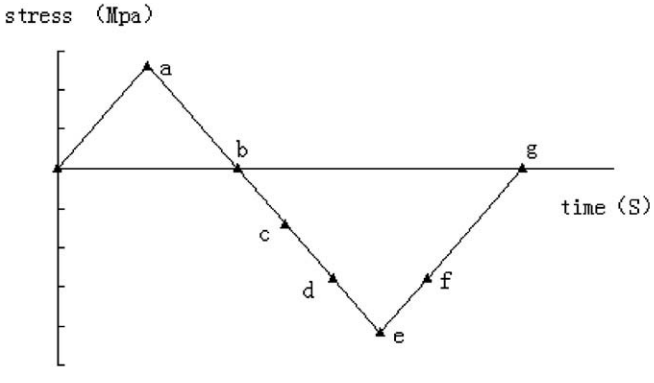

Fig. 2. The loading history.