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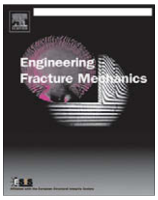

Simulation of ductile crack growth in thin panels using the crack tip opening angle

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The aim of this work is the assessment of the efficiency of the crack tip opening angle (CTOA) with respect to the transferability from one geometry to another, in particular the transferability obtained from Kahn tear tests to M(T) panels. The load–displacement behaviour recorded during a Kahn tear test was reproduced by means of finite element analysis using a variable CTOA as a function of crack length. The CTOA extracted from Kahn tests has then been used to simulate the *R*-curve of M(T) panels with different widths. Experiments and simulations were run first on a 6013-T6 aluminium alloy and then also on butt, friction stir welded butt joints of the same material.

1. Introduction

Light-weight, thin-walled structures used in the aerospace industry have to undergo a thorough validation process that includes also the certification of residual strength in the presence of a crack. Unfortunately, the combination of thickness, yield strength and fracture toughness is generally such that large plasticity develops at the crack tip and, therefore, the stress intensity factor *K* can no longer describe correctly the fracture process. For this motivation the crack growth in thin metallic structures has been extensively studied in the last decades by means of elastoplastic fracture mechanics (EPFM) and several criteria like *J*-integral, crack tip opening displacement (CTOD) or crack tip opening angle (CTOA) and K_{eff} have been proposed. Among these, CTOA or CTOD at a certain distance behind the crack tip have been shown to work well in modelling. Crack growth and instability during the fracture process [1].

In order to evaluate various methods in assessing crack growth resistance and predicting failure of cracked structures, an extensive round-robin project was carried out in 1979–1980 by the ASTM Committee E-24 on Fracture Testing. Several schemes were compared according to their capability of predicting experimental results on three different materials (7075-T651 and 2024-T351 aluminium alloys and 304 stainless steel) with three different specimen geometries: C(T), M(T) and three-hole crack tension specimen (THCTS) [2]. The critical CTOA criterion was able to predict the fracture behaviour for all specimen sizes and came out as the most suited criterion for predicting the fracture resistance of thin-walled structures.

In a more recent work, Scheider et al. [3] have compared CTOA and CZM regarding their ability to model the crack growth in a thin sheet metal and transfer results from an aluminium alloy C(T) specimen to a M(T) panel by means of two-dimensional FE analysis. From the numerical standpoint, the CTOA was computationally less expensive and more robust in comparison with the CZM. A further advantage is that the CTOA concept needs only a single parameter, which can be determined experimentally.

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Nomenclature

CMOD	crack mouth opening displacement
CTOD (δ)	crack tip opening displacement
CZM	cohesive zone model
EPFM	elastoplastic fracture mechanics
FSW	friction stir welding
PS	plane stress only model
PSC	plane strain core
a	crack length
B	specimen thickness
W	specimen width
F_L	plastic limit load
K	stress intensity factor
K_{eff}	effective stress intensity factor according to ASTM 561
σ_Y	effective yield strength for plastic limit load
σ_{YS}	yield strength
σ_{TS}	ultimate tensile strength
δ_5	crack opening displacement measured on a 5 mm gauge length at the initial crack tip
Δa	crack growth

In a CTOA analysis, it is assumed that the near-tip displacement field is characterized by a specific angle that can be used as a fracture criterion. Using 2-D plane stress or plane strain finite element analysis several authors [4–6] showed that in the early stages of crack growth the CTOA is higher than the value needed in the following steady-state crack growth. This condition is reached after a small amount of crack growth which is generally equal to one to two times the thickness. However, using a constant CTOA Newman [7] modelled crack initiation, crack growth and instability in three different geometries with results very close to the experiments.

A higher CTOA value in the early stage of crack growth has indeed been observed by several researchers measuring experimentally the CTOA during the fracture process. This has been shown to be associated with severe crack tunnelling, that means the crack length measured at the surface is lower than the crack length at the interior of the specimen. Mahmoud and Lease [8] showed that, over a wide range in thickness, the value of CTOA is higher when the crack starts to grow and then it shows a decay to a fairly constant value after a small amount of crack growth. Their results pointed out that the transition length and the steady-state CTOA decrease with increasing thickness, with the steady-state CTOA approaching a lower bound for large thicknesses. These findings demonstrate the necessity for a more complete understanding of the role of constraint (or of the stress state triaxiality) on ductile crack growth.

Later, several works by Newman, Dawicke et al., reviewed in [1], showed that a constant CTOA can properly model the fracture process if the correct constraint is modelled at the crack tip. For this reason, a 3D FE analysis is better suited, but also 2-D analyses with a plain strain core in the crack region and plane stress elements elsewhere can be an acceptable compromise between accuracy and modelling complexity, provided the plane strain core addresses the high constraint around the crack tip. A height of the PSC equal to thickness seems to be a reasonable compromise [1]. The plane stress condition away from the crack region allows a proper modelling of yielding.

Dawicke and Newman [9] have carried out specific analyses to assess the capability of CTOA as a 2-D fracture criterion. Initially, they have conducted a large number of experimental tests to determine crack length and tunnelling at a given level of applied stress. Afterwards, they have modelled the crack growth according to the experimental crack shape to determine the CTOA. Tunnelled crack-fronts showed a severe variation in CTOA through the thickness in the first millimetres of crack growth. The surface CTOA agreed well with that obtained experimentally while the CTOA calculated at the interior of the specimen was much lower and increased during the first stage of crack growth.

After the first millimetres of crack growth the CTOA was nearly constant through the thickness. Furthermore the CTOA seems to be independent of specimen size and geometry. Newman et al. [10] have determined a in-plane constraint factor for M(T) and C(T) specimens concluding that the crack length to thickness ratio (a/B) and the uncracked ligament length to thickness ratio (b/B) are the controlling parameters. If Eq. (1) is satisfied, specimens are characterized by the same global constraint factor which is close to plane stress and the CTOA is independent of specimen size and geometry

$$a > 4B, \quad b = (W - a) > 4B \tag{1}$$

Further analysis is necessary in order to determine the influence of the global constraint factor on the critical value of CTOA in the case in which a/B and b/B are lower than 4, since a double-parameter approach may be needed.

Later, Lam et al. [11] have shown that also in the case of a straight crack-front without crack tunnelling, CTOA is higher at the beginning of crack growth. Furthermore, they speculated about a relationship between CTOA and J-integral, at least for power law and perfectly plastic materials, that justifies an initially higher CTOA for a material exhibiting a rising R-curve. The initially higher values are likely to be due to the transition from crack blunting to steady-state crack growth. Their results