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Modelling the R-curve effect and its specimen-dependence

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ABSTRACT

This paper explores the specimen-dependence of the resistance (R-) curve for fracture of materials showing a pronounced R-curve effect. Using a cohesive zone framework, this paper demonstrates how to effectively predict the R-curve for a specimen type whose deformation is shear-dominated (compact tension, CT) from the R-curve of a specimen type whose deformation is bending-dominated (double cantilever beam, DCB). The mathematical relationships between crack extension and crack opening displacements for both CT and DCB specimens are first derived and related to a tri-linear cohesive law. Experimental tests for intralaminar fracture of CFRP are carried out and analysed. Using, as input, the experimental results from the DCB specimen, the cohesive law is shown analytically and using Finite Element (FE) to reproduce accurately the R-curve for the DCB and also to predict accurately the R-curve for the CT specimens.

1. Introduction

Several types of materials, such as concrete and fibre-reinforced composites, often show rising resistance (R)-curves – their resistance to fracture increases as the crack propagates – which are important to model in order to predict accurately the response of such a material during damage propagation. This paper is concerned with modelling the R-curve effect and its specimen-dependence displayed under large scale bridging conditions associated with longitudinal intralaminar fracture in unidirectional laminated composites.

Increasing R-curves can be attributed to toughening mechanisms acting in the wake of the crack; in laminated composites these could be fibre bridging and pull-out, cross-over fibre bridging or z-pins. The length over which these mechanisms act, called process or bridging zone, is often large compared to the characteristic dimensions of the specimen. For instance, in compact tension (CT) specimens, used to measure the fracture toughness of the tensile fibre failure mode in carbon/epoxy, the length of the process zone can be approximately 11 mm for 65 mm wide specimens (Pinho et al., 2006b). When such large-scale bridging conditions prevail, it has been shown that the R-curve is not a material property but is dependent on the specimen geometry (Suo et al., 1992). Similarly, the length of the process zone is in general not constant during crack growth. The specimen-dependency of the R-curve has been experimentally demonstrated in Sørensen and Jacobsen (1998) and Jacobsen and Sørensen (2001) using a double cantilever beam (DCB) specimen loaded with pure moments, for which case the length of the process zone is constant during crack growth, to measure the R-curve associated with mode I intralaminar longitudinal crack growth. R-curves were measured for several values of the height of the DCB's arms and it was found that for a height of 1.5 mm the length of the process zone was in the region of 28 mm, while for a height of 4 mm, the process zone was approximately 56 mm long.

Under large-scale bridging conditions, it has been proposed in Suo et al. (1992) and Sørensen and Jacobsen (1998) to use the bridging law – which relates the traction in the bridging zone with the crack opening displacement – as a material property. Experimentally, the bridging law can be calculated from the knowledge of the R-curve (J_R, later assumed to be the critical energy release rate G_R) and the crack end-opening displacement (δ) for specimens admitting a steady-state (Suo et al., 1992) (e.g. pure moment loaded DCB specimen):

$$\sigma(\delta) = \frac{\partial J_R}{\partial \delta}. \quad (1)$$

Sørensen and Jacobsen (1998) used the pure moment loaded DCB specimen to determine the bridging law associated with cross-over fibre bridging in mode I intralaminar crack growth. With this test configuration, crack growth is under pure mode I and the J-integral evaluated along the boundaries of the specimen is equal to the energy release rate (G) (Suo et al., 1992), which can be expressed as a function of the applied moments, material properties and geometry of the beams. In this case, the bridging law was found to be nonlinear and independent of the specimen geometry. This approach was recently extended to mixed-mode behaviour using the uneven bending moment DCB specimen (Sørensen et al., 2009).

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