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Growth from initial to self-similar shape of an interface crack front

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A B S T R A C T

Initiation and growth towards a self-similar/final shape of an interface crack is analysed. Asymmetric double cantilever beam experiments are performed under prescribed displacement loading conditions. The onset of crack growth from an initially straight front is followed using digital microscope. It is observed that at first the crack grows from the longitudinal axis of the specimen symmetry. Subsequently, the crack spreads in both the longitudinal and the transverse directions finally forming a curvilinear front. From this stage, the crack grows in a self-similar shape and propagates along the interface. Such crack formation may result in a nonlinear force *vs.* displacement relationship which is otherwise related to constituent or interface constitutive nonlinearities. To study the consequences of the initial crack growth process a cohesive zone model is established. The numerical analysis starts with the assumption of a straight crack front configuration and continues up to the self-similar stage of propagation. A maximum cohesive zone stress is used as criterion to determine the position and the shape of the process zone front while critical crack opening is used to follow the crack front shape. It is concluded that the non-linear part of the force *vs.* displacement curve observed during loading can be at least partially interpreted as a crack front reformation from the straight to a steady-state quasi-parabolic shape.

1. Introduction

For adhesive joints, the adherents and the adhesives are often physically and geometrically dissimilar leading to variations of global parameters [1] or local effects like stress gradients at corners and edges [2]. Such deviations from the uniform material or the uniform loading conditions are of special interest when predicting the lifetime of materials and structures. There are two widely used design criteria when dealing with layered materials: a strength of materials approach, where critical stresses or strains are associated to failure, and a fracture mechanics approach which assumes pre-existence of small cracks.

Since the pioneering works of Dugdale [3] and Barenblatt [4], more recent contributions have led to a hybrid approach to a finite fracture mechanics [5–8]. While material properties are studied extensively, relatively little attention has been given to the geometrical processes taking place during crack formation and initial growth. An additional interpretation could be attempted through studies of geometrical changes of crack front morphologies during onset of crack growth. Such attempt can prove supplementary in explaining some of the features attributed otherwise to the constitutive behaviour of the materials [9,10].

The standard methods used to evaluate fracture toughness of layered materials [11] assume that the area of the fractured surfaces depend solely on the crack increment in the direction of crack growth while the width of the crack remains unchanged. This clearly cannot be the case when the crack front is initially straight and the final, self-similar shape is often found curvilinear [*e.g.* 12, 13]. One of the ways to cope with the problem of the initial crack formation is pre-cracking. The processes involve different methodologies leading to the creation of crack fronts with the expected final shape. Although useful in determining the fracture toughness, it have limitations when dealing with real materials and structures. For such, the introduction of pre-cracks is not desirable and for this reason understanding the behaviour in the first stages at crack onset and growth is fundamental for more robust designs.

For many applications, single lap joints, butt joints or pull-out experiments are performed from which the apparent strength of the joint is evaluated. Subsequently, simple strength type criteria are used for design [1]. Other standard approaches are based on the fracture mechanics [9,14]. Among various geometries proposed, those based on cantilever beam geometries are of highest importance [15]. The outcome from the experiments is the critical fracture energy taking form of the steady-state value - characteristic for the propagation process when the crack front shape remains self-similar. Although this is an important material property, it is easy to show that at the onset of crack growth this criterion is not always correct [16–18]. Therefore, it is not clear whether the parameters obtained with the use of the standard procedures and cantilever beam-like specimens are suitable. To cope with

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some of the problems, a finite fracture mechanics approach was proposed [5,7] more recently. It is based on three parameters: strength, toughness and a finite crack length. The originality of the approach is provided by the requirement that at the onset of crack growth, all the parameters and criteria must be fulfilled simultaneously, *viz*. strength, toughness and presence of a crack of a critical length. While very useful and already proven [19,20], the method is not always justified with one of the problems being the one-dimensional nature of the approach in terms of the crack length. Attempts are being made to propose three dimensional formulations [8]. This is of importance for the present study, since it was observed that during the double cantilever beam (DCB) and single cantilever beam (SCB) experiments, the crack front tends to change its shape as a response to the structural behaviour of the beam/plate adherents [21–23]. It is therefore unclear whether the crack length approaches for evaluating the fracture energy *via* the strain energy release rate and the compliance method [24] lead to valid failure criteria. Indeed, many authors have addressed interface fracture with different approaches and setups.

In [25] it is shown that neither the stress intensity factors nor the energy release rate are constant along the crack front. Singularities and crack propagation have been studied in [26] and it is shown that singularities may exist where the crack intersects the free edge – the side of the DCB specimen. It is also shown experimentally that the crack front is not conserving its initial straight shape even in a homogeneous interface system, but, as it is shown in [27] and [28], a concave like shape should be expected. Studies of effects of bonded surface heterogeneities on the crack front morphology have also been made. Analytical solutions provided in [29] and [30] are obtained using the first-order perturbation analysis expanded in [31]. In [32] and [33], dynamic crack growth has been studied with interfaces of variable toughness. In [34], the crack front morphology was studied experimentally and analytically. Heterogeneous interfaces were produced with different combinations of weak and strong adhesion zones along the crack propagation plane. In the works [27–29] it was shown that the interface cracks propagate in a self-similar fashion with a front of concave shape but with a significant convexity close to the free edges of the DCB specimens [35–37]. To take the adhesive layer into account, many of the contributions use the cohesive zone modelling (CZM) method. It was consequently shown that the material behaviour at the crack front can be described by traction-separation relations [38]. The approach was applied with success [39–41] for variety of materials and systems including adhesive bonding resulting in reliable and efficient predictions when implemented in numerical models.

In the present work, the asymmetric double cantilever beam under global mode I loading configuration is used to analyse crack formation and initial growth. The process of the crack front reformation from the initially straight shape to a fully developed self-similar shape (which will be assumed as the final shape of the crack) is presented by results obtained experimentally and by using a cohesive zone model combined with the finite element modelling (FEM). Finally, effects of crack shape reformation on the force *vs*. displacement and the equivalent *R* – curves are presented. In contrast to our previous works, the emphasis in the present work is on the global compliance of the bonded joint.

We show that the non-linear load response should not be solely associated to the non-linear behaviour of materials. At least partially, it can be attributed to the geometric reconfiguration of the crack front. Considering the full crack front formation at the interface, contrary to commonly used one dimensional (1D) beam assumptions with a single crack length parameter, initial values of the energy release rates are much higher than the critical – steady-state values. Such 1D approaches lead to non-conservative values of fracture energy in contrast to the full models. The 1D and the full crack solutions converge to the same steady-state value when the crack front is fully developed.

2. Experimental

2.1. Materials

The main part of the experimental results presented in this contribution refers to a bonded system consisting of polymethamethacrylate (PMMA) flexible adherent bonded with a structural epoxy adhesive to an aluminium adherent. The PMMA (Bayer, Germany) adherent was used due to the transparency. Dimensions were: 25 mm width, *W*, 200 mm length, *L*, and 8 mm thickness, *t*. The Young's modulus of $E = 3 \pm 0.2$ GPa was estimated from a three-point bending test. The Poisson's ratio of 0.34 was taken from the original product brochure. In such a configuration, the aluminium adherent (thickness 10 mm and Young's modulus of 70 GPa) is treated as being infinitely rigid for simplicity. To bond PMMA to aluminium, a bi-component structural epoxy adhesive (Scotch-Weld, DP-460 white supplied by 3 M, USA) was used. The pot time for this adhesive system is around 1 hour allowing multiple specimens to be formed before the resin is settled (the pot time should not be confused with the cross-linking time, which for the present adhesive is around 12 h in ambient conditions).

Prior to bonding, the PMMA and aluminium substrates were sand-blasted with alumina particles with an average size of 100 µm diameter at 6 bar pressure (as measured at the compressor gauge) followed by ultrasonic cleaning in water/ethanol mixture for 10 min at 30 kHz. Subsequently, the PMMA adherents were partially covered with a double face adhesive tape to create multiple well defined straight crack arrest positions along the crack growth plane. First, 20 mm long strips were placed at an initial crack length of $a_0 = 50 \pm 2$ mm. The width of the strips was equal to the width of the adherents. The strips were repeated allowing for 25 mm of crack growth between them, so that 3 crack arrest positions were produced as shown in Fig. 1.

After manual mixing, a drop of the adhesive was applied to the aluminium surfaces between the tape strips. The entire process of adhesive preparation and application amounts to *ca*. 5 min. A dead load was applied to the specimens to allow the drop of the liquid adhesive to spread until reaching tape extremities. This assures that the adhesive cannot leak above the strip regions. The crosslinking continues under the dead load for 24 h in ambient room conditions (controlled, 22^o C and 60% RH). The bondline thickness obtained is $t_a = 0.4 \pm 0.05$ mm.

2.2. Tests

The epoxy adhesive was characterized during the tensile experiment. A micro tensile machine (MTS, UK) was used to evaluate the Young's modulus. Rectangular cross section, flat specimens: 0.4 ± 0.05 mm thick, 6 ± 0.05 mm wide and 25 ± 0.05 mm long (with 19 mm gauge length) were moulded during the process like the one described before. In the present case, the PMMA substrates were left untreated assuring no adhesion and easiness of peeling off tensile specimens. A total of 7 specimens were tested under a controlled displacement rate of 2 mm/min leading to $E_a = 1630 \pm 15$ MPa.

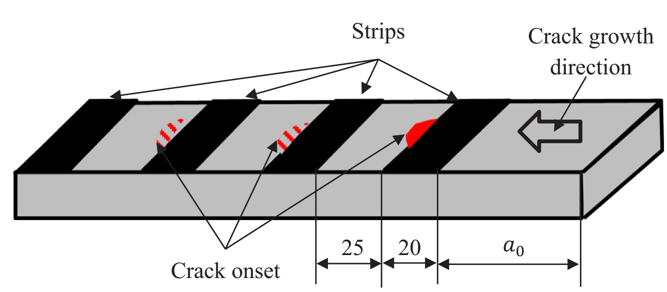

Fig. 1. Schematic representation of half of the specimen with multiple strips allowing crack onset at different locations.