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Research paper

Branching and softening of loading path during onset of crack at elastic-brittle interface

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ABSTRACT

The load response during onset and reformation of an interface crack is investigated experimentally and theoretically using linear-elastic analysis. A number of double cantilever beam experiments is carried out under the prescribed displacement and the prescribed displacement rate loading conditions. During the onset of the interface crack with the initially straight front, the crack grows from the centre of the specimen before adopting a semi-elliptic shape. The shape of the crack front eventually becomes self-similar (sizes of the crack front process zone and the ratio between the crack front depth and its width become invariant) when reaching the free edges of the specimen. As a consequence, during the crack reformation the incremental crack area cannot be attributed to the growth along a single direction. Finite element calculations are implemented in which the recorded crack front morphologies are imposed as the crack front boundary conditions. It is concluded that the load response curve can become non-linear upon the geometrical reconfiguration of the crack front and quantitatively is associated with gradual transition from the plane strain to the plane stress conditions experienced by the adherend during the crack front reformation.

1. Introduction

Fracture mechanics is considered as one of the most important and reliable tools for evaluating and predicting usefulness of materials with flaws. The double cantilever beam (DCB) experiments are proven and well-suited for testing and estimating the resistance to crack growth of layered materials (Chaves et al., 2014; Czabaj and Davidson, 2016; Szekrenyes, 2014). The models based on beam theories are used for data reduction allowing the problem to be treated in the two, out-of-the (crack growth) plane, spatial dimensions. Assumptions are justified once steady-state and self-similar crack growth conditions are expected (the self-similarity, in the present context, refers to the shape of the crack front and the fracture process zone size remaining dimensionally unchanged during the crack growth (Bazant et al., 1991; Bazant and Kazemi, 1990) and as such should not be confused with the general understanding of self-similarity associated to the scale invariance e.g. (Barenblatt, 1979; Bonamy et al., 2006; Mandelbrot, 1983; Ponson et al., 2007)). The increase of the cracked area depends solely on the crack length. While the steady-state, self-similar crack growth stage is specifically important within the damage tolerance philosophy, the crack onset process can turn more critical (Diaz and Caron, 2006; Jensen, 1993; Mendoza-Navarro et al., 2013). For instance, it was found that the values of the strain energy release rate (SERR or ERR), $\mathcal{G}$, were (at least) 20% higher during the self-similar crack growth values compared to the values at the crack onset (Davies, 1996; Davies et al., 1992). Such big discrepancy could be potentially explained by an incorrect data reduction scheme. Indeed, it is recognized, contrary to the assumptions made within the data reduction protocols, that the initially straight crack front is not always straight during (or after in that matter) the propagation (Budzik et al., 2012a, b; Chai and Liechti, 1991; Czabaj and Davidson, 2016; Davidson and Schapery, 1988; Davidson and Yu, 2005; Davidson et al., 2000; Jumel et al., 2011; Liechti et al., 1992). Several phenomena are deemed as an origin for such behaviour. Consider a bonded specimen under fracture mode I loading by a remote stress of magnitude σ. The bondline, of finite and non-negligible thickness, is represented by an isotropic, homogeneous material defined with the Young's modulus E and the Poisson's ratio ν. Along the crack front the bondline experiences a transition from plane stress $\sigma \propto \frac{1}{1-\nu^2}$ near the free edge, to plane strain conditions $\sigma \propto \frac{(1-\nu)}{(1+\nu)(1-2\nu)}$ at some distance from the free edges. Consequently, the stress and the stress intensity factor, $K(K \propto \sigma)$, will be higher under plane strain conditions – in these regions the crack will advance further (Cabello et al., 2016). Following H. Lamb analysis, the shape of the crack can become more complex once the thickness of the adherends converges to zero, or equivalently, the applied bending load is significant (Audoly and

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Pomeau, 2010). The boundary layer effects, introduced by the free edges, become significant (Moberg et al., 2017; Nilsson, 1993; Nilsson and Giannakopoulos, 1990; Nilsson and Storakers, 1992; Nilsson et al., 1993). Moreover, a curvilinear crack front introduces ambiguities as to the definition of the crack length. For layered materials, where the thickness of the bondline is often treated as negligible compared to other characteristic dimensions (thickness and width of the adherends), the anticlastic bending is recognized as an important factor (Budzik et al., 2011b, 2012b; Conway, 1949; Conway and Jaramillo, 1950; Crews et al., 1991; Davidson and Schapery, 1988; Nickola et al., 1967; Popineau et al., 2004). Following the effect of the Poisson's ratio, the anticlastic curvature leads to a curved crack front and is likely to affect the ERR distribution locally along the crack front (Budzik et al., 2012b; Nilsson and Giannakopoulos, 1990; Patinet et al., 2013b) and potentially the load response (Nilsson, 1993). The effect of the crack front shape on the local distribution of $\mathcal{G}$ (or vice versa) has been studied on several occasions. In (Nilsson, 1993) the Mindlin–Reissner plate theory, including the non-linear von Kármán terms, was formulated and resolved using the finite element method. The energy momentum tensor was used to express the $\mathcal{G}$ revealing complex loading state along the crack tip. In Jumel et al. (2011), the Kirchhoff's plate problem was solved semi-analytically assuming a straight crack front. In Jumel and Shanahan (2008), the variational problem was formulated minimizing the global strain energy density to evaluate the resultant crack front morphology. In the aforementioned works the interface was represented by an infinitely thin layer of an arbitrary resistance to fracture. The crack growth was directly, and solely, associated to the constitutive behaviour of the plate. Under such conditions the crack onsets over the entire width of the specimen - a feature, to the best authors knowledge, not confirmed experimentally. The load response was not analysed and a concise phenomenological description of the crack formation process was not provided.

In the present work, the crack reconfiguration is studied experimentally and analytically. Symmetric and asymmetric double cantilever beam, DCB and ADCB respectively, specimens are tested under fracture mode I loading. The loading conditions include two different rates of a displacement and a prescribed displacement. The crack front position and the shape of the crack front are monitored with a digital macroscope through the transparent adherends. It is observed that the incremental crack area is primarily driven by growth in the width direction. A feature not accounted for when using the standard one dimensional crack growth representation. The process is followed by the deviation from the initial loading path. In specific, the initial linear loading path bifurcated to another equilibrium, quasi-linear, path. A novel interpretation of otherwise material non-linearity problem (Jain et al., 2016) is brought to light. The results are interpreted analytically leading to a concise phenomenological description. To gain further insights into to the non-linear behaviour of the load response, adequate finite element calculations are carried out. The experimental crack front morphologies are introduced as the boundary conditions at the crack tip and the resultant load response is evaluated. The results indicate that bifurcation of the loading path is due to transition from the plane strain to the plane stress conditions within the adherends. This transition is enabled by creation of the curved crack front.

2. Experimental

2.1. Materials

The ADCB and DCB specimens were prepared and tested. The former being used to reveal possible effects of the I/II mixed-mode conditions on the crack front shape (Chen and Dillard, 2001; Tvergaard and Hutchinson, 1994). The ADCB specimens consisted of a 200 mm long, transparent polymethacrylate (PMMA, Bayer, Germany) adherends bonded to an equal-length aluminium alloy adherend (7075-T6 series) with a structural epoxy adhesive (Scotch Weld™ DP460, 3M™, USA). For the DCB specimens two PMMA substrates were bonded using the same epoxy adhesive system. The choice of the adhesive was partially dictated by a relatively long pot time (measured from the end of mixing to the application without loss of its final properties) of 1h allowing correct mixing and application of the adhesive without the risk of initial curing. The adhesive is characterized by a linear load response, Young's modulus E_a≅1.6 GPa, up to a load of ≅25 MPa as evaluated from a series of tensile experiments performed on dog-bone specimens using a micro tensile machine (SEMTester, MTI Inc., USA). Exemplary results are shown in Fig. 1 in which the linearity region (95% confidence level) is marked in grey.

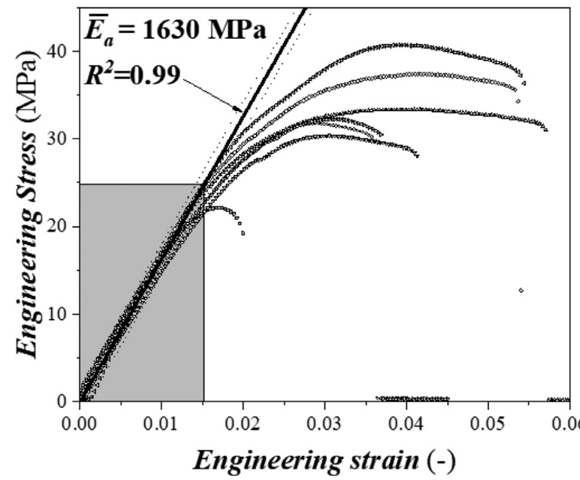

Fig. 1. The results of tensile test performed on the Scotch Weld™ DP460 adhesive.

2.2. Fracture specimens

Prior to bonding, the adherends were sandblasted (with, in average, 100 μm diameter grain corundum), sonicated in a water/ethanol solution (30 kHz for 5 min), rinsed in ethanol and dried with warm air. Two distinctive groups of specimens were prepared. The first, called reference group, consists of the DCB specimens with an initially straight crack front and initial crack length a_0≅50 mm. Ten specimens of this kind were used in evaluating the reproducibility of the bonding and surface preparation procedures, as well as in determining of the fracture energy $\mathcal{G}_c$. In the second group, comprising ADCB and DCB specimens, the surfaces of the adherends were masked using 30 mm bands of an anti-adhesive tape after sandblasting and sonication to create three distinct bonded zones. The bonded zones (between the masking tapes) spanned 20 mm allowing crack formation and growth under the steady-state conditions. The resultant three crack onset positions (with the crack fronts being initially straight) correspond to a_0≅ {50 100 150} mm. For clearness, in Fig. 2a schematic representation of half of the specimens is depicted. All the specimens and substrates have equal b = 25 mm width.

Specimens were bonded following an original procedure. After mixing a controlled amount of resin and hardener, the adhesive was dispensed as a drop on the unmasked areas of the adherends. The adherends were pressed firmly together causing the drop of the adhesive to spread toward the edges of the tape without penetrating it. The specimens were left under dead load for 24h for crosslinking under controlled conditions (22^oC and 60% of relative humidity). Homogeneous adhesive layer of ca. 0.3 mm thickness was obtained as verified using a light emission scanner (VR3200, Keyence, Japan). The properties of the materials are gathered in Table 1.

Consequently, a single specimen contains multiple onset positions allowing the reproducibility of the results and the dependence of the observed phenomena on the initial crack front position to be verified.