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Perturbation analysis of crack front in simple cantilever plate peeling experiment

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ABSTRACT

We have analyzed the effects of a single perturbation of the shape of a crack front on the energy release rate for a bonded joint. In the previous work, perturbation of the crack was introduced experimentally by variable adhesive properties. Accordingly a simple cantilever plate peeling experiment was performed on a specimen constituted from polycarbonate elastic plate bonded with a elastic fragile adhesive to aluminium rigid block. It have been found that fracture energy of such system differs from the expected rule of mixture values. In the following, using von Kármán plate theory, a relatively simple, first order approximation of the crack front perturbation effect is derived. The solution depends on two phenomenological quantities: the amplitude of perturbation and the perturbation wave length. The analytical solution matches reasonably well with existing experimental data.

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1. Introduction

Although the topic of inhomogeneous interfaces is not a recent one [1,2], multilayered materials and structures, with interface adhesion properties varying across the crack propagation plane, are gaining considerable scientific and practical attendance [3–8]. Local changes at the crack front level (crack front morphologies) inevitably lead to modification of structure performance *viz.* weakening or strengthening effects, similar to that observed when using fibre/particles reinforcements of materials. Apart from extensively studied natural and bioinspired/biomimetic surfaces (*e.g.* 'gecko like') [9–12] surface adhesion heterogeneities, by consequence of adhesion mismatch between fibres and matrix, present in any composite materials. Moreover, they are considered for some high-tech applications, *e.g.* optical [4,13] being attractive for future bonding applications *viz.* intelligent interfaces. Most of all, as we believe, they could be an essential tool in understanding effects of heterogeneities and phenomena related to reversible adhesion (attachment/detachment process).

Appreciating the interest in studying this subject, it is surprising to see that only few existing studies treat effects of surface heterogeneities and local, crack front morphology. Most of them are based on the Gao, Rice first order perturbation approach [14–17]. They provide the first-order variation of local mode I stress intensity factor resulting from some small, but arbitrary coplanar perturbation of the front of a semi-infinite crack in an infinite body. Recently, a notable progress has been achieved using extended analytical solutions, generalizations and finite element analysis making the Gao/Rice approach applicable to bonded plates [18-22]. However, direct interactions between crack front perturbation and its effect on global system compliance-easy to obtain experimentally, remains somehow unrevealed. Available local solutions found in the literature do not show convincing match with experimental data available. For instance, it has been shown that fracture toughness contrast as a parameter driving the perturbation solution may lead to incorrect results [17,18]. Finally, amount of data is limited and any new attempt would be desired.

Complementary to the past efforts [24,25] where more empirical approach was proposed in this contribution, we attempt another, analytical, strategy trying to bridge local and global aspects of the crack propagation along heterogeneous interfaces in estimating how the local perturbation of the crack affects globally measured energy release rate.

We analyze a crack front propagating across an interface (defined crack propagation plane) where parallel bands of variable adhesion, *viz.* strong/weak adhesion are produced. Hence, mainly the physical/chemical nature of the interface is modified leaving mechanical effects limited. This is important since, as noted, the relationship between the joint strength and the surface mechanical properties *cf.* roughness depends on other factors and cannot be expressed only as a function of the aforementioned surface parameter [5].

Finally, such introduced variation in surface properties lead to local perturbation of the crack front shape. Using von Kármán plate theory, we found a good agreement with available experimental results. Recognizing that this approach requires further,

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more detailed studies and analysis, the following contribution should be treated as a rudiment for fundamental understanding of complex interactions of fracture process along variable adhesion interfaces.

2. Experimental

2.1. Materials and interfaces

Simple cantilever plate specimen consisting of a elastic, polycarbonate (PC: Makrolon®, Bayer, Germany) plate bonded to a rigid, aluminium block with an epoxy adhesive, as shown schematically in Fig. 1, was subjected to nominally mode I loading (opening mode).

With all the details given in [24], for consistency we recall major geometry/material data. The elastic plate was 4 mm thick (h), 25 mm wide (b), 200 mm long (l) and its Young's modulus, E, as evaluated from the three point bending test, was 1.7 ± 0.1 GPa. The aluminium–magnesium alloy block (AW5754-H0, Alcoa, USA) was 15 mm thick (H), 40 mm wide, 170 mm long, with a Young's modulus, E_{Al}, taken as 70 GPa. The PC plate underwent two different surface treatments, in lengthwise direction, resulting in three parallel bands of weak/strong/weak (W/S/W) or strong/weak/strong (S/W/S) stacking. The ratio between the width of the strong interface to the total width of the specimen, f, was 0, 0.2, 0.24, 0.37, 0.48, 0.5, 0.72, 0.78, 0.87 and 1.

The aluminium and the PC were bonded with a elastic fragile DGEBA (Di-Glycidyl Ether of Bisphenol A) resin cured with a TETA (TriEthyleneTetraAmine) crosslinking agent, both supplied by RadioSpares (Quick Set Epoxy Adhesive, codes: RS 850-940-resin, and RS 850-956-curing agent, RS Components Ltd., Corby, Northants, UK). Curing was effected at 40 °C temperature for 1 h followed by a day in room conditions (ca. 23 °C and ca. 55% RH) to release possible residual stresses which are neglected in the present analysis. The cured adhesive had a Young's modulus of ca. 2 ± 0.2 GPa at 23 °C, evaluated from a Dynamic Mechanical Analysis (dogbone specimens of 3 mm thickness and 10 mm gauge length, tested at 1 Hz frequency with a 10 μm dynamic displacement). To ensure an initially straight crack front, as well as a homogenous bondline thickness ($t_a = 0.3 \pm 0.05$ mm, measured with a digital micro camera), anti-adherent polyethylene strips were placed at each extremity of the zone to be bonded. The fracture energy ratio between weak and strong interfaces was found $G_{cW}/G_{cS} = 0.08 \pm 0.02$ (tested for a set of samples with $f=0$ and $f=1$). This difference is only due to surface properties, *i.e.* in all cases fracture was entirely adhesive, at the PC/epoxy interface. With the scope being on the analytical analysis, in the following we make use only from the final results obtained in [25].

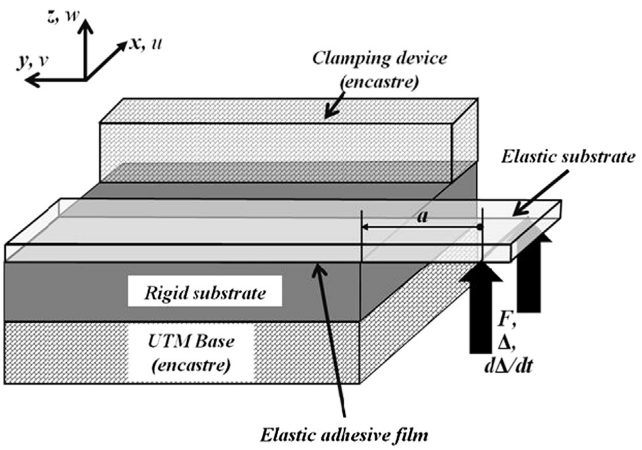

Fig. 1. Schematic representation of the system tested.

2.2. Simple cantilever plate peeling experiment

To propagate a crack, we use simple cantilever plate peeling [7,8,17,20,23]. This configuration, although being criticised for mixed mode conditions at the crack front is however very relevant for interfacial fracture studies. Importantly, even in symmetric configuration mode mixity at the crack front cannot be avoided (at least for a perturbed crack front), since the crack front morphology does not correspond to an equilibrium configuration of the bonded beam. Furthermore, in adhesive joints fracture along the adhesive/substrate interface mean that the crack locus is out from the symmetry plane. A constant, quasi-static, separation rate $d\Delta/dt = 1$ mm/min is applied to the free edge of the elastic beam. With both displacement (Δ) and force (F) being measured in real time a basic geometry analysis allows us to represent the energy release rate (G) in the form [26]:

$$G = \frac{F^2}{2b}\frac{dC}{da} \tag{1}$$

where C is the compliance of the system $C = \Delta/F$. The necessary crack length (a) can be obtained from the Euler-Bernoulli beam analysis setting $w(y=0) = \Delta$. It can be readily shown that such obtained an effective crack length is [25]:

$$a = h\sqrt[3]{\frac{Eb\Delta}{4F}} \tag{2}$$

3. Analysis of crack front perturbation

In the framework of Rice [27], Suo and Hutchinson [28] and Jensen et al. [29], the energy release rate and its separation into mode I, II and III components for an interface crack between two elastic, isotropic layers can be calculated by two separate analyses.

The basic assumption for this separation to be valid is that the curvature of the crack front is large compared to the beam thicknesses. If the beam thickness is small compared to the other, the energy release rate, G, is given by [29]:

$$G = G_{I/II} + G_{III},\; G_{I/II} = \frac{6(1-\nu^2)}{Eh^3}\left(M^2 + \frac{h^2}{12}N^2\right),\; G_{III} = \frac{2(1+\nu)}{Eh}T^2 \tag{3}$$

where $G_{I/II}$ is the combined mode I and II contribution to the energy release rate, G_{III} is the mode $_{III}$ contribution, E, ν and h are, respectively the elastic constants and the thickness of the layer. In (3), M, N and T are the effective bending moment and the membrane forces in the layer at the location of the crack front, as indicated in Fig. 2. As shown later M, N and T can be obtained from the beam deformations. Note that while Eq. (1) is based on global quantities, the energy release rate in Eq. (3) is calculated by local quantities at the crack front.

The analysis leading to (3) can be regarded as a near crack tip analysis and it must be supplemented by a far field analysis providing the effective moment and forces at the crack tip for a particular external geometry and loading.

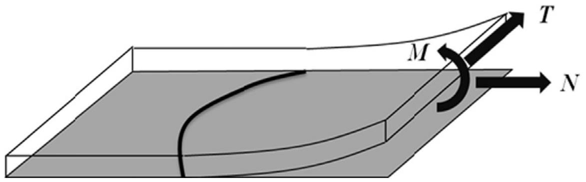

Fig. 2. Loads acting at the crack front.

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