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Experimental study of cracks at interfaces with voids

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Abstract

Heterogeneities are inherent parts of adhesively bonded joints. In order to take the full advantage of the adhesive bonding, it is commonly accepted that the bondline and the interface should be homogenous. Flaws and voids present at surfaces of the adherents or trapped inside the bondline are expected to lower the resistance to fracture. Indeed, with a simple inspection of the force *vs*. displacement curves, as obtained from mode I double cantilever beam experiments for assumed homogenous bond lines, some fluctuations were observed. These fluctuations are due to the aforementioned voids. A set of specimens were designed with strong/weak adhesion zones perpendicular to the crack propagation direction. Specifically, we address the problem of crack propagation along such interfaces with focus on the relation between the process zone size and the size of the void. In this paper, experimental results are presented followed by a fundamental analytical model. This is sufficient to gain phenomenological insight into the process of crack propagation along adhesively discontinuous interfaces.

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1. Introduction

Heterogeneities and adhesive bonding are inherently associated with each other. At the macroscopic joint structure level, bonding is often used to bridge dissimilar (chemically or physically) materials. Once providing kinematic continuity, the stresses inside the materials are necessarily different with steep gradients expected near the interfaces due to mismatch in elastic material parameters as first shown by Dundurs (1969). The adhesive (bondline) itself is also rarely homogenous. It is a common practice that different fillers are used in the constitution of the adhesive to reduce the costs or to increase mechanical or chemical parameters. Also, byproducts could be present in

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the adhesive, curing kinetics can vary across it, air or different gases could be trapped *etc*. Finally, the interfaces are not always physically and mechanically homogenous or intact as desired. Being the most crucial in transferring the load, the interface may suffer from contaminations, lack of or poor surface treatment leading to lower adhesion forces or kissing bonds. Those last are very dangerous and have been given considerable attention over the past years, *e.g.* Brotherhood et al. (2003), due to the fact that the adhesion is severely limited but sufficient to transfer acoustic or ultrasonic waves, as such being hard to detect in a non-destructive manner. From the other side, patterning of the interface is attractive for some of the applications including microelectronic components, Tadepalli et al. (2008). In all cases, understanding the behavior of the joint with a degraded adhesion properties is crucial for reliable and robust design.

While voids (or heterogeneities in general) inside the adhesive or in the bulk polymer received considerable attention, *e.g.* Bresson et al. (2013), it is only in recent years that interface heterogeneities have gained more attention. The perturbation theory of Gao and Rice (1989) and its variations [*e.g.* Willis (2012)] is most of the time used to predict final properties of the bonded joint with varying surface adhesion. The common geometry refers to the peel or double cantilever beam experiment, like in Patinet et al. (2013). Based on the contrast between strong and weak adhesion zones, crack front morphology is also explained. This is however often limited to the case when the interface consists of a strong/weak zone along the crack propagation direction and during steady-state propagation. Recently, an analytical model of a beam on an elastic foundation to analyze the effect of bonded/not-bonded pattern, when stacked perpendicularly to the direction of crack propagation, was proposed by Cuminatto et al. (2015).

In the present paper, the focus is on experimental findings for double cantilever beam under mode I fracture mechanics loading when a constant rate of separation is applied to the adherents. The force *vs*. displacement data are collected for various systems including homogeneous and heterogeneous surface preparation.

Nomenclature

a	crack length
b	width
C	compliance ($=\Delta/F$)
Δ	applied displacement
E	Young's modulus of elasticity of the adherents
E_a	Young's modulus of elasticity of the adhesive
e	thickness of the bondline
F	applied transverse force
G_I	the mode I energy release rate
h	thickness of the adherent
I	second moment of the area of the adherent
l	length of the adherent
λ	bondline 'wave number'
λ^{-1}	wave length ≡ process zone length
v_a	Poisson's ratio of the adhesive
x, y, z	Cartesian coordinate system

2. Experimental

Two PMMA plates of width, b = 25 mm, thickness, h = 5 mm and Young's modulus of elasticity, E, of *ca*. 3.5 GPa, estimated from three point bending experiment, were bonded with an commercial acrylic adhesive (Bostik) to produce double cantilever beam specimens. Half of such a specimen is schematically shown in Fig. 1.