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Analysis of crack trapping in 3D printed bio-inspired structural interfaces

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Abstract

Specific features of biological materials, such as microstructure, heterogeneities or hybrid compositions, already inspired the fabrication of several architected materials. More recently, special emphasis has been placed on the development of damage tolerant interfaces by introducing tailored surface heterogeneities. However, thanks to the current developments in the area of additive manufacturing, the mating substrates can be now fashioned into complex shapes to confer the desired joint behavior. By taking inspiration from the base plate of the *Balanus Amphitrite*, we recently employed 3D printing to fabricate bio-inspired structural interfaces and adhesive bonded Double Cantilever Beam (DCB) fracture specimens. The results of DCB tests have shown a remarkable increase in the total dissipated energy with respect to baseline samples. In this work we supplement our previous study by performing finite element simulations in order to ascertain the variation of the driving force as a function of crack advance. The obtained results, which are analyzed in conjunction with high resolution imaging of the crack propagation process, allow to further elucidate the mechanics of debonding. It is shown that the sub-surface channels can modulate the driving force available for crack growth, introducing a crack trapping ability which depends on the specific geometry of the interfacial region.

Keywords: selective laser sintering; bio-inspired interfaces; double cantilever beam; crack trapping

1. Introduction

The reliability of layered materials represents an important challenge for the manufacturing of current aerospace and automotive structures. An interesting approach to tackle this problem is to design the structural interfaces of the mating substrates. This task can be accomplished by introducing surface heterogeneities which selectively target the interfaces by modifying the toughness landscape Alfano et al. (2014); Hernandez et al. (2017); Heide-Jorgensen et al. (2018). However, recent work by the authors, which leveraged on bio-inspiration and additive manufacturing, indicated that the modification of the sub-surface region of the substrates represents a very promising approach to address the problem Alfano et al. (2018). Biological materials are endowed with peculiar meso- and micro-scale surface and

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sub-surface features which provide extraordinary adhesion properties to a large variety of surfaces. Interestingly, it has been noted that subsurface structures, such as those observed in the *Balanus Amphitrite* by Hui et al. (2011), enable the so called *crack trapping* effect. Earlier works, which focused on the analysis of crack trapping, resorted to micro-scale mechanical tests Glassmaker et al. (2007) and numerical modeling Afferrante and Carbone (2011). Our recent work indicated that bio-inspired crack trapping can be ascertained at the macro-scale by combining 3D printing and adhesive bonding Alfano et al. (2018). In particular, fracture tests were carried out using adhesive bonded Double Cantilever Beam (DCB) specimens with 3D printed bio-inspired structural interfaces. The substrates, which were obtained using Selective Laser Sintering (SLS) of polyamide powder, embedded sub-surface channels with either circular or square cross-sections. Adhesive bonding was carried out using a structural epoxy adhesive. The experimental results have shown that the proposed strategy induces load fluctuations in the global load-displacement response and a significant increase in the total dissipated energy with respect to bulk samples, *i.e.* no channels. A crack trapping effect was observed which effectively delayed crack propagation process and depended on the subsurface channels architecture (*i.e.* shape). It was speculated that the spatial modulation of the stiffness around the interfacial region affects the available driving force for crack growth. The present study further deepen the analysis of our previous results through a set of finite element analyses devoted to the evaluation of the strain energy release rate using the Virtual Crack Closure Technique Krueger (2004).

2. Materials and methods

2.1. Model description

In order to assess the crack trapping effect, a model material system comprising a Double Cantilever Beam (DCB) with subsurface channels has been considered in our previous work Alfano et al. (2018). The substrates were fabricated using SLS (EOS Forminga P110, Germany) using a commercial nylon powder (EOSINT P/PA2200), while adhesive bonding was performed using a bi-component structural epoxy adhesive (Loctite Hysol 9466, Henkel, Germany). Schematic representations of the substrates featuring the relevant geometrical dimensions are reported in Fig. 1a. The total length of the substrate is equal to 150 mm, the width is 15 mm and the thickness is 6 mm. The geometry of the channels is inspired to the base plate of the barnacle *Balanus Amphitrite*, which has been recently analyzed in Hui et al. (2011). Indeed, the samples are provided with channel height to substrate thickness ratio (h/H) comparable to that observed in the barnacle. In the finite element analyses, distinct versions of the channel shape have been considered as indicated in Fig. 1b. A single cell within the substrate is represented by a channel between adjacent pillars.

2.2. Evaluation of energy release rate

For the FE simulations only half of the sample has been considered, which has been modeled has an isotropic, homogeneous and elastic continuum with Young's modulus 1.65 GPa and Poisson's ratio 0.4. The material properties of the substrates were determined experimentally in a previous work by the authors Alfano et al. (2018). The details of the FE mesh around a typical geometrical cell is given in Fig. 2a. The mode I component of the strain energy release rate (G_I) was extracted using the virtual crack closure technique (VCCT) Krueger (2004). Considering a two-dimensional plane stress model featuring eight-noded elements, the mode I and mode II component of the strain energy release rate (*i.e.* G_I and G_{II}), can be obtained as follows:

$$G_I = \frac{1}{2\Delta A}[Z_i \Delta w_i + Z_j \Delta w_m] \tag{1}$$

$$G_{II} = \frac{1}{2\Delta A}[X_i \Delta u_i + X_j \Delta u_m] \tag{2}$$

where ΔA is the crack surface, Z and X are nodal reactions in normal and shear directions, while Δu and Δw are the shear and opening displacements of paired nodes (see Fig. 2b). In the present work only mode I opening conditions were considered and therefore the G_{II} component was not evaluated. The obtained results (G_I) were normalized considering the energy release rate extracted from an identical bulk DCB model (G_0), *i.e.* model B in Fig. 1a.

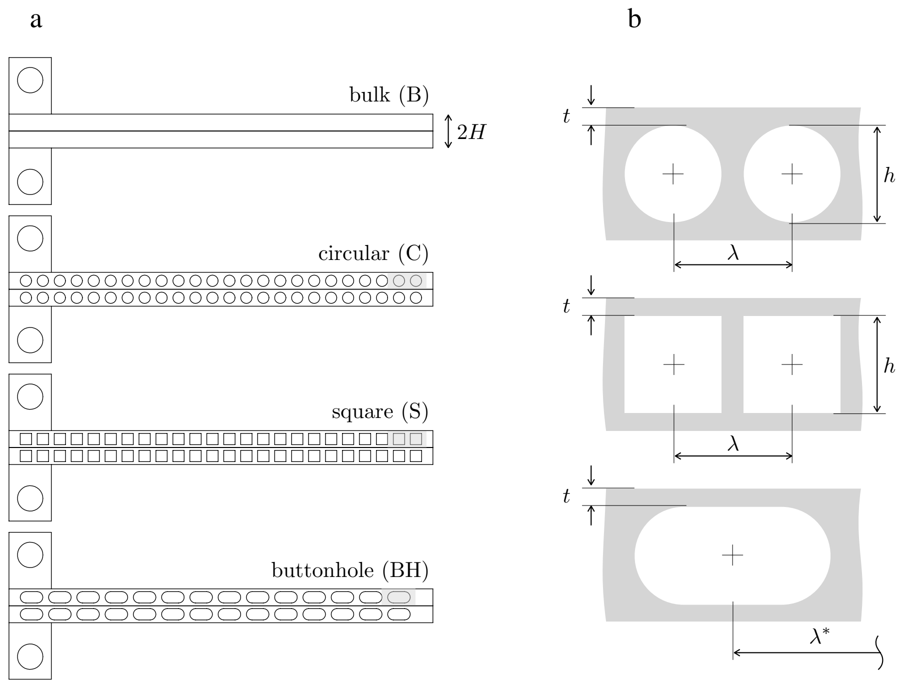

Fig. 1. (a) Double Cantilever Beam samples analyzed in this work; (b) geometrical details of the sub-surface channels (t=1 mm; h=4 mm; λ=6 mm; λ^*=10 mm)

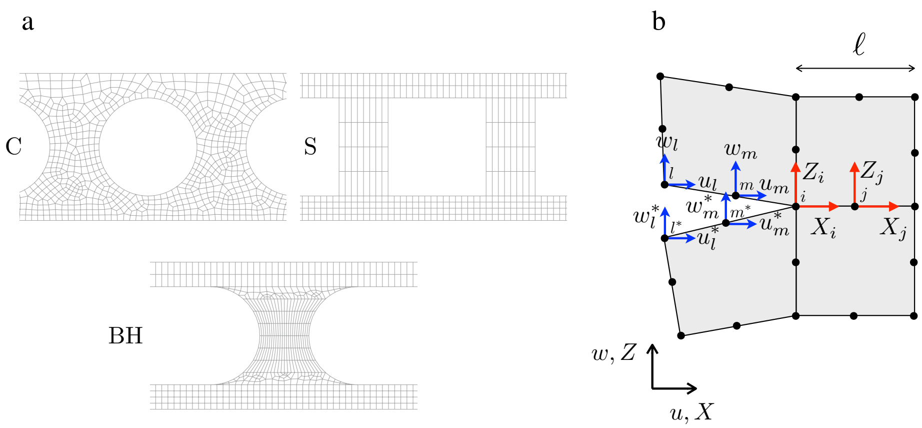

Fig. 2. (a) Details of the finite element mesh employed to extract the energy release rate; (b) VCCT approach for the determination of the mode I and mode II components of the energy release rate. ℓ is the length of the element at the crack tip.

2.3. High resolution imaging

Snapshots of a Region Of Interest (ROI) were captured by a GigE camera (Prosilica GT) with a 2/3″ CCD sensor (Sony ICX625). The lens applied to the camera had a focal length of 80 mm with a maximum f-number equal to f/4.0. Image acquisition was performed using a commercial software (Vic-Snap, Correlated Solutions) and a digital/analog acquisition board (DAQ-STD-8D, National Instruments). A voltage proportional to the displacement of the cross-head of the universal testing machine was used herein to acquire an image every 0.5 mm. A PC workstation was used to store and process the images. For each sample configuration, three tests were carried out to ensure robustness and significance of the obtained results.

3. Results and discussion

The results of the finite element analyses are reported in Fig. 3. The normalized energy release rate (G_I/G_0) is given as a function of the crack advance (Δa), which has been normalized with respect to the channels wavelength (λ). The available rate of energy release rate varies periodically as a function of crack position. The energy which is

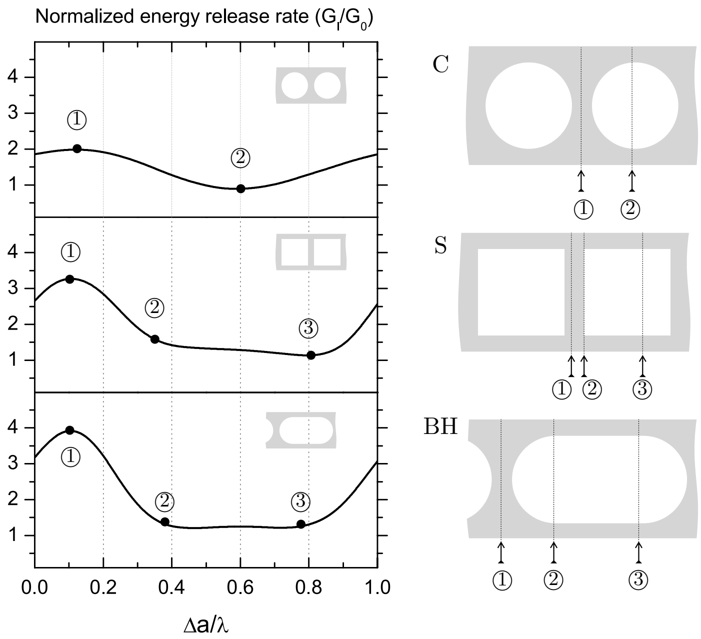

Fig. 3. Normalized energy release rate obtained using the VCCT and corresponding schematic of the subsurface substrates geometry. C: circle; S: square; BH: buttonhole.

supplied to the system by the remote applied loading is either absorbed by the material around the tip or is available to extend the crack: depending on the location of the crack tip, the material near the interface will absorb or release energy. In the latter case, an extra energy, beyond that supplied remotely, is available to propagate the crack. The finite element simulations carried out on the configuration C indicate that the material around the crack tip is releasing energy whenever the crack passes under the pillar (①). In this case the energy flows at the crack tip and the crack can propagate. On the other hand, energy is absorbed when the crack is between the pillars (②) with the occurrence of a crack trapping effect. As a result, there is an increase in the system compliance for cracks located between to consecutive pillars, which is quite beneficial because it enhances the crack trapping ability Afferrante and Carbone (2011). It is noted that for the geometries denoted S and BH the behavior is similar, although the sharper increase in the system compliance promotes higher fluctuations in the driving force. The obtained distribution of the energy release rate has been correlated with the global load-displacement response recorded during the DCB tests. Figure 4 shows selected portion of the load-displacement curves from the fracture tests of DCB samples of both type C and S. Also shown in the figure are a few selected snapshots of the samples taken during crack propagation. The snapshots are referred to a ROI around the crack tip and were deployed to correlate the position of the crack front with the observed load fluctuations and the energy release rate. Notice that the sample geometry named BH has not been explored experimentally herein and is the subject of follow-up work. In general, after the crack starts propagating, the load varies periodically due to the presence of the channels. In particular, the crack shows limited slow (stable) crack extension when the tip is within the compliant region. In this phase the load increases almost linearly, until the crack snaps through the entire single cell and reaches the next pillar. The snap-through process occurs in conjunction with a sudden drop of the remote applied load, from which an increased work of separation is originated. Interestingly, similar behavior was observed during cracking of layered composite materials with a crack perpendicular to the

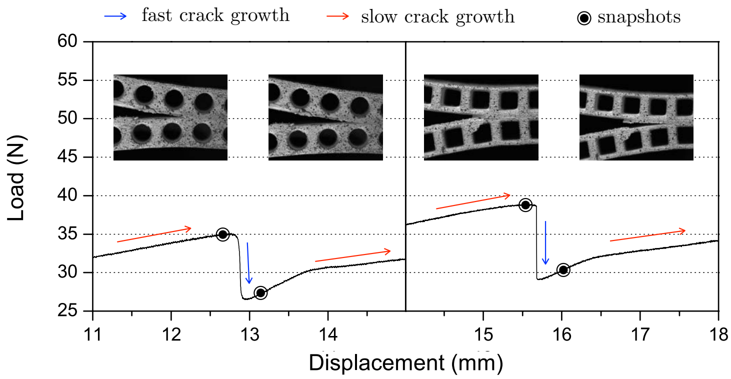

Fig. 4. Global load-displacement responses recorded on samples type C and S. The inserts display selected high resolution images taken in the ROI around the crack front using a CCD sensor.

interface Kolednik (2011); Hsueh et al. (2018). The load fluctuations were indeed determined by a periodic variation of the material Young's modulus and the associated fluctuation of the driving force.

4. Conclusions

The reliability of layered materials represents an important challenge for the manufacturing of current aerospace and automotive structures. By taking inspiration from the base plate of the barnacle *Balanus Amphitrite*, we recently employed 3D printing to fabricate bio-inspired structural interfaces featuring sub-surface channels. A single cell within our architected substrates is represented by a channel between two adjacent pillars. The results of finite element simulations carried out herein were analyzed in conjunction with high resolution imaging of the crack propagation process, and allowed to further elucidate the mechanics of debonding. Our results indicate that elastic energy is drained away from the crack tip when the crack is within the compliant region of the interface, effectively decreasing the driving force (pinning regime). Indeed, when the crack lies between the pillars most of the energy supplied by the remote loading is absorbed by the material surrounding the tip. The absorbed energy, which can greatly exceed that required to grow the crack, is released (in unstable manner) when the crack front is close to a pillar. In particular, the crack snaps through the entire single cell and reaches the next pillar. The snap-through process is accompanied with a sudden drop of the applied load and a release of elastic energy, which is expelled by the material around the front. This explains the substantial increase in the total dissipated energy recorded in mechanical testing. Therefore, the sub-surface channels can modulate the driving force available for crack growth, introducing a crack trapping ability which depends on the specific geometry of the interfacial region.

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