Composites Science and Technology 124 (2016) 81–88

Contents lists available at ScienceDirect

Composites Science and Technology

journal homepage: http://www.elsevier.com/locate/compscitech

Tensile and shear strength of bimaterial interfaces within composite materials

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ARTICLE INFO

Article history:
Received 28 October 2015
Received in revised form
29 December 2015
Accepted 4 January 2016
Available online 7 January 2016

Keywords:
Adhesive joints
Interfacial strength
Stress singularities
Iosipescu test
Joining

ABSTRACT

The determination of the tensile and shear strengths of homogeneous materials can be easily performed by standard tensile and shear (e.g. Iosipescu) tests. Nevertheless, when the determination of these strengths involves a bimaterial interface, the standard samples present bimaterial corner configurations at their free-edges which generate singular stress fields. In the presence of these singular stress fields, the tensile and shear stress distributions are strongly non-uniform at these edges, where failure initiates and propagates along the bimaterial interface. The apparent strength obtained from these tests is not representative of the regularized strength of the bimaterial interface. To eliminate the stress singularities, a small notch is made on one of the materials along the interface perimeter, in this study. This idea, originally proposed by Lauke and Barroso (Compos. Interface, 18:661-669, 2011) for ascertaining tensile strength, is now adapted to ascertain shear strength, using a modified geometry of the Iosipescu sample, and it has also been generalized to configurations involving composite materials. Both proposals, for the tensile and shear tests, are performed using the bimaterial configuration of a composite and an adhesive; a bimaterial interface which typically appears in adhesive joints with composites. The local notch geometry is defined using semi-analytical tools developed by the authors and numerically verified by Finite Element models. The modified bimaterial geometries, tested under tension, demonstrated a higher tensile strength. However, the modified bimaterial geometries tested in shear did not show any clear influence over the failure load with or without the notch in the particular bimaterial configuration tested in this study.

1. Introduction

Failure prediction for structural components containing bimaterial interfaces may require knowledge of the normal and shear strengths of the interface. Failure criteria typically compare some combination of stresses/strains/displacements with their corresponding critical values. This study is mainly motivated by the need to ascertain some of these critical values (in particular the tensile and shear strengths values), for potential failure paths in adhesive joints which involve bimaterial interfaces (Fig. 1), for the purposes of predicting failure initiation. From the three potential failure paths shown in Fig. 1 (which start at the critical corner point, where failure typically begins [2]), path “a” involves only one material (adhesive), whose tensile and shear strengths can easily be determined by standard test procedures. However, paths “b” and “c” involve bimaterial interfaces with different fibre orientations, which might have different strengths. Along failure path “b”, the fibre orientation is perpendicular to the interface plane, whereas along path “c”, the fibre orientation is parallel to the interface plane.

The problem arises when trying to determine the strengths (e.g., the tensile strengths) associated with these alternative failure paths. Fig. 2 shows the natural choices for the bimaterial specimen configurations for determining the tensile strength. Fig. 2a, b and c correspond to failure paths “a”, “b” and “c” respectively. Fig. 2d will be discussed later. Nevertheless, samples in Fig. 2b and c (butt samples with a flat bimaterial interface) have, at the free edges of the samples, bimaterial corner configurations which give rise to stress singularities due to the mismatch of material properties. The tensile stresses are non-uniform along the interface. Thus, the tensile strength at the instant of failure (calculated as the failure load divided by the cross-sectional area of the sample) is not representative of the nominal adhesion strength, under tension, of

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http://dx.doi.org/10.1016/j.compscitech.2016.01.003

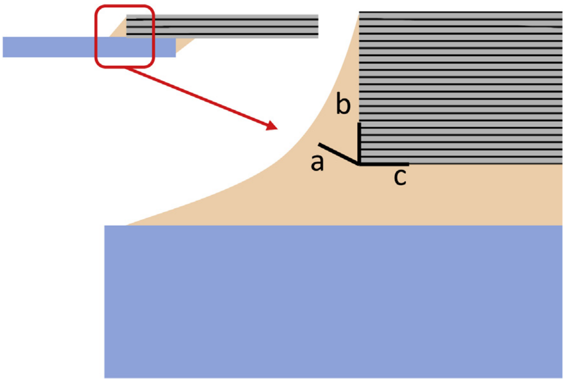

Fig. 1. Failure paths initiated at the critical corner point of an adhesive joint.

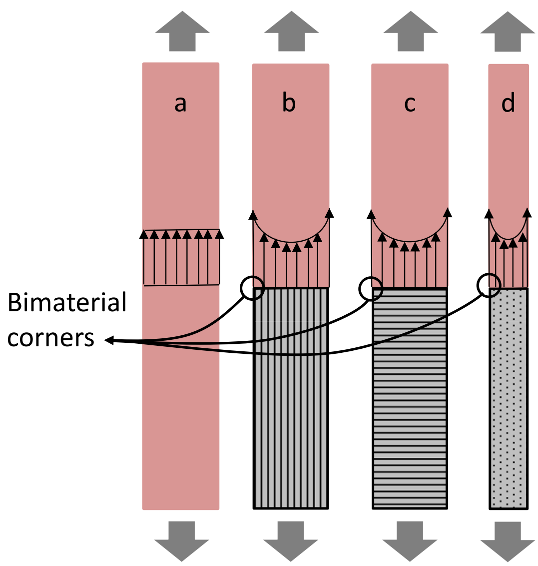

Fig. 2. Reference configurations for determining the adhesion strength: a) adhesive bulk configuration, b) bimaterial configuration with the fibre perpendicular to the interface, c) bimaterial configuration with the fibre parallel to the interface, d) bimaterial configuration with the fibre parallel to the interface and perpendicular to the sample plane.

the interface. The transverse section of these butt samples is of a rectangular shape whose width, represented in Fig. 2, is usually much larger than its thickness.

Lauke and co-workers [3–6] proposed bimaterial samples with a curved interface to avoid the stress singularities. This idea was also used by Wetherhold and Dargush [7] and Chowdhuri and Xia [8] to determine the adhesive strength of epoxy-aluminium joints, and also by Wu [9]. Lauke and Barroso [1] proposed a simpler modification of the butt-test with a flat interface, including a little notch at the free edge, which generates a particular local bimaterial corner configuration and avoids the singular stress field. Although both proposals require the calculation of the corner angles where the singularities vanish, the second option is easier to manufacture. In any case, there are no proposals, to the best knowledge of the authors, for the shear strength determination of bimaterial interfaces. The use of notches to eliminate the stress singularities in the Iosipescu test, with a bimaterial configuration, is the main contribution of the present work. Moreover, the presence of composite materials in the new tensile and shear configurations make the calculations of the stress singularities not straightforward, due to the non-isotropic behaviour of the composite material. In the present work this has been solved using the tool developed by the authors to calculate the stress singularities in multimaterial anisotropic corners [10,11], which also represents a difference with previously mentioned works.

The idea of using notches to relieve stress singularities is not new, e.g. Bijak-Zochowski et al. [12] used photoelastic images. An alternative idea, changing the bimaterial geometry configuration locally, but not using notches, was proposed by Wang and Xu [13] for two isotropic materials.

In the present study, the determination of the tensile and shear strengths of bimaterial interfaces similar to the configurations "b" and "c" in Figs. 1 and 2 will be considered. The proposal made by Lauke and Barroso [1] will be used in order to determine the tensile strength. In order to determine the shear strength, a new proposal, based on a modification of the Iosipescu geometry, will be defined in which the shear stress singularities at the free edges are removed. To achieve this objective, analytical calculations for the local corner configurations will be performed in order to determine the correct angle at which the stress singularity vanishes. Numerical models will be developed to check the uniformity of the shear stress distribution along the flat interface in the shear test. The confirmation of the elimination of the stress singularity in the tensile test sample was carried out beforehand in Ref. [1] for an isotropic bimaterial configuration. Finally, fabrication of the samples and experimental tests will be carried out in tension and shear for the bimaterial configurations "b" and "c" in Fig. 2.

2. Definition of the modified tensile and shear test samples

At a bimaterial corner, assuming linear elastic and anisotropic behaviour of materials, the asymptotic stress field can be singular due to the mismatch in the material properties. Using a polar coordinate reference system with the centre at the corner tip, the stress state is defined by the asymptotic series expansion [10,11]

$$\sigma_{ij}(r,\theta) \approx \sum_{k=1}^{n} K_k \cdot r^{-\lambda_k} f_{ij}^{(k)}(\theta) \tag{1}$$

where K_k are the Generalized Stress Intensity Factors, λ_k are the stress singularity orders, and $f_{ij}^{(k)}(\theta)$ are the characteristic angular shape functions associated to this corner. Both λ_k and $f_{ij}^{(k)}(\theta)$ can be computed semi-analytically following [10,11], where all manipulations are analytical except for the final calculation of the roots of a characteristic equation, which are computed numerically.

For the two bimaterial configurations under analysis (with the fibre orientation perpendicular and parallel to the interface) and for all the corner angles considered (see Figs. 2 and 3), there is only one singular term ($0<\lambda<1$) which dominates the stress field as $r \to 0$ because the associate stresses become unbounded. This fact has been verified by using the Argument Principle (e.g. Refs. [11,14]), which is an excellent tool for identifying the number of roots of a holomorphic function in a particular region of the complex plane. This observation can be explained by the small corner angle (occupied by the bimaterial configuration), considered equal to 180° in Fig. 2 and less than 180° in Fig. 3, which, from a geometrical point of view, does not generate a re-entrant corner configuration. Recall that in homogeneous materials there are no stress singularities at all for such corner angle values (this can be easily shown by applying the Cauchy Lemma at both traction free corner faces). Thus, the stress singularity order computed in the present study is essentially caused by the material mismatch as already mentioned above. Due to the material symmetries, the solution for the generalized plane strain problems for the present corner configurations can be decoupled into the in-plane and anti-plane solutions [15], the singular stress state corresponding to the in-plane