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A design oriented multiaxial stress-based criterion for the strength assessment of adhesive layers

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ABSTRACT

Adhesively bonded joints are becoming widespread in the composites industry and therefore there is a need for quantitative information on the mechanical strength of the material used. The great strength and stiffness of a composites structure may be strongly undermined by their weakest part, the bonded joint. Unfortunately, the testing of adhesives in bulk form may not be representative of their behaviour in a layered state, typically quite thin, because of differences in the polymerization process and lack of adhesive-adherend interfaces. The drawback of the test in thin layer is the stress concentration at the edges, typical in the single lap or t-peel joints, and also the chance of having the adhesive subjected both to a shear and predominant peel stress. This work deals with the characterization of adhesives in thin film under uniform distributions of multi-axial stresses, which is the typical application condition. The test exploits a tubular butt-bonded specimen, previously investigated by the authors, which guarantees a non-singular stress field over the adhesive layer both in shear and normal directions. According to the analytical prediction, in addition to the direct normal stress, both radial and circumferential secondary stresses arise in the adhesive, due to the constrained lateral contraction imposed by the adherends (Poisson's effect). The test campaign investigates two chemically different, commercial adhesives, an acrylic and an epoxy resin. By means of a biaxial testing machine, we applied to the specimens eight different combinations of normal and shear loads ranging from pure tensile to a shear-compressive stress state. As expected, both the pure shear stress and the compressive stresses lead to better performances of the adhesive layer with respect to tensile loading. The authors compare a variety of failure criteria from the literature and propose a simple multiaxial criterion to obtain a failure envelop of the experimental data. The applicability of the criterion is also assessed on experimental tests found in literature on different configurations and gives fairly good results. The outcome of study is a simple stress based, failure criterion, which can be used to predict the failure of several adhesive bonded joints, relying only on monoaxial experimental data.

1. Introduction

The present work deals with the quasi static characterization of a thin layer of structural adhesives through an ad-hoc tubular joint previously developed by the authors. The motivation of the work comes from the need of reliable and simple tools to design bonded structures in an industrial context. Normally in technical literature, two completely different approaches are envisioned. The first one exploits bulk specimens, made with the adhesive with standard dog bone shapes and tested on a tensile machine in the same manner as for metallic materials [1], [2]. The second one determines the adhesive properties by using it in thin film, as typically applied in real applications due to their superior performances [3], [4]. Adhesive producers typically recommend a quite thin adhesive layer for high performance structural joints, according to Huntsman “A layer of adhesive 0.05–0.10 mm thick will normally impart the greatest lap shear strength to the joint” [5] while according to Henkel Loctite the high performance, high stiffness joints are obtained with thin adhesives [6]. Well-established specimens typically possess the single, double or other lap specimen configurations, like the ASTM Standards D1002 and ASTM D3528. However, although simple to make and test, these geometries have complex stress distributions within the bond and give rise to both normal and shear stresses that vary from point to point [7], [8]. Stress singularities at reentrant corners and at points of material discontinuity are also an issue [9] that undermine the meaning of these tests for providing genuine strength properties of the adhesive [10].

Both these procedures have advantages and drawbacks. On one hand, the bulk test does not depend on the specimen geometry, the

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failure strain and stresses are very easy to calculate and the surface preparation of the adherends is not an issue. However, a possible drawback is the potential presence of defects and porosity in the bulk adhesive, not typical in real thin film applications and the complexity of using the failure stress of the bulk for the adhesive joint design, [11]. Even though there has been research work performed on how to avoid defects and porosity during the manufacturing process [12] the difference between thin film and bulk still can be a potential issue [13]. This problem is due to the constant presence of very rigid adherends, which create strong stress concentrations at the corners and highly triaxial stress state in the polymer. The high stress triaxiality is detrimental for the adhesive strength, since, as for many polymers, the adhesives are quite sensible to the mean positive stress applied [7] [8], both for ductile and brittle adhesives. Since the aim of the research is to propose a simple criterion applicable even in the industrial world, the authors consider the adhesive as a two-state material: structurally intact whilst in the elastic linear region, failed in case of plasticization and damage. Although one may argue that this is an oversimplification which can be too conservative, in many situations it is essential that the plasticity of the structural member is to be avoided and therefore this statement is applicable to many real-life situations. The first idea, which is the most natural one, is to borrow from the metal world the standard "von Mises criterion". Some efforts have been made in technical literature [16], but soon the need of an alternative criterion to the classical "von Mises ideal" stress came out, as shown in Fig. 1. The motivation is that the von Mises criterion considers only the distortion strain energy and disregards the dilation strain energy. The main advantage of the thin film test for the adhesive characterization is that the experimental properties are retrieved in a condition that is quite similar to the real application, with the adhesive constrained between two rigid adherends and with the typical thickness used in industrial context.

Two drawbacks are envisioned when testing adhesives in thin film. First, the properties depend on the adherends' material type (steel, aluminium) and on the surface preparations [9] [10], while the adhesive strength is at least function of its thickness [11–13]. Second, considering the typical specimen recommended by ASTM standards, such as the single or double lap joint or the Double Cantilever Beam, it is easy to understand that severe stress concentrations occur at the corners. This phenomenon comes from the elastic mismatch between stiff adherends and flexible adhesive and perturbs the measure of the adhesive properties in the elastic and post-elastic range. These stress concentrations, which can lead to singularities in the stress field, are considered an important dangerous trigger for cracks. Every joint has a

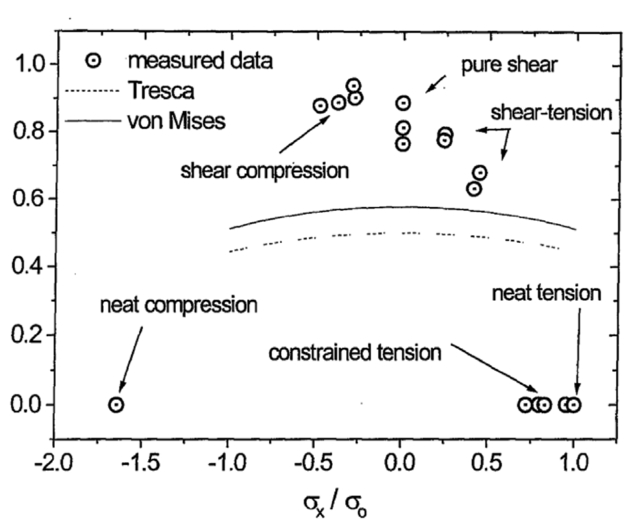

Fig. 1. Experimental data from Ref. [16] on highly constrained adhesive. Classic von Mises and Tresca criteria fails at creating a failure envelop region, since they do not consider the stress triaxiality.

different intensity of the stress concentration, according to Goglio et al. [21] [22], which causes complex problems when comparing adhesive properties retrieved with different specimens. Moreover, it would be important to understand the failure stresses both in tension (mode I) and shear (mode II) [23], since the adhesive behaviour is quite sensitive to the loading direction. Unlike the metals, the polymers are stronger, tougher and more ductile in mode II, while the failure stress and the fracture toughness are lower in mode I. Recently, several authors tried to exploit different specimen geometries in order to apply different loading modes on the same specimen. One interesting configuration involves butt-bonded adherends, so called "Napkin ring" test [24], and this shape has been proven useful both in torsion [19] and in tension [25] by adding stress relief grooves which are able to lower the stress concentrations at the adhesive interface and in the bond line, see Fig. 2. This architecture has two advantages; first, the machining of the adherends is very simple, especially compared to the ASTM Arcan and TAST (ASTM D5656) tests, which has the same purpose. Specifically, the proposed geometry requires a simple turning of the tubular material with a threading tool; second, this configuration allows any desired combination of tension/compression and torsion to be easily obtained. The only additional constraint is that the ASTM tests exploit a simple uniaxial test machine, while the tubular one needs a biaxial machine capable to apply tension and torsion at the same time. Other possible mixed mode test specimen configurations are the mixed mode double cantilever beam [26], the single leg bending [27] and the mixed mode fracture [28] and the modified Arcan test [29] which need quite complex equipment and could hide some potential problems as already discussed in [30].

The present paper exploits the modified butt joint with relief grooves to characterize two different adhesives in thin film. The first one is the Loctite Multibond 330, a general purpose acrylic adhesive [31], while the second one is the Loctite Hysol 3422, a two component, fast curing, epoxy resin [32].

The two adhesives were tested and the failure loads and torques are registered. Thanks to the simple geometry adopted and the absence of stress concentrations, an analytical stress prediction is possible and therefore the maximum normal stresses and shear stresses are calculated.

2. Materials and method

2.1. Experimental campaign

We decided to design the experimental campaign according to the "Design of Experiment" approach [33], where the input variables considered are the axial loading and the shear loading applied to the joint. By combining the two loading conditions, a systematic investigation of the axial (σ) - shear (τ) plane is carried out. The experimental loading conditions involve pure tensile, pure shear and six configurations of mixed loading both in tension and in compression. It was not possible to test the thin adhesive in pure compression since it would have been very difficult to identify the failure point. In fact, having a very thin adhesive lead to possible contact of the adherends, which has to be avoided. Moreover the adhesive properties in compression are better than in tension since polymers are typically quite sensitive to stresses triaxiality [34] so the performed test are more conservative.

Fig. 3 illustrates the eight configurations tested. The positive numbers identify a tensile loading condition, while the negative ones a compressive loading condition. The pure shear test is labelled with a zero.

To define quantitatively these eight experimental loading conditions, we used the angle α of the line in the σ - τ plane, defined as:

$$\alpha = arctg\left(\frac{\tau_{z\theta}}{\sigma_z}\right) \quad (1)$$