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On modelling the behaviour of a ductile adhesive under low temperatures

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ABSTRACT

The objective of the paper is to propose a strategy in order to develop accurate numerical models to describe the behaviour of a ductile adhesive in an assembly under mechanical proportional monotonic loads at different low temperatures. This study requires the use of precise 3D numerical analysis of the stress state within a bonded assembly in order to develop an inverse identification technique starting from the load–displacement curves obtained using a modified Arcan apparatus. First, the influence of the geometry of the bonded assembly close to the free edges of the adhesive on the stress state under a mechanical load at a given temperature is analysed with a 2D numerical analysis. These results allow us to propose some rules in order to define accurate experimental devices for such thermo-mechanical loads. The second part is associated with the estimation of the residual stresses within an adhesive in an assembly and the identification of the material parameters of a 3D elastic–plastic Mahnken–Schlimmer type model, for tensile/compression–shear proportional monotonic mechanical loads and for a temperature range between 20 °C and −60 °C.

1. Introduction

Adhesive joints are widely used as a structural element in various applications (automotive, aerospace, naval…) [1,2]. Two of the main advantages of this joining technique are the weight reduction and the facilitation of joining different materials, especially composites; in fact, this technique does not require holes, as riveted or bolted joints do, which can lead to stress concentrations. However, adhesively bonded joints are also often characterised by significant edge effects associated with geometrical and material parameters. Various simplified approaches, using 1D or 2D models, have been proposed in order to describe the behaviour of some bonded joints [3,4], but often such models cannot describe the effect of stress concentrations which often have an influence on the maximum stress state in the bonded assemblies. Therefore, understanding the stress distribution in an adhesive can lead to improvements in adhesively-bonded assemblies; for instance, designing assemblies which strongly limit the edge effects can be very interesting as stress singularities can contribute to the initiation and propagation of cracks in the adhesive [5,6]. In order to optimise the design of high-tech applications, it is also necessary to take into account the complex, non-linear behaviour of the adhesive (influence of viscous effects, of hydrostatic pressure, complex anelastic flow rule, etc. [7–9]). Moreover, the curing process of adhesives and thermal loads can also induce stresses within the adhesive, especially for stiff substrates [10–12]. The curing process is complex as it involves phase transformations and chemical reactions with volume changes [13]. Moreover; associated with difference in thermal expansion of the adhesive and substrates, thermal stresses evolve during cool down from the curing temperature and during a variation in the service temperature [14]. It is important to notice that various applications are subjected to a wide range of temperatures (for instance between −40 °C and 80 °C for some automotive applications). Such stresses, in combination with the temperature-dependent mechanical behaviour of the adhesive [15] can have a significant influence on the service life of the bonded assemblies [16] and can also change the stress concentrations close to the free edges of the joint [17–19]. Various experimental techniques, often associated with strain measurement, exist to analyse the residual stresses in a bonded joint (neutron and X-ray diffraction techniques…). The analysis of the deformation of a bi-material beam is an easy experimental technique which is often used for the determination of the stress free temperature of the adhesive in an assembly [10,20,21]. However, the viscous mechanical behaviour of the adhesive can reduce the residual stresses [22]. The influence of aging during the service life of a bonded assembly is often associated with a modification in the mechanical properties of the adhesive and can also modify the stress distribution within the assembly [23,24]. It has been shown that the identification of the material parameters of representative models

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for adhesives requires a large data base of experimental results under various compression/tensile–shear tests [25]. Bulk, lap-shear and pull-off tests are usually proposed [15,26] to analyse the mechanical behaviour of the adhesive but the influence of defects and the influence of stress concentrations are often difficult to take into account with such specimens. Herein, experimental results obtained using modified Arcan apparatus, designed to strongly limit influences of edge effects under mechanical loads [27] have been used. In a previous study, results were determined under low temperature (from 20 °C to −60 °C) [19].

The objective of the paper is to develop an accurate numerical model to describe the influence of temperature on the non-linear mechanical behaviour of a ductile adhesive in an assembly under proportional monotonic mechanical loads, i.e. the definition of the temperature-dependent initial elastic limit of the adhesive and the definition of the temperature-dependent flow rules. This study requires the use of precise 3D numerical analysis of the stress state within a bonded assembly in order to develop an inverse identification technique starting from the load–displacement curves obtained using the modified Arcan apparatus results. First, the influence of the geometry of the bonded assembly close to the free edges of the adhesive on the stress state under a mechanical load at a given temperature is analysed in the case of shear and tensile loads. The aim is to underline the influence of stress concentrations under such thermo-mechanical loads in order to propose some rules to define accurate experimental devices. The second part is associated with the estimation of the residual stresses within an adhesive in an assembly and the identification of the material parameters of a 3D elastic–plastic Mahnken–Schlimmer type model, for tensile/compression–shear proportional monotonic loads and for a temperature range between 20 °C and −60 °C.

2. Description of the materials

In order to analyse the influence of the geometry of the specimens on stress concentrations under thermo-mechanical loads, a comparison of numerical results is firstly presented in the case of shear type loadings using the TAST (standard thick adherend shear test [28]) and modified Arcan apparatus [29]. In a second stage, the influence of the local geometry of a bonded specimen, close to the free edges of the adhesive is analysed using modified Arcan apparatus in the case of tensile loads which are often associated with large stress concentrations [27].

2.1. TAST specimen

The single lap joint is the most used test in order to analyse the behaviour of an adhesive in an assembly as the manufacturing of such specimens is quite easy, and they require only a classic tensile testing machine. However, such specimens are associated with complex loading of the adhesive i.e. non uniform shear stress along the overlap length, quite high peel stress at the two ends of the overlap and significant edge effects associated with geometrical and material parameters. TAST type specimens (Fig. 1) [28], and its variant proposed by Althof [30], were designed to simplify the stress distributions in the adhesive. Therefore, they can be seen as optimised simple lap shear configurations but edge effects still exist. Moreover, it has been shown that the use of grooves (Fig. 2) allows a reduction in the stress concentrations [31,32]; thus, such geometries are used herein.

2.2. Modified Arcan device

A modified Arcan fixture, which enables compression or tension to be combined with shear load was previously developed [29].

The use of substrates with thin beaks and clean free edges of the adhesive can significantly limit the peel stress state close to the free edges of the joint. Moreover, an optimisation of the fixing system for the bonded specimen can avoid the pre-loading of the adhesive. In order to prevent parasitic loadings special fixing systems were used to fix the modified Arcan device (Fig. 3). The external diameter of the modified Arcan apparatus used was of 155 mm [33]. To ensure a precise adhesive thickness and a good relative positioning of the two substrates during the bonding process, spacers were manufactured during the machining process of the substrates, in order for the surfaces of the spacers to be used as reference for the manufacture of the bonded surfaces (Fig. 3b). The relative positioning of the two substrates during the bonding process is ensured using screws. Before testing, with the modified Arcan device, the spacers were cut. For such specimens, the area of the bonded section was 50 mm × 9 mm.

Numerical results are presented for two geometries of the bonded specimens used with the modified Arcan device (Fig. 4). The first geometry is associated with straight substrates and straight edges of the free edges of the adhesive and the second represents the bonded specimens proposed for the experimental tests (use of beaks on the substrates and cleaning of the free edges of the adhesive). By clean free edges we mean the surfaces we obtain after eliminating the excess adhesive. The geometry of the clean free edges presents *a* curvature *r* shown in Fig. 4b. Geometries are defined with the following parameters: $L=50$ mm, $H1=20$ mm, $\alpha=30^\circ$, $h=0.1$ mm, $d=0.5$ mm, $r=0.1$ mm and $e=0.2$ mm.

The different experimental results presented in the following were obtained using the epoxy resin Huntsman™ Araldite® 420 A/B with a joint thickness of 0.2 mm and a curing process of 1 h at 110 °C [19].

2.3. Parameters of the numerical simulations under elastic assumption

The elastic properties of both materials, at room temperature, are: $Ea=2$ GPa (Young's modulus), $\nu a=0.3$ (Poisson's ratio) for the

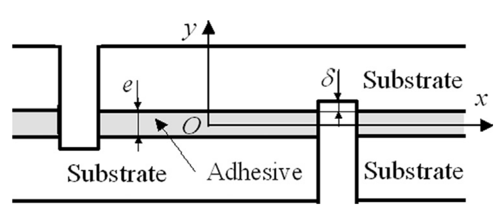

Fig. 2. Geometry of the TAST specimen with deep grooves (central part, not to scale).

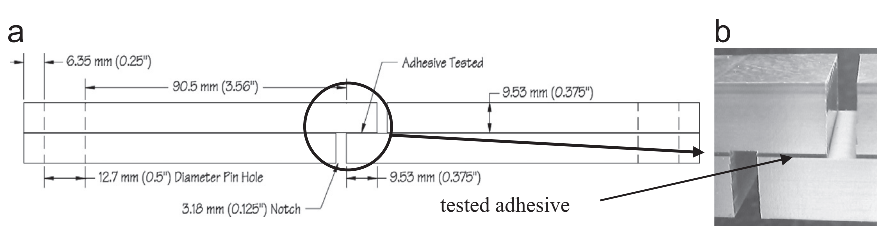

Fig. 1. Presentation of the TAST specimen (width: 25.4 mm) [6]. (a) Geometry and (b) useful zone.