International Journal of Adhesion and Adhesives 80 (2018) 104–114

Contents lists available at ScienceDirect

International Journal of Adhesion and Adhesives

journal homepage: www.elsevier.com/locate/ijadhadh

Use of the modified Arcan fixture to study the strength of bonded assemblies for automotive applications

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ARTICLE INFO

Keywords:
Adhesively-bonded assemblies
Modified Arcan test
Failure mode
Failure envelope

ABSTRACT

Adhesive joints are being increasingly used as a good solution to assemble primary structures of metallic and composite materials. Hence, the analysis of the behaviour of adhesively-bonded assemblies under mixed loadings is a critical issue for industry. This article discusses the use of the modified Arcan device to identify the strength of adhesively-bonded metal/metal and metal/composite assemblies. Different assemblies have been tested and their failure envelopes have been determined. Moreover, analyses have also been made of the influence of some crucial parameters on the behaviour of the assemblies in the study such as the composite surface state, the fabric orientation, the humidity and the presence of grease.

1. Introduction

Nowadays, adhesive joints are being increasingly used to assemble primary structures in almost all engineering applications, e.g. automotive [1], aerospace, medical prosthetics, alternative energy generation, civil engineering [2] and sports devices. This technique provides many interesting advantages for industry. These include the joining of dissimilar materials such as aluminium, steel, titanium, thermoplastic and thermoset composite with different configurations (glass or carbon fibre, ply orientations, textile/laminate/unidirectional, etc.). Conventional assembling methods such as riveting or bolting require the drilling of holes which induces stress concentration on the composite plate and can lead to an early failure of the composite [3,4]. Adhesive joints provide a more uniform stress distribution with an efficient load transfer [5,6]. Hence, adhesively-bonded joints represent a major advance for the use of composite materials in various industrial applications.

The design of such bonded multi-material structures requires the determination of (i) the global stiffness, and (ii) the failure load along with the associated failure mode. These parameters, which mostly depend on the loading, the nature of substrates, the adhesive, and the interfaces, lead to various failure modes illustrated in Fig. 1.

Tests on bulk specimens permit the elastic properties of the adhesive to be determined [7,8]. Some standard tests (Thick Adherent Shear Test [9] or Single Lap Specimens [10]) or non-standard tests (such as the Scarf specimen test [11]) can be used to study the failure of adhesively-bonded specimens. However, most of these tests are not suitable for composite substrates (TAST or Scarf specimen tests are performed on very thick specimens). Moreover, due to the high presence of edge effects on such types of experiments [12], complex tri-axial stresses are located at the edges of the adhesive joint (As shown in Fig. 1), which lead to the onset and propagation of premature cracks that will pilot the global response of the assembly. Since the presence of these stress concentration zones and their influence on the strength of the joint are greatly influenced by the bending moment [13,14], the local geometry of the joint [15], the mechanical properties of the adherends, in particular the plasticity and the stiffness [16–18], the type of loading, etc., it turns out to be quite difficult to extrapolate the results obtained on such traditional specimens to other configurations.

In order to develop a method that can be applied to a large number of bonded assemblies (for example in terms of geometry and loading) and be able to study the adhesion issue without the influence of external parameters such as edge effects, first of all, it is necessary to study the behaviour of bonded joints in a well-controlled stress state. This methodology ensures an accurate characterisation of the joint behaviour that only depends on the interactions between the adherends, the adhesive and the interfaces. Eventually, it will be necessary to include the influence of edge effects, the local geometry and the stress concentration over the global response in order to characterise the adhesive joint in the final application. This paper is focused on the first step; however, as discussed in the last section of this manuscript, it will be necessary to develop a new experimental methodology in order to take into account the multiaxial problem and the influence of external parameters such as the local geometry.

The study of adhesive assemblies in a well-controlled stress state was performed by means of a modified Arcan device proposed

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http://dx.doi.org/10.1016/j.ijadhadh.2017.09.014
Accepted 13 September 2017
Available online 02 November 2017

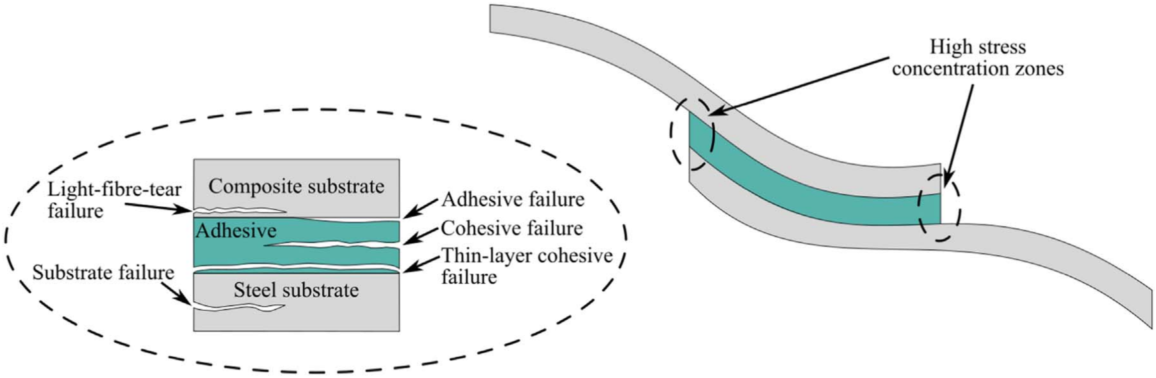

Fig. 1. Representation of different failure modes and locations of high stress concentration zones in adhesively-bonded joints.

by Cognard [19] and based on the works of Arcan [20]. This experimental test has been widely used in diverse experimental and numerical studies to investigate the behaviour of adhesive under different loading configurations (fracture [21], cyclic [22], creep [23], dynamic [24], load temperatures [25]) or to study the strength of composites [26,27].

The aim of the present paper is to study the behaviour up to failure of adhesively-bonded metal/composite and metal/metal assemblies used in automotive applications in a well-controlled stress state. Therefore, the strength of the adhesive and the mode of failure of such specimens subjected to multi-axial loadings have been determined. The paper presents the experimental procedure, the analysis of results concerning the strength of the adhesives and the assemblies of the study. The effect of different parameters such as humidity, fabric orientation and presence of grease has also been also investigated.

2. Experimental procedure

The methodology proposed is based on the modified Arcan fixture to generate mixed tensile/shear loadings and compression/shear loadings on the assemblies. The load is generated by means of a universal tensile machine with a maximum load of 100 kN. The main characteristics of the procedure implemented in this study are detailed below.

2.1. Experimental set-up

The modified Arcan device consists of two half-moon shaped pieces made of high stiffness steel. A bonded specimen is gripped in these two pieces (which are above and below) as shown in Fig. 2-b. Finally, the Arcan apparatus (the two half-moon shaped pieces and the bonded specimen) is placed in a universal tensile machine (see Fig. 2-a). The type of loading is chosen thanks to the angle between the axis of the tensile machine and the normal plane of the bonding surface (angle γ between the v-axis and the z-axis in Fig. 2-c). For the needs of the current study, four different loading types were tested:

- *Tensile loading* when $\gamma = 0°$ (see Fig. 2-d).
- *Quasi-pure shear loading* when $\gamma = 90°$ (see Fig. 2-e).
- *Proportional tensile/shear loading* when $\gamma = 45°$ (see Fig. 2-f).
- *Proportional compression/shear loading* when $\gamma = 135°$ (see Fig. 2-g).

As explained in the introduction, this paper focuses on the investigation of the strength of the adhesive and of the competition between adhesive and cohesive failure in bonded assemblies. Fig. 3 shows the two specimen configurations tested in this study.

The specimen presented in Fig. 3-a was used to study the strength of the adhesive; this specimen was composed of two aluminium substrates adhesively bonded. It is obvious that the $0.4mm$ adhesive layer defines the middle plane of the specimen. This type of specimen will be noted as “adhesive specimen” in the following. Fig. 3-b presents the specimen configuration to study the interaction between the adhesive and the cohesive failure of composite/metal and metal/metal assemblies; a thin plate (composite or metal) was inserted between the two substrates, creating two adhesive layers of $0.2mm$ on each side of the plate. This was decided so as to maintain the total adhesive layer thickness at $0.4mm$. For this second configuration, the composite or metal plate defines the plane of symmetry of the specimen.

In order to reduce the influence of edge effects, the substrates were manufactured with special “beaks” all around the bonded surface of the Arcan substrates [28]. This specific geometry drastically reduces the stress concentrations and permits a quasi-constant stress state to be created with a well-defined maximum stress value (there are no stress singularities). Fig. 4 presents the numerical stress distributions under elastic assumption of an adhesive specimen subjected to different combinations of tensile/shear Arcan loadings. The stress values were plotted along the x-axis at the centre of the adhesive joint and normalized to the maximum stress value. In the case of shear loadings, it can be seen a quasi-pure shear stress with a quasi-constant maximum shear stress at the centre of the joint (Fig. 4-b). In contrast, in tensile loadings, a mixed stress state with a constant tensile stress value along the centre of the adhesive joint and a slightly higher maximum stress near the edges is observed (Fig. 4-d). Finally, the tensile/shear state corresponds to the combination of the previous states.

The post-treatment process was accomplished using the Aramis® Digital Image Correlation Software version 6.3.1. developed by GOM [29]. The DIC system used here is able to measure the relative displacement of the Arcan substrates with a minimum resolution of $1\mu m$. The procedure thus required a speckled pattern applied on one side of the substrates. Two 10 × 3 mm regions defined on the upper and lower substrates were used to measure the displacements (see Fig. 2-a). These regions were always at a distance of 2-mm from the bonded joint for all the specimens tested. This allowed a correct comparison between the results. Note that the relative displacement of the two substrates was composed of the normal displacement “ND” (which is the displacement along the $\vec{n}$ direction) and the tangential displacement “TD” (which is the displacement along the $\vec{t}$ direction). The load applied to the specimen was recorded thanks to the machine load-cell. The ultimate stress was defined as the load applied by the tensile machine before failure divided by the bonded area ($S = 50x9.5mm$). This assumption was not entirely satisfactory since it did not take into account either the non-linear behaviour of the adhesive up to failure or the non-homogeneous 3D stress distribution over the bonded surface (See Fig. 4). However, it was acceptable for this study, since the main objective was the determination of the failure envelope and not the study of the damage behaviour after failure. Some authors have determined a correction coefficient through elastic numerical simulations in order to correlate the maximum numerical values of the shear and tensile stresses on the adhesive joint (respectively τ_{xzmax} and σ_{zzmax}) and the experimental