Paper 48

Proceedings of the Eleventh International Conference
on Computational Structures Technology,
B.H.V. Topping, (Editor),
Civil-Comp Press, Stirlingshire, Scotland

Analysis of the Mechanical Behaviour of Composites and their Bonded Assemblies under Tensile or Compression Shear Out-of-Plane Loads

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Abstract

Composite materials are a key element in weight reduction strategies, so assembly of composite modules and connections between composite and metallic structures are of great importance. Few of the standard adhesive tests are suitable to characterize bonded composite assemblies. In a previous study a modified Arcan fixture, which allows compression or tension to be combined with shear loads, has been designed in order to define an experimental methodology enabling the behaviour of adhesives to be characterized up to failure. It has been numerically shown, that the use of a beak close to the adhesive joint makes it possible to limit the contribution of the singularities due to edge effects. Numerical and experimental results indicate that the test fixture is suitable for obtaining the response of hybrid bonded assemblies (metal-adhesive-composite-adhesive-metal) provided certain conditions are respected to limit the influence of edge effects: i.e. thin composite plate, substrates with beaks, thin adhesive with cleaned free edges. Experimental results underline that the fibre orientations, the characteristics of different plies and the surface preparation all have an influence on the out-of-plane strength of the composite. Some test results, showing the potential of the approach, are presented in the form of failure envelope curves for proportional monotonic out-of-plane loadings. Moreover, some tensile cycling test results with different positive load ratios are also given in order to analyze the behaviour of industrial applications. This study makes it possible to optimize the strength of hybrid bonded assemblies.

Keywords: laminates, adhesion, stress concentrations, mechanical testing, out-of plane loadings, non-linear behaviour, finite element analysis.

1 Introduction

The use of composite materials is a key element in energy reduction strategies, particularly in all areas of transportation. Therefore, the study of the behaviour of assemblies of composites and connections between composites and metallic structures, including bonded assemblies, is of great importance. Complex 3D loadings are needed to analyse the response of both the assemblies and the composites. Moreover, failure in bonded assemblies involving composites is often associated with crack initiation in the adhesive or delamination of the composite plies close to the adhesive joint caused by interlaminar or through-thickness stresses [1-2]. Unfortunately, few experimental devices are proposed in the literature to characterize the mechanical behaviour of composites under out-of-plane loadings. Experimental studies are often realized using simple lap shear type specimens [3-4] which are often associated with large stress concentration [5-6], even if some geometries have been proposed to reduce the influence of peel stresses [3, 7]. Different experimental approaches use thick composite specimens which are not always representative of industrial applications and require special geometries [8-10]. For such thick composite specimens, the geometry of the specimen, the fixing system, and damage generated by machining can result in stress concentrations and subsequent large uncertainties (or scatter) in the experimental results [11]. Ideally, to obtain experimental results representative of industrial applications, there is a need on one hand to use composite plates with quite low thicknesses [12], which are easy to manufacture, and on the other hand to apply a large range of tensile-shear loadings [13-14].

This paper describes an experimental device, using a modified Arcan test, and optimized hybrid bonded assemblies, which limit the influence of edge effects. Different numerical studies have been developed in order to analyze and optimize the design of such a system (geometry of the composite plate, geometry of the substrates, fixing system, etc). In order to obtain reliable experimental results, it is essential to limit the influence of edge effects [14]. This test allows the mechanical behaviour of both composites and hybrid metal/composite bonded assemblies to be analyzed under a large range of proportional tensile-shear out-of-plane loadings. Moreover, it is important to note that failure can occur in the composite, in the adhesive joint or at the composite-adhesive interface according to the tensile-shear loading ratio. An optimization of the adhesive must be performed, especially under shear loadings, as the shear strength of the composite can be higher than that of the adhesive. Experimental results show that the fibre orientations, the characteristics of different plies, and the surface preparation all have an influence on the out-of-plane strength of composites and of hybrid bonded assemblies. Test results, showing the potential of the approach, are presented in the form of failure envelope curves for radial out-of-plane loadings. This study makes it possible to optimize the strength of hybrid bonded assemblies.

2 Numerical models for 2D simulations

In order to present the influence of different parameters on the stress distributions through the adhesive thickness and the composite substrate various 2D finite element simulations have been performed. CAST3M FE software was used here and for all the simulations presented throughout this paper [15]. For simplicity, computations are made assuming linear elastic behaviour of the components and small displacements. The aim is only to analyse the influence of edge effects on the behaviour of SLS specimens at the beginning of loading, before nonlinear material and geometrical effects become significant. However, even with these simplifying assumptions detailed, numerical models are needed in order to model perfect interfaces in these multi-material structures. Various previous studies have highlighted the difficulties in obtaining reliable results. With the standard finite element method, based on the variational principle of minimum potential energy whose single variable is the displacement field, the continuity of the displacement field is satisfied but the continuity of the stress vector is not exactly verified. Therefore, refined meshes are also needed near the interface, in order to obtain good numerical results, especially for large material heterogeneity of the assemblies [16-17]. Various simulations have shown that good numerical results are obtained using meshes with 20 linear rectangular elements for a 0.1mm adhesive thickness. Computations were made in 2D (plane stress) on half of the specimen by applying adequate boundary conditions. Results are presented for glass/epoxy and carbon/epoxy substrates assuming orthotropic behaviour; the material parameters for the adhesive joint, whose behaviour is assumed here to be isotropic, are: E_a = 2.0 GPa, ν_a = 0.3.

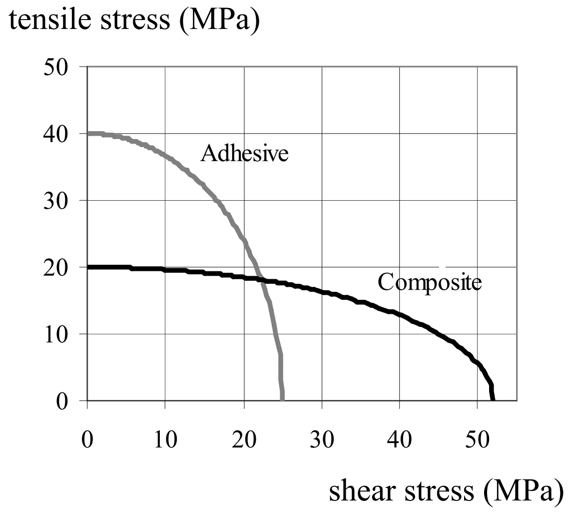


Figure 1: Presentation of the so-called elastic domains for the adhesive and the composite in the tensile stress – shear stress diagram.

The elastic limit equivalent stress for the adhesive used has been identified experimentally under 2D tension-shear loadings (this will be presented in section 4 below) such that:

$$\frac{\sigma_{yy}{}^2}{R_a{}^2}+\frac{\sigma_{xy}{}^2}{S_a{}^2}=1,\ \left[\sigma_{eq\_a}\right]^2=1 \tag{1}$$

with $R_a = 40$ MPa and $S_a = 25$ MPa [14].

For the 2D plane stress studies presented, unidirectional carbon-epoxy composites (300g/m²T700 fibre layers in an epoxy resin, fibers in direction x) are used, as they allow the use of orthotropic models ($E_x = 110$ GPa, $E_y = 6.5$ GPa, $G_{xy} = 6.5$ GPa, $\nu_c = 0.32$). The following classical elastic limit equivalent stress is used for tensile-shear out-of-plane loads:

$$\frac{\sigma_{yy}{}^2}{R_c{}^2} + \frac{\sigma_{xy}{}^2}{S_c{}^2} + \frac{\sigma_{xx}{}^2}{T_c{}^2} = 1, \ \left[\sigma_{eq\_c}\right]^2 = 1 \tag{2}$$

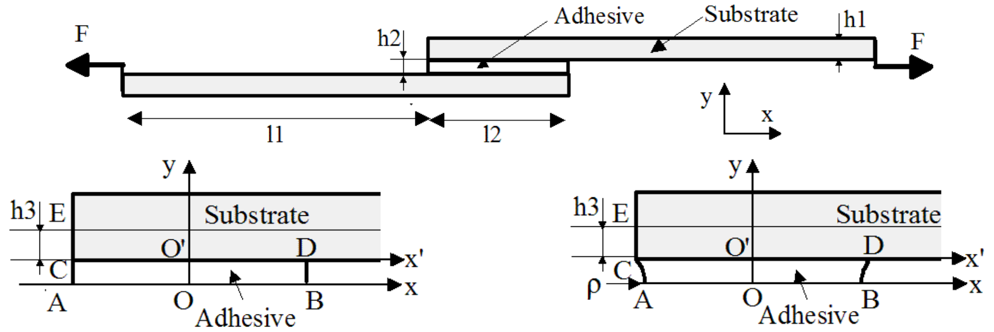
with $R_c = 20$ MPa (interlaminar tensile), $S_c = 52$ MPa (interlaminar shear) and $T_c = 1600$ MPa (in-plane tensile) [14].

Figure 1 presents the so-called elastic domains for the adhesive and the composite in the tensile stress – shear stress diagram.

3 Single lap shear specimens with composite substrates

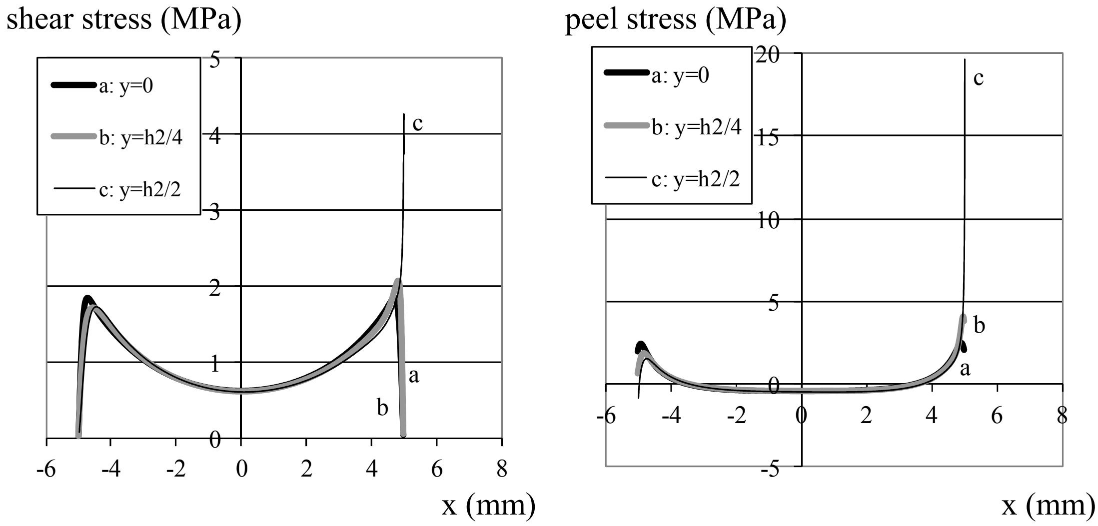
Some numerical results of the behaviour of the classical single lap shear test with composite substrates presented briefly, in order to underline the difficulties encountered in experimental analysis of the mechanical behaviour of hybrid bonded assemblies with composites.

Two geometries of the free edges of the adhesive joints are used in order to emphasise the influence of this geometrical parameter (straight edges and cleaned edges, Figure 2). Other geometries can be used to limit the edge effects [3, 18], but the two geometries examined here are associated with constant thickness of the adhesive joint (a modification of the adhesive thickness can change the mechanical behaviour of joint). Another important parameter is the overlap length, which influences the stress distribution in the adhesive joint. With the assumptions proposed above, the problem to be solved is linear; thus the stress state can be normalised in order to obtain a constant average shear stress.



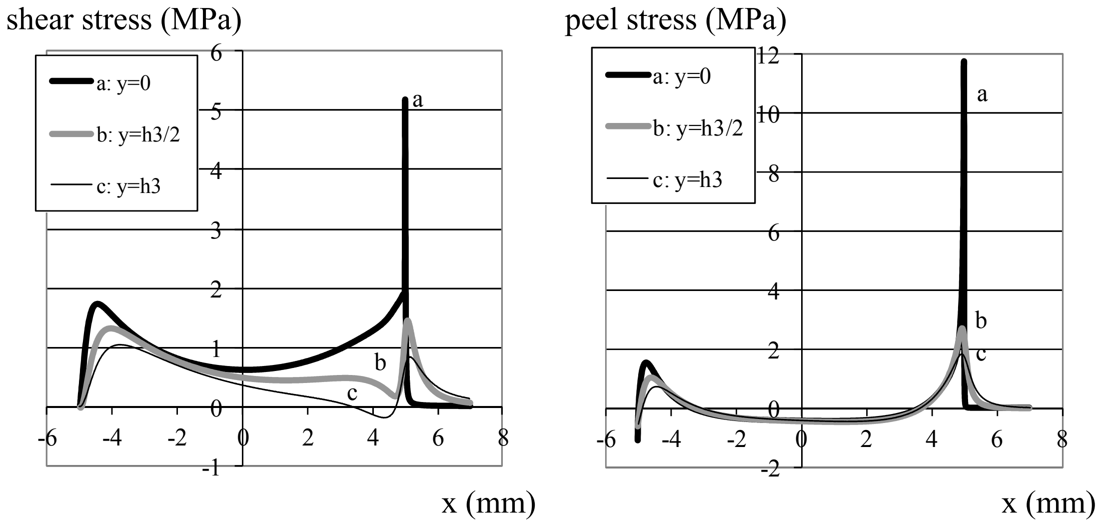
straight edges of the adhesive joint   cleaned edges of the adhesive joint

Figure 2: Geometry of the single lap-shear specimen.



a) shear stress b) peel stress

Figure 3: Shear and peel stresses in the adhesive with respect to the overlap length for straight edges of the adhesive joint and for an average shear stress of 1 MPa.



a) shear stress b) peel stress

Figure 4: Shear and peel stresses in the substrate with respect to the overlap length for straight edges of the adhesive joint and for an average shear stress of 1 MPa.

Figures 3 and 4 present the stress distribution (shear stress: xy stress in the adhesive joint and in the composite substrate for the following values of the parameters: substrate thickness of h1= 3 mm; overlap length of l2 = 10 mm; straight edges of the adhesive. The parameter h3 in Figure 2 is taken as h2 here and varied in order to examine the stress gradient close to the interface in the substrate. Results are presented for different lines with respect to the position y in the adhesive joint (y = 0 is the mid-plane of the adhesive and y = h2/2 corresponds to a line close to the adhesive-substrate interface) extrapolated to the node point next to the interface. It is important to note that, for the adhesive, the edge effects are mainly associated with a strong evolution of the normal stress, close to the free edge of the adhesive near the adhesive-substrate interface; this result can be explained by the boundary conditions. For the substrate, there are also large edge effects close to the substrate-adhesive interface; moreover for the substrate the stress component xx is not equal to zero close to point D (Figure 2) associated with the loading of the specimen, but this stress component has only a small influence on the equivalent stress as it acts in the fibre direction.

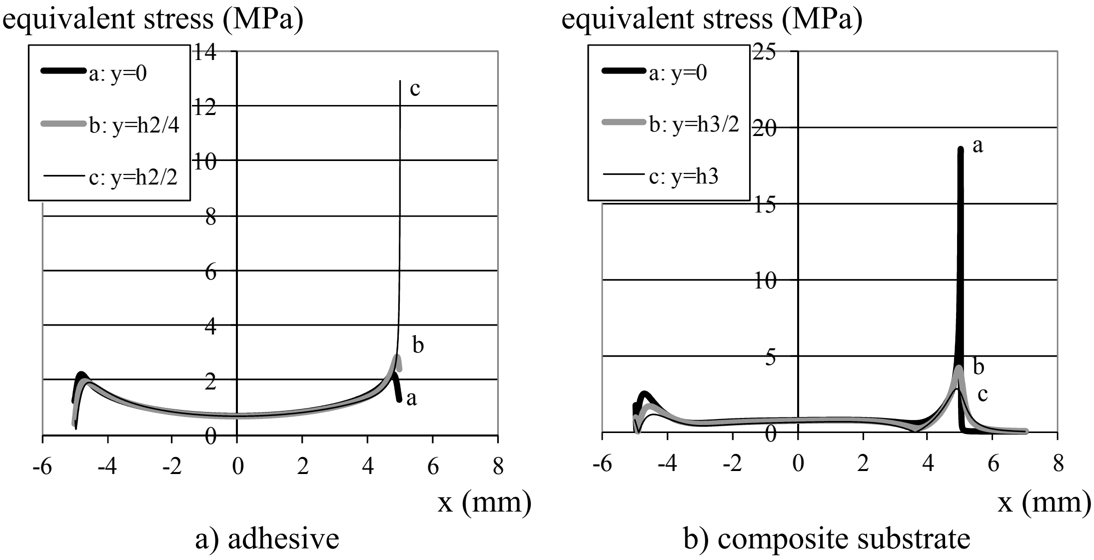


Figure 5: Normalized equivalent stress in the adhesive and the substrate with respect to the overlap length for straight edges of the adhesive joint.

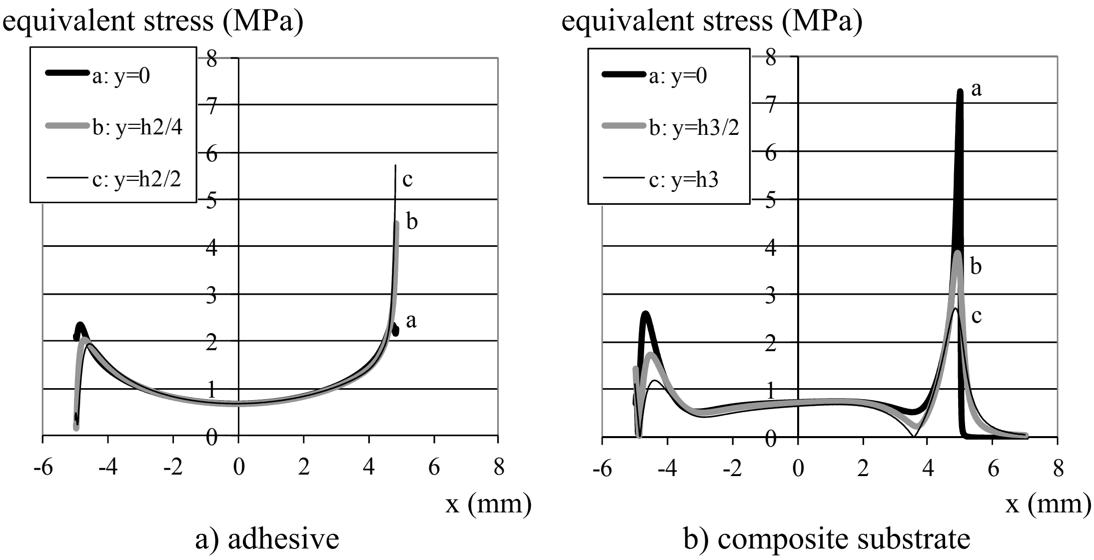


Figure 6: Normalized equivalent stress in the adhesive and the substrate with respect to the overlap length for cleaned edges of the adhesive joint.

For the case of cleaned edges, figure 5 presents the value of the equivalent stress distribution in the adhesive joint, defined by equation (1) and in the composite substrate, defined by equation (2); the value of the equivalent stress in the middle of the adhesive has been normalized to 1. Large edge effects, which can be noted close to point D (Figure 2), can lead to crack initiation in the adhesive [19] and to delamination of the composite plies close to the adhesive joint [3] for a quite low transmitted load. Figure 6 underlines that the use of so-called "cleaned edges" of the free edges of the adhesive, can reduce the influence of edge effects; the cleaned edges are defined by the following relationship: $\rho = 1.5 \times h2$ (Figure 2).

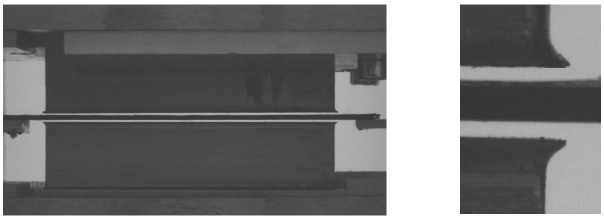
Numerically, it is quite difficult to analyse such problems because it is necessary to use nonlinear models with a reliable failure criterion and reliable interlaminar strength data. Moreover, it is difficult to modify the geometry of the substrates close to point D in order to limit the edge effect.

In the case of adhesively bonded assemblies involving composites, the initiation of the failure is either crack initiation in the adhesive or delamination of the composite plies close to the adhesive joint [3, 14]. However, few experimental devices are proposed in the literature to characterise the mechanical behaviour of composites and their bonded assemblies under tensile/compression-shear out-of-plane loads [9]; those available often use thick composite specimens, not representative of the end application, (Iosipescu type tests [20]). There has been some work on the so-called Arcan test fixture to obtain tensile-shear data [21], but the machining of the composite, the specimen geometry, the fixing system can lead to large scatter in the experimental results [11].

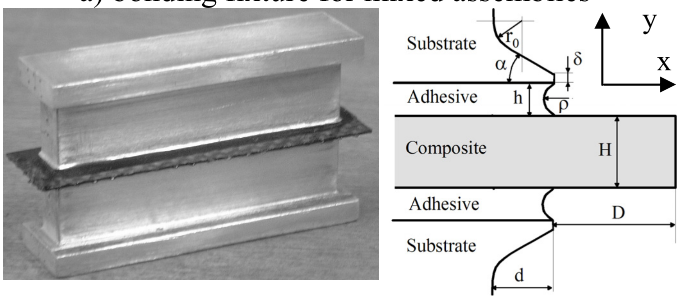
4 Modified Arcan device suited to analyse hybrid bonded assemblies under out-of-plane loadings

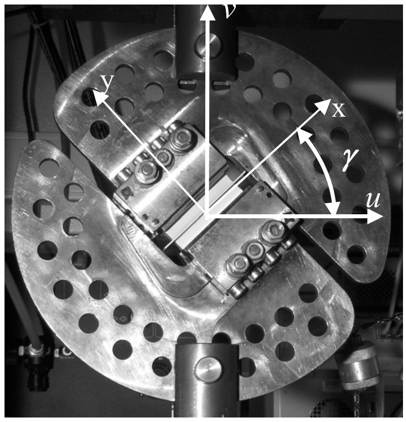
An alternative strategy is to propose an experimental fixture which intrinsically promotes low edge effects for testing adhesively bonded assemblies, in order to prevent crack initiation close to the free edges of the adhesive. In a previous study a modified Arcan fixture, which allows compression or tension to be combined with shear loads, was designed in order to define an experimental methodology enabling the adhesives of interest to be characterized up to failure [22]. It has been shown numerically that the use of a beak close to the adhesive joint makes it possible to limit the contribution of the singularities due to edge effects, and that the geometry of the joint close to the edge is an important parameter. This experimental fixture allows the non-linear behaviour of an adhesive joint to be analyzed for radial tensile-shear loadings [22], and thus precise numerical models can be developed to describe the behaviour of an adhesive in an assembly [23].

The first tests performed using hybrid bonded assemblies (steel, aluminium and composites) have shown a similar behaviour to that of the adhesive, using the proposed procedure [22]. The fixture proposed here to analyse the behaviour of hybrid bonded assemblies with composites is presented in figure 1. A composite plate is bonded between the two metallic substrates. The area of the bonded section is 65 x 10 mm^2 and a special alignment fixture is used in order to obtain a good quality of the geometry of the bonded specimen (Figure 7).



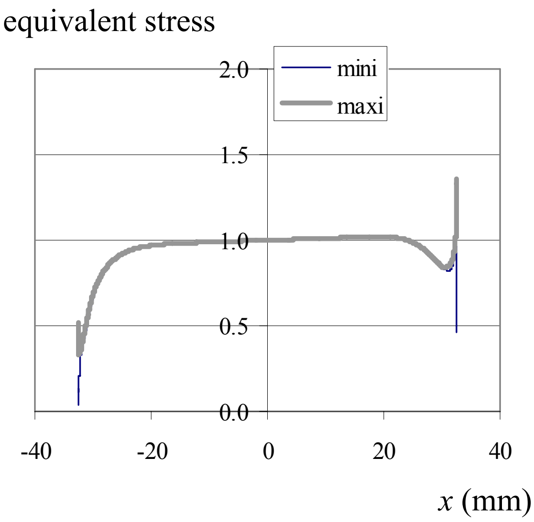
a) bonding fixture for mixed assemblies



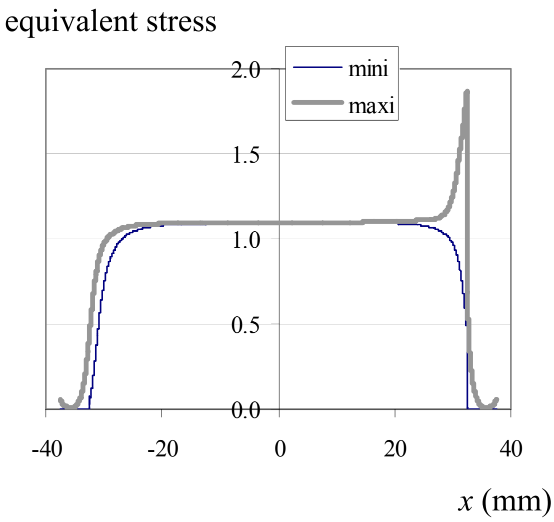


b) geometry of bonded metal/composite assemblies c) tensile-shear loading

Figure 7: Experimental fixture with mixed bonded assembly.



a) adhesive



b) composite

Figure 8: Normalized equivalent stress distribution on the adhesive and the composite under traction-shear loadings, $\gamma = 45°$ (substrates with beaks 45°, cleaned adhesive joint $h = 0.2$ mm, $\rho = 1.5 * h$; composite plate with $H = 4$ mm, $D = 5$ mm).

Figure 8 presents the evolution of the equivalent stress with respect to the x axis ($x \in [-32.5; 32.5$ mm], Figure 7) through the adhesive thickness and through the composite thickness for a tensile-shear loading (i.e. with tensile loading in the normal direction of the middle plane of the composite equal to shear loading, $\gamma = 45°$). To facilitate the analysis of the results, only the minimum and the maximum values are represented in Figure 3. For these simulations, substrates without beaks (α = 45°, Figure 1) and composite plates larger than the substrates (D = 4) were used, in order to limit the adverse effects of machining. The free edges of the adhesive were assumed to be cleaned (ρ = 1.5 * h) as it has been shown that this geometry can reduce the influence of edge effects [17]. But it can be seen that the use of a quite thick composite plate (H = 4 mm) leads to stress concentrations in the adhesive and in the composite plate. Results presented on Figure 4 underline that the use of thin composite planes can strongly limit the influence of edge effects (H = 1 mm).

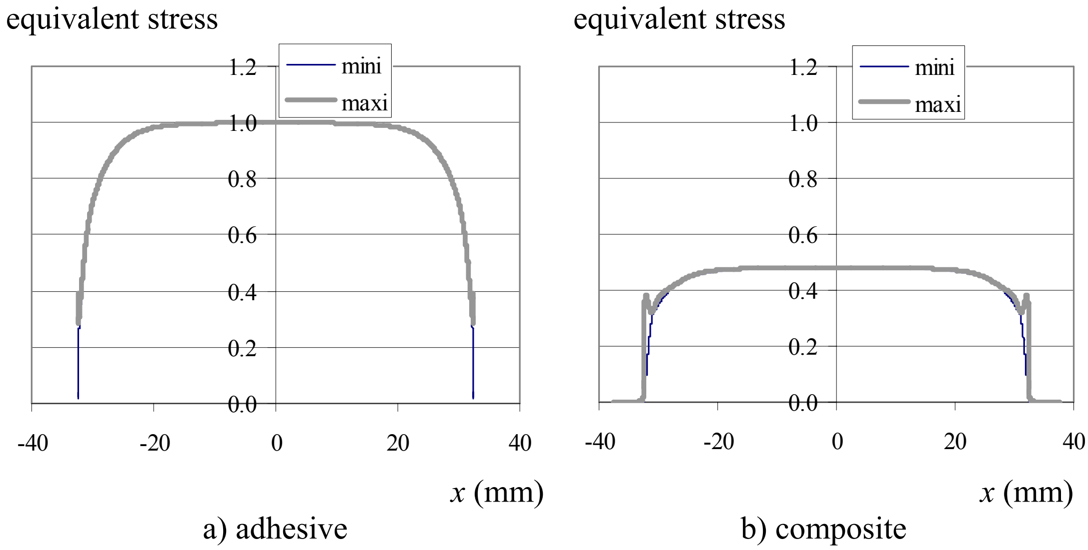
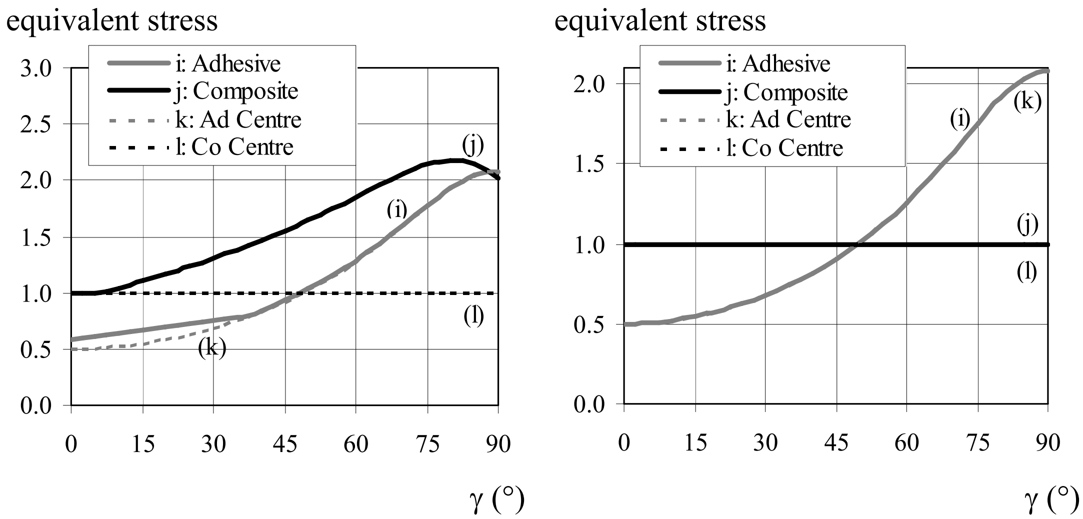


Figure 9: Normalized equivalent stress distribution on the adhesive and the composite under traction-shear loadings, γ = 45° (substrates with beaks 45°, cleaned adhesive joint h = 0.2 mm, ρ = 1.5 * h; composite plate with H = 1 mm, D = 5 mm).

Figure 10 presents, for two different values of the parameters, the evolution of the maximum values of the equivalent stress within the adhesive and the composite with respect to the tensile-shear loading type: $\gamma \in$ [0°, 90]). The straight lines represent the maximum value of the equivalent stress in the adhesive or in the composite. The dashed lines represent the maximum value of the equivalent stress in the central part of the adhesive or of the composite. For a given angle γ, if the two values are not identical, the maximum equivalent stress is obtained close to the free edges; thus stress concentrations exist. For these figures, the equivalent stress in the central part of the composite is chosen equal to 1 for the different angles γ. Thus, with these curves, one can directly obtain the tensile-shear loading types (i.e. the values of the angle γ) for which the elastic limit is first reached in the composite plate. For the different computations the following values of the parameters have been chosen: (α = 30°, D = 5 mm, h = 0.2 mm, ρ = 1.5 * h (cleaned edges).

Figure 10-a underlines that the use of quite thick composite plates (H = 4 mm) leads to stress concentrations, especially in the composite, for a large range of

tensile-shear loadings (γ). Figure 10-b shows that the proposed test, using substrates with beaks, can be used to analyze the behavior of composite plates of 1 mm thickness under out-of-plane loading for $\gamma \in [0°, 50°]$. Above this critical angle the adhesive will fail before the composite. The use of an adhesive with a larger elastic domain can increase the useful tensile-shear loading range.



a) H = 4 mm b) H = 1 mm

Figure 10: Maximum values of the normalized equivalent stresses in the adhesive and in the composite with respect to the tension-shear loading type, $\gamma \in [0°, 90]$ ($\alpha = 30°$, $D = 5$ mm, $h = 0.2$ mm, cleaned edges $\rho = 1.5 * h$).

5 Experimental results

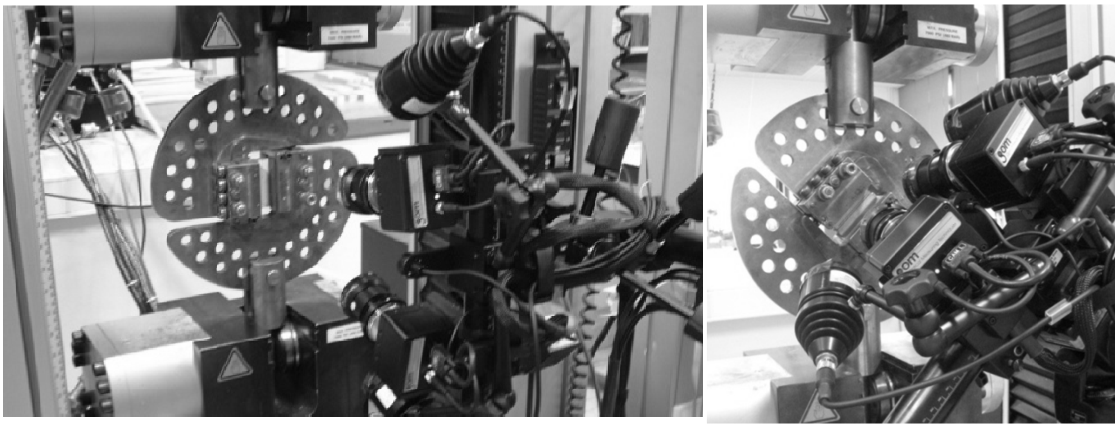
The different experimental results presented in the following have been obtained using the epoxy resin Huntsman™ Araldite® 420 A/B with a joint thickness of 0.1 mm in order to optimize the mechanical behaviour of the joint [17]. Aluminium substrates are used for all the mechanical tests. Composite plates with a thickness of about 2 mm have been used in order to limit the influence of edge effects.

Using a non-contact measurement system based on image correlation (Figure 11), the modified Arcan device allows the relative displacement of the two substrates to be analyzed (in the normal, DN, and tangential, DT, directions) with respect to the prescribed tensile-shear loading (in the normal, FN, and tangential, FT, directions). It is important to notice that the direct analysis of the adhesive deformation is quite complex. For bonded hybrid assemblies, the relative displacement measured corresponds to the deformation of the adhesive and of the composite plate.

In order to analyse the influence of the manufacturing process of the composite, different composite plates, used in boatyard environments have been analyzed (table 1). Materials have been manufactured, in an autoclave with metal plates on both faces in order to obtain similar surfaces using aeronautical type curing (curing at 120° under a pressure of 7 bars for 2 hours).

	A		B		C	
Ply n°	Fibre	Angle	Fibre	Angle	Fibre	Angle
1	G	+/-45°	C1	+/-45°	C2	0°
2	C1	+/-45°	C1	+/-45°	C2	0°
3	C1	+/-45°	C1	+/-45°	C2	0°
4	C1	+/-45°	C1	+/-45°	C2	0°
5	V	+/-45°	C1	+/-45°	C2	0°
6					C2	0°

Table 1. Specimens tested (composite thickness of about 2 mm)
G: Glass satin prepreg 1454/49%/300g/m²
C1: Carbon 0/90° prepreg G0803/M10/42%/3K/285g/m²
C2: Carbon UD prepreg UD/M40J/R367-2/38%/300g/m²



a) shear loading b) tensile-shear loading

Figure 11: Presentation of the modified Arcan device with the measuring system.

Figure 12 presents the experimental results in the normal and tangential directions in the case of tensile-shear out-of-plane loadings (γ = 45°, figure 7, tensile load equal to shear load) for the composite B. The scatter in the experimental results is also quite low for such tests.

For a given hybrid bonded assembly (materials, joint thickness, surface preparations, manufacturing conditions) and for a given loading rate, it is possible to determine the fracture envelope in the tensile stress–shear stress diagram starting from various tensile-shear out-of-plane loadings ($\gamma \in [0°, 90°]$, Figure 7) [14]. Figure 13a presents the fracture envelope for the adhesive used and for composites presented in Table 1. The envelopes are plotted in the normal-shear average stresses in order to facilitate the analysis. Especially, it is possible to notice the difference between composites A and C. The experimental results underline that the strength under monotonic out-of-plane loadings can be strongly influenced by the load direction (influence of the normal and tangential load components).

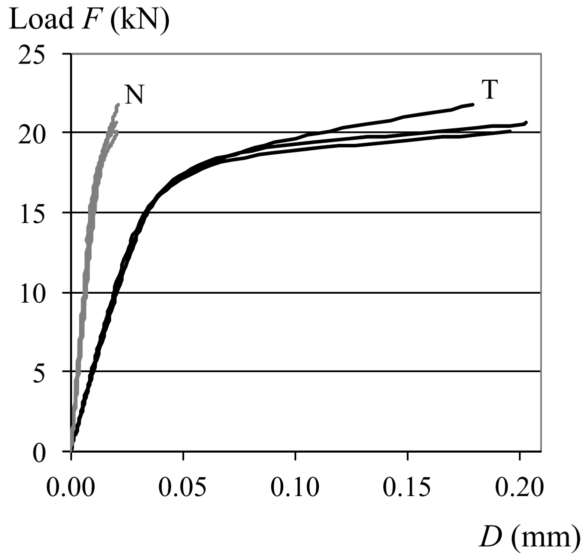


Figure 12: Behaviour under tensile-shear out-of-plane loadings (γ = 45°) for a bonded assembly with the composite B
(N: normal direction; T: tangential direction) – results of 3 tests.

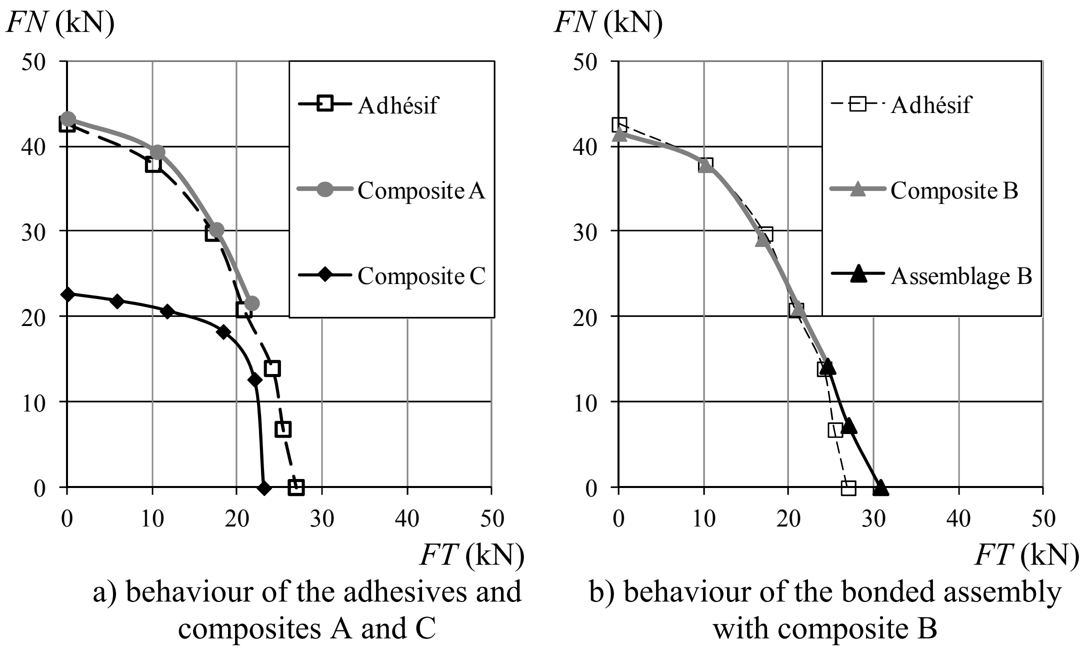


Figure 13: Failure envelope in the normal stress–tangential stress diagram for the adhesive, for different composites and for a bonded assembly under out-of-plane loadings.

Moreover, the failure envelope is completely determined for composite C (with UD in the x direction) and only partially obtained for composite A. It has been numerically shown that for a given hybrid assembly that the failure envelope cannot be determined for loads close to out-of-plane shear conditions as the composite resistance can be higher the adhesive one under shear [14]. In the case of material A, failure occurs within the composite for loadings characterized with $\gamma \in [0°, 45°]$ and occurs at the matrix-adhesive interface for loadings characterized with $\gamma \in [45°, 90°]$. Perhaps, a choice of an adhesive insuring a better compatibility between the adhesive and the composite matrix could allows to obtain a larger determination of the failure envelope.

Figure 13b presents the failure envelope for composite B which is obtained for loadings characterized with $\gamma \in [0°, 60°]$, as for $\gamma \in [60°, 90°]$ failure don't occurs within the composite. The curve in dotted line shows the failure of the assembly, which occurs at the matrix-adhesive interface. These results seem to underline that the presence of the composite increases the strength of the adhesive, especially close to the matrix-adhesive interface.

It is important to notice that failure can occur in the composite, for numerous out-of-plane tensile-shear loads, or at the composite-adhesive interface according to the tensile-shear loading ratio. Thus one can define the fracture envelope for hybrid bonded assemblies.

6 Conclusion

Numerical and experimental results indicate that the modified Arcan test fixture is suitable for obtaining the response of hybrid bonded assemblies (metal-adhesive-composite-adhesive-metal) provided certain conditions are respected to limit the influence of edge effects: i.e. thin composite plates, substrates with beaks, thin adhesive layer with cleaned free edges. This test allows the mechanical behaviour of both composites and hybrid metal or composite bonded assemblies to be analysed under tensile-shear out-of-plane loadings. An optimization of the adhesive must be performed, especially under shear loadings, as the shear strength of the composite can be higher than that of the adhesive. Experimental results show that the fibre orientations, the characteristics of different plies, and the surface preparation all have an influence on the out-of-plane strength of the composite. This study makes it possible to optimize the strength of hybrid bonded assemblies.

More work is underway to clarify the role of composite damage mechanisms in mixed joints. In order to characterize the damage evolution in the composite under out-of-plane loadings, appropriate measurement techniques are being developed, in order to analyze very small displacements. Inverse procedures must also be developed in order to take into account the non-linear behavior of the adhesive and of the composite, as the stress state is not homogeneous for the proposed Arcan type test. Moreover, the experimental analysis of the mechanical behaviour of hybrid bonded assemblies with composites under cyclic tensile-shear out-of-plane loadings is underway; such analyses are very important for industrial applications.

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