ANALYSIS OF THE MECHANICAL BEHAVIOUR OF COMPOSITES AND THEIR BONDED ASSEMBLIES UNDER OUT-OF-PLANE LOADINGS USING A MODIFIED ARCAN TEST

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Keywords: Laminates, Stress concentrations, Mechanical testing, Out-of-plane loadings

Abstract

Composite materials are a key element in weight reduction strategies, so assembly of composite modules and connections between composite and metallic structures is of great importance. But few of the standard adhesive tests are suitable to characterize bonded composite assemblies. An adaptation of a modified Arcan fixture can be used to obtain the response of hybrid bonded assemblies (metal-adhesive-composite-adhesive-metal) provided certain conditions are respected to limit the influence of edge effects. Experimental results underline the influence of various parameters 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. The proposed test also allows the influence of cycling loadings to be analyzed.

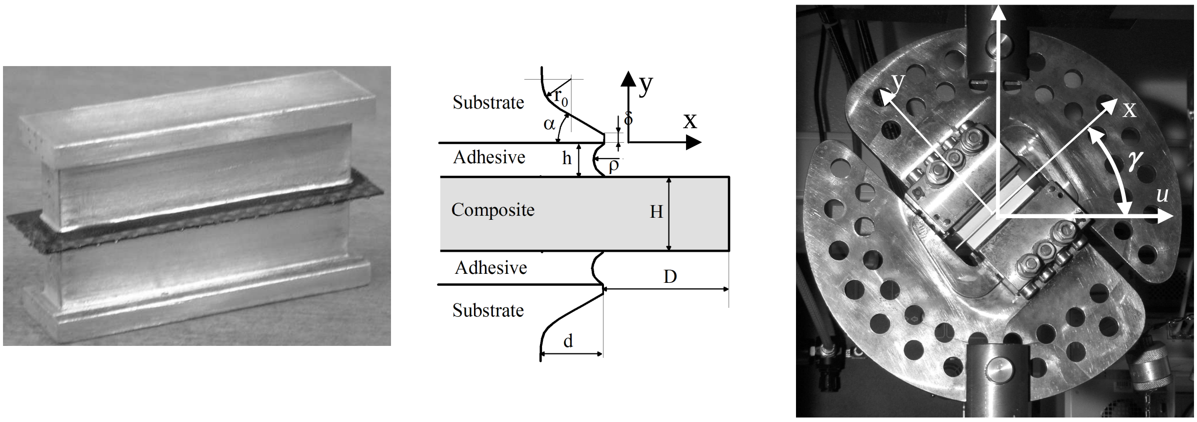
1 Introduction

The use of composite materials is a key element in energy reduction strategies, particularly in all areas of transportation. Therefore, the study of the behavior of assemblies of composites and connections between composites and metallic structures, including bonded assemblies, is of great importance. Complex 3D loadings are needed to analyze 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 behavior of composites under out-of-plane loadings. Experimental studies are often performed using simple lap shear type specimens [3-4] which are associated with large stress concentration [5-6], even if some geometries have been proposed to reduce the influence of peel stresses [3, 7]. Other 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 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 [14]. This test allows the mechanical behavior 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 fiber 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 proportional out-of-plane loadings. Moreover, some experimental results under cyclic loadings with different positive load ratios are also presented in order to analyze the behavior of industrial applications. This study makes it possible to optimize the strength of hybrid bonded assemblies.

2. Analysis of hybrid bonded assemblies

The first tests performed using hybrid bonded assemblies (steel, aluminum and composites) have shown a similar behavior to that of the adhesive, using the proposed procedure [15]. Different studies have shown that large stress singularities, associated with edge effects, can exist for bi-material structures. For bonded assemblies involving composites those effects can limit the transmitted load considerably. The adhesive-composite interface influences the assembly strength, and makes it difficult to analyze the behavior of composites under out-of-plane loadings [14]. The fixture proposed here to analyze the behavior 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 ensure good quality of the geometry of the bonded specimen (Figure 1).



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

Figure 1. Experimental fixture with mixed bonded assembly

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 [14]. Figure 1 presents the fixture designed to analyze the behavior of composites under shear-tensile out-of-plane loadings. Moreover a composite plate larger than the substrates is used [12].

The key advantages of this fixture are the testing of thin composite plates and the use of an adhesive to fix samples. Thin composite plates are often representative of industrial applications, and the design of the proposed fixture allows the influence of edge effects to be reduced, in order to obtain more reliable experimental results. An optimization of the adhesive choice must be performed in order to obtain failure within the composite, not in the adhesive nor at the composite surface; especially under shear loadings, as the shear strength of the composite can be higher than that of the adhesive [14].

3 Experimental results for different composites

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 behavior of the joint [14]. Aluminum 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.

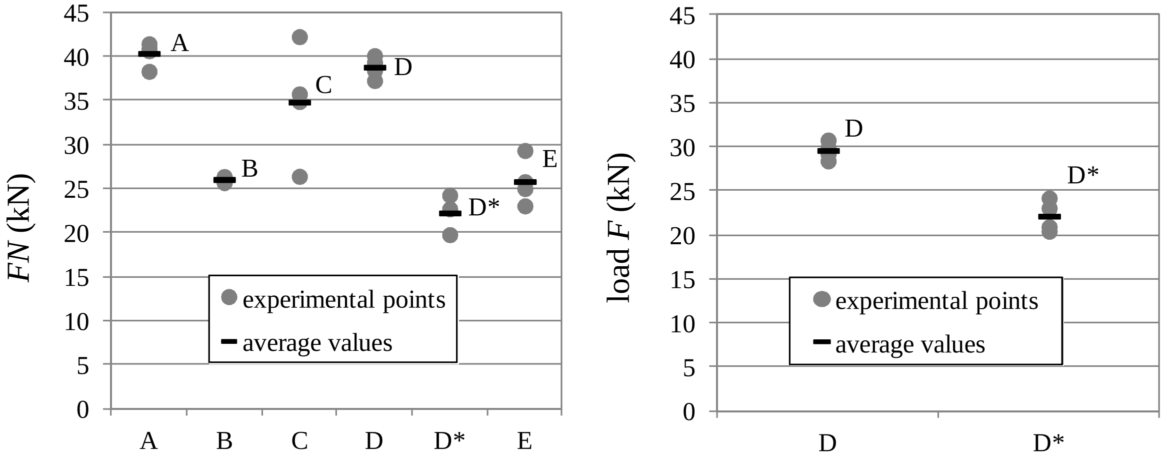
Composite	Ply sequence	Thickness (mm)
A	[G +/-45°, 3 (C1 +/-45°), G +/-45°]	1.64
B	[G +/-45°, C2 0°, C2 90°]s	1.96
C	[G +/-45°, 2 (C2 0°)]s	1.94
D	[5 (C1 +/-45°)]	1.64
D*	[5 (C1 +/-45°)]	1.64
E	[6 (C2 0°)]	1.90

G: Glass satin prepreg 1454/49%/300g/m^2

C1: Carbon 0/90° prepreg G0803/M10/42%/3K/285g/m^2

C2: Carbon UD prepreg UD/M40J/R367-2/38%/300g/m^2

Table 1. Properties of different composites tested.



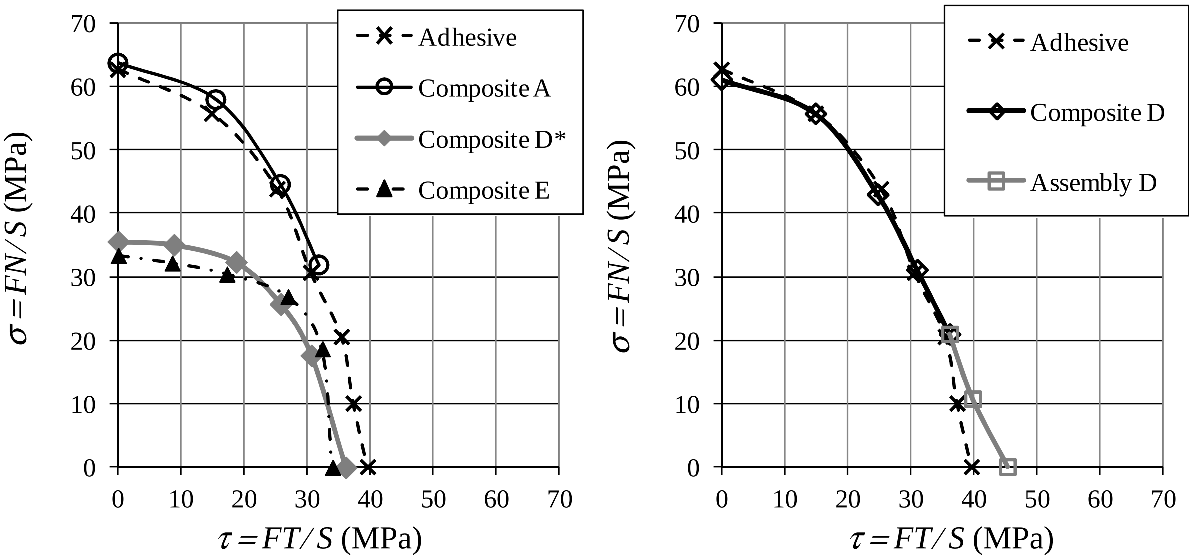
a) tensile loads (γ= 0°)

b) tensile-shear loads (γ= 45°)

Figure 2. Influence of the composite type on the failure load under out-of-plane tensile loads (γ= 0°) and tensile-shear loads (γ= 45°)

Using a non-contact measurement system based on image correlation, 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 note 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 analyze the influence of the manufacturing process of the composite, different composite plates, typical of those produced for racing yachts, have been analyzed (table 1). Material A, B, D and E 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). Material D* has been manufactured using a more usual boatyard environment condition (i. e.: curing at 100° under a pressure of 1.9 bars for 6 hours). The difference between materials D and D* is only the curing process.

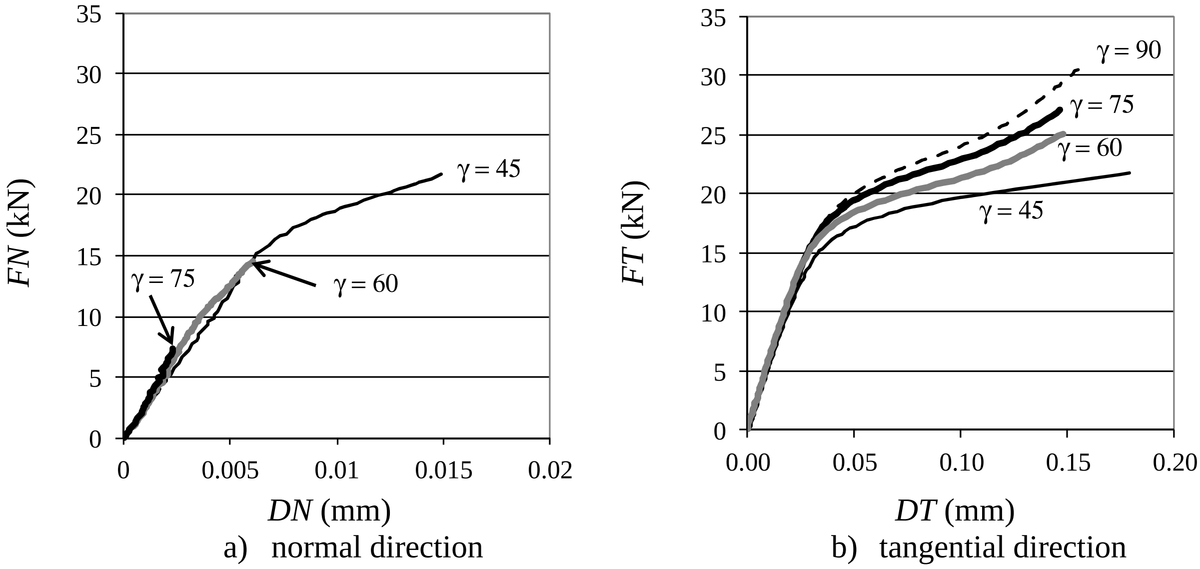


a) behavior of the adhesives and composites A, D* and E

b) behavior of the bonded assembly with composite D

Figure 3. Failure envelopes in the normal stress–tangential stress diagram for the adhesive, for different composites and for a bonded assembly under out-of-plane loadings

Figures 2 and 3 present a summary of experimental results for hybrid bonded assemblies. For each material, 3 or 4 tests have been performed, with failure always in the composite. Figure 2a show the results for the different composite materials presented in Table 1 under tensile loads (γ= 0°). It can be seen that the scatter in the results is larger for material C, perhaps associated with the plies at 90° (thus, in the following, a failure envelope is not presented for this material). Failures are observed at the fiber-matrix interfaces for material B, C and E and by delamination for material A and D. For such loading, materials A and D are more efficient; use of woven reinforcement increases the out-of-plane strength of the composite. Other experimental results under out-of-plane tensile loads (load-displacement curves and failure modes) can be found in [14]. Figure 2b presents the results for composites D and D* under tensile-shear loads (γ= 45°); *F* represents the transmitted load. For these composite materials, lower scatter in the results are obtained under tensile-shear loads than under tensile loads. Figure 3a presents the fracture envelopes for the adhesive used and for composites presented in Table 1 (aeronautical and naval type qualities). The envelopes are plotted in the normal-shear average stresses in order to facilitate the analysis. The average stresses are obtained using the average normal and tangential components for a given load direction and the area *S* of the bonded section (*S* = 650 mm²); σ and τ represent respectively the normal and shear stresses. It has been shown that such a definition of the failure stress is appropriate for experimental results with the modified Arcan fixture for metallic-adhesive-metallic assemblies using a ductile adhesive [15]. A more precise definition of failure stress requires the use of an inverse identification technique as under elastic behavior the stress state is not homogeneous in the assembly. It is interesting to note the difference between composites D and D*, for which only the curing processes are different (pressure and temperature). These 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). Moreover, the failure envelope is completely determined for composite D* and only partially obtained for composite D. For material E (with UD in the *x* direction) a complete determination of the failure envelope is also obtained, while for material A the failure envelope is partial.



a) normal direction

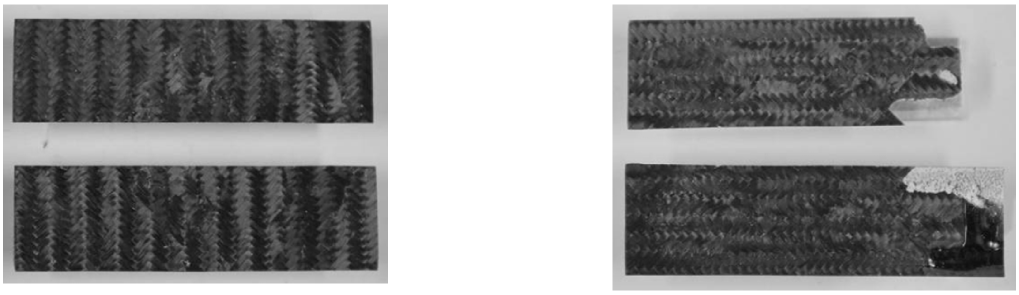
b) tangential direction

Figure 4. Load-displacement curves for the different out-of-plane loads for bonded assemblies with composite D

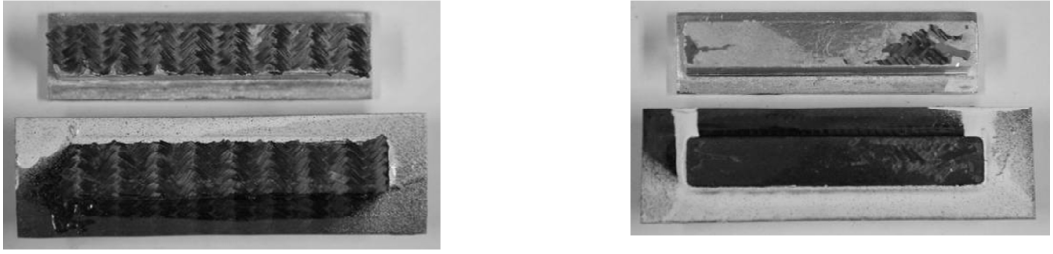
Figure 3b presents the failure envelope for composite D, which is obtained for loadings characterized with $\gamma \in$ [0°, 60°], as for $\gamma \in$ [60°, 90°] failure does not occur within the composite. The failure envelope of the assembly is also presented, which occurs at the matrix-adhesive interface. These results indicate that the presence of the composite increases the strength of the adhesive, especially close to the matrix-adhesive interface. As the adhesive thickness is low, a mixing of elements between the matrix and the adhesive can increase the adhesion. Therefore, it is important to search for other adhesives with higher mechanical properties and to analyze in more detail the influence of different parameters (nature of materials, curing process ...) on the behavior of the matrix-adhesive interfaces. Nevertheless, it is important to note that failure can occur in the composite, for numerous out-of-plane tensile-shear loads, or at the composite-adhesive interface, depending on the tensile-shear loading ratio. Thus one can define the fracture envelope for hybrid bonded assemblies, which is an important point for their design.

Figure 4 presents the load-displacement diagram for hybrid bonded assemblies with the composite D, for different loadings (γ = 45°, 60°, 75° and 90°) in the normal and tangential directions. The displacement represents the relative displacement of the two aluminum substrates; thus, it includes the deformation of the composite and that of the two adhesive layers. These results show the influence of the direction of the tensile-shear loading on the behavior of the assembly. A complete analysis of these experimental results requires the development of inverse identification techniques using finite element models in order to identify the non-linear behavior (plasticity, damage) of the composite and of the adhesive-matrix interface under out-of-plane tensile-shear loads, assuming the mechanical behavior of the adhesive to be known.

The analysis of the failure modes, for composite D (Figure 5), shows the influence of the direction of the tensile-shear load in the case of monotonic loads. Failure is located in the middle plane of the composite for loadings characterized with $\gamma \in$ [0°, 45°]. Beyond this, when the shear part of the load increases (increasing of angle γ up to 90°) the localization of the failure is close to the adhesive-matrix interface.



a) γ= 0°, 15° and 30° b) γ= 45°

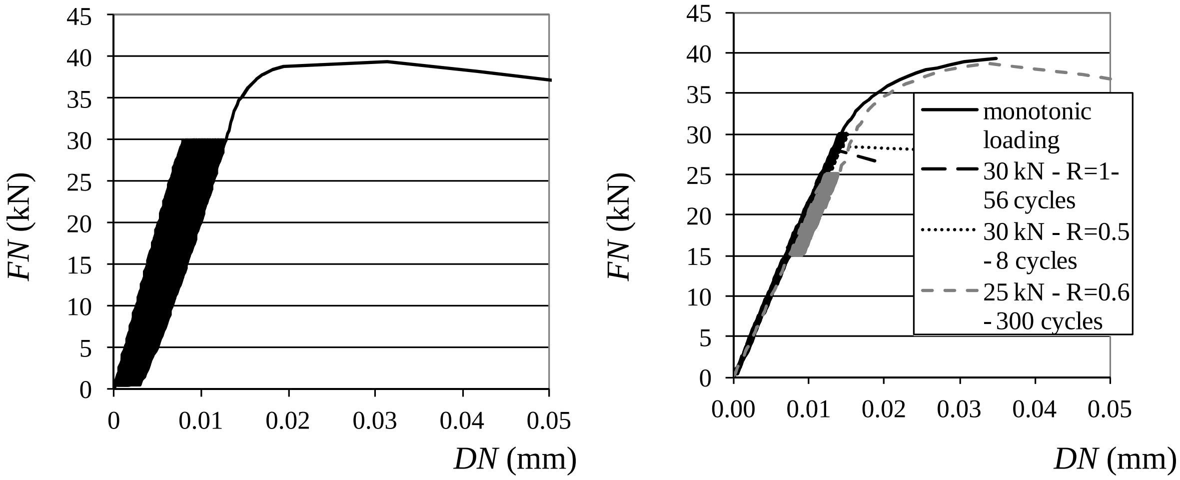


c) γ= 60° d) γ= 75° and 90°

Figure 5. Failure mode for composite D with respect to the direction of the tensile-shear load

4 Behavior under cyclic loadings

The aim of this first stage of an ongoing project is to analyze the mechanical behavior of hybrid bonded assemblies under more complex history loadings, in order to take into account industrial type applications.



a) adhesive b) hybrid bonded assemblies

Figure 6. Behavior under tensile out-of-plane loadings for the adhesive and for hybrid bonded assemblies with composite D

Some out-of-plane tensile cycling test results with different positive load ratios are presented. First, figure 6a presents the behavior of the adhesive under tensile cyclic loadings (this test is performed with an aluminum-adhesive-aluminum assembly). During the cyclic loading, an anelastic deformation of the adhesive is observed which depends on the mechanical loading. For such tests the scatter in the results is quite low; other results can be found in [15]. Secondly, figure 6b presents experimental results using hybrid bonded assemblies (i.e. an aluminum-adhesive-composite-adhesive-aluminum assembly). For these tests the material D has been used with different positive load ratios. Figure 7 presents the failure mode within the composite for such tests. For such assemblies, the scatter in the experimental results seems to be larger, especially for the number of cycles before failure. Perhaps, these results are associated with the influence of defects in the composite material. More tests have to be done in order to complete the preliminary study and complementary analyses have also to be developed to understand and model the mechanical behavior of such hybrid bonded assemblies under complex out-of-plane loadings.

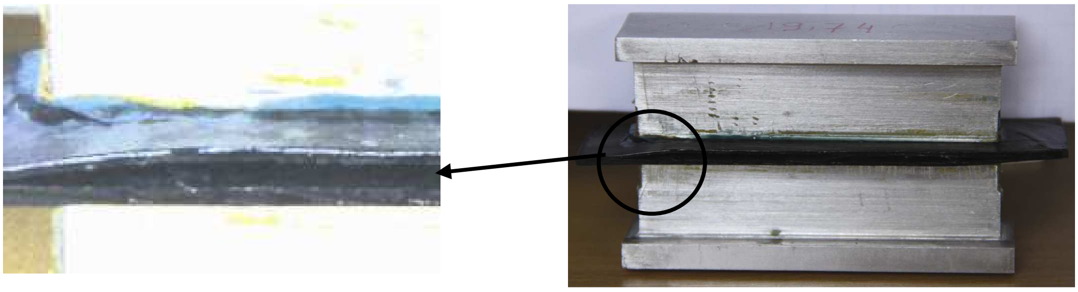


Figure 7. Failure mode of the composite D under tensile out-of-plane loadings

4 Conclusions

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 behavior of both composites and hybrid metal/composite bonded assemblies to be analyzed under a large range of proportional tensile-shear out-of-plane loadings. The key advantage of this fixture, using hybrid bonded assemblies, is to strongly limit the influence of edge effects. 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 fiber 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. 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 hybrid bonded assemblies with composites, especially under cyclic loadings. 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 composite [16] and of the adhesive [17], as the stress state is not homogeneous for the proposed Arcan type test.

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