EXPERIMENTAL STUDY AND MODELLING OF THE BEHAVIOUR OF HYBRID BONDED ASSEMBLIES FOR RACING YACHTS

R. Créac'hcadec[a], J.Y. Cognard[a], L. Sohier[b] and P. Davies[c]

[a] *Laboratoire Brestois de Mécanique et des Systèmes, ENSIETA, 2 rue F. Verny, 29806 Brest Cedex 09*

[b] *Laboratoire Brestois de Mécanique et des Systèmes, UBO, 6 Av. Le Gorgeu, CS 93837, 29285 Brest*

[c] *Service Matériaux et Structures, IFREMER, 29280 Plouzané*

Romain.Creachcadec@ensieta.fr, Jean-Yves.Cognard@ensieta.fr,
Laurent.Sohier@univ-brest.fr, Peter.Davies@ifremer.fr

ABSTRACT

The pleasure boat industry uses adhesively bonded assemblies, of composite and metal/composite structures, on a daily basis, but the prediction of the behaviour of these bonded joints is still approximate. An experimental study of the behaviour of the adhesive in a metal/composite joint is proposed here, using the Arcan test developed previously to characterize assemblies of metallic substrates. A detailed analysis of the stress distribution through the joint thickness provides important information to allow the geometry to be optimised to limit edge effects. Moreover this test is well suited to analyze the behaviour of composites under out of plane loadings which is essential in order to optimize hybrid bonded assemblies. In order to evaluate the mechanical performances of the bonding of a rail (used to guide the mainsail) to a composite mast on a racing yacht a specific experimental device has been developed: the aim is to analyse the influence of critical parameters such as rail geometry and mast surface characteristics.

1. INTRODUCTION

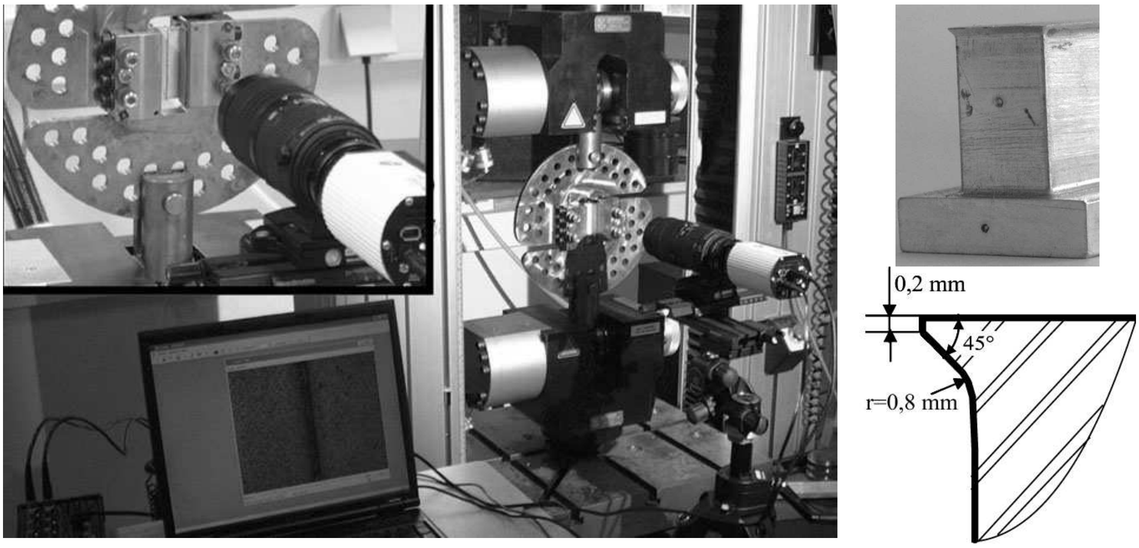
Polymer matrix composites are widely used in marine structures. Assembly by adhesive bonding offers many advantages [1] and major aerospace projects have addressed its use in aircraft structures, but a lack of confidence currently limits the marine use of this technology. If applications are to be extended it must be clearly demonstrated that the strength of adhesively bonded structures can be predicted accurately. There are several approaches to the strength analysis of bonded joints [2], but the analysis of the mechanical behaviour is made difficult by the stress singularities due to edge effects [3-5]. Difficulty in modelling the failure of even simple joints (composite/composite lap shear specimens) highlighted the need for more reliable constituent input data [6].

The industrial applications concerned, in particular adhesively bonded mixed joints (composite joining metal, such as the assembly of a sail guide rail to a composite mast for racing yachts), are characterized by the use of joints of relatively thick adhesive, at least 0.5 mm. In previous work an experimental methodology has been developed enabling the adhesives of interest to be characterized up to failure. A modified Arcan fixture, which allows compression or tension to be combined with shear loads, has been designed [5]. It has been numerically shown, on one hand, that the use of a beak close to the adhesive joint makes it possible to strongly limit the edge effects; and on the other hand, that the geometry of the joint near the edge is an important parameter. This experimental fixture associated with non-contact extensometry allows us to analyze, for radial loadings, the non linear behaviour of an adhesive joint (epoxy resin Vantico™ Redux 420 has been used).

The aim of the present work is to extend the analysis to assemblies involving composite materials. An experimental study of the behaviour of the adhesive in a metal/composite joint is proposed here using the Arcan test developed previously to characterize assemblies of metallic substrates. A composite plate was bonded between two metallic

substrates [7]. The results indicate that the test fixture is suitable for obtaining the response of adhesive systems under a large range of loading conditions. It is important to note that we obtain a similar behaviour for a mixed joint or a classic assembly; except for tests under traction-shear loadings where failure by delamination of the composite is often obtained for a low relative displacement of the substrates. More work is underway to clarify the role of composite failure mechanisms in mixed joints.
A detailed analysis of the distribution of the stress in the thickness of the adhesive joint has provided important information on the loadings of the adhesive joint and of the composite. This study makes it possible to optimize the dimensioning of this type of assembly. The objective is to limit the edge effects in order to increase the acceptable maximum loading of the assembly. Experimental tests, replacing the composite plate by a metal plate, are proposed to validate this numerical study. Moreover this experimental test allows us to characterize the behaviour of thin composites under out of plane loadings: the Arcan fixture allows us to apply traction or compression loadings in the normal direction of the middle plane of the composite combined with tangential loadings.
A test to characterize the bonding of a rail (used to guide the mainsail) to a composite mast on a racing yacht is being employed to analyse the influence of critical parameters (rail geometry, mast surface characteristics…) and will allow the potential of adhesive bonding to be demonstrated on a real industrial structure.

2. ANALYSIS OF THE BEHAVIOUR OF BONDED JOINT



Arcan fixture & displacement measurement system   Substrates

Figure 1: Presentation of the experimental device.

In order to be able to study the behaviour of the adhesive as a function of the normal stress component, a modified Arcan fixture has been developed, which enables compression or tension to be combined with shear loads (Fig. 1). Numerical simulations in linear elasticity, for bi-material structures show that the use of a special geometry for the substrate (a beak close to the adhesive joint) makes it possible to eliminate the contribution of the singularities due to edge effects [3]. One wants to obtain the most uniform possible stress field in the adhesive joint and maximum stress in the centre in order to limit the influence of defects. Moreover non linear simulations taking into account the fixing system of the substrates on the supporting fixture were used to optimise the design of the complete fixture in order to prevent pre-loading of the adhesive joint [6]. To preserve the simplicity associated with the Arcan fixture, and the use of a traditional tensile testing machine, a specimen with rectangular section was proposed taking into account the problems involved in machining. This experimental fixture associated with non-contact extensometry and optimization techniques allows us to analyse, for radial loadings, the non linear behaviour of an adhesive joint (epoxy resin Vantico™ Redux 420 has been used). The second step was to develop a model in order to represent the evolution of the relative displacement of both extremities of the adhesive joint as a function of the stress state. The model retained allows us to use joint type elements which strongly reduce the numerical cost with respect to classical elements. As the numerical simulations, performed for linear behaviour of constituents, have shown a non uniform evolution of the stress state in the adhesive joint, inverse techniques are used to identify the parameters of the model. For monotonic loadings, a plastic behaviour with isotropic hardening and with a specific yield surface, gives good results [3].

3. ANALYSIS OF HYBRID BONDED ASSEMBLIES

3.1 Experimental results

The aim of the present work is to extend the analysis to assemblies involving composite materials. Tests with the Arcan fixture showed that the nature of the substrates (aluminium or steel) does not modify the identification of the properties of the adhesive. To analyze the behaviour of mixed assemblies, i.e. an assembly metal-adhesive-composite-adhesive-metal, the experimental procedure was adapted. To ensure correct positioning of the substrates and composite plate, an assembly fixture was developed (Fig. 2).

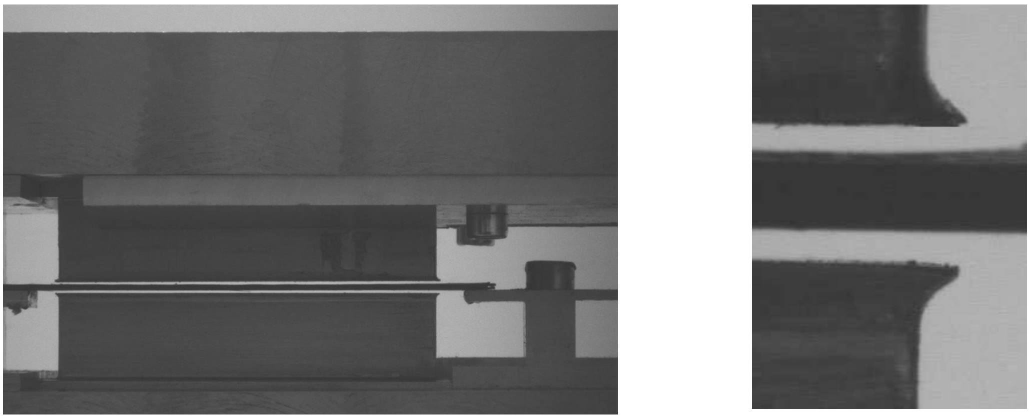
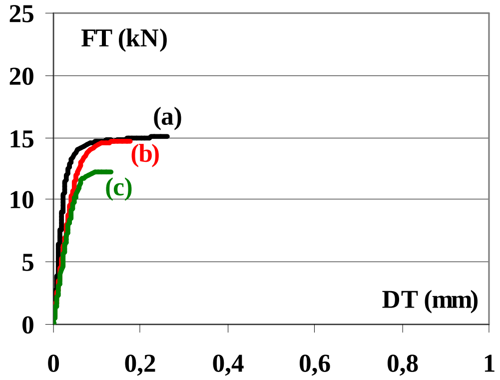


Figure 2: Bonding fixture for mixed assemblies with composites.

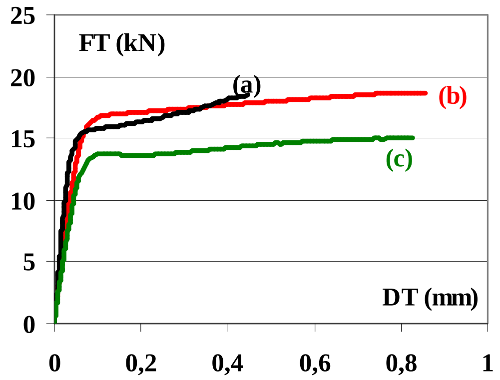
Figure 3 presents the results for various tests (45°: tension-shear; 90°: shear and 135°: compression-shear). This figure presents the results for a simple joint of adhesive (a); a mixed joining with cleaning of the adhesive, allowing to limit the effects edge (b) and a mixed joining with burs of adhesive. For these tests, the thicknesses of the composite plates and joints of adhesive are respectively about 1 mm and 0.45 mm. As there are two joints of adhesive for the mixed tests, the relative displacement of the aluminium substrates is double the value measured in the standard tests for a given loading. It is important to note that we obtain a similar behaviour for a mixed joint or a classic assembly; except for tests under traction-shear loadings where failure by delamination of the composite is obtained for a low relative displacement of the substrates.

Moreover, the comparison of the curves (b) and (c) shows the importance of the edge effects.

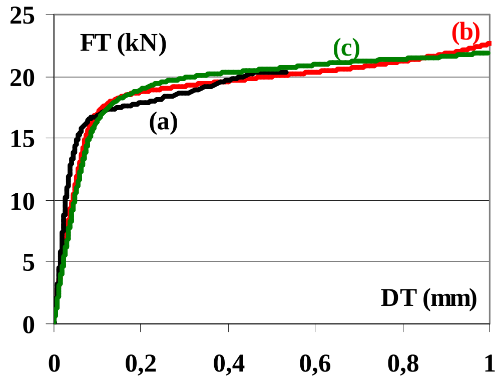


Tension-shear (45°)

two joints & composite - rupture mode (45°)



Shear (90°)



Compression-shear (135°)

Figure 3: Testing of bonded aluminium-composite assemblies (tension/compression-shear)
(a) simple aluminium assembly - (b) mixed assembly – (c) mixed assembly with fillet.

3.2 Analysis of edge effects

The study of the stress distribution in an adhesively bonded joint showed the importance of the geometry of the substrate and the edge of the adhesive joint on the edge effects [3]. These parameters are important for the dimensioning of mixed bonded assemblies [8-9].

Various calculations were carried out under the assumptions of isotropic linear elasticity with the aim of evaluating the maximum values of the stresses in the thickness of the joint of adhesive (Jo) and of the composite (Co) for the mixed assemblies tested with the Arcan fixture under tension-shear loadings (45°). For these simulations, 20 elements per thickness of 0.1mm of adhesive were used for the meshes in order to ensure a good quality of the results [10-11].

Figure 4 presents the maximum values of the von Mises equivalent stress (the stress is normalized to 1 in the centre of the adhesive joint); these curves show the importance of the edge effects. We have used: three geometries of the edge of the adhesive (fig. 4); two thicknesses of the joint of adhesive (e1 = 0.2 mm and e2 = 0.4 mm) and two thicknesses of the composite (h1 = 1 mm and h2 = 4 mm). The substrates are in aluminium (Young Modulus Ea = 80 GPa); for the adhesive joint we have: Ej = 2.2

GPa and for the composite two sets of parameters are used (A and B): EcoA = 80 GPa and EcoB = 8 GPa. For different materials the Poisson's ratio is: ν = 0.3.

These results show that the association of the beak and the geometry "i" makes it possible to limit the maximum stresses in the adhesive joint and the composite. Moreover for case "i" the maximum stress in the adhesive is inside the joint whereas for cases "ii" and "iii" the maximum stress is within the interface between the adhesive joint and the substrate (the interfaces are in general the most critical zones of these adhesively bonded joints).

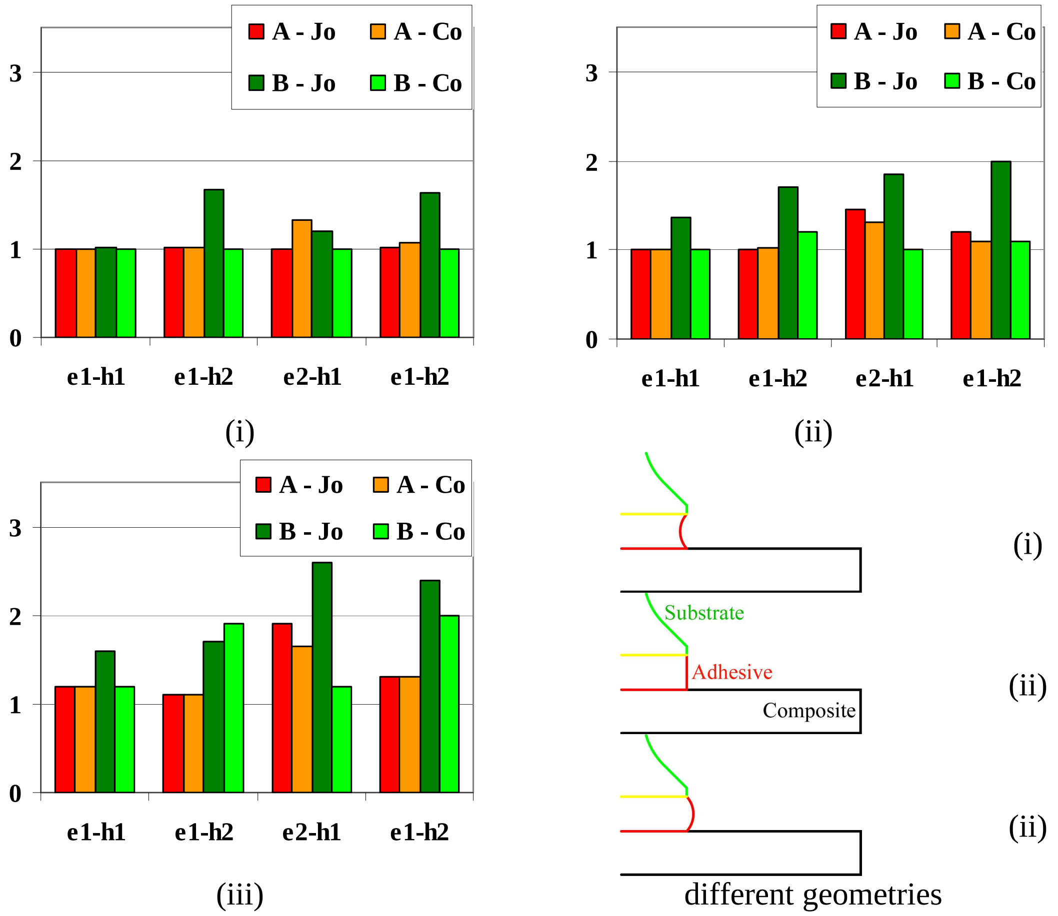


Figure 4: Analysis of edge effects in mixed bonded assemblies (Arcan test – tension-shear loadings).

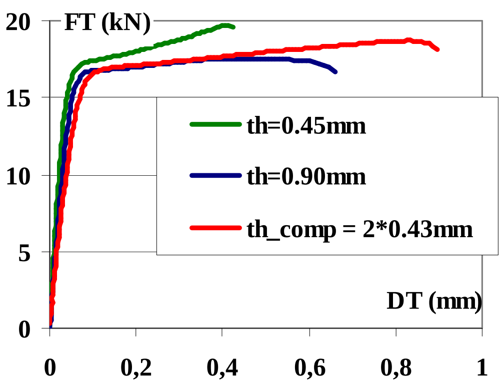
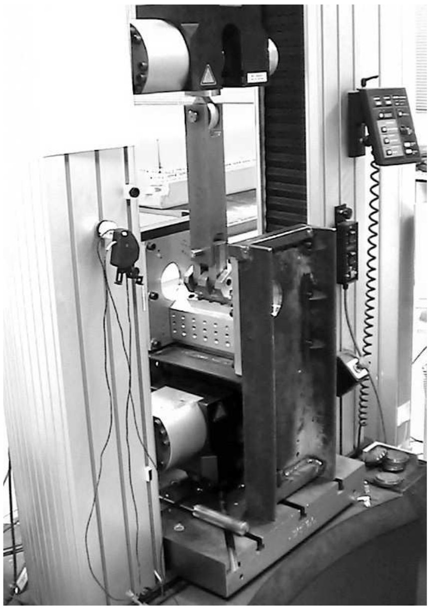


Figure 5: Experimental results for mixed bonding under shear loading.

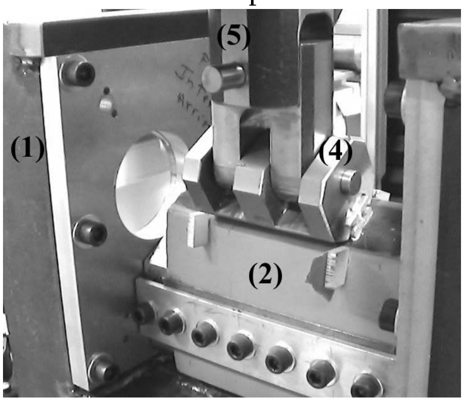
Tests in which the composite plate was replaced by an aluminium plate make it possible to validate some results of the previous numerical study (fig. 5). The experimental results, presented on figure 3, confirm the influence of the geometry of the edge of the adhesive joint on the behaviour of the bonded assembly. An increase in the thickness of the joint increases the maximum value of the relative displacement of the two ends of the joint but limits the maximum value of the transmissible load. These results show that the mixed joining, carried out with two joints of adhesive, has an intermediate behaviour between that of a joint of double adhesive thickness and association in series of two joints of the same adhesive thickness.

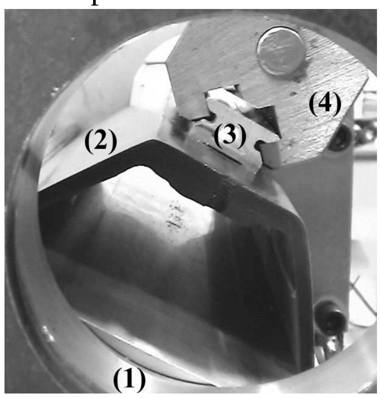
3.3 Experimental results on mini-structures

industrial problem



experimental fixture





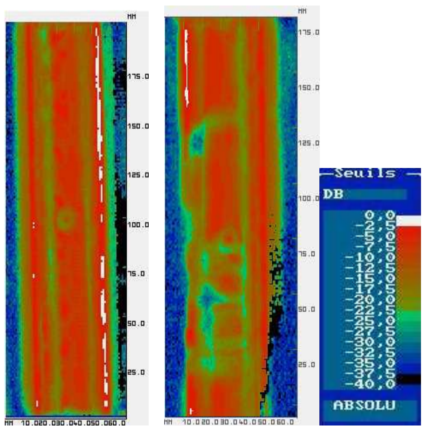
1 - support 2 - mast 3 - rail 4 - trolley 5 - loading

experimental fixture (zoom)

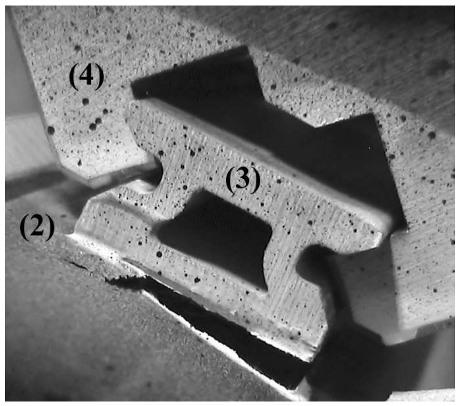
Figure 6: Presentation of the experimental device.

With respect to the hybrid bonded assemblies studied previously, the joining of a rail on a composite mast (fig. 6) presents important differences. Here, it is necessary to consider the joining of an aluminium part to a massive composite structure whose geometry must respect constraints related to manufacture, and in addition the loads imposed by the sail lead to a more complex loading of the adhesive joint.

Thus, it was necessary to develop an experimental test on mini-structures, representative of the application concerned, in order to analyze the influence of the various geometrical parameters and loadings (cyclic loading, creep …). The first objective of this test is to analyze and optimize the behaviour of this type of hybrid bonded assembly; it is necessary to study the influence of various solutions making it possible to limit the edge effects for this application and to check the delamination resistance of the mast knowing that the mast is not usually designed for such constraints, because of the presence of attaching bolts. A detailed analysis of this test requires comparisons between experimental and numerical results; it is an interesting example to validate the numerical tool which is under development in order to optimise adhesively-bonded structures.
The analysis of various configurations requires the development of a relatively simple experimental device. Thus, to carry out this test, we have fixed the back face of a mast of a 60 foot IMOCA racing yacht onto a modular support allowing us to load the rail in various configurations using a tensile testing machine (fig. 6). During the design of this fixture, different technical solutions have been used to limit the parasite effects; moreover improvements are under development. In order to obtain a test representative of the real problem, starting from a piece of mast, various Finite Element computations were carried out.
The first results (fig. 7) show delamination of the first layer of the laminate; the lower layers seem to be undamaged.



US inspection before and after test



Failure by delamination of the first layer of the composite mast

Figure 7: First results.

The first tests to characterize this industrial type hybrid bonded assembly were made directly on part of the mast of a racing yacht with part of a rail. However, this approach is complex, as the different parts of this assembly have not been designed for using only an adhesive joint: the classical assembly uses an adhesive joint and bolts; thus the parameters of this assembly have to be analyzed in order to optimize the transmitted loading.

4. OPIMISATION OF HYBRID BONDED ASSEMBLIES

In order to optimize the studied hybrid bonded assembly, at least two main points have to be analyzed. On one hand, an optimization procedure of the design of the composite based on resistance to delamination under out-of-plane loadings (in the normal direction of the mean plane of the composite) has to be performed. On the other hand, it has been shown that the geometry of the substrate close to the edge of the joint and the local geometry of the joint near the free edge are two important parameters which must be addressed in order to limit the stress singularities for adhesively-bonded joints; thus in order to increase the transmitted loading of the hybrid bonded assemblies, an optimisation of the geometry of the different parts is also useful.

4.1 Optimisation of the design of the composite

A study is in progress to analyze the behaviour of mixed assemblies with composite plates more resistant to tension loading in the normal direction of the middle plane of the composite. Thus, different composite plates have been tested with the modified Arcan fixture. The results for three different composites classically used in a boatyard environment (with different peel plies) are presented on figure 8 for tension-shear loadings. Those results underline that the proposed test is able to analyse the behaviour of thin composite plates under out-of-plane loadings. More work is underway to clarify the role of composite failure mechanisms in mixed joints.

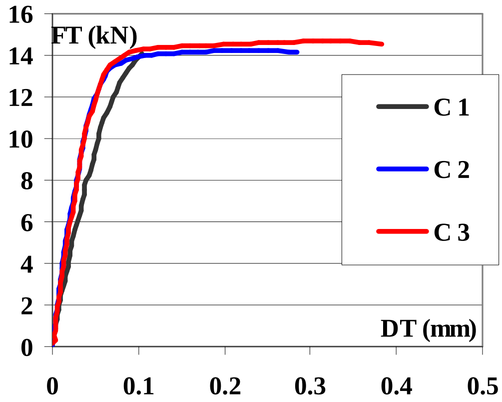


Figure 8. Analyse of different composites under tension-shear loadings.

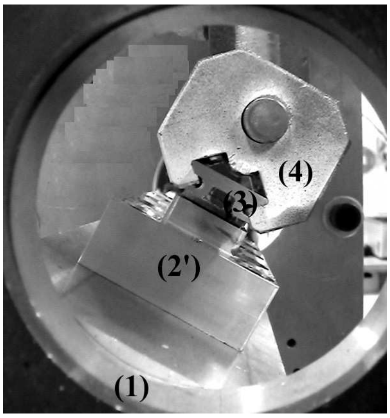
4.2 Optimisation of the design of the geometry of the different parts

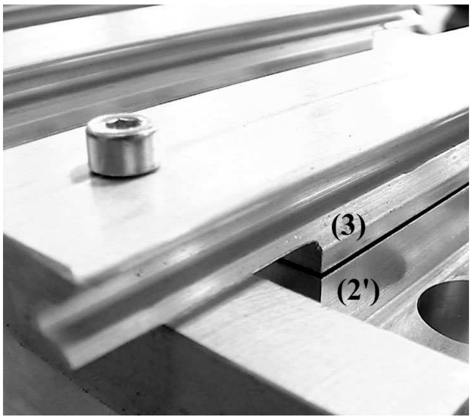
In order to analyse the influence of the edge effects on the behaviour of the assembly studied here, a modification of the experimental device has been proposed. The idea is to limit the difficulties; as we are analysing geometric effects we have replaced the composite mast part ((2) on figure 6) by an intermediate aluminium support ((2') on figure 9). Precise positioning of the different parts is obtained by the use of a special fixture during bonding, figure 9.

Four different geometries have been tested. Geometry "a" is characterised with straight edges of the rail and of the support. For geometry "b" a larger intermediate support is used with straight edges. Geometry "c" uses sharp beaks on the two parts to limit the influence of edge effects. For geometry "d", a small increase in the thickness of the joint is proposed to limit the influence of edge effects. For the different tests, the edge of the adhesive is cleaned in order to reduce the edge effects.

For the real application with hybrid bonded assemblies the loading is characterized with tension-shear and bending; the influence of edge effects are different to those for Arcan tests with only tension-shear loadings. Therefore such assemblies require a specific study.

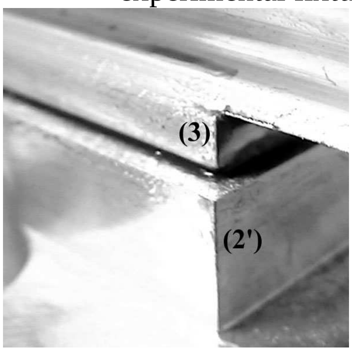
Figure 10 presents the transmitted load (at failure) for first tests with a part of the composite mast (figure 6) and for the different geometries with an intermediate aluminium support. For each geometry, four tests have been made in order to analyze the result variability. Significant differences are obtained for the different configurations. Numerical simulations have shown that the edge effects are lower for geometries “c” and “d” than for geometries “a” and “b”. Moreover it is important to note that experimental results are less scattered with strategies which strongly limit the edge effects. The cleaning is more difficult to manage for geometry “d” than for geometry “c”, which may explain some differences between the two solutions.

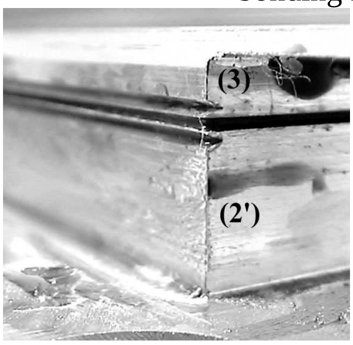


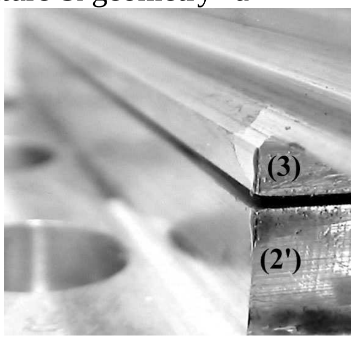


1 - support 2’ - intermediate support 3 - rail 4 - trolley

experimental fixture bonding fixture & geometry “a”







geometry “b” geometry “c” geometry “d”

Figure 9: Presentation of the experimental device with intermediate support.

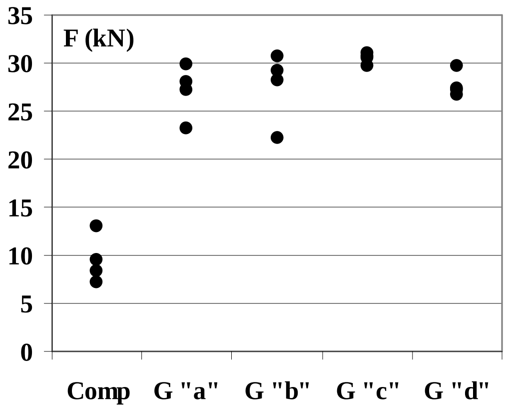


Figure 10: Examples of results.

6. CONCLUSIONS

An experimental procedure has been developed to analyze the behaviour of mixed bonded assemblies with composites, by using the Arcan test initially proposed for metal substrates. This allows us to characterize the behaviour of thin composites under out-of-plane loadings: the Arcan fixture allows us to apply tension or compression loadings in the normal direction of the middle plane of the composite combined with tangential loadings. Based on this procedure the design of the composite can be optimized, in order to increase the transmitted load for hybrid bonded assemblies.

Moreover, in order to optimize industrial hybrid bonded assemblies, a test to characterize the bonding of a rail (used to guide the main sail) to a composite mast on a racing yacht has been developed. A fixture has been designed in order to analyze the influence of critical parameters (rail geometry, mast surface characteristics…). For these assemblies, the choice of the geometry of the substrates (for instance the use of beaks) and the geometry of the edge of the adhesive joint make it possible to strongly limit the influence of the edge effects, and thus to increase the transmissible load by the assembly.

Tests are underway to complete these studies. The ultimate aim of this ongoing project is to develop numerical tools for the optimisation of adhesively-bonded marine structures.

ACKNOWLEDGEMENTS

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