EXPERIMENTAL STUDY AND MODELLING OF THE BEHAVIOR OF HYBRID BONDED ASSEMBLIES IN MARINE APPLICATIONS

Cognard J.-Y.*, Créac'hcadec R.*, Davies P., Sohier L.*****

*** Mechanics of Naval and Offshore Structures, ENSIETA, 29806 Brest Cedex 09, France**
**** Materials and Structures group, IFREMER Centre of Brest, 29280 Plouzané, France**
***** Laboratoire d'Ingénierie Mécanique et Electrique, UBO, 29285 Brest Cedex, France**

Keywords: *Adhesion, Composite, Marine structures, Finite Element, Non-linear behavior.*

Abstract

This study is concerned with increasing the performance of composite structures by the use of adhesively bonded joints. The applications are particularly related to the marine field and underwater structures; for instance, the assembly of a sail guide rail to a composite mast for racing yachts (hybrid bonded assemblies). Adhesively bonded joints offer many advantages for the design of such structures, but a lack of confidence limits the current use of this technology. Therefore, first, different tests and numerical analysis are proposed to optimize such hybrid bonded assemblies. Then, in order to simplify the analysis of the influence of the temperature, and of ageing in the marine environment, on the non-linear behavior of the adhesive, a modification of a standardized fixture is proposed. Moreover this fixture can improve the analysis of the behavior of the adhesive.

1 Introduction

The pleasure boat industry uses adhesively bonded assemblies, of composite/composite and metal/composite structures, on a daily basis, but the prediction of the behavior of these bonded joints is still approximate [1, 12]. Bonded assemblies in a boatyard environment involve joining of large parts, variable adhesive thickness, simple preparation of surfaces and cure at a low temperature.

An experimental study of the behavior of the adhesive in a metal/composite joint is proposed here using the Arcan test developed previously to characterize assemblies of metallic substrates [5]. A detailed analysis of the stress distribution through the joint thickness provides important information to allow the geometry to be optimized to limit edge effects. In order to complete this work, a test to characterize the bonding of a rail (used to guide the main sail) to a composite mast on a racing yacht is being employed to analyze the influence of critical parameters (rail geometry, mast surface characteristics…).

For naval applications, it is important to analyze the influence of the temperature, and of ageing in the marine environment, on the non-linear behavior of the adhesive. The proposed Arcan fixture makes it possible to carry out these tests but the standardized fixture TAST (ASTM D5656-95) appears better suited for such studies [3]. A comparison of the experimental results in shear for these two tests showed differences in the non-linear behavior. A detailed study of the distribution of the stresses in the adhesive joint, for the TAST fixture, showed that the edge effects are very significant. The experience gained during improvement of design of the Arcan assembly (limitation of the edge effects and control of the stress distribution in the adhesive joint) made it possible to propose modifications of the TAST fixture to give a more "reliable" analysis of the behavior of the adhesive. Tests are underway to complete this study.

2 Analysis of the behavior of bonded joint

The first objective of a previous study was to define an experimental methodology enabling the adhesives of interest to be characterized up to failure [5]. A modified Arcan fixture [2], which allows compression or tension to be combined with shear loads, has been designed. It has been numerically shown, on one hand, 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 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 and optimization techniques allows us to analyse, for radial loadings, the non linear behavior 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 behavior 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 behavior with isotropic hardening and with a specific yield surface, gives good results [6, 7].

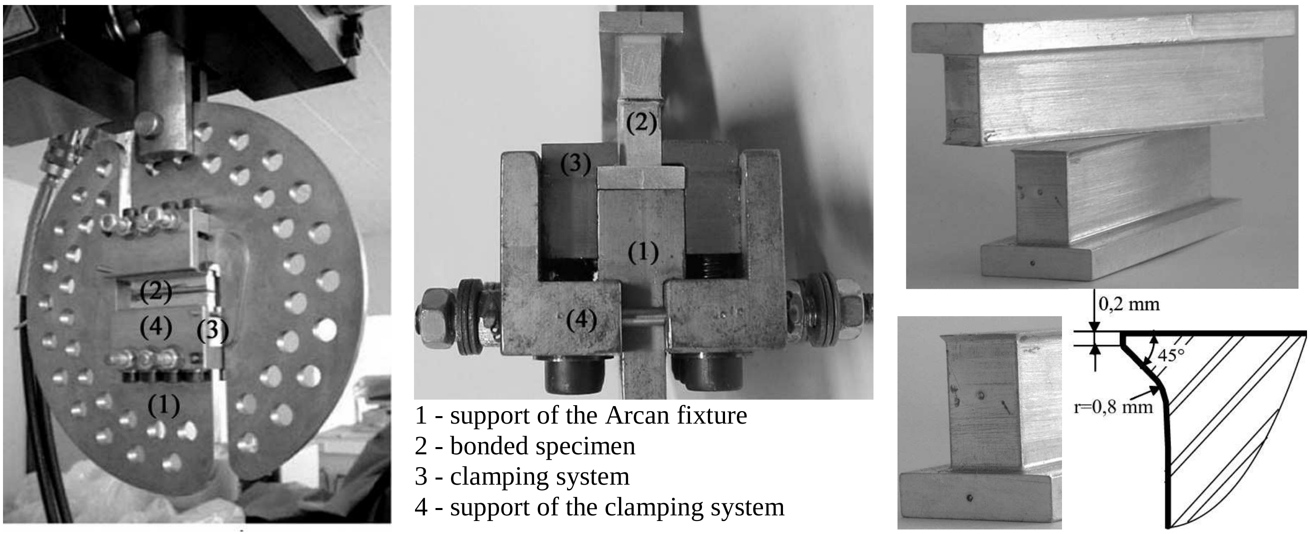
3 Analysis of hybrid bonded assemblies

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 behavior 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 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 1mm and 0.45mm. 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 behavior 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.

A study is in progress to analyze the behavior of mixed assemblies with composite plates more resistant to tension loading in the normal direction of the middle plane of the composite; this is important, in particular, for applications such as the rail on composite masts. More work is underway to clarify the role of composite failure mechanisms in mixed joints.



(a) Arcan fixture (b) mounting of the specimen (c) substrates with the beak

Fig. 1: Presentation of the experimental device (Arcan fixture).

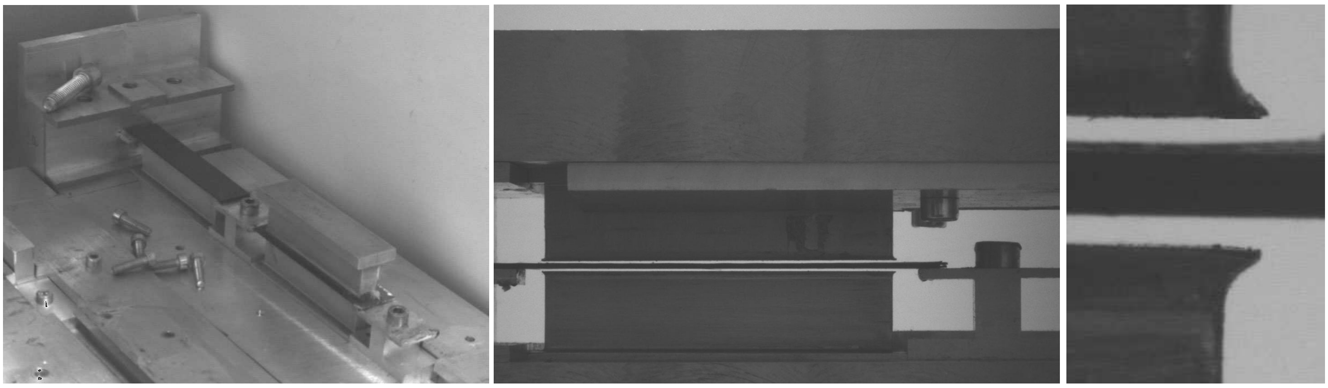
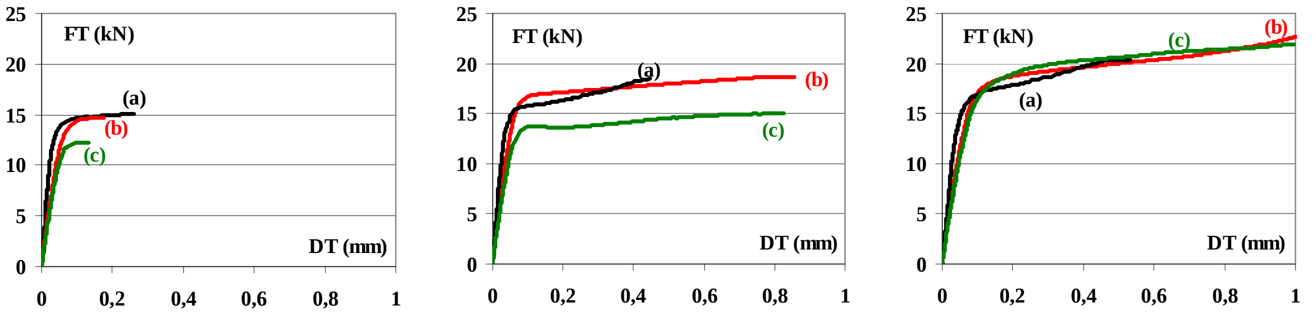


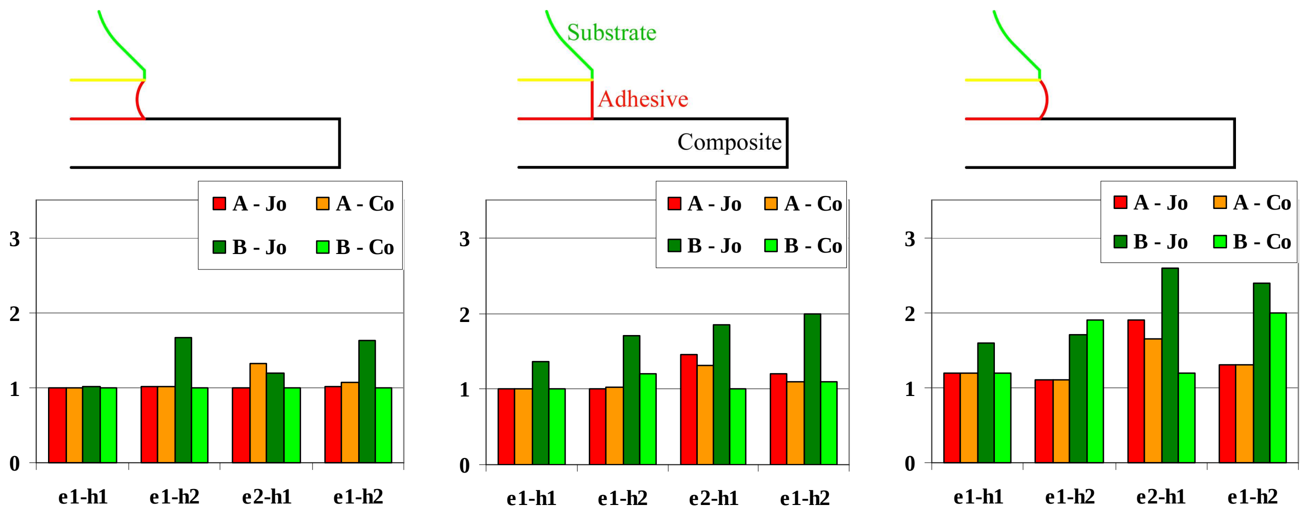
Fig. 2. Bonding fixture for mixed assemblies with composites.



(a) simple aluminium assembly - (b) mixed assembly – (c) mixed assembly with fillet

Tension-shear (45°) Shear (90°) Compression-shear (135°)

Fig. 3. Testing of bonded aluminium-composite assemblies (tension/compression-shear)



(i) (ii) (iii)

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

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 [4, 7]. 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 [4, 7]. 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=0.2mm and e2=0.4mm) and two thicknesses of the composite (h1=1mm and h2=4mm). The substrates are in aluminium (Young Modulus Ea=80GPa); for the adhesive joint we have: Ej=2,2GPa and for the composite two sets of parameters are used (A and B): EcoA=80GPa and EcoB=8GPa. 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).

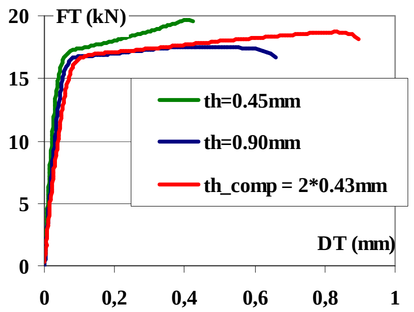


Fig 5. Experimental results for mixed bonding under shear loading

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 behavior 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 behavior between that of a joint of double adhesive thickness and association in series of two joints of the same adhesive thickness.

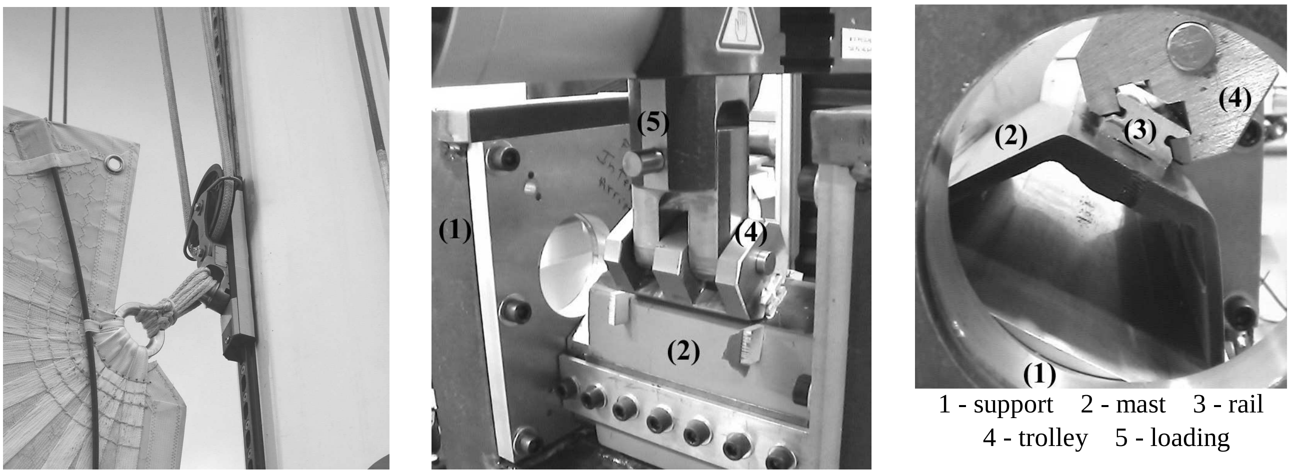
3.3 Experimental results on mini-structures

With respect to the hybrid bonded assemblies studied previously, the joining of a rail on a composite mast (fig. 8-a) 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 behavior 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 [7].

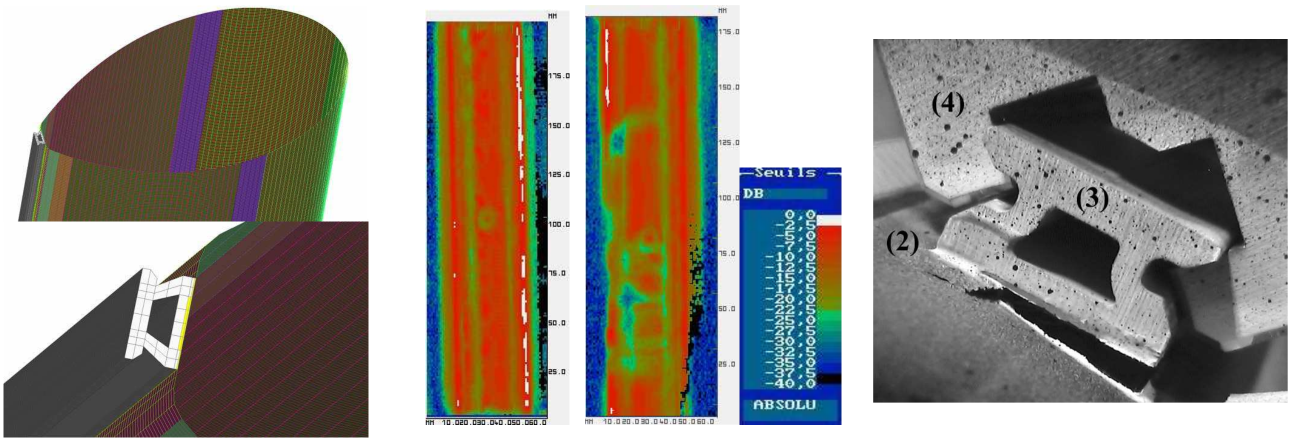
The analysis of various configurations requires the development of a relatively simple experimental device. Thus, to carry out this test, we have fixed the back face of a mast of a 60 foot IMOCA racing yacht onto a modular support allowing us to load the rail in various configurations using a tensile testing machine (fig. 8-b). 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 (fig. 9-a).

The first results (fig. 9-bc) show a delamination of the first layer of the laminate; the lower layers seem to be undamaged. An optimization procedure of the composite based on resistance to delamination under normal loadings (in the normal direction of the mean plane of the composite) is underway.



(a) Industrial problem (b) experimental fixture

Fig. 6. Presentation of the experimental device.



(a) FE simulations – comparison mini-structure / complete mast (b) US inspection before and after test (c) Failure by delamination of the first layer of the composite mast

Fig. 7. First results.

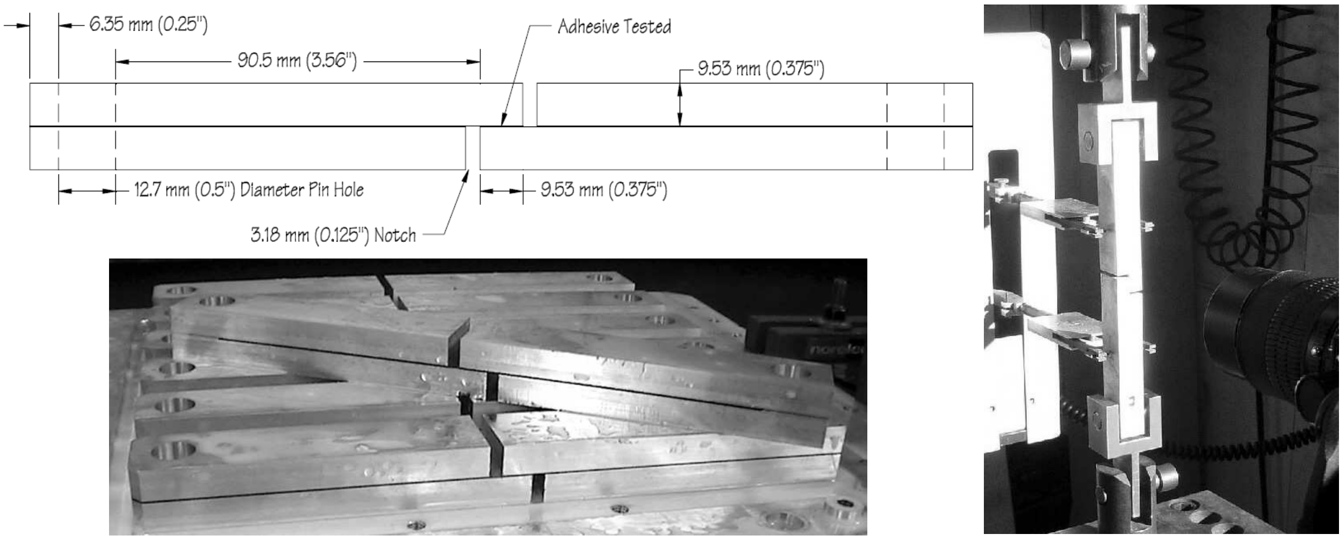
4 Optimization of a shear test

Optimization of adhesively bonded joints for naval applications requires improved characterization of the adhesive behavior. In particular, it is important to analyze the influence of the temperature, and of ageing in the marine environment (seawater, sun, temperature), on the nonlinear behavior of the adhesive. The proposed Arcan fixture makes it possible to carry out these tests but the standardized fixture TAST [3] (shear test with thick substrates) appears better suited for the analysis of the ageing of the adhesive (fig. 8).

The first step of this study was to make a comparison between the experimental results obtained with the Arcan fixture under shear loading and with the TAST test.

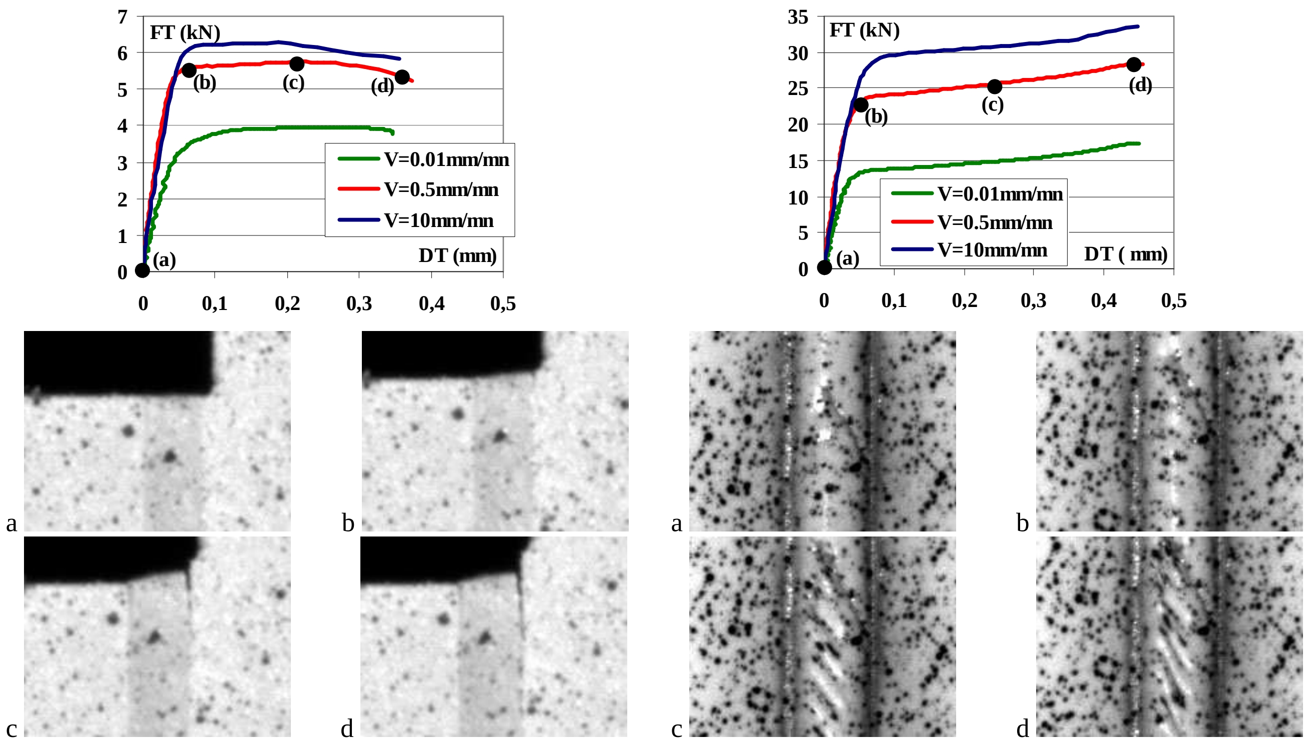
4.1 Experimental results

A non-contact extensometry system based on image correlation, is proposed to analyse the kinematics of the bonded joint deformation, for the TAST test. A standard extensometer is used to verify the relative displacement of the substrates (fig. 8). Figure 9 presents the experimental results, obtained with a Redux 420 adhesive for a preparation similar to that used in boatyard environment, for various imposed speeds of the displacement of the crosshead of the tensile testing machine. For these tests, corresponding to shear loading of the adhesive, we can plot the evolution of the effort transmitted by the joint (denoted by FT) with respect to the relative displacement of the two ends of the adhesive joint (denoted by DT).



(a) Geometry of the TAST specimen (b) Experimental test

Fig. 8. Presentation of the TAST specimen (width: 25.4mm).



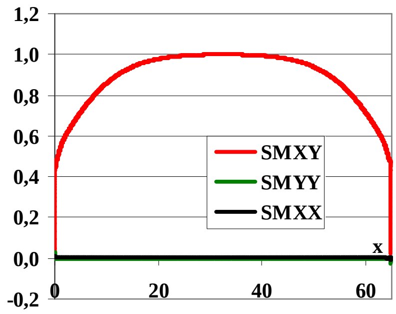
TAST ARCAN - Shear

Fig. 9. Experimental results, joint thickness: 0.5mm.

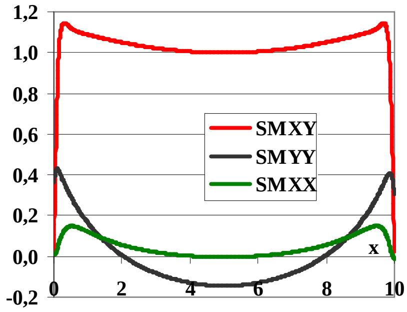
Figure 9 also presents the evolution of the deformation of the adhesive joints for the tests corresponding to a rate of 0.5mm/min. for the crosshead displacement of the tensile testing machine. Similar tests have been performed with the Arcan fixture using the same preparation conditions. Figure 9 presents also those results.

It is important to note that the sections Sc of the adhesive plane are different for the two tests: Sc=9.53x25.4mm^2 for the TAST test and Sc=10x65mm^2 for the Arcan test. A comparison of the experimental results in shear for these two tests showed differences in the non-linear behavior. On one hand, for the Arcan test a "homogeneous" deformation of the adhesive joint is observed. On the other hand, for TAST test cracks appear quickly at the two edges of the adhesive joint close to the interface adhesive-substrate. The evolution of these cracks, visualized by the image analysis, has been observed for various adhesives and various types of substrates (aluminium and steel).

4.2 Analysis of the experimental results



(a) Arcan test under shear loading



(b) TAST test

Fig. 10. Stress distribution in the mean plane of the adhesive

Figure 10 presents, for the two tests, the distribution of the stresses in the mean plane of the adhesive joint under the assumption of linear elastic behavior for the various components (aluminium substrates: Ea=80 GPa, νa=0.3; adhesive: Ec=2.2 GPa, νc=0.3). The computations are made in 2D. On this figure the shear stress is identified as "SMXY" and it is normalized to "1" in the middle of the joint. These results show differences between the two tests, especially near the edges of the adhesive joint.

As the numerical simulations, performed for linear behaviour of constituents, have shown a non uniform evolution of the state of stress in the adhesive joint, inverse techniques are used to identify the parameters of the model in the case of the Arcan test. For such monotonic loadings, elasto-plastic behavior with isotropic hardening allows us to represent the experimental results accurately [6].

For the TAST test, ASTM D5656-95 proposes to define the "limit" of elasticity starting from the change of slope in the diagram of average stress FT/Sc versus relative displacement DT; Sc is the section of the adhesive plane. As the stress distribution in the mean plane of the adhesive is not uniform, the maximum shear stress, for aluminium substrates, is close to 1.14*FT/Sc. This value is obtained starting from the results presented on figure 10; 3D calculation gives similar results. This procedure, inspired by the inverse identification technique developed for the Arcan test, makes it possible to obtain a slightly higher value for this elastic limit. The value denoted by "rupture" is associated with the ultimate load.

Figure 11 presents a comparison of the analysis of the experimental results from the two tests.

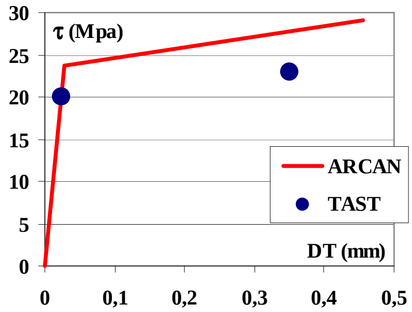
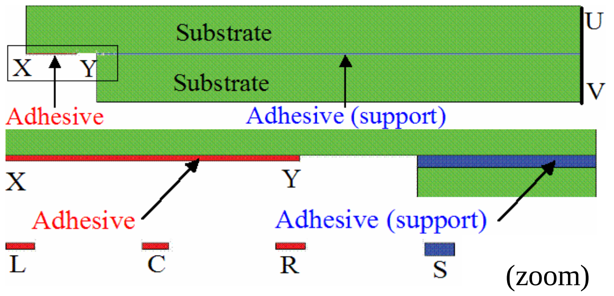


Fig. 11. Identified behavior for the adhesive joint under shear loading

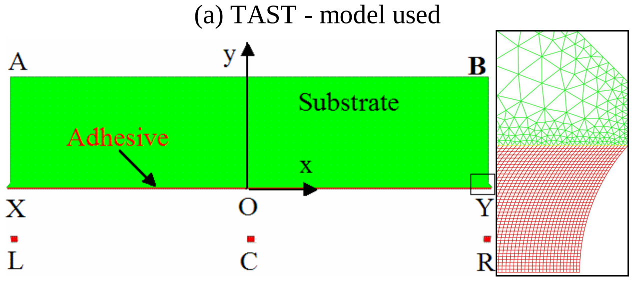
4.3 Analysis of the edge effects

To analyse the differences observed for the two tests, it is interesting to study the distribution of the stresses through the thickness of the adhesive joint [10, 11]. This analysis requires fine meshes to ensure the quality of the results; models using 40 linear elements in the half thickness of the joint of adhesive (e=0.2mm) are used. For the TAST test, an analysis in 2D is carried out from half of the model by using adequate boundary conditions (anti-symmetric type conditions) in the average plane of the adhesive joint (segment [X, Y], fig. 12). An imposed displacement on the segment [U, V] represents the loading. Figure 13 shows the important edge effects in the adhesive (useful zone) at the ends of the interface adhesive-substrate. The different curves are associated with a position y in the adhesive joint; y=0 represents the average plane of the adhesive joint. Moreover, it is important to note that there are also important edge effects in the zone noted "S" on figure 12 ("non-useful" zone).

Figure 13 also presents the results for the Arcan test under shear loadings; the geometry of the end of the joint of adhesive (obtained by cleaning before curing) and the presence of the beak makes it possible to strongly limit the edge effects for various loadings [7].



(a) TAST - model used



(b) Arcan - model used

Fig. 12. Models used and notations

This detailed study of the distribution of the stresses in the adhesive joint, for the TAST fixture, showed that the edge effects are very significant. Those numerical results help to explain the differences between the experimental results obtained for the two tests.

4.5 Influence of the non linear behaviour

The adhesive joint having a strongly non linear behavior, in particular under shear loadings, it is interesting to take into account these aspects in the analysis of these tests. Simulations were carried out under the assumptions of the finite transformations and elasto-plastic behavior of the adhesive, identified starting from the Arcan tests under shear loading (fig. 11). For these applications, where the shear stress component in the adhesive is dominating, the use of a usual elasto-plastic model with isotropic hardening is acceptable.

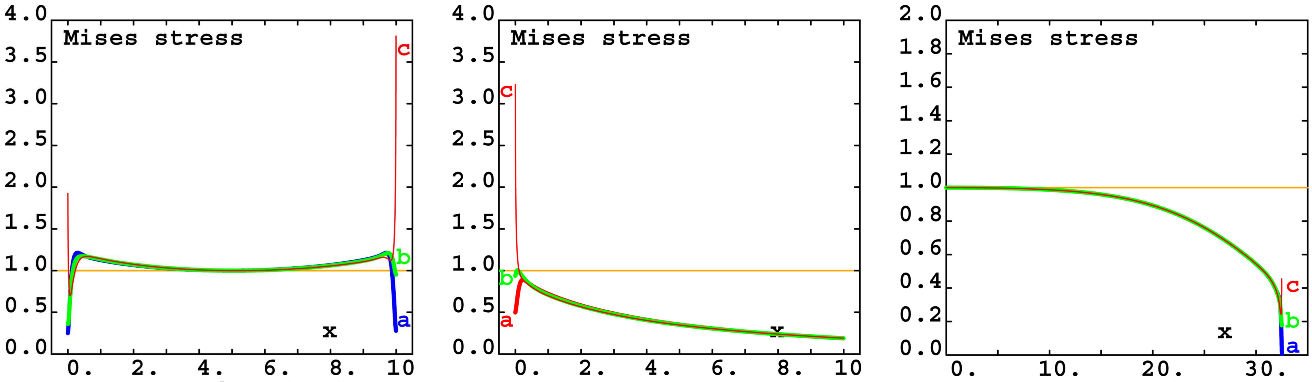
Figures 14 and 15 present results for the different zones analyzed, presented in figure 12 (L, C, R and S for the TAST test; L, C and R for the Arcan test). Figures 14-a and 15-a present, for a relative displacement of the ends of the joint of DT=0.07mm and a thickness of the joint of adhesive of 0.4mm, the state of the cumulated plastic deformation; for each zone the extreme values are registered with the top). The TAST test is characterized by the development of zones strongly plasticized at the edges of the adhesive joint close to the interface (a "zoom" of the scale makes it possible to better visualize the phenomenon). For the two tests, the central parts of the adhesive joint are loaded in a similar way. The non linear geometric effects can explain the differences between zones L and R. Figures 14-b and 15-b present, with respect to DT, the evolution of the maximum value of the cumulated plastic deformation in the different zones; moreover, for the Arcan test the solutions are also plotted for the elements of the adhesive joint located at the two edges of the interface adhesive-substrates (references r and l).

This study underlines the differences between these two tests. For the TAST test, the zone close to the interface is the more stressed part of the adhesive joint; therefore cracks can appear near them. On the other hand, for the Arcan test, the adhesive joint is stressed in a much more homogeneous way; moreover, the maximum value (close to the central part) is obtained close to the free edge of the adhesive but not near the interface; it is important to note that the interface adhesive-substrate is often the "weaker" part of the assembly. Thus the Arcan test makes it possible to obtain relative displacements DT more important than the TAST test. It is important to underline that these simulations give indicative results. Figures 14-c and 15-c present the Load-Displacement diagrams for the two tests; the results obtained are similar to the experimental data. These figures also present the time associated with the beginning of plasticity within the center zone and at the edges of the adhesive joint.

4.6 Proposition of a modified TAST test

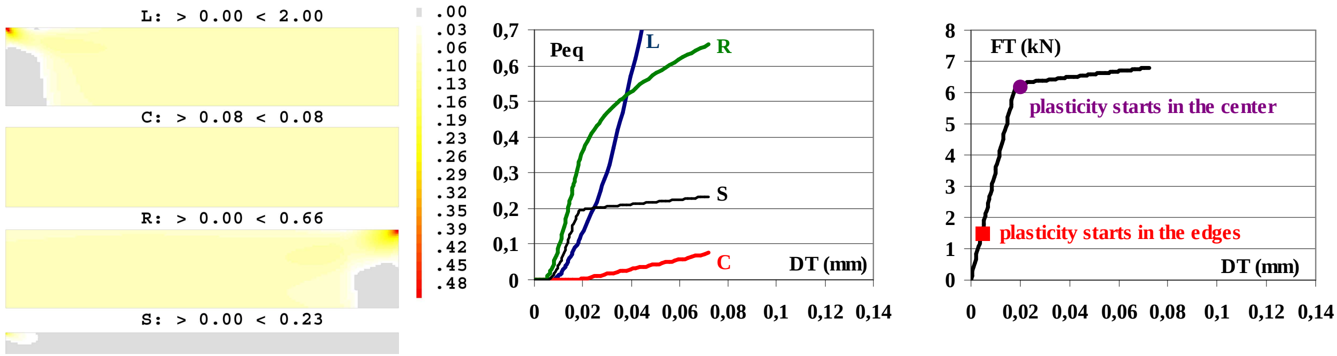
The principal difference between the two tests is associated with the edge effects. It is thus natural to study the influence of the use of beaks in order to limit these effects in the case of the TAST test. The machining of the beaks requires the machining of grooves much larger on both sides of the useful part of the joint of adhesive (fig. 9-b).

The numerical analysis of this modification of the geometry of the substrates close to the useful part of the joint of adhesive makes it possible to approach the properties of the Arcan device, in particular the use of sharp beaks can strongly limit the edge effects. As the machining of the beaks is not easy a second possibility is to use a "TAST" assembly with small samples ((1), fig. 16-c) which can be cut out of the bonded plates used for the machining of "normalized" TAST test (parallelepiped height approximately 20mm with an adhesive joint of Sc=9.53x25.4 mm² section in the mid-plane). This device thus uses a support ((2), fig. 16-c) and a fastening device ((3), fig. 16-c).



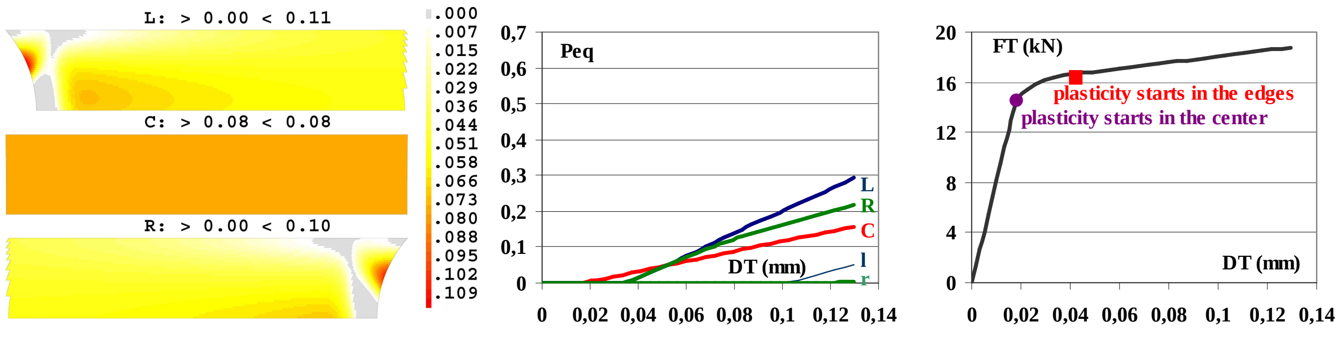
TAST- central part (X-Y) TAST - « support » (near S) Arcan – (O-Y)

Fig. 13. Stress distribution in adhesive thickness (a: y=0 ; b: y= e/2 ; c: y=e).



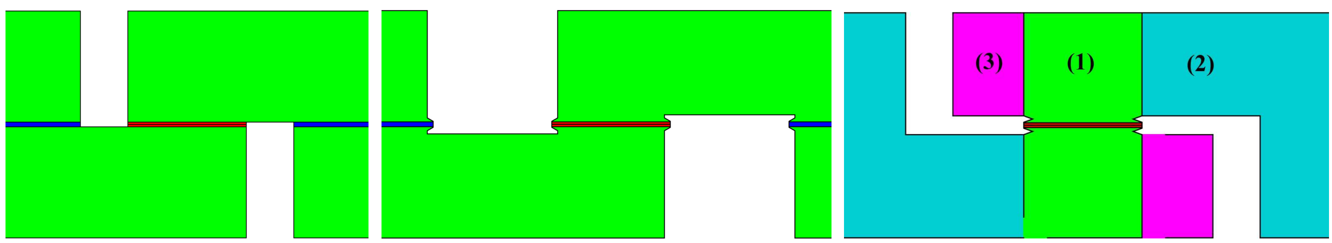
(a) Cumulated plasticity for DT=0.07mm (b) Evolution of cumulated plasticity (c) Load-Displacement diagram

Fig. 14. Results of the non linear simulation for the TAST test.



(a) Cumulated plasticity for DT=0.07mm (b) Evolution of cumulated plasticity (c) Load-Displacement diagram

Fig. 15. Results of the non linear simulation for the Arcan test.



(a) Normalized test (b) Machining of beaks (c) Modified test

Fig. 16 : Proposed modifications to TAST geometry to reduce edge effects.

The first results, obtained starting from a prototype device, seem to be promising. Moreover, this device is well suited to the study of the influence of the ageing of adhesive; indeed, it uses small samples which can be easily cut out of bonded plates having been exposed to an ageing cycle. The manufacture of modified TAST samples, characterized by an important stiffness in bending, in order to limit the parasitic effects, is in progress.

5 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. Moreover, in order to optimize industrial type 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 proposed. This 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 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. An optimisation of the design of the composite is also necessary.

For naval applications, it is important to analyze the influence of the temperature, and of ageing in the marine environment, on the non-linear behavior of the adhesive. For such complex experimental tests the use of the TAST fixture can be interesting. A detailed study of the distribution of the stresses in the adhesive joint, for the TAST fixture, showed that the edge effects are very significant.

The experience gained during improvement of design of the Arcan assembly have made it possible to propose modifications to the TAST fixture, to give a more "reliable" analysis of the behaviour of the adhesive. Moreover this device is well suited to analyze the influence of the ageing on adhesive properties; indeed, it uses small samples removed from bonded plates having been exposed to ageing.

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.

References

[1] Adams R.D.. "*Adhesive bonding: Science, technology and applications*", Woodhead Publishing Limited, 2005.

[2] Arcan L., M. Arcan M., Daniel L., “SEM fractography of pure and mixed mode interlaminar fracture in graphite/epoxy composites”, ASTM Tech. Publ., Vol. 948, pp 41-67, 1987.

[3] ASTM D5656-95, "*Standard Test Method for Thick-Adherend Metal Lab-Shear Joints for Determination of the Stress-Strain Behavior of Adhesives in Shear by Tension Loading"*, ASTM, pp 473-478, 1995.

[4] Cheikh M., Coorevits P., Loredo M., “Modelling the stress vector continuity at the interface of bonded joints”, *Int. J. Adhesion & Adhesives*, Vol. 22, pp 249-257, 2001.

[5] Cognard J.Y., Davies P., Gineste B. and Sohier L., “Development of an improved adhesive test method for composite assembly design”, *Composite Science and Technology*, vol. 65, pp 359-368, 2005.

[6] Cognard J.Y., Davies P., Sohier L. and Créac’hcadec R., "A study of the non-linear behaviour of adhesively-bonded composite assemblies", *Comp Structures*, Vol. 76, pp 34-46, 2006.

[7] Cognard J.Y., Créac’hcadec R., Davies P. and Sohier L., "Numerical modelling of the non-linear behavior of adhesively-bonded assemblies", in "*Inovation In Engineering Computational Structures Technology*", Saxe-Coburg Publications, ISBN 1-874672-27-X, Chapter 11, pp 225-247, 2006.

[8] Da Silva L.F.M. and Adams R.D., "Techniques to reduce the peel stresses in adhesive joints with composites", Inter. *J. Adhesion & Adhesives*, Vol. 27, pp 227-235, 2007.

[9] Khalili S.M.R., Mittal R.K. and Gharibi Kalibar S., A study of the mechanical properties of steel/aluminium/GRP laminates, *Material Science and Engineering A*, Vol. 412, pp 137-140, 2005.

[10] Leguillon D. and Sanchez-Palancia E., "*Computation of singular solutions in elliptic problems and elasticity*", Editions Masson, Paris, 1987.

[11] Magalhães A.G., De Moura M.F.S.F. and Goncalves J.P.M., "Evaluation of stress concentration effects in single-lap bonded joints of laminate composite material", *Inter. J. Adhesion & Adhesives*, Vol. 25, pp 313-319, 2005.

[12] Tong L. and Steven G.P., "*Analysis and design of structural bonded joints*", Kluwer, 1999.

Acknowledgements

The authors acknowledge the Bretagne Region of France for supporting this work.