DEFINITION OF A SIMPLE TEST TO CHARACTERIZE THE NON-LINEAR SHEAR BEHAVIOUR OF THE ADHESIVE IN AN ASSEMBLY

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ABSTRACT

The objective of this study is to define a reliable tool for dimensioning of adhesively bonded assemblies. For naval applications, it is important to analyze the influence of the temperature, and of ageing in the marine environment, on the non-linear behaviour of the adhesive. A modified Arcan fixture makes it possible to carry out these tests but the standardized fixture TAST appears better suited for such studies. A comparison of the experimental results in shear for these two tests showed differences in the non-linear behaviour. 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 behaviour of the adhesive. Moreover this test is well adapted to the study of the influence of the ageing on adhesive properties under shear loading.

1. INTRODUCTION

Adhesively bonded joints offer 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. This work is a part of an ongoing project aimed at developing numerical tools for adhesively bonded marine structures. Difficulty in modelling the failure of even simple joints highlighted the need for more reliable constituent input data [2-3].

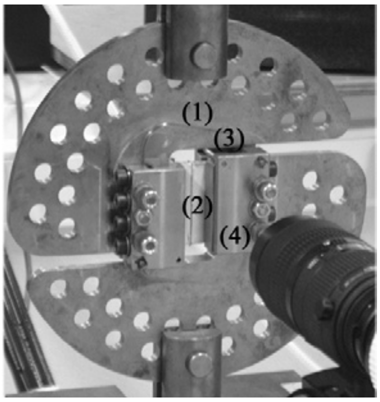
In a first study, an experimental methodology enabling the adhesives of interest to be characterized up to failure was proposed [2, 4]. A modified Arcan fixture, which allows compression or tension to be combined with shear loads, has been designed enabling the adhesives of interest to be characterized up to failure. 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 local geometry of the joint near the edge is an important parameter. The experimental results allowed us to analyze different aspects of the non-linear behaviour of the thin adhesive film with respect to the loading conditions.

The optimization of adhesively bonded joints in naval applications requires improved characterization of the adhesive. 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 behaviour of the adhesive. The proposed Arcan fixture makes it possible to carry out these tests but the standardized fixture TAST (shear test with thick substrates) [5] appears better adapted for the analysis of the ageing of the adhesive. A comparison of the results in shear for these two tests showed differences in the non-linear behaviour.

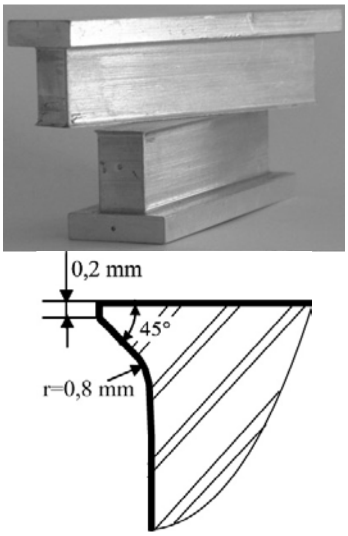
A detailed study of the distribution of the stresses in the adhesive joint, for the TAST fixture, showed that the edge effects are very significant. These edge effects in the TAST fixture can lead to an incorrect analysis of the behaviour of the adhesive, in particular whenever an adhesive failure type is dominating [6].
An additional numerical study shows possibilities, which are easy to apply, for limiting the influence of the edge effects for TAST fixture. Moreover, using experience gained during improvement of design of the Arcan assembly made it possible to propose a modification of the TAST fixture to obtain a more "reliable" analysis of the behaviour of the adhesive. This device is also well adapted to the study of the influence of the ageing on adhesive properties; indeed, it uses small samples which can be removed from bonded plates having been exposed to ageing. The first experimental results from the proposed modified TAST are presented.

2. ARCAN-TAST COMPARISON

The first objective of a previous study was to define an experimental methodology enabling the adhesives of interest to be characterized up to failure [2, 4]. A modified Arcan fixture [7], 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 behaviour of an adhesive joint (epoxy resin Vantico™ Redux 420 has been used).



1 - support of the Arcan fixture
2 - bonded specimen
3 - clamping system
4 - support of the clamping system
Arcan fixture



Substrates

Figure 1: Modified Arcan fixture.

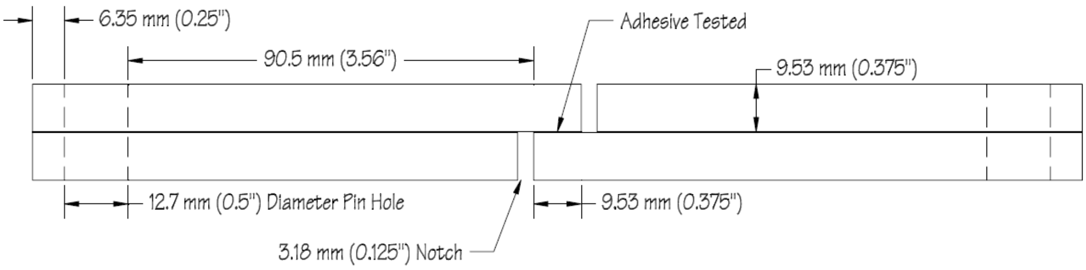
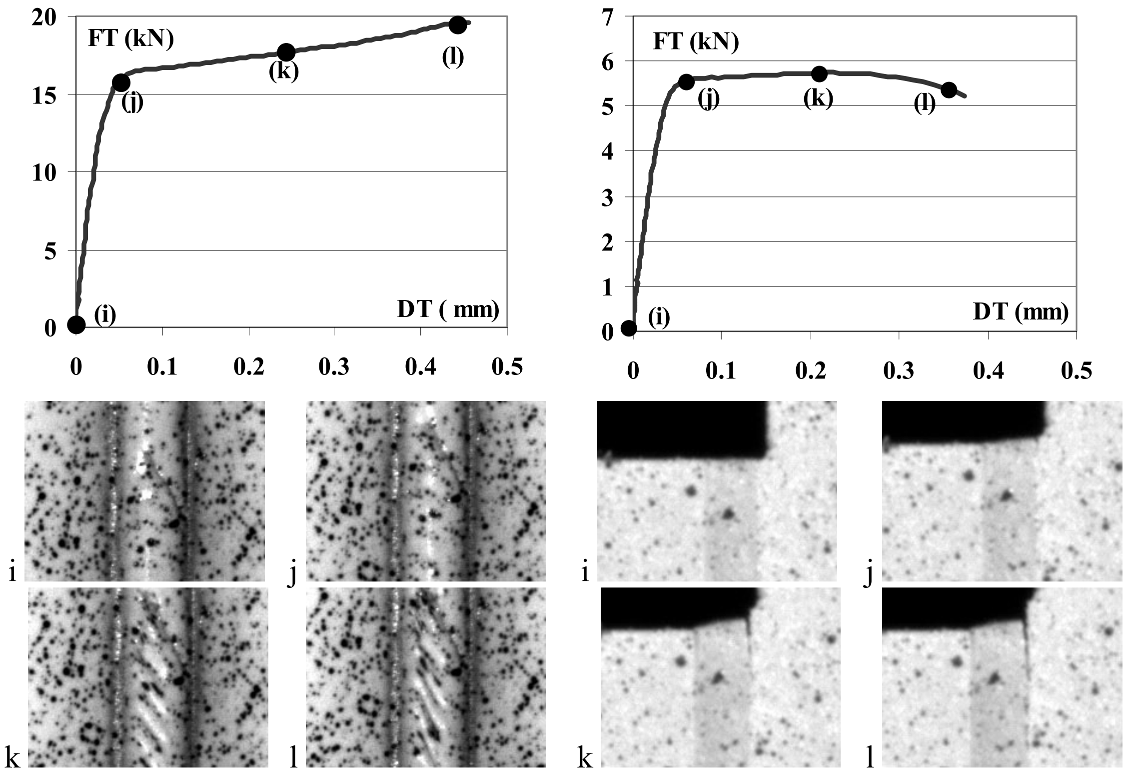


Figure 2: Presentation of the TAST specimen (width: 25.4mm).

Optimization of adhesively bonded joints for naval applications requires improved characterization of the adhesive behaviour. In particular, it is important to analyze the influence of the temperature, and of ageing in the marine environment (seawater, sun, temperature), on the non-linear behaviour of the adhesive. The proposed Arcan fixture makes it possible to carry out these tests but the standardized fixture TAST appears better suited for the analysis of the ageing of the adhesive (fig. 2).

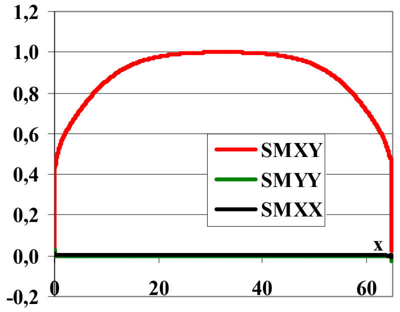
The first step of this study was to make a comparison between the experimental results obtained with the Arcan fixture under shear loading and with the TAST test. A non-contact extensometry system based on image correlation, is proposed to analyse the kinematics of the bonded joint deformation, for the TAST test. Figure 3 presents the experimental results, obtained with a Redux 420 adhesive for a preparation similar to that used in boatyard environment, for a speed of the displacement of the crosshead of the tensile testing machine of 0.5mm/min. For these tests, corresponding mainly 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). Figure 3 also presents the results of similar tests performed with the Arcan fixture using the same preparation conditions. It is important to note that the sections Sc of the adhesive plane are different for the two tests: Sc = 9.53x25.4 mm^2 for the TAST test and Sc = 10x65 mm^2 for the Arcan test. A comparison of the experimental results in shear for these two tests showed differences in the non-linear behaviour. On one hand, for the Arcan test a "homogeneous" deformation of the adhesive joint is observed. On the other hand, in TAST tests cracks appear quickly at the two edges of the adhesive joint close to the adhesive-substrate interface. The evolution of these cracks, visualized by the image analysis, has been observed for various adhesives and various types of substrates (aluminium and steel).



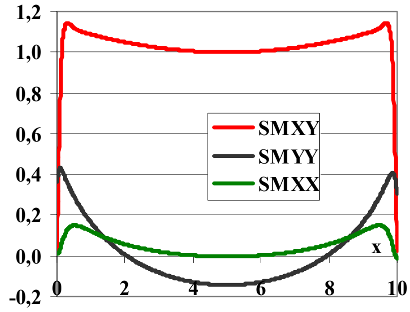
Arcan test under shear loading TAST

Figure 3: Experimental results, joint thickness: 0.5mm.

Figure 4 presents, for the two tests, the distribution of the stresses in the mean plane of the adhesive joint under the assumption of linear elastic behaviour 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 behaviour with isotropic hardening allows us to represent the experimental results accurately [2].
For the TAST test, ASTM D5656-95 proposes defining 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. A 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 [6].



Arcan test under shear loading



TAST

Figure 4: Stress distribution in the mean plane of the adhesive.

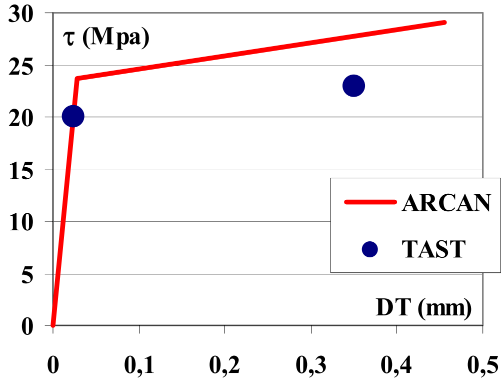
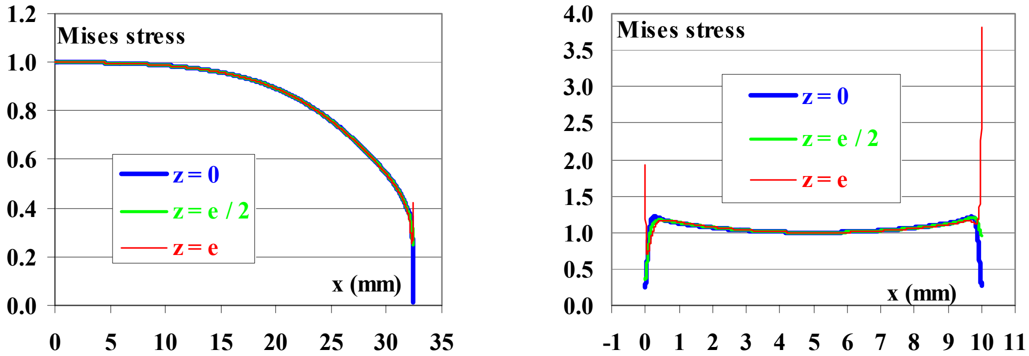


Figure 5: Identified behaviour for the adhesive joint.

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 [2; 8-9]. This analysis requires fine meshes to ensure the quality of the results [3]; models using 40 linear elements in the half thickness of the joint of adhesive (e=0.2mm) are used. Figure 6 shows the important edge effects in the adhesive at the ends of the interface adhesive-substrate. The different curves are associated with a position z in the adhesive joint; z=0 represents the average plane of the adhesive joint; z=e is close to the adhesive/substrate interface. Figure 6 also presents the results for the Arcan test under shear loading; 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 reduce the edge effects significantly [2].



Arcan test under shear loading TAST

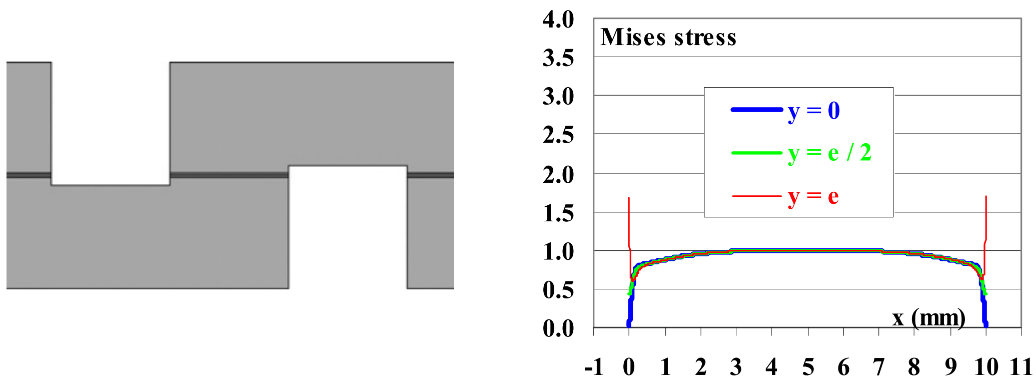
Figure 6: Stress distribution in adhesive thickness.

Moreover, for the TAST test, a numerical study taking into account the non-linear behaviour of the adhesive and the finite deformations of the adhesive joint, shows that there is a localization of the plasticized zones close to the adhesive-substrate interface near the free edge of the joint. These results can explain the initiation of cracks [6].

3. PROPOSAL OF AN IMPROVED TAST FIXTURE

3.1 Edge effects for the TAST test

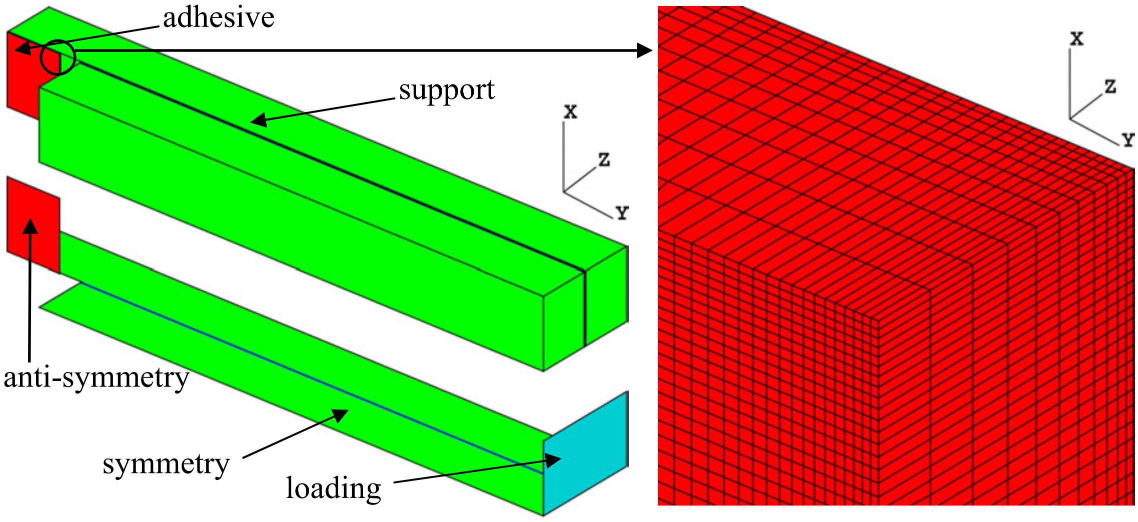
The principal difference between the two tests is associated with the edge effects. First, it is important to note that simply machining deeper grooves changes the stress distribution in the adhesive joint and reduces the edge effects with respect to the normalized TAST approach, as shown in figure 7. Those results should be compared with the results for the normalized TAST (fig. 6). Another technique to modify the stress distribution through the thickness of the adhesive joint is to leave some adhesive in the bottom of the grooves (i.e. machining shallower groves). In order to reduce the edge effects sharp beaks can also be used, but the machining is not easy.



Machining of deeper grooves Normalized stress through the thickness

Figure 7: Proposed modification to TAST geometry to reduce edge effects.

In order to complete the previous computations, which have been made in 2D, some 3D models have been used to analyse the stress distribution in the adhesive joint. To limit the size of the numerical model, the calculation was made on a quarter of the TAST specimen using adequate boundary conditions (fig. 8). A precise computation of the edge effects requires refined meshes, especially close to the adhesive/substrate interface [3], thus an adapted mesh was used (fig. 8). The complete model contains 592591 nodes (1777773 degrees of freedom) and 790140 linear elements; the adhesive is meshed with 592591 nodes (1121796 d.o.f.) and 790140 linear elements. The computation is made under elastic assumptions for the different parts.



Model & boundary conditions　　　　Mesh of the adhesive (zoom)

Figure 8: Model used for 3D calculation for TAST specimen.

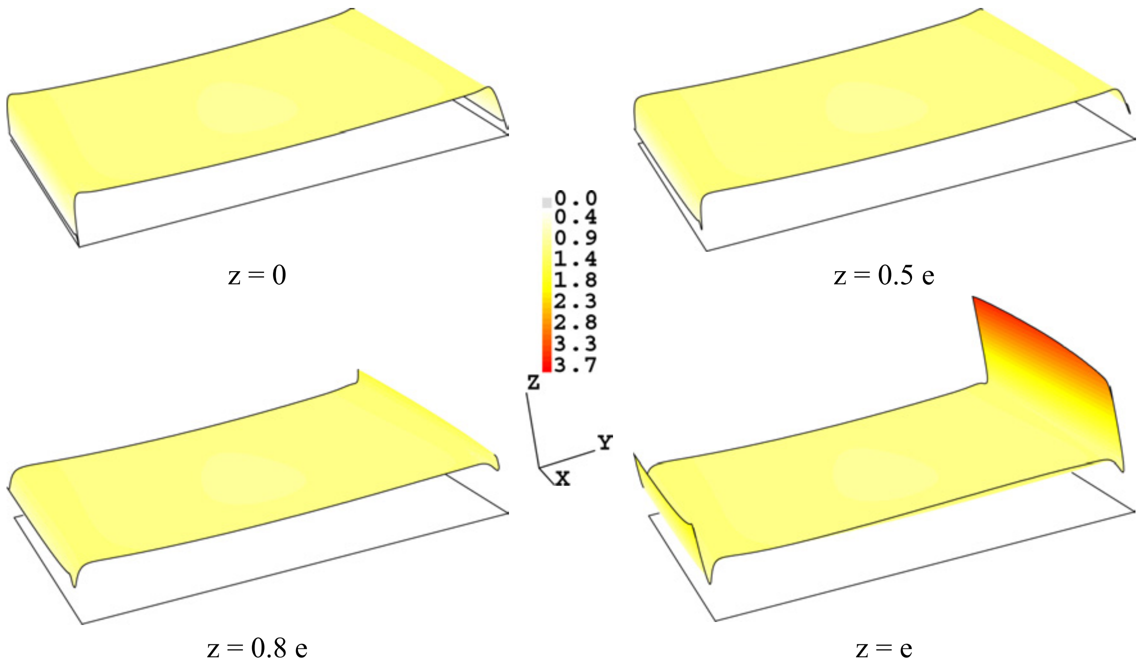
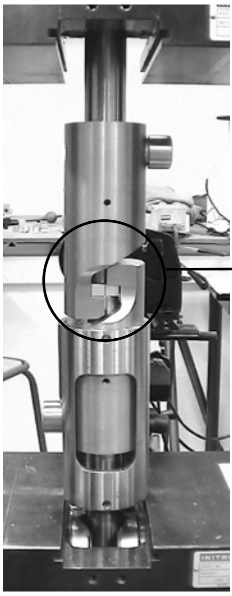
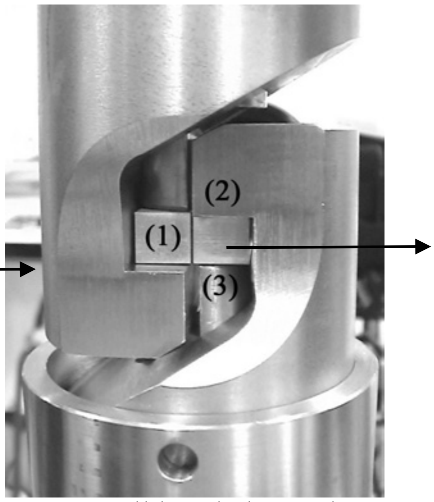


Figure 9: Mises equivalent stress through the thickness of the adhesive joint.

Figure 9 shows the evolution of the Mises equivalent stress through the thickness of the adhesive joint. The drawings show different positions in the adhesive joint; z=0 represents the average plane of the adhesive joint; z=e is close to the adhesive-substrate interface. For a given plane in the adhesive (given z) the Mises equivalent stress is represented in the z axis. For these drawings, the average shear stress in the adhesive is normalized in order to obtain an average equivalent Mises stress equal to 1. It is important to notice that the results are close to those obtained with a 2D model; the edge effects are mainly close to the free edges of the adhesive in the loading direction (y axis).

3.2 Improved TAST fixture





1 - small bonded sample
2 - support
3 - fastening device

Small bonded samples

Figure 10: Prototype modified TAST fixture and small bonded samples.

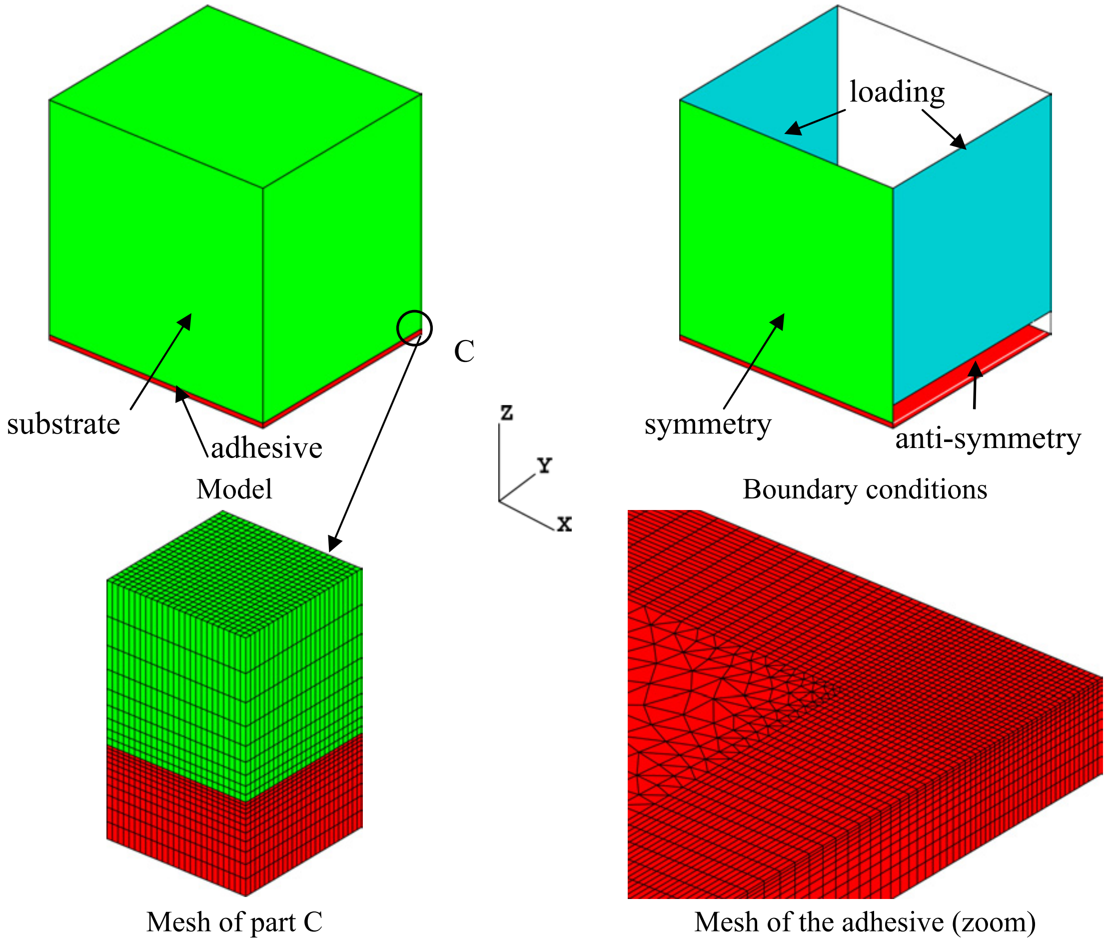


Figure 11: Model used for 3D calculation of modified TAST specimen.

In order to improve the TAST fixture the first step is to use small bonded samples (fig. 10) which represent the useful part of the TAST specimen (parallelepiped height approximately 20 mm with an adhesive joint of Sc = 9.53x25.4 mm² section in the mid-plane). Thus the modified TAST fixture uses a support ((2), fig. 10) and a fastening device ((3), fig. 10).

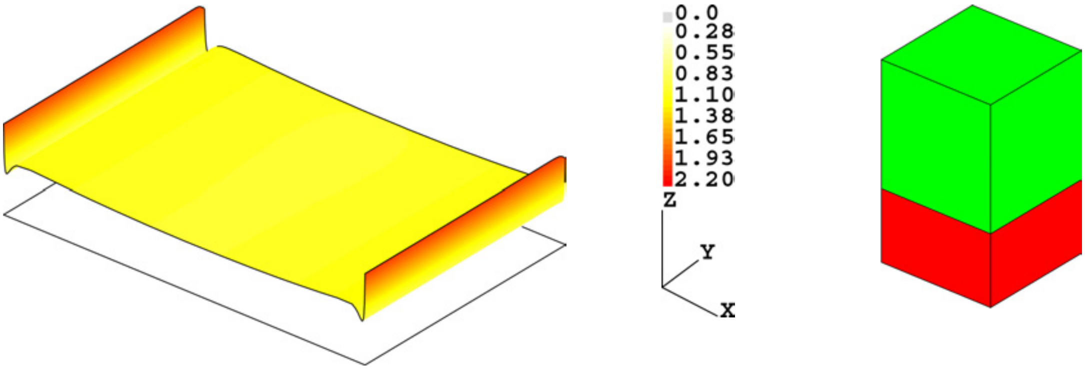


Figure 12: Edge effects for modified TAST specimen with parallelepiped specimens.

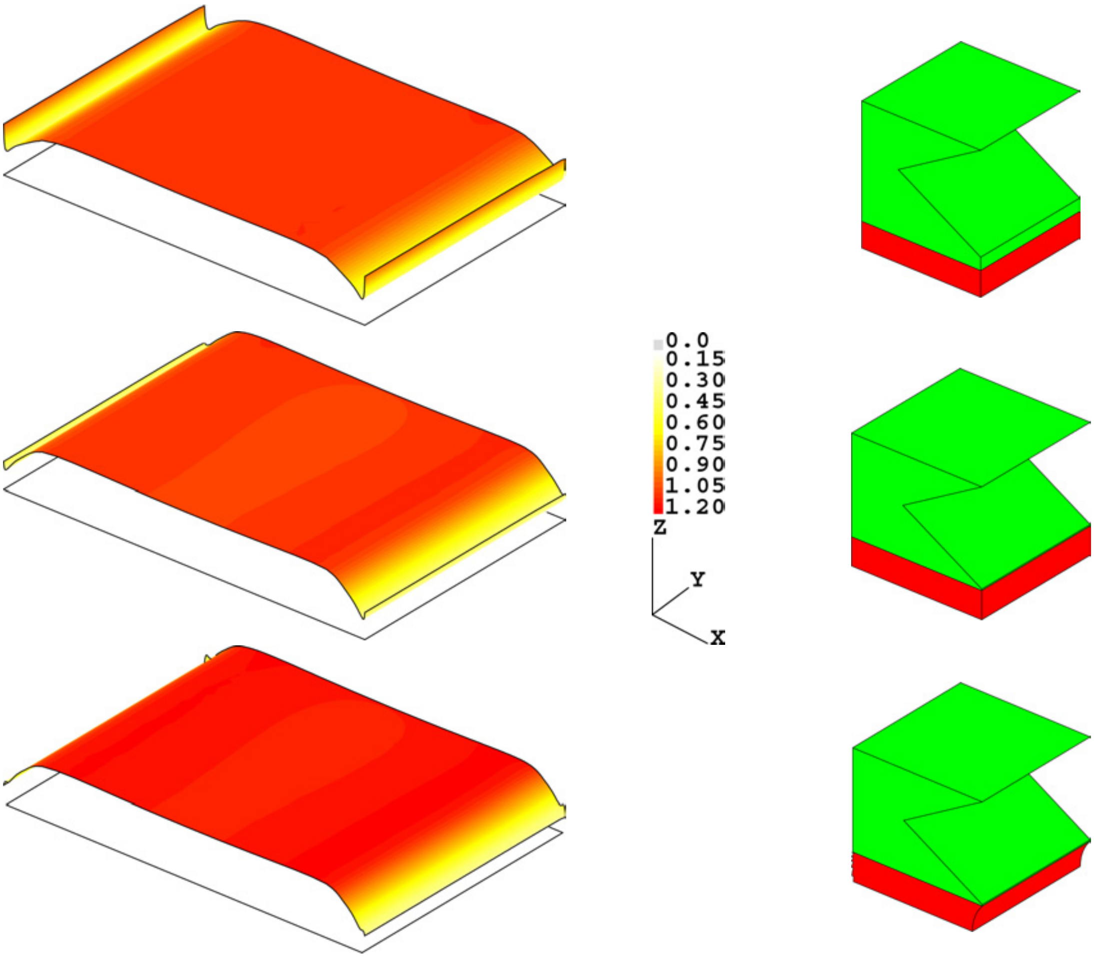
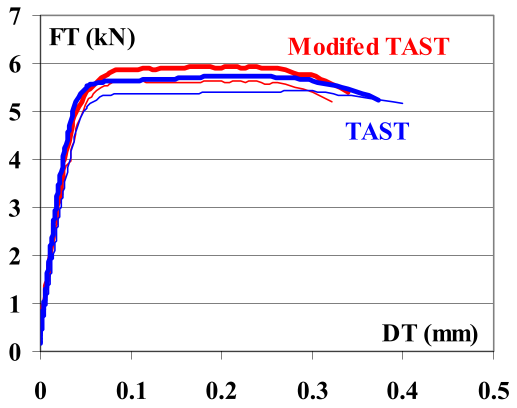


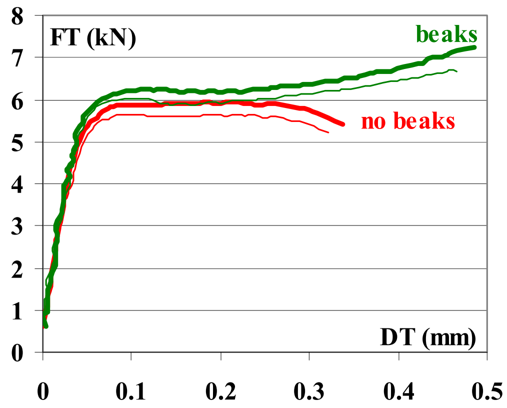
Figure 13: Edge effects for modified TAST specimen with different geometries.

In order to analyse the mechanical behaviour of the fixture, 3D models have been used with the assumption of elastic behaviour for the different parts. To limit the size of the numerical model, the calculation was made on a quarter of the specimen using adequate boundary conditions (fig. 11). The complete model contains 577145 nodes (173435

d.o.f.) and 638782 linear elements; the adhesive is meshed with 577145 nodes (763452 d.o.f.) and 638782 linear elements. Figure 12 presents the Mises equivalent stress close to the interface adhesive-substrate under the same conditions as for the previous computation. It is important to note that the edge effects are lower than those of the standard TAST specimen, because the rigidity of the support is quite important but is not taken into account in this computation. For the TAST specimen the edge effects are larger for aluminium supports than for steel substrates.
Figure 13 presents the edge effects for different geometries of the small bonded samples. It can be shown that the machining of a sharp beak and the cleaning of the edge of the adhesive allow edge effects to be reduced considerably .



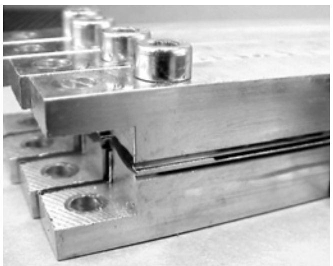
Comparison TAST-Modified TAST



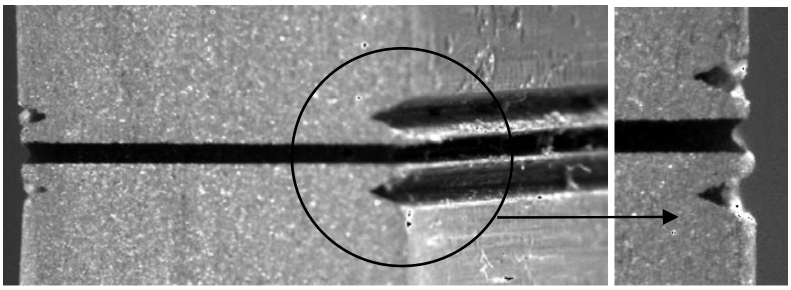
Influence of beaks

Figure 14: Experimental results with the modified TAST fixture.

Figure 14 presents the first experimental results obtained with the modified TAST fixture. On one hand, results are nearly similar for the TAST and the modified TAST fixtures. The high stiffness in bending of the modified TAST support, which is necessary in order to limit parasitic effects, can explain the small differences. And on the other hand, the machining of a sharp beak and the cleaning of the edge of the adhesive give experimental results which are similar to those obtained with the Arcan fixture under shear loading.
Those geometries allow to the edge effects to be limited but they are not easy to obtain starting from bonded plates. The solution proposed is to use bars in which beaks have been machined before bonding; so the samples are cut out of the bonded bars (fig. 15). The optimization of the manufacturing of those specimens in order to limit parasitic effects is currently underway.



Bonding of bars



Geometries of the beak and the free edge of the adhesive

Figure 15: Manufacturing of the small bonded samples with beaks.

6. CONCLUSIONS

The objective of this study is to define a reliable tool for dimensioning of adhesively bonded assemblies. For naval applications, it is important to analyze the influence of the temperature, and of ageing in the marine environment, on the non-linear behaviour of the adhesive. A modified Arcan fixture makes it possible to carry out these tests but the standardized fixture TAST appears better suited for such studies. A comparison of the experimental results in shear for these two tests showed differences in the non-linear behaviour. 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 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 first results, obtained starting from a prototype device, are promising. The optimization of the manufacturing of the small bonded specimens for the modified TAST fixture is in progress in order to limit parasitic effects.

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