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Experimental Investigation for the Design of Epoxy Bonding in Joints of Carbon Fibre Laminates

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Abstract

Numerous applications involve the use of composite material in order to increase the ratio between strength and weight and in order to increase the flexibility of the design. There is an intensive use of this material also in naval building, principally for recreational boat. Experimental and numerical tests allow having a deep knowledge of the response of this kind of material in different load conditions. In order to accommodate the complexity of the design, usually it is necessary to use bonding for jointing different elements. The work deals with a series of experimental tests for the assessment of the head joint between two carbon laminates. Tests carried out with different angles between the two linked elements in order to evaluate the response of the bonding to different stresses direction. The studied conditions are for 45°, 90°, 135° and 180° with forces applied in both closing and opening direction. The bonding under investigation has a double epoxy resin glues. Thanks to these series of experimental tests is possible to take care about the worst condition of load and try to avoid it during the preliminary phase of design.

Keywords: Bonded joints, carbon fibre laminates, nautical design, adhesive

INTRODUCTION

In the last years, the most used materials for building recreational boat like yachts are composites. The principal differences with the conventional shipbuilding materials, such as steel or aluminium alloys are reported by Mouritz et al. [1]. There are many advantages in using this new type of materials and the principal ones are resumed by Gibson [2]. Usually the most cited ones are the mechanical aspects, but in many cases the use of composites allows to have a reduction of weight and this leads to a reduction of the environmental impacts as reported by Barone et al. [3]. The manufacturing of the boat with the composite is a very difficult stuff and can be made with two different techniques: hand lay-up [4] and vacuum infusion [5]. In terms of environmental impacts the better manufacturing way is the second one as reported with a life cycle evaluation by Cucinotta et al.[6]. The great flexibility of the composite material allows to choice the better solution in function of the request of the project. In the preliminary phase is important to take in account the loads and so optimize the distribution of material along the boat. There are different tools to predict the interaction of the boat with the water, in many cases a suitable and preliminary process involves the use of computational fluid dynamics technique [7–11]. The great disadvantage of the composite material is the complexity in the prediction of the failure. There are several types of failure and the mechanical simulation is not sufficiently accurate for predict them so it is necessary to investigate these failures with experimental tests. Many studies involve the tensile, flexural and torsional stiffness of these kind of materials [12] and the respectively failure modes [13] . Cyclic dynamic and impact loads play a fundamental role during the life of sandwich composite in marine applications. In both cases, the principal approach used for the evaluation of the response is the experimental way. For cyclic dynamic loads, an approach with the use of the life fatigue limit and the mechanics of fracture is used by Orifici et al. [13] in order to improve the knowledge of the fatigue limit of these materials. The impact response was studied by different authors, Belingardi et al [14] proposed new indexes for the assessment of the damage during drop test impacts, Cucinotta et al. [15], by means optical measurements, added a new index based on the volumetric damage during single and repeated impacts. Principally in the complex structures, there is need to use structural bonding. Usually this part is the weakest one and so there is need to know the behaviour of the bonding subjected to different loads condition. Banea et al. [16] resumed the principal types of adhesive used for jointing composite structures. Zou et al. [17] proposed an assessment of the torsional effect on two jointed sandwiches with an epoxy resin bonding for application in submerged pipes. The temperatures effects were investigated by Da silva et al. [18] with particular interest on the mixed adhesive joints. Dulieu-Barton et al [19] use an experimental and numerical approach in order to evaluate the stresses in sandwich tee joints for ship applications.

This paper deals with the assessment of the behaviour of carbon laminates joints bonded at different angles. The angles tested are 45°, 90°, 135° and 180°. The carbon laminates are made with 6 different layers, each of them with twill texture, for a total thickness of 3 mm. The head connection is obtained with a biphasic epoxy resin and, in order to conduct the different angle tests, a home-made grip system is designed. Tests carried out both in opening and closing direction with a small pre-load applied. Finally, some considerations are developed for each angle with particular interest on the failure modes of the bonding respect to the moment applied.

MATERIALS AND METHODS

The study was conducted by carrying out experimental tests on carbon laminates joints bonded at different angles. The specimens were subjected to tensile and compressive forces. Since the two components of the joint create an angle, the tensile and compressive forces were, respectively, forces of Opening and of Closing of the joint itself, as in Figure 1.

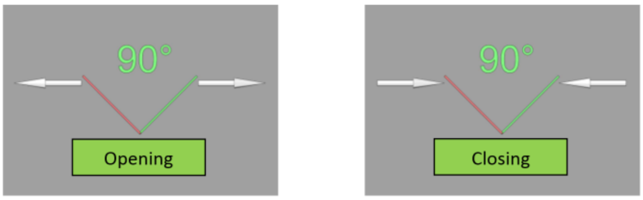

Figure 1. Opening and Closing forces

In particular, joint Opening and Closing tests were conducted on specimens with a bonding angle of 45°, 90° and 135°, and tensile tests on flat samples, i.e. with a bonding angle of 180° (Figure 2).

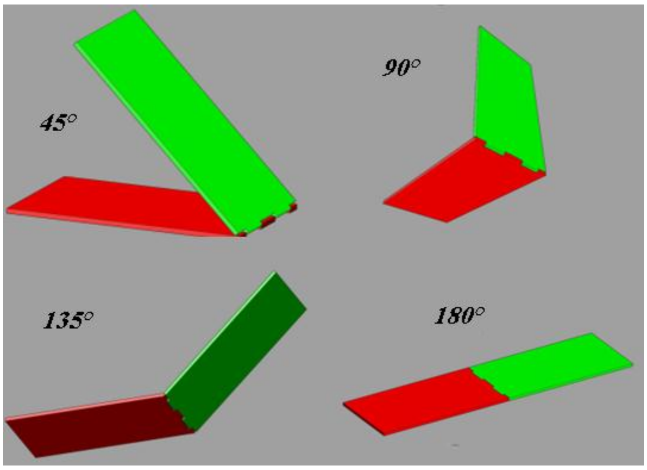

Figure 2. The four joints typologies

The specimens were made of composite material consisting of six layers of carbon TC 416 T and EMT 125 resin at 40% for a total of 3 mm. The fabric code means:

TC = carbon fibre

416 = weight (g/m^2)

T = 90° twill

The twill is 2x2, in this way there are good envelopability, wettability and isotropy.

The resin is a bi-component commercial epoxy, suitable for autoclave machining in marine environments. The specimens are made by a head connection of the two shaped elements with a tenon and mortise system.

The bonding takes place in two following phases:

1. For capillarity by contact, by the use of a commercial epoxy adhesive
2. For filling (welding cord type), by the use of a commercial epoxy adhesive

In the Figure 3, it is possible to see the two different adhesives in the front and the back (specimen at 135°). The capillarity adhesive has an ivory colour, while the filling adhesive has a pink colour.

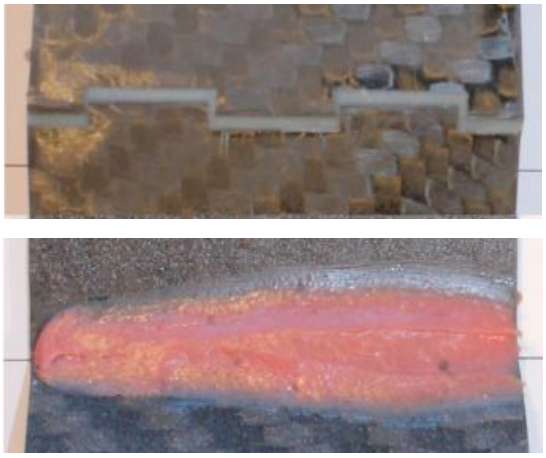

Figure 3. Front of the joint (above) and back (below). In the front it is well visible the DP 410 adhesive that has an ivory colour and in the back the 9323 B/A that has a pink colour

The epoxy adhesive for capillarity offers high values of toughness and high resistance to the marine environmental conditions. The high polymerization speed and the low viscosity allow using it for capillarity. This type of adhesive is used in the head connections thanks to the high wettability and a low degree of sliding; these two properties, combined with the high polymerization rate, allow the glue to infiltrate within the gaps left by the coupling and the natural porosity of the specimens by filling the interstices. When solidifying, glue creates a compact coupling between the two parts. Its high tenacity offers excellent responses to dynamic efforts avoiding the formation of superficial cracks that would weaken the material.

International Journal of Applied Engineering Research ISSN 0973-4562 Volume 12, Number 12 (2017) pp. 3182-3187

The other epoxy adhesive is a structural one. It is a two-component tissotropic adhesive that is polymerizable in cold conditions. This adhesive has the task of resisting to the shear stress by offering a good mechanical strength even in precarious environmental conditions. This kind of glue has been adopted for the good compromise between the responses of traction and compression stresses. It was applied in the internal part of the specimens as if it was a welding cord. The natural roughness of the surface of the specimens in the back, that is the opposite side to the mold, has strengthened the adhesion so much so there were very few surface detachment phenomena.

Making a comparison with the world of metal joints, it is possible to compare the capillarity bonding with a brazing and the structural bonding with a welding.

In the Figure 4 is visible a detail of the tenon and mortise system. The backlashes are 0.2 mm.

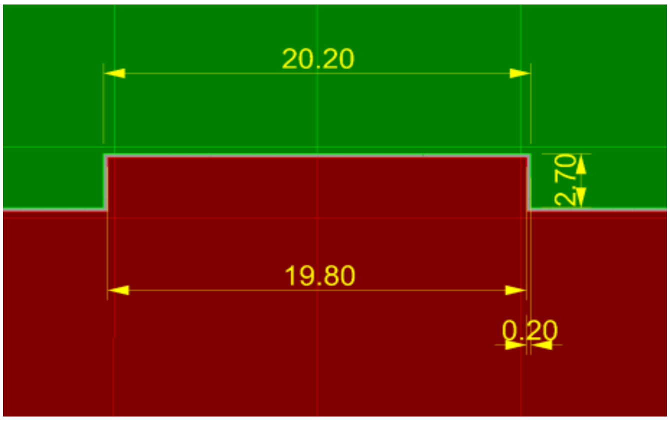

Figure 4. The tenon-mortise system

To carry out the tests, a gripping system was designed on purpose. The apparatus (Figure 5) must be able to adapt to all the test angles and to adapt itself during the specimen deforming and the translation of the clamps.

Figure 5. - The apparatus for the tests

The system consists of two steel plates connected by a cylindrical hinge. An element consists of the clamping area and the other connects itself to the specimen by mean of bolts. The hinge permits to not transmit the bending moment to the bonding (Figure 6).

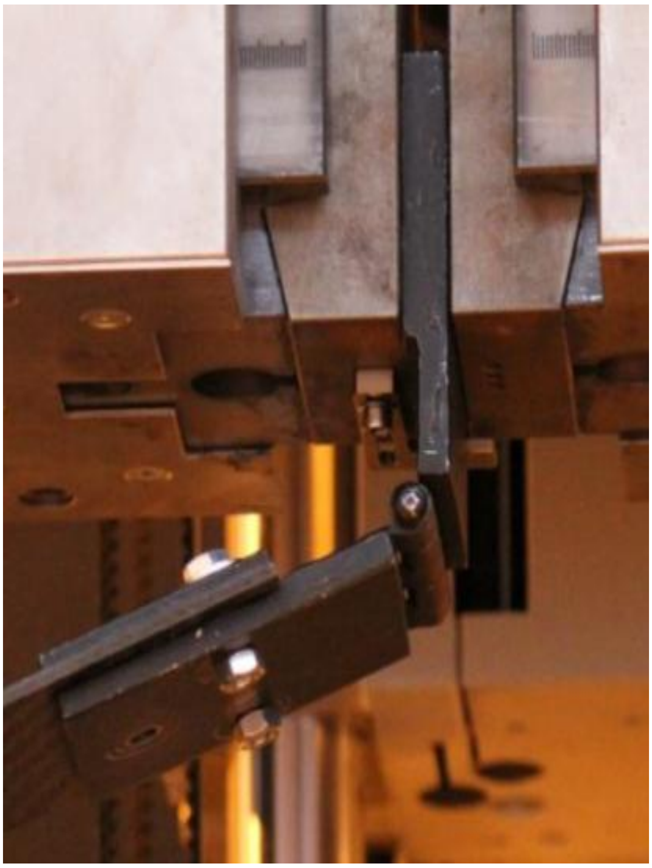

Figure 6. Particular of the gripping system

Tests were carried out with a small preload of 5 N in order to retrieve any backlash in the clamping system. Tests were carried out at a constant velocity of 10 mm/min. Each angle, except 180°, has been tested both in opening and closing of the joint. For each kind of geometry, three samples were tested.

RESULTS AND DISCUSSION

In all the tests carried out, as was foreseeable, always the bondings have failed. Almost always, the epoxy adhesive cord breaks out, thus showing a good adhesion of the glue to the base material.

In the cases where the failure occurs by detachment of the cord, the joint resistance is much lower. The breakages have been, almost always, sudden. Only in a couple of tests, the sample before giving up completely had a partial recover. The obtained results, in terms of average breaking strength, are shown in the figures. In Figure 7, the results are presented using a percentage system, indicating the test that has opposed the smallest resistance (the one with the closing at 90°) as 100% and the other as multiple.

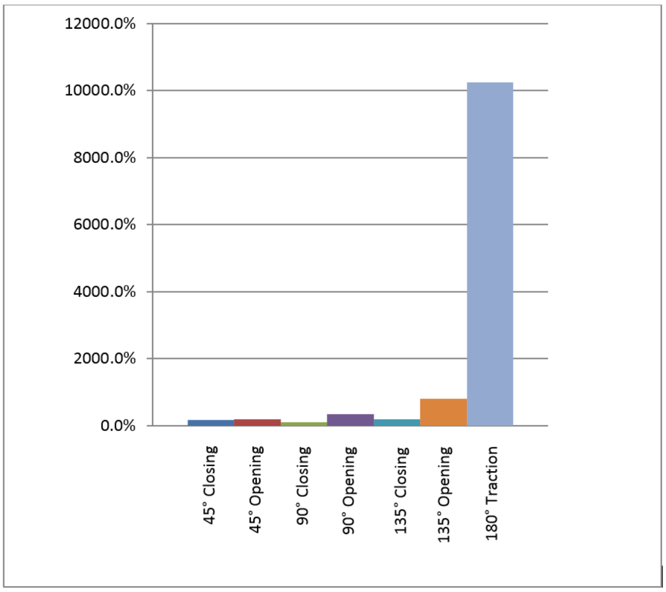

Figure 7. Percentage breaking forces

The samples at 180°, that were subjected to a pure tensile test, had a breaking load of two orders of magnitude greater than the other joints. For this reason, in order to improve the readability, in Figure 8 is shown a graph in which are reported only the data of the other specimens.

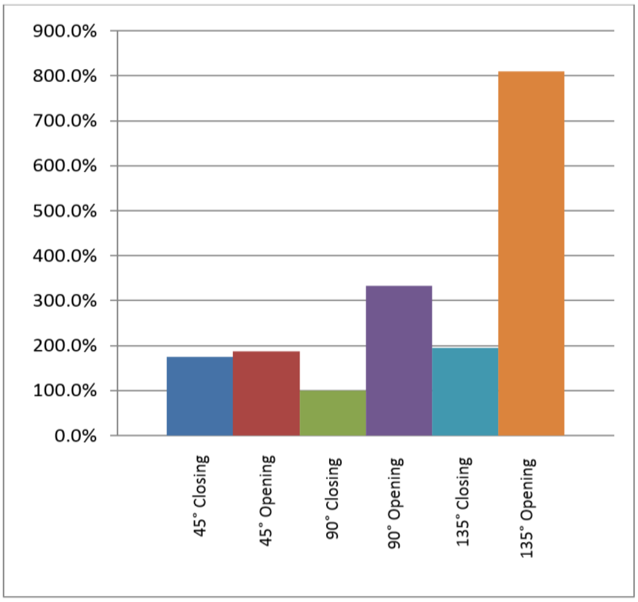

Figure 8. Particular of the percentage breaking forces, without the 180° samples

It should also be noted that each specimen, in correspondence of the bonding, is subject to a different bending moment depending on the different lever arms that are function of the angles. It is therefore evident that the characteristics of the joints are strongly influenced by the bonding angle. In particular, larger it is the angle and larger it is the lever arm, consequently the specimens resist better for the big angle. In particular, the 180° specimens do not have an arm and they are the most resistant. In order to compare the different tests, an absolute method of comparison was chosen for taking into account the different lever arms that the different topology of the specimens involves. The considered parameter was is the applied bending moment and, in particular, the maximum bending moment before the breaking.

This parameter was chosen, instead of the breaking stress, for the following considerations:

- For the same section, moment and stress are directly proportional
- While the moment is easy to calculate, the stress depends on the breaking section that is not easy to determine and which depends greatly on the shape of the bonding cord and how it is broken.
- Working with stress would test the adhesive materials. Instead, the purpose of the tests is to test the quality of the joints varying the connecting angles.
- Changing the bonding angle also changes the shape of the cord. Comparing the moments, it is possible to evaluate the joint efficiency, rather than the adhesives used.

The moment has been calculated by multiplying the force (detected by the testing machine) for the lever arm, taking into account that it changes continuously during the test due to the deformation of the specimen. Flat specimens (180°) are instead evaluated for traction force, as they are not subject to moment. Also in this case, in order to report the obtained results, the percentage method was used, assuming the least resistant sample (90° Closing) as 100%. The results are summarized in the Figure 9 and in the Table 1.

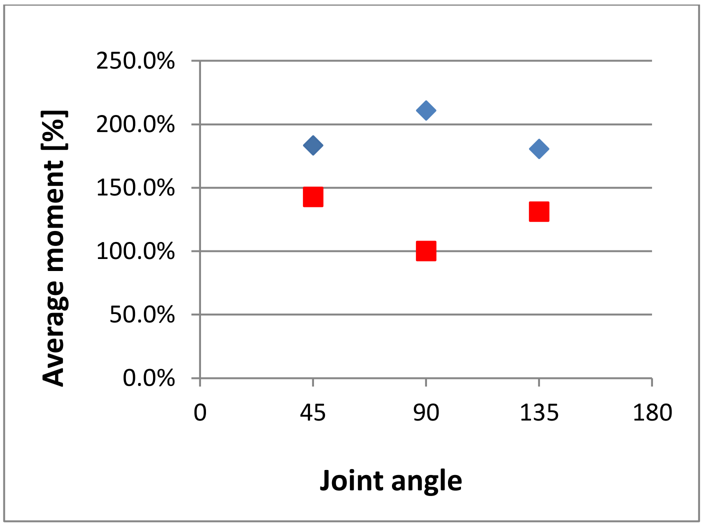

Figure 9. Average breaking moments

International Journal of Applied Engineering Research ISSN 0973-4562 Volume 12, Number 12 (2017) pp. 3182-3187

Table 1. Average breaking forces and moments

Angle	Stress condition	Average force	Average moment
45°	Closing	175.6%	142.6%
45°	Opening	187.1%	183.2%
90°	Closing	100.0%	100.0%
90°	Opening	332.6%	210.7%
135°	Closing	194.3%	131.2%
135°	Opening	810.0%	180.5%
180°	Traction	10256.3%	-

The table 2 shows the variation coefficient of the moment, for each joint typology. The coefficient, defined as

$$CV = \sqrt{\frac{1}{n}\sum\left(\frac{M_i}{|\mu|}-1\right)^2}$$

thanks to the normalization with the medium value, has the advantage, respect to the standard deviation, of making the results of different joint typologies comparable one with each other.

Table 2. Variation coefficients of the moments

Angle	Stress condition	Variation coefficient of the moment
45°	Closing	0.25
45°	Opening	0.05
90°	Closing	0.03
90°	Opening	0.10
135°	Closing	0.07
135°	Opening	0.11
180°	Traction	-

In a very limited number of cases, an adhesive detachment has occurred from the surface. In the most severe case, this has led to a decrease of the moment of 37%. Since this problematic occurs only in the 45° specimens, it is probable that the decay of the mechanical characteristics is due to the difficulty of the cord preparation in the sharp angles. The following pictures show a case of detachment (at 45°, Figure 10) compared with a case of normal cord rupture (at 90°, Figure 11), both for Closing condition.

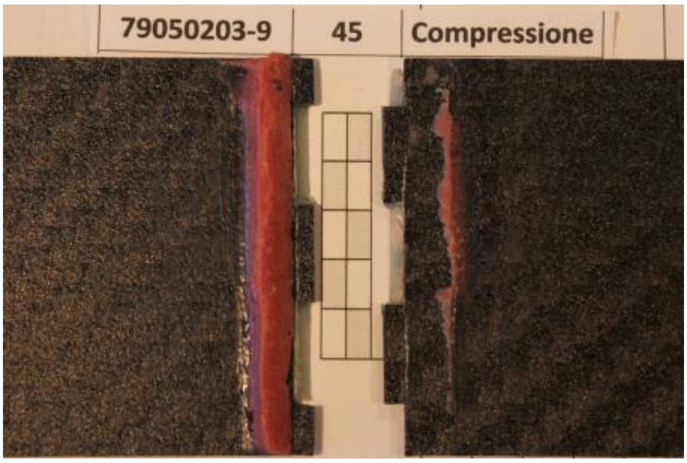

Figure 10. A case of bonding cord detachment

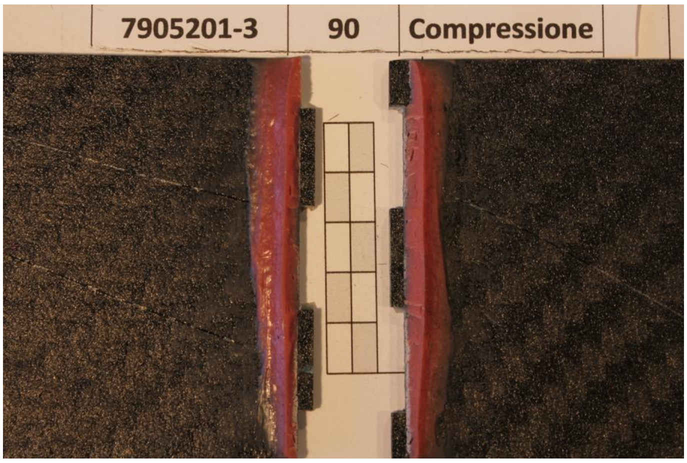

Figure 11. A case of bonding cord rupture

CONCLUSIONS

In conclusion it is noted that:

- The Opening behaviour of the joints is always better than the Closing one.
- The best Opening behaviour is for the 90° bondings, instead the worst is for 135°
- The best Closing behaviour is for the 45° bondings, instead the worst is for 90°
- The 90° joint is at the same time the one with the best mechanical characteristics in Opening and the worst in Closing condition.
- The joint that has less difference in Opening and Closing behaviour is that at 45°. It is also the joint that has the highest variation coefficient.
- From the foregoing considerations, combined with a visual examination of the bonding, it is found that the 45° joints are the most dependent on the quality of the

bonding (probably because it is the most difficult to implement).

- For pure traction, the specimens (flat plate at 180°) resist with a force value (and consequently stresses) of two orders of magnitude greater than those in the other specimens.

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