MECHANICAL BEHAVIOUR OF SPR/CO-CURED COMPOSITE TO ALUMINIUM JOINTS

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Keywords: Hybrid joints, self piercing riveting, adhesive bonding

Abstract

In this paper a mixed system to obtain metal-composite joints is investigated. With this aim three kind of joint were realised: adhesive by co-curing technique, mechanical by self piercing riveting and the new mixed one.

In particular, aluminium alloy of 2 mm thickness, was used as metal substrate. Whereas, an unidirectional glass laminate with the same thickness, realised by hand lay-up technique, was used as composite substrate. The composite panel was made of a two part epoxy resin (SP 106 supplied by Resintex srl) and 4 layers of UD glass with a real weight of 370 g/m2.

Co-curing technique was performed to obtain adhesive joints: the co-cured bonding utilizes excessive resin of FRP as the adhesive, so that aluminium and FRP adherends are bonded. Following this way, both the curing and joining process of the analyzed joints were achieved simultaneously avoiding the use of further adhesive at interface between the substrates. This allows to eliminate a process phase (i.e. adhesion) with a considerable saving in terms of manufacturing times. Moreover, the use of a co-cured adhesive joint results in several advantages: i.e. presence of one interface (composite-metal) while in a secondary bonding there are two interfaces (composite-adhesive and adhesive-metal); reduction of shear effect due to the thickness of the adhesive.

In the self piercing riveting process, the rivet pierces the composite substrate, placed at the top of the joint, and deforms the aluminium sheet due to the effect of a counter-die. Preliminary tests were conducted to determine the oil pressure in the riveting system, and therefore to evaluate the appropriate riveting load.

Finally, the two kind of joining techniques (i.e. adhesive and mechanical) were combined in order to realise a mixed joint with the aim to improve the joint performances, i.e. adding the self-piercing rivet during the curing process of the resin. By doing so, the Authors try to find out if and when the action of the rivet, during the joining process, can be optimised avoiding cracks or delaminations insurgence, that is a typical problem when glass-fibre laminates are riveted with metal sheet.

The joint substrates had the following sizes: 200 mm x 50 mm x 2 mm; the overlapping area was 50 mm x 50 mm. Then the rivet is punched at the centre of the overlapping zone in the SPR or mixed joints. The realised samples (i.e. five for each configuration) were characterized by single lap joint tests in agreement with the ASTM D1002 with a test rate of 1 mm/min.

1 Introduction

Nowadays, in several applications, traditional materials, like steel or metal alloys, are widely used with innovative ones, as composite fiber reinforced polymer (FRP) to obtain hybrid structures. In these structures the weak point is represented by the joint. So it is very important achieve structural joints able to bear elevated loads. Different materials can be joined mechanically, adhesively or through a combination of both techniques.
An adhesive joint between composite and metal structures can be realized through two methods: secondary bonding [1]-[4] and co-curing [5]-[7]. In the secondary bonding technique a structural adhesive is used as interlayer between the adherends.
In the co-curing bonding technique the adhesive role is played by the same resin used as matrix of the composite substrate. In this manner, both the curing and joining process can be achieved at the same time and it is not easy to distinguish the adhesive layer between the substrates. The co-curing technique is usually preferred over secondary bonding, especially in shipyards or in other fields in which the production time have to be short.
The mechanical connection gives high mechanical properties and they are easy to realize with several techniques (i.e. bolting, riveting and self-piercing riveting).
Among these last, one of the most important cold joining technologies is the self-piercing riveting (SPR) both to connect metal structures [8]-[10] but also to connect metal to composite structures [11]-[13].
In the last years both the academic world and the industrial one have focused their attention to the mixed joints between metal and composite sheets: i.e. joints that combine co-cured, or secondary bonding adhesive technique, with mechanical connections [14], [15].
Aim of this work is to evaluate the influence of curing time of the epoxy resin used both as matrix of the composite substrate and as adhesive between metal and composite structures, on the mechanical performances of aluminium alloy to GFRP composite SPR/co-cured bonded joints.
In particular, the mixed joints were realized by inserting the rivets after 2 hours, 5 hours and 24 hours, respectively, from the initial time of the curing process of the epoxy resin (i.e. the moment of mixing resin with its hardener).

2 Experimental Setup

2.1 Materials and manufacturing

Aluminium alloy 6082 T6 samples (dimension 200 mm x 50 mm, thickness 2 mm) were used as metal substrates.
On the other hand, the stacking sequence of the composite substrates was constituted of five layers of UD glass (unidirectional oriented fibers, with areal weight of 370 g/m2) in a matrix of epoxy resin (SP 106 supplied by Resintex) mixed with own curing agent. In Table 1 the mechanical properties of the substrates obtained by performing tensile preliminary tests, are reported.

Material	Aluminium alloy 6082 T6	UD glass/epoxy
Tensile strength [MPA]	310.2 ± 1.4	205.7 ± 55.7
Tensile Modulus [GPa]	70 ± 0.7	145 ± 22

Table 1. Mechanical properties of the substrates to be joined.

The aluminium substrates were previously mechanically treated with sandpaper (P60) and cleaned with acetone. Co-curing technique was performed to obtain adhesive joints.

A single effect hydraulic riveting press produced by Textron Fastening Systems SN2, characterized by maximum oil pressure equal to 500 bar, maximum load 60 kN, ad a cycle time of 2s, was used to realize the mechanical joints.
The rivets with diameter 3,9 mm and length 4.5 mm, was made of Austenitic steel and coated by an 11 µm protective layer of zinc. For each mechanical or mixed joint, the rivets were inserted in the centre of the overlapping area, that has a square shape (i.e. 50 mm x 50 mm). As suggested by the literature [11]-[13], in the self piercing riveting process the composite substrates were placed at the top of the joint since the lower sheet undergoes the highest deformation.
The manufacturing of the mixed joints has consisted in two different phases: at the beginning the adhesive bonding was performed through the co-curing technique, then the rivet was inserted to mechanically connect the metal with composite sheets.
Up to now, in the production of a mixed hybrid joint, the mechanical connection is performed when the curing process of the resin can be considered finished.
As discussed in the introduction section, the principal objective of this work is to evaluate if the curing time of the epoxy resin affects on the performances of the mixed hybrid joints. To this aim three different mixed joints were produced at varying the insertion time of the rivet: i.e. after 2 hours, 5 hours and 24 hours from the initial time of the curing process, respectively.
The details of all realised and tested joints in this work are reported in Table 2.

Joint	Curing time [h]	Oil pressure [bar]	designation	samples
adhesive	X	x	ad	5
	X	280	mech-280	5
mechanical	X	300	mech-300	5
	X	320	mech-320	5
	2	180	2h-180	5
	2	220	2h-220	5
	2	240	2h-240	5
	5	220	5h-220	5
mixed	5	240	5h-240	5
	5	280	5h-280	5
	24	280	24h-280	5
	24	300	24h-300	5
	24	340	24h-340	5

Table 2. Joint realised.

2.2 Mechanical Testing
In order to evaluate the tensile strength and failure modes of the joints, the single-lap configuration was chosen. Mechanical tests were carried out using a UTM by Zwick Roell, equipped with a load cell of 250 kN. All the test were performed with a cross-head speed equal to 1 mm/min.

3 Results and Discussion

A total of joints 65 (i.e. 5 co-cured adhesives, 15 mechanical and 45 mixed ones) were tested using the single-lap configuration.
The failure load obtained for adhesive co-cured joints was equal to 11.52 kN ± 1.58 kN.
As for the mechanical joints, three different values of the oil pressure of the riveting system were investigated (i.e. 280 bar, 300 bar and 320 bar), by carrying out five tests for each condition investigated. In particular the maximum failure load and the minimum deviation

standard are obtained by setting the oil pressure to 300 bar: i.e. equal to 2.52 kN and 0.63 kN, respectively.

The results of the mixed joints are summarized in Figure 1 that shows the average values of the failure load and the error bars, determined after lap joint tests. Moreover in the same figure the average values of the failure load for the adhesive joints are reported by means of the dotted lines in order to make a comparison.

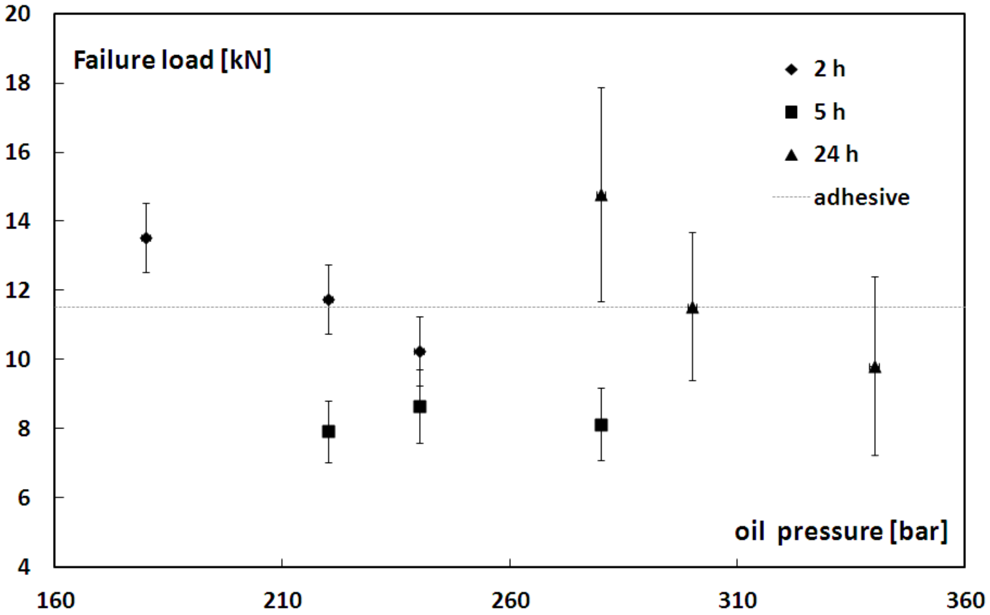

Figure 1. Failure loads of the mixed joints investigated.

In particular, it is possible to observe that:

• for the '2h' joints the failure load varies between 13.54 ± 0.65 kN, 11.74 ± 1.25 kN and 10.26 ± 0.99 kN for the '2h-180', '2h-220' and '2h-240' joints, respectively, so the higher resistance is obtained with the oil pressure equal to 180 bar. Such value is 17.5% higher than that of the adhesive joints.

By observing the joints before the test it is possible to point out the effect of the increasing oil pressure. Figure 2 shows the overlapping areas of the mixed joints realized by inserting the rivet with the oil pressure equal to 240 bar and 220 bar, respectively: it is clear that at higher pressure values the rivets penetrate too much in the composite substrates, so irreversible cracks were generated in the composite substrate causing the premature failures of the joints.

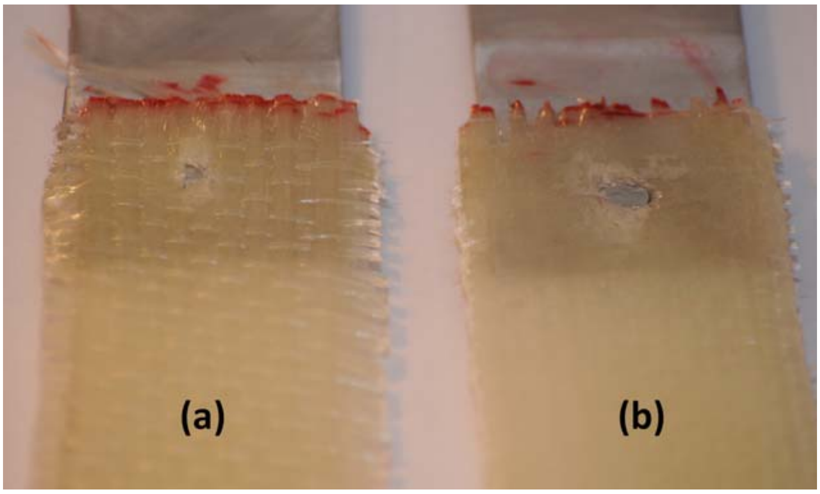

Figure 2. Overlapping areas of (a) '2h-240' and (b) '2h-220' mixed joints.

• If the rivets are inserted after 5 hours from the initial time of the curing process of the resin the failure load of ‘5h-220’, ‘5h-240’ and ‘5h-280’ joints are equal to 7.93 ± 0.89 kN, 8.64 ± 1.06 kN and 8.13 ± 1.04 kN, respectively. For this condition, the resistance of the mixed joints is lower than adhesive ones.

• if the rivets are inserted after 24 hours from the initial time of the curing process of the resin, the failure load of ‘24h-280’, ‘24h-300’ and ‘24h-340’ joints are equal to 14.78 ± 3.09 kN, 11.54 ± 2.14 kN and 9.82 ± 2.58 kN, respectively. In this case the better resistance is obtained by setting the oil pressure of the riveting machine equal to 280 bar. This last value is 28.3 % higher than that of the adhesive joints. Moreover the resistance of the joints hardly decreases by increasing the oil pressure of the riveting system.

From the preliminary visual inspection of the ‘24h-340’ joints, it is possible to notice that the high pressure of the rivet insertion frequently causes both a delamination area at the interface between composite and metal (Figure 3) and a damaging area of the deformed metal at the bottom of the rivet connection (i.e. in the metal deformed by the rivet against the bottom die), as shown in Figure 4a. As comparison, Figure 4b shows the deformed metal at the bottom of the rivet connection of the ‘24h-280’ joints.

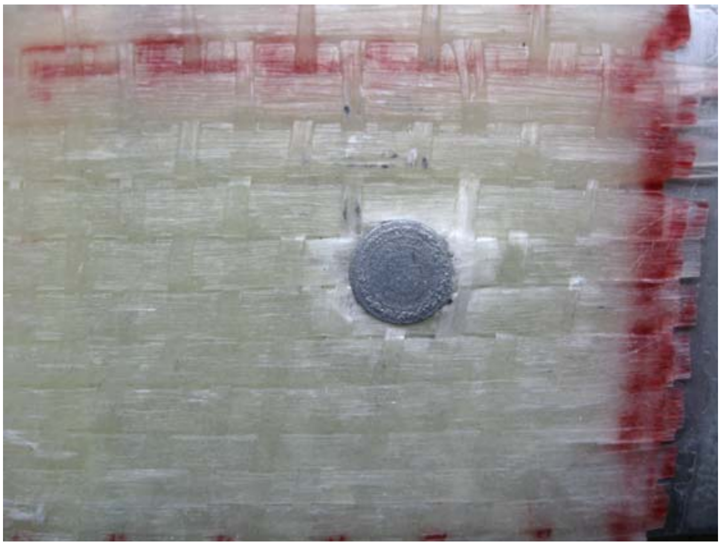

Figure 3. Delamination at the substrates interface of ‘24h-340’ joints.

Figure 4. The deformed sheet at the bottom of the rivet: (a) damaged for ‘24h-340’ joints; (b) sound for ‘24h-280’ joints.

In comparison with the self-piercing riveting joints, all mixed joints show higher resistance: this means that the presence of the adhesive layer between the metal and composite substrates gives beneficial effects to the mechanical connection, independently from both the moment of insertion of the rivet and the riveting load. Naturally this consideration is valid only with respect to the configuration of the single lap joint (overlapping surface 50x50mm) with one rivet. This result could be different both changing the overlapping lengths and the number of rivets on this last surface.

It is possible to notice that, by inserting the rivet after 2 hour or 24 hours, we obtain the best adhesion condition: in the first case because the rivet is inserted when the resin is still liquid and, consequently, the curing process takes place after the rivet insertion ('2h' mixed joint); in the second case because the resin has fully cured before the rivet insertion ('24h' mixed joint). Moreover, when the rivet is inserted after 5h from the initial time of the curing process, the oil pressure seems to have not significant effect on the joint resistance, probably because the effect of low adhesion is higher than the damaging caused by the rivet action or it adds its effect with the one of the rivet.

Typical load/displacement curves obtained during the tensile tests of the single lap joints are reported in Figure 5.

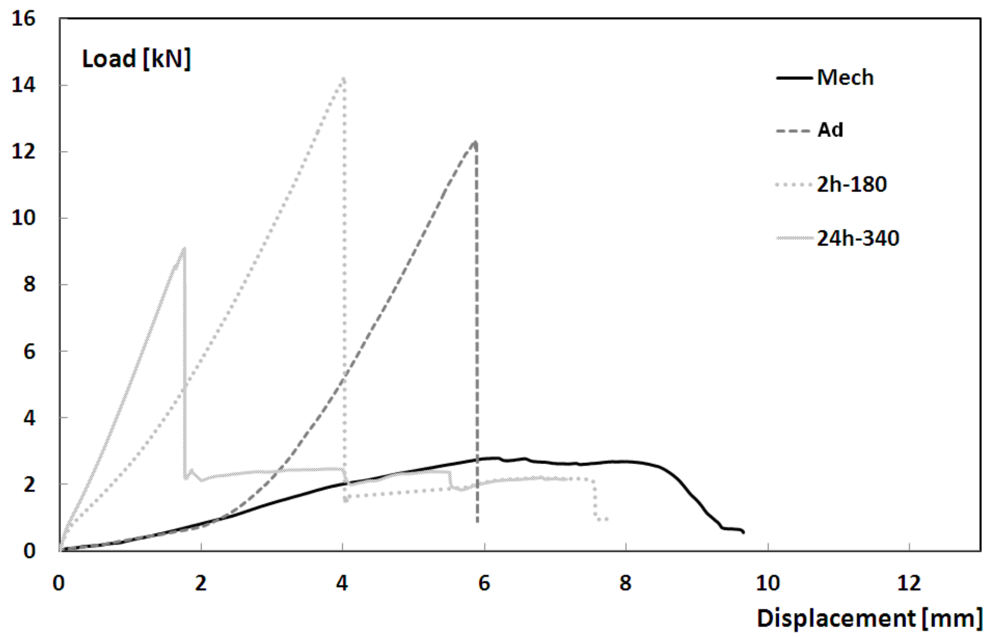

Figure 5. Load-displacement curves for mechanical, adhesive and mixed joints.

The general trend observed for almost all the adhesive joints is elastic until the fracture occurrence. Mechanical joints showed different behaviour at varying pressure caused by the resistance of the rivet. Generally, they exhibited an elastic trend followed by a slow decrease of the resistance due to the presence of the interlocking from the rivet and the substrates.

The hybrid joints instead exhibited at first the typical elastic trend due to the adhesion effect, after the collapse of the adhesive surface they showed a residual strength due to the presence of the rivet.

The resistance of the mixed joints are increased by the presence of the rivet for certain value of the oil pressure (i.e. the case '2h-180' shown in Figure 5). Vice versa, when the rivet insertion causes damages in the bonding process, the achieved value of the mixed joint resistance is lower than the adhesive one, even though the joints still maintain a residual strength due to the presence of the rivet (i.e. the cases '24h-300' and '24h-340' shown in Figure 6).

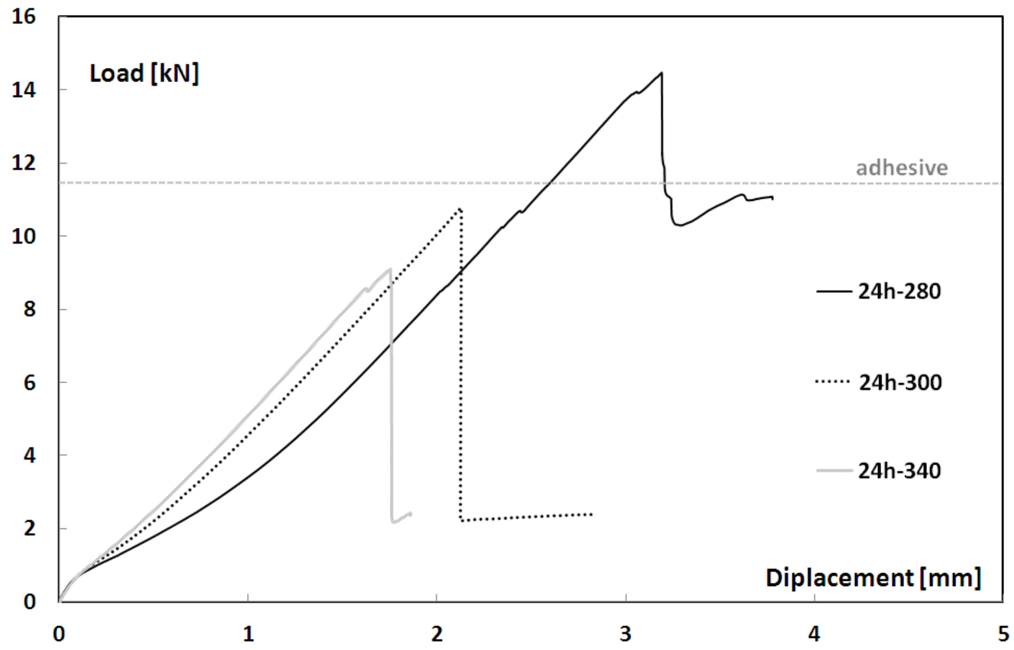

Figure 6. Load-displacement curves for the '24h' mixed joints.

3 Conclusions

In this work the influence of the curing time (i.e. the time of inserting the rivets) of the epoxy resin used both as matrix of the composite substrate and as adhesive between metal and composite structures, on the mechanical performances of aluminium alloy to GFRP composite SPR/co-cured bonded joints, is evaluated.

The mechanical characterizations have shown that:

• if the rivets are inserted when the resin is in its fluid state, the best condition of the riveting system is obtained with the oil pressure equal to 180 bar: i.e. the resistance of the mixed joints decreases by increasing the oil pressure of the riveting system and, only by setting the oil pressure equal to the above value, the ‘2h’ mixed joints show better performances in comparison with the adhesive ones.

• if the rivets are inserted after 5h from the initial time of the curing process, the resistance of the mixed joints is lower than that of the adhesive ones and this value is not influenced by the value of the oil pressure. Consequently, in order to realize mixed joint with better properties than adhesive ones, it is not useful to insert the rivets after 5h (i.e. probably when the epoxy resin is in it rubber state).

• if the rivet is inserted after 24h from the initial time of the curing process, the best condition of the riveting system is obtained with the oil pressure equal to 280 bar: i.e. the ‘24h-280’ mixed joints show a failure load 28.2% higher than that of adhesive ones. By increasing the oil pressure the resistances of the ’24h-300’ and the ‘24h-340’ mixed joints are the same and 14.7% lower than that of the co-cured joints, respectively.

• what is more, the ‘2h’ hybrid joints show much reliable resistance with respect to both the ‘24h’ and adhesive ones.

Definitely, this paper shows that when an adhesive/SPR mixed joint has to be realized, since both the rheological conditions of the resin and its chemical reactivity changes during the curing process, the time of inserting the rivet is a critical parameter that influences the quality and, consequently, the mechanical properties of the joints.

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