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AN EXPERIMENTAL STUDY OF GFRP-ALUMINIUM BOLTED-BONDED JOINTS

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Abstract
In this paper an experimental study of mechanical performance of hybrid bonded-bolted joints has been performed and, in order to highlight the contribution of adhesive and bolts, the results have been compared with those of simply bonded and simply bolted joints. The experimental results have shown that by using an appropriate joint configuration, the presence of the bolts lead to a significant decreasing of the shear and peeling stresses in the adhesive layer and, consequently, such hybrid joints perform higher tensile strength and fatigue life.

1 Introduction
The use of composite materials for the manufacturing of mechanical components and systems requires the use of reliable joints between composite materials (reinforced with glass fiber, carbon fiber, etc.) and traditional materials (aluminum, steel, titanium) nowadays widely used to made the primary structures of machines. Such a junctions can be made by using adhesive bonded joint or mechanical (bolted, riveted etc) joints.
As it is well known, the main disadvantages related to the use of mechanical joints are due to the significant stress concentration around the hole and also to the fiber damage during drilling (micro and macro localized damage that can compromising the structural integrity of the joint). Moreover, for the specific properties of the composites [1], the use of joints different from the traditional ones such as bolting and welding is necessary [2-3], and the bonding is in general the technique that allows the user to obtain the best efficiency [4-7]. The main disadvantages of the adhesive bonded joints are related to the decay of the mechanical properties in presence of aggressive environments especially at temperatures higher than room temperature.
In order to combine the advantages of the two joints techniques, in the last years Hybrid Bolted-Bonded joints (HBB) combining a classical mechanical fastening (bolting) and a classical adhesive bonding, or a co-cured joint, have attracted great interest [8-10]. Although several research papers are present in literature, today there is not a sufficient knowledge of the mechanical properties of hybrid joints, and no reliable design methods there are at the designer disposal.
Hybrid joints have been often considered in literature in order to repair and/or improvement of damage tolerance. In detail, Hart-Smith [11-12] have been carried out a theoretical study on bonded/bolted joints between CFRP and titanium. They found that, although no significant

strength increment is observed respect to simply bonded joints (at room temperature, 98% of the applied load is transferred by the adhesive), the hybrid joints show benefits in the repair of bonded joints to limit the propagation of the damage.
Fu Maofeng and Mallick [13] studied the static and fatigue behavior of hybrid joints (bolted/bonded). The authors have carried out an experimental investigation on the effect of different configuration of washers in single lap joints. The authors observed that the performance of hybrid joints depend significantly on the shape of the washer and then on the particular distribution of the stresses due to the bolt tightening.
In the present paper static and fatigue tests on composite/metal double lap joints made by using bolted/bonded techniques, were carried out by varying the main influence parameters as overlap length and bolt tightening; in particular, a joint between unidirectional fiber glass epoxy composites (GFRP) and aluminum alloy Al 2024 T6 was considered. The purpose of this study is to give a contribution to the knowledge of the mechanical performance of hybrid joints, also by comparing the HBB joint performance with those of simple bonded and simple bolted joints.

2 Experimental set-up

The internal adherend is a GFRP unidirectional laminate $[0°]_{16}$ with a total thickness of 4 mm, while external adherends are in aluminum alloy Al 2024-T6 with a thickness equal to 1.2 mm. A schematic illustration of the bolted/co-cured hybrid joints is shown in Fig. 1.

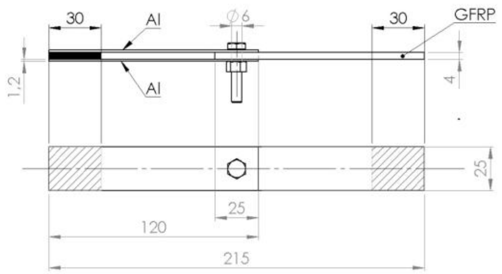


Figure 1. Geometric configuration of double lap joint studied.

The geometry was chosen to have a joint almost balanced, in particular the length of overlap has been chosen equal to 25 mm that is the minimum length calculated through the classical theory of bonded joints. Although in the aerospace field in order to further increase the reliability of the bonded joints, the design trend is to use overlap lengths equal to twice the minimum length acceptable.
The GFRP laminates were made using the hand lay-up technique and vacuum bag. The mechanical characteristics of GFRP laminate are: E_1=39.5 GPa, E_2=7.3 GPa, G_{12}=3.9 GPa, ν_{12}=0.336, σ1,R=552 MPa; the mechanical characteristics of the aluminum alloy used are: E_{Al}=67600MPa, $\sigma_{s,Al}$=140MPa e $\sigma_{r,Al}$=252,6MPa. As regards the choice of adhesive, in order to ensure a good adhesion with the composite, the same thermosetting epoxy resin of low viscosity without diluents used for the manual lamination of the laminates GFRP was used; the epoxy resin (type SX10) has Young's modulus E_a = 3 GPa and tensile strength $\sigma_{r,a}$ = 60 MPa.
To obtain a sufficient roughness of the surfaces to be bonded, in the manual lamination of the composite is used a special peel-ply which leaves on the outer surfaces of the laminate, to polymerization, the imprint of its weave; for aluminum, however, is been treated with unidirectional abrasion of the surfaces with emery cloth (grade P60) and subsequent cleaning of parts by acetone.

The bonds were carried out following a precise protocol, i.e. the cleaning of parts with acetone, applying of the adhesive, using calibrated shims to ensure a constant thickness of the adhesive as much as possible (about 0.1 mm) and closing of the joint under slight pressure by means of clamps and polymerization at room temperature for at least 36 hours. For bolting occurred a M6 hexagon head UNI 5727 with a length of 20 mm suitably has been tightened.

3 Static tests

The static tests on Al-GFRP joints were performed using a hydraulic materials testing machine MTS 810 with load cell of 100 kN. All experimental tests were conducted in displacement control with a speed of 1.2 mm/min follow the ASTM D3528-96 standard.
The experimentation initially involved the study of static behavior, the determination of tensile strength and failure modes of these joints for each of the considered geometries. Then the parameters were chosen to be imposed for carrying out the fatigue tests. In order to monitor the failure modes of joints an HD digital camera type Canon 5D with repeated acquisition for the entire duration of experimental tests, was used.

3.1 Static results

Figure 2 shows the typical load-displacement curves for the different configurations of joints studied in this work; the represented load is the total applied to the joint, while the indicated displacement is the one of the crossbar of the machine test. The lateral surface of the specimen was painted with white fragile paint to evaluate the exact initial point in which the adhesive bonding yields, but also to highlight the evolution of all stages of delamination at the interface aluminum-composite.

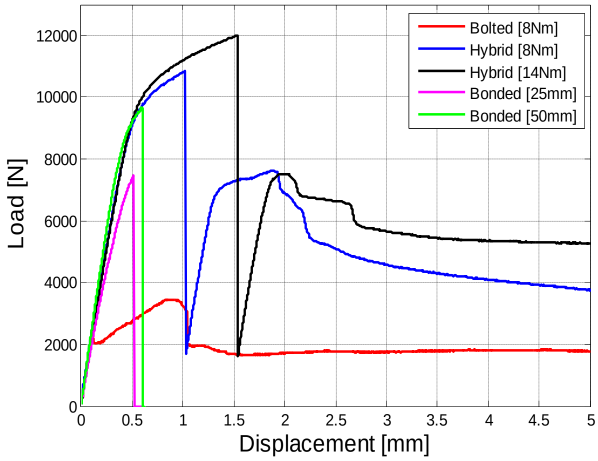


Figure 2. Load-displacement curves for different configurations of GFRP-Al joints.

The load vs. displacement diagram obtained for bonded specimens was linear until the failure; is possible to note that the breaking of the adhesive takes place in correspondence of the leading edge of the laminate GFRP (point A) and propagates up to the point of attachment of the aluminum (point B) (figure 3), where there are, as is known, the maximum shear and peel stresses. The rupture of bonded joints is of adhesive at the interface between adhesive and aluminum. The adhesive used has a high fracture toughness and low ductility compared to structural adhesives typically used in aerospace applications.

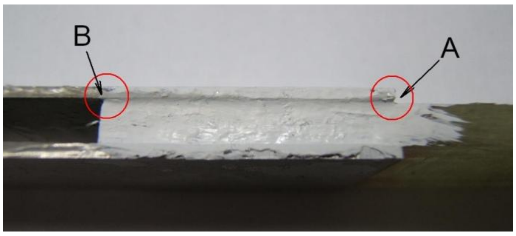


Figure 3. Failure mode of bonded joints: the starting point (A) and end point (B) of failure.

In the aeronautical/aerospace field simply bonded joints are designed with overlap length twice the limit indicated by the classical theory of bonded joints. Therefore it is very interesting analyze the effects of increased overlap length in a simply bonded joint. The failure mode is the same as already seen for the bonded joints with overlap length equal to 25 mm (Figure 2).

In order to transmit a part of the load through the friction among the adherents, it is very important the bolt torque. Tensile tests were carried out varying this parameter (Figure 4).

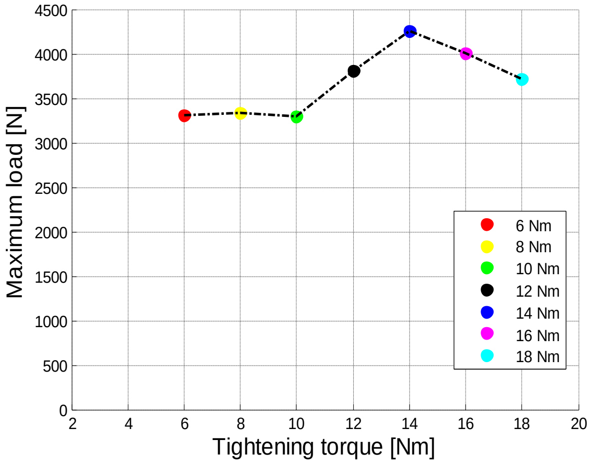
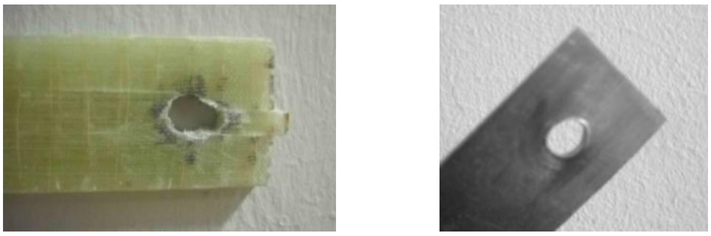


Figure 4. Tensile strength of bolted joint varying torque load.

The experimental tests have shown that the maximum load transmitted reaches the maximum value in correspondence of the preload equal to 14 Nm; increasing of this value the maximum load decreases due to excessive compression produced damaging the composite. In the present work a torque of 8 Nm was used to avoid the damage of the composite due to excessive pressure applied.

In figure 2 it's possible to observe that at the first elastic phase, characterized by the transmission of the load essentially by friction, follows a sliding and a subsequent recovery of the load characterized by a mixed load transmission, by friction and shear. To the achievement of the maximum load follows a progressive damage of the lamina GFRP for compression and rupture of the joint takes place, as expected because of the low values of shear strength of the unidirectional composite, for shear failure of the lip of the GFRP laminate (see Figure 5a); the two sheets of aluminum instead show little damage with a limited-roundness of the hole (see figure 5b). In the case of hybrid joints the maximum load is greater than the bonded joints due to the bolt (see figure 2). After the breaking of the adhesive, although the load is transferred full to the bolt and the load-displacement curve becomes qualitatively similar to that of simply bolted joints, the loads are now higher by about 88% and this is found in the same load of breakage. This may be explained by the increased friction between the adherents due to the presence of the adhesive, a phenomenon that decreases the shear stresses of the lip responsible for the final rupture of the joint. The average ultimate load of the hybrid joints is about 54% higher than that of simply bonded joints.



(a) (b)

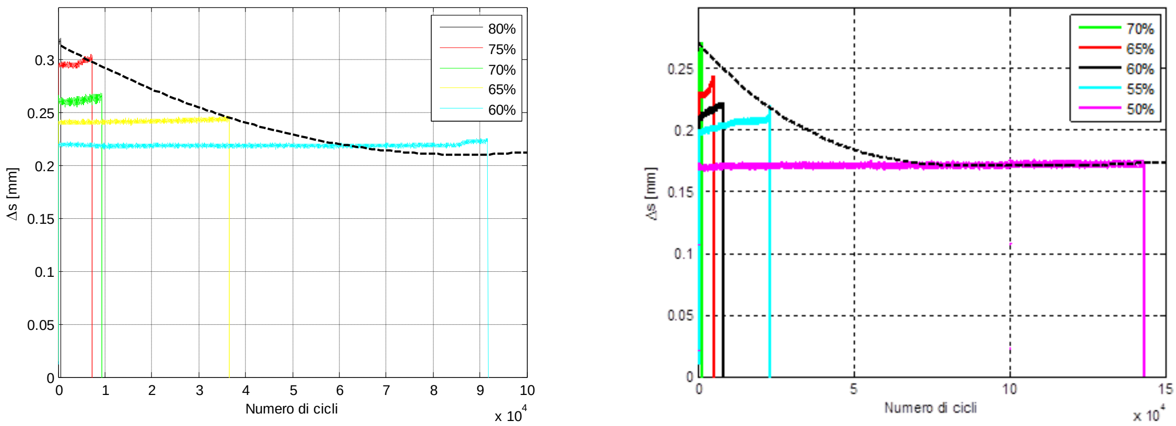
Figure 5. Damage modes of bolted joints - a) GFRP laminate and b) aluminum alloy sheet.

It is observed as the hybrid joints studied characterized by damage which is the sequence of the failure modes of the two types of joints (Figure 6), of the first bonded (adhesive failure) and that after bolted (shear failure of the lip).

To complete the analysis on the real advantages of hybrid joints (bonded/bolted) tensile tests were conducted on hybrid joints with tightening torque of the bolt equal to 14 Nm that maximizes the performance of mechanical fasteners.

4 Fatigue tests

Even the fatigue tests were carried out with the material testing machine MTS 810 with a 100 kN load cell. The tests were performed at different percentages of the maximum static load relative to each configuration. In each test, the ratio (R) between the minimum and maximum load has been set equal to 0.1 (tensile-tensile) with a frequency of load application equal to 10 Hz. The analyzes performed on the simply bonded joints, "ordinary" and "aeronautical", produced the following curves that represent the amplitude $\Delta s = s_{max}-s_{min}$ elongation (s) of the specimen under the fatigue load as a function of the number of cycles N, for each of the load levels analyzed.



(a) (b)

Figure 6. Δs-N curves - a) ordinary bonded joints and b) aerospace bonded joints.

In the case of bonded joints "ordinary" (overlap length equal to 25 mm), is not observed any damage to the joint before failure; while for the glue joints "aeronautical" (overlap length equal to 25 mm) is interesting to note that for maximum load exceeding 50% of the breaking load static, fatigue produces a slow damage to the glued seam, but in both cases the fatigue life ends with rupture of the crash, which occurs due to breaking of the adhesive layer at the interface aluminum-adhesive.

Figure 7 shown the tipical Δs-N curves for simply bolted joints. Also in this case a fatigue damage is not observed, and the failure occurred unexpectedly.

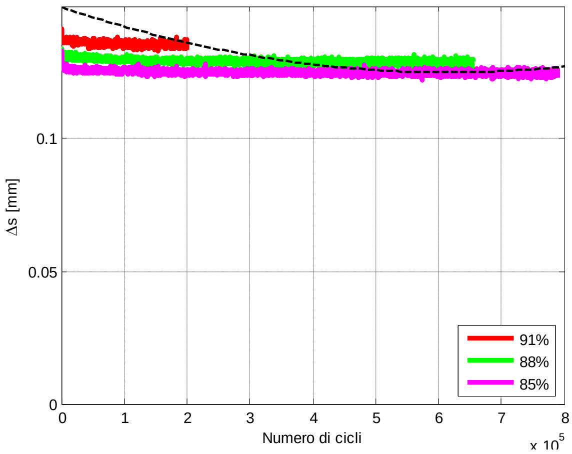
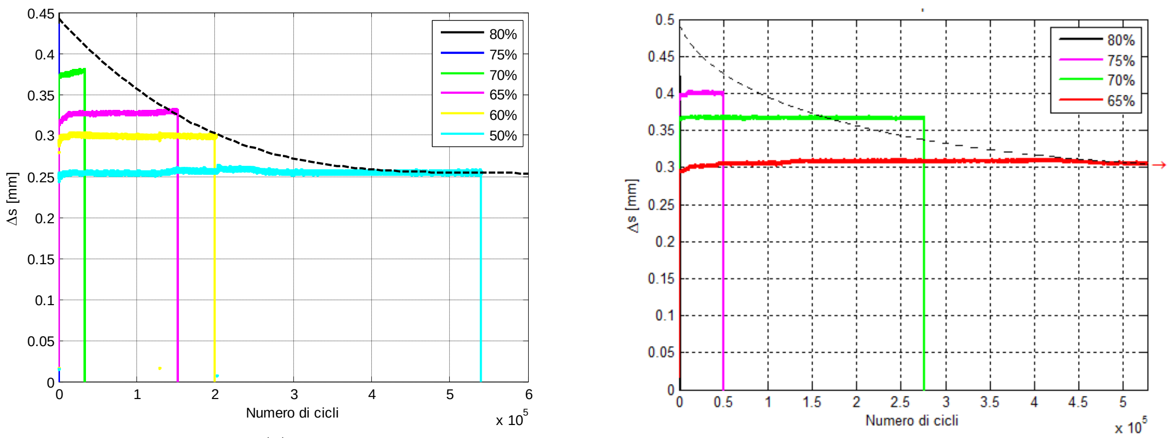


Figure 7. Δs-N curves for bolted joints.

The fatigue failure occurred, as in the case of static load, due to the shear lip of the composite that occurs as a result of the interference-bolt composite.

Figure 8 shown the typical Δs-N curves for hybrid joints with torque of 8 Nm and 14 Nm.



(a) (b)

Figure 8. Δs-N curves for hybrid joints – a) 8Nm and b) 14Nm.

For all levels of the maximum applied load, it is possible to observe that after occurred adhesive failure there was the total rupture of the joint, since the applied load is higher than the static tensile strength of simply bolted joints.

4.1 Fatigue results

Figure 11 shows the Wöhler curves for each type of studied joints, in order to evaluate the actual goodness of the hybrid joints in the presence of fatigue loads. In particular, it is observed as the fatigue strength of hybrid joints is much higher than that of simply bonded joints, which in turn is higher than that of simply bolted joints. In order hybrid joints have a

significant increase in the fatigue strength compared to aeronautical/aerospace joints, although the fatigue ratio is constant, about to 0.65.
For example, for a maximum load equal to about 7000 N the fatigue life grown from about 10^3 cycles, for aeronautical/aerospace joint, to 10^5 cycles for a hybrid joint with preload of the bolt to 8 Nm, while, in this load the fatigue life results to be infinite by the use of hybrid joints with the bolt tightening torque of 14 Nm. For a load of 6000 N the fatigue life grown from about 10^3 cycles of bonded joints, approximately 10^4 cycles of aeronautical/aerospace joints and a virtually infinite life for both configurations of studied hybrid joints.

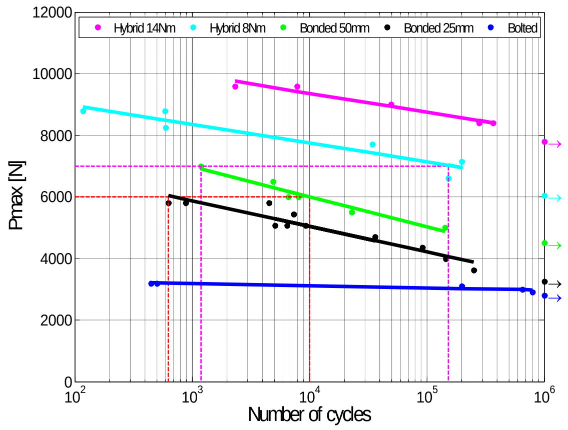


Figure 9. Comparison of Wöhler curves relating to different types of investigated joints.

5 Conclusions

In the present paper, through experimental analysis the mechanical behavior of double lap hybrid joints between GFRP-aluminum was studied, made by bolting and bonding. For a better understanding of the results, as well as the hybrid joints the corresponding simply bonded and simply bolted joints were studied.
The study has revealed as to the special material examined, in terms of static strength bonded joints have better performances than bolted joints: the tensile strength is about twice that of the bolted joint which is limited by the low shear strength of unidirectional composites. The situation is reversed in terms of energy absorption: the bolted joint, which gives rise to a progressive failure accompanied by large deformations, has a energy absorption of 4 times greater than that of the bonded joint. It is therefore a joint potentially more resistant to impact.
In the hybrid joints the failure is dominated by bonding, while the energy absorption is dominated by bolting. Contrary to the indications of literature in the hybrid joints there is a good synergism of the two joining techniques; in particular it was observed from static tests:

- a significant increase in tensile strength, equal to about 25% compared to simply bonded joints, caused by the reduction of the maximum stresses on the adhesive due to the presence of the hole;
- a significant increase in energy absorption, equal to about twice that of the coupling simply bolted, due of the beneficial effects of the increased friction between the adherents produced by the presence of the adhesive;

The work was carried out with the study of the fatigue behavior of studied joints. The parameters of comparison were: the trend of the elongation as a function of the number of cycles, the number of cycles to failure, and the failure mechanism. At every load level and for all types of joints from the diagrams elongation-number of cycles, there was a sudden failure of the joint.

In particular in hybrid joints, after the adhesive failure, there is not a change in joint stiffness and an increase of the number of cycles due to the interference between the bolt and adherends; this is due to unidirectional configuration of the composite which, at load levels significantly higher than those tolerable by the simply bolted joint, is unable to maintain the integrity of the joint.
However by Wöhler curves, it is observed that the hybrid joints support, for an equal number of cycles, loads considerably higher compared to the simple mode of joining. In the hybrid joints the increased fatigue life is not due the interference between the adherents and the bolt after the failure of bonding, but is due to the effects of the bolt preload that leads to a lowering of the maximum peeling stress.

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