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# Analysis of CFRP/Al hybrid laminates flexural strength

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**Abstract**

Very high mechanical properties, such as high strength, high damage tolerance and low weight, can be reached by coupling composite laminae and metal sheets: in such a manner a new material is obtained: the Fibre Metal Laminate (FML). The diversification of the thickness and the number of layers is suitable to change the structural properties. In order to analyse the influence of these factors on flexural strength, some types of CFRP/aluminium sheet FMLs were manufactured and their structural properties were investigated by means of three-point bending tests. It was discovered that both the studied elements affected the flexural strength of FML; in particular, this mechanical characteristic decreased with the existence of an adhesive film between the metal sheet and the composite plies, whereas it augmented if only one metal sheet was used instead of two ones.


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*Keywords:* fibre metal laminates; carbon fibre reinforced plastic; three-point bending test.

## 1. Introduction

A novel class of material is more and more employed for several applications in various industrial field: Fibre metal laminates (FMLs); this is due to the fact that this kind of hybrid laminate possesses outstanding structural characteristics. FLMs are a type of hybrid laminate formed by metal sheets and composite material layers, that give to the FMLs the excellent mechanical properties; as indicated by Xu et al. (2017) and Rajkumar et al. (2014), the most widespread FMLs in aeronautical industry is the GLARE (Glass Laminate Aluminium Reinforced Epoxy), that is made of aluminium and glass fibre composite, but the CARALL (carbon fibre reinforced aluminium laminates), that is based on CFRP (carbon fibre reinforced polymer), is stronger than the former one, especially for tensile loads, as

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asserted by Botelho et al. (2006). In the researches of Kim et al. (2015), superior structural characteristics, such as yield strength, energy absorption capacity and fatigue strength, were ascribed to carbon-based FMLs instead of aramid or glass fibre-based ones. An extraordinary particularity characterizes this kind of hybrid laminates: the structural properties can be simply customized to reach specific properties by changing the thickness and the number of layers and the composite ply orientation, as described by Şen et al. (2015).

In general, the load conditions acting on structural frames are bending ones, so these constitute the most studied failure mode, as stated by Bellini et al. (2019a and 2019b). Among past researches on this subject, Hu et al. (2015) studied the flexural characteristics of CARALLs reinforced with titanium and PMR polyimide, finding a high mechanical strength in condition of both room and elevated temperature. Mamalis et al. (2019) investigated the improvement of mechanical performance through chemical and physical treatment of the FML aluminium sheet. Li et al (2016) studied the influence of adhesive thickness on the structural characteristics of this material, while Wu et al. (2017) the effect of the layer thickness. Hamill et al. (2018) investigated the galvanic corrosion of CARALL based on aluminium sheets and bulk metallic glass, finding a better behaviour for the latter. Lawcock et al. (1998a and 1998b) explored the influence of fibre treatment on the both static and dynamic structural behaviour of FML. Dhaliwal and Newaz (2016) evaluated the consequence of the metal layers distribution along the laminate thickness by testing some CARALL specimens characterized by the presence of carbon laminate as the external layers. In this case, they determined that the studied stacking sequence conferred to the laminate more strength compared to that of standard CARALL. Instead, Xu et al. (2017) examined the influence of the metal sheet strength and the composite ply orientations on the in-plane bending properties of CARALLs, measuring an increment of the bending strength proportional to the longitudinal fibres amount and the metal strength. Moreover, they paid attention to the progressive failure mode: in a first moment the metal layers yielded and the composite layers suffered tension damage in the zone below the neutral axis and compression damage above the neutral axis; then the unstable deformation made the delamination start in the laminate mid-span. The in-service bonding behaviour and the surface preparation are two issues that must be considered when adopting FMLs, and composites in general, for critical parts production, as asserted by Bellini et al. (2018) and Sorrentino et al. (2018).

In this work, the flexural characteristic of different kinds of CARALL specimens were analysed, with the aim of delineating the influence of both the layer thickness and the CFRP/metal interface on the flexural strength.

## 2. Materials and methods

In order to examine the effects of each factor taken into consideration in this work, that are the bonding method and the stacking sequence, a full factorial plan was conceived for the experimental activity, that imposed 2 levels for each factor, as reported in table 1. As regards the stacking sequence, two different kinds of FMLs were prepared: the first one was formed by an aluminium sheet and two composite material ones, while the other one was made of two metal sheets and three composite material layers. As concerns the bonding method, the interface between metal and composite was made with a structural adhesive or the resin contained in the prepreg ply. It must be highlighted that the composite reinforcement adopted in this work was in fabric form instead of unidirectional fibres, that are in general employed in the literature. The hybrid laminates analysed in this study were fabricated through the vacuum bag process, a manufacturing technology typically employed for producing parts made of composites material (Sorrentino et al. 2009). The process consisted in different step: at first, a release agent was spread on the mould surface, in order to allow laminate removal at the end of the process, and then the aluminium sheets and carbon fibre prepregs were stacked on the prepared mould surface, following the sequence reported in Table 1. Then the laminate was covered with a release film and a breather cloth, necessary to avoid laminate sticking with the other ancillary materials and gases bubble entrapment in the laminate, respectively. After, the laminates were heated in an autoclave for resin cure. At the end of the curing process, the laminates were extracted from the mould and cut into 160 mm x 20 mm specimens. As visible in Fig. 1, the flexural strength of the laminates was calculated by three points bending test according to ASTM D790: the span between support was 136 mm, while the loading speed was 6 mm/min. The flexural strength, indicated as $\sigma_f$, was calculated from the load P measured on the specimen through the following relation, given the distance between the supports L, the specimen thickness h and the specimen width b:

$$\sigma_f = {}^{3\,P\,L}\!/_{2\,b\,h^2} \tag{1}$$

Table 1. Full factorial plan employed in this study.

| Factor | Level value |
|---|---|
| Adhesive | Resin, AF 163 2k |
| Number of sheet metal | 1, 2 |

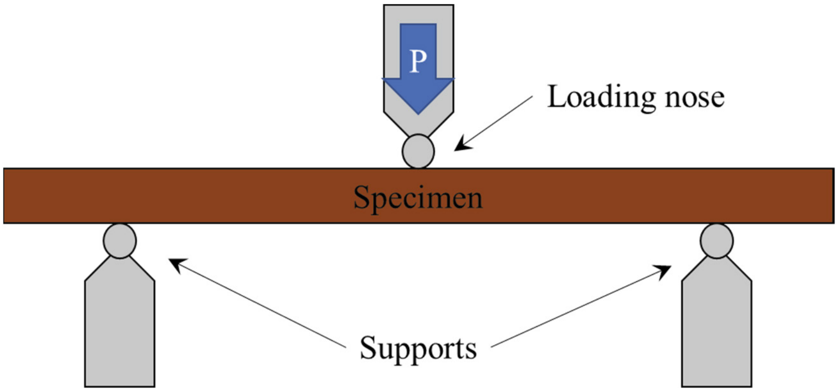


Fig. 1. Schematization of three-point bending test.

## 3. Results and discussion

As a result of the three-point bending tests, the laminate with one aluminium sheet bonded with adhesive (type A) was characterized by a flexural strength oscillating between 562.75 MPa and 641.86 MPa, whereas the same laminate without the adhesive (type B) presented a flexural strength between 644.25 MPa and 734.00 MPa. The laminates manufactured with two metal layers and bonded with adhesive (type C) had a flexural strength ranging from 468.88 MPa to 553.30 MPa, while the similar one without adhesive (type D) from 498.38 MPa to 641.38 MPa. It must be highlighted that the findings of this investigational campaign well agree with other researches carried out on the hybrid laminates, executed by Pan et al. (2017), Rajian and Kumar (2018) and Dhaliwal and Newaz (2016). As reported in table 2, the CoV (Coefficient of Variation) was very low for all the investigated FML types, reaching only in one occasion 10%: this fact witnessed the high repeatability of the experimental tests.

Table 2. Flexural strength values [MPa] calculated for the tested specimen.

| | Type A | Type B | Type C | Type D |
|---|---|---|---|---|
| Mean | 607.07 | 673.04 | 513.59 | 561.36 |
| St. dev. | 33.64 | 41.09 | 37.66 | 59.79 |
| CV% | 5.54% | 6.11% | 7.33% | 10.65% |

From the data presented in Figure 2, it can be deduced that the laminate characterized by the highest strength was that one with a single metal sheet bonded without adhesive, instead the laminate presenting the lowest value was that one produced with two aluminium sheets and bonded with adhesive. Therefore, it can be asserted that the bonding with structural adhesive had a negative effect on the material strength, while the effect relevant to the presence of a single metal sheet was positive.

A statistical analysis was performed on the numerical results obtained in order to confirm the significance of the above statements. In Table 3 the ANOVA (Analysis of Variance) results are reported: the number of metal sheets factor was the most influencing since it had a contribution of more than 50%, instead the presence of the adhesive at the interface was less affecting. The contribution of the interaction between the two factors can be neglected as it is less than 0.5%. The estimation of p-value confirmed the above finding; in fact, its value for both the single factors was less than 5%, the commonly assumed value for rejecting the hypothesis of means equality, while for the interaction one it was higher than the threshold value.

Table 3: ANOVA analysis of experimental data obtained for flexural strength.

| Source | Seq SS | Contribution | F-value | P-value |
|---|---|---|---|---|
| n. sheet | 42087.7 | 53.41% | 21.55 | 0.1% |
| adhesive | 23937.6 | 16.42% | 6.62 | 2.4% |
| n. sheet * adhesive | 330.9 | 0.42% | 0.17 | 68.8% |
| error | 23439.7 | 29.75% | | |
| total | 78795.9 | 100.00% | | |

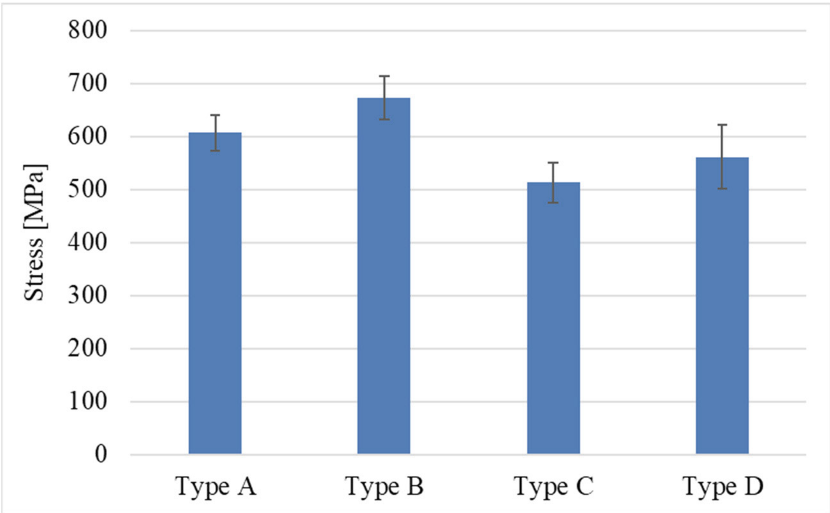


Fig. 2. Flexural strength registered for the tested CARALL.

## 4. Conclusions

The polluting emissions are at the centre of the public opinion, so their reduction is highly desirable and can be reached, among other solutions, by the reduction of vehicles weight in the transport sector. In the light of these statements, the employment of the FMLs is destined to expand in the future, since these materials possess outstanding structural properties coupled with the low weight. However, the knowledge of FMLs structural properties needs further investigations, since different topics can be investigated, ranging from the static and dynamic characteristics definition to durability tests, in terms of both fatigue life and corrosion resistance. This is necessary because the deep knowledge of FML structural properties is needed for the accurate simulation of the material performance, essential for designing and validating structures made of hybrid laminates; in fact, FMLs are halfway between a structure and a material, so for each specific application the material itself must be designed, besides the structure geometry, in order to sustain the loads in the most efficient way.

In the present paper a study is carried out on CARALL with the aim of defining the flexural properties as a function of laminate characteristics, such as the metal/composite interface, that can be constituted by adhesive or prepreg resin, and the thickness of the layers, that is due to the number of sheets. Laminates with different characteristic were tested following the three-point bending test method in order to define which of the abovementioned factor was the most influencing. From the experimental results it can be concluded that the most efficient laminate was that one with a single metal sheet bonded without adhesive, instead the worst laminate, in terms of flexural strength, was that one presenting two aluminium sheets bonded with adhesive. These findings were confirmed by statistical analysis too.

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