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Analysis of fracture characteristics in aluminium-CFRP hybrid laminate subject to three-point bending loading

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Abstract

Fibre metal laminates represent a family of hybrid laminates with interesting mechanical properties, due to their lightness. Flexural loads are very frequent in structural parts; therefore, the investigation of the failure mode and the fracture behaviour connected to this loading state is crucial, and it constitutes the core of the present work, in which the effect of the metal-composite material interface type on the fracture mode was investigated. Some specimens were produced considering two different types of interfaces: in the first case the bonding of the aluminium sheets to the CFRP was guaranteed by structural adhesive, in the second case no adhesive was used, relying on the prepreg resin bonding capabilities. The produced samples were tested according to the three-point bending procedure, varying the support span, and the fracture surface morphology was analysed. It was found that the presence of the adhesive influenced the fracture mode and the resultant fracture surface morphology.

Keywords: Fracture characteristics; Fibre metal laminates; Flexural load.

1. Introduction

New materials presenting significant structural characteristics coupled to low weight are more and more required for several applications in different industrial fields, such as automotive and aeronautics. A class of materials that is able to meet these requirements is that of FMLs (Fibre Metal Laminates). These are hybrid laminates formed by metal sheets alternated to composite material layers. One of the most used FML is the GLARE (Glass Laminate Aluminium

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Reinforced Epoxy), constituted by aluminium sheets and unidirectional glass/epoxy composite, as stated by Rajkumar et al. (2014). However, according to Kim et al. (2015) and Xu et al. (2017), FMLs based on CFRP (Carbon Fibre Reinforced Polymer), that are indicated as CARALL (Carbon Fibre Reinforced Aluminium Laminate), are becoming increasingly popular due to the higher mechanical characteristics, despite the corrosion issue suffered (Pan et al. (2017), Hamill et al. (2018)).

Among the possible loading conditions that can act on structural frames, one of the most diffused is the bending one; consequently, several articles report studies on this topic, as asserted by Bellini et al. (2019a, 2019c). In fact, Romli et al. (2017) studied the mechanical behaviour of a carbon/epoxy FML subjected to quasi-static loading, considering different crosshead displacements. In that study, the aluminium-composite bonding was enhanced by treating the metal sheet through a sanding process. Li et al. (2016) prepared several FML specimens by varying the quantity of adhesive in order to optimize the interface characteristics and improve the manufacturing process efficiency. Sathyaseelan et al. (2015) compared the mechanical properties of two FMLs presenting different stacking sequences, manufactured through hand layup and compression moulding. Similar research was carried out by Wu et al. (2017), who tested laminates with different stacking sequences maintaining the same composite material volume fraction, and by Bellini et al., who studied both the influence of the stacking sequence and the metal/composite interface on the flexural behaviour (Bellini, Di Cocco, et al. 2019d), the failure energy (Bellini, Di Cocco, et al. 2019b), and the interlaminar shear strength (Bellini, Di Cocco, and Sorrentino 2020). Rajan and Kumar (2018) tested different CARALL samples to evaluate the influence of the areal density and the thickness on both the tensile strength and the flexural strength of such laminates. Mamalis et al. (2019) produced FMLs with different chemical and physical treatments on the surface of the aluminium sheet to analyse their effect on the reliability of the aluminium-composite interface. Ostapiuk et al. (2017) studied the effects of the composite material type and the laminate thickness on the mechanical properties of the laminate. Vasumathi and Murali (2013) substituted a part of carbon reinforcement with natural fibres, in order to reduce the costs of material.

The aim of the present work is the analysis of the flexural behaviour of CARALL laminates. In particular, the attention was focused on the analysis of fracture characteristics; in fact, a study of micrographs taken on the broken samples was carried out. This work is organized in several steps: first of all, there is the definition of the laminates to be tested, in terms of the type of interface between the metal and the composite. In fact, the behaviour of such kind of material relies mainly on this. The experimental procedure was determined too, and it was the three-point bending test. This type of mechanical test is characterized by practicability and simplicity; in fact, both long and short beams can be tested by varying the distance between the supports, that is the span. Once the types of the interface and the tests had been identified, the laminates were manufactured through the vacuum bag process, and then the specimens were cut from the produced laminates to be tested. Finally, there is the presentation and the analysis of the results. In particular, micrographs were taken to better understand the type of fracture, by adopting scanning electron microscopy inspections.

2. Material and methods

In this work, the effect of layer adhesion has been investigated, paying attention to the fracture morphology. For assessing the influence of the adhesive interface between the carbon/epoxy composite material and the aluminium sheet on the mechanical performance of the hybrid material, two different laminates were tested: in the first case, a structural adhesive, typically used in the aeronautical field, that was the AF 163 2k, was used to bond the layers of the different material; in the second case, no adhesive was used and the bonding interface depended on the self-adhesive capacity of the resin of the prepreg material. Both the studied FMLs presented CFRP laminates as external layers: this is a configuration studied only in some works, such as that of Dhaliwal and Newaz (2016). The prepreg material used to produce these layers was made of epoxy resin and carbon fabric, presenting a 2x2 twill wave style. The thickness of a single ply was 0.35 mm. The metal sheets adopted in this work were made of EN AW 6060 aluminium alloy, and had a thickness of 0.6 mm. Considering that each composite material layer was composed by six plies, the nominal thickness of the analysed hybrid laminates was 4.8 mm. It must be highlighted that in the case of the laminate with the adhesive, the thickness of this film was a tenth of mm, so the thickness of the laminate became 5 mm.

As concern the process adopted for the manufacturing of the laminates, the prepreg vacuum bagging technology was adopted thanks to its easiness. The first step consisted in preparing all the required raw materials, such as the aluminium sheets, the plies of carbon fibre prepreg, and the adhesive patches, that were cut in the right dimensions. After, all the different materials were stacked on the mould as indicated in the previous paragraph. After the completion of the stacking sequence, the arranging of the vacuum bag was needed for the cure in the oven. Consequently, the prepared laminate was covered with the ancillary materials, that were the release film and the breather cloth, and the whole stack was closed in a vacuum bag and sealed with butyl tape. Finally, the mould was connected to the vacuum pump to draw the air present in the bag, and it was put in the oven for the cure cycle. For the curing of the CARALL laminate, a temperature cycle suitable for both the prepreg material and the adhesive was chosen. It consisted of a heating ramp of 2 °C/min, a dwell at a constant temperature of 127 °C and a cooling ramp till 40 °C.

At the end of the manufacturing process, the produced laminates were taken from the mould and the specimens to be tested were extracted by cutting them with a diamond disk saw. Both types of specimens, that are the short and the long beams, were extracted from the same laminate, as visible in Fig. 1. As indicated in the ASTM D790 standard, that is that one considered for determining the flexural strength, the dimensions of each specimen were based on the laminate thickness; therefore, the length of each specimen was 160 mm, while the width was 20 mm. As concerns the remaining parameters, the loading nose speed was 6 mm/min, while the span length was 136 mm. Instead, the ASTM D2344 was taken into consideration for determining the dimensions of the specimen for the interlaminar shear strength test, which were 25 mm in length and 10 mm in width. In this case, a loading nose speed of 1 mm/min and a span length of 20 mm were adopted for the three-point bending test.

Fig. 1. The scheme of the specimens represented on a laminate to be cut.

The fractured specimens were analysed by using an SEM (Scanning Electron Microscope). A sample was extracted from the centre of each long specimen, where the fracture occurred, to the right dimension to be fixed on the stub. In the case of the short beams, their dimensions were smaller, and it was possible to install them on the stub without cutting them, as visible in Fig. 2.

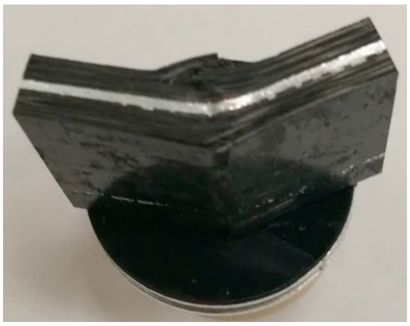

Fig. 2. One of the specimens analysed in this work clamped on a stub for SEM observation.

3. Results

In this paragraph, the description of the fracture features found in the broken specimens is reported for the different types of laminates and loading conditions. As concerns the long beam specimen presenting an aluminium-composite interface made of adhesive, the SEM observation reported in Fig. 3 evidenced, in the upper zone of the specimen, the presence of the fibres failure due to crushing, caused by compressive stress, as well as the presence of cracks in the transversal bundles, both parallel and orthogonal to the composite ply direction, and the separation of the composite plies, also this due to compression. As concerns the lower zone, the breakage of the longitudinal fibres was due to tensile stress. It can be noted that a crack developed in a transversal bundle passed into the longitudinal one, but it was arrested by the adhesive layer, and it did not pass into the aluminium.

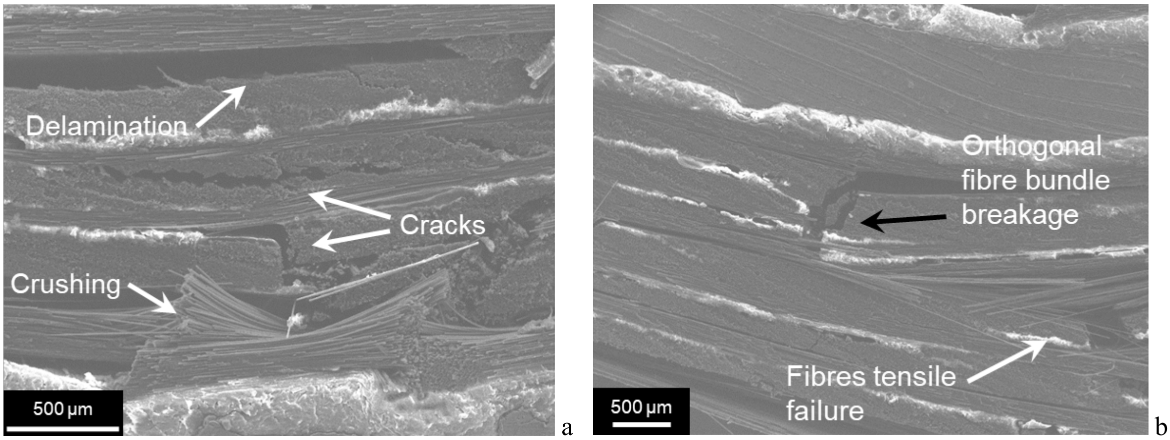

Fig. 3. Fracture morphology for the long beam specimen bonded with adhesive: a) upper zone; b) lower zone.

As concerns the short beam specimen of the same laminate, the SEM investigation visible in Fig. 4 evidenced the separation of the different plies of composite material, that is the delamination, and the presence of cracks in the transversal bundles, but only in the direction parallel to the plies, that constitutes the intra-layer delamination. Moreover, the failure of the interface between adhesive and aluminium can be noted.

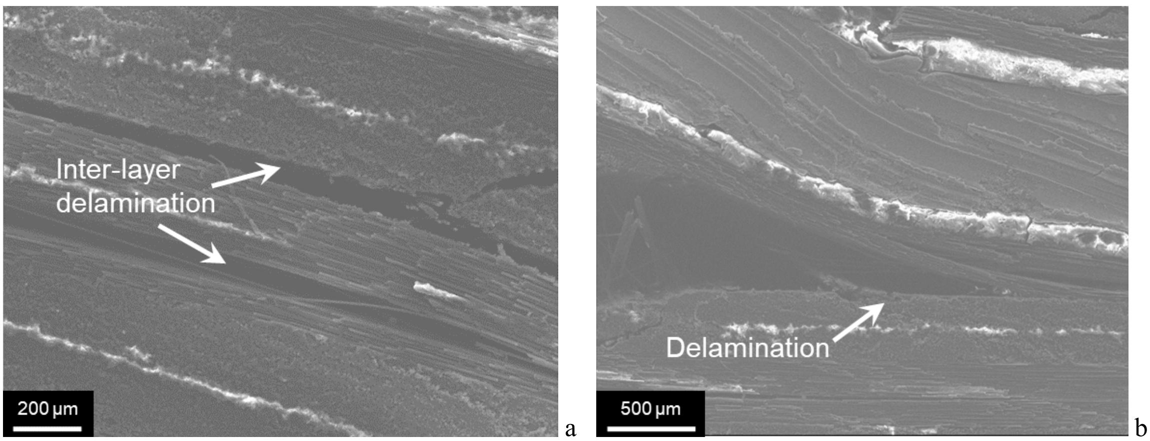

Fig. 4. Fracture morphology for the short beam specimen bonded with adhesive: a) upper zone; b) lower zone.

The fracture characteristics recognized for the long beam specimens without adhesive were similar to those found in the specimens bonded with the adhesive, as can be noted in Fig. 5. In fact, the SEM analysis highlighted the failure mode of longitudinal fibres, which was crushing in the upper zone and tensile failure in the lower zone, and the presence of cracks in the transversal bundles. Moreover, also in this case, the crack did not pass from the composite plies into the aluminium sheet. In fact, there was the complete separation of the composite from the metal, even if some parts of the composite bundles remained attached to the metal.

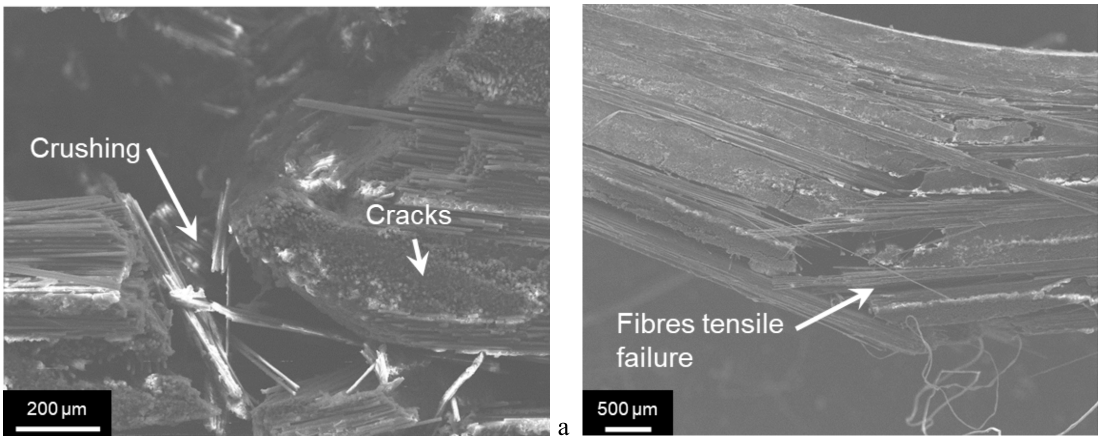

Fig. 5. Fracture morphology for the long beam specimen bonded with prepreg resin: a) upper zone; b) lower zone.

Finally, the failure characteristics of the short beam specimen extracted from the laminate without the adhesive were studied. As found for the other short beams, the SEM showed the presence of ply separations and cracks in transversal bundles in both the upper and the lower zone, while the normal failure of longitudinal fibres was not found. Also in this case, the interface between composite and aluminium was broken, leading to the complete separation of the specimen into three parts (the upper and lower laminates and the central aluminium sheet).

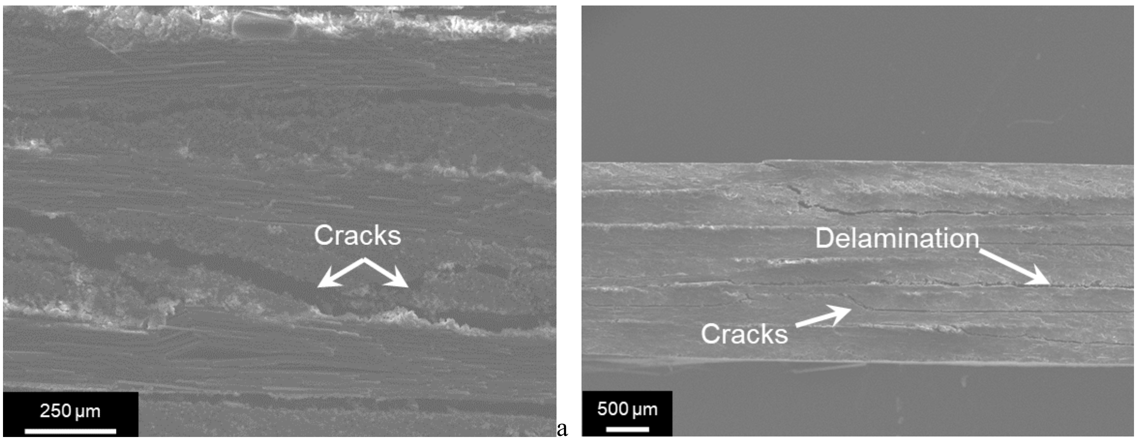

Fig. 6. Fracture morphology for the short beam specimen bonded with prepreg resin: a) upper zone; b) lower zone.

4. Conclusion

The aim of the present work concerns the analysis of the flexural behaviour of FMLs (Fibre Metal Laminates) with different metal-composite interfaces. In particular, the morphology of the fractured specimens was studied. Two ways were chosen to realize this interface: a structural adhesive film was inserted between the two materials or not; in this case, the bonding relied on the composite material resin. The three-point bending test was chosen to evaluate the mechanical characteristics of the produced laminates, and different stress states were analysed changing the span distance. The analysis of micrographs, taken by an SEM (Scanning Electron Microscope), evidenced that the fibre failure was the main failure reason for the specimens subjected to flexural load, while the delamination was the main cause for failure induced by the shear load. Finally, it must be remarked that the specimens bonded with the composite material resin only showed a complete separation of the layers, even if a thin layer of resin remained on the aluminium surface. On the contrary, the interface did not result broken in the case of the specimens with the structural adhesive.

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