Visual Abstract

Fracture micrographic analysis of a carbon FML under three-point bending load

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ABSTRACT. The core of the present work concerns the analysis of the failure mode and the fracture process induced by the flexural load in Fibre Metal Laminates (FMLs). The influence of the connection layer placed between the composite ones and the metal sheets on the fracture mode was analysed. The considered FML was made of aluminium sheets interposed with carbon fibre reinforced polymer (CFRP) layers, joined with two different types of interface: by using a structural adhesive, or by relying on the bonding capacity of the prepreg resin. Then, the mechanical performances of the produced laminates were determined through the three-point bending test procedure, and the support span was varied to investigate different loading conditions. Finally, the fracture surface morphology was analysed by using both optical and scanning electron microscopes. The type of interface was found to influence the strength of the studied FML, and different fracture modes were observed, depending on the loading condition.

KEYWORDS. Fibre metal laminates; Fracture features; Flexural behaviour.

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INTRODUCTION

Several advanced industrial applications demand high performance materials, presenting both high mechanical properties and lightweight at the same time [1,2]. FMLs (Fibre Metal Laminates) represent a class of material that is suitable to fulfil the abovementioned targets. In fact, they consist in hybrid laminates composed of composite material plies stacked alternately with metal sheets [3]. Today, the most diffused FML, that is called GLARE (Glass Laminate Aluminium Reinforced Epoxy), is made of 2024 aluminium grade sheets interleaved to composite material with S2 glass fibres [4]. However, there are several studies demonstrating that CARALLs (Carbon Fibre Reinforced Aluminium Laminate), that are FMLs made of aluminium and CFRP (Carbon Fibre Reinforced Polymer), present better mechanical characteristics and, for this reason, they are more and more used for advanced structural applications [5,6]. However, it must be considered that these laminates are subjected to corrosion issues, due to galvanic interaction between carbon fibre and aluminium, and some countermeasures should be considered to improve the material corrosion resistance [7,8].

Bending load is among the most diffused loading conditions that can rest on structural frames; for this reason, flexural properties of materials are quite important and some investigations in this sense have been carried out on FMLs [9,10]. The effect of crosshead displacement rate on the mechanical characteristic of a CARALL subjected to quasi-static loading was studied by Romli et al. [11], that investigated five different loading rates. To improve the composite/aluminium interface, the authors modified the aluminium surface roughness by sandpaper. It was found that the laminate tested with the lowest rate presented the highest strength, due to the possibility to have ductile deformation in the aluminium sheets. The influence of adhesive quantity on the mechanical peculiarities of FML was studied by Li et al., that carried out several different experimental tests on the aluminium-lithium based FML [12]. Taking into account different loading conditions, they found that a reasonable adhesive quantity was suitable to obtain high mechanical performance, but a disproportionate one was detrimental, even if the optimal quantity depended on the loading scheme. The tensile behaviour of FML at high strain rates was studied by Khan and Sharma by using a Split Hopkinson Tension Bar [13]. FMLs with metal layers inside were compared to others without metal layers inside, and a similar strength was found for both types. The outcome of the stacking sequence on the structural features of CARALL was analysed by Sathyseelan et al., that produced two different laminates through hand-layup and compression moulding [14]. Different loading conditions were analysed, and a numerical routine was introduced to calculate the mechanical peculiarities of the studied laminates. The effect of layer thickness variation was investigated by Wu et al., that prepared CARALL samples for the three-point bending test by using the hot-press process [15]. A relation between the flexural modulus and the layer thickness was found, while the latter did not influence the mechanical strength. The effect of multiple-site damage cracks on the fatigue peculiarities of FML was examined by Wang et al. from a theoretical point of view [16]. They proposed a model suitable for symmetric FML joints that did not take into account secondary bending effects. Three-point bending tests were implemented also by Bellini et al. to explore the outcome of the layer thickness, the bonding style and the stratification order on the flexural behaviour [17], the interlaminar shear strength [18], and the failure energy [19]. It was highlighted that the composite-metal junction made of structural adhesive improved the interlaminar shear strength but worsened both the flexural strength and stiffness. The effect of the stratification sequence and surface density on the bending and tensile strength of the material was investigated by Rajan and Kumar too [20]. They prepared and tested laminates with different stacking sequences and found an improvement in the mechanical properties with the increase of both investigated parameters. The impact of the surface preparation of the aluminium sheets on the structural reliability was studied by Mamalis et al. [21]. Different physical and chemical treatments were carried out on the sheet surface before the thermoplastic FML production, and an improvement of the surface wettability was found in all the cases; in turn, this improved the adhesion between layers. The influence of the laminate thickness and the constituent material type on the structural characteristics of the laminate was investigated by Ostapiuk et al. [22]. Both carbon/epoxy and glass/epoxy composites were coupled to sheet metal with different thickness, and different failure mechanisms were observed, but irrespective of metal thickness and reinforcement type. The influence of fibre type was analysed by Vasumathi and Murali too [23]. A part of carbon fibre was substituted by jute fibre, to obtain a cheaper laminate, and both magnesium and aluminium were used as metal layers.
The intent of this work is to study the flexural peculiarities of CARALL laminates, produced by considering different types of metal-composite interfaces. The investigation of fracture features received special attention; in fact, the analysis of micrographs taken from the fracture surfaces of the specimens was conducted after the mechanical testing. This project is subdivided into various stages: first and foremost, the style of interface layer placed between the composite and the aluminium was defined for the laminates to be evaluated, since the behaviour of such materials is largely determined by the bonding conditions between layers. The three-point bending was designed as the technique for the experimental test, because this form of structural test for materials is simple and practical; in fact, by simply changing the span distance between the supports of the sample, both long and short ones can be examined. Then, on the basis of the aforementioned experimental plan, both the types of laminates to be studied were produced by applying the vacuum bag process and the specimens were cut from them, by considering the dimensions required for both short and long specimens. Finally, the specimens were tested, and the fracture surfaces were examined by using both SEM (Scanning Electron Microscope) and LOM (Light Optical Microscope).

MATERIALS AND METHODS

The influence of the adhesion type between the metal and the composite in a carbon FML has been examined in this study, with a focus on fracture morphology. Two diverse types of FML were investigated to determine the impact of the contiguity interface between the carbon/epoxy layers and the aluminium one on the structural characteristics of the studied FML. In fact, this bonding interface was obtained by introducing a ply of AF 163 2k, that is a structural adhesive, or by relying on the no adhesive was used, and the connection was granted by the bond capability of the composite matrix. Therefore, in this latter case, no adhesive was used. CFRP laminates formed the external layers in all the FMLs tested: this is a configuration that has only been studied in a few publications, for instance, Dhaliwal and Newaz [24]. The carbon cloth prepreg used to create the composite material layers had a 2x2 twill wave pattern, while the matrix was an epoxy resin. The thickness of a single prepreg ply was 0.35 mm, while the thickness of the metal sheets used in this project, made of EN AW 6060 aluminium grade, was 0.6 mm. The theoretical thickness of the investigated FML was 4.8 mm, based on the fact that 12 composite plies were used for each laminate, and were grouped six by six. It should be noted that the thickness of the adhesive film was 0.1 mm, so the theoretical thickness of the laminate presenting the structural adhesive was 5 mm.

The vacuum bagging method was used for the laminate manufacturing process due to its simplicity. The initial stage was to prepare all the necessary raw materials, such as the EN AW 6060 sheets, the prepreg plies, and the AF 163 2k patches, which were all cut to the correct size. Following that, the various materials were layered on a steel plate, that constituted the mould, as described in the preceding paragraph, forming two different laminates: one with the adhesive and another without. After the stacking sequence was completed, the vacuum bag needed to be arranged for the oven cure. As a result, the prepared laminates were coated with supplementary materials, such as the release pellicle and the breather cloth, and the entire stacks were closed with butyl tape in a vacuum bag. Then, this latter was linked to a vacuum pump, which drew the gases out of the bag itself, and it was placed in the oven for curing. A temperature cycle that was adequate for the polymerization of both the prepreg and the structural adhesive was selected for the curing of the CARALL laminate. It included a 2 °C/min heating ramp, a 127 °C constant temperature dwell, and a cooling ramp to 40 °C. The manufactured laminates were removed from the vacuum bag at the end of the production process, and the samples to be examined were obtained by sawing them using a diamond disk saw. Both kinds of samples, that are short and long ones, were taken from the same FML plate, whose dimensions were 210 x 110 mm2, as visible from the drawing in Fig. 1. The size of the samples was based on the FML thickness, as specified in the ASTM standards. As concerns the specimens for the calculation of the flexural strength, their length was 160 mm, and their width was 20 mm. As for the other test parameters, the loading nose rate was 6 mm/min, and the span distance was 136 mm. Instead, the ASTM D2344 was used to determine the dimensions of the interlaminar shear strength samples, which were 10 mm wide and 25 mm long. As concerns the remaining test requirements, the loading nose rate was 1 mm/min and the span distance was 20 mm.

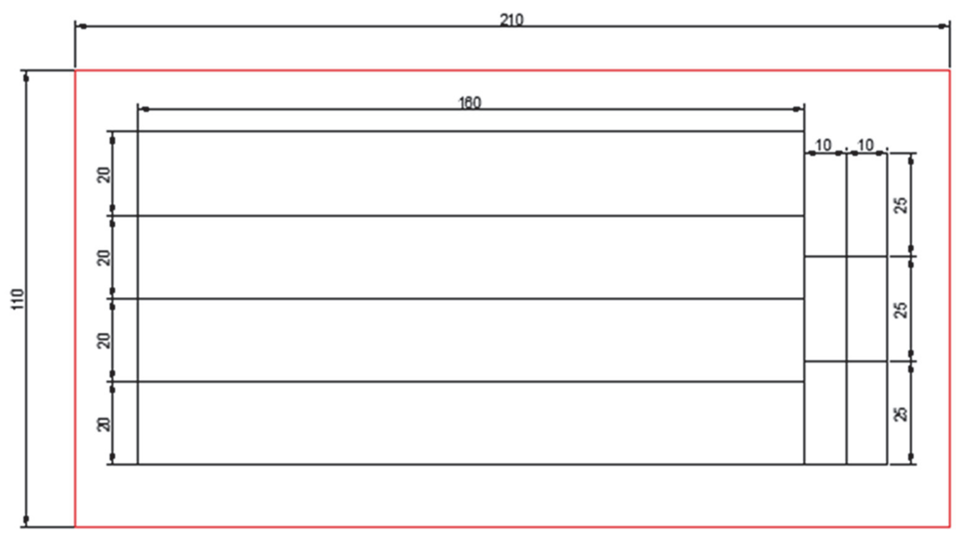

Figure 1: The arrangement of specimens to be cut from a laminate.

Both an SEM and a LOM were used to examine the specimens after the bending test. For the former, a specimen was taken from the central zone of each long beam specimen, that is the point where the specimens resulted broken, and cut to the correct size to be mounted in the SEM vacuum chamber. Being the length of the short beams lower, they were mounted directly in the SEM chamber avoiding the cutting operation, as shown in Fig. 2a. As concerns the specimens for the LOM analysis, a three-step preparation was necessary: cutting a sample from a specimen, mounting the sample, and polishing the surface. After selecting the portion of interest, each specimen was dissected by using a water-cooled abrasive disk saw and was then mounted on resin panels. To prevent heat damage to the specimens, a resin that cured at room temperature was considered, and 24 hours were necessary for its complete reticulation. Each sample was ground with silicon carbide disks and polished by using a felt disk with alumina aqueous suspension, yielding the samples shown in Fig. 2b.

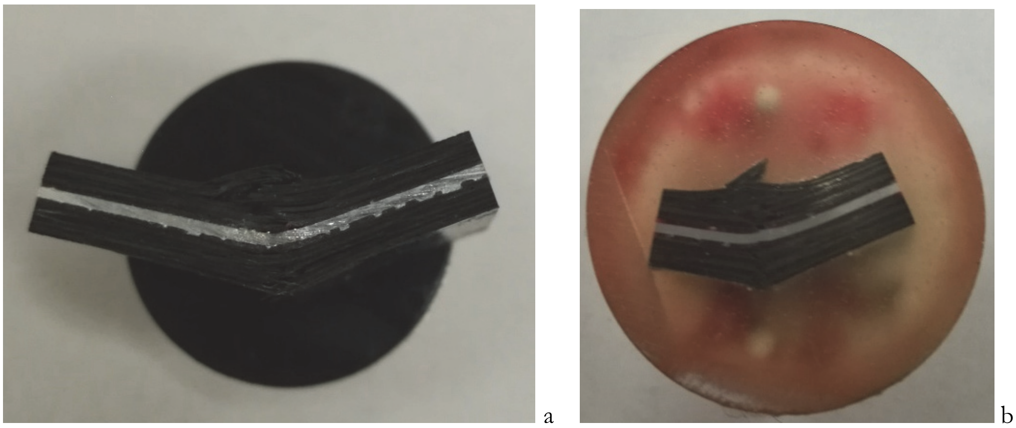

Figure 2: Specimens prepared for a) SEM observation, b) LOM observation.

RESULTS

The first material property to be discussed is the flexural strength: the normal stress σ_n, that is the prevailing stress state in the long beam, was computed through the subsequent equation:

$$\sigma_n = \frac{3Pl}{2bh^2} \quad (1)$$

in which the load on the specimen is represented by *P*, the span distance by *L*, the sample thickness by *h*, and the sample width by *b*. The specimen with the prepreg resin interface, that is the one called "without adhesive", was the strongest, as the flexural strength of about 675 MPa was attained; instead, the other one, that is called "with adhesive", reached 603 MPa. Examining the results for both categories of specimens, reported in Fig. 3a, it can be noted that the type of interface affected the flexural strength. In fact, this parameter decreased with the presence of the adhesive, that is a weaker material compared to composite one. As concerns the interlaminar shear strength τ_{ILSS}, that is a characteristic stress state of the short beam, it was estimated through the subsequent equation:

$$\tau_{ILSS} = \frac{3P}{4bh} \quad (2)$$

In this case, the strongest laminate was that presenting the AF 163 2k at the interface between the aluminium and the CFRP. In fact, the value of 48 MPa was obtained for that laminate; instead, the laminate bonded without the structural adhesive presented a value of 40 MPa. From this result, it can be easily determined that the nature of the interface strongly affected the interlaminar resistance too; however, in this case, the structural adhesive increased the laminate strength.
The stress-displacement curves are reported for both the long and the short beam specimens in Fig. 4. In the former case, it can be noted that both the specimens with and without the adhesive presented a similar trend; in fact, there was a linear stress increment, that concluded as the highest stress was attained, and was succeeded by a pseudo-elastic tendency, characterized by a sequence of stress increments and decrements. The most remarkable difference consisted in the maximum stress attained, as said before. Another minor difference was noted in the slope of the linear part, representing the stiffness of the laminate, that was slightly higher for that with the adhesive. A similar curve shape was observed for the interlaminar shear strength, even if in the case of the specimens with adhesive the linear increase was followed by a knee before the maximum point, probably due to the plasticization of the adhesive itself, absent in the other laminate. In both cases, a residual load capacity can be noted.

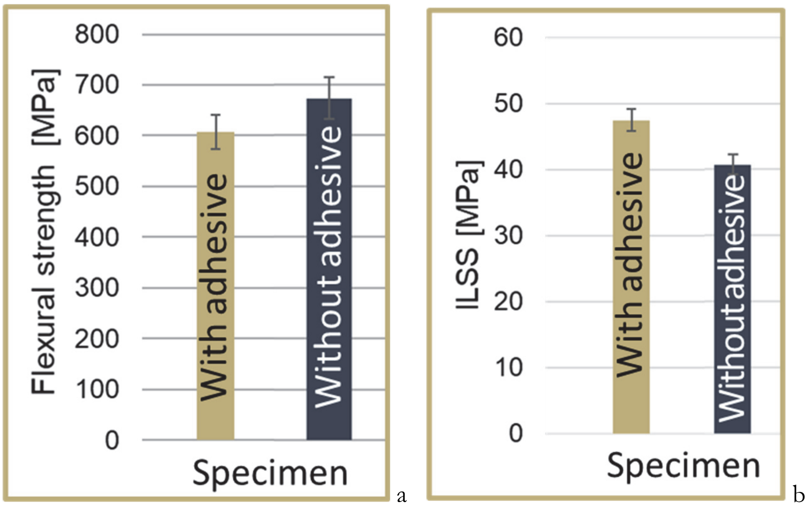

Figure 3: Flexural strength (a) and interlaminar shear strength (b).

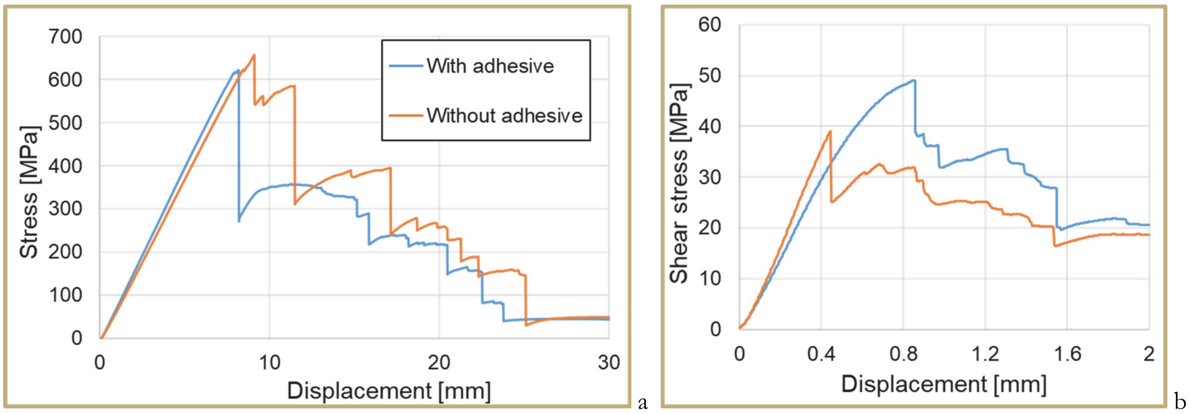

Figure 4: Stress-displacement curves for (a) long and (b) short beam specimens.

Two opposing elements influence flexural and shear strengths: on the one hand, the presence of adhesive improves interfacial bonding and, as a result, improves the shear behaviour of these hybrid laminates, while, on the other hand, it decreases the reinforcement volumetric content and, consequently, the material strength. Therefore, a deeper study of micrographs obtained on the fracture surface was conducted to achieve a better knowledge of the failure mode.

The SEM observation of the long beam specimen with the structural adhesive at the aluminium-composite interface, visible in Fig. 5, revealed the presence of fibre failure due to crushing in the higher portion of the sample, as well as cracks in the crosswise bundles, in both horizontal and vertical directions, and the complete split of the composite plies. All these observed failure modes were due to compression. Instead, the collapse of the longitudinal fibres in the bottom zone was caused by tensile forces; in fact, no crushing was noted. A crack occurred in a crosswise bundle and crossed into the longitudinal one, but it was stopped by the AF 163 2k layer and did not penetrate the metal. The optical microscope investigation revealed a similar behaviour, and the integrity of both the aluminium-adhesive and composite-adhesive interfaces can be seen in the micrographs in Fig. 6.

The LOM analysis revealed the existence of both intra-layer and inter-layer delaminations in the short beam of the same laminate, in both the top and the bottom zone, caused by shear stresses, as visible in Fig. 7. The absence of normal loads, both tensile and compressive, obviously prevented the creation of orthogonal cracks in transversal bundles and the rupture of longitudinal fibres. As reported in Fig. 8, also the SEM analysis revealed delamination, or the separation of distinct plies of composite material, as well as cracks in the crosswise bundles, but only in the horizontal direction, indicating intra-layer delamination. However, the failure of the junction between metal and adhesive may be seen, despite the fact that the LOM did not detect this phenomenon, probably because of the mounting and polishing procedures.

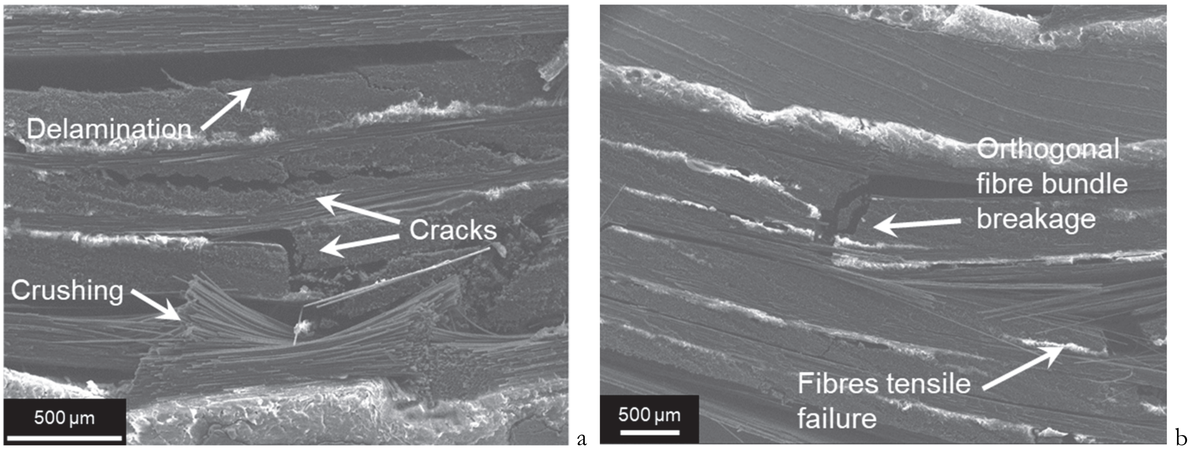

Figure 5: SEM micrographs of the long beam specimens with structural adhesive: a) top section, b) bottom section.

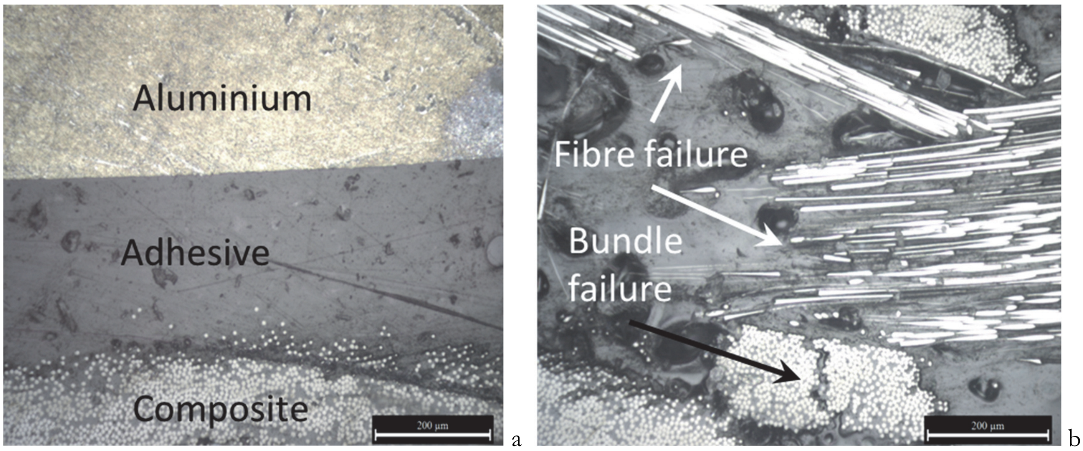

Figure 6: LOM micrographs of the long beam specimens with structural adhesive: a) top section, b) bottom section.

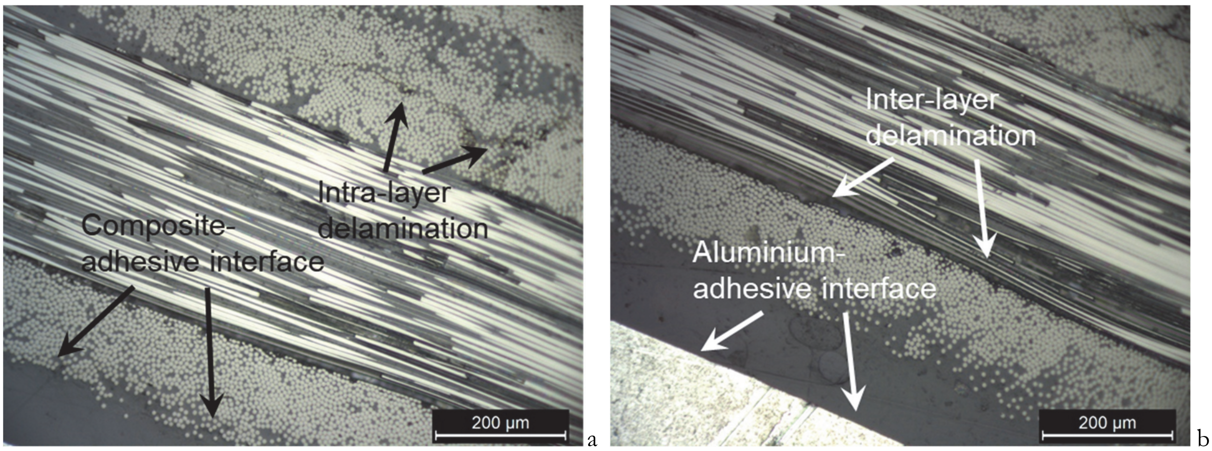

Figure 7: LOM micrographs of the short beam specimens with structural adhesive: a) top section, b) bottom section.

Long beam specimens without adhesive bonding had fracture characteristics that were similar to those found in specimens joined with adhesive. The SEM study revealed the longitudinal fibres failure mode, which was tensile failure in the bottom section and crushing in the higher one, as well as the existence of cracks in the crosswise bundles. Furthermore, the crack did not grow through the CFRP plies into the metal sheet in this situation. Even though some sections of the reinforcement bundles stayed stuck to the metal, the composite was completely separated from the metal, as visible in Fig. 9a. The LOM study revealed that a tiny film of resin was present on the aluminium (Fig. 9b), indicating that the failure was not at the composite/aluminium interface, but rather within the composite itself.

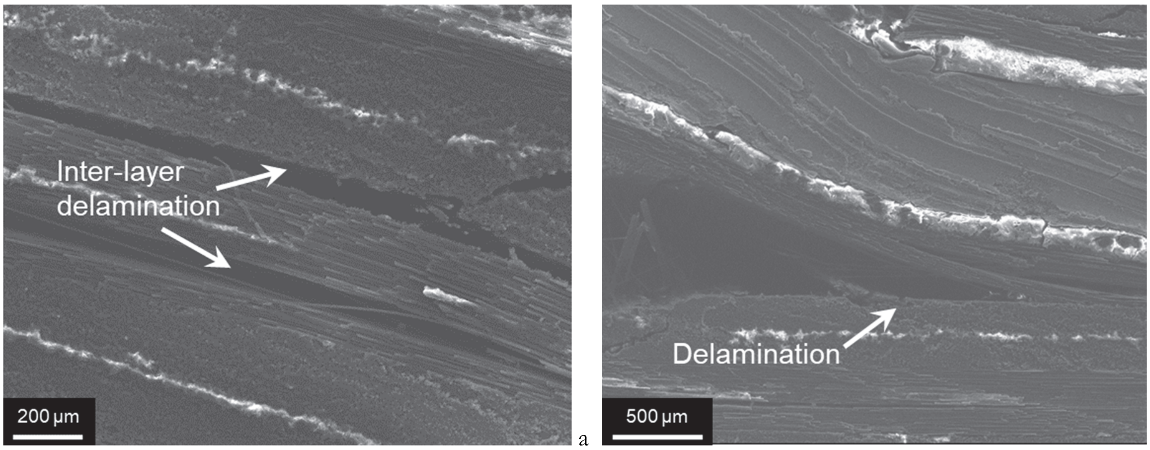

Figure 8: SEM micrographs of the short beam specimens with structural adhesive: a) top section, b) bottom section.

Ultimately, the collapse properties of the short beam sample cut from the FML bonded with the prepreg resin were investigated. The SEM micrographs, reported in Fig. 10a, revealed the existence of ply splits and cracks in crosswise bundles in both the higher and bottom sections, similar to the other short beam, but no normal longitudinal fibre failure. As visible in Fig. 10b, LOM examinations evidenced that the interface between CFRP and metal was damaged also in this case, resulting in the specimen being completely separated into three elements (the top and bottom CFRP laminates and the metal sheet).

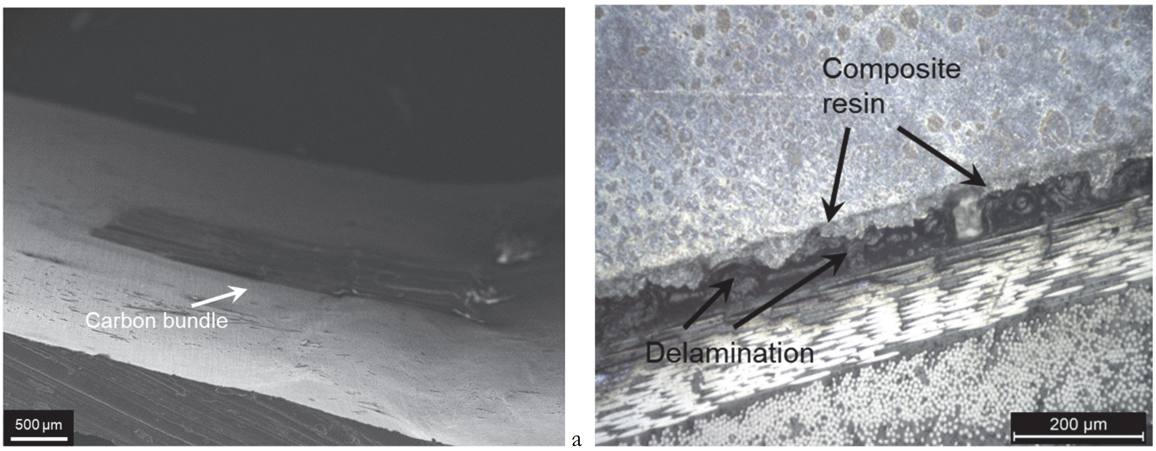

Figure 9: Long beam sample without structural adhesive: a) SEM micrograph of a composite chip, b) LOM micrograph of the composite resin layer bonded to the aluminium.

CONCLUSIONS

The goal of this study is to examine the flexural characteristics of FMLs (Fibre Metal Laminates) presenting various composite-metal interfaces. Two options were chosen for realizing this interface: inserting a thin ply of structural adhesive between the two materials or assigning the task of bonding to the composite material resin. The three-point bending test was selected to assess the structural properties of the FMLs created, and distinct stress states were investigated as the span distance was varied. The inclusion of the adhesive reduced the resistance to flexural stresses but enhanced resistance to shear loads, according to the results of the experiments. In fact, an improvement of 12% was found for the former mechanical parameter, passing from the specimen presenting the structural adhesive to the other one, while a difference of 20% was found for the latter parameter. The appearance of the fractured specimens was also investigated through micrographic analysis, in order to achieve a better interpretation of the failure mode. The analysis of the micrographs of the failure zone revealed that the collapse of the fibres was the primary source of failure in specimens subjected to flexural load. In particular, the crushing of the reinforcement due to compressive stress was noted in the top half of the specimens, while the tensile breakage was found in the lower half, due to tensile stress. On the contrary, delamination of the composite material was the primary cause of failure in specimens subjected to shear load, and both inter-layer and intra-layer delamination were observed. Only the specimens without the structural adhesive demonstrated the full separation of the different materials, even if a tiny coating of resin belonging to the composite remained on the aluminium surface.

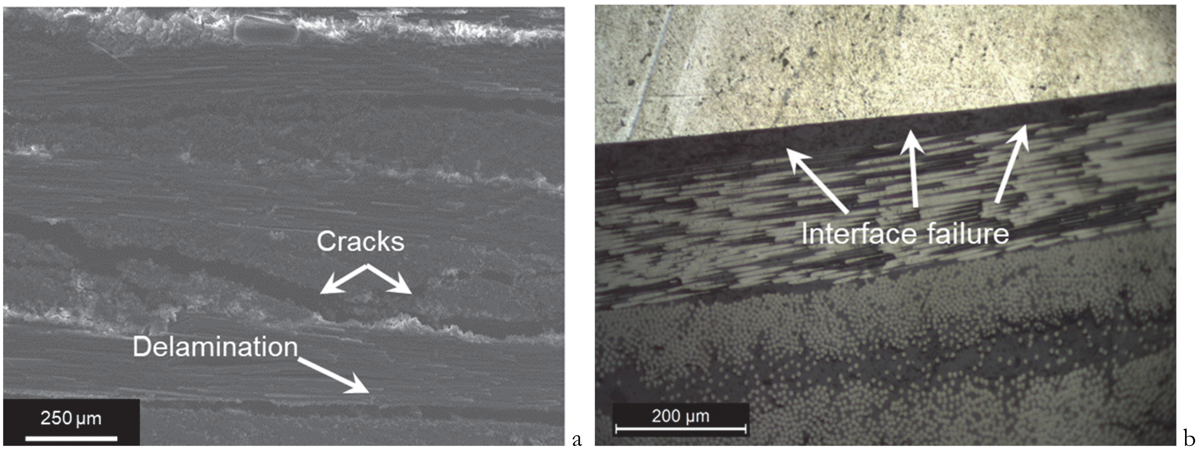

Figure 10: Short beam sample without structural adhesive: a) SEM micrograph of crack and delamination, b) LOM micrograph of the CFRP/aluminium interface failure.

REFERENCES

[1] Koziol, M. (2019) Evaluation of classic and 3D glass fiber reinforced polymer laminates through circular support drop weight tests. Compos. Part B Eng. 168, pp. 561–571, DOI: 10.1016/j.compositesb.2019.03.078.

[2] Figlus, T., Koziol, M., Kuczyński, Ł. (2019) The effect of selected operational factors on the vibroactivity of upper gearbox housings made of composite materials. Sensors 19(19), DOI: 10.3390/s19194240.

[3] Şen, I., Alderliesten, R.C., Benedictus, R. (2015) Lay-up optimisation of fibre metal laminates based on fatigue crack propagation and residual strength. Compos. Struct. 124, pp. 77–87, DOI: 10.1016/j.compstruct.2014.12.060.

[4] Rajkumar, G.R., Krishna, M., Narasimhamurthy, H.N., Keshavamurthy, Y.C., Nataraj, J.R. (2014) Investigation of Tensile and Bending Behavior of Aluminum based Hybrid Fiber Metal Laminates. Procedia Mater. Sci. 5, pp. 60–68, DOI: 10.1016/j.mspro.2014.07.242.

[5] Kim, J.G., Kim, H.C., Kwon, J.B., Shin, D.K., Lee, J.J., Huh, H. (2015) Tensile behavior of aluminum/carbon fiber reinforced polymer hybrid composites at intermediate strain rates. J. Compos. Mater. 49(10), pp. 1179–1193, DOI: 10.1177/0021998314531310.

[6] Xu, R., Huang, Y., Lin, Y., Bai, B., Huang, T. (2017) In-plane flexural behaviour and failure prediction of carbon fibre-reinforced aluminium laminates. J. Reinf. Plast. Compos. 36(18), pp. 1384–1399, DOI: 10.1177/0731684417708871.

[7] Hamill, L., Hofmann, D.C., Nutt, S. (2018) Galvanic Corrosion and Mechanical Behavior of Fiber Metal Laminates of Metallic Glass and Carbon Fiber Composites. Adv. Eng. Mater. 20(2), pp. 1–8, DOI: 10.1002/adem.201700711.

[8] Pan, L., Ali, A., Wang, Y., Zheng, Z., Lv, Y. (2017) Characterization of effects of heat treated anodized film on the properties of hygrothermally aged AA5083-based fiber-metal laminates. Compos. Struct. 167, pp. 112–122, DOI: 10.1016/j.compstruct.2017.01.066.

[9] Bellini, C., Di Cocco, V., Iacoviello, F., Sorrentino, L. (2019) Experimental analysis of aluminium carbon/epoxy hybrid laminates under flexural load. Frat. Ed Integrità Strutt. 49, pp. 739–747, DOI: 10.3221/IGF-ESIS.49.66.

[10] Bellini, C., Di Cocco, V., Iacoviello, F., Sorrentino, L. (2019) Flexural strength of aluminium carbon/epoxy fibre metal laminates. Mater. Des. Process. Commun. 1(November 2018), e40, DOI: 10.1002/mdp2.40.

[11] Romli, N.K., Rejab, M.R.M., Bachtiar, D., Siregar, J., Rani, M.F., Harun, W.S.W., Salleh, S.M., Merzuki, M.N.M. (2017)

The behavior of Aluminium Carbon/Epoxy fibre metal laminate under quasi-static loading. IOP Conf. Ser. Mater. Sci. Eng. 257, 012046, DOI: 10.1088/1757-899X/257/1/012046.
[12] Li, H., Hu, Y., Fu, X., Zheng, X., Liu, H., Tao, J. (2016) Effect of adhesive quantity on failure behavior and mechanical properties of fiber metal laminates based on the aluminum-lithium alloy. Compos. Struct. 152, pp. 687–692, DOI: 10.1016/j.compstruct.2016.05.098.
[13] Khan, S.H., Sharma, A.P. (2019) Failure assessment of fiber metal laminates based on metal layer dispersion under dynamic loading scenario. Eng. Fail. Anal. 106(July), 104182, DOI: 10.1016/j.engfailanal.2019.104182.
[14] Sathyaseelan, P., Logesh, K., Venketasudhahar, M., Dilip Raja, N.. (2015) Experimental and Finite Element Analysis of Fibre Metal Laminates (FML'S) Subjected to Tensile , Flexural and Impact Loadings with Different Stacking Sequence. Int. J. Mech. Mechatronics Eng. 15(03), pp. 23–27.
[15] Wu, X., Pan, Y., Wu, G., Huang, Z., Tian, R., Sun, S. (2017) Flexural behaviour of CFRP/Mg hybrid laminates with different layers thickness. Adv. Compos. Lett. 26(5), 168–72.
[16] Wang, W., Rans, C., Benedictus, R. (2018) Theoretical analysis of fatigue failure in mechanically fastened Fibre Metal Laminate joints containing multiple cracks. Eng. Fail. Anal. 91(January), pp. 151–164, DOI: 10.1016/j.engfailanal.2018.03.012.
[17] Bellini, C., Di Cocco, V., Iacoviello, F., Sorrentino, L. (2019) Influence of structural characteristics on the interlaminar shear strength of CFRP/Al fibre metal laminates. Procedia Struct. Integr. 18, pp. 373–378, DOI: 10.1016/j.prostr.2019.08.177.
[18] Bellini, C., Di Cocco, V., Sorrentino, L. (2020) Interlaminar shear strength study on CFRP/Al hybrid laminates with different properties. Frat. Ed Integrità Strutt. 51, pp. 442–448, DOI: 10.3221/IGF-ESIS.51.32.
[19] Bellini, C., Di Cocco, V., Iacoviello, F., Sorrentino, L. (2019) Failure energy and strength of Al/CFRP hybrid laminates under flexural load. Mater. Des. Process. Commun. (October 2019), pp. 1–6, DOI: 10.1002/mdp2.109.
[20] Rajan, B.M.C., Kumar, A.S. (2018) The Influence of the Thickness and Areal Density on the Mechanical Properties of Carbon Fibre Reinforced Aluminium Laminates (CARAL). Trans. Indian Inst. Met. 71(9), pp. 2165–2171, DOI: 10.1007/s12666-018-1348-2.
[21] Mamalis, D., Obande, W., Koutsos, V., Blackford, J.R., Ó Brádaigh, C.M., Ray, D. (2019) Novel thermoplastic fibre-metal laminates manufactured by vacuum resin infusion: The effect of surface treatments on interfacial bonding. Mater. Des. 162, pp. 331–344, DOI: 10.1016/j.matdes.2018.11.048.
[22] Ostapiuk, M., Bieniaś, J., Surowska, B. (2017) Analysis of the bending and failure of fiber metal laminates based on glass and carbon fibers. Sci. Eng. Compos. Mater. 25(6), pp. 1095–1106, DOI: 10.1515/secm-2017-0180.
[23] Vasumathi, M., Murali, V. (2013) Effect of alternate metals for use in natural fibre reinforced fibre metal laminates under bending , impact and axial loadings. Procedia Eng. 64, pp. 562–570, DOI: 10.1016/j.proeng.2013.09.131.
[24] Dhaliwal, G.S., Newaz, G.M. (2016) Experimental and numerical investigation of flexural behavior of carbon fiber reinforced aluminum laminates. J. Reinf. Plast. Compos. 35(12), pp. 945–956, DOI: 10.1177/0731684416632606.