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Research Article

Numerical Modelling of Fibre Metal Laminate Flexural Behaviour

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The employment of hybrid materials is frequently a solution for applications demanding high structural performances. FMLs (Fibre Metal Laminates) represent a group of hybrid materials, composed of metal sheets and composite material layers, and they exhibit good mechanical properties due to the presence of both types of material. The aim of this article is to introduce an FEM numerical model suitable for the prediction of the flexural behaviour of aluminium sheets/carbon fibre composite FMLs. Particular attention was paid to the simulation of the interface between the metal and the composite material. Therefore, the model for the three-point bending loading of two types of specimens was prepared: a specimen type presented a structural adhesive at the interface, while the other one was bonded by using the resin of the composite material. Experimental tests were carried out to validate the numerical model, and both the obtained load-displacement curves and the failure characteristics were compared with the results of numerical simulation. The appropriateness of the proposed model was witnessed by the correspondence between experimental and numerical results.

1. Introduction

Hybrid materials are often used for several applications in different industrial fields since their structure confers high mechanical performances, due to the combination of the characteristics of the different constituents. However, the mixture of distinct constituting materials is suitable to obtain new hybrid materials for nonstructural employment too, for example, for energy applications [1, 2] or for simplifying the manufacturing process [3]. Among hybrid materials, FMLs (Fibre Metal Laminates) are more and more considered for different applications [4, 5]. These materials present high stiffness to weight and strength to weight ratios, due to the presence of composite layers and good toughness, conferred by the aluminium sheets [6, 7]. Other interesting properties are the high fatigue resistance and high damage tolerance, given by composite material [8, 9]. FMLs were initially developed for aeronautical applications, thanks to the abovementioned characteristics. The most diffused type of FML is the GLARE (Glass Laminate Aluminium-Reinforced Epoxy) that is made of glass fibre-reinforced polymer layers alternating to aluminium sheets, and it is largely employed for the construction of the Airbus A380, the biggest plane in the world [10]. However, other types of composite materials or metal sheets can be considered for the production of such laminates. For instance, carbon fibre-reinforced polymer and aramid fibre-reinforced polymer combined with aluminium foils originate the CARALL (Carbon Fibre-Reinforced Aluminium Laminate) and the ARALL (Aramid Fibre-Reinforced Aluminium Laminate), respectively [11, 12]. In the same manner, metals other than aluminium can be considered; for example, carbon fibre composite and titanium sheets result in the TiGr (Titanium Graphite) material [13].

In the present article, a numerical model for the calculation of stress and displacement fields in an FML specimen subjected to three-point bending load is presented. In particular, the model is able to take into account not only the normal stresses developing into the specimen, especially near the external surfaces, but also the interaction at the metal-composite interface. In that manner, it is possible to simulate the bending behaviour of laminates produced according to different solutions; in fact, in this work, the bonding between the metal and the composite material was warranted in two distinct ways: in a case, a structural adhesive was considered; in the other case, the adhesion was achieved thanks to the resin of the composite material.

In the literature, it is possible to find various works dealing with the simulation of the structural comportment of FMLs, since this kind of hybrid material is employed for several purposes. A numerical model was proposed by Wittenberg et al. to replace experimental tests for projecting the fuselage shear panels in aeronautical application [14]. The definition of the best ply orientation angles for several loading conditions was obtained by Nam et al. by introducing genetic algorithms in the numerical simulation [15]. A superior mechanical behaviour of FMLs compared to standard composite materials was found too. A nonlinear model was introduced by Bikakis and Savaidis to predict the mechanical response to both loading and unloading in FML plates subjected to lateral indentation caused by a circular hemispherical tool [16]. It was found that the increase in the maximum indentation load caused an increase in the depth of the permanent dent, while the increase in the plate radius produced a decrease in the dent depth. Zolkiewski investigated the sources of error affecting the numerical simulation accuracy, carrying out both experimental and numerical tests on FMLs with laminate external layers made of composite material or steel sheets [17]. The lack of knowledge about material properties was found as the main source of error. In subsequent work, other sources of inaccuracy were identified in the mesh construction and the modelling of boundary conditions [18]. The proper definition of the mesh element dimensions was deemed as one of the most influencing factors in the accuracy of the numerical model for the simulation of impact mechanical behaviour [19]. To improve the prediction accuracy in the numerical calculation of bolt junctions in TiGr, a progressive failure constitutive model was introduced in the 3D model of the composite material layers by Hundley et al., finding an increase in the simulation accuracy for increasing values of the joint edge-distance ratio [20]. The static mechanical performances of FML were predicted through an explicit time integration scheme numerical model by Dhaliwal and Newaz [21]. The proposed numerical model was able to simulate the progressive damage of the material by considering both the stress-based material failure and the shear stress delamination. Another numerical model, able to predict the delamination after impact compression, was presented by the same researchers [22]. The proposed model presented a good accuracy at lower impact energy levels, but it was less precise for higher ones. The cohesive zone model was introduced in the numerical simulation to predict the interlaminar failure behaviour of the laminate by Xu et al. who investigated the in-plane flexural characteristics of an FML constituted by CFRP (Carbon Fibre-Reinforced Polymer) and aluminium sheets [23]. The cohesive zone modelling was considered by Lopes et al. in a numerical model for the simulation of the bonding between two different layers. The proposed model was used to simulate the end notched flexure, the double cantilever beam, and the mixed-mode beam loading conditions by using the finite element method [24]. Both the tensile and shear stress-strain characteristics of FML material were simulated by Iaccarino et al. through a simplified numerical model based on a variation of the classical lamination theory [25]. Both the anisotropy and the inelastic behaviour of the aluminium sheets were considered in the model, and experimental tests were carried out both to determine in a precise manner the mechanical characteristics of the base materials and to validate the proposed model. A new FML material, obtained by employing natural fibres instead of carbon ones in an aluminium-based FML, was introduced by Vasumathi and Murali who presented a numerical model to evaluate the mechanical properties of that material, like flexural, impact, and tensile behaviour [26].

The present article is subdivided into different phases. At first, the case study was defined, in terms of the choice of the loading conditions to be considered for the mechanical test of the material, and the laminate characteristics were identified too, such as the material type, the stacking sequence, and the interface kind. Then, the numerical model for the analysis of the flexural behaviour was determined, defining the material properties, the boundary conditions, and the mesh dimension. Particular attention was paid to the definition of the interface between the metal and the composite material layers. Experimental tests carried out considering the same laminate characteristics and loading conditions were necessary for the validation of the model. Therefore, laminates with the same stacking sequence, in terms of both material type and layer numbers, were produced by using the vacuum bag process; then, specimens for the three-point bending test were cut from the manufactured laminate

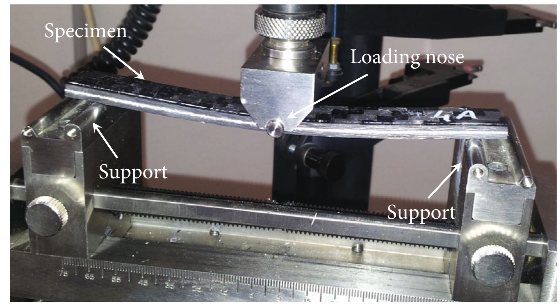


Figure 1: Specimen subjected to three-point loading.

Table 1: Material properties for the aluminium.

Property	Value
Young's modulus	70 GPa
Yield strength	100 MPa
Poisson's ratio	0.3
Density	2700 kg/m^3

Table 2: Material properties for the CFRP composite.

Property	Value	Property	Value
In-plane Young's modulus	60 GPa	In-plane shear modulus	3290 MPa
Out-of-plane Young's modulus	9 GPa	Out-of-plane shear modulus	3450 MPa
In-plane tensile strength	700 MPa	Poisson's ratio	0.3
In-plane shear strength	207 MPa	Density	1550 kg/m^3

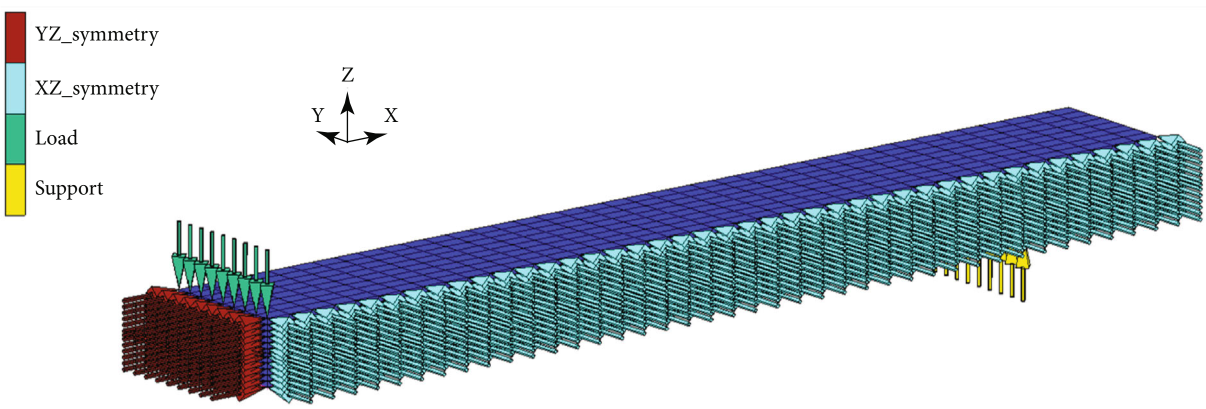


Figure 2: Boundary conditions of the numerical model.

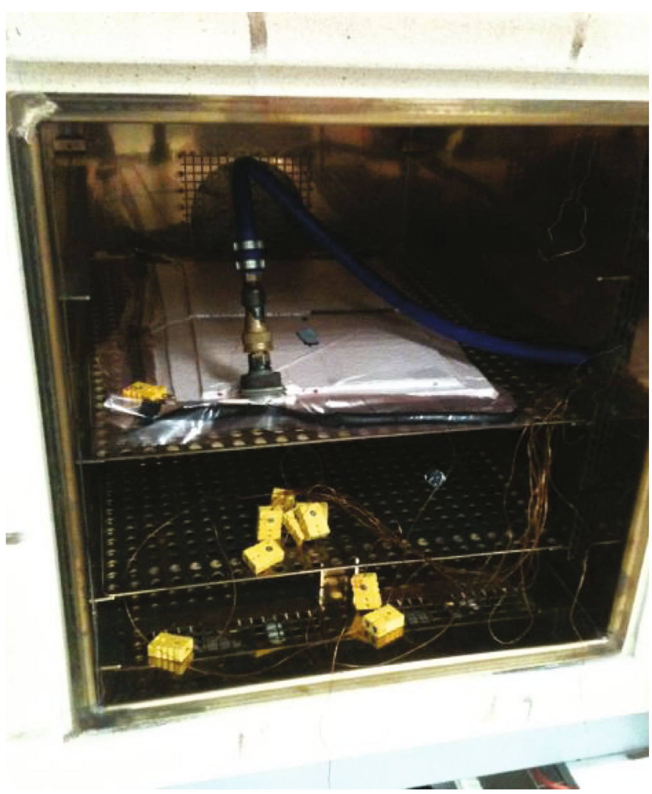


Figure 3: Cure of the laminates in the oven.

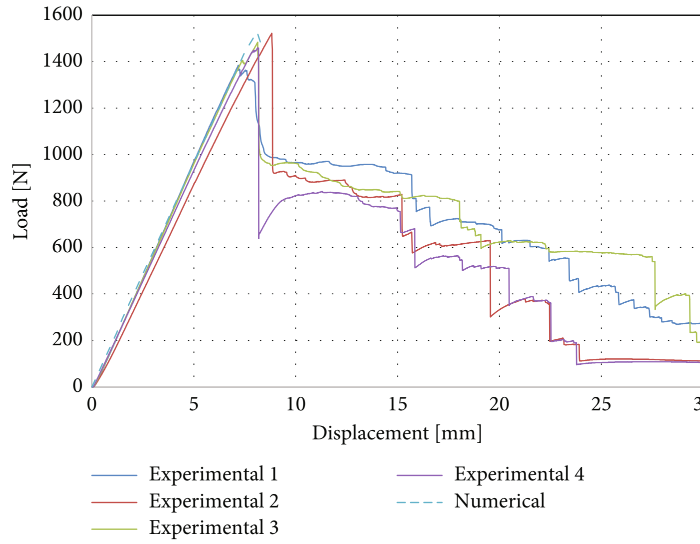


Figure 4: Comparison between experimental and numerical results for the specimen bonded with the adhesive.

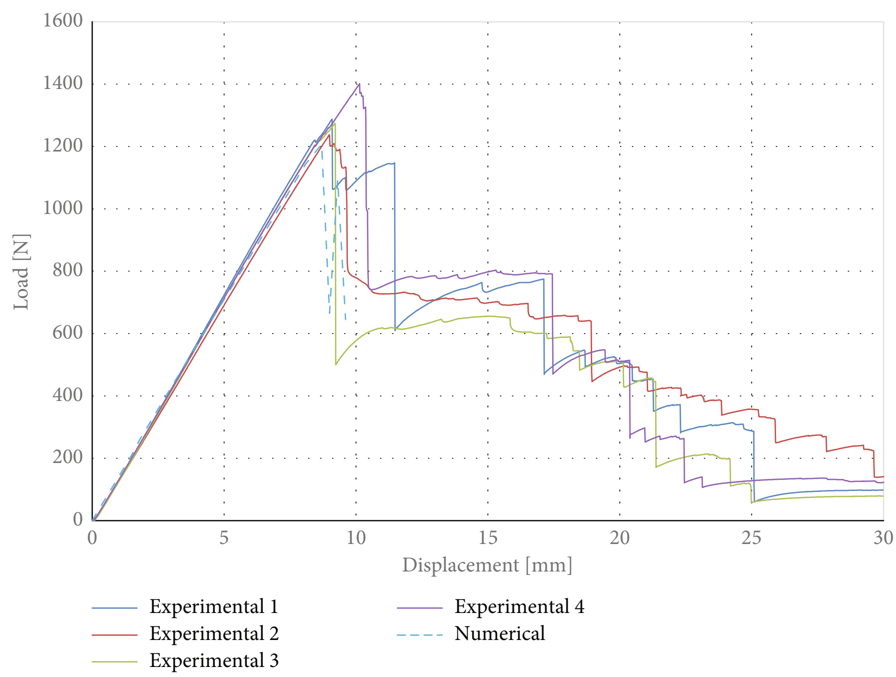
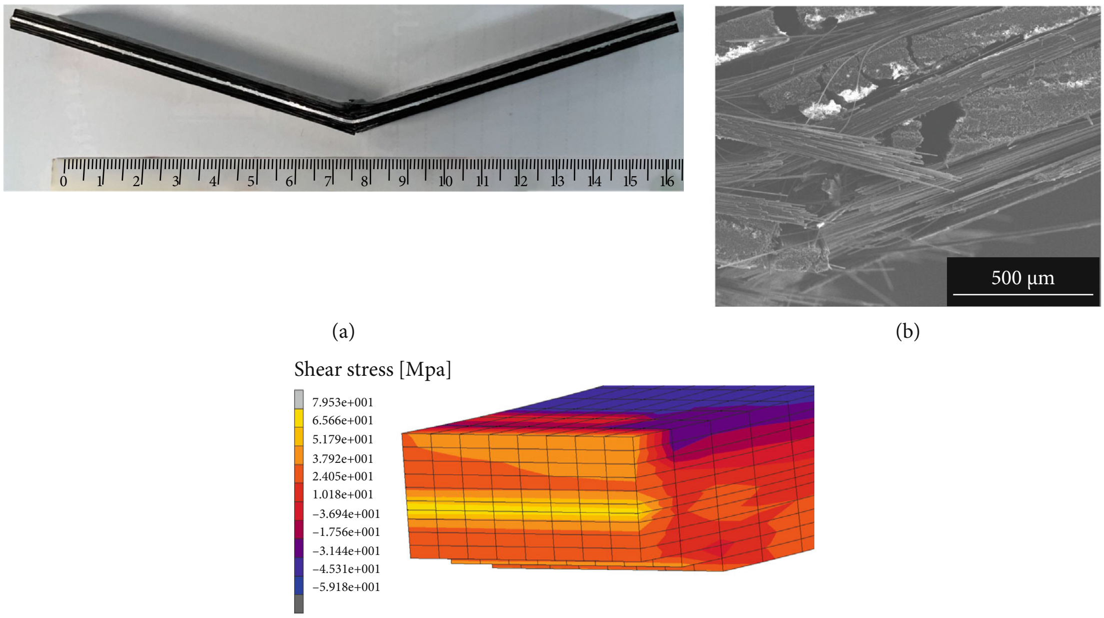


Figure 5: Comparison between experimental and numerical results for the specimen bonded with the resin.

and tested following the same scheme of the simulations. The comparison between the numerical model and the experimental tests was performed by evaluating the load-displacement curves obtained through the two methods and by comparing the damage mechanisms found in the material through micrographic analysis with those obtained by numerical simulation.

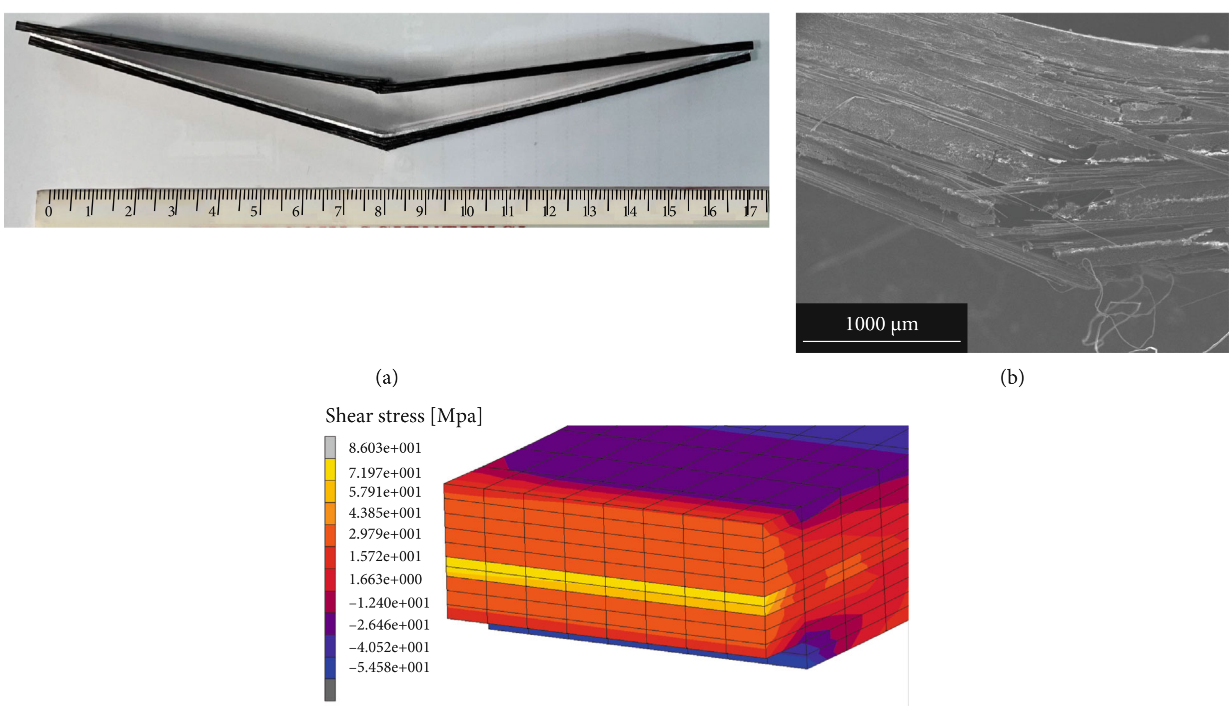
2. Materials and Methods

In the present work, the FML material taken into consideration was the CARALL. It was composed of an aluminium sheet in the centre, with a thickness of 0.6 mm, and two CFRP layers in the external zones. The prepreg ply was made of twill fabric, with a surface density of 300 g/m^2 and a fibre content of 38%. Each CFRP layer was constituted by six composite plies, whose thickness was 0.35 mm; therefore, the thickness of the complete stack was about 5 mm. It is important to bear in mind this thickness value since it was used to define the specimen dimensions. The interface between the aluminium and the CFRP was obtained in two different manners: in a case, a layer of AF 163 2k, which is a structural adhesive for aeronautical applications, was incorporated in the lamination sequence, in correspondence



(a) (b) (c)

Figure 6: Failure in the specimen with adhesive at the interface: (a) complete specimen; (b) broken fibres in the lower zone; (c) numerical model results.



(a) (b) (c)

Figure 7: Failure in the specimen without adhesive at the interface: (a) complete specimen; (b) broken fibres in the lower zone; (c) numerical model results.

of the interface; in the other case, no adhesive was inserted at the interface and the bonding between the two materials relied on the adhesive capabilities of the composite material resin.

The most important parameter in the three-point bending test is the distance between the supports, which is called span. This distance must be enough high in order to reduce shear stresses and emphasize the effect of normal stresses.

The preponderance of one type of stress rather than the other is in fact linked to the ratio between the span and the specimen thickness, which must be higher than 16 for obtaining normal stress prevalence. Therefore, being the laminate thickness equal to about 5 mm, a span length equal to 136 mm was defined. Moreover, the length and the width of the specimen depended on its thickness too; in this case, the former parameter was fixed to be 160 mm and the latter 20 mm. The diameter of the loading nose was equal to 10 mm, while that of the supports was equal to 8 mm. Finally, the last parameter to be defined was the loading application rate. It depended on the specimen thickness, the span length, and the rate of straining of the outer surface, which must be equal to 0.011/min. Therefore, considering the values of these parameters that have been defined above, a crosshead motion rate of 6 mm/min was chosen. An instance of a specimen subjected to three-point bending is visible in Figure 1.

The mesh for the numerical model was formed by brick elements. In particular, 5 elements were considered along the thickness of each CFRP layer and two for the aluminium sheet. As concerns the width and the length of the specimen, 8 elements were considered along the former direction and 20 along the latter one, respectively. Considering that the geometry and load symmetries were exploited, only a quarter of the specimen was simulated; therefore, 640 elements were used for the aluminium sheet, while 1600 were necessary for each composite layer. A linear elastic mechanical model with plasticity was chosen for the aluminium sheet, while an elastic orthotropic material with damage effect was preferred for the composite material. The material properties are reported in Tables 1 and 2 for the former and the latter material, respectively.

As abovementioned, two planes of symmetry were exploited for the simulation of the three-point bending test. These planes were perpendicular to the main plane of the specimens (which is the plane parallel to the material layers) and parallel to the specimen faces. To simulate the symmetry condition, all the displacements perpendicular to the symmetry planes were blocked, while the in-plane ones were allowed. Therefore, the displacement in the X direction was blocked for the YZ plane, while the displacement in the Y direction was blocked for the XZ plane. The support was simulated by blocking the displacement in the Z direction of the nodes positioned at 68 mm from the surface representing the specimen centre. The load, instead, was simulated by assigning a displacement to the nodes placed at the intersection between the YZ plane and the upper surface. All the cited boundary conditions are visible in Figure 2. The interface between the two different materials constituting the FML, which are the aluminium sheet and the CFRP, was simulated by considering a glued contact. This means that all the relative motions between the two surfaces in contact were not allowed, by applying tying on all displacement degrees of freedom of the nodes in contact. The interface failure was simulated by considering the breaking of the nodal connection as soon as a determined shear stress level was reached.

The validation of the numerical model was carried out by comparing the load-displacement curves obtained from the simulation with those obtained from experimental tests. Therefore, producing an FML plate was necessary, from which the specimens were extracted. The aforementioned plate was manufactured through the vacuum bag process: first of all, a flat aluminium plate, which was used as a mould, was covered with a release agent. After the prepreg plies, the aluminium sheet and the adhesive film patches were cut and prepared for lamination. Then, these materials were stacked according to the designed sequence: 6 prepreg plies were layered down, followed by the aluminium sheet and by the other 6 prepreg plies. For the FML bonded with the structural adhesive, an adhesive patch was added before the metal sheet and another right after. The so-prepared stacks were covered with the ancillary materials, which are the release film, the breather cloth, and the vacuum bag. This last was sealed by employing a butyl rubber tape, placed along the mould edge, and the vacuum was created under the bag. The laminates were cured in the oven, as visible in Figure 3, maintaining an adequate vacuum level, at a temperature of 127°C, that was suitable for the polymerization of both the composite material and the adhesive, and then, they were cooled at room temperature, demoulded, and cut by using a diamond disk saw.

3. Results

The validation of the proposed numerical model was carried out by comparing the load-displacement curves obtained from the experimental tests with that calculated from simulation for both types of laminates. The results concerning the flexural behaviour of the specimens extracted from the laminate with the structural adhesive at the metal/composite interface are reported in Figure 4. It can be noted that the repeatability of the tests is elevated, particularly in the former part of the curves, which is characterized by a linear load increment. The linear trend ended as the maximum load was reached, and it was followed by a sudden load drop and a pseudo-elastic trend. The repeatability in the second part of the curves was not high, but this zone is usually discarded because it involves the damage and the failure of the material, so it has no interest for design purposes. As concerns the numerical modelling results, it can be seen that the linear increase in the load was predicted perfectly, as well as the maximum load. The simulation ended right after the attainment of the load peak, at the beginning of the pseudo-elastic load decrease, so it is not possible to express an opinion on the model capability to predict the material behaviour in this zone. However, as aforementioned, this portion of the curve is useless.

Figure 5 describes the load-displacement trend recorded for the specimens extracted from the laminate where the aluminium-CFRP interface was realized through the resin of the prepreg. It can be noted that the shape of the curves was similar to the former ones, those relevant to the specimens bonded with the adhesive. In fact, each curve presented a linear load increment till a maximum value of the load, which was followed by a pseudo-elastic trend. The differences consisted in the maximum attained load, which ranged from 1240 N to 1400 N, while for the adhesive-bonded specimen, the range was from 1390 N to 1510 N, and the displacement at break ranged from 8 mm to 10 mm, while in the previous case, it was included between 5 mm and 8 mm. As in the previous case, the experimental repeatability was very good for the first part of the curve, till the maximum load, while the scatter was higher in the second part. As concerns the curve obtained through the numerical simulation, it can be noted that it satisfactorily predicted the mechanical behaviour of the FML till the maximum load point, while the simulation ended a few steps after this point. Therefore, it can be concluded that the proposed numerical model is suitable to simulate the mechanical behaviour of both types of laminates, so it is able to take into account the different kinds of metal-composite interfaces.

The numerical model was further validated by comparing the fracture characteristics noticed in the broken specimens with those that can be found in the virtual model. As concerns the FML presenting the structural adhesive at the metal-composite interface, the composite layers remained attached to the aluminium sheet, as visible in Figure 6(a), so the interface was not damaged. Moreover, the failure was characterized by the breakage of the fibres in the lower surface and in the centre, in correspondence of the loading nose, caused by tensile stress, as visible in Figure 6(b). Crushing of the fibres, due to compressive stress, was observed in the upper surface. The numerical model highlighted the same findings; in fact, as visible in Figure 6(c), the failure of the elements was located in the same zone as described above. Furthermore, the colour map of the shear stress did not show any sudden transition at the metal-composite interface, witnessing the integrity of the interface itself.

As concerns the other type of FML, without the structural adhesive, it can be noted that the failure was due not only to the fibre breakage in the lower surface, as in the previous case, but also to the failure of the aluminium-CFRP interface. In fact, in Figure 7(a), the upper composite layer is completely separated from the aluminium sheet, denoting scarce shear strength of the laminate bonded with the resin of the composite. It should also be noted that in other samples, the bottom layer, and not the upper one, came off, as in the illustrated case, but this does not affect the above conclusion. Moreover, the failure of the fibres in the lower zone of the specimen can be noted in Figure 7(b). The numerical simulation found similar results; in fact, as reported in Figure 7(c), the failure of the element in the central-lower zone happened; moreover, a step in the shear stress value can be observed, near the interfaces, denoting the delamination phenomenon.

4. Conclusions

The present article deals with the numerical simulation of the mechanical behaviour of FMLs (Fibre Metal Laminates). The introduced model was able to take into account the type of bonding at the interface between the metal sheets and the composite material layers. In fact, a nodal connection was considered at the interface between the composite material mesh and the metallic material mesh, which was able to break when a specific shear stress level was attained. The proposed model was validated through the comparison against experimental results; therefore, specimens for the three-point bending test were produced, by considering two different types of bonding at the metal-composite interface: one was assured by a structural adhesive, while the other relied on the gluing capability of the resin of which the composite material was made. The comparison between the experimental test results and the numerical ones evidenced the suitability of the model for the prediction of the bending behaviour of FML specimens; in fact, the load-displacement curve calculated through the numerical model was included among the experimental trends for both types of specimens. A further comparison was carried out on the failure modes: in the case of the interface obtained by using the structural adhesive, the specimen failure was caused by that of the external lower fibres, while in the other case, the failure of the metal-composite interface occurred before that of the external fibres. These damage peculiarities were found in the numerical results too. In the future, the proposed model can be extended to other stress conditions, for instance, that one arising in the three-point bending of a short beam.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

This work was performed as part of the authors' employment at the Department of Civil and Mechanical Engineering, University of Cassino and Southern Lazio. The authors declare that there is no conflict of interest regarding the publication of this article.

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