Effects of stacking sequences on the Interlaminar Shear Strength of CF/PEKK composites

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Abstract: *High performance thermoplastic composites for aerospace primary structures are increasingly studied in the last years. However few articles report the properties of the PEKK/CF composite material for structural applications. In this paper the Interlaminar Shear Strength of laminates obtained with different stacking sequencies of unidirectional layer obtained from a PEKK/CF prepreg tape was evaluated. A modification of the ASTM D2344 standard is proposed for obtaining a valid failure mode, considering the less brittle behaviour of the thermoplastic matrix compared to thermosets. Furthermore, this testing campaign was carried out performing a 2D Digital Image Correlation. Results show how, the modified testing parameter are crucial to obtain shear failure mode for the considered carbon fibre reinforced thermoplastic composite.*

Keywords: TPC; PEKK; ILSS; Composites; DIC

1. Introduction

Polymer matrix composites (PCM) are more and more used for the development of primary structures in the aerospace industry due to their high strength-to-density and stiffness-to-density ratios and superior physical performances that enables a weight reduction of the aircrafts' overall weight, without the reduction in the structure's performance [1]. In the last decade, the usage of thermoplastic polymers for the matrix composition has drawn the attention of researchers and industries due to some advantages given by the nature of these materials. The main advantages of these polymers are related to their production process that is faster and cheaper. Indeed, since nowadays most of the used matrix are thermoset resins, where a long cure process is needed with associated high production costs. The thermoplastic composites do not need a curing step making the production process faster and simpler. For this reason, it is considered of great importance to study the performances of these materials obtained through out-of-autoclave production processes as thermoforming or automated tape layering [2].

Even if thermoplastic matrices are usually tougher than their thermoset counterparts [7], thermoplastic based composites (TPC) are subjected to the phenomenon of delamination too. Delamination can be also caused by a poor adhesion between the fibres and the matrix, a potential source of lower overall mechanical properties in TPC [3]. Due to this fact, in literature there are many experimental data regarding the performances of TPC about the inter-lamina fracture toughness with exception to the ones composed by poly-ether-ketone-ketone (PEKK) matrix where few data are available.

PEKK is an aerospace grade semicrystalline polymer with a wide operational temperature range and capable to withstand high mechanical loads. It is therefore an aim of this work to provide

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information regarding the interlaminar properties of the carbon fibre reinforced PEKK composites, in particular on the Interlaminar Shear Strength (ILSS) of the component produced by thermoforming.

2. Material

For the testing campaign, it has been used APC PEKK-CF from Solvay, a prepreg tape whose typical applications include aircraft structures, space components and other structural engineering parts. The prepreg is characterized by a 60% of fibre content in volume. The laminates were processed through hot-press moulding. The lay-up of the different prepreg sheets was wrapped up using Kapton foils to avoid the flow of the matrix and to maintain the desired geometry of the laminate. The package was then heated up to 370 °C without pressure applied, once reached the final temperature it has been applied a pressure of 10 bar for 20 minutes. Finally, the lamina was left to cool down in air with and the pressure was released once the temperature was lower than the expected glass transition (about 159 °C).
Three laminates were produced varying the stacking sequences to study the interlaminar properties changes with the variation of the fibre orientation along the thickness. Three representative sequencies were selected: Unidirectional 0°, $[90°/0°]_{8S}$ and $[0°/90°/45°/-45°]_{4S}$. All the three laminates are symmetric. Subsequently, the three laminates of dimensions 120x120x4 mm have been cut through waterjet to obtain the Short Beam Test specimens.

3. Method

For the evaluation of the Interlaminar Shear Strength (ILSS), it has been followed the ASTM standard D2344/D2344M, initially using cylinders of diameters of 6 mm and 3 mm for the loading nose and supports, respectively, as specified in the normative. As described in ASTM D2344, the tests were conducted on specimens nominally 4 mm thick, 8 mm wide and 24 mm long and the span between the support rollers was set to 16 mm. The rate of the loading nose's movement was set to 1 mm/min as specified in the standard.
To obtain a valid failure mode caused by interlaminar shear, in the case of $[90°/0°]_{8S}$ specimens, the dimension of the cylinders has been increased to avoid localised crushing on the specimen given by the stress concentration that arise in the interfaces between specimen and support/loading rollers. This aspect may underestimate the ILSS value caused by a compressive damage that may occurs before shear failure [4-6]. The diameter of the support rollers was then set to 4.5 mm while the diameter of the loading nose was incremented until a correct failure mode was obtained. Tests were conducted with a diameter of 8 mm, 10 mm, 12 mm, 16 mm and 20mm. This test method, in the case of unidirectional specimens, is useful also to determine the shear behaviour of the material through the creation of stress stain curves [6].
The strain field on the lateral surface was reconstructed using the 2D digital image correlation (DIC). For this aim, the surface of the specimen was preliminary coated with an opaque white water-based spray paint and subsequently a random pattern of black dots on the white background was created with a black paint as it is shown in Figure 1.
The tests were recorded using a Canon EOS 70D camera with a resolution of 1920×1080 pixels and 24 photograms per second. The images were calibrated manually obtaining a scale of 0.033 mm/pixel. For the analysis, the commercial software GOM Correlate version 2020 was used.
The shear strain values, obtained through the DIC analysis, were validated performing a SBS test with a strain gauge of grid dimension of 0.6x1 mm, placed at 45° in the midway between the loading nose and the support roller. The strain gauge was applied in the thickness midplane, on the opposite face with respect the one recorded by the camera.

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After the test, the failure modes on the specimens were analysed with the optical microscope, Nikon model Eclipse LV105N.

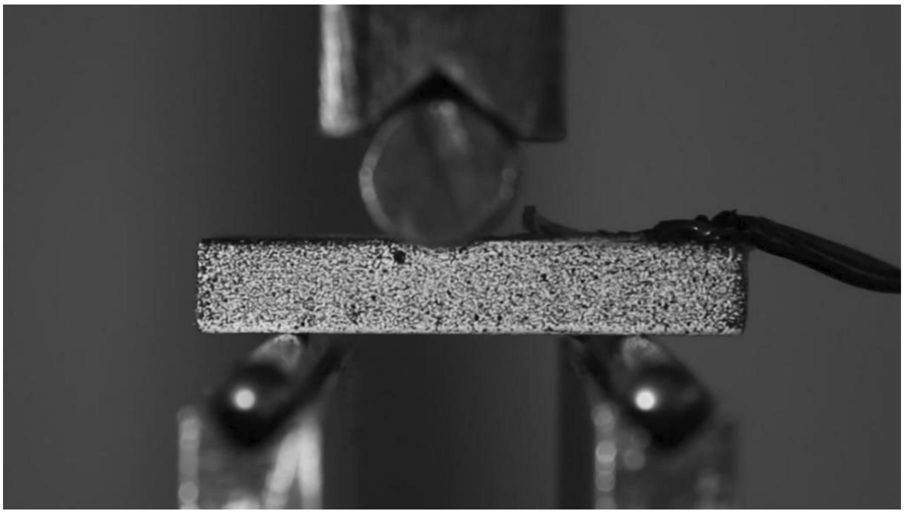

Figure 1. Picture of the test validated through strain gauge

4. Results and discussion

As specified in the ASTM D2344 standard, the short beam strength is evaluated using the classical beam theory which states that the shear stress varies parabolically through the thickness of the specimen reaching, in the midway plane, the maximum value given by Eq. (1) in the case of a beam with rectangular cross section:

$$\sigma_{xy} = \frac{3}{4} \frac{P_M}{b \cdot h} \quad (1)$$

where P_M is the maximum value of the reaction force experienced by the test machine during the test, b is the width of the specimen and h is its thickness. Despite the simplicity of the theory used it has been shown that provides a good approximation of the real state of stress experienced by the specimen [6].

Values obtained with the different stacking sequencies can be seen in Figure 2. As it was expected, the unidirectional specimens have a higher value of ILSS. Indeed, in the case of layers with the same direction, during the production process of the laminate the fibres from adjacent plies tend to interlace between them making the laminate more homogeneous. The distinction between plies is faded and fibre bridging phenomenon can occur [3].

The specimen with a stacking sequence of $[0°/90°/45°/\text{-}45°]_{4S}$ are the ones with the lowest value of ILSS. It has been also noted a higher standard deviation on the values of the short beam strength. The reason of the higher variability on the ILSS values could be the fact that usually the non-zero ply interfaces are characterised by a higher level of variability regarding the thickness of the matrix region between plies, causing a high variability on the interlaminar fracture toughness [7]. As it can be seen in Figure 3, multiple delamination occurs along the thickness of the specimen, in some cases the interlaminar fracture branches and some smaller intralaminar fractures of the matrix are observed in the non-zero direction plies.

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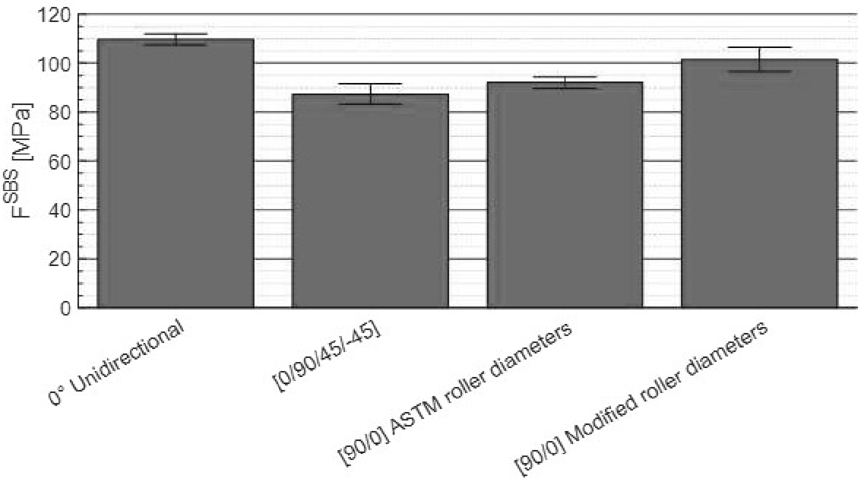

Figure 2. ILSS values of the different lay-up sequencies

Regarding the $[90°/0°]_{8S}$ specimens, it has been observed a failure mechanism not valid for the determination of the ILSS. As can be observed in Figure 3, the failure is triggered by a compression buckling failure next to the loading nose position. The cause of this behaviour could be the ductile nature of the thermoplastic matrix that experience an extensive compression yielding below the loading nose position [8]. Stress concentration in this region leads to intensive deformation of the matrix. the result of the elevated deformation gradient with respect the region on the side of the loading nose position leads to the matrix cracking in the plies with a 90° direction and to a tensile failure of the carbon fibres in the 0° plies.

The presence of this failure behaviour prior to the delamination can give an underestimation of the ILSS. Since this problem is caused by the stress concentration due to the contact of the loading nose on the specimen's surface, the dimensions of the loading nose and the support rollers were increased to assure a larger contact area and reducing the local stress values. The same technique was adopted in other research works on different materials [5-6]. The compressive failure was avoided using a loading nose diameter of 20 mm and a diameter for the support rollers of 4.5 mm.

The test was repeated with this configuration and as expected, higher values of short beam strength were obtained (see Figure 2). It is worth noting how the variability of the results with the new configuration has increased significantly, indeed as in the case of the $[0/90/45°/-45°]_{4S}$ specimens, the ILSS for non-zero ply interface is characterised with a high variability, and this is not true for the compressive failure mode experienced by the specimen tested with the standard ASTM dimension of the rollers.

As it is possible to see in Figure 3, the fracture is interlaminar but there is also present delamination migration inside the 90° plies. This happens because of the shearing directions that tends to drive the fracture upward or downward, inside the laminate until it reaches the interface with the ply with the fibers directed in the delamination growth [8]. The presence of the fibers along the length of the specimen avoids the propagation of the fracture along the direction of the thickness, while in the 90° plies the fracture is free to grow in the matrix.

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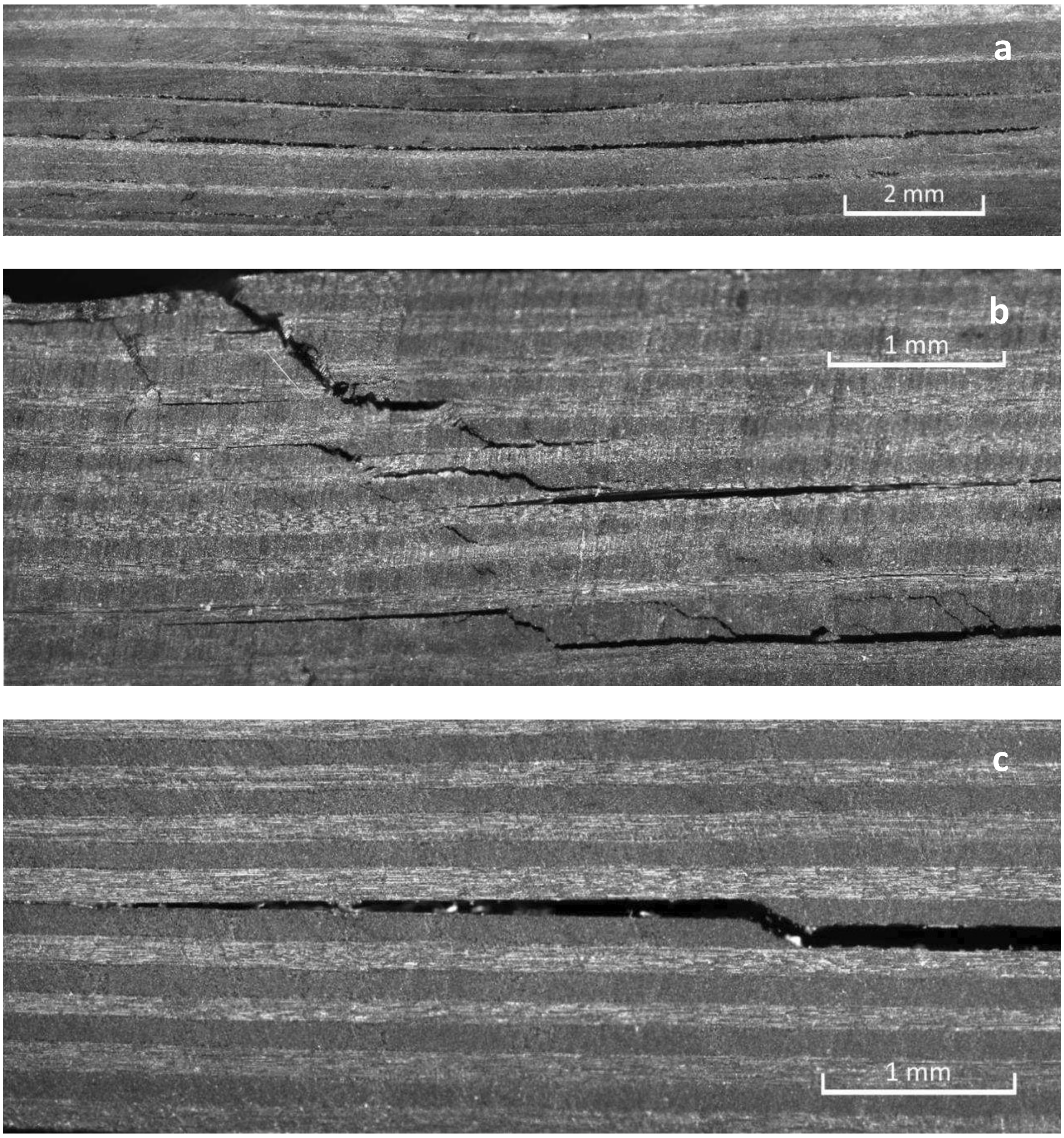

Figure 3. Fracture morphology in a [0°/90°/45°/-45°]$_{4S}$ specimen (a), [90°/0°]$_{8S}$ specimen tested with standard roller dimensions (b) and [90°/0°]$_{8S}$ specimen tested with modified roller dimensions (c).

In Figure 4 is reported the result of the DIC regarding the shear distribution exhibited by a unidirectional specimen during the test. The strains refer to a frame taken during the linear part of the loading curve. The distribution of the shear strain along the thickness is in accordance with the theory and the maximum values are in the midplane thickness, in the region between the loading nose and the support rollers. In this region, where most of delamination occurs (indicated in the figures with the red boxes), the shearing contributions are predominant, and the low gradient allows to evaluate the maximum shear strain by spatial averaging the strain values obtained through DIC.

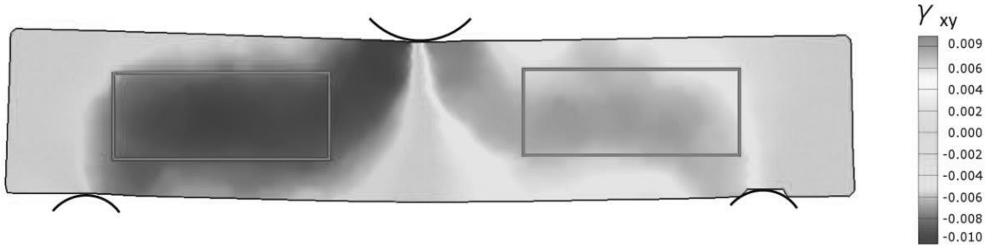

Figure 4. Shera stain field evaluated through DIC on a unidirectional specimen

5. Conclusions

From the results obtained with the short beam strength test campaign it is clear how a modification on the ASTM standard regarding the loading roller dimensions should evaluated considering the nature of the polymeric matrix. For matrices that tends to experience a higher plastic response, as most of the thermoplastic polymers, the dimensions of the rollers need to be increased.

The results of the DIC can also be used for the assessment of the shear stress-strain strain constitutive law of the material and to model the interlaminar and intralaminar fracture behaviour. Due to the nature of the thermoplastic matrix, the composites can exhibit plastic behaviour in the directions perpendicular to the fibres' direction. A correction on the Eq. (1) may be necessary for the evaluation of the maximum shearing stress experienced by the specimen at higher loads where non-linearities cannot be neglected.

6. References

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