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INTERLAMINAR SHEAR STRENGTH OF CONTINUOUS CARBON FIBER REINFORCED THERMOPLASTIC COMPOSITES MANUFACTURED BY 3D PRINTING

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Abstract. *In this paper the interlaminar shear strength (ILSS) of continuous carbon fiber reinforced thermoplastic composites (CFRTP) manufactured by 3D printing is evaluated. Firstly, the manufacturing process used to fabricate the specimens as well as the test procedure are detailed. After that, the results obtained from the performed tests are compared to the results present in the literature. They showed to be very promising, which contributes to enlarge their application. Finally, the main characteristics of short-beam shear failure modes are discussed with the support of microscopical analysis.*

Keywords: *3D printing, carbon fiber composites, experimental material properties, interlaminar shear strength*

1. INTRODUCTION

Nowadays polymer matrix composite materials have been successfully used in many industries, such as aerospace, automotive, marine and military, among others (Dutra and Almeida, 2015). In this context, it is very important to know the mechanical properties of a composite material viewing the correct design of the final structure. Among the several mechanical properties applied in the structural design, the interlaminar shear strength (ILSS) is generally a critical point. This can be linked to the fact of layered materials do not present fibers oriented along the thickness direction to support the interlaminar shear load. Thus, several studies to characterize this property, as well as its improvement, have been conducted over the last years (Bowles and Frimpong, 1992; Ozkoc *et al.*, 2004; Fan *et al.*, 2008; Ahmed and Vijayarangan, 2008).

In the studies performed by Ozkoc *et al.* (2004) the interlaminar shear strength of short glass fiber reinforced acrylonitrile-butadiene-styrene (ABS) and polyamide 6 (PA6) were experimentally evaluated. The glass fibers were embedded into the polymer matrix using a hot-press and different fiber surface treatments were also applied. The PA6 matrix specimens presented values about $15MPa$ for the interlaminar shear strength while ABS matrix specimens did not exceed $7MPa$ for the interlaminar shear strength.

In Fan *et al.* (2008) studies were conducted in order to improve the interlaminar shear strength of glass fiber reinforced epoxy composites. In this context, carbon nanotubes were inserted in the regions between fabric layers. The authors verified that the enhanced material presented an interlaminar shear strength value of $38.4MPa$. This represents an improvement of about 18% when compared to the glass fiber reinforced epoxy without adding carbon nanotubes.

In their work, Ahmed and Vijayarangan (2008) investigated the effect of stacking sequence on tensile, flexural and interlaminar shear properties of woven jute-glass fabric reinforced polyester composites. The maximum value obtained for the interlaminar shear strength was $16.8MPa$. In their work it is also mentioned that a common glass fiber reinforced epoxy composite presents an interlaminar shear strength range from $30MPa$ up to $75MPa$ (which is compatible to the results found by Fan *et al.* (2008)).

In the mentioned works, it is possible to notice that traditional manufacturing processes of composite materials were used to fabricate the specimens. Currently, there are other processes, such as 3D printing, that are also capable of producing parts in composite materials. These manufacturing processes will be further detailed in Section 2. In any case, it must be said that works evaluating the interlaminar shear strength of 3D printed parts could not be found in the available literature. As observed in the literature review, this mechanical property is very important to the design of composite structures.

In this context, the present work aims to fill this gap in the literature evaluating the interlaminar shear strength of composite specimens manufactured by 3D printing. In addition, the work also aims to present an innovative 3D printing process capable of producing parts with excellent mechanical properties that consequently can enlarge the application of printed parts.

2. MANUFACTURING PROCESS

Today, the Additive Manufacturing (AM) term is more related only to the 3D printing processes but in fact it contemplates the manufacturing processes whose final parts are built by adding material. For example, the main composite manufacturing processes like Automated Tape Laying (ATL), Automated Fiber Placement (AFP) and also the Hand-Layup process can be described as an AM process since the parts are made layer-by-layer. According to ASTM F2792 (ASTM, 2012), the AM process consists of 'joining materials to produce parts from 3D model data, usually layer upon layer, as opposed to subtractive methodologies'.

According to Quan *et al.* (2015) this novel class of manufacturing process presents characteristics which allow the construction of very complex final parts with minimal loss of material, which is not always possible with traditional subtractive methods. In traditional methods there are many known cases where the accessibility of tools is limited, leading a complex part to be built in several small parts and then assembled.

Among the AM processes it can be cited the Fused Filament Fabrication (FFF). In this process, the 3D CAD model is initially sliced into successive layers where the thickness can be defined according to the desired finishing but always respecting the maximum resolution of the printer. It is also possible to configure some printing parameters such as infill speed, nozzle extrusion temperature, infill type and total infill percentage. After configuration, these settings are transformed into command lines that are interpreted by the printer system so the part can be printed. Finally a filament of thermoplastic material is melted into an extrusion nozzle and the beads are deposited side by side to form a layer. These layers are successively deposited on top of each other to build the part. Figure 1 presents an schematic view of how the FFF process works.

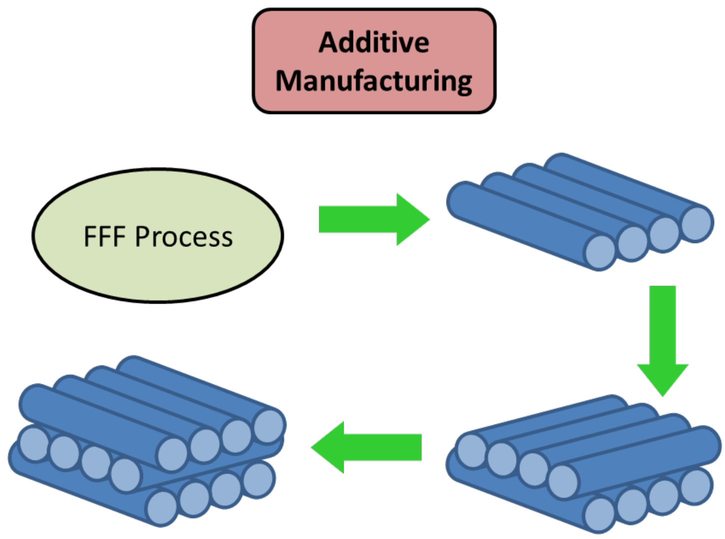

Figure 1. In the Fused Filament Fabrication the beads are deposited side-to-side until a layer is completed. The final part is composed by the deposited layers.

In the present study, a modified FFF process was used to manufacture the samples. It consists of a new patented process by Markforged (2015). The MarkOne® printer is able to produce parts reinforced by continuous carbon fibers, Kevlar® or fiberglass. The operating principle remains the same as conventional FFF printers. However, the MarkOne® printer presents a secondary extrusion nozzle that works with a continuous fiber reinforced filament which is deposited continually in raster or contour paths. The raster angle can also be adjusted for each layer in order to produce stronger parts along the loading directions. Figure 2 presents an schematic view of the fibers embedded into the thermoplastic material. Finally, it should be mentioned that all the specimens tested in this work were printed using the carbon fiber reinforced thermoplastic filament.

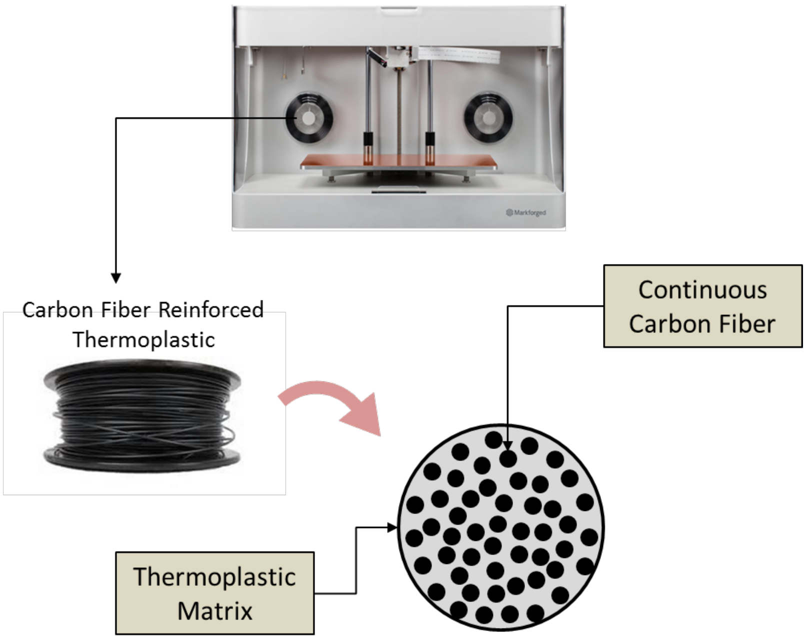

Figure 2. FFF process of continuous carbon fiber reinforced thermoplastic Markforged (2015).

3. METHODOLOGY

3.1 Interlaminar shear strength

The Interlaminar Shear Strength (ILSS) can be described as the matrix shear strength between two adjacent layers in a composite material. Although there exist many international standards describing testing methods to obtain this property, its exact determination still remains a challenge. Among the test methods applied to obtain approximated values for the Interlaminar Shear Strength it can be cited the Short-Beam Strength (SBS) and Compression Shear Test (CST). These methods provide good approximations for the Interlaminar Shear Strength.

The SBS method is often used due its simplicity regarding both specimens preparation and test apparatus. In the industry, the SBS test is also used as quality inspection for composite properties dominated by the matrix. The test method, as suggested by its name, requires a relatively thick short-beam which is tested under three-point bending load. The ASTM International organization presents the standard ASTM D2344M (ASTM, 2016) which determines the short-beam strength of high-modulus fiber-reinforced composite materials. The specimen can be obtained from a curved or a flat laminate up to $6mm$ thick and both multidirectional and pure unidirectional laminate can be tested. In case of multidirectional specimens being tested, at least 10% of fibers shall be along the span direction.

According to ASTM D2344M (ASTM, 2016), the flat specimen geometries shall respect the following recommendations based on the specimen thickness h:

$$L = 6h, \tag{1}$$

$$b = 2h, \tag{2}$$

where L is the specimen length and b is the specimen width. The Figure 3 presents the typical flat specimen geometry.

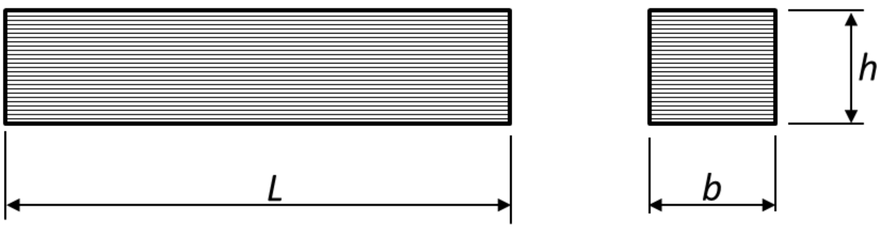

Figure 3. Typical flat specimen geometry.

3.2 ILSS configuration

The typical ILSS flat specimen configuration is presented in Fig. 4 (ASTM, 2016). The span length S shall be adjusted based on the measured thickness such that $S = 4h$. The loading nose (upper cylinder) shall be $6.0 \pm 0.50mm$ diameter. The supports (lower cylinders) shall be $3.0 \pm 0.40mm$ diameter. During the test, the applied load P is recorded as well as the crosshead displacement. Moreover, the maximum load, final load and the load at any discontinuities shall be also recorded.

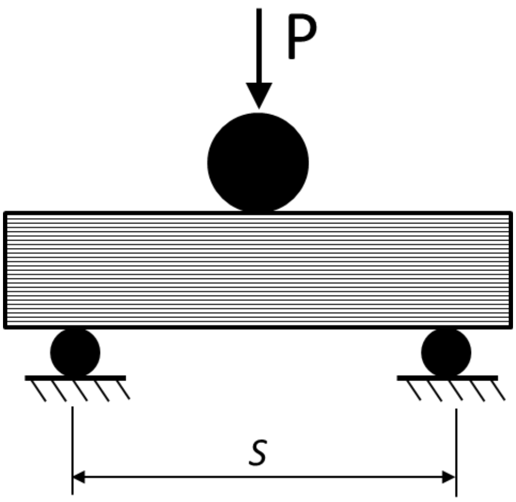

Figure 4. Typical flat specimen configuration (ASTM, 2016).

In view of ASTM D2344M (ASTM, 2016) recommendations, the specimen dimensions were carefully defined and they are presented in Tab. 1. Firstly, a small carbon fiber reinforced thermoplastic matrix plate with 28 layers was manufactured with the MarkOne® printer. The printer slicing software automatically sets the extrusion nozzle temperature and infill speed according to the applied material. The layer thickness was set to $0.125mm$ (default value when carbon fiber reiforced filament is used). In order to respect ASTM D2344M (ASTM, 2016) required tolerances, the plate was cut into flat ILSS specimens using the precision composite plate saw Extec Labcut 5000 present at the Lightweight Structures Laboratory.

After cutting the specimens, they were labeled in order to be traceable back to the raw material and to not influence the test method. The defined sequence of name for each specimen is shown in Fig. 5. In this test, the spool number (represented by X) and plate number (represented by Y) were the same for all tested specimens. However, this methodology was adopted viewing to possible future works and tests thus preserving the traceability.

Table 1. Defined specimen dimensions.

Layers	$h[mm]$	$L[mm]$	$b[mm]$	$S[mm]$
28	3.5	21.0	7.0	14.0

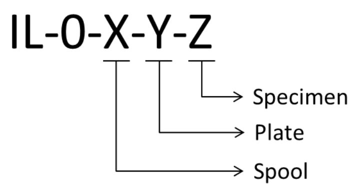

Figure 5. Defined sequence of name for each specimen.

3.3 Testing machine and fixtures

The specimens were tested in a mechanical testing machine INSTRON Model 5982 (Fig. 6) present in the Lightweight Structures Laboratory (LEL) of the Institute for Technological Research (IPT) located at São José dos Campos, São Paulo, Brazil. An INSTRON bending fixture system with interchangeable anvils INSTRON (2017) was used to apply load to the specimens. All required data were recorded by the INSTRON acquisition system. It shall be remarked that the loading nose was carefully located equidistant between the side supports in order to provide to correct load application. Figure 7 presents a similar testing fixture used in this study (INSTRON, 2017).

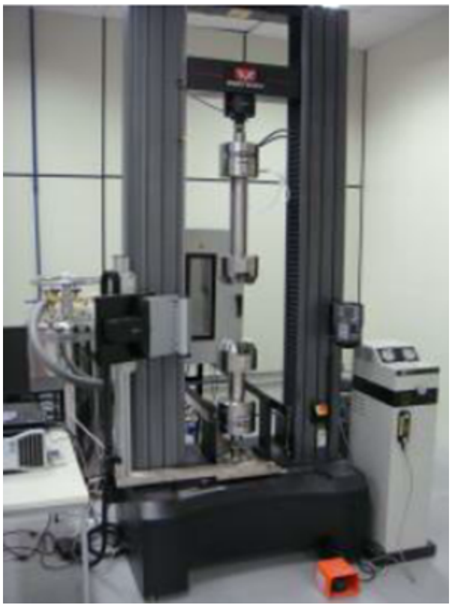

Figure 6. INSTRON Testing Machine present in the Lightweight Structures Laboratory at São José dos Campos, São Paulo, Brazil.

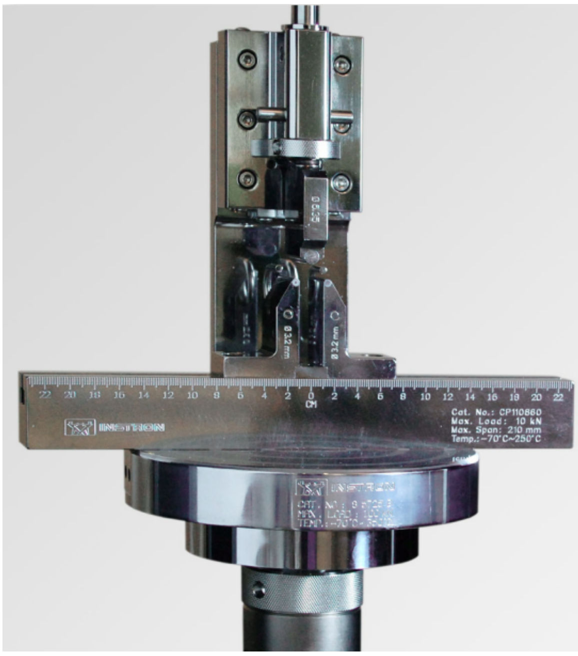

Figure 7. Three-Point Bend Loading and Support Anvils required by ASTM D2344M (ASTM, 2016; INSTRON, 2017).

3.4 Calculation

According to the FAA Technical Report CT-93 III (FAA, 1993) the stress states in the specimens are highly complex. Thus non-uniform shear stress distribution and small depths make measurement of strains impossible. Due to nonuniform shear stress distribution along the mid-plane, shear strength is often over estimated and perhaps for this reason the test sometimes yield strengths comparable to in-plane shear strengths. The short-beam strength F^{sbs} can be obtained according to ASTM D2344M (ASTM, 2016) as indicated in Eq. (3). Nevertheless, this approach gives only a measure of the strength since the stress state is highly complex.

$$F^{sbs} = \frac{3}{4}\frac{P_m}{bh}, \tag{3}$$

where P_m is the maximum load observed during the test.

3.5 Failure mode

The failure mode in SBS test is very important viewing that the failure can be influenced by flexural and contact stress resulting in mixed failure mode. According to ASTM D2344M (ASTM, 2016), the following typical failure modes can be identified visually:

- Interlaminar Shear;
- Flexure (Compression or Tension);
- Inelastic Deformation.

4. RESULTS

4.1 Testing parameters

In this study, five specimens were tested under three-point bending load. The specimens were tested under room temperature conditions (21^oC) without previous conditioning. The speed of testing was controlled by the crosshead movement at a rate of $1.0mm/min$. The specimens were carefully centered into the test fixture overhanging the side support centers by the minimum required distance. After inserted into the test fixture, the specimens were loaded at the specified rate and throughout the tests a load drop-off was not seen. Thus the specimens were loaded until a two-piece failure was identified. A video-camera was placed in front of the specimens in order to help identify the failure. The identified failures were confirmed after microscope analysis and they will be detailed later.

4.2 Load-displacement curves

Figure 8 presents the recorded load versus crosshead displacement acquired throughout the test for the five specimens. The results are very consistent to typical curves for the short-beam shear test even though their thermoplastic matrix. In this context, no load drop-off was identified.

4.3 Short-Beam strength

Table 2 presents the computed Short-Beam Strength for the tested sample. Except for the first tested specimen, the obtained values for the Short-Beam Strength were very close to each other. The deviation experienced in the first specimen can be attributed to a premature failure whose cause is under investigation.

Table 2. Short-Beam Strength.

Specimen	$P_m[N]$	$F^{sbs}[MPa]$
IL-0-0-1-1	1235	34.9
IL-0-0-1-2	1406	40.4
IL-0-0-1-3	1384	40.2
IL-0-0-1-4	1353	39.4
IL-0-0-1-5	1276	39.1
Max	1406	40.4
Avg	1331	38.8
Std	72.3	2.2

4.4 Optical microscope analysis

In order to confirm the obtained failure modes all specimens were analyzed before and after testing. An optical microscope Olympus model DSX-HRSU equipped with a $5\times$ magnification lens present at the Lightweight Structures Laboratory was used in the analyses. Figures 9 and 10 present the microscope analysis for the specimens IL-0-0-1-1

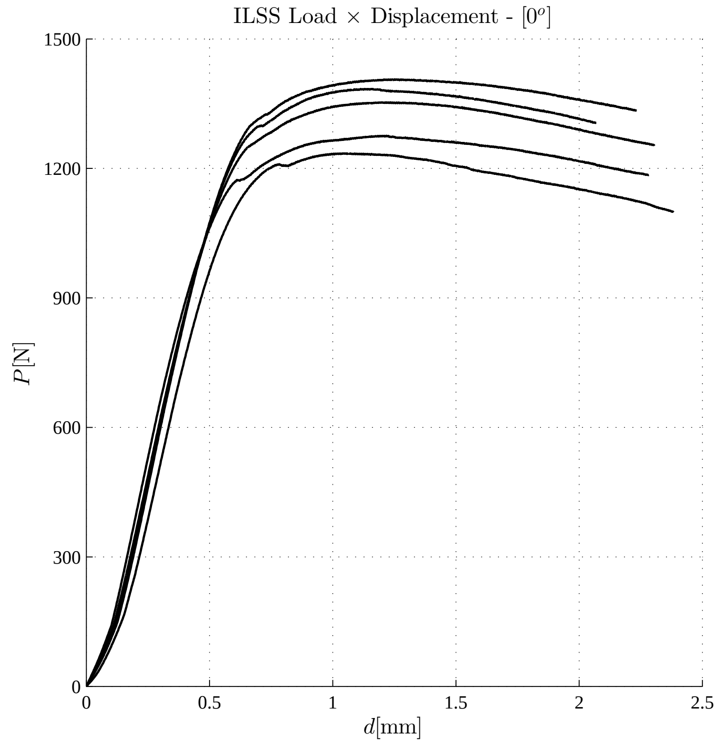

Figure 8. Recorded load versus crosshead displacement.

and IL-0-0-1-5 respectively. The obtained images shows that specimens failed by both interlaminar shear (delaminations between layers) and compression (fractured fibers on the loading nose region) due to flexural load.

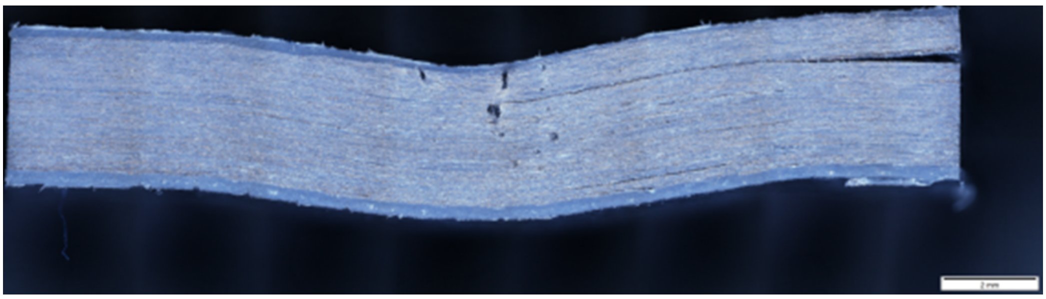

Figure 9. Microscopical analysis of tested specimen IL-0-0-1-1 magnified $5\times$.

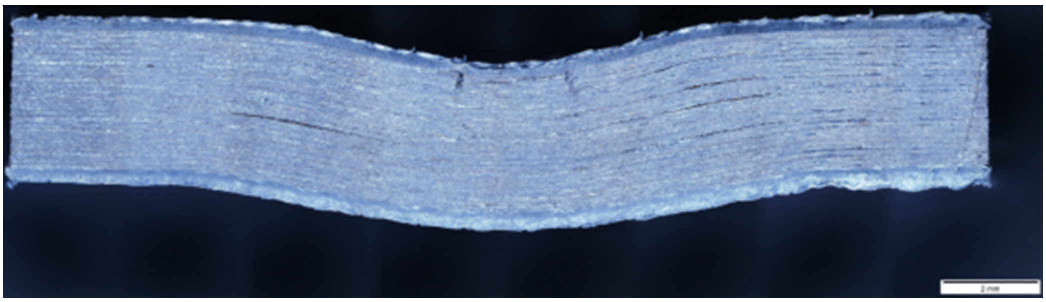

Figure 10. Microscopical analysis of tested specimen IL-0-0-1-5 magnified $5\times$.

Although it is possible to identify the failure modes in the tested specimens, large deformations occurred before failure. The particularities in these cases are mentioned by FAA (1993).

5. CONCLUSIONS

In the present work, short-beam shear specimens were 3D printed, cut and experimentally tested in order to evaluate the interlaminar shear strength of continuous carbon fiber reinforced thermoplastic. The innovative FFF process applied in this work was also presented and detailed. The short-beam tests showed that the investigated material presents interlaminar shear properties comparable to those produced by traditional composite manufacturing process. Although the obtained results are very promising the short-beam test for fiber reinforced thermoplastic composite materials demands further microscopical analysis in order to confirm the failure mode. The microscopical analysis performed in this work demonstrated that specimens failed by both interlaminar shear and flexural loads. As seen in the available literature, thermoplastic matrix is more susceptible to fail in a combination of different failure modes when tested in the three-point bending load. In future works, the compression shear test can be applied in order to also determine the interlaminar shear strength of the investigated material. As the compression shear test minimizes the influence of non-desired failure modes, the excellent results presented in this work can still be improved.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

ASTM, 2016. "ASTM D2344 /D2344M-16, Standard Test Method for Short-Beam Strength of Polymer Matrix Composite Materials and their Laminates". Technical Report, ASTM International, West Conshohocken, PA. www.astm.org.

ASTM, 2012. "ASTM F2792-12a, Standard Terminology for Additive Manufacturing Technologies". Technical Report, ASTM International, West Conshohocken, PA. www.astm.org.

FAA, 1993 "Test Methods for Composites a Status Report: Volume III Shear Test Methods". Technical Report, U.S. Department of Transportation, Federal Aviation Administration. DOT/FAA/CT-93/17, III, FAA Technical Center. Atlantic City.

Ahmed, K.S. and Vijayarangan, S., 2008. "Tensile, flexural and interlaminar shear properties of woven jute and jute-glass fabric reinforced polyester composites". *Journal of Materials Processing Technology*, Vol. 207, No. 1 – 3, pp. 330 – 335. ISSN 0924-0136. doi:http://dx.doi.org/10.1016/j.jmatprotec.2008.06.038.

Bowles, K.J. and Frimpong, S., 1992. "Void effects on the interlaminar shear strength of unidirectional graphite-fiber-reinforced composites". *Journal of Composite Materials*, Vol. 26, No. 10, pp. 1487–1509. doi: http://dx.doi.org/10.1177/002199839202601006.

Dutra, T.A. and de Almeida, S.F.M., 2015. "Composite plate stiffness multicriteria optimization using lamination parameters". *Composite Structures*, Vol. 133, pp. 166 – 177. ISSN 0263-8223. doi: http://dx.doi.org/10.1016/j.compstruct.2015.07.029.

Fan, Z., Santare, M.H. and Advani, S.G., 2008. "Interlaminar shear strength of glass fiber reinforced epoxy composites enhanced with multi-walled carbon nanotubes". *Composites Part A: Applied Science and Manufacturing*, Vol. 39, No. 3, pp. 540 – 554. ISSN 1359-835X. doi:http://dx.doi.org/10.1016/j.compositesa.2007.11.013.

Markforged Inc, 2015. "The future of manufacturing". https://markforged.com. Accessed: 2017-03.

Ozkoc, G., Bayram, G. and Bayramli, E., 2004. "Effects of polyamide 6 incorporation to the short glass fiber reinforced ABS composites: an interfacial approach". *Polymer*, Vol. 45, No. 26, pp. 8957 – 8966. ISSN 0032-3861. doi: http://dx.doi.org/10.1016/j.polymer.2004.10.026.

Quan, Z., Wu, A., Keefe, M., Qin, X., Yu, J., Suhr, J., Byun, J.H., Kim, B.S. and Chou, T.W., 2015. "Additive manufacturing of multi-directional preforms for composites: opportunities and challenges". *Materials Today*, Vol. 18, No. 9, pp. 503–512. ISSN 1369-7021. doi:http://dx.doi.org/10.1016/j.mattod.2015.05.001.

Illinois Tool Works Inc, 2017. "INSTRON Composite Test Fixture Flexural and Interlaminar Shear". http://www.instron.us/en-us/products/testing-accessories/grips/application-specific-accessories/composite/options/cp106695. Accessed: 2017-03.

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