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# EXPERIMENTAL AND ANALYTICAL METHODS FOR DETERMINING INTERLAMINAR SHEAR STRENGTH OF COMPOSITES MADE BY FDM 3D PRINTING

**Nenad GRUJOVIĆ[1*], Strahinja MILENKOVIĆ[2], Fatima ŽIVIĆ[3]**

[1] 0000-0002-8765-2196, Faculty of Engineering, University of Kragujevac, Sestre Janjić 6, 34000 Kragujevac, Serbia, E-mail: gruja@kg.ac.rs;

[2] 0000-0002-5822-4846, Institute for Information Technologies, University of Kragujevac, Jovana Cvijića bb, 34000 Kragujevac, Serbia, E-mail: strahinja.milenkovic@kg.ac.rs;

[3] 0000-0003-2509-187X, Faculty of Engineering, University of Kragujevac, Sestre Janjić 6, 34000 Kragujevac, E-mail: zivic@kg.ac.rs;

## 1. Introduction

Fused Deposition Modeling (FDM) 3D printing of fiber-reinforced composites involves a complex interplay of materials, processing parameters, and environmental conditions that all influences resulting mechanical properties [1]. Different measurement methods are used to evaluate these effects on the final materials properties and performance. This paper presents experimental and analytical methods for determining interlaminar shear strength of PLA/PVDF composites made by FDM 3D printing.

## 2. Influential Factors in FDM 3D Printing of Composites

Fabrication of composites can be realised by FDM 3D printing which is a low-cost promising technology, but there are still significant challenges related to dimensional accuracy, repeatability and mechanical properties, due to a number of different influential factors governing the printing process, thus reflecting the final composite properties. In Main groups of influential factors and possible variables, for FDM 3D printing of fiber reinforced composites, are shown in Fig.1, including the variables representing the influence of the filament materials, processing parameters and external influences. For example, in the case of fiber reinforced composites, different methods are used for short, continuous or nano/micro reinforcing fibers [1–3]. Material-related factors essentially determine how the composite will be produced, including the subsequent measurement and characterization techniques to be used. Matrix material, fiber material and weight or volume fraction of reinforcements, together with fiber orientation (alignment during extrusion or intentionally designed in certain way) will further reflect on the interfacial bonding or adhesion between fiber and matrix.

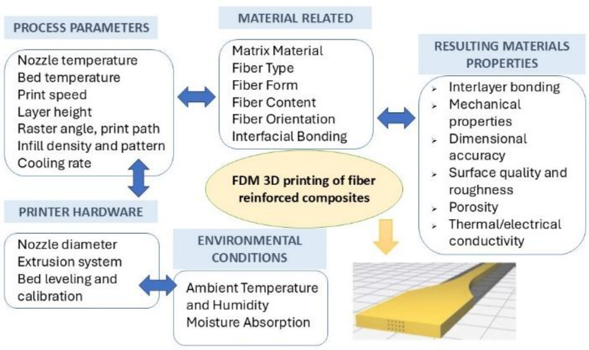


**Fig. 1.** Influential factors in FDM 3D printing of composites.

Process parameters have a major influence on the final composite properties [4]. Nozzle temperature affects matrix viscosity and fiber wetting and bed temperature influences adhesion and warping. Print speed impacts fiber alignment and extrusion consistency. Layer height affects interlayer bonding and surface finish, while raster angle and print path control internal structure and anisotropy, whereas infill density and selected pattern influences stiffness and strength. The cooling rate affects residual stresses and crystallinity.

Printer hardware like nozzle diameter limits fiber size and deposition rate and depending on the extrusion system (single or multiple nozzles) different phases within the composite can be simultaneously printed or not. Bed leveling and calibration affects dimensional accuracy. Ambient temperature and humidity affect material flow and bonding and moisture absorption is especially critical for hygroscopic materials.

## 3. Measurement and Characterization Methods

Different characterization methods are used for composites depending on the targeted material properties and specific applications. Mechanical properties can be determined by different methods, including tensile testing (ASTM D638 or ISO 527) to measure strength, modulus, elongation; flexural testing (ASTM D790) for bending behavior; impact testing (e.g. Charpy or ASTM D256) to assess toughness; interlaminar shear strength (ASTM D2344) for delamination resistance. Microstructural analysis is commonly done using scanning electron microscopy (SEM) to observe fiber-matrix interface, porosity and failure modes, while optical microscopy is used for layer morphology and fiber distribution analysis. The 3D internal structure, porosity and voids can be characterized through computed tomography (CT).

Thermal properties can be determined through differential scanning calorimetry (DSC) that can provide data on crystallinity, glass transition temperature (Tg) and melt temperature (Tm) and by using thermogravimetric analysis (TGA) for fiber content and thermal stability. Dynamic mechanical analysis (DMA) is advanced technology that can provide valuable data for dynamical mechanical behavior, including material viscoelastic behavior and damping.

Depending on the material type and final application, rheological behavior can be also demanded to determine flow behavior of composite melt or viscosity as a function of shear rate [5]. Dimensional and surface quality are very important and challenging with FDM printing since the printed parts commonly experience certain degree of warping in the case of poorly selected printing parameters, such as nozzle temperature not in accordance with Tg temperature of the printed materials. Post processing is usually applied to provide adequate surface roughness.

### *3.1 Interlaminar Shear Strength (ILSS)*

Interlaminar Shear Strength (ILSS) is a critical mechanical property in laminated or layer-based structures, such as those produced by FDM printing, where layer bonding and interlayer adhesion is inherently weaker due to the layer-by-layer nature of the process. It reflects the material's ability to resist sliding between layers, which is often a failure mode in 3D printed composites and especially pronounced in the case of fiber reinforced composites. In laminated composites (like FDM-printed parts), interlaminar shear refers to in-plane shear between adjacent layers. These layers are typically bonded by weaker adhesive forces (e.g., diffusion bonding or partial melting in FDM). ILSS represents the maximum shear stress that a composite material can sustain between its layers before failure occurs. For FDM printing, it is necessary to ensure consistent fiber orientation, layer thickness, and infill pattern, whereas surface finish and voids can significantly affect results. The characterization of such samples needs to capture interlayer effects, by testing samples in different build directions (XY, XZ, YZ).

Shear stress in layered materials is calculated according to the equation (1):

$$\tau = \frac{F}{A} \tag{1}$$

where $\tau$ is shear stress, $F$, applied load parallel to the surface and $A$, area over which the load is applied. However, this basic formula assumes uniform shear over a flat interface, which is not the case in practice. Therefore, we use mechanical test methods that induce a dominant interlaminar shear stress state.

Standard methods to measure ILSS, commonly using universal testing machine, are short beam shear test (SBS) (ASTM D2344, ISO 14130), double notch shear test (ASTM D3846) and Iosipescu shear test (ASTM D5379). Additionally, digital image correlation (DIC) with high-resolution digital cameras is an optical method that tracks surface deformation to measure full-field strain distribution and is often used together with other standard tests for more insight into strain localization.

### *3.2 Short Beam Shear (SBS)*

The SBS test is the most common method for measuring ILSS, relying on a three-point bending setup with a very short span-to-thickness ratio (~4:1). The test induces shear stress primarily in the mid-plane. In a beam under three-point bending, stress distribution includes bending stresses (normal stress) and shear stresses (transverse shear). A short span increases the shear component relative to bending, forcing failure in shear rather than in tension/compression. Therefore, the interlaminar shear stress is maximized at the mid-plane (neutral axis) of the beam, and can be calculated as approximate maximum shear stress (at neutral plane), according to the equation (2):

$$\tau = \frac{0.75\,F}{b \cdot d} \tag{2}$$

where $F$ is maximum load before failure, $b$ is sample width $d$, is sample thickness. This formula is derived from beam theory using first-order shear deformation theory (FSDT) and assumes: uniform shear stress distribution over the mid-plane; linear-elastic, isotropic behavior and negligible friction or support compliance.

Flexural Strength ($\sigma_f$) is also typically measured using a 3-point bending test (ASTM D790), according to the equation (3):

$$\sigma_f = \frac{3FL}{2bd^2} \quad (3)$$

where $\sigma_f$ is Flexural strength (MPa), $F$ is load at fracture, $L$ is support span, $b$ is sample width and $d$ is sample thickness.

Materials characterization in scope of ILSS tests commonly include determination of failure modes and stress concentrations since ILSS tests often show delamination between layers, shear-induced cracking at the layer interface and fiber pull-out or matrix cracking. The point of the first significant load drop in the force-displacement curve typically indicates interlaminar shear failure. Microstructural properties such as layer adhesion (especially in FDM), voids/porosity, reinforcing fiber orientation and length and thermal residual stresses have significant effects on interlaminar shear strength. Standard SBS test for ILSS has certain limitations. The SBS test is not purely shear-dominant, and some bending stress exists. It is sensitive to sample geometry and surface quality. Stress redistribution or plasticity within composite phases can result in overestimate of ILSS. In FDM, results can vary significantly based on build direction and layer adhesion quality.

ILSS measurement can be complemented by considering advanced methods like finite element modeling (FEM) modelling that simulates 3D stress states and identifies true shear distributions, including possibility to account for nonlinear or viscoelastic material behavior. Furthermore, digital image correlation (DIC) can capture real-time strain fields, validating assumptions of uniform shear. Fractographic analysis is commonly used to analyze fracture surfaces and confirm interlaminar failure.

## 4. Case study

FDM 3D printed composite samples were made of polylactic acid (PLA) matrix, reinforced with α-phase polyvinylidenfluorid (PVDF) fibers [6]. We tested several build orientations, with pronounced differences between [0, 90] and [-45, +45] orientations (Fig 2a), regarding Interlaminar Shear Strength (ILSS). We performed uniaxial tensile test (Fig 2b) and three-point bending test (Fig. 2c). Samples with [-45, +45] orientation showed better tensile strength, since they could endure significantly higher strain in comparison to [0, 90] (almost two-fold increase). The point of the first significant load drop in the force-displacement curve that indicates interlaminar shear failure (Fig. 2c) was significantly higher in the case of samples with [-45, +45] orientation (approx. 10 mm displacement) compared to [0, 90] samples (approx. 6.9 mm displacement), thus indicating significantly better shear strength for [-45, +45] samples.

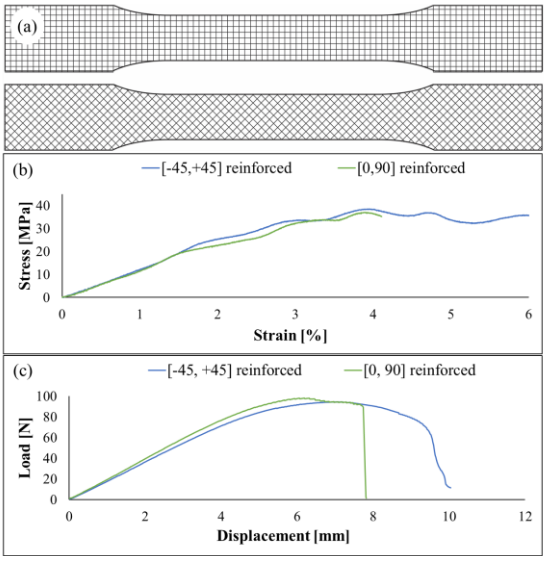


**Fig. 2.** a) Design of samples for 3D printing; b) Stress-strain curves for tensile tests; c) Load – displacement curves for three-point bending tests

Calculated values of interlaminar shear strength (ILSS) and flexural strength, according to the equations (2) and (3) and geometrical dimensions of the samples (width of 12.7 mm and thickness of 3.4 mm), are given in Table 1. These values are rough representations since they do not account for several other influential factors that need to be considered.

**Table 1.** Calculated approximate values of Interlaminar Shear Strength (ILSS) and Flexural strength

| | Maximum load before failure [N] | Interlaminar Shear Strength (ILSS) [MPa] | Flexural strength [MPa] |
|---|---|---|---|
| [0, 90] | 98 | 1.70 | 61.33 |
| [-45, +45] | 100 | 1.74 | 59.03 |

The numerical difference is small (0.04 MPa or about 2.35% difference) and may fall within the margin of experimental error or standard deviation of the testing method. Horizontally built [0, 90] samples may exhibit weaker interlayer bonding leading to lower ILLS. Inclined [-45, +45] samples may allow better layer fusion, sometimes improving ILLS. Even a small improvement like 2.35% difference can suggest enhanced fusion or reduced voids in [-45, +45] orientation over [0, 90] orientation.

Material type in this test (PLA or PLA reinforced with PVDF can amplify or dampen orientation effects. Printing parameters (e.g., temperature, printing speed) can influence slightly better adhesion in one orientation, depending on the material type. The increase of 2.35% could be attributed to a more consistent deposition in [-45, +45] direction. Even the small difference of 2.35% may indicate more reliable interlayer performance, especially important for structurally critical parts. In the case of PLA/PVDF composite used here in the tests, fiber alignment due to orientation can slightly affect the shear strength. Also, as noted previously, stress redistribution or plasticity within composite phases can result in overestimate of ILSS.

Further study should be carried out, such as SEM microscopy to see if microstructural differences (e.g., voids, layer fusion) correlate with this small change. More samples across different orientations will be tested in the future for more accurate conclusions on the influences of build orientations on the total shear strength and ILLS. Therefore, further evaluation is needed, because calculated ILSS values indicate slight difference, while curves in Fig 2c clearly indicate significant differences between these two orientations.

It should be noted that composite preparation has a very important role for the final mechanical properties in the sense that it is necessary to provide consistent fiber orientation, layer thickness, and infill pattern what is rather challenging in 3D printing and especially in hand-layup of the reinforcing fibers. An inconsistent fabrication from these aspects can introduce unplanned anisotropy in the printed part and accordingly it is necessary to test samples in different build directions (XY, XZ, YZ) to capture interlayer effects. Also, surface finish and void content can significantly affect results, both governed by the complex interplay between different processing parameters. Additionally, environmental conditioning, such as influences originating from moisture or temperature pre-conditioning can greatly affect final properties of 3D printed parts.

## 5. Conclusions

Both experimental and analytical methods for determining interlaminar shear strength of PLA/PVDF composites made by FDM 3D printing showed that build orientation has significant influence on the resulting interlaminar shear strength. Simple analytical models can be used for rough estimations, but further analysis is needed to account for several influential factors such as geometrical dimensions, fiber and matrix properties and processing parameters of FDM printing, including viscoelastic behavior that cannot be captured by these simple models.

For high precision applications, even the small ILLS improvements can influence the design decisions. Specific orientations are selected for critical shear-loaded components. ILLS test method helps in optimizing part orientation to provide appropriate function and strength.

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