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A Study of the Flexural Behavior of 3D-Printed PLA Dovetail and Screw Joints Considering Chemical Adhesive Usage

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Abstract

Additive manufacturing (AM) also known as 3D printing led to a revolution in the manufacturing sector, as it shortened the time-to-market of new products, facilitated intricate design, and more importantly mass customization. One of the well-known AM processes is fused deposition modeling (FDM) which can create polymer-based parts. The restricted size of printed part is a major problem in FDM due to its limited chamber size. The oversized model issue was addressed by some researchers, proposing the segmentation and division of large models as a solution for this problem. This study aims to investigate the effect of flat dovetail and round screw joints as segmental joining methods with the placement of cyanoacrylate adhesive between the polylactic acid (PLA) segments on the flexural strength of the final joined PLA parts. The results revealed that the use of cyanoacrylate adhesive significantly enhances the flexural strength of round screw joints in PLA prototypes, while it reduces the flexural strength of flat dovetail joints, with the positive impact on round screw joints being more pronounced.

Keywords
Additive manufacturing (AM), Segmentation, Fused deposition modeling (FDM), Flexural strength and Toughness

1. Introduction

The FDM process is one of the AM techniques that produces polymeric components based on the addition of materials according to the layer-by-layer building principle as all AM technologies. layer-by-layer approach allows for the creation of complex geometries that would be difficult to manufacture using traditional subtractive methods. (Sai & Yeole, 2001; Mohamed et al. 2015). Polylactic acid (PLA) material is predominantly used for parts fabrication in FDM due to its distinguished properties which make it a suitable material for various applications (Farah et al. 2016a). The limited size of the FDM building chamber constitutes a significant challenge, which has a direct reflection on the restricted size of the printed part, especially if the desired design requires a large prototype. A segmentation of large-scale models by dividing the whole model into printable small segments, considering the original geometry of the model can be a potential solution (Li & Peng 2020). The selection of joining techniques for the resulting segments is considered a key factor in determining the performance of the final part in real applications. Several joining methods can be proposed, including adhesive materials, mechanical assembly, and welding, each offering distinct advantages and suitability depending on the specific requirements of the application, such as environmental resistance, ease of assembly, and the need for disassembly or repair (Özenç et al. 2022). The decision regarding the selection of the suitable type of joining technique between segments depends on the application requirements that the final formed part will perform, including factors such as the required strength, durability, environmental exposure, thermal or electrical conductivity, and whether the joint needs to be permanent or removable for maintenance or future modifications.

Objectives

This study aims to apply a comprehensive methodology to investigate the impact of the segmental joining method, joint shape, and cyanoacrylate adhesive usage factors on the mechanical behavior of joined 3D-printed PLA segments under flexural loading.

2. Literature Review

Some researchers in the AM field addressed the segmentation approach and proposed several methods to divide the whole model into small segments to overcome the size limitations issue. For example, a method used a sequence of cutting planes to segment a 3D model by analysis of the model shape and the geometric configuration. The proposed method is applied to various complex shapes, and it showed an outstanding ability to print the segments without support (Karasik et al. 2019). The partitioning method is also used to minimize and eliminate the sacrificial support needs for shell models. That method deployed a skeleton-based algorithm for partitioning the 3D model into a minimum parts as possible without supports and cracks in the assembled surface. Then, they validated the proposed algorithm using different models and they studied many important parameters, such as printing time and the number of partitions(Wei et al. 2018). The assembly of the portioning parts is quite important to ensure that these parts are joined seamlessly, maintaining the structural integrity and aesthetic quality of the final product. Therefore, plenty of studies evaluate different adhesives, welding methods, and mechanical joining approaches, and compare their efficiency and effectiveness. ASA and NCF polymer materials are printed using the FDM 3D printing machine and bonded together using cyanoacrylate (CA) and epoxy adhesives to investigate which adhesive gives the highest adhesive strength, the results of the single lap shear test showed that (CA) adhesive gives much higher adhesive strength than Epoxy with approximately 1810 KN for ASA and 2310 KN for NCF as compared to Epoxy adhesive with 470 KN for ASA and 860 KN for NCF (Yap et al. 2020).

In addition, Different welding techniques are investigated in the literature to investigate various responses to achieve acceptable joints, in this study Spin friction welding is used to join ABS and PLA printed parts using an extrusion 3d printing machine (MEX) to test the effect of the welding parameters on the weld joint efficiency, this welding technique showed higher welding efficiency than other joining/welding techniques such as adhesive bonding and friction stir welding (Tiwary et al. 2024). Another study was conducted on the Microwave-assisted welding technique to join ABS and PLA materials printed using an FDM machine, the lap shear test showed high weld efficiency for this technique compared to adhesives, friction stir and ultrasonic welding (Tiwary et al. 2023). The advanced joining technique of infrared laser irradiation is also used to join PLA-printed material, tensile test is used to evaluate this technique at different energy densities of pulse (Ed) and the highest tensile strength is obtained at the minimum (Ed) rate by almost 346.54 N for 2.21/Cm^2 (Vazquez-Martinez et al., 2020). Another kind of joining technique the snap-fit mechanical joining technique was studied because it is widely used to join components, in this research, the snap-fit parameters such as the mating angle and the inner, separation diameters are tested using tensile and compression tests and compared to a newly derived equation that showed accurate results for certain ranges (Torossian & Bourell 2020).

3. Methods

3.1 PLA-joints modeling and fabrication

a 2^2 factorial design with three replicates was implemented to study the effect of the segmental joining method and cyanoacrylate adhesive usage on the flexural strength of printed PLA segments. The selected factors and their corresponding levels are shown in Table 1. First, a flat dovetail and round screw PLA segments were created in CAD-solid work software. The models of flat dovetail and round screw PLA segments are shown in Figures 1 and 2 respectively. It is worth mentioning that for the screw segments, round PLA joints were created, whereas, for the dovetail segments, flat PLA joints were created. All segments of flat dovetail and round screw were modeled and printed according to ASTM D790 standards (Dhinesh et al. 2021). The geometrical characteristics of flat dovetail and round screw PLA joints are illustrated in Figures 3 and 4, respectively. Table 2 displays the geometrical dimensions of PLA joints.

Table 1. Factors and their levels.

Factor	Levels	
Segmental joining method	Flat Dovetail joint	Round screw joint
Cyanoacrylate adhesive usage	Without Cyanoacrylate adhesive	With Cyanoacrylate adhesive

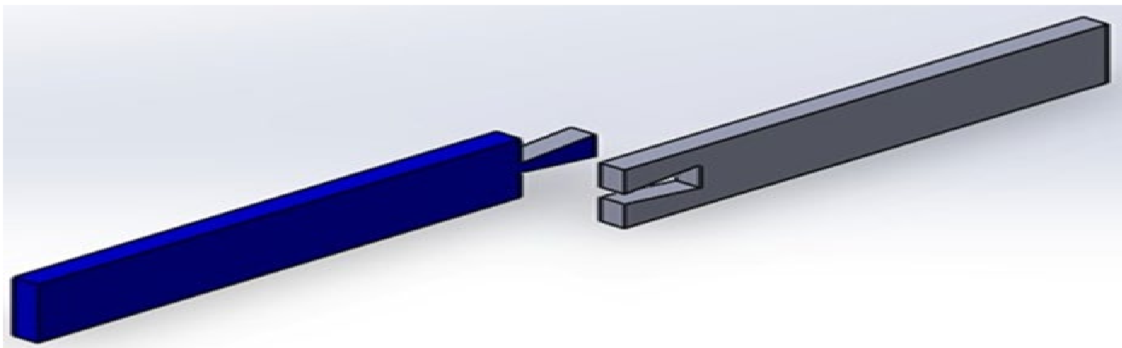

Figure 1. Flat dovetail segments CAD model.

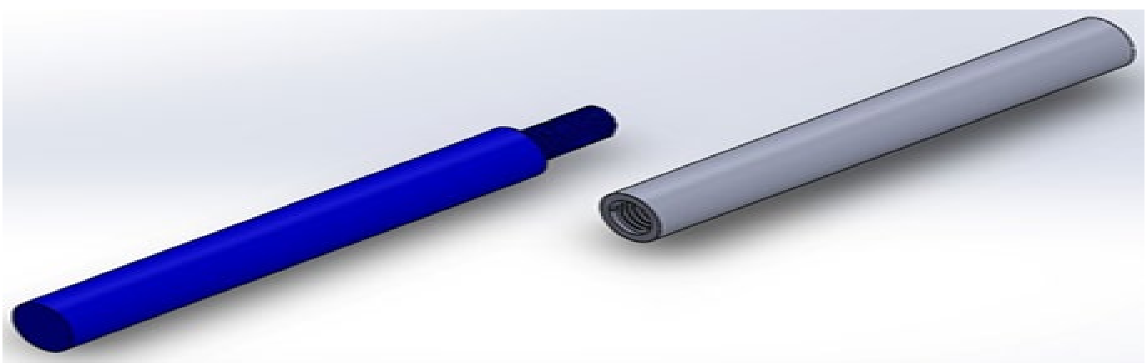

Figure 2. Round screw segments CAD model.

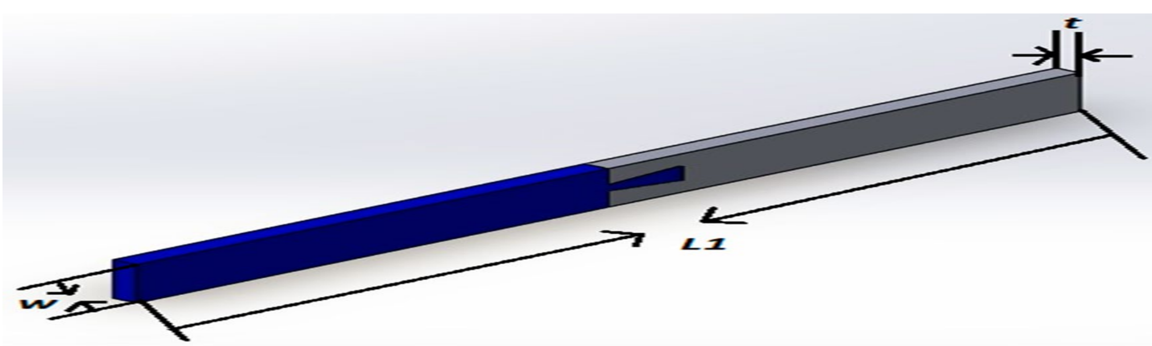

Figure 3. The geometrical characteristics of flat dovetail joint.

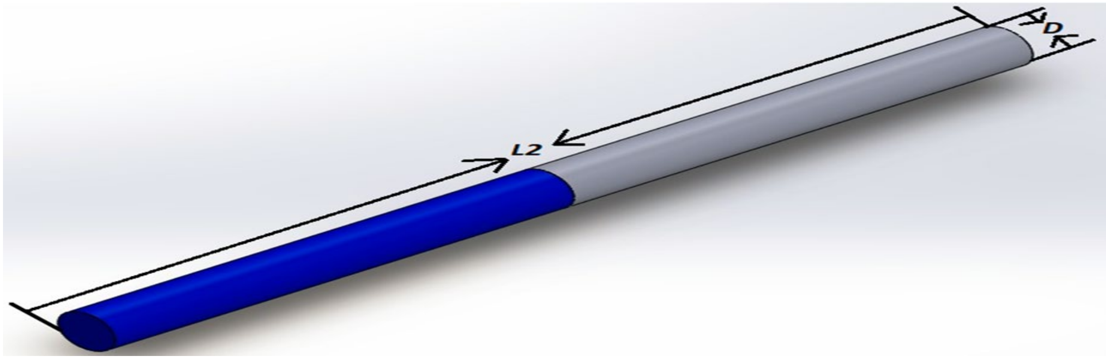

Figure 4. The geometrical characteristics of round screw joint.

Table 2. The geometrical dimensions of dovetail and screw joints in (mm).

Length (L1)	127
Width (w)	12.7
Thickness (t)	3.2
Length (L2)	138.2
Diameter (*D*)	7.2

All PLA segments were printed using FDM process. The actual printed flat dovetail and round screw PLA segments before and after joining are shown in figures 5 and 6, respectively.

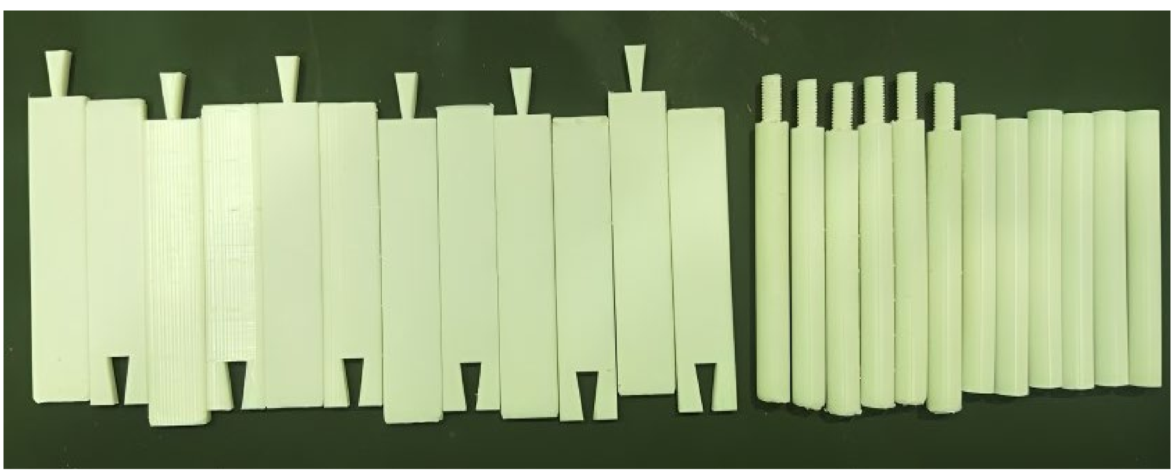

Figure 5. The actual printed flat dovetail and round screw PLA segments before joining.

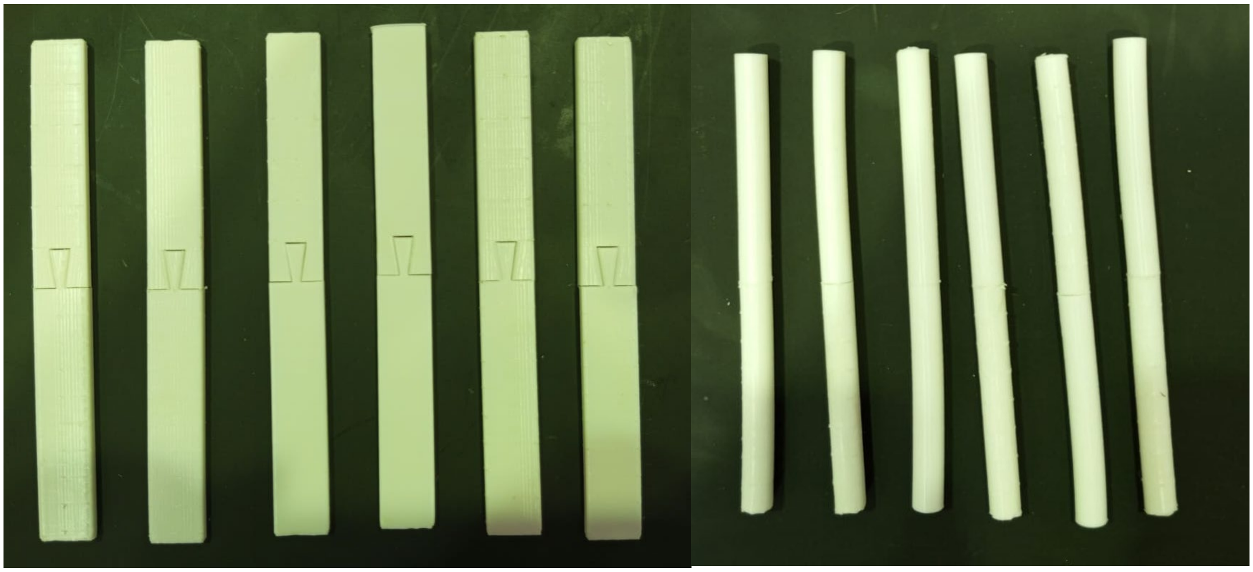

Figure 6. The actual printed flat dovetail and round screw PLA segments after joining.

3.2 Three-point bending test

A three-point bending test was conducted on 12-flat dovetail and round screw joints by universal testing machine (UTM) to understand the mechanical behavior of flat dovetail and round screw joints without and with cyanoacrylate adhesive. The type of used adhesive between segments was selected carefully to be convenient for PLA material nature (Farah et al., 2016b). Four joining categories were considered for testing, with three replicates for each category. Table 3 illustrates the four joining categories and their symbols.

Table 3. Joining categories and their symbols.

Joining category	Symbol
Dovetail joint without cyanoacrylate Adhesive	$\boldsymbol{D_j}$
Dovetail joint with cyanoacrylate Adhesive	$\boldsymbol{D_{jc}}$
Screw joint without cyanoacrylate Adhesive	$\boldsymbol{S_j}$
Screw joint with cyanoacrylate Adhesive	$\boldsymbol{S_{jc}}$

4. Data Collection

The obtained experimental data from three-point bending mechanical testing of each replicate that is associated with each joining category were load and deflection, then these data were used to find the flexural stress-deflection curve and the flexural toughness for each replicate to understand the mechanical performance under flexural loading for the different joining categories using the following mathematical formulas (Steadman, 1970; Alander et al., 2005):

$$\sigma_f(dov) = \frac{3F g_{dov}}{2wt^2} \tag{1}$$

$$\sigma_f(scr) = \frac{8F g_{scr}}{\pi D^3} \tag{2}$$

$$T_f(dov) = \int_0^{\delta(fracture)} \sigma_f(dov)\, d\delta \qquad (3)$$

$$T_f(scr) = \int_0^{\delta(fracture)} \sigma_f(scr)\, d\delta \qquad (4)$$

Where:

σf (dov): The flexural stress of flat dovetail joint (MPa),

σf (scr): The flexural stress of round screw joint (MPa),

Tf (dov): The flexural toughness of flat dovetail joint (MPa. mm),

Tf (scr): The flexural toughness of round screw joint (MPa. mm),

δ (fracture): The deflection at fracture point (mm),

F: The Applied load (N),

g dov: Span length between the centers of two supports for flat dovetail joints setup (51.2 mm),

g scr: Span length between the centers of two supports for round screw joints setup (115.2 mm).

5. Results and Discussion

5.1 Flexural stress-deflection curves

The flexural stress of the different joining categories was found by the direct application of formulas (1) and (2), then the flexural stress versus deflection curve was plotted for each replicate. The flexural stress (σ_f)-deflection (δ) curves of dovetail joints without cyanoacrylate adhesive ($\boldsymbol{D_j}$), dovetail joints with cyanoacrylate adhesive ($\boldsymbol{D_{jc}}$), screw joints without cyanoacrylate adhesive ($\boldsymbol{S_j}$), and screw joints with cyanoacrylate adhesive ($\boldsymbol{S_{jc}}$) are shown in figures 7, 8, 9, and 10, respectively.

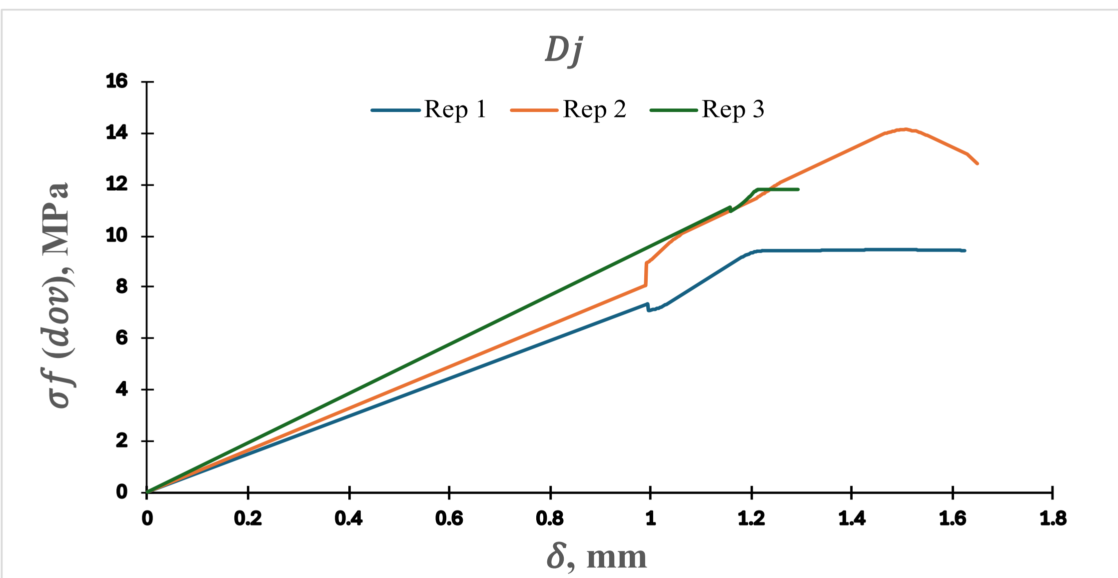

Figure 7. Flexural stress-deflection curves for $\boldsymbol{D_j}$.

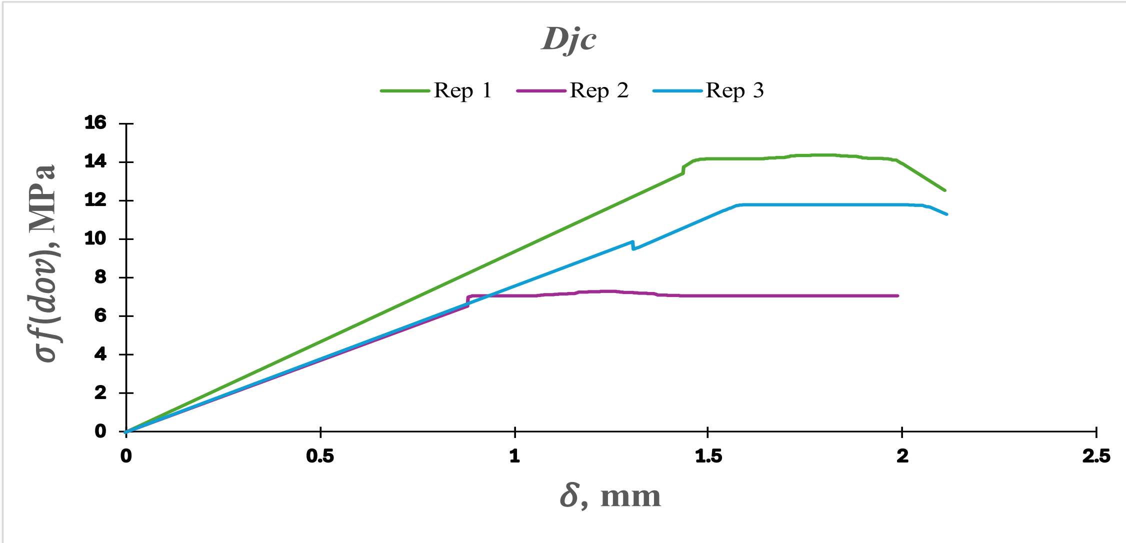

Figure 8. Flexural stress-deflection curves for $\boldsymbol{D_{jc}}$.

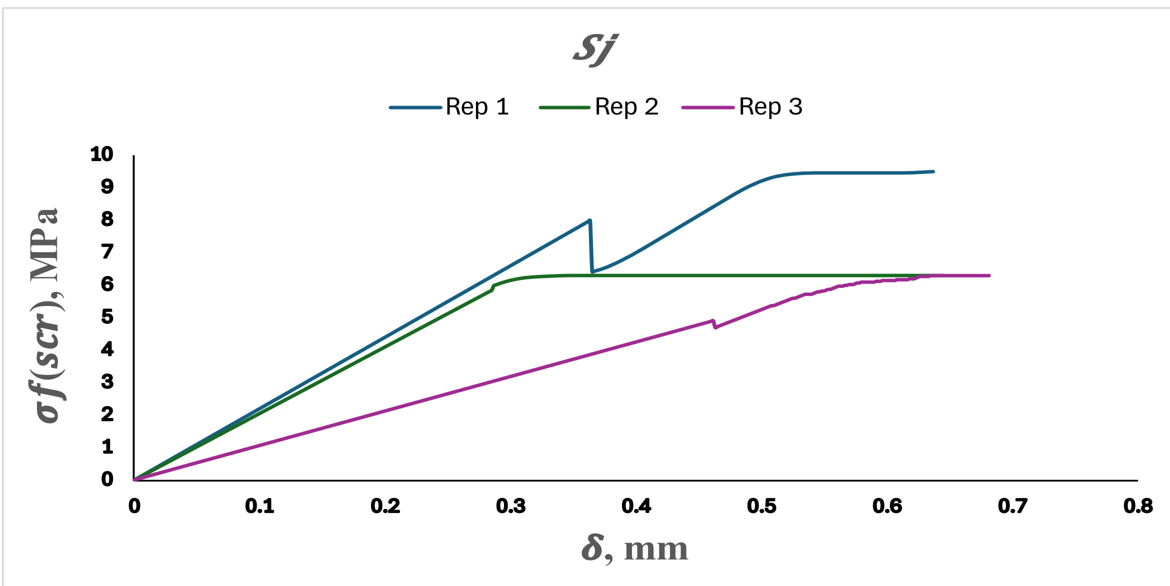

Figure 9. Flexural stress-deflection curves for $\boldsymbol{S_j}$.

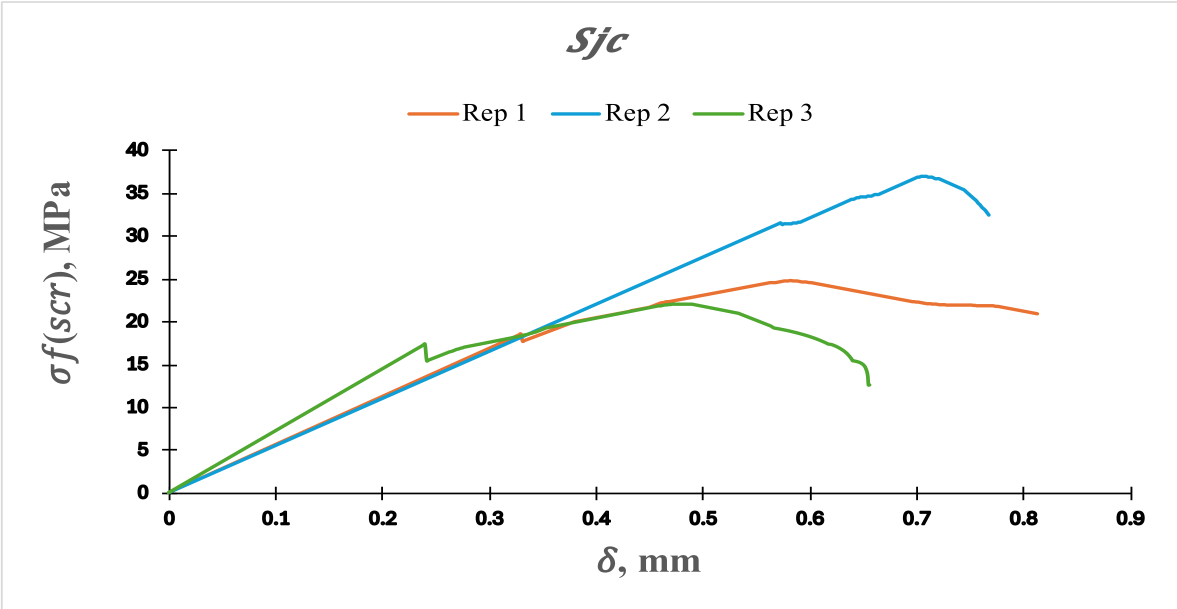

Figure 10. Flexural stress-deflection curves for $\boldsymbol{S_{jc}}$

The flexural stress-deflection curves show that the screw joints tend to result in higher flexural strength compared to the dovetail joint and that the adhesive improved the strength of the joint when the type of joint was screwed. To support these observations, a statistical analysis was performed, and results presented in latter sections.

5.2 Flexural mechanical properties

The flexural mechanical properties are key indicators of material's performance under bending and are essential for understanding its mechanical behavior and suitability for various applications. Some of the flexural mechanical properties can be extracted directly from stress (σ_f)-deflection (δ) curves for the different joining categories and their replicates that are shown in sec. 5.1, such as the flexural strength, deflection at fracture point, and corresponding deflection to the flexural strength. The corresponding mechanical properties for each joining category and its replicates are shown in Table 4 and 5. The flexural toughness of dovetail joining categories and screw joining categories were calculated by the direct application of mathematical formulas (3) and (4), respectively.

Table 4. Flexural properties for $\boldsymbol{D_j}$ and $\boldsymbol{D_{jc}}$ joining categories.

Joining category / Mechanical property	$\boldsymbol{D_j}$			$\boldsymbol{D_{jc}}$		
	Rep 1	Rep 2	Rep 3	Rep 1	Rep 2	Rep 3
$\boldsymbol{\sigma_{f(dov)}}$ (MPa)	9.49	14.17	11.8	14.36	7.32	11.8
$T_f(dov)$ (MPa.mm)	9.35	12.08	8.00	19.09	10.77	15.67
$\boldsymbol{\delta_{(f)}}$ (mm)	1.43	1.5	1.2	1.77	1.24	1.59
$\boldsymbol{\delta_{(fracture)}}$ (mm)	1.62	1.65	1.30	2.11	1.99	2.11

Table 5. Flexural properties for $\boldsymbol{S_j}$ and $\boldsymbol{S_{jc}}$ joining categories.

Joining category / Mechanical property	S_j			S_{jc}		
	Rep 1	Rep 2	Rep 3	Rep 1	Rep 2	Rep 3
$\boldsymbol{\sigma_{f(scr)}}$ (MPa)	9.47	6.29	6.29	24.87	36.98	22.00
$T_f(scr)$ (MPa. mm)	3.97	3.09	2.41	13.84	15.76	10.06
$\boldsymbol{\delta_{(f)}}$ (mm)	0.54	0.35	0.64	0.58	0.70	0.47
$\boldsymbol{\delta_{(fracture)}}$ (mm)	0.64	0.64	0.68	0.81	0.77	0.66

Where: δ (f): the corresponding deflection to flexural strength (mm).

5.3 Statistical analysis and interpretation

The statistical analysis of the two-level full factorial design was performed on Minitab statistical software to investigate the effect of the segmental joining method and cyanoacrylate adhesive usage on the flexural strength data of the different joining categories using a two-way interaction statistical model. Analysis of variance (ANOVA) reveals that the model is statistically significant (*P*-value = 0.003), which means at least one of the studied factors or more (either segmental joining method or cyanoacrylate adhesive usage or both) influences the flexural strength of tested joining categories, Also, ANOVA showed that the segmental joining method, cyanoacrylate adhesive usage factors were statistically significant (*P*-values less than 0.05). The results showed that both factors have positive effects, which indicates that the selected joining method and the adhesive placement between the segments of PLA prototype influence on the flexural strength of final joined part. Figure 11 represents the main effects plot, which obviously demonstrates that the flexural strength was the best when the selected joining method is round screw joint with adhesive placement between the PLA segments.

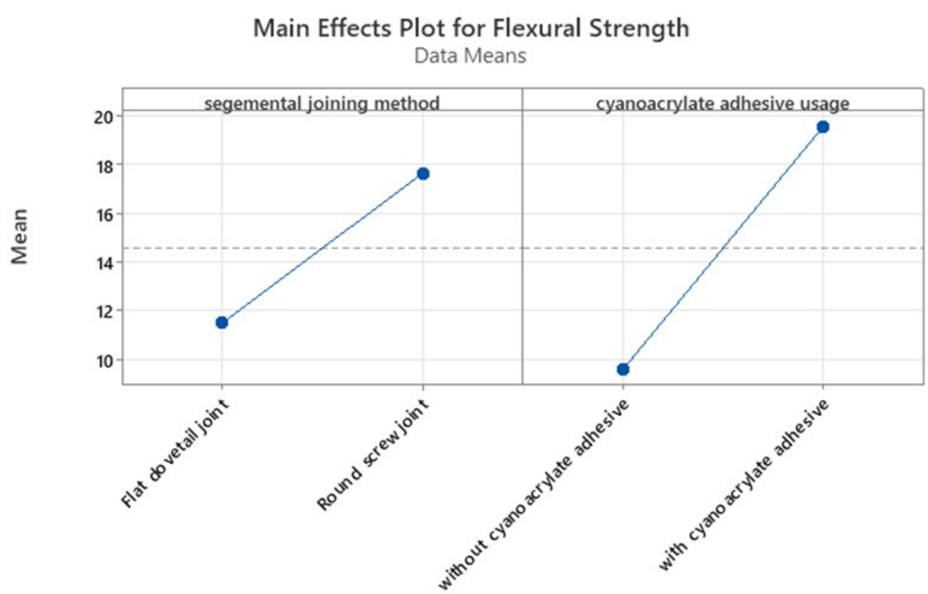

Figure 11. Main effects plot for flexural strength.

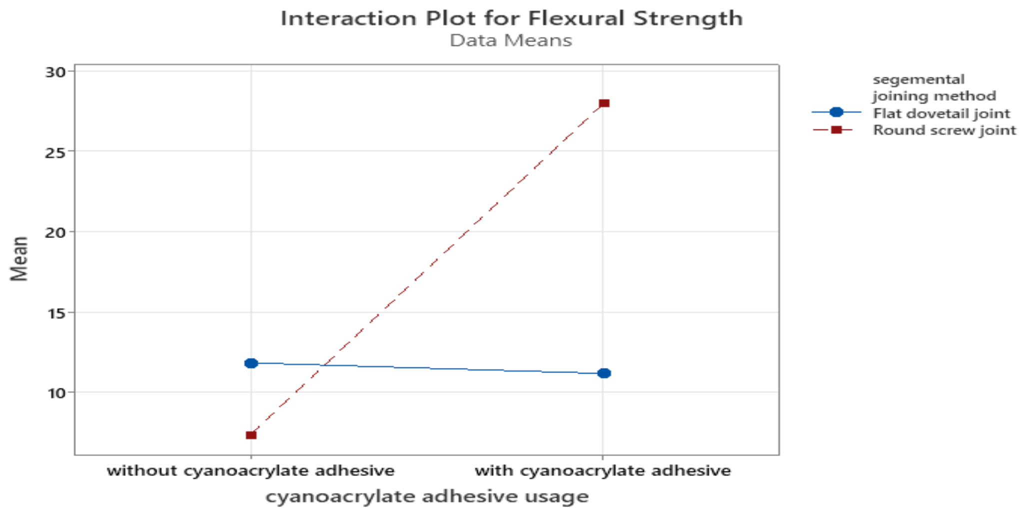

Figure 12. Interaction plot for flexural strength.

Depending on figure 12, which represents the segmental joining method-cyanoacrylate adhesive usage interaction plot. The placement of cyanoacrylate adhesive significantly increased the flexural strength of round screw joints but decreased the flexural strength of flat dovetail joints. However, the positive effect of the adhesive on the flexural strength was more pronounced in round screw joints compared to the negative effect on flat dovetail joints, which is a strong indication that the effect of the cyanoacrylate adhesive usage on flexural strength depends on the type of used joint.

6. Conclusion

An experimental study has been carried out on a set of 3D-printed PLA segments to study the effect of segmental joining methods with and without cyanoacrylate adhesive on the mechanical behavior of different joining categories under flexural loading. The key findings from this study are as follows:
The mechanical behavior of joined 3D-printed PLA segments under flexural loading is greatly affected by the joining method and the adhesive usage.

The combination of round Screw Joints with cyanoacrylate adhesive significantly enhances the flexural strength of the final joined part. The use of cyanoacrylate adhesive for flat dovetail joints negatively impacts flexural strength. Therefore, the effectiveness of cyanoacrylate adhesive depends on the used segmental joining method.
Overall, the study provides valuable information about the mechanical properties of joined 3D-PLA segments, highlighting the importance of choosing suitable bonding methods to achieve optimal mechanical performance for 3D-printed structures.

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