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RESEARCH ARTICLE

# Effect of printing orientation and thickness of 3D printed PLA beam on the flexural performance: A combined experimental and simulation study

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**Abstract –** The mechanical properties of 3D printing results especially using fused deposition modeling (FDM) are affected by process parameters including printing speed, infill density, printing patterns and printing orientations. In this study, the effect of 2 different printing orientations (top and front orientation) and thicknesses on the bending deflection behavior of polylactic acid (PLA) beams is investigated. In addition, finite element analysis was conducted to simulate the bending test. Test specimens were produced using FDM with 4 different thicknesses: 2.75 mm, 3.00 mm, 3.25 mm, and 3.50 mm. For each thickness, the two printing orientations (top and front) were applied, resulting in 8 specimen variations in total. Three-point bending using a custom testing device based on ASTM D790 is used to evaluate its deflection. The results show that printing orientation influences the bending behavior of 3D printed PLA structures, especially in thinner specimens and that the specimens printed in the top orientation yield a result that align more closely with FEA simulations.

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## 1. Introduction

Three-dimensional printing (3D printing) is a part of additive manufacturing (AM) process which involves manufacturing physical objects layer by layer from a 3D computer aided design (CAD). Due to small to no parts being discarded, this process is a low-waste manufacturing process which makes it a sustainable alternative to the conventional subtractive manufacturing process. Among the various methods such as fused deposition modeling (FDM), stereolithography (SLA), digital light processing (DLP) and selective laser sintering (SLS), the FDM process is the most common method due to its ease of use [1]. Common materials used for the FDM method are thermoplastics such as polylactic acid (PLA) and acrylonitrile butadiene styrene (ABS). Due to environmental concerns and the availability of petroleum-based plastics such as ABS, biodegradable materials such as PLA have become one of the widely utilized materials in FDM 3D printing [2]. However, similar to other materials, PLA has mechanical limitations that requires improvement and assessment using standardized testing methods. There are several methods that have been studied to improve mechanical properties of PLA. Arora, et al. (2025) investigated PLA composites infused with betel nutshell-derived biocarbon (BNAC) and reported a tensile strength increase of up to 51.1% and a flexural strength improvement of 24.5% at low doping levels [3]. Similarly, PLA modified with pinus sylvestris char achieved a 25% and 98% increase in bending and tensile strength, respectively, compared to neat PLA [4]. Another study utilized activated carbon derived from durian husk waste, resulting in a 28.05% increase in tensile strength, a 17.12% rise in Young's modulus, and a 10.11% improvement in elongation at break [5]. Similarly, Natayu, et al. (2025) [6] improved the 3D printed resin with additional halloysite nanotubes for hot embossing applications. Besides composites, blending PLA with several additives or do post processing on the printed parts may also improve its performance. Heidari and Garmadi (2026), for example, blend PLA with polybutylene adipate terephthalate (PBAT) and Joncryl using response surface methodology resulted in ductility improvements, with elongation at break increasing by 2314% and toughness by 2418% [7]. On the other hand, Alonso-González, et al. (2025) blend PLA with rice bran, which resulted in a decrease in tensile strength from 26 MPa to 11 MPa [8]. Natayu, et al. (2024) improved 3D printed parts by annealing the parts [9]. On the study, they annealed the printed parts at 95 °C and 145 °C for 30, 60, and 120 minutes, then tested the materials in tensile tests. The results showed that the parts that were annealed at 95 °C for 30 minutes provides the highest Young's modulus and ultimate tensile strength compared to other parameters.

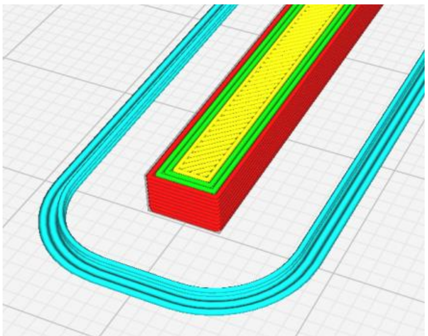
Mechanical properties of the objects that were printed in 3D can also be improved through printing parameters that were used. Some parameters of the 3D printing that can be adjusted are the infill density, nozzle temperature, print speed, or build plate temperature. A study by Abualbandora et al. reported that increasing the extrusion temperature may increase the tensile strength, reduces surface roughness and surface defects of the material. A lower extrusion temperature increases the chances of air gaps forming between the deposited layers. Therefore, maintaining an appropriate extrusion temperature is important to ensure proper adhesion [10]. Magdum et al. investigated the effects of several infill densities, layer thickness and shell thickness of PLA material in FDM printing. Results shows that mechanical properties are observed to increase with the increase of layer thickness [11]. A similar study by Mishra et al. reported that as infill density increases from 50 – 90% results in a lower stress concentration, higher load bearing capacity and better material deposition [12]. Another way is to use unique raster orientation, such as research by Baharlou and Ma. In their research, they improve tensile modulus and interlayer adhesion of the printed object using quasi-isotropic layups raster orientation [13].

Various tests can be performed to assess the mechanical properties of 3D printed results and their improvements. One of the mechanical testing procedures is three-point bending. This test was conducted by applying a load on the centre of the specimen, which typically in a shape of a beam, while it being supported on both sides of the specimen. This bending test results in the material's flexural modulus which will be useful for material selection when designing a structure [14–16]. Bending test can also provide a critical fatigue characterization and to ensure realistic stress distribution [17]. The test, however, should be designed carefully, according to established standards, such as ISO 178 and ASTM D790 [17,18]. The outcome of this test may also depend on how the materials is fabricated [19], it is important to investigate the influence of the printing parameters on the mechanical performance. Faidallah, et al., for example, highlights the need of geometric optimization in additive manufacturing applications, which requires tensile and bending test for a comprehensive mechanical evaluation [20]. Therefore, in this article, the parameter of the 3D printed specimen were evaluated and tested to get the optimized mechanical properties. To further explore the effect of thickness and printing parameters on the mechanical properties of 3D-printed materials, this paper investigates the effects of thickness and print orientation on the strength of 3D-printed beam structure. In this study, 4 different thickness and 2 different printing orientations are investigated: (a) the front view of the beam parallel to the build plate (front view orientation), and (b) the top view parallel to the build plate (top view orientation). The method selected for mechanical testing is a three-point bending testing using a custom testing apparatus. The fabrication of the test specimens uses FDM and PLA as the printing material. In addition, finite element analysis was performed in order to simulate the three-point bending.

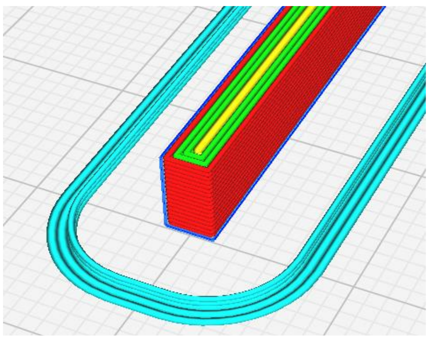
## 2. Materials and Methods

### 2.1 3D Printing Process

The filament material used in this research is PLA+ with a tensile strength of 20.6 MPa and an elastic modulus of 0.4 GPa These values were obtained through a tensile test conducted on 5 specimens printed using the same parameters as those used in the bending test. The test specimens were designed according to ASTM D790 in the form of rectangular beams with length of 120 mm and a width of 5 mm, while the thickness was varied between 2.75 mm, 3.00 mm, 3.25 mm and 3.50 mm. The samples were fabricated using Anycubic Mega i3 FDM 3D printer and sliced with the Ultimaker Cura software. Two different printing orientations were applied namely the top view and front view (Figure *1*). Combined with the varied thickness, there are a total of 8 different specimen variations produced. The printing parameters were kept constant throughout all specimen variations, which is shown in Table *1*.



(a)



(b)

Figure 1. Illustration of the a) Top orientation and b) front orientation

Table 1. 3D printing parameters

| Parameter | Value | unit |
|---|---|---|
| Infill density (zig-zag pattern) | 25 | % |
| Extruder temperature | 210 | °C |
| Bed temperature | 60 | °C |
| Layer height | 0.2 | mm |
| Wall thickness | 1.2 | mm |
| Fan speed | 100 | % |
| Printing speed | 50 | mm/s |
| Support | - | - |

The three point bending test apparatus was prepared and built using 3D printing in accordance with ASTM D790 which is shown in Figure 2. The custom specimen has a support length of 40 mm. The upper part of the apparatus, which weighs 134 grams, allows weights to be placed on top of it, which acts as the load for the specimen. Experimental on three point bending test was conducted using the built bending apparatus in which each variation was tested for three times. Weights were applied incrementally, starting from 44.14 Newtons with and ending at 59.84 N with an increment of 1.96 N. The load in which the specimen experiences catastrophic failure was recorded. The maximum load is then used to estimate the bending strength of PLA as validation process of the methodology of the machine. The estimated bending strength was calculated using the three-point bending strength equation as shown in equation (1).

$$\sigma = \frac{3FL}{2bd^2} \tag{1}$$

Where, $F$ is the maximum applied force, $L$ is the distance of the support, $b$ is the width, and $d$ is the thickness of the specimen. The resulting bending strength values then compared with published data for PLA obtained using standardized methodology and machine to assess validity and consistently to the current measurements. To obtain deflection, the captured images of the specimen were imported to SOLIDWORKS, and the unit were set to millimetres. Since the length of the specimen is known to be 120 mm, a reference line of the same length was drawn in SOLIDWORKS and the image was scaled to match the reference line. The deflection is then measured using the sketch feature. Figure *3* shows the illustration to measure deflection.

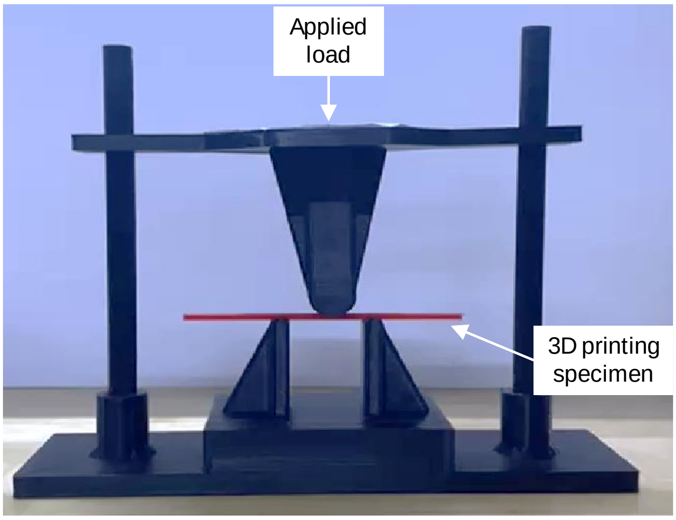



Figure 2. Custom three-point bending apparatus made using 3D printing

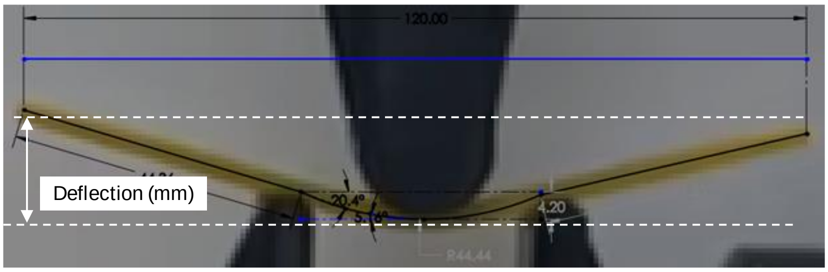



Figure 3. Method to measure deflection using SOLIDWORKS

**2.2 Finite Element Analysis**

Finite element analysis (FEA) was conducted using the SOLIDWORKS static simulation for all specimen variations. The model was configured as a simply supported beam with a dimension and loading conditions similar to the experimental setup, where a single concentrated load was applied at the middle, as illustrated in Figure *4*. A curvature-based mesh with the finest mesh density was applied during the simulation, with the minimum and maximum element size of 0.68 mm and 1.21 mm respectively. The simulation was performed to predict deflection without considering the printing orientation.

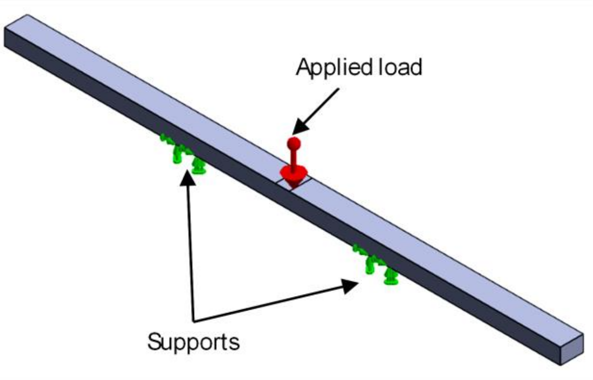



Figure 4. Isometric view of the finite element model of the three-point bending

## 3. Results and Discussion

### 3.1 Three-point Bending Analysis

The three-point bending experiments show that some specimens experiencing bending as the load increases. While some others are fracture when the load reached certain value. The deflection and breaking load were then determined. In the cases where fracture occurred, the cracks propagated rapidly from the loading point. The resulting fracture surfaces appeared relatively smooth, typical characteristic of brittle failure. Figure 5 shows some representative specimens after undergoing the three-point bend test. Table 2 shows the data of the final load and final conditions for three different specimens for three trials.

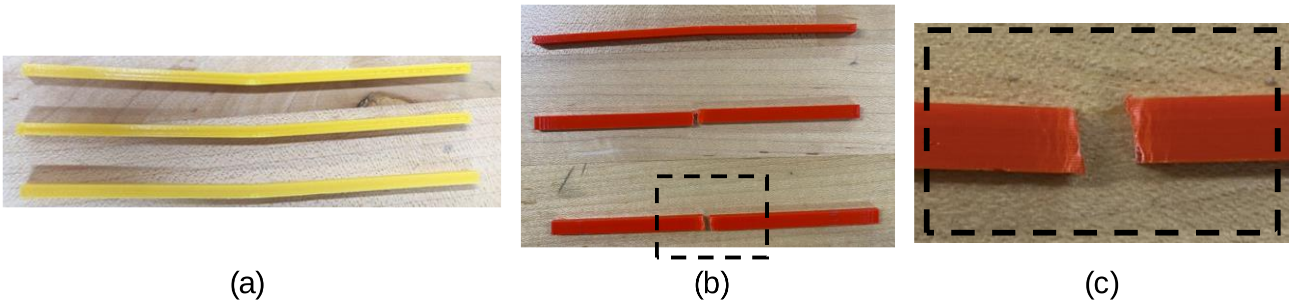


Figure 5. (a) 3D printed specimens experiencing bending only, (b) 3D printed specimens experiencing fracture, (c) Zoom view of the fracture specimen indicating brittle fracture

Table 2. Breaking force of all specimens for three trials each

| Thickness (mm) | Printing orientation | Trial 1 (N) | Trial 2 (N) | Trial 3 (N) |
|---|---|---|---|---|
| 2.75 | Top | 66.12 | No fracture | 66.12 |
| 2.75 | Front | No fracture | 70.04 | 70.04 |
| 3.00 | Top | No fracture | No fracture | 72.99 |
| 3.00 | Front | No fracture | No fracture | No fracture |
| 3.25 | Top | No fracture | No fracture | No fracture |
| 3.25 | Front | No fracture | No fracture | No fracture |
| 3.50 | Top | No fracture | No fracture | No fracture |
| 3.50 | Front | No fracture | No fracture | No fracture |

The measurement results were validated by estimating the bending strength of the PLA specimens and comparing the values with data reported in the literature in a comparable, standardized conditions. The bending strengths were calculated from the maximum applied force from the results and the specimen geometry using the relation given in equation (1). Table 3 shows the calculated bending strength for each specimen.

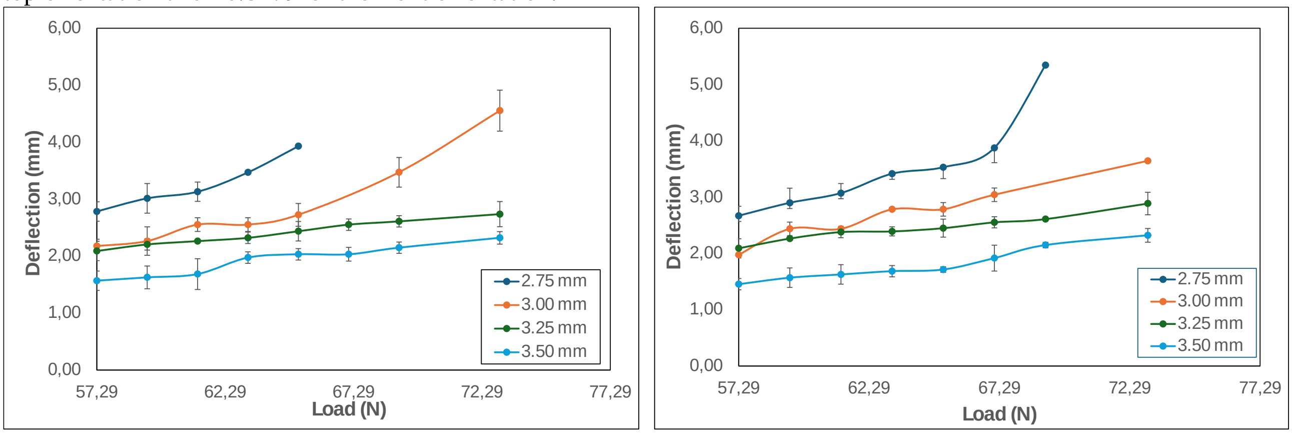
Table 3. Bending strength of the specimens

| Thickness (mm) | Printing orientation | Maximum load on fracture (N) | Estimated bending strength on fracture (MPa) |
|---|---|---|---|
| 2.75 | Top | 66.12 | 104.92 |
| 2.75 | Front | 70.04 | 111.14 |
| 3.00 | Top | 72.99 | 97.32 |
| 3.00 | Front | No fracture | No fracture |
| 3.25 | Top | No fracture | No fracture |
| 3.25 | Front | No fracture | No fracture |
| 3.50 | Top | No fracture | No fracture |
| 3.50 | Front | No fracture | No fracture |

The estimated bending strength in Table 3 indicate that PLA specimens exhibit bending strength in the range of 97.32 to 111.14 MPa. These values fall within the range of bending strength reported for PLA in previous studies that used comparable, standardized bending condition [21,22]. The values for specimens which did not fracture were not use due to uncertain maximum load to calculate the bending strength.

### 3.2 Effect of Thickness towards Deflection Angle

Figure 6 shows that as the specimen thickness increases, the deflection decreases for both top and front printing orientations. The reduction continues with increasing thickness, with the lowest deflection observed at 3.50 mm. On average, increasing the specimen thickness from 2.75 mm to 3.00 mm resulted in a reduction in deflection of approximately 24.43% for the top orientation and 20.61% for the front orientation. Further increasing the thickness from 3.00 mm to 3.25 mm reduced the deflection by around 14.60% for the top orientation and 11.19% front orientation. Lastly, when the thickness was increased from 3.25 mm to 3.50 mm, the deflection decreased by approximately 20.20% for the top orientation and 26.82% for the front orientation.




(a) (b)

Figure 6. Plot of deflection vs load for various specimen thicknesses using (a) top and (b) front printing orientations

### 4.3 Impact of Printing Orientation towards Deflection

From Figure Figure 7 (a) to (d), it can be observed that specimens printed in the top orientation generally exhibit higher deflection compared to those printed in the front orientation. This indicates that the layer influences the bending response, with the front printing orientation resulting in less deformation under the applied load. When comparing each thickness individually, the 2.75 mm specimen printed in the top orientation failed earlier than the front orientation. At 3.00 mm, the top orientation shows higher deflection (4.55 mm) compared to the front orientation (3.68 mm) at the maximum applied load. For 3.25 mm and 3.50 mm, the deflection was observed to be almost identical, with differences of less than 0.3 mm between orientations. Specifically, the 3.25 mm specimen shows slightly higher deflection for the front orientation, while the 3.50 mm specimen shows slightly higher deflection for the top orientation.

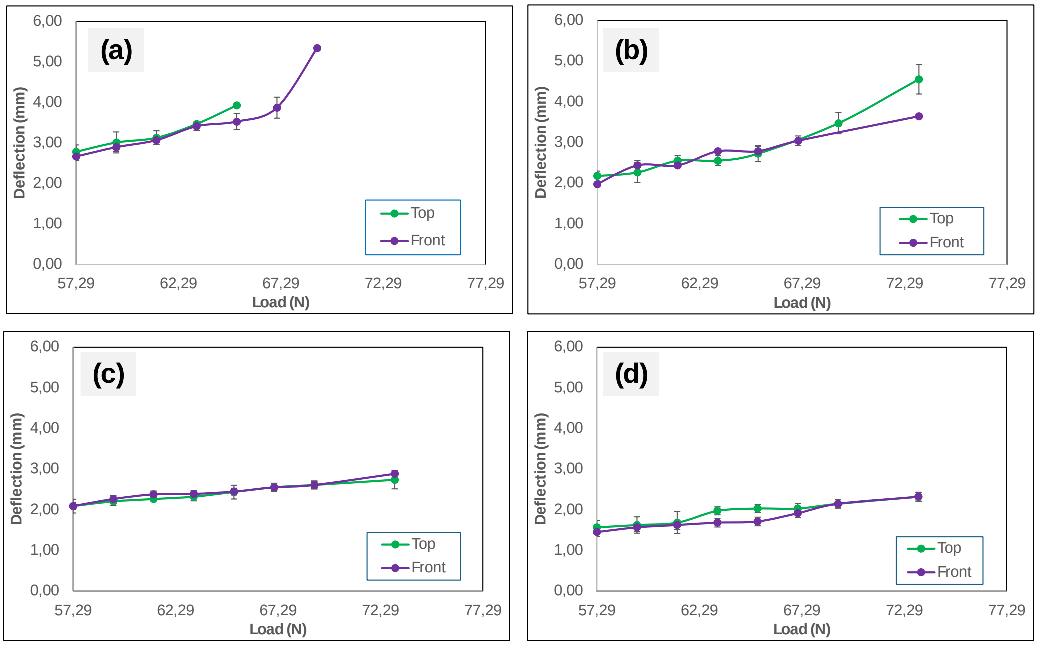



Figure 7. Plot of deflection vs load to compare effect of the printing orientation at various specimen thicknesses a) 2.75 mm, b) 3.00 mm c) 3.25 mm and d) 3.50 mm

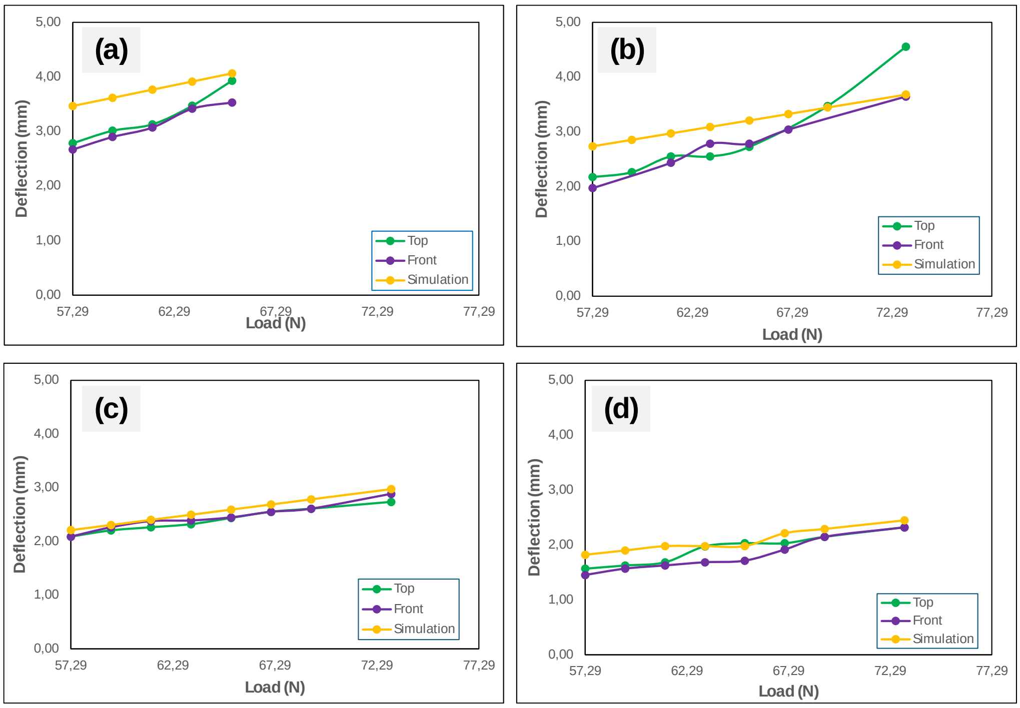



Figure 8. Plot of deflection vs load to compare effect of the printing orientation and simulations at various specimen thicknesses a) 2.75 mm, b) 3.00 mm c) 3.25 mm and d) 3.50 mm

### 3.4 Finite Element Analysis Results

Figure 8 (a-d) show the comparison of FEA simulation and experimental data for both top and front orientations. Deviation values were calculated based on the average percentage differences across all applied loads for each specimen thickness. For the 2.75 mm specimens, the average deviation between simulation and experiment is 13.54% for top orientation and 17.41% for the front orientation. At 3.00 mm, the deviation is found to be 16.03% and 13.31% for top and front orientations respectively. For the 3.25 mm specimens, the deviation decreased to 6.08% (top orientation) and 4.1% (front orientation). Lastly, for the 3.50 mm specimen, the deviation increased slightly to 8.22% (top orientation) and 13.58% (front orientation). These results indicate that the smallest deviations were observed at the 3.25 mm specimens, while the largest was observed at the 2.75 mm specimens. On average, the top orientation shows a smaller deviation of 10.97% compared to the front orientation, which has a deviation of 12.10%. This indicates that the top orientation is slightly closer to the FEA simulation.

## 4. Conclusions

In this study, the effects of printing orientation on the three-point bending deflection of 3D printed PLA specimens were investigated. Four different specimen thickness, 2.75, 3.00, 3.25 and 3.50 mm were tested for both top and front printing orientation. In general, specimens printed in the front orientations exhibited a lower deflection than those printed in the top orientations, except for the 3.25 mm where the front orientation shows a slightly higher deflection. The differences in deflection between the two orientations are more significant at smaller thickness and gradually decreased as specimen thickness increased. In addition, the three-point bending experiment of top orientation shows closer deflection with finite element simulation results, with an average deviation of 10.97% compared to 12.10% for the front orientation. The largest deviation between experiment and simulation was observed at the 2.75 mm specimen with the smallest deviation observed at the 3.25 mm specimens. These findings show that printing orientation influences the bending behavior of 3D printed PLA structures, especially in thinner specimens and that the specimens printed in the top orientation yield a result that align more closely with FEA simulations.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**Declaration of Competing Interest**

The author declares no conflicts of interest.

**Credit Authorship Contribution Statement**

Kushendarsyah Saptaji (Conceptualization; Validation; Visualisation; Writing – review & editing; Supervision)
Annisa Nurcahyati Puspita Dewi Sutardi (Methodology; Formal analysis; Data curation; Writing - original draft; Investigation; Resources)
Nathan Wijaya (Methodology; Data curation; Investigation; Resources)
Nikolas Krisma Hadi Fernandez (Methodology; Validation; Formal analysis; Writing-original draft)
Cholik Chan (Conceptualisation; Methodology; Supervision)
Anwar Ilmar Ramadhan (Formal analysis; Writing – review & editing)
Tedi Kurniawan (Formal analysis; Writing – review & editing)

**Availability of Data and Materials**

The data supporting this study's findings are available on request from the corresponding author.

**Ethics Declarations**

This study did not involve human participants or animals. Ethical approval was therefore not required.

**Generative Artificial Intelligence Declarations**

The authors claim that artificially intelligent-assisted technologies, such as generative AI, were not used to generate content, ideas, or theories. We have just utilised AI to enhance readability and refine the language. This was used with extreme human control and oversight. The authors take full responsibility for reviewing and approving the content.

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