Exploring Building Orientation Effects on Mechanical Properties in FDM Technology: A Two-Scale Numerical Analysis

Explorer les effets de l'orientation des bâtiments sur les propriétés mécaniques dans la technologie FDM : une analyse numérique à deux échelles

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ABSTRACT. Additive manufacturing, particularly Fused Deposition Modeling (FDM), has revolutionized the fabrication of customized products, offering an opportunity to make complex parts. However, inherent complexity of these parts demands attention to analyze them, especially in understanding their mechanical properties. This study uses a homogenization method to determine these properties using two scale technique. Our investigation explores the influence of building orientation (Flat, On-edge, Up-right) on longitudinal Young's modulus. To achieve this, we begin by creating the appropriate Representative Volume Element (RVE) which embodies the microstructure of 3D printed specimens. Subsequently, we calculate orthotropic properties of this RVE using Material Designer tool. Then, these properties are integrated into the subdivided specimen using material Referencess within ANSYS Workbench. And finally, we validate our numerical findings with experimental results.

RÉSUMÉ. La fabrication additive, en particulier le Dépôt de fil fondu (DFF), a révolutionné la fabrication de produits personnalisés, offrant une opportunité de créer des pièces complexes. Cependant, la complexité inhérente de ces pièces nécessite une attention particulière pour les analyser, notamment pour comprendre leurs propriétés mécaniques. Cette étude utilise une méthode de l'homogénéisation pour déterminer ces propriétés en utilisant une technique à deux échelles. Notre investigation explore l'influence de l'orientation de fabrication (Flat, On-edge, Up-right) sur le module de Young longitudinal. Pour ce faire, nous commençons par créer l'élément de volume représentatif (RVE) approprié qui incarne la microstructure des spécimens imprimés en 3D. Ensuite, nous calculons les propriétés orthotropes de ce RVE en utilisant l'outil Material Designer. Puis, ces propriétés sont intégrées dans le spécimen subdivisé en utilisant des références de matériaux dans ANSYS Workbench. Enfin, nous validons nos résultats numériques avec des résultats expérimentaux.

KEYWORDS. FDM, homogenization method, RVE, Two-Scale, Numerical Analysis, Interface, Building orientation.

MOTS-CLÉS. DFF, méthode d'homogénéisation, RVE, méthode à deux échelles, analyse numérique, interface, orientation d'impression.

1. Introduction

Fused Deposition Modeling (FDM), has emerged as a transformative technology in modern manufacturing, enabling the fabrication of highly customized and complex parts with efficiency and flexibility. This technology has found widespread applications across various industries, ranging from aerospace and automotive to healthcare and consumer goods. However, the large adoption of FDM technology is hampered by understanding/predicting the mechanical properties of 3D printed parts, which are influenced by various factors of printing parameters such as building orientation. This parameter in FDM impacts the mechanical strength and surface finish of printed parts [CHAU 23, ĆWI 17, GON 22, KHA 22]. It determines the need for support structures, influencing print time and material usage. Additionally, proper building orientation minimizes warping and ensures dimensional accuracy. Ultimately, selecting the optimal building orientation enhances part performance in FDM printing.

In this context, many researchers focus on the homogenization method to predict the mechanical properties of printed parts [ANO 22, BEL 03, CAL 17, EZZ 23, MAR 21, SOM 18, SPI 23]. This involves analyzing material composition, microstructure, and process parameters to accurately estimate the overall stiffness and rigidity of printed part. Especially, a two-scale numerical analysis approach was employed [SOM 18, ANO 19], integrating microscale and macroscale analyses. At microscale, Representative Volume Element (RVE) is used to model the microstructure of 3D printed components [OMA 19, ANO 19, RAY 20, FER 21]. It provides insights into material behavior at a microstructural level. While, macroscale analysis involves subdividing specimens into distinct regions [EST 18, FER 21, SOM 18], considering the orientation of printed lines and integrating microscale-derived properties into macroscale using material References [EST 23].

Despite extensive study of various printing parameters such as grid infill, layer thickness, and infill density…, the interaction between concentric infill and building orientation remains relatively unexplored. Our research seeks to fill this void, offering valuable insights into how this combination impacts mechanical properties and overall performance of 3D printed parts.

In this study, we aim to investigate the influence of building orientation on the longitudinal Young's modulus of 3D printed parts (Specimen). Furthermore, we will analyze the impact of interface mechanical properties on longitudinal Young's modulus. using the two-scale homogenization method, we can effectively study how printing parameters affect elastic properties. The current investigation employs simulation techniques, the Material Designer plugin in ANSYS is used to calculate orthotropic properties and ANSYS Workbench for material integration and analysis. Obtained numerical results are compared with experimental ones from [REV 20], in order to validate the accuracy of the proposed numerical model and identify areas for improvement. And in the next section, we will present finite element model.

2. Material and methods

2.1. *Two-scale numerical simulation*

Our methodology comprised several steps:

a. Creation of RVE without Interface: Initially, a Representative Volume Element (RVE) was generated without interfaces, focusing only on modeling voids at microscale [SAN 21].
b. Creating the 3D model (specimen) using ASTM D638 standard in figure 1 and 3D printing parameters in table 1.
c. Injection of Properties into Specimens: The calculated properties were then integrated into the specimens using material Referencess within ANSYS software [EST 23].
d. Calculation of Equivalent Young's Modulus: The equivalent Young's modulus was computed at macroscale for the specimens [NIK 23, SOM 21].
e. Comparison of Numerical and Experimental Results: The numerical results were compared with experimental data obtained from another article [REV 20], ensuring validation and accuracy of numerical model.
f. Creation of RVE with Interface: Subsequently, an RVE with interfaces was developed, incorporating both voids and interfaces at microscale. This was done to align with experimental results observed at macroscale.

2.2. CAD Model of 3D printed specimen

The properties of the PLA material used in this work are provided in table 2, the specimens were fabricated according to ASTM D638 standard dimensions, as illustrated in figure 1, and printing parameters used for the fabrication of the specimens are detailed in table 1.

Parameters	Values
Layer height	0.16 mm
Flow rate (mm3/s)	4.8
Number of top/bottom layers	5
Nozzle diameter (mm)	0.4
Top and bottom thickness	0.6 mm
Printing temperature	210 °C
Printing speed	50 mm/s
Infill pattern	Concentric
Infill density	100%
Building orientation	Flat, On-edge, Up-right

Table 1. *3D printing parameters for numerical simulation [REV 20]*

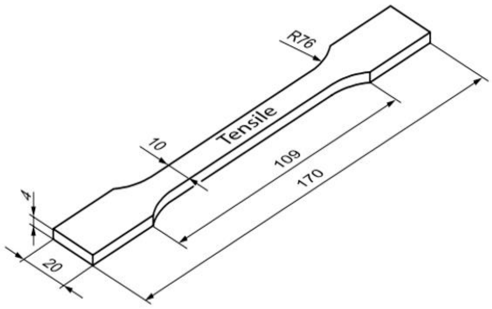


Figure 6. *ASTM D638 standard of the specimen dimension in mm [REV 20]*

Mechanical properties	Value
Tensile strength (MPa)	35.6
Tensile modulus (MPa)	3420
Density (g/m3)	1.24

Table 2. *Mechanical properties of the polylactic acid (PLA)-based materials provided by the manufacturer* [REV 20]

2.3. Calculation of orthotropic properties using Representative Volume Element (RVE)

2.3.1. Creation of RVE Geometry without interface

The CAD models of sample and Representative Volume Elements (RVEs) were generated using CATIA V5 software, adhering to printing parameters outlined in table 1. These RVEs were specifically designed to capture the microstructure of 3D printed part at microscopic level, such as layers, beads, and voids [CHE 20]. The RVEs offered the possibilities to calculate the material properties along (X-axis, Y-axis, Z-axis for the young's modulus) as shown in figure 2, we use this References with (X-axis, Y-axis, Z-axis) to assign the material properties in the macroscale [EST 23], the calculated elastic properties without interface using material designer are given in table 2.

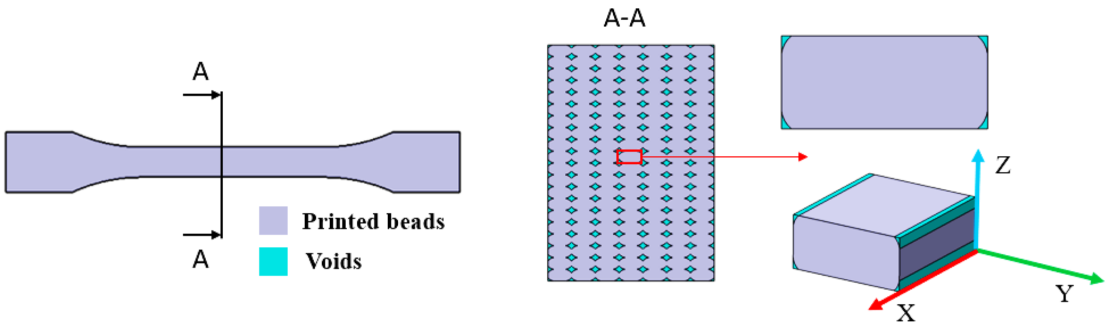


Figure 7. *Geometry of RVE without interface at 100% infill density using concentric infill pattern, displaying voids in blue and PLA material in gray.*

2.3.2. *Creation of RVE Geometry with interface*

Figure 2 presents the Representative Volume Element (RVE) with interface between printed layers and lines [PER 21]. This interface, characterized by linear elastic properties, was developed after observing an error more than 5% (in the case of RVE without interface) between experimental and numerical results as given in table 3. The mechanical properties of interface are lower than those of bulk PLA introduced in the RVE without the interface. By incorporating this interface, we aimed to enhance the accuracy of our simulations and better understand the impact of interface behavior on overall material properties. Calculated elastic properties with interface using material designer are given in table 2.

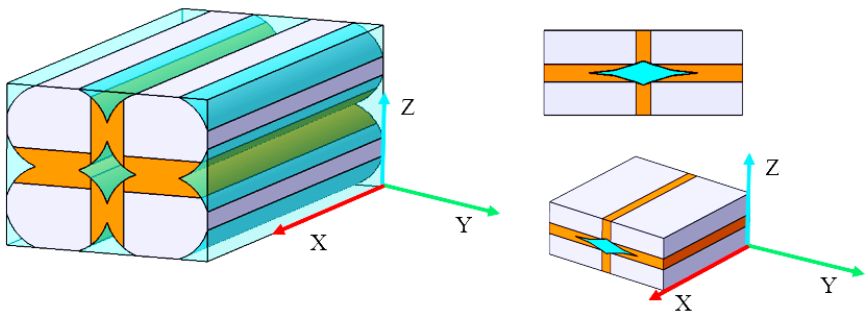


Figure 8. *Geometry of RVE with interface at 100% infill density using concentric infill pattern, displaying voids in blue and PLA material in gray.*

2.3.2. *Calculated orthotropic properties*

Orthotropic properties calculated from this RVE with interface using Material Designer are listed in table 3.

	E1 (MPa)	E2 (MPa)	E3 (MPa)	G12 (MPa)	G23 (MPa)	G31 (MPa)	nu12	nu13	nu23
RVE without interface	3371.9	3070.1	3305.9	1192.1	1210.2	1236.9	0.35	0.35	0.33
RVE with interface	3253.2	2973.6	3187.6	1138.8	1139.6	1182.7	0.35	0.35	0.32

Table 3. *Elastic moduli of the RVE without interface*

2.4. *Building orientation modeling*

Building orientation usually refers to how a part or object is positioned during the printing process in the context of manufacturing or 3D printing. Figure 1 illustrates diverse orientations of buildings examined in our study Flat, On-edge, Up-right.

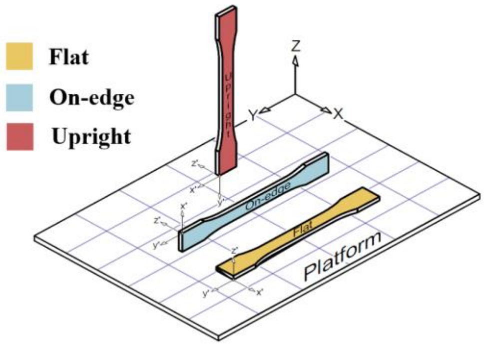


Figure 9. *Building orientation (Flat, On-edge, Up-right)*

Figure 5a, 6a, 7a show different regions of the specimen (infill, wall, top and bottom layers). Each of these regions has a specific material orientation: Infill and wall are printed at different angles along the X-axis, as shown in Figure 5c, 6c, 7c, while top and bottom layers are printed with 45°. We use the calculated elastic properties from the microscale to be injected to this model with respect of material Referencess as shown in figure 5b, 6b, 7b.

2.4.1. *Building orientation modeling – flat*

Flat Orientation: In this orientation, the object is printed with its largest surface parallel to the build platform,

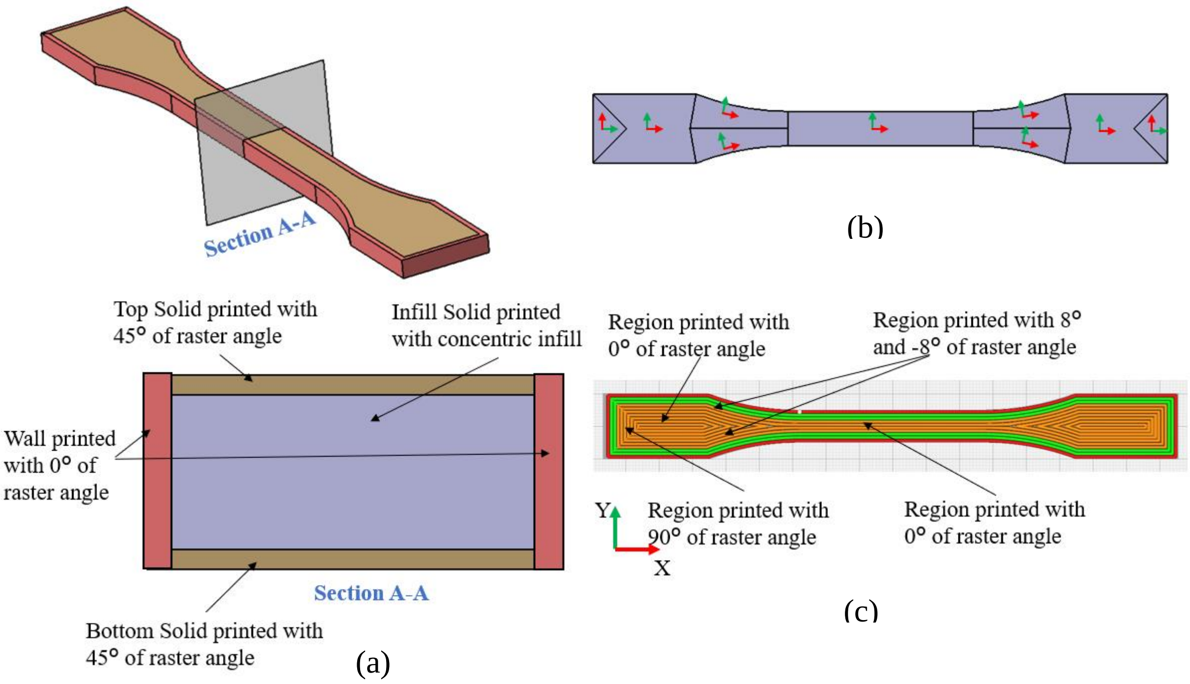


Figure 10. *Printed specimen with On-edge building orientation (a) different region in specimen (b) material orientation in the infill and wall*

2.4.2. *Building orientation modeling – On Edge*

On Edge Orientation: Here, the object is printed standing on one of its edges, with its longest dimension perpendicular to the build platform,

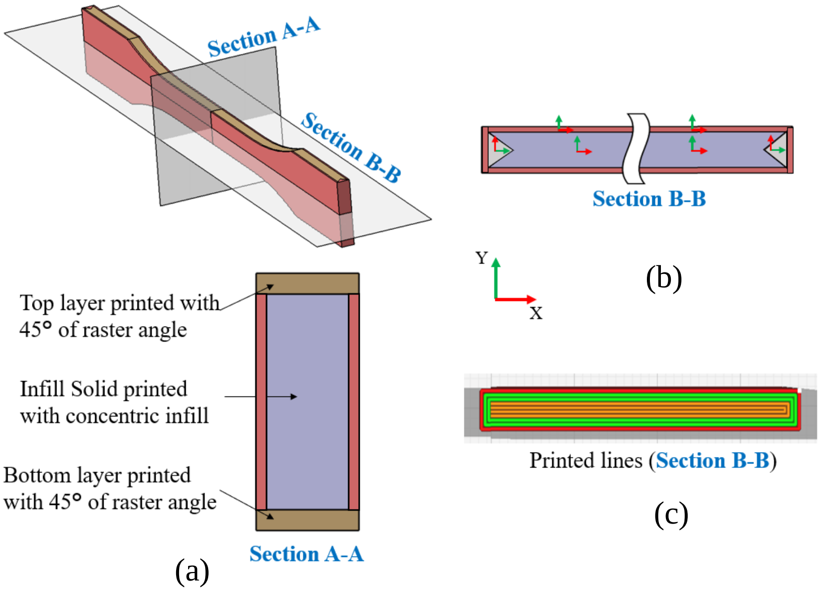


Figure 11. *Printed specimen with On-edge building orientation (a) different region in specimen (b) material orientation in the infill and wall*

2.4.3. *Building orientation modeling – Up-right*

Up-right Orientation: In this orientation, the object is printed standing Up-right, with its height perpendicular to the build platform.

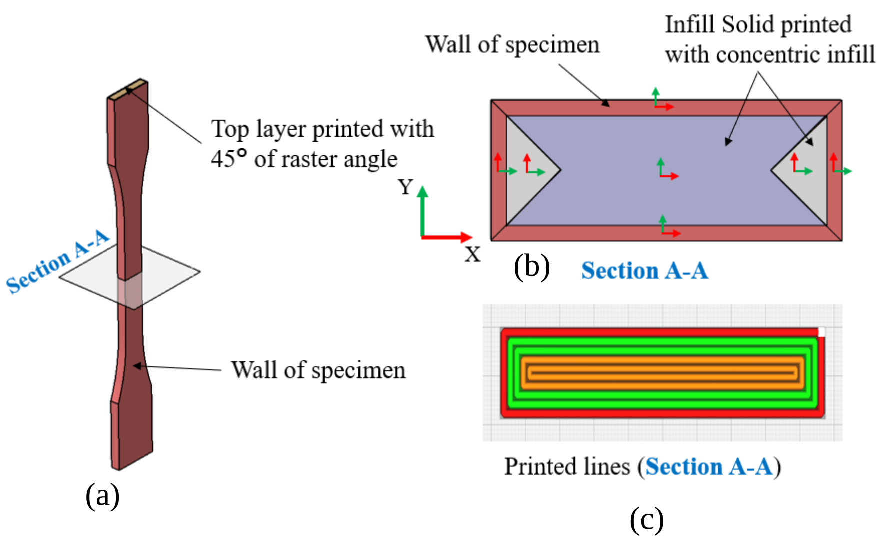


Figure 12. *Printed specimen with On-edge building orientation (a) different region in specimen (b) material orientation in the infill and wall*

2.4.4. *Finite element method*

2.4.4.1. *Meshing Convergence and Mesh in the Model*

Meshing convergence ensures accuracy by refining mesh until results stabilize. Our study used iterative refinements, decreasing element size until changes in key results were negligible. The final mesh, consisting of element size equal to 0,9 mm.

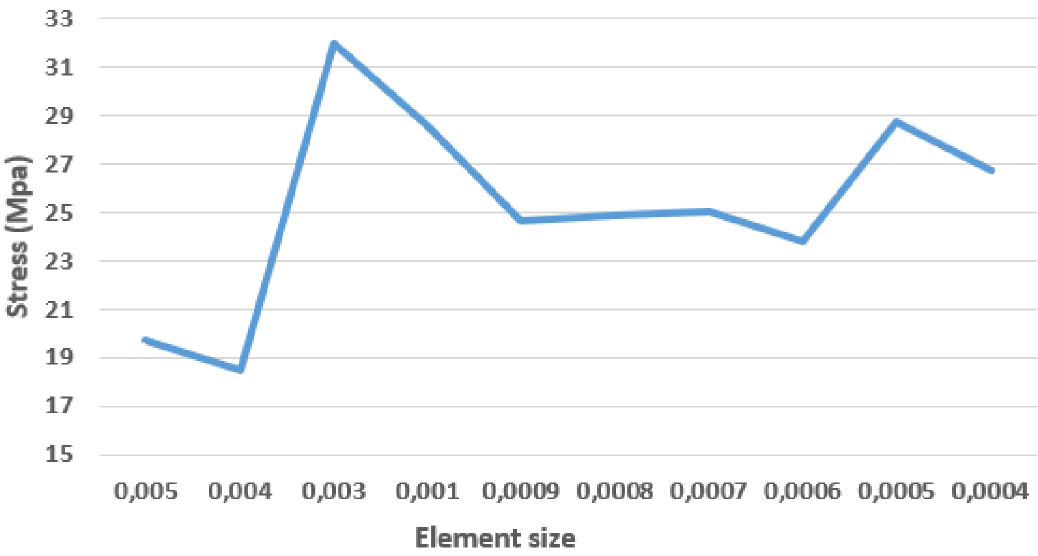


Figure 13. *Mech convergence*

2.4.4.2. *Limit Conditions: Fixation and Applied Forces*

Boundary conditions were applied to simulate real-world scenarios accurately. One side of the specimen was fixed, preventing any movement (zero displacements in all directions). In the opposite side was applied a displacement.

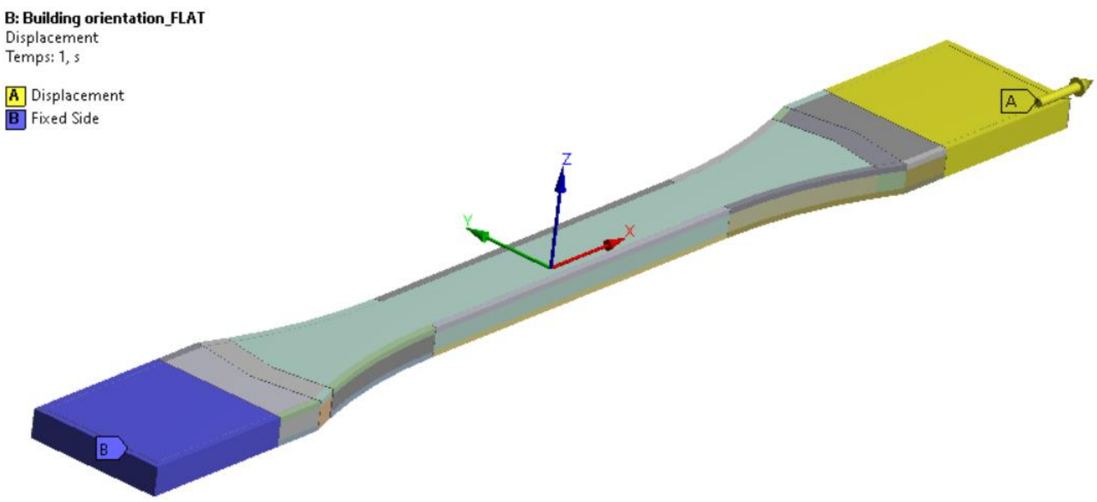


Figure 14. *Boundary conditions*

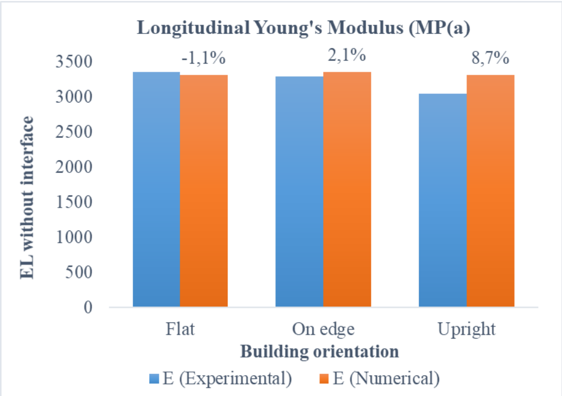
3. Results and discussion

A comparison was made between simulated results and experimental data obtained from tensile tests as reported in article [REV 20]. Table 4 presents the equivalent Young's Modulus of the specimens without and with considering interface at microscale.

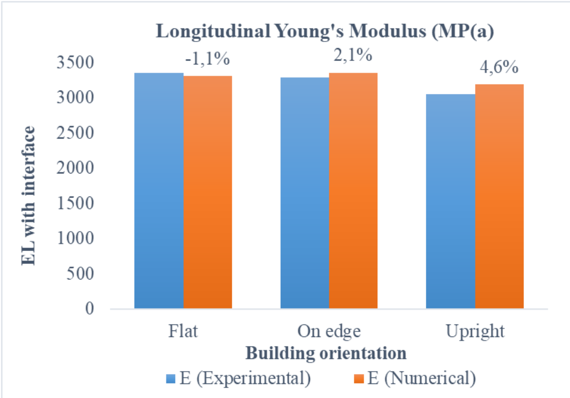
	Building orientation	Young's modulus (MPa) (Experimental test) [REV 20]	Std	Young's modulus (MPa) (Numerical simulation)	Error (%)
RVE Without Interface	Flat	3350	90	3311.96	-1.1%
	On-edge	3290	90	3357.54	2.1%
	Up-right	3050	600	3313.84	8.7%
RVE With interface	Flat	3350	90	3311.96	-1.1%
	On-edge	3290	90	3357.54	2.1%
	Up-right	3050	600	3188.88	4.6%

Table 4. *Longitudinal Young's Modulus of the specimen in the case of RVE without / with interface*

The following graph in figure 6 illustrates the correlation between simulated and experimental results, shedding light on the accuracy of our numerical models.



(a)



(b)

Figure 15. *Comparison of Equivalent Young's Modulus: Simulated vs. Experimental Data [REV 20] (a) Without Incorporating Interfaces at Microscale (b) With Incorporating Interfaces at Microscale.*

The incorporation of the interface in Representative Volume Element (RVE) give significant improvements in the accuracy of our numerical simulations. Initially, using RVE without interface, we observed an error more than 5% between experimental and numerical results as shown in Table 3 and in figure 6a. This considerable error highlighted the necessity to account for the interface between printed layers and lines, which was not initially considered.

By developing an interface characterized by linear elastic properties, we addressed this error. The mechanical properties of this interface were determined to be lower than those of bulk PLA, reflecting the weaker bonding and potential micro voids between layers. After injecting these modified properties into macroscale model, we observed a reduction in error to less than 5%.

In summary, our results indicate that inclusion of an interface within the RVE is crucial for accurately capturing the mechanical behavior of 3D printed materials. This methodological refinement bridges the gap between experimental observations and numerical predictions, ensuring that our simulations more closely reflect the real-world performance of these materials. Future work will focus on further refining the interface properties at macroscale and exploring their impact under various loading conditions to continue enhancing the predictive capabilities of our models.

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4. Conclusion

This paper presents the influence of printing parameters, such as building orientation, and interface properties, on Longitudinal Young's Modulus of printed specimens. First, we have created a Representative Volume Elements (RVEs) that accurately capture the microstructure of 3D printed specimens, and using these RVEs, we have calculated the orthotropic properties using Material Designer tool in ANSYS software. These properties were then integrated into a subdivided specimen within ANSYS Workbench, and our numerical findings were compared with experimental results. Initially, an error has been found between the numerical and experimental results for Upright of building orientation equal to 8,7%. therefore, by incorporating interfaces into the RVE model, we significantly reduced this error to less than 5% for enhancing the accuracy of our predictions. Consequently, this approach provides a valuable tool for designing and optimizing of printing parameters, and reducing the need for extensive experimental testing.

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