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Mechanical characteristics and FEA-based non-uniform infill density approaches for Fused Deposition Modelling (FDM)-printed components: A literature review

Mhd. Fahri Meihanda Putra*, **Syahril**, **Delima Yanti Sari**

Department of Mechanical Engineering, Faculty of Engineering, Universitas Negeri Padang, **Indonesia**

*Corresponding Author: mfahrimeihandap@gmail.com

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Abstract: Fused Deposition Modelling (FDM) is one of the most widely used additive manufacturing (AM) technologies for producing functional polymer components. However, commercially available slicing software generally applies a uniform infill density throughout the entire component without considering the actual stress distribution, resulting in excessive material usage in low-stress regions and unnecessary increases in component weight. This literature review synthesizes current knowledge on the mechanical characteristics of FDM-printed components and evaluates Finite Element Analysis (FEA)-based non-uniform infill density approaches as a promising strategy for structural optimization. The reviewed literature covers the effects of anisotropic behaviour, internal voids, infill density, infill pattern, and the integration of FEA with topology optimization techniques for FDM components. The findings indicate that the layer-by-layer deposition process produces pronounced mechanical anisotropy and introduces internal voids that influence structural performance. The relationship between infill density and mechanical strength is positive but nonlinear, whereas different infill patterns at the same density can produce variations of up to 82% in flexural strength. Although FEA provides reliable estimates of stress distribution, prediction errors of approximately 8.67–12% remain because conventional simulations assume homogeneous and isotropic materials that do not accurately represent the actual characteristics of FDM-printed components. Furthermore, FEA-based multi-zone non-uniform infill density strategies have been reported to increase peak load by up to 49% and bending stiffness by up to 46% compared with conventional uniform-density configurations. Overall, this review demonstrates that FEA-based non-uniform infill density is a promising design optimization strategy for functional FDM-printed components by improving structural performance while reducing unnecessary material usage. Future research should focus on density transition design and experimental validation to improve the reliability and practical implementation of this approach.

Keywords: additive manufacturing; fused deposition modelling; finite element analysis; non-uniform infill density; topology optimization; anisotropy

1. Introduction

Additive Manufacturing (AM) is a manufacturing technology that produces three-dimensional objects through the layer-by-layer deposition of materials, fundamentally differing from both subtractive and formative manufacturing processes (Tofail et al., 2018). One of the most widely adopted AM technologies is Fused Deposition Modeling (FDM), which fabricates components by depositing thermoplastic filaments layer by layer according to computer-aided design (CAD)-based toolpaths (Sandanamsamy et al., 2023). The ability of FDM to manufacture complex geometries within relatively short production times has enabled its transition beyond rapid prototyping toward the fabrication of functional end-use components (Wicaksono & Felix Krisna Aji Nugraha, 2022).

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The mechanical performance of FDM-printed components is strongly influenced by printing parameters, including layer thickness, build orientation, raster angle, infill pattern, and infill density (Birosz et al., 2022). The interaction among these parameters determines the interlayer bonding quality and the internal void distribution within FDM-manufactured components (Dai et al., 2025). Unlike homogeneous materials, which generally exhibit relatively uniform mechanical properties in all directions, FDM-printed components are inherently anisotropic, with their mechanical performance depending on both the printing orientation and the loading direction (Zohdi & Yang, 2021). The degree of anisotropy has been reported to reach approximately 50%, which is considerably higher than that of resin-based additive manufacturing technologies such as Selective Laser Sintering (SLS) and Stereolithography (SLA) (Kazmer, 2017).

In current practice, commercial FDM slicing software generally applies a uniform infill density throughout the entire component volume without considering the actual stress distribution within the structure (J. Liu et al., 2022; Steck et al., 2024). This approach may result in unnecessary material consumption in low-stress regions while increasing the overall weight of the printed component. To address this limitation, several studies have integrated Finite Element Analysis (FEA) with topology optimization techniques, including Bi-directional Evolutionary Structural Optimization (BESO) and Bio-Inspired Remodeling Algorithm (BIRA), to determine infill density placement based on stress distribution. These approaches have demonstrated improvements of up to 49% in peak load capacity and 46% in structural stiffness compared with conventional uniform-density configurations (Pais et al., 2022; Toth & Padayachee, 2023).

This paper presents a literature review that integrates current knowledge on the mechanical characteristics of FDM-printed components and non-uniform FEA-based infill density approaches. In this study, FEA is not considered a tool for predicting the absolute mechanical strength of printed components; rather, it serves as a design-support tool for determining the optimal placement of infill density zones prior to the printing process.

2. Additive manufacturing

AM is a manufacturing technology that fabricates three-dimensional objects from CAD models through the layer-by-layer deposition of materials, fundamentally differing from conventional subtractive and formative manufacturing processes (Zhou et al., 2024). A comparison between AM and conventional manufacturing processes is presented in Figure 1. This manufacturing principle provides a fundamental advantage by enabling precise control over a component's internal structure, including material distribution and density, through software-based process parameter adjustments without altering its external geometry (F. Liu et al., 2026). The general workflow of the AM process is illustrated in Figure 2.

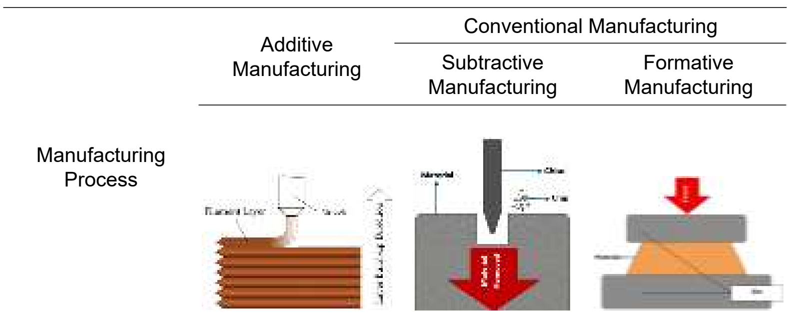

Figure 1. Comparison of additive manufacturing and conventional manufacturing processes (Buss et al., 2026)

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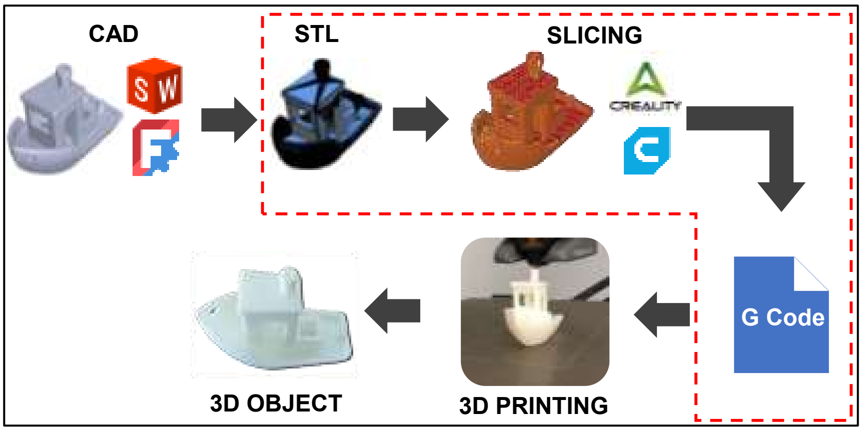

Figure 2. Schematic illustration of the additive manufacturing process from CAD model to the fabricated component

3. Fused deposition modelling

FDM is an AM technology that fabricates three-dimensional components by extruding molten thermoplastic filaments through a nozzle and depositing them layer by layer according to toolpaths generated from CAD models (Bol & Šavija, 2023). The fundamental configuration and layer-by-layer deposition mechanism of the FDM process are illustrated in Figure 3. The ability of FDM to produce components with complex geometries, short production times, and lower equipment costs than conventional manufacturing technologies has extended its application beyond rapid prototyping to the fabrication of functional end-use components (Seifollahi & Kabir, 2025).

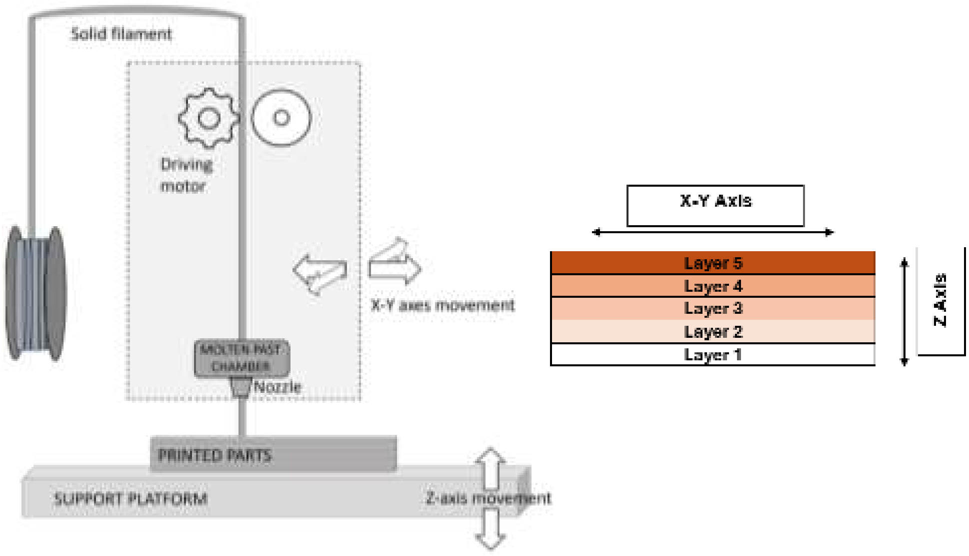

Figure 3. Schematic illustration of the FDM printing process, showing filament extrusion and layer-by-layer deposition (Acierno & Patti, 2023)

The mechanical performance of FDM-printed components is governed by several printing parameters, including layer thickness, nozzle diameter, extrusion temperature, printing speed, build orientation, raster angle, infill pattern, and infill density. These parameters collectively influence the interlayer bonding quality, internal void distribution, and the mechanical response of the printed component under applied loading (Fico et al., 2022). Representative examples of non-functional and functional FDM-printed components are presented in Figure 4.

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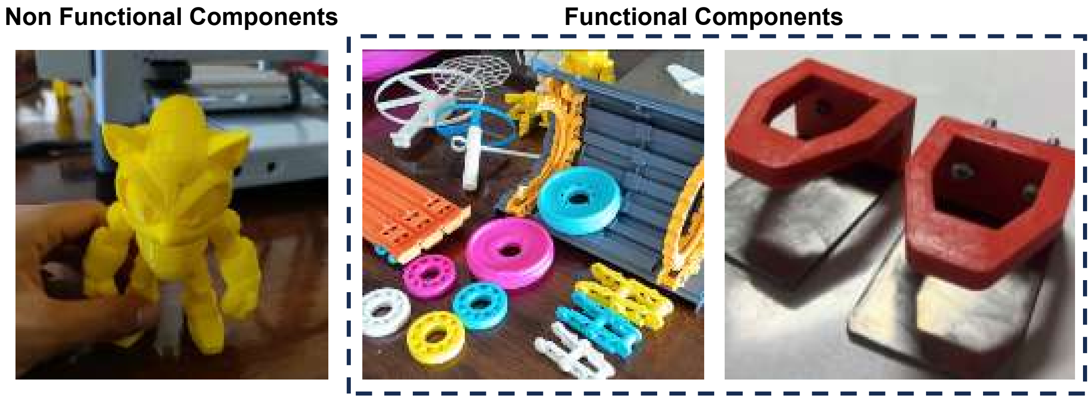

Figure 4. Examples of non-functional and functional FDM-printed components

4. Anisotropy in FDM-printed components

FDM-printed components exhibit mechanical characteristics that differ fundamentally from those of homogeneous materials because they are fabricated through a layer-by-layer deposition process (Hozdić & Hozdić, 2025; Vosynek et al., 2018). Unlike homogeneous materials, which generally exhibit relatively uniform mechanical properties in all directions, FDM-printed components possess anisotropic mechanical behavior, with their strength depending on both the build orientation and the loading direction (Ahn et al., 2002; Bandinelli et al., 2024). The conceptual difference between the mechanical behavior of homogeneous materials and FDM-printed components is illustrated in Figure 5.

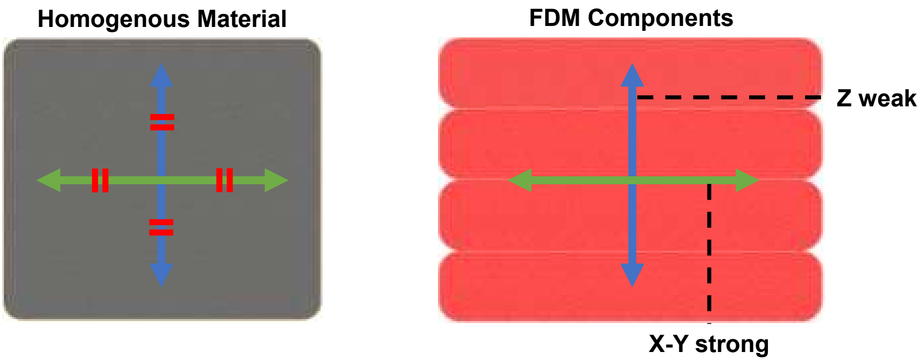

Figure 5. Conceptual illustration comparing the mechanical behavior of homogeneous materials and FDM-printed components

During the FDM process, extruded filaments form continuous deposition paths that undergo thermal fusion within each layer, resulting in strong in-plane bonding. In contrast, interlayer bonding is formed primarily through residual heat transferred from the newly deposited material, leading to consistently lower strength between adjacent layers than within the layer itself (Sukumaar et al., 2026). The quality of this interlayer bonding is strongly influenced by the nozzle temperature. An increase of 20 °C in nozzle temperature has been reported to improve interlayer fracture resistance by approximately 15% and fracture toughness by 38% (Aliheidari et al., 2018). Among the major AM technologies, FDM exhibits one of the highest degrees of anisotropy, reaching up to approximately 50% (Dizon et al., 2018; Monzón et al., 2017). A comparison of the degree of anisotropy among major AM technologies is presented in Figure 6.

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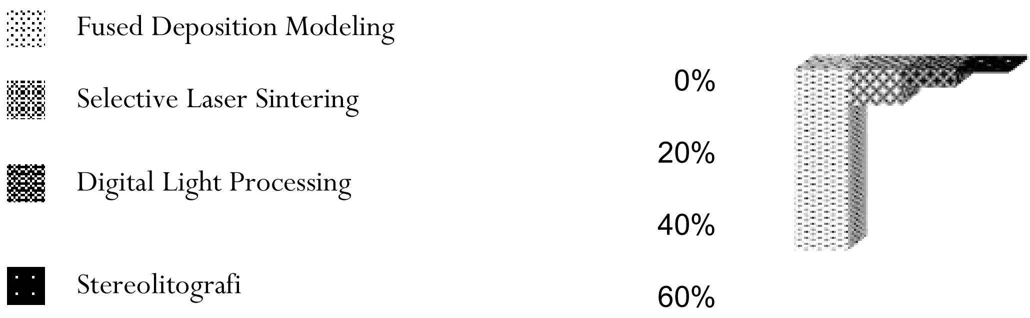

Figure 6. Comparison of the degree of anisotropy among major AM technologies

Several studies have reported inconsistent findings regarding the influence of build orientation and raster angle on the mechanical performance of FDM-printed components, depending on the loading conditions and testing methods. The principal printing parameters, including build orientation and raster angle, are illustrated in Figure 7. Under a flat build orientation, a raster angle of 45° has been reported to produce higher fracture toughness than a raster angle of 0° (McLouth et al., 2017). In contrast, three-point bending tests conducted in accordance with ASTM D790 using PLA specimens demonstrated that a raster angle of 0° provided superior flexural performance, achieving a flexural strength of 78 MPa compared with 40.7 MPa for specimens printed with a 45° raster angle (Ramírez-Prieto et al., 2025). Furthermore, the anisotropic nature of FDM-printed components limits stress redistribution around geometric discontinuities because the mechanical strength along the Z-direction is substantially lower than that of the X–Y plane, thereby reducing the capacity for local plastic deformation that is typically observed in isotropic materials ((Boztepe & Haskul, 2026).

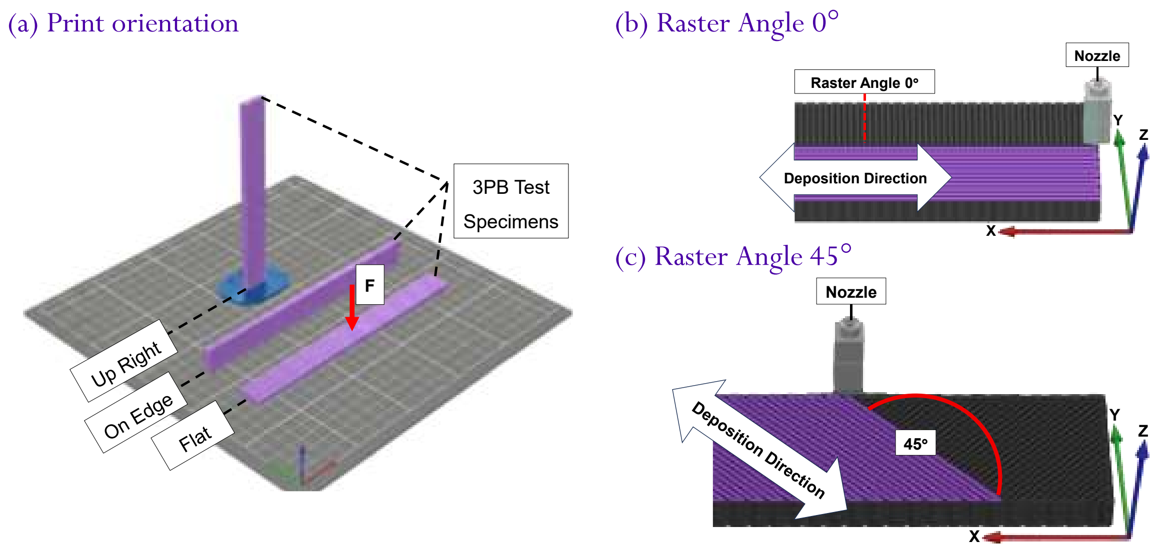

Figure 7. Illustration of the principal printing parameters of FDM: (a) build orientation, (b) 0° raster angle, and (c) 45° raster angle

5. Internal voids in FDM-printed components

Previous studies have identified three categories of internal voids in FDM-printed components that collectively contribute to the discrepancies between FEA predictions and experimental results. These categories are summarized in Table 1 (Garg et al., 2025). Representative examples of the three types of internal voids are illustrated in Figure 8.

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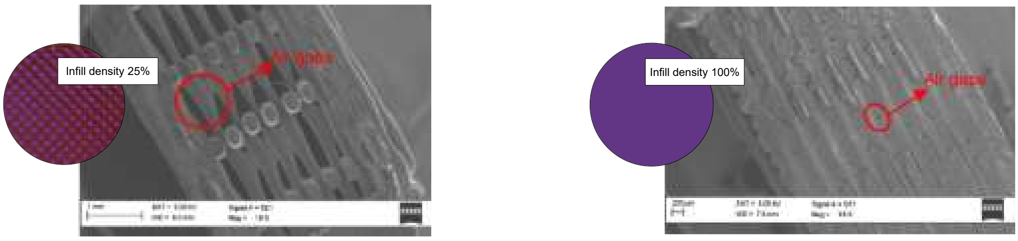
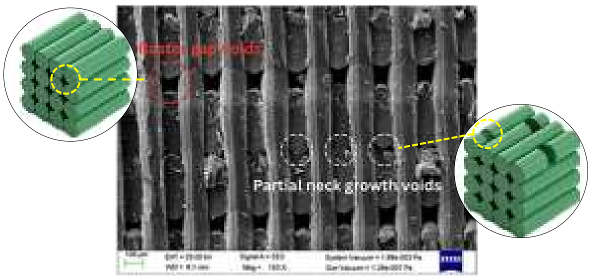
Table 1. Categories of internal voids in FDM-printed components (Garg et al., 2025)

Category	Description	Scale	Cause	Control Parameter
Macro infill voids	Intentionally designed air spaces between adjacent infill paths	mm / visible to the naked eye	Infill density lower than 100%	Infill density
Raster gap voids	Small gaps between adjacent deposited filaments	0.1–0.5 mm	Imperfect extrusion and local temperature variations	Optimized nozzle temperature and printing speed
Partial neck growth voids	Microscopic voids within individual deposited filaments	µm	Extrusion temperature fluctuations and moisture absorption by the filament	Dry filament and stable extrusion temperature



(a) Macro infill voids



(b) Raster gap voids dan partial neck growth voids

Figure 8. Categories of internal voids in FDM-printed components: (a) macro infill voids (Abeykoon et al., 2020), and (b) raster gap voids and partial neck growth voids (Garg et al., 2025)

6. Infill density and infill pattern in FDM-printed components

Infill density is defined as the percentage of solid material volume relative to the total volume of a component and is specified through slicing software prior to printing. It has been identified as a more influential factor than layer height in determining the flexural strength of FDM-printed components (Iacob et al., 2025). The effect of infill density and layer height on the flexural strength of FDM-printed specimens is illustrated in Figure 9. The relationship between infill density and the mechanical strength of FDM-printed components is positive but nonlinear. Although each 20% increase in infill density results in a measurable improvement in mechanical strength, the rate of improvement decreases significantly above an infill density of 60%, where the corresponding increase is limited to

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approximately 5.7% (Yang, 2025). Conversely, the strength-to-weight ratio is highest at relatively low infill densities (<60%) and gradually decreases as the infill density increases (Öteyaka et al., 2021).

Infill pattern refers to the geometric arrangement of filament deposition paths within the interior of a printed component (Sriya Ambati & Ambatipudi, 2022). At the same infill density, different infill patterns can produce variations of up to 82% in flexural strength and nearly a twofold difference in structural stiffness (Lubombo & Huneault, 2018). Among the commonly used infill patterns, the Gyroid structure, which belongs to the class of Triply Periodic Minimal Surface (TPMS) geometries, exhibits near-isotropic mechanical behavior with an anisotropy index approaching zero and achieves the highest elastic modulus (872.51 MPa) at an infill density of 20%. In contrast, the Cubic pattern provides the highest tensile strength and yield strength among several infill patterns at infill densities of 40% and above (Bean et al., 2022; Fekiač et al., 2025; Garg et al., 2025).

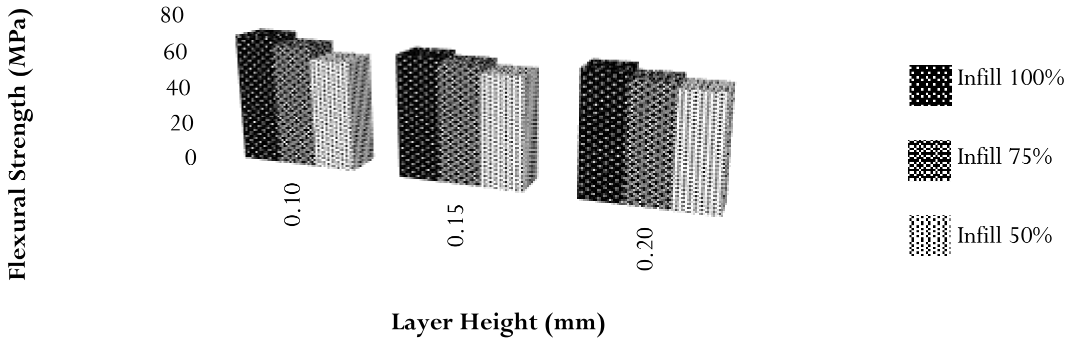

Figure 9. Effect of infill density and layer height on the flexural strength of FDM-printed specimens (prepared by the authors based on data reported by Iacob et al., 2025)

7. FAE of FDM-printed components

FEA is a numerical method used to analyze structural geometries by discretizing the computational domain into a finite number of small elements (mesh) and simultaneously solving the governing stress–strain equilibrium equations (Paul, 2021). The fundamental workflow of the FEA process is illustrated in Figure 10. The most commonly used output parameter is the von Mises stress, a yield criterion that combines tensile, compressive, and shear stresses into a single scalar value that can be directly compared with the yield strength of the material (Pranata et al., 2025).

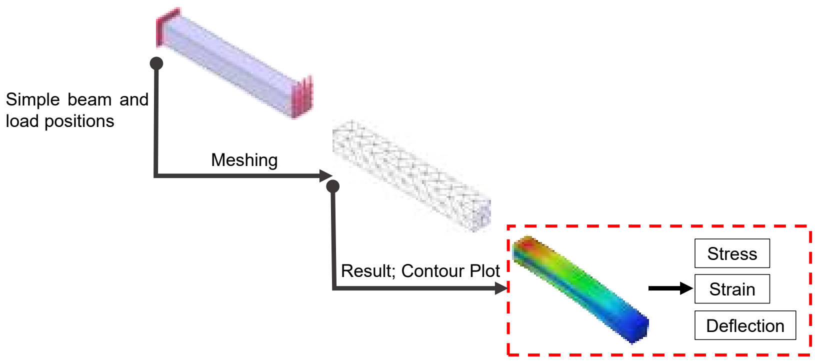

Figure 10. Fundamental workflow of FEA

The accuracy of FEA for FDM-printed components is limited by two fundamental assumptions that do not accurately represent the actual characteristics of printed parts. First, FEA assumes that the material is homogeneous and fully dense, whereas FDM-printed components contain internal voids, including macro infill voids, raster gap voids, and partial neck growth voids. Second, FEA assumes isotropic

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material behavior with identical mechanical properties in all directions, whereas FDM-printed components exhibit anisotropic mechanical behavior that depends on both the build orientation and the loading direction (Kuznetsov et al., 2018). These limitations are quantitatively reflected by discrepancies between numerical predictions and experimental results, including errors of approximately 8.67% in three-point bending tests for specimens with 50% infill density and a rectangular infill pattern, and approximately 12% in tensile tests (Bachhav et al., 2023; Garg et al., 2025). Consequently, FEA is more appropriately regarded as a tool for the relative comparison of different design configurations rather than for predicting the absolute mechanical strength of FDM-printed components (Raja et al., 2025).

Table 2. Comparison between FEA assumptions and the actual characteristics of FDM-printed components

FEA Assumption	Actual Characteristics of FDM-Printed Components	Reference
Homogeneous, fully dense material without internal voids	Presence of macro infill voids, raster gap voids, and partial neck growth voids	(Garg et al., 2025)
Identical mechanical properties in all directions (isotropic behavior)	Anisotropic mechanical behavior, with strength dependent on build orientation and loading direction	(Kuznetsov et al., 2018; Zohdi & Yang, 2021)

8. FEA-based non-uniform infill density in FDM-printed components

The fundamental concept of this approach is to distribute the infill density non-uniformly according to the structural requirements of the specimen. In practice, commercially available slicing software for FDM generally provides only uniform infill density throughout the entire component and does not offer a mechanism for generating customized infill structures that follow the stress distribution (Birosz & Andó, 2023). To address this limitation, previous studies have integrated FEA with the Bi-directional Evolutionary Structural Optimisation (BESO) method to determine stress-based infill placement without modifying the external geometry of the component. In this approach, three-dimensional Cubic, Gyroid, and Octet infill patterns are assigned to regions subjected to high stress, while lower-density Rectilinear infill is applied to regions experiencing lower stress. This strategy has been reported to increase the peak load by 49% and the bending stiffness by 46% compared with conventional uniform infill structures (Toth & Padayachee, 2023). The concept of FEA-based non-uniform infill density using the BESO method is illustrated in Figure 11.

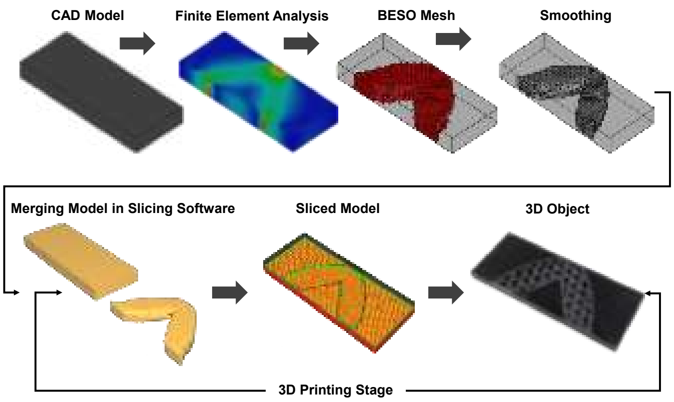

Figure 11. Concept of FEA-based non-uniform infill density using the BESO method (Toth & Padayachee, 2023)

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A similar topology optimisation approach employing the BIRA has also been compared with the BESO method under configurations with and without smoothing transitions between density zones. The bending test results demonstrated that non-uniform density specimens without smoothing transitions exhibited lower stiffness than specimens with uniform density. However, after the application of smoothing transitions, the stiffness of the non-uniform density specimens exceeded that of the uniformly filled specimens (Pais et al., 2022). The comparison between the BESO and BIRA approaches is presented in Figure 12. Density transitions within a single specimen introduce two forms of discontinuity. The first is a geometric discontinuity, manifested by the enlargement of raster gap voids at the interface between adjacent density zones, which may serve as new crack initiation sites (El Omari et al., 2024; Tronvoll et al., 2018). The second is a mechanical discontinuity, characterized by stress concentrations arising from abrupt local stiffness variations at the transition boundaries (Budynas & Keith Nisbett, 2015).

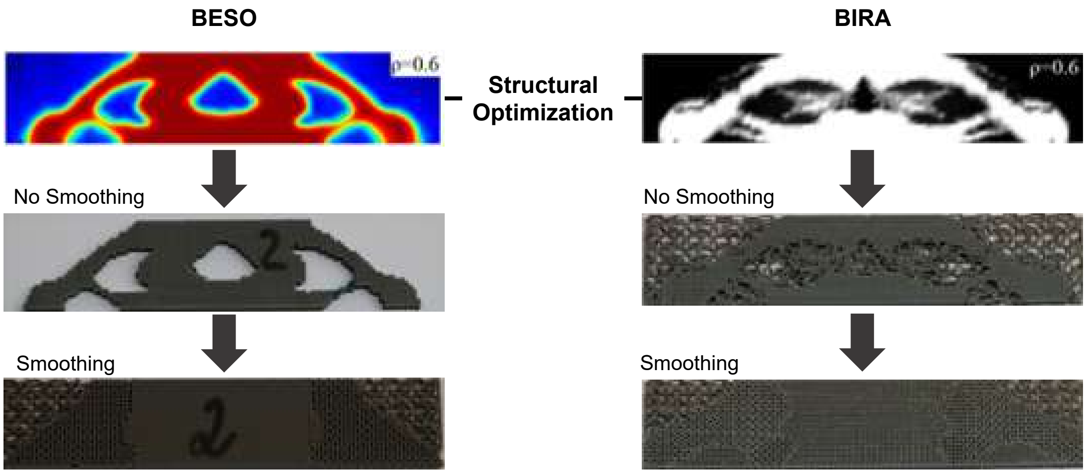

Figure 12. Comparison of non-uniform infill density concepts using the BESO and BIRA methods (Pais et al., 2022)

An alternative approach investigated different combinations of infill densities between the shell and core regions of PLA specimens subjected to tensile and impact tests. The results demonstrated that an appropriate distribution of infill density could simultaneously improve mechanical performance and reduce component weight compared with a uniform infill density configuration. Specifically, a dense shell combined with a sparse core achieved a tensile strength of 48.2 MPa while reducing the specimen weight by approximately 5% relative to specimens with uniform infill density (Tanveer et al., 2019). This concept is illustrated in Figure 13.

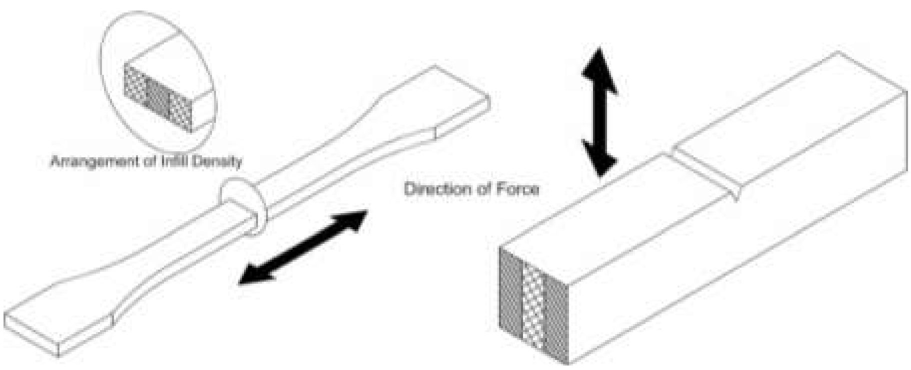

Figure 13. Concept of non-uniform infill density for tensile and impact loading conditions (Tanveer et al., 2019)

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Conventional FDM components generally employ a uniform infill density throughout the entire geometry. In the context of this literature review, however, the infill density is optimized according to the stress distribution obtained from FEA. The von Mises stress distribution, together with the corresponding strain and deflection fields, is used as a guideline for defining the density zones within the component. Regions experiencing higher stress are assigned higher infill densities, whereas lower-density infill is allocated to regions subjected to lower stress. The proposed concept of FEA-based non-uniform infill density adopted in this review is illustrated in Figure 14.

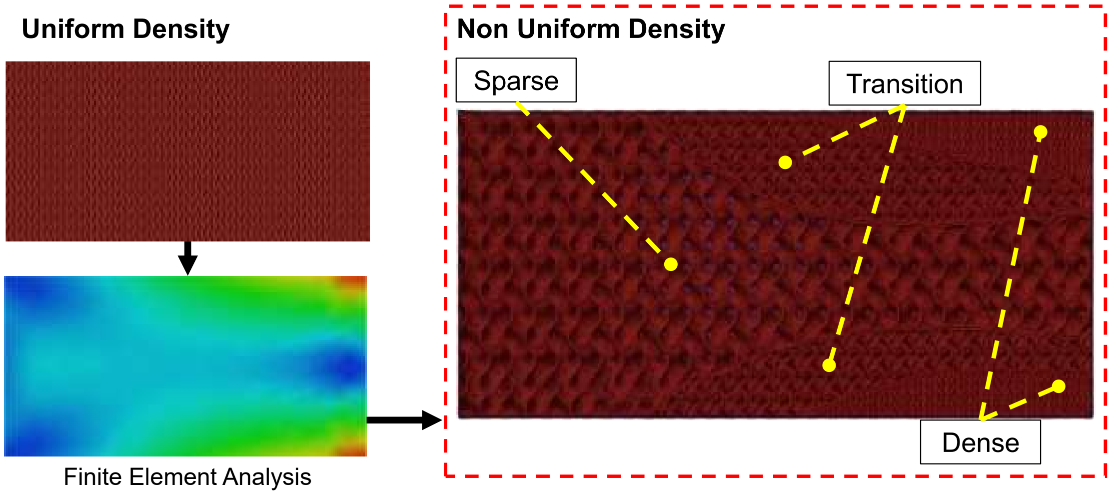

Figure 14. Proposed concept of FEA-based non-uniform infill density

9. Conclusion

This literature review demonstrates that the mechanical characteristics of FDM-printed components cannot be considered equivalent to those of homogeneous materials. The layer-by-layer deposition process inherently produces anisotropic mechanical behavior and introduces multiple categories of internal voids, both of which contribute to the discrepancies between FEA predictions and experimental measurements of mechanical strength. Among the printing parameters, infill density and infill pattern have been consistently identified as the most influential factors governing the flexural strength of FDM-printed components. Their relationship with mechanical performance is positive but nonlinear, indicating that increasing the material density does not always result in a proportional improvement in mechanical strength, particularly at higher infill densities.

FEA serves as an effective tool for estimating the stress distribution within FDM-printed components. However, its predictive accuracy is constrained by the assumptions of homogeneous, fully dense, and isotropic materials, which do not adequately represent the actual characteristics of FDM components containing internal voids and exhibiting anisotropic mechanical behavior. Consequently, FEA should be regarded primarily as a tool for identifying appropriate infill density distributions rather than as a method for predicting the absolute mechanical strength of FDM-printed components.

FEA-based non-uniform infill density strategies, including topology optimization approaches such as BESO and the BIRA, as well as shell–core density combinations, have consistently demonstrated the potential to enhance structural performance while improving material efficiency compared with conventional uniform infill configurations. Nevertheless, these approaches also introduce new challenges associated with geometric discontinuities and mechanical discontinuities at the interfaces between adjacent density zones. Without appropriate transition mechanisms, such as smoothing, these discontinuities may act as potential sites for structural failure initiation and may even reduce the stiffness of the component below that of conventional uniform-density configurations.

Overall, this review indicates that the concept of FEA-based non-uniform infill density represents a promising design optimization strategy for functional FDM-printed components by enabling material distribution to be aligned with structural requirements according to the predicted stress distribution. However, its successful implementation depends on the effective treatment of density transition zones and a more comprehensive understanding of the interactions between manufacturing-induced imperfections and FEA predictions. Therefore, further experimental investigations are required to validate and refine this non-uniform infill density design framework before it can be widely implemented in functional FDM applications.

Author's declaration

Author contribution

Mhd. Fahri Meihanda Putra: Conceptualization, Literature search and screening, Writing – original draft. **Syahril**: Supervision. **Delima Yanti Sari**: Validation methodology.

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Data availability

Not applicable, as this study did not generate or analyse any new data.

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Conflict of interest

The authors declare that there are no conflicts of interest related to this research or the publication of this article.

Ethical clearance

Not applicable.

AI statements

Gemini, and Claude.Ai were used to improve the grammatical structure, sentence coherence, and translation of this article from Indonesian into English to enhance readability. All AI-assisted outputs were carefully reviewed by the authors to ensure their accuracy, precision, and contextual relevance to the research topic and data presented. The authors take full responsibility for the entire content of this article.

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