Recent Developments in Finite Element Modelling of Stress in 3D Printed Structural Blocks

Rohit Kumar
Research Scholar
M. Tech
Sri Satya Sai University of Technology & Medical Science
Sehore, Madhya Pradesh, India

Dr Priyanka Jhavar
Associate Professor
Mechanical Engineering
Sri Satya Sai University of Technology & Medical Science
Sehore, Madhya Pradesh, India
priyanka.jhavar10@gmail.com

Sachin Baraskar
Head of Department
Mechanical Engineering
Sri Satya Sai University of Technology & Medical Science
Sehore, Madhya Pradesh, India

Abstract: 3D printing has changed the way parts are designed by allowing for increased complexity of shapes, more efficient use of material, and customization. However, the stepwise nature of additive manufacturing (AM) has resulted in known issues of inherent problems like anisotropy, material residual stresses, and mechanical heterogeneities in structural components made via AM. Finite Element modelling (FEM) has gained recognition as an important computational method to simulate and evaluate the stress behaviour of these types of components. This research note provides a systematic overview of the latest advancements to FEM methods that apply to structural components produced by 3D printing, including anisotropic and multi-scale material modelling approaches, modified meshing methods, coupled thermo-mechanical modelling, and other hybrid validation methods that incorporate experimental measurements and creative applications of machine learning for more accurate prediction. This research note also highlights material and structural properties, printing parameters that influence stress distributions, and various challenges such as computational demands, material limitations, environmental issues, etc. Overall, FEM can serve an important role in advancing reliability, design optimization, and industrial applications of AM components when these challenges are addressed. This note represents an important orientation for engineers that wish to push the boundaries of simulation-based design and prediction modelling in additive manufacturing.

Keywords: 3D Printing, Finite Element Modelling (FEM), Stress Analysis, Structural Blocks, Anisotropy, Thermo-Mechanical Simulation, Multi-Scale Modelling, Material Properties, Computational Simulation.

I. INTRODUCTION

AM techniques can produce products from a variety of materials that include composites, metals, polymers, and ceramics. Metal AM, or MAM, has potentially affected a wide range of industries more than any of the others. For example, MAM has recently been employed to successfully print a number of surgical titanium implants in the medical industry [1]. 3D-printing (3DP), or additive manufacturing, is the process of building products or components with digital product information layer upon layer. 3DP allows the creation of complex geometries; for example, lattices or honeycombs, which cannot be created with conventional manufacturing (CM) methods. With redesign, AM technologies can build existing products in a manner that involves fewer raw materials but possibly greater usefulness and lightness. While there are numerous applications still in the exploratory phase, one can print costly and unusual materials such as human tissue with minimal scrap [2]. Additive Manufacturing (AM), commonly referred to as the Third Dimension Printer, has made possible the up risining and design of intricate structures in industries. Layering components refers to a building process rather than subtractive procedure, hence allowing for total design freedom, ability for customization, and less material waste. Through AM processes such as FDM, SLA, SLS, and DMLS, engineers can create complex geometries and internal features that are usually impossible or very costly to produce conventionally. This capability has come to be highly regarded in aerospace, biomedical, automotive, and civil infrastructure, where increasingly demanding specifications for lightweight, high-strength, and rather complex geometry come in constant need [3]. Being structural systems and elements, blocks, brackets, frames, and support structures are major load-bearing parts that demand the highest mechanical performance standards. Typically, AM technologies are brought to bear in the rapid prototyping, functional testing, and even end-use of these components. But the layer-wise build process significantly influences their performance with induced anisotropy, voids, and residual stresses. The mechanical behaviour of 3D-printed structural blocks and their failure behaviour under various stress conditions become a very important issue from the viewpoint of safety and reliability. Thus, knowledge of stress distribution, failure modes, and deformation in these blocks is essential to the design and optimization of such units. Accordingly, to meet the constantly increasing demand for accurate predictive modelling, stresses applied to objects printed in 3D under actual load conditions are should be modelled and evaluated by an increasing number of researchers with the Finite Element Methods (FEM) [4]. AM processes can produce different types of materials, including ceramic, glass, metals, polymers, and composites. AM processes typically involve two types of power sources: laser-based, or electron-beam-based. A variety of AM processes will create material and parts for energy systems including materials extrusion, powder-bed fusion, and direct energy deposition (DED).

Additionally, there is development for other methods using mechanical energy to consolidate, like friction stir additive manufacturing (FSAM), which provide high build rates and reduced porosity along with the ability to create very large parts [5].

A. Importance of Stress Analysis in 3D Printed Parts

Stress analysis is an important aspect of 3D printed component evaluation because it dictates structural integrity, reliability, and functional performance in use. 3D printed parts can have anisotropic mechanical properties that differ depending on print direction, infill density, and materials because of the layer-by-layer deposition that occurs. The end result is mechanical behaviour that is less predictable, particular when loaded dynamically [6]. Stress analysis informs engineering of all locations of stress concentration, possible failure points, and deformation characteristics before physical testing or deployment, and offers the opportunity to design safer and more efficient design cycles. Also, accurate stress modelling is necessary to minimize part geometry for optimalization, select suitable materials, and minimize fatigue, warping, and delamination risks, specifically for load-bearing or high-performance functions such as aerospace, medical implants, and automotive parts [7].

B. Role of Finite Element Modelling

Finite Element Modelling (FEM) is central to understanding and predicting the mechanical behaviour of 3D printed components, particularly under varying conditions of stress. FEM is a computational method that discretizes complex geometries into smaller workable elements so that the behaviour of these elements under applied loads, thermal loads, and boundary conditions can be accurately simulated. In additive manufacturing, FEM provides vital information regarding how stress is distributed over a printed structure, where and how deformations are likely to occur, and under what conditions failure will initiate [8]. As the unique material properties of 3D printed items, such as anisotropy, layer-wise adhesion, and internal porosity, FEM makes it possible to model these with high fidelity, often utilizing real material data, printing parameters, and geometry imperfections inherent to the AM process [9]. In addition to basic structural analysis, FEM is also a basis tool for optimization, validation of design, and improvement of performance in 3D printed components. It allows designers to create hundreds of concepts without extensive physical prototyping, significantly reducing development time and cost. For instance, FEM can be used to analyse the impact of infill patterns, orientation, or support structures on the ultimate stress distribution and mechanical behaviour of a printed part. In addition, with advancements in coupled multi-physics simulations, which encompass thermo-mechanical, fluid-structure interactions, FEM can now provide a more unified view of the relationship between the environmental conditions and loads experienced by AM components, over time [10]. This predictive function is essential not only for ensuring the reliability and safety of mission-critical parts, but also for driving innovation in weight savings, materials science, and bespoke manufacture in industries such as aerospace, automotive and biomedical engineering [11].

II. FINITE ELEMENT ANALYSIS IN ADDITIVE MANUFACTURING

Finite Element Methods (FEM) are computational methods employed to solve approximately complex engineering problems, especially those related to structural mechanics, heat transfer, and fluid flow. Simply put, FEM operates by breaking down a large, intricate domain such as a 3D printed component into a mesh of smaller, discrete elements. These components are coupled at nodes, and physical law-based governing equations (e.g., stress-strain relations or heat conduction) are formulated across them. By simultaneously solving these equations, FEM is able to compute the behaviour of a structure under loads, boundary conditions, or environmental factors. The agility of this approach makes it capable of addressing irregular geometries, inhomogeneous materials, and non-linear responses all of which are typical in 3D printed parts owing to their layer-by-layer manufacturing and diverse internal structures [12]. 3D printed components tend to have anisotropic and heterogeneous properties, i.e., their mechanical behaviour can be highly direction dependent with respect to build direction, layer adhesion, infill density, and thermal history. FEM allows engineers to accurately model these parameters through the use of directional material properties, simulating the development of residual stresses, and assessing localized stress concentrations. In addition, FEM can be employed in the design phase to recursively design part geometries for performance and longevity, and in post-processing analysis to model how printed components will respond to operational stress. As additive manufacturing technology advances, FEM continues to be a building block of virtual testing, offering invaluable insights that mitigate the necessity for large-scale physical prototyping while increasing the safety and dependability of printed parts [13]. Modelling 3D printed structures involves a variety of intricate challenges as a result of the intrinsic nature of the additive manufacturing (AM) process that radically differs from conventional manufacturing processes. Anisotropic behaviour of printed materials is one of the main challenges to capture with precision, since mechanical properties like strength, stiffness, and toughness can differ incredibly depending on print orientation, layer adhesion, and infill pattern [14]. In contrast to isotropic materials with constant properties in all directions, parts produced by 3D printing usually tend to have poorer mechanical properties along the build direction due to inhomogeneous interlayer bonding and micro voids. Another significant difficulty is the modelling of residual stresses that build up during printing, particularly in thermoplastic and metal additive manufacturing, where thermal gradients and cooling rates can produce warping, shrinkage, or cracking. Precisely modelling these process-generated defects and residual stresses in a finite element analysis calls for advanced material characterization and frequently real-time monitoring or calibration based on experimental data [15]. In addition, the geometric variability and complexity of printed structures like complex lattice infills or topologyoptimized shapes call for very fine meshes and computationally demanding simulations, which can take a large amount of time and resources for analysis. The absence of standardized material models, and variability in printing conditions (e.g., speed, temperature, layer thickness), further makes FEM predictions for 3D printed parts unreliable and not generalizable. These issues underscore the imperative for continuous improvement in simulation methods, material modelling, and inclusion of process-aware parameters to improve fidelity and utility of FEM in additive manufacturing [16]. Fused deposition modeling (FDM) is a production method based on the use of an external filament (wire) of the thermoplastic material figure 1.

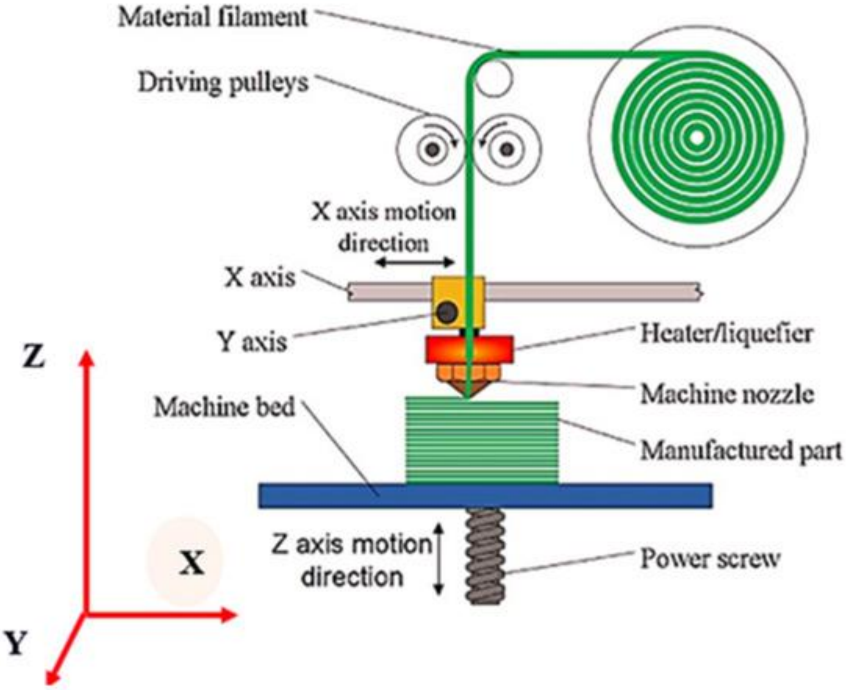

Figure 1. FDM technology [17]

III. MATERIAL AND STRUCTURAL CONSIDERATIONS IN 3D PRINTED BLOCKS

Material selection is critical to the mechanical response of 3D printed blocks because varying materials have distinct properties that directly affect strength, stiffness, ductility, and thermal stability. The most popular materials utilized in additive manufacturing are thermoplastics (such as PLA, ABS, PETG), engineering polymers (such as nylon, PEEK), metals (such as aluminium alloys, stainless steel, titanium), and carbon- or glass fiber-reinforced composites. Each of these materials behaves in different ways upon loading; for example, PLA is brittle but stiff, while nylon provides greater flexibility and impact resistance [18]. Metals printed through processes like Selective Laser Melting (SLM) or Direct Metal Laser Sintering (DMLS) tend to display high strength but can be prone to residual stresses and anisotropic behaviour as a result of rapid thermal cycling. Knowledge of the intrinsic mechanical properties of these materials is key to providing a correct model of their stress behaviour, especially in finite element analysis where material models have to be representative of reality [19]. Besides material selection, the printing parameters have a huge impact on the stress distribution and mechanical performance of 3D printed blocks. The main parameters are layer height, print speed, nozzle temperature, build orientation, and infill density. For instance, components with thinner layers and larger infill densities tend to exhibit enhanced strength and reduced stress concentration because of improved interlayer bonding and material continuity [20].

Orientation building can be especially influential, since the stresses will tend to concentrate at the layer interfaces, so that parts printed vertically will be more prone to delamination under tensile loading. In addition, random thermal gradients during printing can produce internal stresses, warping, or size inaccuracies, which in turn influence the mechanical performance of the part. These process-related variations call for vigilant control and optimization of printing parameters, particularly in cases where the intention is to create load-carrying or high-performance parts [21]. Hence, a successful stress analysis of 3D printed blocks should combine material properties and processing conditions to give a realistic and comprehensive appreciation of their structural performance. Neglecting one factor will lead to poor predictions and suboptimal designs, particularly in applications involving high reliability [22]. Finite Element modelling is a valuable tool for modelling how these variables interact by enabling engineers to model different material responses under different printing conditions and load cases. Including sophisticated material models and process-aware simulations allows for better prediction of stress, improves part reliability, and helps to optimize design and manufacturing conditions for optimal performance in real-world environments [23].

IV. ADVANCES IN FEM TECHNIQUES FOR STRESS MODELLING

3D printing has stimulated one of the most substantial advances in Finite Element modelling (FEM) for additive manufacturing (AM) the creation of anisotropic material models that capture the direction-dependent mechanical properties in printed parts. As a result of the layer-by-layer build process, 3D printed parts tend to have diminished interlayer cohesion with respect to in-plane strength. Conventional isotropic models cannot describe this, resulting in improper stress prediction [24]. Anisotropic models account for stiffness, strength, and fracture toughness variation in different axes, providing a better prediction of actual mechanical performance. Models are most important when simulating load-bearing components or structures under complex stress conditions, as anisotropic models allow planes of weakness to be an initiation site for failure [25]. Along with anisotropy, multi-scale material models are being incorporated into FEM to simulate behaviour over a range of length scales—from microstructural details to macroscopic performance. These models employ data from simulations at lower scales (e.g., molecular dynamics or microscale finite element models) to drive macroscale properties, allowing for simulations that simulate the effect of porosity, microcracks, and layer fusion [26]. Multi-scale modelling is particularly useful in the prediction of failure mechanisms and the description of how defects at small scales develop into large-scale deformation or fracture. By integrating these methodologies, scientists can gain a more integrated and predictive understanding of the performance of 3D printed parts under conditions relevant to practice [27].

Reliable meshing is a key to successful FEM simulation, and for AM components, new meshing techniques have developed to counteract the geometric complexity and layer-by-layer build-up common in 3D printed parts. Conventional meshing methods tend to fail for the complex shapes and irregularities in printed parts, particularly for lattice infills, thin walls, and internal cavities. New meshing techniques, including adaptive meshing and voxel-based meshing, have been developed to enhance accuracy without high computational expense [28]. Adaptive meshing densifies the mesh in areas of highest stress or geometric detail so that finer elements are used where they are most important while using coarser elements in less critical zones to minimize simulation time. Voxel-based meshing, for example, has become increasingly popular in AM as it sits comfortably with the layer-by-layer nature of printing. It discretizes the geometry into cubic elements that match the build resolution and supports assigning layer-specific material properties [29]. Voxel meshes also provide the capability to include print path information, which allows for more accurate simulation of print-induced anisotropy and thermal history. These new meshing techniques considerably improve the precision and effectiveness of stress analysis in FEM, giving engineers improved tools for capturing the subtle mechanical behaviour of additively manufactured structures [30].

A. Thermo-Mechanical FEM Simulations

Coupled thermo-mechanical simulations are a significant improvement in simulating the intricate relationships between mechanical stress and temperature in 3D printed components. In the course of the additive manufacturing process particularly in metal printing high thermal gradients and quick heating/cooling cycles cause residual stresses, warping, and even microcracking. Combining thermal and mechanical analyses enables FEM to model these effects more realistically using temperature-dependent material properties, thermal expansion, and time-dependent material layer deposition. These models can forecast how heat buildup and heat transfer influence stress distribution, part deformation, and dimensional stability [31]. Such coupled simulations are of great use in the optimization of print parameters and minimizing post-processing needs. For instance, simulating the manner in which residual stresses form during a print allows designers to optimize scan strategies, support structures, or pre-heating conditions in order to reduce defects prior to the actual fabrication. The models help predict distortions that can occur and impact final part geometry, thereby minimizing prototyping trial-and-error. With the ongoing advancements in computational capability, coupled thermo-mechanical FEM becomes progressively more viable for study and industry use, providing an important tool for enhancing part quality and reliability in AM [32].

Three-dimensional printing (3DP) has made tremendous progress in various fields such as pharmaceuticals, biomedical engineering, construction, and material science. Personalized drug delivery with intricate structures and controlled release is possible through 3DP in the pharmaceutical industry, as evidenced by FDA-approved drugs such as Spritam® and IND-approved formulations of Triastek [33]. Outside of medicine, AM is valued for its material efficiency, minimal post-processing requirements, and compatibility with Industry 4.0, but challenges such as material compatibility and expense remain [34]. For biomedical purposes, 3DP facilitates innovation in implants, prostheses, and tissue engineering [35], but volumetric printing, piezoelectric composites, and hydrogel structures with tissue-like biological mimicry are some of the developments that have emerged [36]. Technologies like fused filament fabrication (FFF), binder jetting, and stereolithography enable customization of pharmaceutical dosage forms to advance personalized medicine [37]. In building construction, 3DP is transforming into large-scale concrete printing despite the challenge of developing materials [38]. Environmental concerns are increasing, particularly with polymers, leading to investigation of AM's energy and material footprint [39]. In addition, 3DP is evolving flame-retardant polymer architectures [40], binder jetting of metal components [41], and high-accuracy photocuring techniques such as SLA and DLP for biomedical applications [42].

Table 1 Comparative Analysis of 3D Printing Technologies

Ref. No.	**Focus Area**	**Key findings**	**Applications**	**Challenges**	**Printing Method**	**Material Types Used**
[33]	Pharmaceutical 3D printing & personalized drugs	FDM, SLS, SLA in drug manufacturing	Customized dosage forms, polypills	Regulatory, material, and printing complexity	Pharmaceutical/Medical	Polymers, pharmaceutical compounds
[34]	3D printing processes, materials, Industry 4.0	Multiple AM processes and materials	Engineering components, Industry 4.0	Material compatibility and cost	Engineering/Industrial	Polymers, composites, metals
[35]	Biomedical applications of 3D printing	Surgical, prosthetic, and tissue engineering uses	Medical implants, organs, prostheses	Technology adoption and integration	Biomedical	Biomaterials, polymers
[36]	Advances in 3D printing techniques & materials	Volumetric, composite, and hydrogel printing	Bioengineering, aerospace, high-tech materials	Material innovation and cost-efficiency	Advanced Materials	Hydrogels, composites, polymers, metals
[37]	Personalized medicine through pharmaceutical 3D printing	Inkjet, SLS, FFF, binder jetting for polypills	Precision medication and dose tailoring	Clinical implementation, personalization	Pharmaceutical/Personalized Medicine	Pharmaceutical powders, polymers
[38]	3D printing in concrete construction	Cement-based 3D printing methods	Large-scale construction projects	Material formulation and equipment scale	Construction	Concrete, cementitious materials
[39]	Environmental impact of AM	Polymer-based AM methods	Industrial AM sustainability	Environmental impact documentation	Environmental/Industrial	Polymers
[40]	Flame-retardant polymers using 3D printing	Polymer flame retardants via AM	Fire-safe polymers for various uses	Material performance and structural design	Polymer/Fire Safety	Polymers with flame retardants

[41]	Binder jetting in metal AM	Binder Jet 3D Printing (BJ3DP)	Metal prototyping and industrial parts	Post-processing, densification control	Metal AM	Metal powders
[42]	Photocuring 3D printing technologies	SLA, DLP, LCD, CLIP, MJP	High-precision biomedical parts	Material limitations, process challenges	Photopolymerization	Photopolymers

V. CHALLENGES IN 3D PRINTING

Three-dimensional printing (3DP), though revolutionary, poses a number of engineering, material, and processing-related issues that have to be resolved to facilitate its universal application in industries. The most important one is the anisotropy associated with 3D printed parts, which results in non-homogeneous mechanical properties based on orientation and order of layer deposition. In contrast to isotropic products produced by conventional processes, interlayer bonding is usually weaker in 3D printed products, resulting in inconsistencies in tensile strength, fatigue life, and impact toughness [43]. This directionality complicates precise mechanical prediction and failure modelling, especially under load-bearing conditions. Residual stresses that arise due to thermal gradients during printing can also cause part warping, cracking, or deformation. These effects are particularly significant in metal additive manufacturing (MAM) as a result of high-rate heating and cooling, which produce thermal strains and material shrinkage difficult to predict and model accurately without sophisticated simulation tools [44].

A second major challenge is material complexity and standardization of processes. As additive manufacturing accommodates a broad range of materials such as polymers, metals, ceramics, and composites not all materials are suitable for all 3DP processes. Problems of limited printable alloys, thermal degradation of polymers, variable sintering in ceramics, and low interfacial adhesion in composites hinder performance and design freedom. Moreover, the absence of standard material models and globally adopted benchmarking protocols also makes simulation accuracy and real-world verification even more challenging [45]. The constraints have direct effects on the reliability and replicability of printed components, particularly in fields with severe regulating stipulations like aerospace, medicine, and defence. Further, post-processing operations such as heat treatment, support removal, and surface finishing, which in many cases are required to achieve quality requirements, impose time and expense on the production process contradicting the fundamental promise of rapid manufacturing [46].

Computational and environmental difficulties also limit the scalability of 3D printing. It is difficult to simulate additive manufacturing accurately, particularly in FEM, due to the need for dense meshing, multi-scale modelling, and the coupling of various physical fields (thermal, mechanical, and at times chemical), which can be computationally intensive and time-consuming [47]. Furthermore, the increasing focus on sustainable manufacturing has led to criticism of the environmental sustainability of 3DP technologies. Even though additive manufacturing is sometimes promoted based on minimized material waste and energy efficiency over subtractive methods, the environmental impact can be highly variable with respect to the material, energy source, and necessary post-processing. For instance, polymer printers can release toxic volatile organic compounds (VOCs), while metal printers tend to use large amounts of energy for powder bed fusion or sintering. Hence, if 3D printing is to ultimately realize its industrial and ecological promise, coming research needs to focus on material development, process refinement, standard simulation protocols, and eco-efficient methodologies [48].

VI. Conclusion

3D printing has emerged as a revolutionary manufacturing method, requiring sophisticated computational methods such as finite element modelling (FEM) to predict stress behaviour in structural elements with high accuracy. With the increasing complexity and performance requirements of printed items, FEM becomes an indispensable tool for investigating stress distributions, capturing anisotropy and material heterogeneity effects, and optimizing designs specific to additive processes. Techniques like anisotropic and multi-scale material models, advanced meshing algorithms, and coupled thermo-mechanical simulations have greatly enhanced the accuracy of FEM in mimicking actual conditions. They not only contribute to increased structural reliability of 3D printed components but also make product design more efficient by minimizing physical prototyping. Nevertheless, various challenges still remain that limit the complete achievement of FEM in AM applications. These are the absence of standardized material databases, high computational expense, and the simulation complexity of layered deposition and residual stress accumulation. Moreover, constraints in material compatibility, printing precision, and environmental sustainability still influence the scalability of 3D printing technologies. Yet, continued study of hybrid modelling methods, the integration of machine learning, and real-time simulation provides fertile avenues for surmounting these challenges. By closing the distance between physical testing and computational simulation, FEM will continue to have a revolutionary role in expanding the limits of what additive manufacturing can do for structural component design and performance.

Conflict of Interest: The corresponding author, on behalf of second author, confirms that there are no conflicts of interest to disclose.

References

[1] Armstrong, M., Mehrabi, H., & Naveed, N. (2022). An overview of modern metal additive manufacturing technology. *Journal of Manufacturing Processes*, *84*, 1001-1029. https://doi.org/10.1016/j.jmapro.2022.10.060

[2] Savolainen, J., & Collan, M. (2020). How additive manufacturing technology changes business models?–review of literature. *Additive manufacturing*, *32*, 101070. https://doi.org/10.1016/j.addma.2020.101070

[3] Jadhav, A., & Jadhav, V. S. (2022). A review on 3D printing: An additive manufacturing technology. *Materials Today: Proceedings*, *62*, 2094-2099. https://doi.org/10.1016/j.matpr.2022.02.558

[4] Rouf, S., Malik, A., Singh, N., Raina, A., Naveed, N., Siddiqui, M. I. H., & Haq, M. I. U. (2022). Additive manufacturing technologies: Industrial and medical applications. *Sustainable Operations and Computers*, *3*, 258-274. https://doi.org/10.1016/j.susoc.2022.05.001

[5] Sun, C., Wang, Y., McMurtrey, M. D., Jerred, N. D., Liou, F., & Li, J. (2021). Additive manufacturing for energy: A review. *Applied Energy*, *282*, 116041. https://doi.org/10.1016/j.apenergy.2020.116041

[6] Alzyod, H., & Ficzere, P. (2023). Material-dependent effect of common printing parameters on residual stress and warpage deformation in 3D printing: a comprehensive finite element analysis study. *Polymers*, *15*(13), 2893. https://doi.org/10.3390/polym15132893

[7] Khosravani, M. R., Božić, Ž., Zolfagharian, A., & Reinicke, T. (2022). Failure analysis of 3D-printed PLA components: Impact of manufacturing defects and thermal ageing. *Engineering Failure Analysis*, *136*, 106214. https://doi.org/10.1016/j.engfailanal.2022.106214

[8] Ursini, A., Grazzini, A., Matrone, F., & Zerbinatti, M. (2022). From scan-to-BIM to a structural finite elements model of built heritage for dynamic simulation. *Automation in Construction*, *142*, 104518. https://doi.org/10.1016/j.autcon.2022.104518

[9] Safa, B. N., Read, A. T., & Ethier, C. R. (2021). Assessment of the viscoelastic mechanical properties of the porcine optic nerve head using micromechanical testing and finite element modeling. *Acta biomaterialia*, *134*, 379-387. https://doi.org/10.1016/j.actbio.2021.07.022

[10] Seventekidis, P., Giagopoulos, D., Arailopoulos, A., & Markogiannaki, O. (2020). Structural Health Monitoring using deep learning with optimal finite element model generated data. *Mechanical Systems and Signal Processing*, *145*, 106972. https://doi.org/10.1016/j.ymssp.2020.106972

[11] Guo, Q., Yao, W., Li, W., & Gupta, N. (2021). Constitutive models for the structural analysis of composite materials for the finite element analysis: A review of recent practices. *Composite Structures*, *260*, 113267. https://doi.org/10.1016/j.compstruct.2020.113267

[12] Baiges, J., Chiumenti, M., Moreira, C. A., Cervera, M., & Codina, R. (2021). An adaptive Finite Element strategy for the numerical simulation of additive manufacturing processes. *Additive Manufacturing*, *37*, 101650. https://doi.org/10.1016/j.addma.2020.101650

[13] Chergui, A., Beraud, N., Vignat, F., & Villeneuve, F. (2020, June). Finite element modeling and validation of metal deposition in wire arc additive manufacturing. In *International joint conference on mechanics, design engineering & advanced manufacturing* (pp. 61-66). Cham: Springer International Publishing. https://doi.org/10.1007/978-3-030-70566-4

[14] Baktheer, A., & Classen, M. (2024). A review of recent trends and challenges in numerical modeling of the anisotropic behavior of hardened 3D printed concrete. *Additive Manufacturing*, 104309. https://doi.org/10.1016/j.addma.2024.104309

[15] Liu, D., Zhang, Z., Zhang, X., & Chen, Z. (2023). 3D printing concrete structures: State of the art, challenges, and opportunities. *Construction and Building Materials*, *405*, 133364. https://doi.org/10.1016/j.conbuildmat.2023.133364

[16] Goh, G.D., Sing, S.L. & Yeong, W.Y. A review on machine learning in 3D printing: applications, potential, and challenges. Artif Intell Rev 54, 63–94 (2021). https://doi.org/10.1007/s10462-020-09876-9

[17] Matúš, M., Križan, P., Kijovský, J., Strigáč, S., Beniak, J., & Šooš, Ľ. (2023). Implementation of Finite Element Method Simulation in Control of Additive Manufacturing to Increase Component Strength and Productivity. *Symmetry*, *15*(11), 2036. https://doi.org/10.3390/sym15112036

[18] Shakoor, M. (2021). FEMS–A mechanics-oriented finite element modeling software. *Computer Physics Communications*, *260*, 107729. https://doi.org/10.1016/j.cpc.2020.107729

[19] David Müzel, S., Bonhin, E. P., Guimarães, N. M., & Guidi, E. S. (2020). Application of the finite element method in the analysis of composite materials: A review. *Polymers*, *12*(4), 818. https://doi.org/10.3390/polym12040818

[20] Kudela, J., Matousek, R. Recent advances and applications of surrogate models for finite element method computations: a review. *Soft Comput* 26, 13709–13733 (2022). https://doi.org/10.1007/s00500-022-07362-8

[21] Cremonesi, M., Franci, A., Idelsohn, S. *et al.* A State of the Art Review of the Particle Finite Element Method (PFEM). *Arch Computat Methods Eng* **27**, 1709–1735 (2020). https://doi.org/10.1007/s11831-020-09468-4

[22] Bakhtiari, H., Aamir, M., & Tolouei-Rad, M. (2023). Effect of 3D printing parameters on the fatigue properties of parts manufactured by fused filament fabrication: a review. *Applied Sciences*, *13*(2), 904. https://doi.org/10.3390/app13020904

[23] Rimašauskas, M., Jasiūnienė, E., Kuncius, T., Rimašauskienė, R., & Cicėnas, V. (2022). Investigation of influence of printing parameters on the quality of 3D printed composite structures. *Composite Structures*, *281*, 115061. https://doi.org/10.1016/j.compstruct.2021.115061

[24] Liu, W., Huang, J., Pang, Y., Zhu, K., Li, S., & Ma, J. (2023). Multi-scale modelling of evolving plastic anisotropy during Al-alloy sheet forming. *International Journal of Mechanical Sciences*, *247*, 108168. https://doi.org/10.1016/j.ijmecsci.2023.108168

[25] Zhao, Y., Song, Q., Ji, H., Cai, W., Liu, Z., & Cai, Y. (2022). Multi-scale modeling method for polycrystalline materials considering grain boundary misorientation angle. *Materials & Design*, *221*, 110998. https://doi.org/10.1016/j.matdes.2022.110998

[26] Liu, W., Pang, Y. A multi-scale modelling framework for anisotropy prediction in aluminium alloy sheet and its application in the optimisation of the deep-drawing process. Int J Adv Manuf Technol 114, 3401–3417 (2021). https://doi.org/10.1007/s00170-021-07060-z

[27] Jiang, Q., Deshpande, A., & Dasgupta, A. (2022). Multi-scale crystal viscoplasticity approach for estimating anisotropic steady-state creep properties of single-crystal SnAgCu alloys. *International Journal of Plasticity*, *153*, 103271. https://doi.org/10.1016/j.ijplas.2022.103271

[28] Jadayel, M., & Khameneifar, F. (2020). Improving geometric accuracy of 3D printed parts using 3D metrology feedback and mesh morphing. *Journal of Manufacturing and Materials Processing*, *4*(4), 112. https://doi.org/10.3390/jmmp4040112

[29] Cam, S., & Gunpinar, E. (2023). Fluid flow-inspired curvature-aware print-paths from hexahedral meshes for additive manufacturing. *Computer-Aided Design*, *159*, 103500. https://doi.org/10.1016/j.cad.2023.103500

[30] Egan, P. F. (2023). Design for additive manufacturing: recent innovations and future directions. *Designs*, *7*(4), 83. https://doi.org/10.3390/designs7040083

[31] Zhou, X., & Han, L. (2024). Coupled thermo-mechanical field-enriched finite element method for simulating the thermal failure process of quasi-brittle solids. *Engineering Fracture Mechanics*, *295*, 109803. https://doi.org/10.1016/j.engfracmech.2023.109803

[32] Sepe, R., Greco, A., De Luca, A., Caputo, F., & Berto, F. (2021). Influence of thermo-mechanical material properties on the structural response of a welded butt-joint by FEM simulation and experimental tests. *Forces in Mechanics*, *4*, 100018. https://doi.org/10.1016/j.finmec.2021.100018

[33] Wang, S., Chen, X., Han, X., Hong, X., Li, X., Zhang, H., ... & Zheng, A. (2023). A review of 3D printing technology in pharmaceutics: technology and applications, now and future. *Pharmaceutics*, *15*(2), 416. https://doi.org/10.3390/pharmaceutics15020416

[34] Jandyal, A., Chaturvedi, I., Wazir, I., Raina, A., & Haq, M. I. U. (2022). 3D printing–A review of processes, materials and applications in industry 4.0. *Sustainable Operations and Computers*, *3*, 33-42. https://doi.org/10.1016/j.susoc.2021.09.004

[35] Bozkurt, Y., & Karayel, E. (2021). 3D printing technology; methods, biomedical applications, future opportunities and trends. *Journal of Materials Research and Technology*, *14*, 1430-1450. https://doi.org/10.1016/j.jmrt.2021.07.050

[36] Karakurt, I., & Lin, L. (2020). 3D printing technologies: techniques, materials, and post-processing. *Current Opinion in Chemical Engineering*, *28*, 134-143. https://doi.org/10.1016/j.coche.2020.04.001

[37] Vaz, V.M., Kumar, L. 3D Printing as a Promising Tool in Personalized Medicine. *AAPS PharmSciTech* **22**, 49 (2021). https://doi.org/10.1208/s12249-020-01905-8

[38] Khan, M. S., Sanchez, F., & Zhou, H. (2020). 3-D printing of concrete: Beyond horizons. *Cement and Concrete Research*, *133*, 106070. https://doi.org/10.1016/j.cemconres.2020.106070

[39] Khosravani, M. R., & Reinicke, T. (2020). On the environmental impacts of 3D printing technology. *Applied Materials Today*, *20*, 100689. https://doi.org/10.1016/j.apmt.2020.100689

[40] Vahabi, H., Laoutid, F., Mehrpouya, M., Saeb, M. R., & Dubois, P. (2021). Flame retardant polymer materials: An update and the future for 3D printing developments. *Materials Science and Engineering: R: Reports*, *144*, 100604. https://doi.org/10.1016/j.mser.2020.100604

[41] Mostafaei, A., Elliott, A. M., Barnes, J. E., Li, F., Tan, W., Cramer, C. L., ... & Chmielus, M. (2021). Binder jet 3D printing—Process parameters, materials, properties, modeling, and challenges. *Progress in Materials Science*, *119*, 100707. https://doi.org/10.1016/j.pmatsci.2020.100707

[42] Quan, H., Zhang, T., Xu, H., Luo, S., Nie, J., & Zhu, X. (2020). Photo-curing 3D printing technique and its challenges. *Bioactive materials*, *5*(1), 110-115. https://doi.org/10.1016/j.bioactmat.2019.12.003

[43] Goh, G.D., Sing, S.L. & Yeong, W.Y. A review on machine learning in 3D printing: applications, potential, and challenges. *Artif Intell Rev* **54**, 63–94 (2021). https://doi.org/10.1007/s10462-020-09876-9

[44] El-Sayegh, S., Romdhane, L. & Manjikian, S. A critical review of 3D printing in construction: benefits, challenges, and risks. *Archiv.Civ.Mech.Eng* **20**, 34 (2020). https://doi.org/10.1007/s43452-020-00038-w

[45] Ghilan, A., Chiriac, A.P., Nita, L.E. *et al.* Trends in 3D Printing Processes for Biomedical Field: Opportunities and Challenges. *J Polym Environ* **28**, 1345–1367 (2020). https://doi.org/10.1007/s10924-020-01722-x

[46] Chadha, U., Abrol, A., Vora, N.P. *et al.* Performance evaluation of 3D printing technologies: a review, recent advances, current challenges, and future directions. *Prog Addit Manuf* **7**, 853–886 (2022). https://doi.org/10.1007/s40964-021-00257-4

[47] Nazir, A., Gokcekaya, O., Billah, K. M. M., Ertugrul, O., Jiang, J., Sun, J., & Hussain, S. (2023). Multi-material additive manufacturing: A systematic review of design, properties, applications, challenges, and 3D printing of materials and cellular metamaterials. *Materials & Design*, *226*, 111661. https://doi.org/10.1016/j.matdes.2023.111661

[48] KS, J. H., Subramaniam, M. P., KT, M. K., Sreeram, P., Parvathi, S., PS, S., ... & Raghavan, P. (2024). Fabrication and challenges of 3D printed sensors for biomedical applications-Comprehensive review. *Results in Engineering*, *21*, 101867. https://doi.org/10.1016/j.rineng.2024.101867