

# Structural Integrity Analysis of 3D Printed Square Blocks Using Finite Element Methods

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**Abstract:** This effort presents a holistic structural integrity study of the 3D printed blocks using the Finite Element Method (FEM). For analysis purposes, simple 25 mm × 25 mm × 25 mm block has been selected, using different 3D printing materials such as Thermoplastic Polyurethane (TPU), Acrylonitrile Butadiene Styrene (ABS), Polyethylene Terephthalate Glycol-modified (PETG), and Polylactic Acid (PLA). Finite Element Analysis (FEA) was performed to evaluate the compressive strength, fatigue life, safety factor, and natural frequencies of the printed blocks in the vertical and horizontal positions. Model construction involves layer-by-layer deposition through ACP-Pre, with a 1 mm thickness per layer, making 25 layers for each block. Structural, fatigue and modal were simulation under a compressive load of 12200 N using a meshed model consisting of 8424 nodes and 7225 quadrilateral elements. The results show the deformation behaviour, equivalent stress distribution, fatigue life, and safety factors of each material depending on the orientation of print and the material properties that influence mechanical performance. The findings will, hence, support the design and reliability optimization of 3D printed components in engineering and industrial applications.

**Keywords:** 3D Printing, Additive Manufacturing, Finite Element Analysis (FEA), Structural Integrity, Fatigue Analysis, Modal Analysis, Compressive Strength, Safety Factor, PLA, ABS, PETG, TPU, Stress Distribution.

## I. INTRODUCTION

Finite Element Method has taken much of the study into the stress performance of 3D printed square blocks to different horizons, which is really vital in assessing the behaviour of square blocks under mechanical loading. Advancements in 3D printing in the whole engineering and manufacturing spectrum necessitate carrying out an assessment of structural integrity, particularly where strength and durability of such structures are critical. The geometry simply is square blocks, most widely accepted in modular applications, making them pure models for stress distribution analysis [1]. FEM also allows thorough simulation of elements by subdividing structures into a number of elements taking into account material properties, print orientation, and fill patterns, and solving very effectively the anisotropic nature and infill variability in 3D

printed materials where conventional methods become inappropriate [2]. Such prediction actually may be used for guiding the optimization processes to be able to increase the load-bearing capacity with experimental validation for ensuring accuracy of the model using FEM [3]. The technology of 3D printing started way back in 1980 for rapid prototyping, yet today it has evolved into the mainstream of manufacturing with sections such as automotive, aerospace, and health bearing some impact [4]. It enables the creation of complex geometries through layer-by-layer construction from digital models, supported by advancements in materials such as polymers, metals, ceramics, and composites [5]. The technologies such as Fused Deposition Modelling (FDM), Stereolithography (SLA), Selective Laser Sintering (SLS), and Direct Metal Laser Sintering (DMLS) offer different possibilities with regard to accuracy and compatibility with materials [6]. In addition to improving the customization and lower cost of production, 3D printing has many research fronts yet to be traversed, whether it be around consistency of materials, scaling, or post-processing [7].

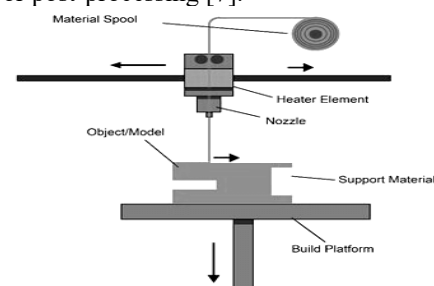


Figure 1 FDM 3D Printing Diagram [8]

The standard Fused Deposition Modelling 3D printing process comprises the melting of thermoplastic filament and extrusion through a nozzle which builds up an object layer by layer, as shown in Figure 1. Support structures can also be made for the stability of the printed structures [8]. Since the major technological breakthrough in 1980s, from which 3D printing was then regarded as very costly rapid prototyping [9], 3D printing has now embraced a growing expansion of applications within industrial sectors, including aerospace, healthcare, automotive, and consumer sectors [10] through several techniques like FDM, SLA, SLS, and DMLS [11]. 3D printing is a common rationalization of open-source innovations at reduced costs

which permits only highly personalized, tool-less production of very complex, lightweight parts for improved performances [12-14]. Rapid prototyping, therefore, reduces development cycles and increases cost-effectiveness through material optimization and human labour reduction [15][16]. Stress performance evaluation of 3D printed structures is of utmost importance because it varies, according to construction by layers, as an anisotropic property aligns directly on mechanical reliability [17][18]. Proper stress analysis including the identification of high-stress zones and design refinement with fillets and optimized infill, ensures safety across all industries [19-22]. Finite Element Analysis (FEA) is useful in modelling the stress fields and the respective points of failure, which will verify such models through laboratory studies for realistic predictions in performance considering factors such as print direction, infill density, and material type [23-28]. In addition, FEA can rapidly enable parametric studies and iterative design optimizations which increase durability, reduce waste, and dramatically lower production costs [29].

**A. Types of 3D Printed Square Blocks**

Bathes geometry of solid 3D printed blocks in investigations of material selection and printing methods towards structural integrity and mechanical performance. This involved comparing uniform material distribution standard square blocks with optimized designs made using either honeycomb or lattice infills for improved strength-to-weight ratios [30][31], while geometry choice was application-specific load requirement based [32]. Some of the key applications of 3D printing include Fused Deposition Modelling (FDM) for low-cost versatility, Stereolithography (SLA) for precision but brittle parts, and Selective Laser Sintering (SLS) for strong and durable parts among others. Indeed, material selection plays a vital role in the behaviours of stress, where PLA, ABS, PETG, and composites offer different balances between toughness, flexibility, and durability [33-35]. Also, the effectiveness of the above properties in loading performance includes tensile strength, elastic property, and durability [36][37]. Amongst all aforementioned techniques, FDM is the most popular and widely used, which extrudes by layer pellets of thermoplastics by layers [38], yet the anisotropic nature of the FDM part in layer adhesion, infill density, and print orientation will necessitate optimization for mechanical strength under stress [39].

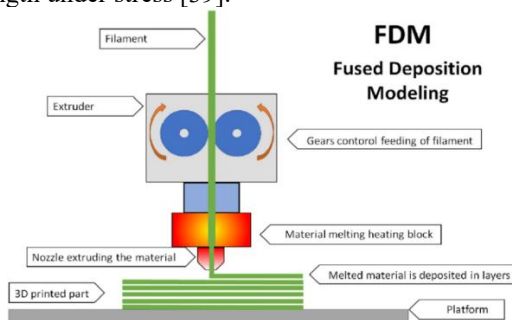


Figure 2 A diagram of the 3D printing process using the FDM technique [40]

Figure 2 shows the Fused Deposition Modelling (FDM) process, which is among the most widely used methods in 3D printing, whereby thermoplastic filament is fed into a

heated extruder, melts in the heated block, and extrudes through a nozzle that builds up the object layer by layer on the platform [40]. FDM is a first choice because it is simple, inexpensive, and versatile in the production of prototypes and functional parts. SLA, a very commonly used technique, offers the highest accuracy and the best surface finishes by selectively curing liquid photopolymer resins with a UV laser, thus generating parts that are very well detailed [41]. Parts produced by SLA, however, are generally more brittle than those produced by FDM due to the less tough nature of the photopolymer resins, making them unsuitable for mechanical applications subjected to static or cyclic stresses. Moreover, SLA involves post-processing steps such as washing and UV curing, which may increase the time consumed in the manufacturing of parts [42].

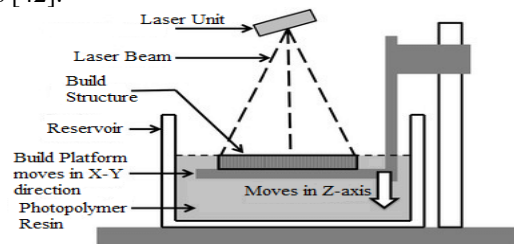


Figure 3 Schematic representation of Stereolithography (SLA) process (Image courtesy of 3D Systems) [43]

In the Stereolithography (SLA) 3D printing process illustrated in Figure 3, a laser beam selectively cures photopolymer resin layer by layer as the build platform moves downward along the Z-axis through a resin bath, and the highly accurate X-Y motion ensures precise positioning between subsequent layers resulting in high-resolution prints [43]. In contrast, Selective Laser Sintering (SLS) provides even superior mechanical performance via the application of high-powered lasers to sinter powdered materials, such as nylon or metal, forming parts layer-by-layer without requiring support structures from the surrounding powder bed [44]. Due to the ability to produce strong isotropic parts with excellent durability that are ideal for stress-resistant applications, SLS differs considerably from commonly used FDM prints that generally present anisotropy in their mechanical properties. Although SLS tends to be costlier and involves post-processing of parts to remove excess powder, it continues to be a preferred process in the aerospace and automotive industries due to the critical need for mechanical strength and reliability [45].

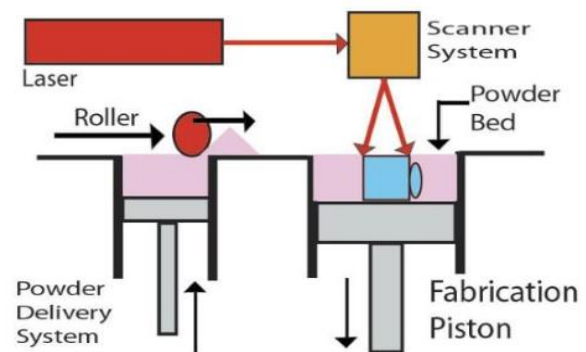


Figure 4 Selective Laser Sintering SLS 3D Printing [46]

The Selective Laser Sintering (SLS) for 3D printing is illustrated in Figure 4. In this case, a laser beam, guided by a scanner system, selectively fuses some powdered material (nylon or metal) onto a powder bed [46]. As the laser sinters each layer, the powder delivery increases upward to supply fresh material while a roller evenly spreads a new thin layer across the build area. Then the fabrication piston goes downwards, allowing the process to be repeated layer by layer until the whole object is formed, which gives rise to a strong, hard 3D printed part.

### **B. Applications of 3D Printed Square Blocks**

This study presents a survey of applications for 3D printed square blocks throughout structural, engineering, manufacturing, and educational areas, emphasizing their flexibility and customization potential. In structural applications, 3D printed modular blocks with internally complex geometries such as lattices or honeycombs provide lightweight yet strong solutions, ideal for aerospace, automotive, and portable frameworks, as well as being used as prototyping building blocks for stress testing and design refinement [47][48]. The blocks find application in engineering and manufacturing to facilitate the production of customized, stress-bearing parts for robotics and aerospace while optimizing weight, fortitude, and integration into complex systems—especially where traditional manufacturing would be too expensive or impractical [49][50]. These blocks serve as effective teaching aids for stress-strain analysis and material behaviours studies with hands-on student experimentation on diverse geometries, infill patterns, and materials, thus linking theory to practice [51][52][53]. Topological optimization reinforces high-stress areas and minimizes mass, guaranteeing that the resulting 3D printed parts are lightweight, strong, and viable even under rigorous real-world obligations.

### **C. Importance of Stress Analysis in 3D Printed Blocks**

Although critical owing to anisotropic behaviours arising from construction from layers, 3D Printed components must be structurally sound. Finite Element Analysis (FEA) has hence become the most utilized method to simulate stress distributions over a component, predict high-stress zones, and locate possible points of failure. These enable design optimizations such as adding fillets, altering wall thickness, and altering infill patterns to withstand said conditions in critical fields, such as aerospace, automotive, and healthcare, providing enhancement in durability and safety [54][55][56]. Strength and stiffness of the 3D Printed parts would greatly differ depending on the type of material, print orientation, and internal geometry, thus enabling accurate predictions on their behaviours under different loading conditions—tensile, compressive, shear, and fatigue—that proved important to their reliability. More

improvements are established through optimization of print parameters such as layer height, print speed, infill density, and infill style, which all appear to have instrumental effects on mechanical properties [57]. Typical topological optimization techniques help reinforce such areas with high-stress, as well as reduce sections that require less strength, creating under pressure lightweight yet robust structures for harsh applications. Such selection of appropriate materials, combined with their optimized geometry, gives rise to 3D printed components that easily comply with performance requirements while being lightweight or cost- and resource-effective, thus ushering in a more efficient and sustainable manufacturing process [58].

## **II. LITERATURE REVIEW**

The qualifying procedure or 3D printing is the latest technology which currently kicking off in industries such as automotive, aerospace, construction, electronics, and biomedicine, and those few of its last advances can be mentioned as fiber integration into plastic resins for mechanical property improvement [59]. Additive manufacturing imparts innovative ideas like smart materials in order to improve manufacturing convention but still limits with the slowness of printing [60]. Evolving since the 1970s, 3DP has expanded through technology improvements that include CAD tools and improvements in materials to make the technology much more reliable and efficient [61]. The trend of 3D printing into actual products increased in mass production in the automotive, health care and agricultural sectors [62]. Even though printed plastics exhibit anisotropic mechanical weaknesses, the performance was enhanced due to fillers and optimization of parameters in methods such as FDM, DLP, SLA, SLS, PLP, and electron beam melting [63]. Finite element model updating (FEMU) aims at filling the gap separating numerical simulations and real-world structural behaviour through parameter assumption refinement using experimental data [64]. In construction, 3D printing becomes part of Industry 4.0 by automation, adaptability, and sustainability that can be advanced with FEM analysis for structural evaluation [65]. Stress-strain behaviour simulated by FEA perfectly matches the tensile strength of biodegradable PLA and could provide the important design input [66]. Analysis of infill patterns on the PLA demonstrated that the honeycombs were the best in terms of tensile and fracture properties, attached with gravity-beneficial force ratios [67]. By marrying FEM with CAD, scaffolds can be designed and printed with mechanically engineered properties for different internal architectures in tissue engineering [68].

Table 1 Comparative Summary of Studies on 3D Printing and Finite Element Analysis

Reference	Method	Parameter	Key Finding	Outcome
[59]	3D Printing & Composite Study	Fiber integration into plastic resins	Enhanced mechanical properties of 3D printed composites	Future opportunities for further improvements
[60]	3D Printing Overview	Smart materials in manufacturing	3D printing growth despite challenges like slow speeds	Broader industrial applications
[61]	Historical Review	Development of CAD & SLA	Improved reliability and affordability in 3D printing	Increased adoption across fields
[62]	Industry Application Survey	CAD to Object Production	Growth in automotive, healthcare, and agriculture	Open-source mass customization
[63]	Comparative Techniques Review	FDM, DLP, SLA, SLS, PLP, EBM parameters	Influence of process parameters on part quality	Optimization strategies proposed
[64]	FEMU Technique	Model Updating, Structural Testing	FEMU refines FEM models for accuracy against real structures	Effective structural modelling
[65]	Construction Application Study	FEM applied to 3D printed structures	AM central to Industry 4.0 in construction	Promotes automated and sustainable practices
[66]	FEA Simulation	PLA material modelling, stress-strain	Accurate simulation improves design input for biodegradable PLA	Better prediction of mechanical behaviour
[67]	Infill Pattern Experiment	Different infill geometries in PLA	Honeycomb infill showed superior mechanical properties	Optimized strength and lightweight design
[68]	Tissue Engineering Application	FEM-CAD designed 3D printed scaffolds	Different scaffold geometries predict mechanical behaviours	Advanced tissue-specific scaffold design

### III. OBJECTIVES

3D printing is an additive manufacturing process that creates actual three-dimensional objects from digital models by depositing materials layer by layer. Compared with conventional manufacturing methods, it has the ability to produce highly complex geometries with minimal wastage of materials. The present study aims to evaluate compressive strength, fatigue life, factor of safety, and natural frequencies of square blocks printed in 3D with different materials.

There are following objective of the present study.

- ❖ Calculation shall be done on alternating stresses of the different materials adapted for the project, namely TPU (Thermoplastic Polyurethane), ABS (Acrylonitrile Butadiene Styrene), PETG (Polyethylene Terephthalate glycol-modified) and PLA (Polylactic Acid).
- ❖ To create layer wise three-dimensional CAD model using ACP (Pre) for FEM analysis.
- ❖ To explore the overall deformation & equivalent stress layer wise, four different 3D printed materials will be used to perform compressive tests utilising structural analysis techniques for different orientations.
- ❖ Using a fatigue tool, do fatigue analysis to look at the duration of fatigue and safety factor.
- ❖ To verify the natural frequency using six possible modes by performing the model analysis.
- ❖ Compare the results obtained from the above analysis and validate with the base paper.

### IV. METHODOLOGY

Rapid prototyping and manufacture changes are made much easier and quicker by 3D printing technology compared to the classical routes. For this effort, a simple 25 mm x 25 mm x 25 mm block was used for performing fatigue, structural, and modelling experiments with several 3D printing materials, including TPU, ABS, PLA, and PETG. Finite Element Analysis (FEA) was done together with compression tests of static structural analysis to provide the required information regarding deformation and equivalent stress distribution. Fatigue analysis, in this case, indicated the designing life span alongside the safety factor of each material while modal analysis was carried out to determine natural frequencies of the square block.

Table 2 Material properties

Property	TPU	ABS	PLA	PETG
Density [Kg/m <sup>3</sup> ]	1660	1040	1290	1290
Coefficient of thermal expansion	11x10 <sup>-6</sup>	72x10 <sup>-6</sup>	27x10 <sup>-6</sup>	68x10 <sup>-6</sup>
Young Modulus GPa	5.50	2.3	4.8	2.1

Poisson's Ratio	0.3897	0.3	0.3	0.3
Bulk modulus [MPa]	8.3107E+6	109167E+9	4E+9	1.75E+9
Shear modulus [MPa]	1.9788E+6	8.8462E+8	1.846E+9	8.0769E+8
Tensile Yield strength [MPa]	79.3	35.9	57.9	53
Tensile Ultimate strength [MPa]	96	26.4	47.9	45.8

$K = \text{Bulk Modulus}$   
 $\nu = \text{Poisson's ratio}$   
 $G = \frac{1}{2} \left( \frac{E}{1 + \nu} \right)$

Where:  
 $G = \text{Shear modulus}$

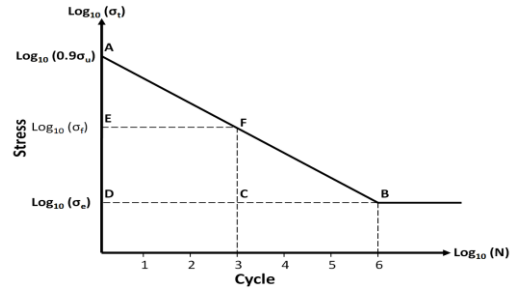


Figure 5 S-N curve

**A. Calculation of Bulk modulus and shear modulus**

$E = 3k(1 - 2\nu)$

$K = \frac{E}{3(1 - 2\nu)}$

Where:

$E = \text{Young modulus}$

**B. Calculation of fatigue strength at different cycle**

$Log_{10}(\sigma_f) = Log_{10}(0.9\sigma_u)$   
 $-\frac{Log_{10}(0.9\sigma_u) - Log_{10}(\sigma_e)}{Log_{10}(10^6) - Log_{10}(10)}$   
 $\times [Log_{10}(N) - Log_{10}(10)]$   
 $\sigma_e = 0.3\sigma_u$

Table 3 Calculation of alternating stress for different materials

Cycle	Log <sub>10</sub> (N)	Alternating Stress TPU [MPa]	Alternating Stress ABS [MPa]	Alternating Stress PLA [MPa]	Alternating Stress PETG [MPa]
10	1	86.39	23.76	43.11	41.22
20	1.3	80.89	22.15	35.42	33.94
50	1.699	74.25	20.18	27.28	26.21
100	2.0	69.36	18.81	22.40	21.56
200	2.3	64.94	17.53	18.41	17.75
2000	3.3	52.13	13.88	9.57	9.29
10000	4	44.67	11.78	6.05	5.90
20000	4.3	41.85	10.98	4.97	4.86
1E+5	5	35.88	9.32	3.15	3.09
2E+5	5.3	33.59	8.69	2.58	2.54
2E+5	5.3	33.59	8.69	2.58	2.54

Finite Element Analysis (FEA) is very valuable because it can compute values at discrete elements, which makes it best suited for estimating all kinds of local effects or mechanical behaviour in complex geometries, loads, and material properties. Structural analysis in FEA is used to determine possible displacement, stress, strain, and forces under steady loading conditions, where the inertia and damping effects are neglected. On the contrary, modal analysis gives natural frequencies and mode shapes of structures that are critical inputs for dynamic loading conditions and forms the basis for further analyses such as harmonic response, random vibration, and spectrum analysis. It begins from the general equation of motion and resolves acceleration, velocity, and displacement at every point in the structure. Hence, it is the most important input for the structural design under dynamic forces.

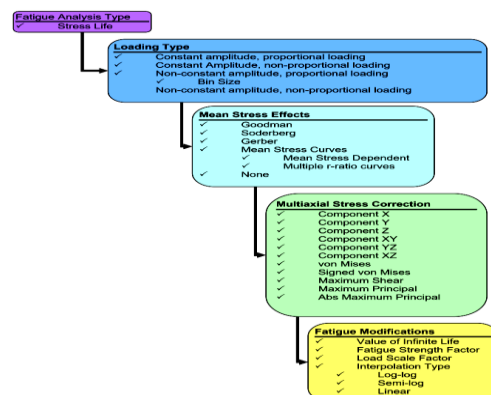


Figure 6 Fatigue analysis type stress life decision tree  
 Fatigue denotes the repeated damaging action of the material due to different loadings and strain conditions. One of the primary characteristics of fatigue is that the applied loading does not cause appreciable plastic

deformations or premature failure. Instead, a component breaks once cumulative damages reaches a critical threshold or after it has experienced a specified number of load variations. The constituent fatigue is the progressive damage accrual within a material subjected to repeated load and strain until it prompts failure at a certain upper limit or threshold of cumulative damage even without plastic strain. Simply put, it defines the strength loss of a component after being subjected to cycles of loading for a long duration of time. Fatigue analysis traditionally takes three approaches: Fracture Mechanics, Strain Life, and Stress Life. Among the three, only Strain Life and Fracture Mechanics are interlinked with ANSYS Fatigue Module. Strain Life is concerned about crack initiation; it assesses fatigue with a lesser number of cycles and is more focused on Low Cycle Fatigue (LCF). The behaviour is captured by the equation known as the Strain Life Relation. Stress Life handles High Cycle Fatigue (HCF) because it is built on S-N curves and has historically dealt with rather high cycle counts. A variety of empirical methods, including Gerber, Goodman, and Soderberg theories, which use static property data for materials as well as S-N data to account for any mean stress, can be employed to assist with being stressed Life calculations that incorporate different mean stresses or r-ratios. Alternatively, mean stress could also be directly assigned through interpolation between the material curves.

$$\frac{\sigma_{Alternating}}{S_{Endurance\ limit}} + \frac{\sigma_{mean}}{S_{Yield\ strength}} = 1$$

$$\frac{\sigma_{Alternating}}{S_{Endurance\ limit}} + \frac{\sigma_{mean}}{S_{Ultimate\ strength}} = 1$$

$$\frac{\sigma_{Alternating}}{S_{Endurance\ limit}} + \left(\frac{\sigma_{mean}}{S_{Ultimate\ strength}}\right)^2 = 1$$

The fatigue life refers to the number of cycles to which a material can be subjected under fatigue loading with

constant amplitudes and predicts how long the model will survive before some failure occurs; it is used in Stress Life analysis whenever alternating stresses fall below a certain threshold defined by the S-N curve. Fatigue damage measures the degree of fatigue-related deterioration with respect to design life, such that a damage value exceeding unity suggests failure before the intended life. The fatigue safety factor plots display the probability of fatigue failure, with values less than one indicating failure before time. The evaluation of the biaxiality indicator takes a state of stress given by the comparison of principal stresses and defines pure uniaxial state, pure shear state, or an actual full biaxial state. Fatigue sensitivity analysis models how a certain loading event interacts with an entity's vulnerability to fatigue failure and provides the option to display this information either as Log-X, Log-Y, Log-Log, or Linear through a control panel to enhance interpretability.

The Preprocessor phase in strength analysis is concerned with preparing the model through geometric build-up, material property information, and elemental mesh generation. These geometries are built in ANSYS itself, imported from CAD software, or built by hand, while material performance is defined through the use of constants for simulation purposes. The discretization of the structure into nodes and elements, be they beams, bridges, plates, shells, or solids, produces the elemental mesh, these groups having more mechanical control on the quality of the mesh. The Solution Processor stage follows with loading the nodes or elements, and the computer solves the governing equations using the finite element method giving values of nodal degree-of-freedom as major outputs. Finally, the Postprocessor stage consists of result examination, which appears in graphical displays, tabular listings, or additional data manipulation as load case combinations to fully understand the behaviour of the modelled scenario analysed. In this way, the algorithm for both structural and fatigue finite element analysis is being introduced in Section 4.6.



Figure 7 The algorithm utilised for structural and fatigue finite element analysis

**C. Finite element analysis of square block for different materials**

For the creation of square block ACP-pre is use where block has been created by combining two or more layered materials. Several layers, materials, thicknesses, and orientations are all part of the intricate definitions of layering. As seen in the figure 8, the square block was created using the dimensions 25 mm x 25 mm x 25 mm as.

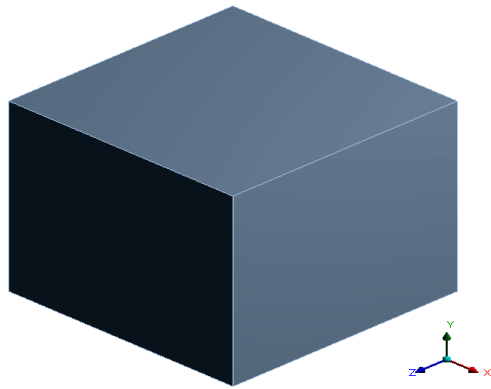


Figure 8 CAD model of square block

For the creation of vertical layer of square block, set the direction of fibers in vertical (+Y) direction with thickness of 1 mm for each layer as shown in figure 9. In the present work total 25 layers has been created in five modelling groups per ply having five layers in each group.

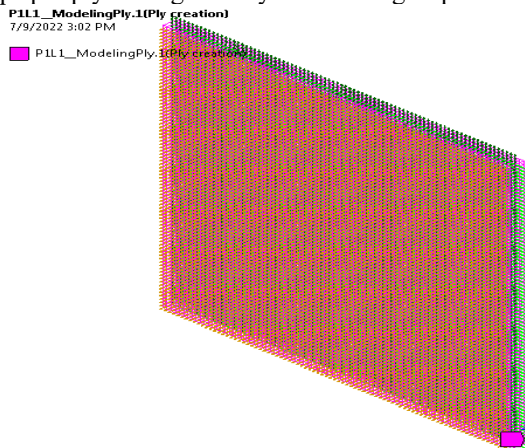


Figure 9 (a): Orientation of vertical layer

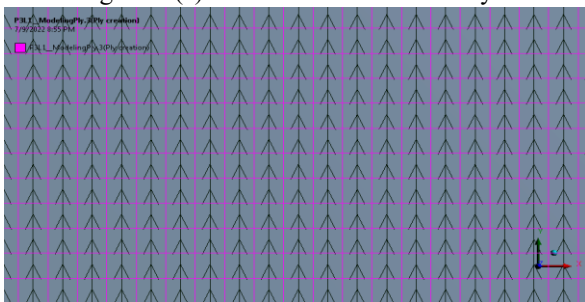


Figure 9 (b): Direction of fibers of vertical layer

For the creation of horizontal layer of square block, set the direction of fibers in horizontal (+X) direction with thickness of 1 mm for each layer as shown in figure 10. In the present work total 25 layers has been created in five modelling groups per ply having five layers in each group.

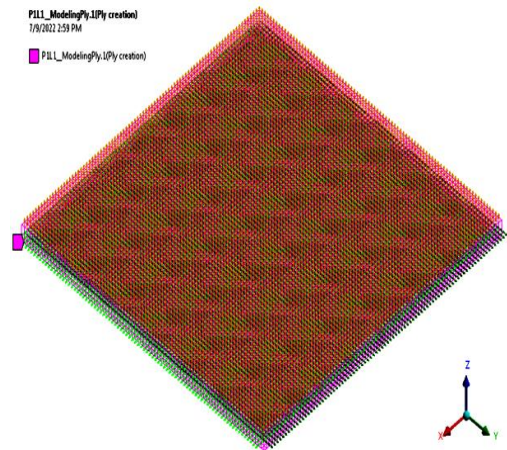


Figure 10 (a): Orientation of horizontal layer

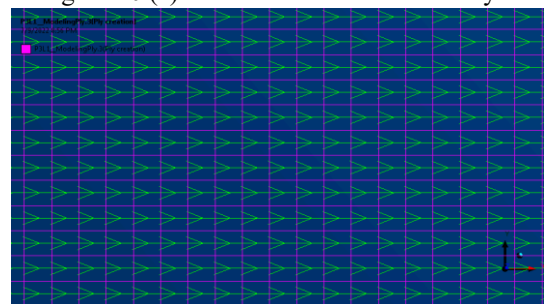


Figure 10 (b): Direction of fibers of horizontal layer

After creation of modelling groups per and all 25 layers of square block, convert all ply in one solid for further structure, Fatigue and Model analysis and then imported for meshing of square block.

**1. Meshing**

One of the most important processes in finite element analysis is meshing, which divides CAD geometry into many tiny pieces known as mesh. In the current work, 8424 nodes and 7225 elements of 1.2 mm element size were generated. Quadrilateral elements have been created as shown in figure 11.

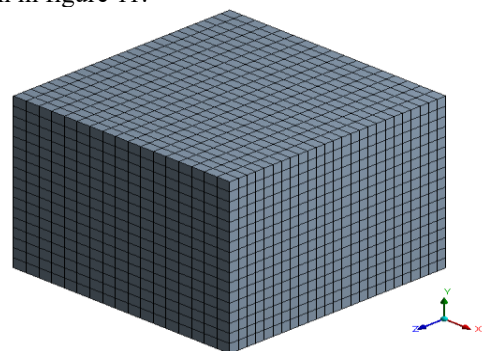


Figure 11 Meshing of square block

Table 4 Some properties of 3D printing materials

Parameters	ABS (Acrylonitrile Butadiene Styrene)	TPU (Thermoplastic Polyurethane)	PETG (Polyethylene Terephthalate glycol- modified)	PLA (Polylactic Acid)
Impact strength	High	High	-	High
Durability	High	High	High	High
Flexibility	Low	Very High	Low	Low

Chemical resistance	High	Medium- High	High	Low
Water resistance	Medium	Medium	High	Medium
Nozzle Extruder Temperature (°C)	230-260	220-250	210-250	190-210

**D. Boundary Condition**

For the creation of square block ACP-pre is use where block has been created by combining two or more layered materials.

1. Create material library for the Thermoplastic Polyurethane (TPU), Acrylonitrile Butadiene Styrene (ABS), Polyethylene Terephthalate glycol-modified (PETG) and Polylactic Acid (PLA).
2. For the fatigue analysis need to calculate alternating stress for all create material library as mentioned in table 4.
3. Apply material for the creation of layers for square block for 3D printing.
4. Apply orientation (horizontal and vertical) of layers and rosette with 1 mm thickness.

In the above figure 12 arrow represents the direction of load in which the load has been applied to that of the axes. The vertical axis represents an axial load that act on the side of each layer of the object and the horizontal axis represents an axial load that act on the perpendicular to each layer of the object.

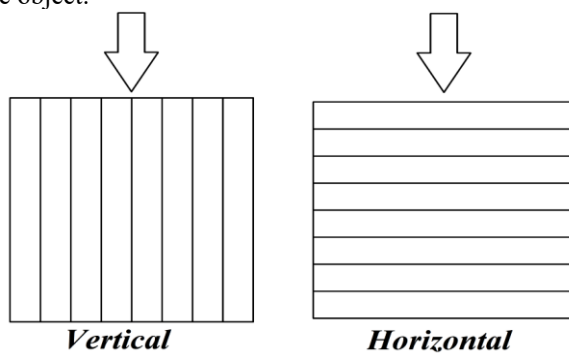


Figure 12 Layering axis and applied load direction

5. Create 5 modelling group in and set five plies in each group with different orientation.
6. Convert all ply in one solid for the further structure, Fatigue and Model analysis and then imported for meshing of square block.
7. Build a mesh with 7225 total elements and 8424 total nodes for 1.2 mm elements that are of the quadrilateral type.
8. To conduct the compressive test, carry out structural analysis by applying a compressive force of 12200 N to the square block's top layer while maintaining the lower side fixed.
9. Use the fatigue tool to check the duration of fatigue and safety factor.
10. Model study with six potential modes must be done in order to determine the natural frequencies.

**V. RESULT AND DISCUSSION**

Fatigue, modal, and compression tests were performed on the 3D finite element model of a square block with a side length equal to 25 mm. It also includes a static structural

analysis. Materials used for test specimen manufacture were TPU, ABS, PETG, and PLA. The block was produced by layering materials in ACP-Pre and applying rosettes of 1 mm in thickness along the horizontal and vertical orientations. The model consisted of 8424 nodes and 7225 quadrilateral elements with an element size of 1.2 mm. The top surface was loaded with a compressive load of 12200 N, while the bottom was fixed. The fatigue analysis understood alternating stress, design life, and safety factor while the modal analysis gave six natural frequencies.

**A. Comparative analysis of total deformation for various materials under vertical loading**

Table 5 Total Deformation of Various Materials under Applied Compressive Load

Applied Compressive Load [N]	Total deformation for TPU under vertical loading [mm]	Total deformation for ABS under vertical loading [mm]	Total deformation for PLA under vertical loading [mm]	Total PETG deformation under vertical loading [mm]
-1220	3.62E-03	8.71E-03	4.17E-03	9.50E-03
-2440	8.70E-03	1.74E-02	8.35E-03	1.90E-02
-3660	1.38E-02	3.14E-02	1.50E-02	3.42E-02
-4880	1.96E-02	4.70E-02	2.25E-02	5.13E-02
-6100	2.75E-02	6.62E-02	3.17E-02	7.22E-02
-7320	3.77E-02	9.06E-02	4.34E-02	9.88E-02
-8540	4.93E-02	1.18E-01	5.68E-02	1.29E-01
-9760	6.16E-02	1.48E-01	7.10E-02	1.62E-01
-10980	7.47E-02	1.79E-01	8.60E-02	1.96E-01
-12200	8.84E-02	2.13E-01	1.02E-01	2.32E-01

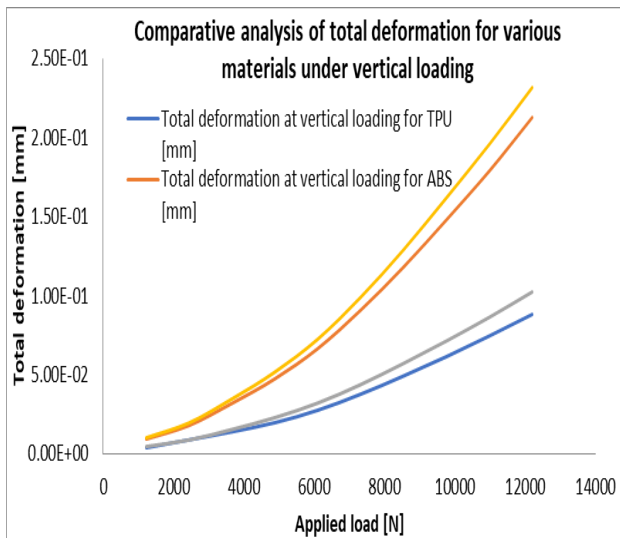


Figure 13 Comparative analysis of total deformation for various materials under vertical loading

**B. Comparative analysis of total deformation for various materials under horizontal loading**

Table 6 Total Deformation of TPU, ABS, PLA, and PETG under Horizontal Loading for Varying Compressive Loads

Applied Compressive Load [N]	Total deformation for TPU under horizontal loading [mm]	ABS's overall deformation when subjected to horizontal loading [mm]	Total deformation for PLA under horizontal loading [mm]	Total deformation for PETG under horizontal loading [mm]
1220	3.63E-03	8.71E-03	4.18E-03	9.50E-03
2440	7.25E-03	1.74E-02	8.35E-03	1.90E-02
3660	1.31E-02	3.14E-02	1.50E-02	3.42E-02
4880	1.96E-02	4.71E-02	2.25E-02	5.13E-02
6100	2.76E-02	6.62E-02	3.17E-02	7.22E-02
7320	3.77E-02	9.06E-02	4.34E-02	9.89E-02
8540	4.93E-02	1.19E-01	5.68E-02	1.29E-01
9760	6.17E-02	1.48E-01	7.10E-02	1.62E-01
10980	7.47E-02	1.80E-01	8.60E-02	1.96E-01
12200	8.85E-02	2.13E-01	1.02E-01	2.32E-01

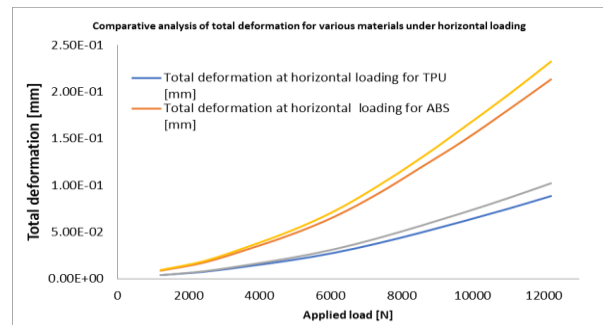


Figure 13 Comparative analysis of total deformation for various materials under horizontal loading

**C. Comparison of maximum equivalent stress for various materials**

Table 7 Peak Equivalent Strain and Maximum Equivalent Stress for Various Materials under Vertical and Horizontal Loading

Materials	Peak equivalent strain, measured in MPa, during load on the vertical plane	The maximum equivalent stress [MPa] experienced when the horizontal layer is loaded
TPU	34.406	46.933
ABS	30.425	40.016
PLA	30.425	41.016
PETG	33.93	46.317

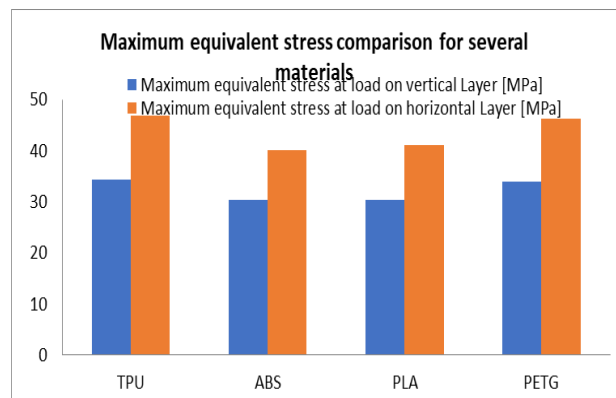


Figure 14 Maximum equivalent stress comparison for several materials

**D. Comparison of the fatigue life of various materials**

Table 8 Fatigue Life of Materials under Vertical and Horizontal Loading

Materials	Life of fatigue under load in a vertical layer	Life of fatigue under load in a horizontal layer
TPU	6.065E+5	7.8125E+5
ABS	5.391E+6	6.8432E+6
PLA	1250.4	1362.3
PETG	5.725E+5	6.1688E+5

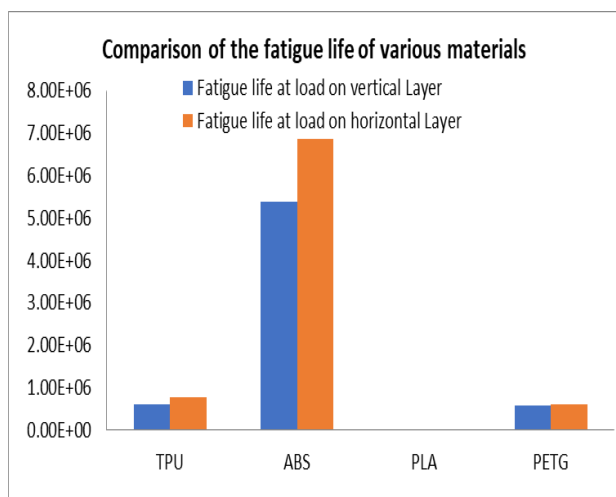


Figure 15 Comparison of the fatigue life of various materials

**E. Results of a security factor comparison for different materials**

Table 9 Factor of Safety for Materials under Vertical and Horizontal Loading

Materials	Factor of safety while loading a vertical layer	Factor of safety while loading a horizontal layer
TPU	0.6145	0.6296
ABS	0.18239	0.18687
PLA	0.04028	0.041274
PETG	0.035116	0.035979

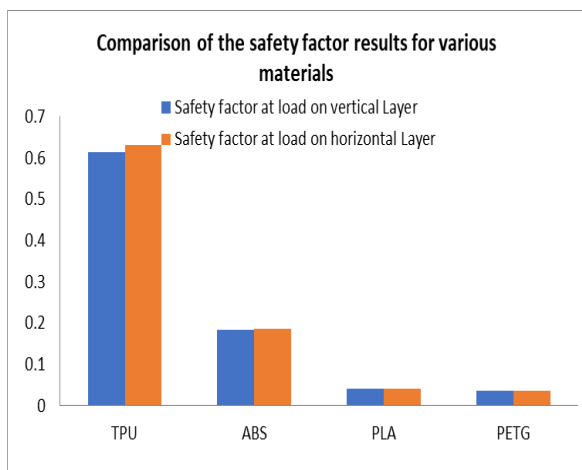


Figure 16 Comparison of the safety factor results for various materials

**VI. CONCLUSION**

A finite element analysis was performed on 3D printed square blocks made of TPU, ABS, PETG, and PLA materials, which described their behaviour under compressive and cyclic loading in great detail. The results obtained have shown that deformation, equivalent stress, fatigue life, and safety margins are significantly affected by the type of material used, as well as printing orientation and structure. TPU and PETG were relatively more flexible and durable, while PLA had the lowest fatigue life and safety factors under the loads it was subjected to. The polymer, ABS, was also strong but demonstrated average

deformation characteristics. It was also possible to prove that horizontal orientation always gives slightly better fatigue life than that of vertical layering. It was discovered that modal analysis is combined with natural frequencies to predict dynamic behaviour in operational conditions. These results brought about conclusions, stressing the need for careful material choice, optimization of layer thickness, and refinement of design to increase the structural integrity of 3D printed components, thus paving the way for such components to be used more broadly in load-bearing and critical applications.

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

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