Enhancing Design and Prototyping: The Impact of 3D Printing and Finite Element Analysis

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Abstract: *With 3D printing-or additive manufacturing-complex and personalized objects are being fabricated by building from the ground up, layer by layer, from digital models. In return, instead of conventional manufacturing, the technology culturing at an increased rate encourages intricate designs and rapid prototyping within industrial walks such as manufacturing, health care, and even aerospace. The major techniques are FDM, DLP, and MJF; all of them have different advantages concerning resolution, speed, and material properties. FEM is complementary to 3D printing and completes it with the capability of highly detailed numerical simulations of complex systems, decomposing them into manageable finite elements in order to predict structural behavior, stress, and thermal performance. Consequently, together, 3D printing and FEM increase innovation, design optimization, and problem-solving in engineering and manufacturing.*

Keywords: *3D printing, additive manufacturing, Fused Deposition Modeling (FDM), Digital Light Processing (DLP), Multi Jet Fusion (MJF), Finite Element Analysis (FEM), rapid prototyping, numerical simulations, structural behavior.*

I. INTRODUCTION

3D printing, also known as additive manufacturing, is a technology that creates three-dimensional objects by layering material based on a digital model. Unlike traditional manufacturing methods, which often involve subtracting material from a larger block, 3D printing builds objects layer by layer, allowing for intricate designs and complex geometries. The process begins with designing a digital 3D model using computer-aided design (CAD) software. This model is then converted into a file format, such as STL, that the 3D printer can interpret.

Once the digital model is ready, the 3D printer reads it and starts creating the object by laying down material in successive layers. The materials used in 3D printing can vary widely, including plastics, resins, metals, and even food. After the object is printed, it often undergoes post-processing, such as removing support structures, sanding, or painting, to achieve the desired finish. 3D printing has revolutionized industries like manufacturing, healthcare, and aerospace by enabling rapid prototyping, customized production, and the ability to produce complex designs that would be difficult or impossible with traditional methods [1].

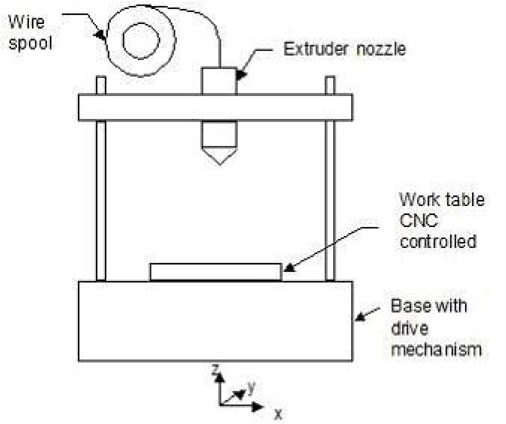

Figure 1 Schematic diagram of 3D printer [2]

The figure 1 illustrates a basic schematic of a 3D printer that operates using the Fused Deposition Modeling (FDM) technique. In this process, a material, typically a plastic filament, is fed from a wire spool into a heated extruder nozzle. The extruder melts the filament and deposits it precisely onto the work table, building the object layer by layer. The movement of the extruder nozzle across the work table is controlled by a CNC (Computer Numerical Control) system, allowing it to move in the X and Y directions to create the desired pattern.

The work table, which supports the object being printed, may also move in the Z direction, enabling the printer to build up the object vertically. The entire system is supported by a base that contains the drive mechanism, which ensures the accurate movement and positioning of the extruder and work table. This precise control allows for the detailed and intricate construction of 3D objects, layer by layer, in a method that is central to the functioning of FDM 3D printers [2].

A number of layer-by-layer manufacturing technologies are referred to as 3D printing. Each has a different method for forming metal and plastic components. They might also differ in terms of durability, surface quality, choice of materials, speed, and cost of manufacture.

A. Types of 3D printing

There are several types of 3D printing, which include:

i. **Digital Light Process (DLP):** DLP is like SLA but uses a digital mask to solidify resin, enabling faster printing of larger objects. DLP's resolution is based on pixel size, while SLA's is on laser spot size. SLA typically offers higher resolution and surface finish [3].

ii. **Multi Jet Fusion (MJF):** MJF is a powder-based 3D printing technology that produces high-resolution, precise objects with low porosity and smooth surfaces. Unlike SLS, it uses an inkjet print head with binder fluids instead of a laser, building components layer by layer. This results in detailed and consistent prints, ideal for fine-resolution applications [4].

B. Finite Element Analysis

The Finite Element Method (FEM) is a numerical technique widely used in engineering and mathematical problem-solving, especially for complex systems involving partial differential equations. It works by breaking down a large, complex problem into smaller, simpler parts called finite elements, which are connected at specific points known as nodes to form a mesh. Mathematical equations that describe the behavior of the system—such as stress, strain, or heat transfer—are formulated for each element. These individual equations are then assembled into a larger system that models the entire domain. The resulting system of equations is solved numerically to approximate the behavior of the entire structure or system. After obtaining the solution, the results are typically visualized to interpret stress distributions, temperature fields, or other critical factors. FEM's ability to handle complex geometries, material properties, and boundary conditions makes it an indispensable tool in fields like structural analysis, fluid dynamics, and thermal analysis [5].

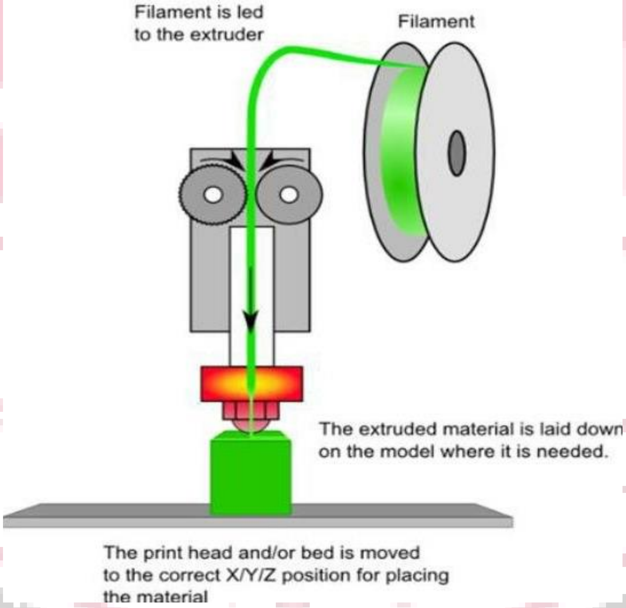

Figure 2 FDM 3D printer schematic [6]

C. Significance

The significance of 3D printing models lies in their ability to revolutionize design and manufacturing processes by enabling rapid prototyping, customization, and cost-effective production. These models allow for the creation of complex, detailed structures that are difficult or expensive to produce with traditional methods. They facilitate innovation by allowing for on-demand production and exploration of new designs and materials. Additionally, 3D printing reduces inventory and waste, supports personalized solutions, and serves as a valuable educational tool in various fields [7].

D. Applications

i. **Healthcare:** 3D printing has revolutionized practices with patient-specific implants, customized prosthetic limbs, and precise surgical planning models. By using CAD data and CT scans, 3D printing produces implants and prosthetics with exact fits, enhancing comfort and function. It also allows for the creation of accurate organ replicas for better surgical planning, leading to safer and more efficient procedures. Additionally, 3D-printed drug delivery devices enable personalized medicine with precise dosage control [8].

ii. **Aerospace:** 3D printing is pivotal for producing lightweight, durable components, crucial for reducing fuel consumption and production costs. This technology minimizes waste and shortens lead times, enhancing efficiency. For example, Airbus has integrated thousands of 3D-printed parts into its aircraft, achieving notable weight and cost savings. Moreover, NASA uses 3D printing for creating satellite parts and spacecraft components, reducing the need for spare parts on space missions [9].

iii. **Automotive:** 3D printing 3D printing is revolutionizing product development, transforming it from a novel technology to an essential tool. Industry leaders like Ford and Porsche are harnessing 3D printing methods such as selective laser sintering (SLS) and fused deposition modeling (FDM) to expedite the prototyping process, enabling rapid testing and refinement of designs. This acceleration not only fosters faster innovation but also significantly reduces time to market, making 3D printing a key driver of progress in automotive engineering and design [9].

II. LITERATURE REVIEW

Catasta, A. et al. (2024) [10] highlighted the growing interest in employing 3D-printed models for planning and training in simulation-based vascular surgery. The study aims to provide an overview of the current use of 3D printing technology in vascular surgery. To do a systematic review, the following four databases were searched: PubMed, the internet of sciences, the Cochrane Library, and Scopus (last search date: March 1, 2024). Included were publications that dealt with the treatment of aneurysmal or stenotic/occlusive cardiovascular illnesses. Included were res that described the outcomes of employing 3D-printed models; case reports and very short series of cases (less than five printed models or tests/simulations) were excluded. 22 studies were ultimately analyzed and included. Computerized tomography angiography (CTA) was the primary diagnostic technology that generated the pictures that were used as the basis for the 3D-printed models. The CTA data was processed using medical imaging software; the most often used applications were Mimics (Materialise NV, Leuven, Belgium), ITK-Snap, and 3D Slicer (Brigham and Women's Hospital, Harvard University, Boston, MA). In the post-processing phase, Autodesk Meshmixer (San Francisco, CA, USA) & 3-matic (Materialise NV, Leuven, Belgium) were the most frequently utilized mesh-editing tools. The most popular 3D printing techniques were PolyJet TM, Fused Deposition Modeling (FDM), and Stereolithography (SLA). When training and planning is done with 3D-printed models, physician's confidence as well as performance seem to rise by up to 40%; processing time and contrast volume use also seem to reduce to variable degrees.

Wu, X. et al. (2024) [11] Organ-on-a-chip (OOC) allows precision fluid manipulations in microfluidic systems, and simulates the chemical, mechanical, and physiological aspects of tissues, making it a promising technique for physiological modeling and biological drug screening. The rise of several three-dimensional (3D) printing processes may be linked to the significant improvement in technology in recent decades. Utilizing materials like polyethylene glycol resins, 3D printing may produce microfluidic chips as well as biomimetic tissues utilizing bioinks that are like cell-loaded hydrogels. This review of recent developments in OOC provides a systematic summary of the materials that are used for direct or indirect OOC 3D printing, the 3D printing techniques for creating OOC, and applications of OOC-based 3D printing in models of the heart, arteries, veins, liver, and intestines. The paper also outlines the industry's obstacles and future objectives in a goal to promote innovative uses of 3D printing technology to enhance OOC.

Ma, L. et al. (2023) [12] provided that 3D printing and artificial intelligence (AI) will develop into technologies that have a significant impact on humanity. It is anticipated that animal carcasses will give way to 3D printed patient-specific organ models, which will educate patients to offer workable remedies and provide preoperative training scenarios that mimic the operating room. Owing to the intricacy involved in the manufacturing process, 3D printing is currently only occasionally utilized in clinical settings. Issues with this technology include poor MRI/CT picture clarity, lengthy consuming times, and inadequate realism. Artificial Intelligence has proven to be an excellent problem-solving tool in 3D printing. This study presents the concept of artificial intelligence (AI) used for 3D printed organ fabrication. Lastly, a discussion is had regarding the possible use of AI with 3D printed organ models. The application of AI in printed in 3D organ model manufacturing is anticipated to become a reality due to the synergy between artificial intelligence (AI) and 3D printing that will boost organ models manufacturing and facilitate medical preparatory training in the medical profession.

Sun, Z. et al. (2023) [13] Research has indicated that 3D printing is finding more and more applications in the medical field, such as medical education, surgical simulation and preparation, facilitating doctor-patient or clinician-to-clinician communication, and the development of optimal CT (computed tomography) imaging protocols. This paper details our experience using a 3D printer facilities to create a range of low-cost, specific to patients models for medical applications. These models include tailored models for cardiovascular disorders (ranging from congenital heart abnormalities to artery aneurysm, aorta dissection, and coronary arteries disease) and cancers (including cancer of the lung, cancer of the pancreatic gland, and biliary sickness) based on CT data. We also designed and manufactured special 3D-printed models, such calcification coronary plaques to mimic severe coronary artery calcification and a 3D-printed breast model to mimic breast cancer MRI. For the purpose of assessing their potential as educational and therapeutic resources, the majority of these 3D-printed models went under CT scanning, with an exception of the breast tissue model, which was evaluated using MRI. The outcomes were positive. It was determined that the models fairly and effectively depicted the physiology and pathophysiology of various body areas. Our capacity to produce low-cost, easily accessible 3D-printed models shows the potential of integrating 3D printing technology into medical educational and clinical environments.

Niu, Q. et al. (2023) [14] explained that the strength of rock excavation and engineering is significantly impacted by the presence of cracks or other discontinuities. Thus, preparing defective rock or rocky-like samples is a major difficulty in rock masses for mechanics testing. The discipline of rock masses mechanics and engineering has found great potential in the use of 3D printing technology in recent years. In order to create rock samples with flaws, traditional test procedures in rock masses mechanics testing are reviewed and discussed in this paper. The use of 3D printing techniques in rock masses mechanics is then discussed from the remaining three angles, based on a thorough study of earlier studies. This comprises one-time printed samples and printed casting molds that are precise. The final one is a printed model, which consists of both large-scale physical models and small-scale businesses samples for mechanical testing. Next, the merits and demerits of utilizing 3D printed specimens in mechanical assessments are examined, along with the accuracy of their replication of actual rock. The samples created using 3D printing technology have special benefits over conventional rock samples that are obtained from the natural world or artificial samples that resemble rocks, such as increased tests repeatability, visualization of the interior structure of the rock, and stress distribution. Thus, the application of 3D printing technology in the subject of mineral mass mechanics has a lot of promise. Nevertheless, there are drawbacks to 3D printing materials as well, namely their current lack of accuracy and robustness. Lastly, a proposal is made for the potential use of the technology for 3D printing in the field of rock mass mechanics study.

III. OBJECTIVES

Printing with 3D technology is a type of manufacturing process using additives that creates tangible, three-dimensional objects from digital information. Using this method, layers of material are printed using a 3D printer until a whole object is produced. The use of 3D printing makes it possible to produce even complex geometries with minimal waste of materials compared to conventional fabrication. The main objective to this present work to investigate the compressive strength, fatigue life, safety factor and natural frequencies of the square block for 3D printing using different materials.

There are following objective of the present work.

1. To calculate alternating stress for different materials used in this work such as Thermoplastic Polyurethane (TPU), Acrylonitrile Butadiene Styrene (ABS), Polyethylene Terephthalate glycol-modified (PETG) and Polylactic Acid (PLA).
2. To create layer wise three dimensional CAD model using ACP (Pre) for FEM analysis.
3. 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.
4. Using a fatigue tool, do fatigue analysis to look at the duration of fatigue and safety factor.
5. To verify the natural frequency using six possible modes by performing the model analysis.
6. Compare the results obtained from the above analysis and validate with the base conditions.

IV. METHODOLOGY

Engineers are using 3D printing to quickly create and refine prototypes, potentially replacing traditional manufacturing methods. This study evaluated a 25 mm square block made of various materials, analyzing its structural integrity, compression, and fatigue. Results revealed deformation, stress levels, material lifespan, and equilibrium frequency.

Table 4.1 Material properties

Property	**TPU**	**ABS**	**PLA**	**PETG**
Density [Kg/m^3]	1660	1040	1290	1290
Coefficient of thermal expansion	11x10^{-6}	72x10^{-6}	27x10^{-6}	68x10^{-6}
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

A. Calculation of Bulk modulus and shear modulus

Bulk modulus:

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

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

Where:
E = Young modulus
K = Bulk Modulus
ν = Poisson’s ratio

Shear modulus:

$$G = \frac{1}{2}\left(\frac{E}{1+\nu}\right)$$

Where:
G = Shear modulus

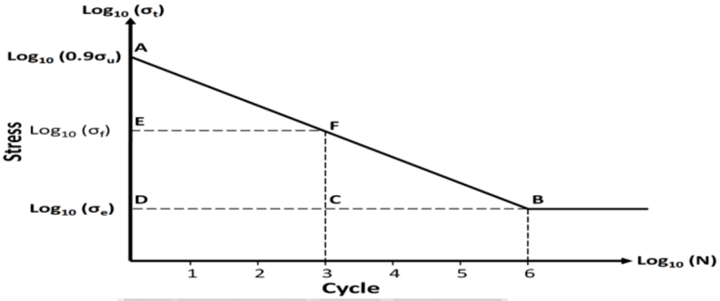

Figure 3: S-N curve

B. Calculation of fatigue strength at different cycle

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

$$\sigma_e = 0.3\sigma_u$$

σ_u for TPU = 86.4 MPa	σ_e for TPU = 25.92 MPa
σ_u for ABS = 26.4 MPa	σ_e for ABS = 7.38 MPa
σ_u for PLA = 47.9 MPa	σ_e for PLA = 14.37 MPa
σ_u for PETG = 45.8 MPa	σ_e for PETG = 13.74 MPa

Table 4.2 Calculation of alternating stress for different materials

Cycle	Log$_{10}$ (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
1E+6	6	28.80	7.38	1.63	1.62

C. Introduction of Finite Element Analysis

Finite element analysis is a tool for solving complex engineering problems by calculating constant values element by element. It helps estimate local effects and mechanical characteristics in models with varied physical attributes, providing precise answers where traditional methods struggle with complex geometry, loads, and material properties.

Structural analysis

Structural analysis assesses the displacements, stress, strain, and forces in a structure under stable load conditions, assuming the load and response vary steadily over time without significant damping or inertia effects.

Modal analysis

Modal analysis identifies a structure's natural frequencies and mode shapes, essential for understanding its vibration behavior and informing further analyses like harmonic response and transient analysis.

$$[M]\{\ddot{u}\} + [C]\{\dot{u}\} + [K]\{u\} = \{f(t)\}$$

Where:
M = Mass of the body
$\ddot{\mu}$ = Acceleration of the body
C = Damping Factor
$\dot{\mu}$ = Velocity of the body
K = Stiffness
u = Displacement
$f(t)$ = Load applied on the object
For Model analysis
$[M]\{\ddot{u}\} + [K]\{u\} = \{0\}$

Fatigue Analysis

Fatigue occurs when a material accumulates damage from repeated loads and strains, leading to failure once damage reaches a critical level or after a set number of load cycles.

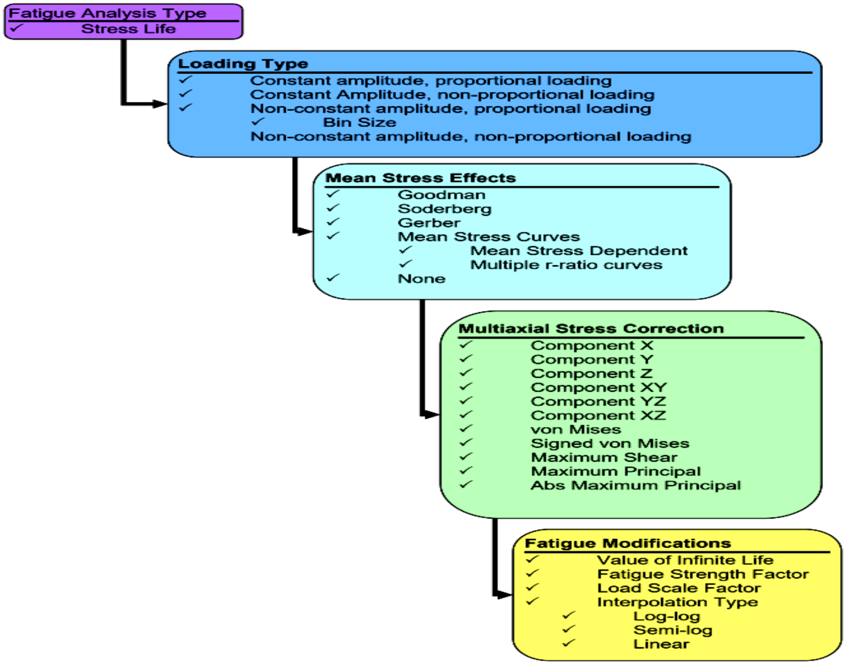

Figure 4 Fatigue analysis type stress life decision tree

Fatigue is the accumulation of damage in a material due to repeated loads and strains, leading to failure after a certain number of cycles. It indicates a component's weakening over time. Fatigue analysis methods include Strain Life, Stress Life, and Fracture Mechanics, with the first two available in the ANSYS Fatigue Module. Strain Life focuses on crack initiation and Low Cycle Fatigue (LCF).

$$\frac{\Delta\varepsilon}{2} = \frac{\sigma_f{}'}{E}\left(2N_f\right)^b + \varepsilon_f{}'\left(2N_f\right)^c$$

Where:
$\frac{\Delta\varepsilon}{2}$ = Total strain amplitude
$\sigma_f{}'$ = Fatigue strength coefficient
E = Elasticity modulus
N_f= The number of failure cycles
b = Fatigue strength exponent (Basquin's exponent)
$\varepsilon_f{}'$= Fatigue ductility coefficient
c = Fatigue ductility exponent
The two cyclic stress-strain parameters are part of the equation below

$$\Delta\varepsilon = \frac{\Delta\sigma}{E} + 2\left(\frac{\Delta\sigma}{K'}\right)^{1/n'}$$

Where:
$\Delta\sigma$ = 2x the stress amplitude
K' = Cyclic strength coefficient
n' = Cyclic strain hardening exponent

Stress Life handles High Cycle Fatigue (HCF) because it is built on S-N curves and has historically dealt with rather high cycle counts.

Mean stress corrections for stress life

Empirical methods like Gerber, Goodman, and Soderberg theories adjust for mean stress in Stress Life analysis using static material properties and S-N data, or by interpolating between material curves.

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

$$Goodman\ Equation = \frac{\sigma_{Alternating}}{S_{Endurance\ limit}} + \frac{\sigma_{mean}}{S_{ultimate\ strength}} = 1$$

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

General Fatigue Results

Fatigue Life: Displays the remaining cycles until failure under constant or varying loads, indicating the lifespan of a part. For example, if a model's life is 24,000 cycles and an hour of loading equals one cycle, the estimated life would be 1,000 days.

Fatigue Damage: Shows damage at a specific design life. If the fatigue damage value is over 1, it indicates failure before the design life ends.

Fatigue Safety Factor: A contour chart showing the safety factor against fatigue failure. Values below 1 indicate failure before the design life ends.

Biaxiality Indication: Measures stress type, where 0 represents uniaxial stress, –1 pure shear, and 1 pure biaxial stress.

Fatigue Sensitivity: Analyzes how loading affects fatigue results in critical areas, with options for different chart scaling (Log-X, Log-Y, Log-Log, or Linear).

D. The different analysis steps involved in FEM analysis

i. **Preprocessor:** In ANSYS preprocessor, the model setup involves building the model (either directly, using CAD, or within ANSYS), defining materials by their constants, and generating an element mesh by discretizing the problem into finite elements, ensuring accurate simulation results.

ii. **Solution Processor:** In this stage, the problem is solved by compiling relevant facts and using the finite element method in ANSYS. The computer calculates the nodal degrees of freedom, which form the main solution output. The process involves applying loads to elements or nodes and obtaining the solution, provided the problem is correctly defined.

iii. **Postprocessor:** The general postprocessor is where the analysis results for the entire model are reviewed. Postprocessors can perform more complex data transformations, such combining load cases, in addition to graphic presentations and tabular listings.

E. The algorithm utilised for structural and fatigue finite element analysis

Figure 5 The algorithm utilised for structural and fatigue finite element analysis

F. Finite element analysis of square block for different materials

i. **CAD modeling of desing-1:** For the creation of square block ACP-pre is use where block has been created by combining two or more layered materials. Layering involves complex definitions that include numerous layers, materials, thicknesses and orientations. The dimensional parameter used to create square block is 25 mm x 25 mm x 25 mmas shown in figure.

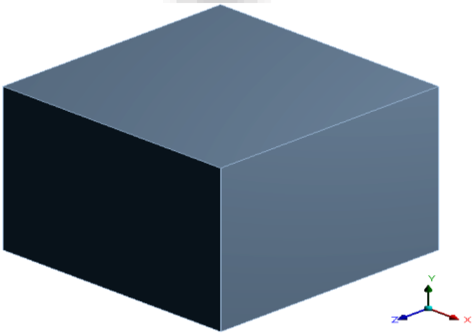

Figure 6 CAD model of square block

ii. **Vertical Layering:** 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. In the present work total 25 layers has been created in five modeling groups per ply having five layers in each group.

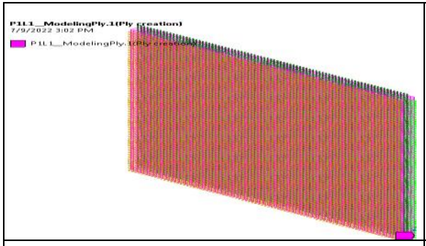

Figure 7 (a): Orientation of vertical layer

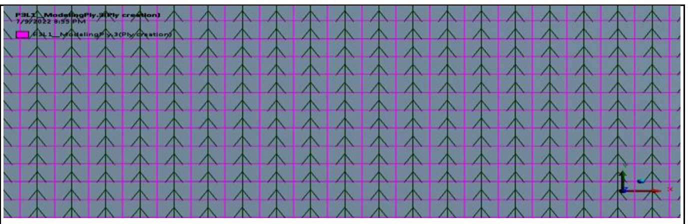

Figure 7 (b): Direction of fibers of vertical layer

- **iii. Horizontal Layering:** 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. In the present work total 25 layers has been created in five modeling groups per ply having five layers in each group.

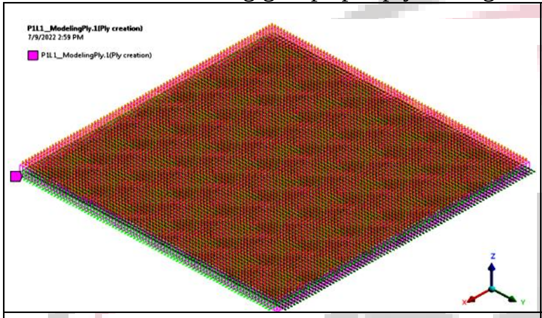

Figure 8 (a):Orientation of horizontal layer

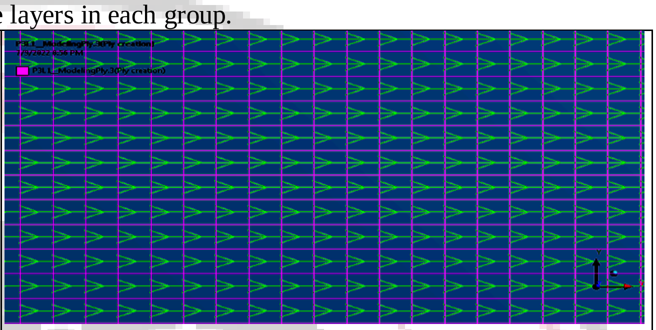

Figure 8 (b): Direction of fibers of horizontal layer

After creation ofmodeling 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.

- **iv. Meshing:** A crucial step in the finite element analysis process is meshing, which divides CAD geometry into a huge number of tiny parts. In the current study, 8424 nodes and 7225 elements with a 1.2 mm element size were formed overall. As seen in the illustration, quadrilateral components have been formed.

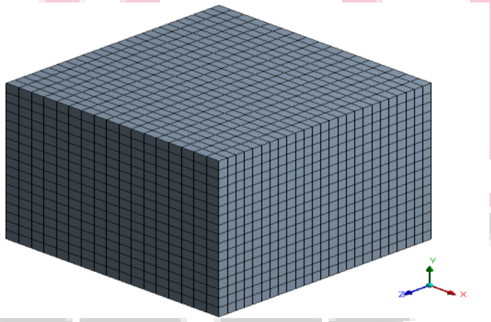

Figure 9 Meshing of square block

- **v. Properties of some 3D printing materials**

Table 4.3 Some properties of 3D printing materials

Parameters	TPU (Thermoplastic Polyurethane)	ABS (Acrylonitrile Butadiene Styrene)	PLA (Polylactic Acid)	PETG (Polyethylene Terephthalate glycol-modified)
Strength of impact	High	High	High	-
Sturdiness	High	High	High	High
Adaptability	Very High	Low	Low	Low
Resistance to chemicals	Medium- High	High	Low	High
Resistance to water	Medium	Medium	Medium	High
Temperature of Nozzle Extruder (°C)	220-250	230-260	190-210	210-250

V. RESULTS AND DISCUSSION

The study involved finite element analysis of a 25 mm³ square block using materials like TPU, ABS, PETG, and PLA. It included static structural analysis for compression, yielding deformation and stress data, fatigue analysis for material durability and safety, and modal analysis for natural frequencies. The block was created with layered materials, had 8,424 nodes and 7,225 quadrilateral elements (1.2 mm size). A compressive force of 12,200 N was applied to the top layer, and fatigue and modal analyses were performed to assess health, safety, and natural frequencies.

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

Table 5.1 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 deformation at vertical loading for PETG [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

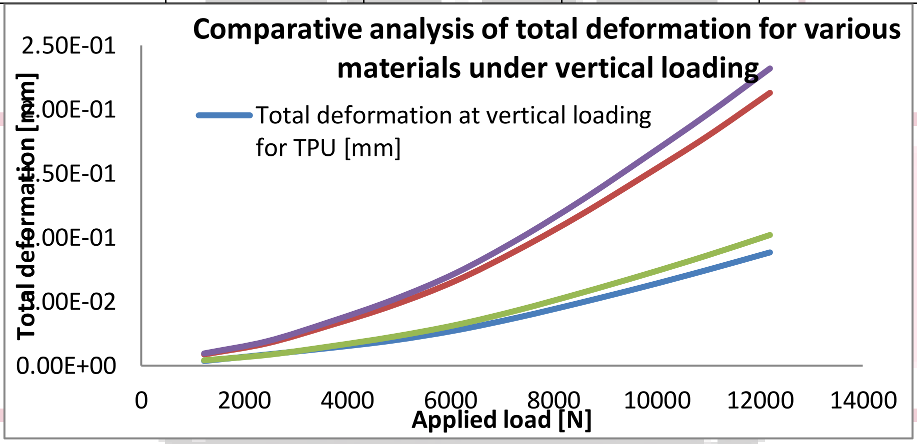

Figure 10 Comparative analysis of total deformation for various materials under vertical loading

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

Table 5.2 Total Deformation of TPU, ABS, PLA, and PETG under Horizontal Loading for Varying Compressive Loads Total

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

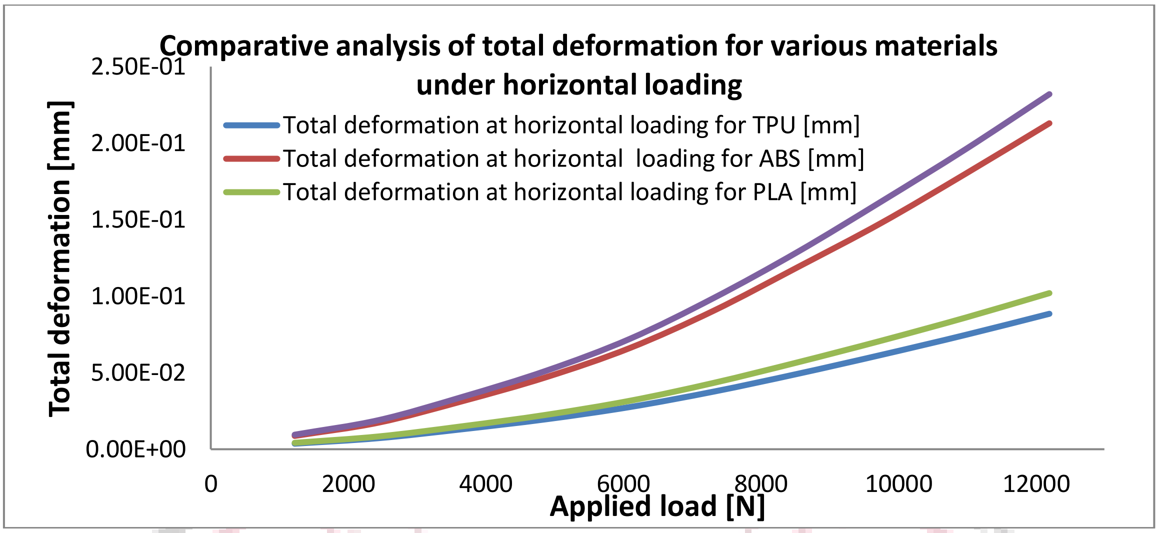

Figure 11 Comparative analysis of total deformation for various materials under horizontal loading

C. Results analysis of Equivalent stress layer wise for different material

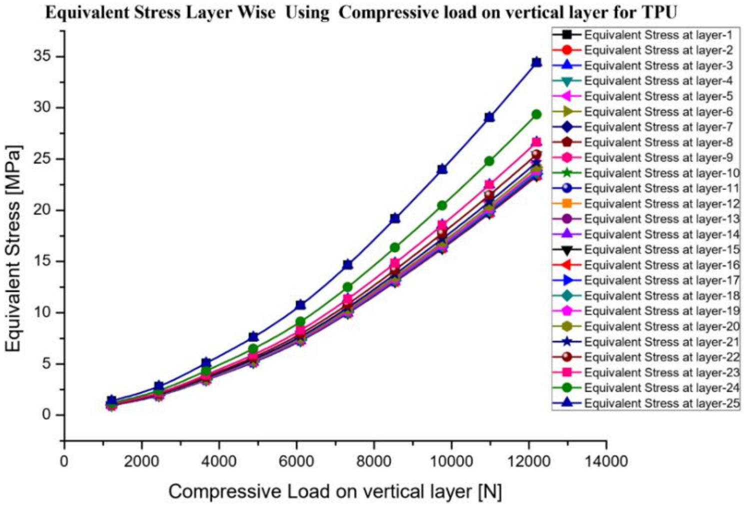

Figure 12 Equivalent stress layer wise using compressive load on vertical layer for TPU

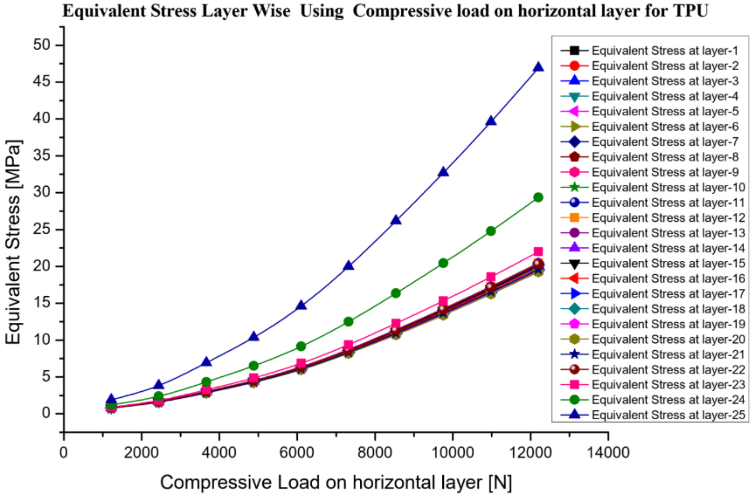

Figure 13 Equivalent stress layer wise using compressive load on horizontal layer for TPU

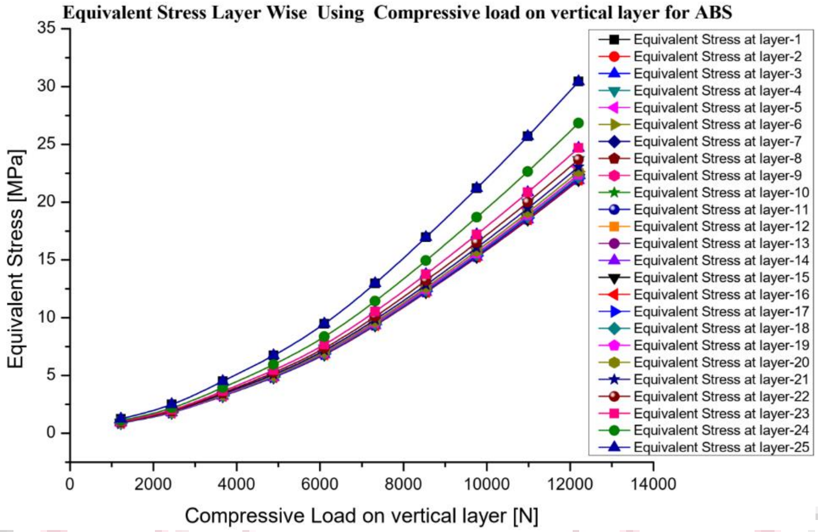

Figure 13 Equivalent stress layer wise using compressive load on vertical layer for ABS

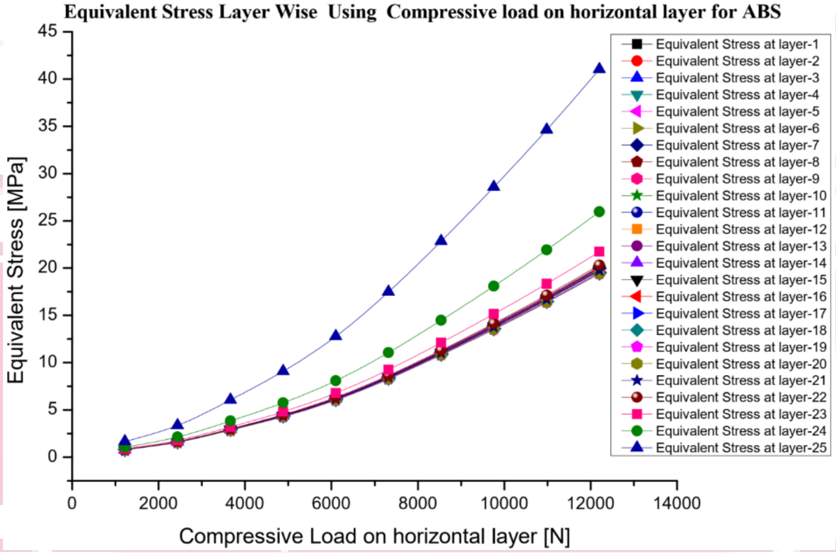

Figure 14 Equivalent stress layer wise using compressive load on horizontal layer for ABS

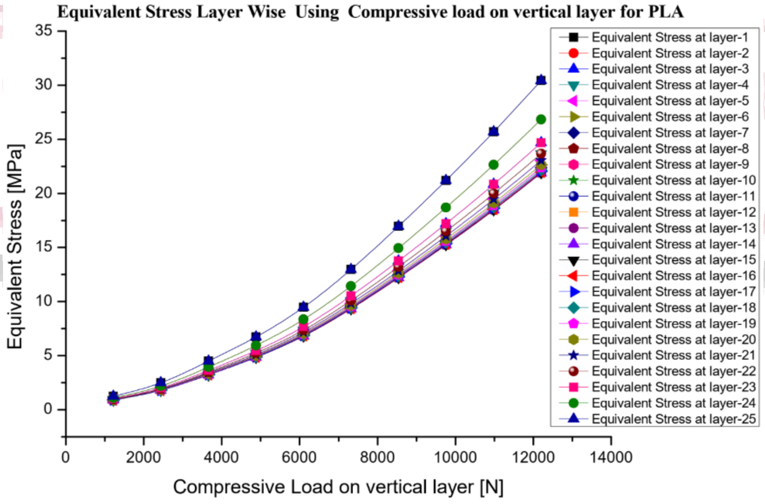

Figure 15 Equivalent stress layer wise using compressive load on vertical layer for PLA

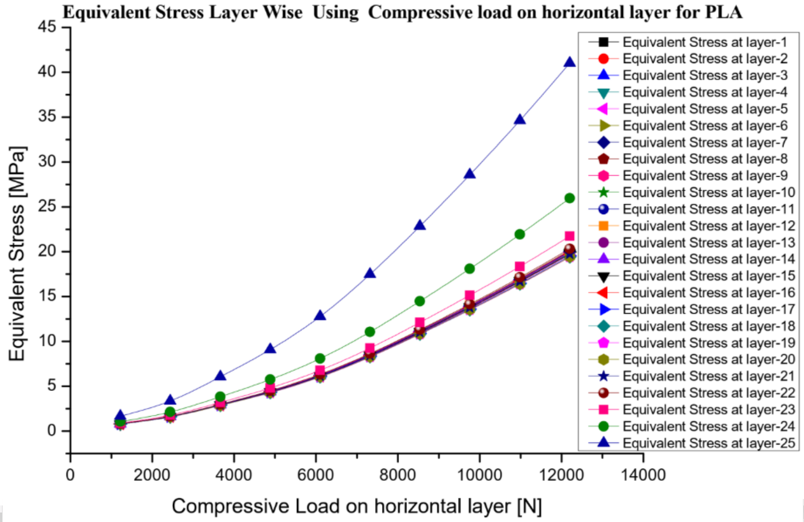

Figure 16 Equivalent stress layer wise using compressive load on horizontal layer for PLA

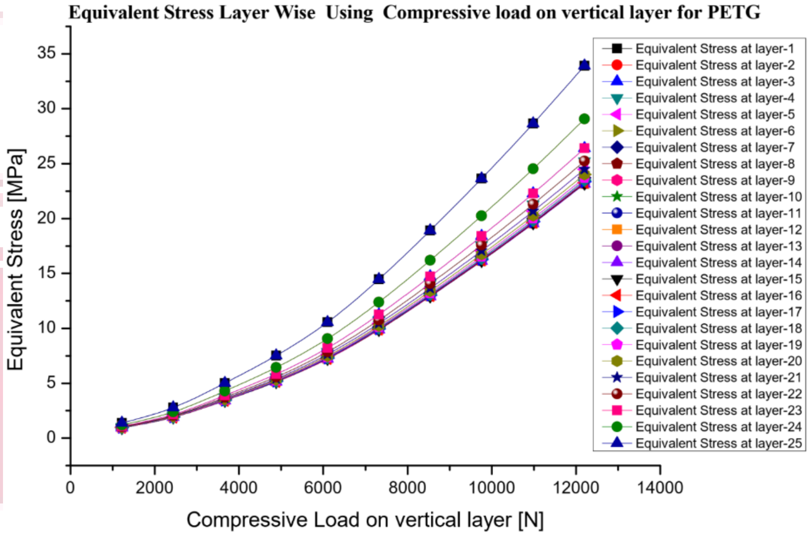

Figure 17 Equivalent stress layer wise using compressive load on vertical layer for PETG

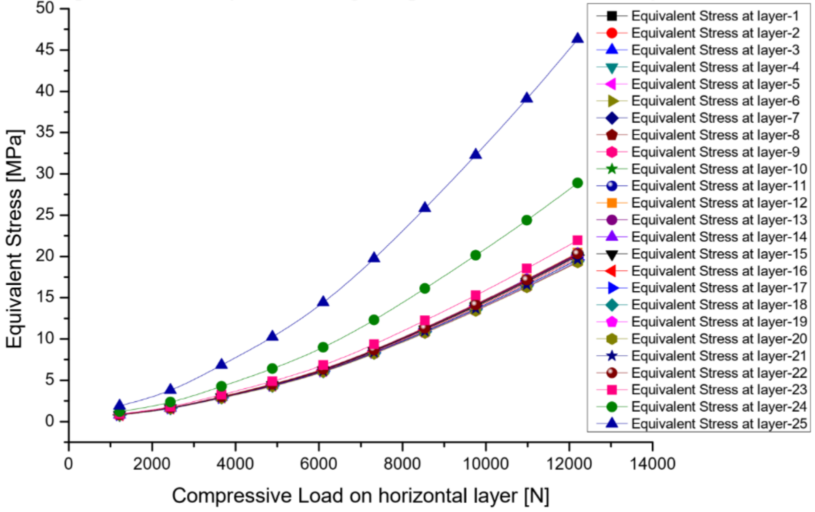

Figure 18 Equivalent stress layer wise using compressive load on horizontal layer for PETG

D. Comparison of maximum equivalent stress for various materials

Table 5.3 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

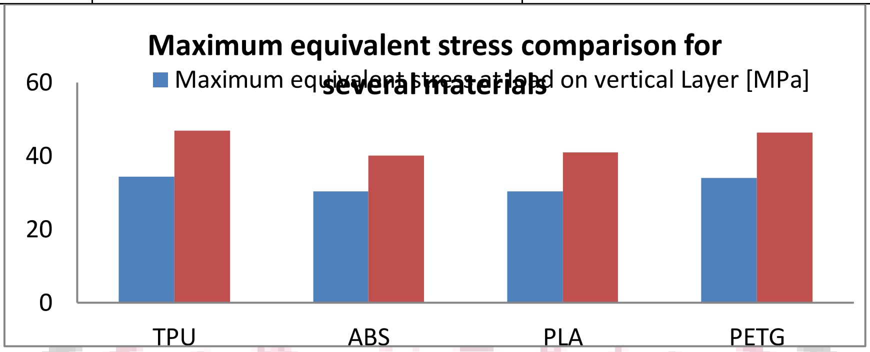

Figure 20 Maximum equivalent stress comparison for several materials

E. Comparison of the fatigue life of various materials

Table 5.4 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

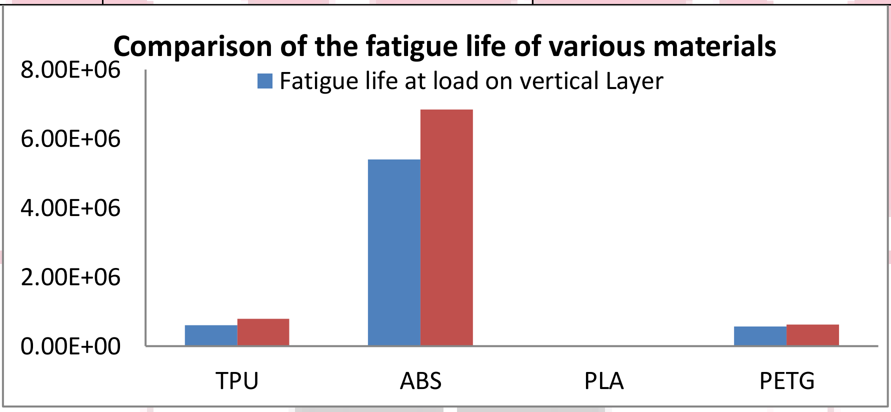

Figure 21 Comparison of the fatigue life of various materials

F. Results of a security factor comparison for different materials

Table 5.5 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

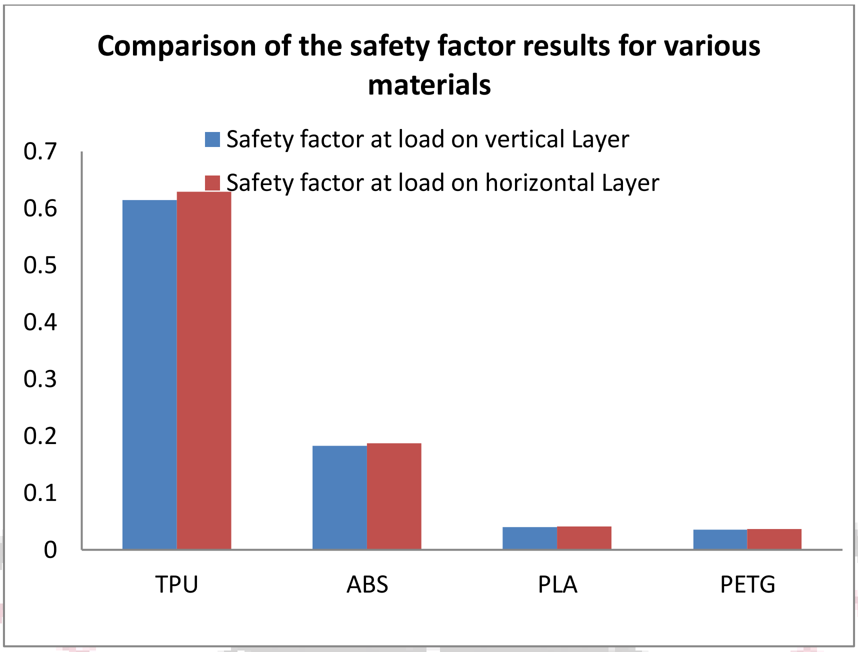

Figure 22 Comparison of the safety factor results for various materials

VI. Conclusion

- 3D printing, or additive manufacturing, has revolutionized the creation of complex and customized objects by building them layer by layer from digital models. Unlike traditional methods, it allows for intricate designs and rapid prototyping across diverse industries including manufacturing, healthcare, and aerospace. The technology encompasses various methods such as Fused Deposition Modeling (FDM), Digital Light Processing (DLP), and Multi Jet Fusion (MJF), each with distinct advantages in terms of resolution, speed, and material properties.
- Finite Element Analysis (FEM) complements 3D printing by providing detailed numerical simulations of complex systems. It breaks down large problems into manageable finite elements, enabling precise predictions of structural behavior, stress, and thermal performance. Together, 3D printing and FEM offer powerful tools for innovation, design optimization, and efficient problem-solving in engineering and manufacturing.

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