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# Design of scaffold with controlled internal architecture using Fused Deposition Modeling (FDM)

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***Abstract*****: *In bone tissue engineering, scaffolds play a vital role in regeneration of tissue. It acts as a template for cell interaction and formation of extracellular matrix to provide structural support to newly formed bone tissues. The scaffold design and manufacturing with additive manufacturing method are still challenging. The parameters of scaffold structure are pore size, pore interconnectivity, porosity, and surface area to volume ratio, strength and stiffness of the material. Among these, porosity is directly influencing stiffness and strength of the structure. Higher porosity can accommodate more number of tissues and interconnected pore allow uniform distribution of cells in the scaffold structure. The objective of this work is to develop scaffold structures with controlled internal architecture using FDM and evaluate the percentage variation in compressive strength and structural modulus of scaffold structures. The internal architecture is controlled by porosity and pore size of scaffold with custom defined tool path of FDM system in pre-processing software. In this work, using the custom defined tool path with minimum slice thickness, the scaffold developed are found with maximum porosity of 82.7% and compressive strength varied from 1.76 MPa to 9.34 MPa and structural modulus of scaffold varied from 52.2 MPa to 212.MPa. These results showed that FDM process is suitable for tissue engineering applications. The material used in this study is ABS, which is biocompatible.***

***Keywords: Scaffold, FDM, cortical bone, implants, porous structure.***

## I. INTRODUCTION

Artificial implants are widely used to restore the functionality of damaged bones to overcome the limitations of natural bone grafting. The artificial implants are made of synthetic materials. Usually, the presence of implants inside the biological system create problems such as aseptic loosening and stress shielding between the implant and natural bone due to mismatch of the stiffness of materials. This leads to the second surgical procedure for the patients. To overcome these problems, researchers are focusing on tissue engineering (TE). It is an interdisciplinary field that combines the knowledge of engineering material and cells to regenerate damaged tissue [1].

In bone tissue engineering, scaffold is used to produce patient-specific biological substitutes to regenerate damaged bone tissue. The scaffold is a 3D porous structure, act as template or carrier to regenerate new tissue. It should satisfy the mechanical and biological properties such as pore size, shape, porosity, surface area, stiffness and strength of biomaterial [2, 3].

The scaffolds are fabricated using conventional techniques such as solvent-leaching, gas foaming, and fiber bonding. Lack of mechanical strength and uniformity in the distribution of pore in these methods qualify these conventional techniques not suitable for bone scaffold [4].

In the scaffold guided bone tissue engineering, 3D porous structures are used to fill the cavity in case of disease or large segmental fracture [5]. The regeneration of tissue in scaffold depends on internal architecture, shape and size of the replacement site, scaffold material and manufacturing method [6].The scaffold should be 3D and porous with interconnected pore network to transport nutrients to develop vascular structure and transport metabolism activities [7, 8].The scaffold structure should have adequate mechanical strength and stiffness, particularly for the reconstruction of load-bearing bone [9].

In the last decades, rapid prototyping techniques are used to manufacture 3D porous structure with interconnected pores for tissue engineering applications [10]. Several researchers are working on the scaffold structure to develop simplified internal architecture, functionally equivalent to the bone in porosity, density, stiffness, and strength [11]. To achieve this, scaffold are designed using periodic porous unit cells in three directions and evaluated mechanical stability using finite element analysis. But, they lack to meet the natural bone architecture [12].

The Rapid Prototyping technology potentially involved to manufacturing of tissue scaffold [13]. The basic principle of rapid prototyping is layer by layer manufacture of 3D object from virtual model information [14]. The 3D model of the component is imported into pre-processing software and sliced into 2D layers of the same height. Each 2D layer is built sequentially on the build platform. Though many methods are available, customization of scaffold architecture by satisfying mechanical and biological requirements still remain as a challenge [15].

Fused Deposition Modelling (FDM) is one of the commonly available rapid prototyping systems. In this, the focus is mainly on the external architecture. The software of the FDM system designs the support structure automatically.

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The user does not have control over the internal architecture and RP parameters, normally. In this work, the RP parameters are modified to create different internal architecture. The modified process flow of FDM process is shown in Fig. 1.

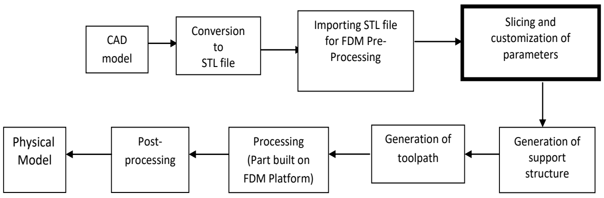



**Fig. 1. Process flow of FDM System**

The prepared CAD model is converted into STL format using the geometric modelling software. This STL file is imported to the pre-processing software of the FDM system. The build orientation of the model and the machine specific parameters are specified to prepare layer (slice) modelling. In addition to this, the air gap, number of layers per unit block, selected tool tip, road width and selected laydown pattern are also specified in the system using customization of tool path. The layering (slicing) model is prepared by the software. Then the support material model is developed along with the tool path. On acceptance of these models, the processing starts and the FDM model is prepared. The post processing is done to remove the support material from the physical model of the scaffold [16, 17].

The aim of this study is to prepare a layer block with different calculated porosities by varying the FDM process parameters. The porosities of the manufactured layer blocks are measured and verified. Suitable model process parameters are identified and used to model sample mid-diaphysis of femur bone model. The models are checked for porosity. Compression test is performed for 10 % compression of these models along the longitudinal axis to find the structural strength.

## II. DESIGN OF TISSUE SCAFFOLD

### A. Layer block of virtual model

In this work, the scaffold is printed using Stratasys® 3D printer (Model - Fortus360mc) with porosity controlled internal architecture. Initially, a typical rectangular prism of size 32.0 mm × 25.5 mm × 13.5 mm is modeled using CATIA [10]. It is converted into STL file format and exported into pre-processing software (Insight®) in the FDM system. The virtual model was oriented horizontally and sliced for T10 tip (nozzle) having a slice thickness of 0.127mm. The internal architecture of honeycomb pattern with controlled pore size and geometry are designed using FDM system parameters such as slice thickness, road width, air gap between roads, and raster angle. Four different raster laydown patterns viz. $0/90^0$, $0/60/120^0$, $0/45/90^0$ and $0/45/90/135^0$ are designed with minimum slice thickness (0.127 mm), raster width (0.2032 mm) and a maximum air gap between roads (1.27 mm). The schematic diagram of laydown pattern of layer-blocks (building) are shown in Fig. 2 (a) to (d). The required number of layers are used to create these laydown patterns. Each pattern are in different shapes. The calculated parameters and porosity are given in Table- I.

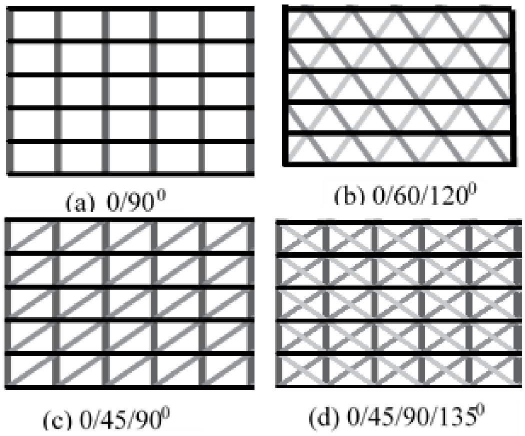
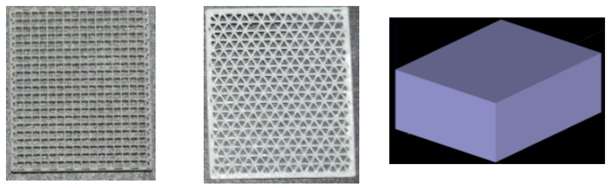



**Fig. 2. Schematic diagram of Laydown pattern**

In the pre-processing stage, the internal architecture design parameters are defined for each layer or unit pattern and saved as a custom group. The software generates the required support structures along with 2D layer information. The scaffolds is built in the FDM platform, and sent to post-processing to remove the support structure of water soluble SR30 material, which is supplied by the Stratasys® for FDM system.

The porosities of the four manufactured scaffolds were found to check whether the prepared scaffolds are within the specified porosity. The representative models of layer blocks with 0 / 900 laydown pattern and 0 / 60/1200 laydown patterns developed using FDM was shown in Fig. 3(a) and (b). A representative layer block developed using 0 / 900 laydown pattern is shown in Fig. 3(c).



a) Square pore ($0/90^0$) b) Triangular pore ($0/60/120^0$) c) CAD Model

**Fig. 3. Representative Layer blocks developed using FDM**

**Table – I: Calculated Porosity of scaffold using unit cube method**

| Layer -block | Laydown pattern | Road diameter (mm) | Area of cross-section ($mm^2$) | Road length (mm) | Volume of road ($mm^3$) | Apparent volume ($mm^3$) | Porosity (%) |
|---|---|---|---|---|---|---|---|
| 1 | $0/90^0$ | 0.2032 | 0.0352 | 994.5 | 35.01 | 207.26 | 83.11 |
| 2 | $0/60/120^0$ | | | 1810.5 | 63.73 | 310.90 | 79.50 |
| 3 | $0/45/90^0$ | | | 2805.0 | 98.74 | 310.90 | 68.24 |
| 4 | $0/45/90/135^0$ | | | 3570.0 | 125.66 | 414.53 | 69.69 |

## III. ASSESSMENT OF POROSITY

Porosity affects both the structure and nutrient flow performance of scaffold. The porosity is defined as the ratio between void volume to the apparent volume of the scaffold structure. The porosity of porous structure is assessed by various approaches such as unit cube, mass technique, relative density method, Archimedes method, microscopic and SEM analysis [18]. In the present work, unit cube method and relative density method are used to analyse and verify the porosity of the developed scaffold.

### A. *Porosity calculation using unit cube method*

The calculation of porosity using unit cube method is done as the ratio between total volumes of porous scaffold structure (Vroad) to the apparent volume of porous structures (Vapp) [19, 20]. It is expressed as follows.

$$p\ (\%) = (1 – (V_{road} / V_{app})) \times 100 \qquad …(1)$$

The total volume of the scaffold material is calculated from the known deposition pattern. This approach is adopted for the calculation of porosity of regular honeycombed scaffold fabrication, with the assumption that, scaffold struts are uniform and the layers formed do not fuse into the other. In this, strut diameter and layer spacing are considered to be equal and consistent. After modeling the scaffold, porosity of the scaffold is calculated using this method.

### B. *Porosity calculation using relative density method*

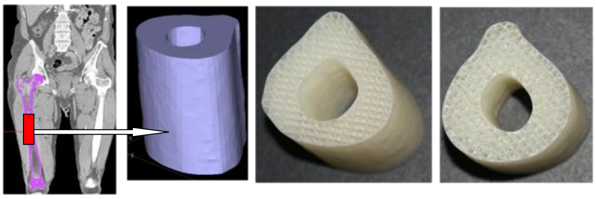
The relative density is defined as the ratio between the density of the scaffold structure (ρ*) to the density of the scaffold material (ρs) [19, 20]. It is expressed as follows.

$$p\ (\%) = (1-(\rho^*/\rho_s)) \times 100 \qquad …(2)$$

The density of porous scaffold is calculated as the ratio between the mass of tissue scaffold to the apparent volume of the scaffold. The material density of ABS is taken as 1.05 gm/cm3 from the catalog of Stratasy®, USA. The porosity of the manufactured scaffold is measured using this method for verification.

## IV. DESIGN AND MANUFACTURING OF SCAFFOLD FOR MID-DIAPHYSIS OF A HUMAN FEMUR

In this study, the 3D model of a segment of mid-diaphysis of the human femur (cortical bone) is reconstructed from CT images (source: SRM Hospital and Research Centre) using Mimics® (Materialise interactive medical image control system, Materialise Inc., Belgium) software and saved in STL file format. Then, STL file is imported into the FDM system for preprocessing. The scaffold is designed and manufactured with the same method used for layer block. A few fabricated femur bone samples are shown in Fig. 4. It has an irregular outer shape. The overall dimensions are 26.7 mm outer diameter, 11.5 mm of inner diameter with a cortical thickness of 6 to 7 mm. It is modeled and manufactured with 30 mm length / height. The apparent volume of the femur bone measured from STL file is 13833 $mm^3$. The porosity of the femur bone scaffold is calculated using the relative density method for square ($0/90^0$) and triangular ($0/60/120^0$) pore geometry as 82.17% and 82.37% respectively. This is the maximum porosity obtained for these two laydown patterns using FDM. So, porosities which are less than this for the scaffold can be manufactured by controlling the road diameter and air gap. The calculated mechanical properties are given in Table II.



CT-image segmented using MIMICS® | Femur bone mid-diaphysis model | FDM Scaffold ($0/90^0$) | FDM Scaffold ($0/60/120^0$)

**Fig. 4. FDM scaffold for femur bone Mid-diaphysis segment**

**Table – II: Calculation of mechanical properties of femur bone scaffold**

| Laydown pattern | Apparent Volume ($cm^3$) | Scaffold Weight (g) | Density of scaffold ($g/cm^3$) | Porosity (%) | Compressive strength (MPa) | Structural Modulus (MPa) |
|---|---|---|---|---|---|---|
| $0/90^0$ | 13.83 | 2.590 | 0.187 | 82.17 | 2.50 | 57.20 |
| $0/60/120^0$ | | 2.561 | 0.185 | 82.37 | 1.76 | 29.90 |
| $0/45/90^0$ | | 4.988 | 0.361 | 65.66 | 9.35 | 149.75 |
| $0/45/90/135^0$ | | 5.460 | 0.395 | 62.41 | 7.35 | 212.21 |

## V. MECHANICAL TESTING OF BONE SCAFFOLD

### A. Compression Testing

The compression test is performed using Universal Testing Machine (TUE CN-200) on the scaffolds. The compressive load and displacement are recorded. The test is performed upto 3 mm compression (10%) of the total height of specimen. The cress-head travel rate was controlled with 0.3 mm/min. The compressive strength of the scaffolds is calculated from the linear slope of the stress-strain curve. A representative stress-strain curve plot is shown in Fig.5.

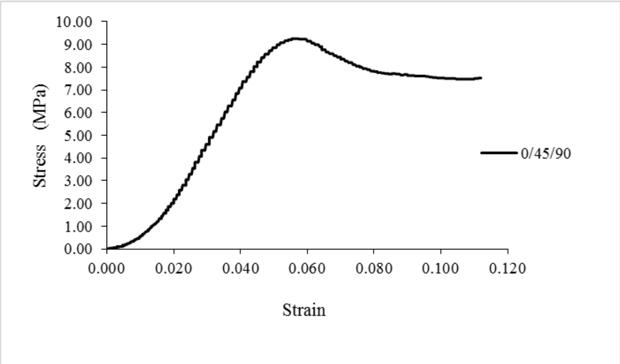



**Fig. 5 Stress-strain curve for $0/45/90^0$ laydown pattern of scaffold**

## VI. RESULT AND DISCUSSION

In the present work, the layer blocks are manufactured using T10-tip with minimum slice thickness and maximum air gap between roads using FDM-Fortus-360mc rapid prototyping machine. The porosity of the layer blocks are calculated and found maximum of 83.1 % for the $0/90^0$ laydown pattern. It is closely followed by $0/60/120^0$ pattern at 79.5 %. In FDM system, the layer thickness depends on tooltip size. These square and triangular pore sizes are controlled 1250 µm, which is in good agreement with the earlier results obtained by the researchers [10, 20]. The compressive strength of femur bone mid-segment scaffold is varying from 1.756 to 9.385 MPa the compressive strength predicted in this study is comparable with literature [20] scaffold modeled using ABS material. The structural modulus was computed in this work varies from 29.90 to 212.21 MPa. These results are in good agreement with literature, i.e., 81.2 % porosity model developed with ABS Materials [19]. In four layer model, the porosity is slightly low compared to three layer $0/45/90^0$ model. But the structural strength is higher in the four layer model. So, in general, as the layer increases the porosity decreases and the compressive strength and structural modulus are increases. These results are comparable with previous study found in the mechanical properties of scaffold developed with ABS material [19]. As per the literature, the compressive strength of human femur bones varies between 112 MPa and 205 MPa, [21], whereas the compressive strength for trabecular bone ranges between 3.21 MPa to 17.5 MPa [22]. Hence, the scaffold manufactured using ABS material with large pore size is suitable for bone tissue regeneration and no difference found in cell growth of PLA according to the literature [20]. So, these scaffold may be suitable for soft tissue regeneration in terms of mechanical properties.

## VII. CONCLUSION

In this work, the FDM - Fourtus360mc system is used to manufacture bone tissue scaffolds with controlled internal architecture. The layer blocks are developed with minimum layer thickness and maximum porosity of scaffold and adopted for human femur bone mid-diaphysis segment. It is concluded that,

- The compressive strength indicates that it depends on road width and the air gap between raster regardless of the lay-down pattern. It is comparable with theory.
- The laydown pattern mainly influences the structural modulus of the scaffold. In this study, $0/45/90/135^0$ laydown pattern results high structural modulus.
- This study gives a confidence to use FDM-Fortus 360mc system for scaffold design and manufacture for tissue engineering applications.
- This study helps to design and optimize scaffold internal architecture in multi-scale models.
- There is a possibility for un-dissolved water soluble support structure inside the micro pore. It might reduce the porosity, whenever the pore size decreases.
- Further study is required for the characterization of the scaffold to explore the morphology at microscale level.

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