DESIGN AND MANUFACTURING OF A SCAFFOLD FOR BIOMEDICAL APPLICATIONS USING ADDITIVE MANUFACTURING

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ABSTRACT

The injury caused by trauma, burns, or disease often results in soft tissue getting damaged which leads to improper function and permanent destruction in human body. For regeneration of damaged tissue, temporary structures are required to guide the growth of new tissue. These structures are known as scaffolds. Scaffold must provide temporary mechanical function within a tissue defect during tissue regeneration.The scaffolds have three-dimensional porous structures. This porous scaffold with interconnected network is needed to guide cell attachment and growth. Additive Manufacturing or popularly known as 3D Printing is an innovative technology that allows complex physical prototypes to be directly constructed from 3D-CAD model. It is widely used in many applications including in medical applications such as tissue engineering. The aim of this research work is to design and fabricate a bio medical scaffold for soft tissue using FDM 3D printing technology that helps to improve the growth of new tissue. The tissue considered in this work is soft tissue i.e. human skin.

KEYWORDS: Scaffold, Tissue Engineering, Additive, Manufacturing, Fused Deposition Modeling

Tissue engineering is an emerging area of science. It's a novel, interdisciplinary field that combines basic principles of engineering and biology in order to replace or improve biological functions. Referring to clinical applications, the most important goal of tissue engineering is to overcome the numerous limitations of current treatments that are based on organ transplantation and biomaterial implantation. Tissue Engineering involves basically three elements: scaffolds, cells and biomolecules. Therefore, it is necessary to carefully choose which combination better fits for the desired application [1].Tissue engineering uses support structures or scaffolds for regeneration of tissue.The scaffold should contain interconnected holes to satisfy required porosity level. Porosity is an essential parameter to ensure sufficient supply of nutrients and metabolites. The design of the scaffold plays an important role in maintaining the strength of the scaffold. CAD software is used to create many such porous structure models with different pore size. The scaffold is required to be designed for mechanical capacity. The material selection depends upon the closeness to the properties of soft tissue i.e. human skin. For any bio compactable material to act as a good scaffolding material, the properties of the scaffold implant material should be same as that of the natural tissue.

LITERATURE REVIEW

Antreas Kantaros et.al [2] in his work fabricate a cubic specimen of 35 mm × 35 mm × 35 mm (width ×height× length) using P430 ABS material. Saito E et.al [3] explained the need for soft tissue scaffolds with controlled porosity and mechanical properties. They developed a wavy fiber scaffold design, also fabricated these complex scaffold architectures from the biodegradable polymer polycaprolactone (PCL). These scaffolds have tightly controlled porosity, yet exhibit a controlled range of moduli and yield strains that fall within reported values for many soft tissues. Derek H. Rosenzweig et.al [4] compared the fabrication of large-pore 3D-printed acrylonitrile butadiene styrene (ABS) and polylactic acid (PLA) scaffolds for cell in growth, viability, and tissue generation.

PROBLEM DEFINITION

The aim of this research work is to design and fabricate bio medical scaffold for soft tissue using Fused Deposition Modelling (FDM) Additive Manufacturing (AM) process. Following are the objectives of the current study:

- To develop 3D CAD model of the scaffold structures
- Finite Element Analysis of modeled scaffold structures
- Calculation of porosity of modeled scaffold structures
- Fabrication of scaffold using FDM Additive Manufacturing Process.
- Conducting compression test on UTM (Universal Testing Machine)
- Validation of FEA results with compression test

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RESEARCH METHODOLOGY

The various steps involved in solving the problem discussed in the earlier section are, creating 3D CAD model of the bio medical scaffold in Rhinoceros 5, importing the 3D CAD model into Solid work Simulation software (Version 15) for performing Finite Element Analysis and finally validating the results by performing compression test on UTM

Modeling of Scaffold Structures

To create a 3 D model of the bio medical scaffold for soft tissue, the dimension are taken from the literature [2]. Using these dimensions, by changing the structure of the unit cell for the same outer dimensions two models of the bio medical scaffold for the soft tissue were created in Rhinoceros version 5 software. Fig 1 illustrates the first model (M1) i.e. having unit cell structure as cylindrical rod inner sphere, while Fig.2 illustrates the second model (M2) having unit cell structure as Solid Sphere Interconnected Rod.

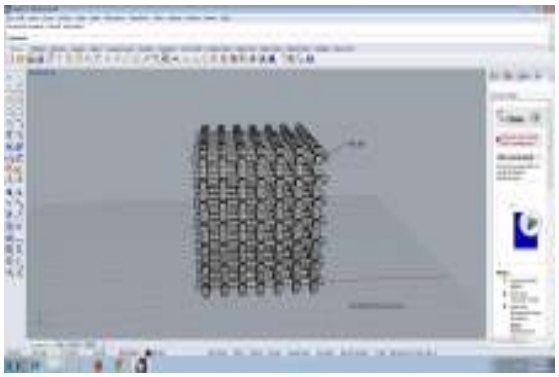

Figure 1: Cylindrical Rod Inner sphere scaffold Structure (Model M1)

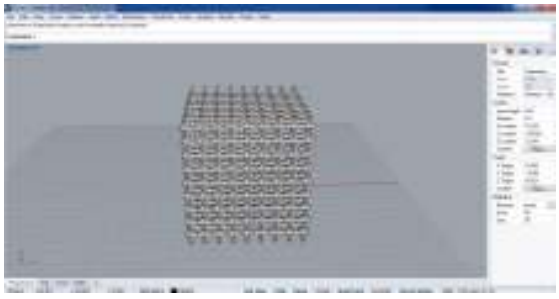

Figure 2: Solid Sphere Interconnected Rod

Finite Element Analysis of Modeled Bio Medical Scaffolds

The 3D CAD model of the implant was saved in Rhino software in .stp format and then it was imported into solidwork simulation v15 software for Finite Element Analysis. The analysis type was selected as static structural. The next steps involves meshing the 3D model and followed by applying boundary conditions. The material selected for Finite Element Analysis was Polylatic Acid (PLA) and Acrylonitrile Butadiene Styrene Poly carbonate (ABS PC). The density of ABS PC is 1.07g/cm^3 and PLA 1.25 g/cm^3.

Fig 3 illustrates boundary conditions applied on cylindrical rod inner sphere scaffold structure with bottom end fixed (green colour) and top end subjected (pink colour) to a uniform distributed load.

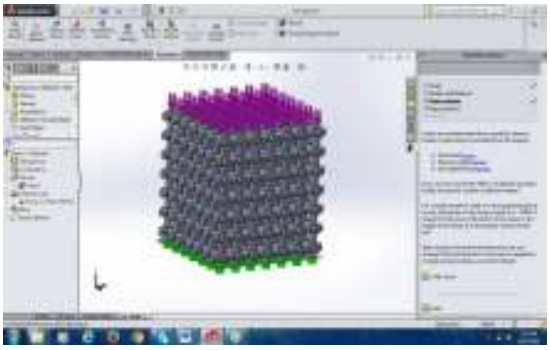

Figure 3: Boundary Conditions applied to Model M1 scaffold structure

Fig 4 illustrates meshed view of Model M1 scaffold, having 2,42,774 nodes and 1,42,799 elements.

Figure 4: Meshed view of Model M1 scaffold structure

Similarly the boundary condition and loads were applied to the Model (M2) of the scaffold structure. In case of the solid sphere interconnected rod i.e. Model M2 the number of nodes are 5,69,263 and the number of elements are 3,32,711 and the type of element selected for both models is Tetra4 because of the complexity of the structure and reducing the computational time. Fig.5 and Fig.6 illustrates the boundary condition and meshed view of Model M2 of the scaffold structure.

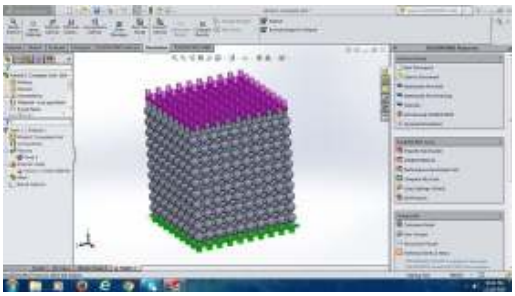

Figure 5: Boundary Conditions applied to Model M1 scaffold structure

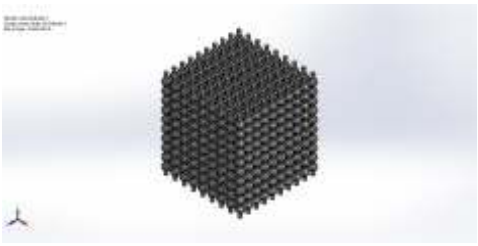

Figure 6: Meshed view of Model M2 scaffold structure

For both the type of models i.e. M1 and M2 a uniformly distributed load varying from 1000 N to 4000 N was selected for analysis. Fig. 7 and Fig. 8 illustrate's the total deformation and the von mises stress developed due to a load of 1000 N for ABS material respectively.

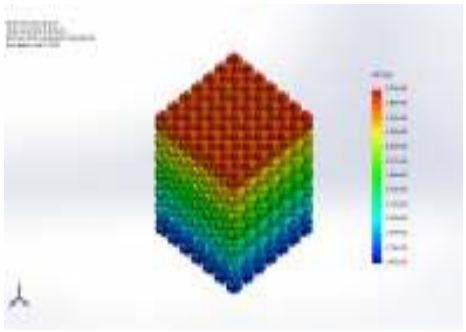

Figure 7: Deformation of Model M1 Scaffold structure made with ABS PC

Material for uniformly distributed load of 1000N

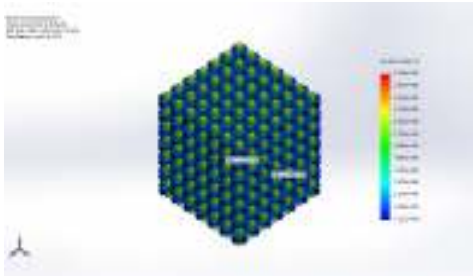

Figure 8: Von misses Stress distribution on Model M1 Scaffold Structure

made with ABS material for a uniformly distributed load of 1000N

Fig. 9 and Fig.10 illustrates the total deformation and Von Mises stress distribution due to a load of 1000 N for PLA material.

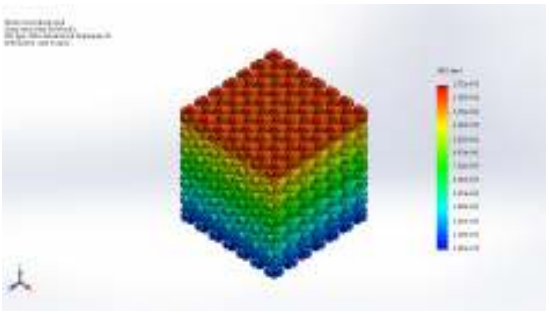

Figure 9: Deformation of Model M1 Scaffold structure made with PLA

material for uniformly distributed load of 1000N

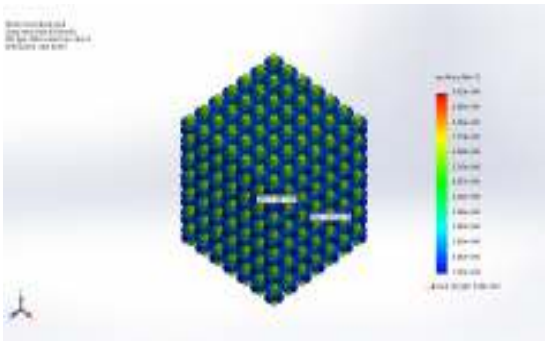

Figure 10: Von misses Stress distribution on Model M1 Scaffold Structure

made with PLA material for a uniformly distributed load of 1000N

Similarly analysis is carried out for Model M2 scaffold structure made with PLA and ABS material.

Porosity Calculations for Scaffolds Modeled

Porosity of biomedical scaffolds was calculated by gravimetric method given by Hua-Mo Yin [6].

$$\text{Porosity} = [1 - (\rho / \rho_c)] \times 100\ \% \qquad (1)$$

Where ρ is the apparent density of the scaffold and is defined as the mass divided by the volume of porous scaffolds, while ρ_c represents the density of compact scaffold structure. The density of the ABS PC is 1.07 g/cm^3 and the density of PLA is 1.27 g/cm^3.

Sample porosity calculations for PLA material for Model M1 scaffold structure is shown below.

Mass of cylindrical rod inner scaffold = 0.013 g

Volume = 0.125 cm^3 from CAD model developed

ρ = (mass / volume) = (0.013/0.125) = 0.104 g/cm^3

ρ_c= 1.27g/cm^3

Porosity = [1- (ρ / ρ_c)] x 100 %

= [1- (0.104/1.27)] = 91.1 %

Table 1 and Table 2 illustrates the porosity values obtained for PLA and ABS PC Scaffold Structures for both the models.

Table 1: Calculated porosity of PLA biomedical Scaffolds

Scaffold Model	Porosity
Cylindrical rod inner sphere (M1)	91.1%
Solid sphere interconnected rods (M2)	75.5%

Table 2: Porosity values of ABS PC biomedical Scaffolds

Scaffold Model	Porosity
Cylindrical rod inner sphere (M1)	90.3 %
Solid sphere interconnected rods (M2)	75 %

Fabrication of Biomedical Scaffold

After FEA and porosity calculations, the 3D CAD model of the two scaffold structures is saved in .STL file format in rhino software and then imported into Solidworks software version 15. It is then, again saved in Solidworks software as .STL file format with fine resolution. It is then imported to flash print software for positioning the model before it is uploaded into a 3D printing machine i.e. flashforge finder. Flash forge finder uses Fused Deposition Modelling (FDM) additive manufacturing process. Fig. 11 illustrates the Scaffold structure in flash print software.

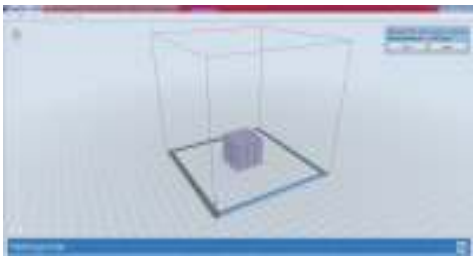

Figure 11: Scaffold structure in flash print software

Fig 12 and 13 illustrates the model of the cylindrical rod inner sphere scaffold structure(Model M1) and Solid Sphere Interconnected Rod (Model M2) respectively fabricated on Flash Forge printer.

Figure 12: Fabricated model of cylindrical rod inner sphere scaffold structure

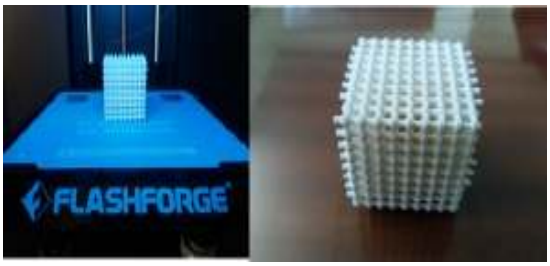

Figure 13: Fabricated model of Solid Sphere Interconnected Rod

Compression Test on Biomedical Scaffold

After fabrication of Bio Medical scaffold, Compression test was done on Universal Testing Machine (UTM) for PLA material. Fig 14 shows the shape of the cylindrical rod inner sphere scaffold structure before and after the compression test.

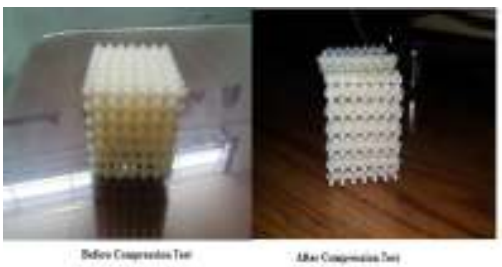

Figure 14: Shape of Model 1 scaffold structure before and after the compression test

Similarly Fig.15 illustrates the shape of the Model 2 scaffold structure before and after the compression test

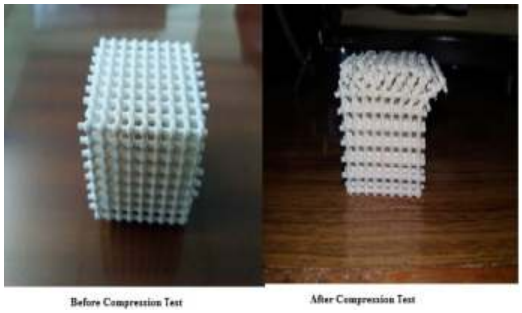

Fig.15: Shape of Model 2 scaffold structure before and after the compression test

RESULTS AND DISCUSSION

Table 3 and Table 4 illustrates the results obtained from FEA for different bio medical scaffolds made with ABS PC and PLA material.

Table 3: Von mises stress and displacement values of bio medical scaffold made with ABS PC material

Scaffold Models	Load (N)	Von Mises Stress (MPa)	Displacement (mm)
Cylindrical rod inner sphere	1000	9.7	0.15
	2000	19.4	0.31
	3000	29.2	0.47
	4000	38.2	0.63
	4500	43.8	0.71
Solid sphere interconnected rod	1000	9.9	0.13
	2000	19.9	0.27
	3000	28.89	0.41
	4000	39.85	0.55
	4500	49.8	**0.69**

From the above results it can be seen that the failure of ABSPC scaffold takes place at a load of 4500 N i.e. stresses developed for both models i.e M1 and M2 of scaffold structure are 43.8 MPa and 49.8 MPa which is exceeding the allowable stress of ABS PC material i.e. 40 MPa.

Table 4: Von mises stress and displacement values of bio medical scaffold made with PLA material

Scaffold Models	Load (N)	Von Mises Stress (MPa)	Displacement (mm)
Cylindrical rod inner sphere	1000	9.8	0.15
	2000	19.6	0.30
	3000	29.4	0.45
	4000	39.2	0.60
	5000	49.1	0.76
	6000	58.9	0.90
Solid sphere interconnected rod	1000	9.79	0.09
	2000	19.58	0.19
	3000	29.38	0.29
	4000	39.17	0.38
	5000	48.97	0.48
	6000	58.70	0.58

From the above results it can be seen that the failure of PLA scaffold takes place at a load of 6000 N i.e. stresses developed for both models i.e. M1 and M2 of scaffold structure are 58.9 MPa and 58.70 MPa which is exceeding the allowable stress of PLA material i.e 50 MPa.

Validation of FEA Results with Compression Test

Fig 16 illustrates the load versus displacement graph obtained after FEA and compression test for Model M1 scaffold structure made with PLA material.

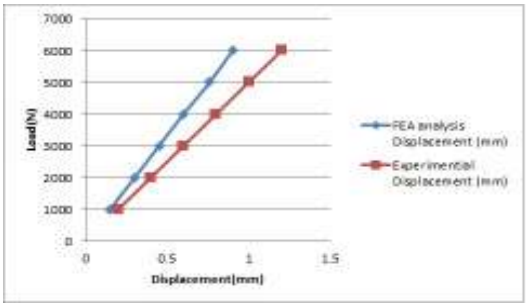

Figure 16: Load versus Displacement graph for Model M1 Scaffold Structure made with PLA by FEA and Compression test

Fig 17 illustrates the load versus displacement graph obtained by FEA and compression test for Model M2 scaffold structure made with PLA material

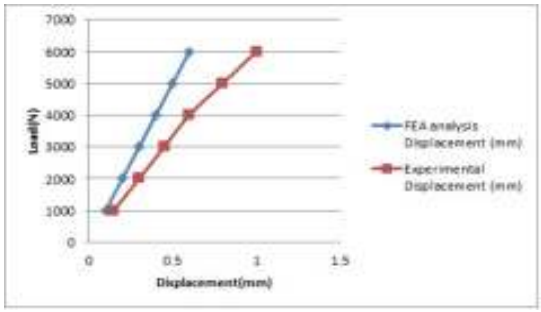

Figure 17: Load versus Displacement graph for Model M2 Scaffold Structure made with PLA by FEA and Compression test

CONCLUSIONS

The aim of this paper was to design and fabricate biomedical scaffolds for soft tissue using FDM 3d printing process. In this paper two scaffold structures were modeled using Rhinoceros Version 5 CAD software and fabricated using Flash Forge FDM 3D printer. From the above results, it can be seen that for Cylindrical rod inner sphere the Maximum vonmises stresses developed before failure for ABS PC and PLA material were found to be 38.2 MPa and 49.1 MPa respectively whereas the porosity values were found to be 91.1% and 90.3%. For Solid sphere inner rod scaffold the vonmises stresses developed before failure for ABS PC and PLA material were found to be 39.85 MPa and 48.97 MPa respectively whereas the porosity values were found to be 91.1% and 75%. Also from the above results it can be seen that for soft tissue Model 2 is performing better than Model 1 in terms stress and displacement. Similarly PLA material is performing better than ABS PC material in terms stress and displacement. The present work can be further extended by developing few more scaffold structures and also by selecting hard tissue for analysis.

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