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Design and development of bio- compatible scaffold with CAD tool and FEA for Additive manufacturing

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Abstract

Tissue engineering is the study of about regeneration of damaged tissue, by applying bio- compatible scaffold which provides required mechanical strength to sustain load of body parts. These scaffold having porosity to reduce the weight of scaffold and allow proliferation of tissue within it. The complex shape scaffold with porosity were very difficult to design and develop. Additive manufacturing technique is used for the fabrication of complex 3D design in layer by layer by using CAD data of 3D design.Additive manufacturing proven its importance in building highly complex part with accuracy in shorter lead time, but it is only restricted to creativity of user in form of CAD data. Modeling of scaffold is very important, because further development process depends upon it . So for ease in modeling of scaffold a unique CAD tool has to developed by using CATIA and VB macros software which generates a particular equation for particular shape scaffold and generalized on standard scaffold as per ASTM standards. Polyamide (nylon), material were used to fabricate standard and customized scaffold in selective laser sintering (SLS) machine.The analysis were done by using ANSYS software,and experimental compression test were done to find mechanical properties. The comparison of result shows the deviation which proves the versatility of the tool.

Key words: Additive manufacturing, Bio- scaffold, CAD, Tissue engineering, Unit block, SLS machine.

Introduction

In tissue engineering it is deals with all possible alternatives to recover damaged tissue or bone by applying bio-compatible scaffold on the damaged part. The bio- compatible scaffold provides cell proliferation with in it when it is seeded with cells. The main aim of scaffold is to provide mechanical strength so that it can sustain load of the part, and to provide bio- chemical condition for cell proliferation and proper tissue formation. The scaffold must be bio- compatible, bio- degradable and non -toxic in nature to the human body. As the bone has complex internal structure ,so scaffold which have to replace damaged part would also have complex structure due to it just looks like the bone structure.

Earlier bio- compatible scaffolds were produced by solvent casting, Thermally induced preparation, fiber bonding technique etc., but there was many limitations of these processes for manufacturing of scaffold and also it takes too much time for manufacturing and also gives less accurate scaffolds. With the invent of Additive manufacturing it become possible to built complex parts in less time and also produces precise and accurate 3D parts. The 3D model of the part is designed by using CAD, after that this CAD file of the design has to be converted into .STL file (Triangulated data) which is accepted by all AM machines for conversion of design into reality.

Additive manufacturing can be used to fabricate scaffold of complex shape but its only restricted to the creativity of CAD designer, because the input data accepted by AM machines is in form of CAD data. And designing of scaffold by CAD is difficult job, so a unique CAD tool will be developed in this project, which simplifies the designing and modeling of scaffold.

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Unit blocks are the architectural building blocks of the scaffold. there are six types of unit blocks based on shape, structure ,porosity and each having different mechanical properties, so the selection of unit blocks is a numerical analysis were done by using ANSYS software to find the theoretical effective stiffness of particular unit blocks, and selection of unit blocks were based on it.once the unit block were selected then the CAD tool is applied on it which generates an equation as per our given input parameters and subject to applied on the standard scaffold model which creates the customized model as per our requirement.

Problem formulation - A No. of literature's survey were studied, and mainly focus were on papers published of last ten years. As per literature's researches , reviews, used technology and future scope suggestion made in research papers some points were high lighten on which work may be done to improve methods by taking some corrective and innovative actions. The points are-

Selection of material - The selection of material for fabrication of scaffold in an important step, because material properties will affects the mechanical properties like, effective stiffness, strength, porosity etc. The selected material should also be bio- compatible and non- toxic in nature. The material should also compatible for selected AM technique. So various related materials like PLA, PA, PEG, PCL, PGA, ABS, PHOH etc. were studied and their properties were summarized by analytic outcomes and the best material with having sufficient strength, porosity, heat resistance capability and of low cost been selected. Based upon our criteria we find Polyamide (PA) best suited for fabrication. It is easily available, low cost and also bio- compatible and non- toxic in nature.

Selection of AM machine - The another issue for optimization is selection of AM technique which is best for part building as per complexity of scaffold, porosity and material acceptability. A no. Of AM technique were surveyed like SLA, FDM, EBM, LOM,SLS etc. Based on their mode of operation, capability of building complex shape in less time. Selective laser sintering (SLS) technique were found best suited to fulfill our criteria.

CAD modeling - The complex shape of scaffold is initially designed by using CAD technique which has to be transferred to AM machine in AM acceptable format for fabrication. Designing of complex shape scaffold were the tough task. Previous literature uses another method for ease is CAD designing like, Lev podshivalov et. al (2013) uses geometric modeling of patient specific Micro- CT images, J.C. Dinis et. al (2014) uses open source software tool for design of scaffold based on triply periodic minimal surface geometrical database. So for better and ease in modeling of scaffold we have to create a unique CAD tool which simplifies the CAD designing. The main aim of this project is to develop CAD tool for easier modeling of complex shape.

CAD- AM interface - The designed model of scaffold has to be converted into the language accepted to AM machine. Generally all AM machines uses .STL file (triangulated data), which creates slices of the 3D object into layers for better inter- connectivity of layers and also better recognition of part orientation. When the designing process become completed then it has to converted into .STL file and subject to transfer into AM machine. .STL file becomes defacto standard for CAD data conversion into AM acceptable language. But for slicing operation .STL file has to deal with a lot of virtual lines for computing the intersection , and this calculation of interaction between geometry and plane not gives the efficient slicing operation and so that it sacrifices accuracy of built part. So in future for efficient slicing operation an alternative option for .STL has to be fined.

Methodology

The methodology for this project consists of following steps.

Selection of unit block - The unit block for scaffold fabrication has to be selected based on their higher effective stiffness, which were formulated from analysis by using ANSYS. Six types of ASTM standard unit block specimens were studied and three types of unit block had been selected for further procedures based on their higher effective stiffness.

FEA of unit block structures - The selected unit blocks were subjected to finite element analysis, to find the effective stiffness of the unit blocks in order select max. Three unit blocks for validation of result with experimental outcomes, based on higher effective stiffness and porosity. FEA test were carried for modeled structure to find reaction force, which is use to put in following formula to derive effective stiffness for each unit block.

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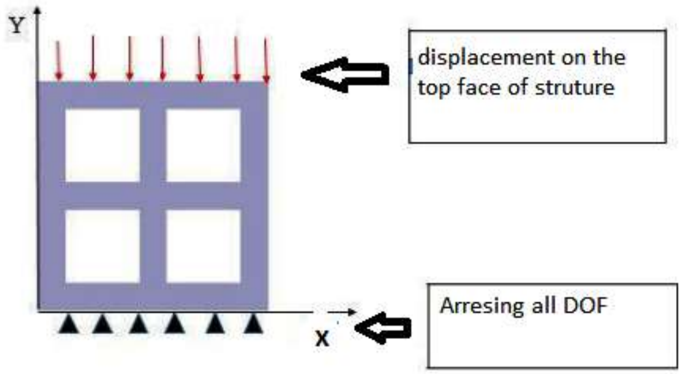

Fig. 1. Boundary conditions for analysis

$$E_s = \frac{F_r \times l_o}{A \times \Delta l}$$

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Where,
E_S - Effective stiffness of structure, lo- initial length
F_R - Reaction force at unit block, l- length after compression.

Design of 3D structure with CAD - After selection of unit blocks, the 3D structure were developed by using CAD. The standard ASTM size (5×5×5) mm cubes of square hole, cylindrical cut and sphere hole scaffold with 50- 60 % porosity were constructed through 3 dimensional design software CATIA. The arrangement of unit blocks were as per unit blocks structure. The strut size were taken from 800 µm to 850 µm.

Development of CAD tool - A unique CAD tool has to be developed by using CATIA V5 and VB Macros, which produces an equation formula which is based on input parameters given by the designer as like extrude height, pad length, pore size, strut size etc. The equation formed by CAD tool is applied on the designed standard scaffold, which produces the required shape of scaffold.

CAD- AM interface - The designed model of scaffold by using CAD has to be transferred in the AM machine for further fabrication of scaffold. All AM machines accepted .STL file format (triangulated data) to understand the geometry and patterning system of the model. The scaffold model, designed by CATIA is saved into .STL format and it were brought to the AM machine.

AM process - Selection of AM technique were based on part envelope, build time, part properties, lead time and material used for fabrication a suitable AM machine have to selected. Generally, FDM, SLA, SLS, 3DP , AM machines were used to fulfill this purpose, but among all of them have different characteristic for fabrication of object, mode of operation, selection of material. As per our requirements SLS machine were selected for fabrication of object. SLS have many advantages over another AM process like, wide range of material available, more porous part can be built, and high strength material can be used to fabricate by SLS technique. The complex structure of scaffold can be fabricated in SLS machine in form of layer by layer additive process.

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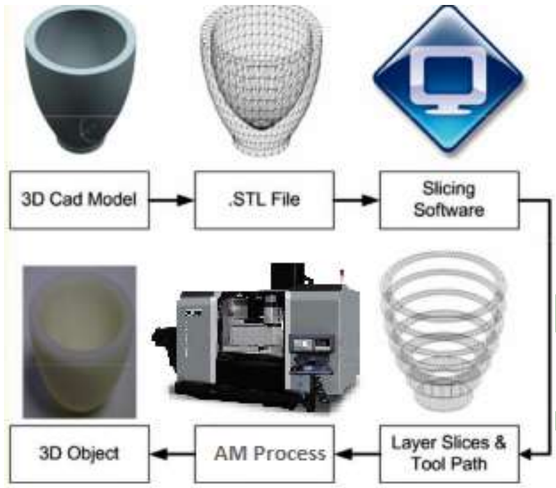

Fig. 2. AM process

Development of CAD tool -
The unique CAD tool is developed by using CATIA V5 software and VB Macros. Virtual basics is event driven programming language and integrated development environment (IDE) which is created by Microsoft. VB enables us for rapid application development (RAD) by using graphical user interface (GUI) application. We can create an application by using component provided by the visual basic program.
CAD tool consists of following processes-
Addressing of location system - This program gives us the system address of the bone where it has to replace by scaffold. This program decides the pathway of further procedures of designing of scaffold.
Program for Axis generation - This program were creates for axis generation system of the bone for better positioning and orientation of customized scaffold designing. This program generation axis system parameters in X,Y,Z direction.
Patterning of unit block - This program makes the pattern of arrangement of unit block in X,Y,Z, directions around the bone by using patterning operation. This program also enables the spacing between the unit blocks for their better inter connectivity.
Intersection of bone scaffold by Boolean operation - This is the important part of the CAD tool which intersects the standard scaffold in the desired as per patient specific scaffold. It converts the standard model in the desired model by Boolean operation.
So, when the CAD tool is applied to the standard designed scaffold after input the parameters then a equation is generated and applied on the standard scaffold which converts the design into desired shape.

Input parameters for square hole scaffold
1. Pore size
2. Spacing unit block
3. Address of bone block
4. Pad length (extrude height)
5. Co- ordinates of outer and inner square- AX,AY & CX,CY.

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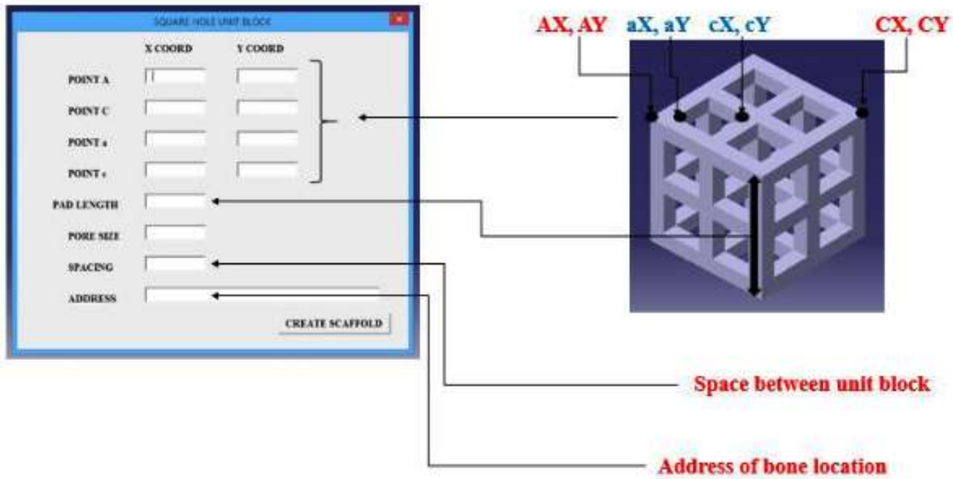

Fig. 3. Input parameter form for square hole scaffold

Fabrication - As per required pore size, pad length, spacing between unit block entered in the user form provided by CAD tool, customized scaffold design were created in the CATIA software. The CAD data of scaffold has to be converted into .STL file (triangulated data) format and subject to export AM application software for fabrication of 3D scaffold. As per structural strength, object accuracy, bio compatibility and better pore inter connectivity we had select selective laser sintering (SLS) technique for fabrication of object. The material used for fabrication of scaffold were polyamide (nylon) which has greater strength and high heat resistant and also non- toxic for human body.

Selective laser sintering (SLS) is the laser based technique, which fabricate the material layer by layer by using powder as support material, radiant heaters and computer controlled laser. the slicing software in the SLS converts the part representation into no. Of cross- section layers.In SLS process a CO_2 laser is used, and parts are built by sintering process when laser beam from CO_2 laser hits the thin layer of powdered material, the interaction of laser raises with the powder material raises the temperature up to the melting point which results in particle bonding, and fusing of material from the previous layer. The building of the object is done layer by layer, the next layer is deposited on the top of the sintered previous layer by feeding of additional layer of powder by roller feed mechanism.

Once the fabrication of object completed, it allowed to cool in process chamber of SLS and after that it has to be removed from the bed. The extra powder material were removed from pores of the scaffold and required post-processing has to be done for better surface finish.This manufacturing methodology enables the SLS to build more complex parts with more accuracy and within short lead time.

A wide range of materials like metals, ceramics and polymers may be used in SLS for fabrication. We had used polyamide (PA) 2200 polymer (bio- compatible material) to fulfill our criteria.

Fig. 4. Fabricated specimen of scaffolds

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Results and discussion

We had made analysis for selection of unit block structure which are architectural building block of scaffold. Effective stiffness were calculated for particular type of unit block structures by convergence test performed by Finite element analysis (FEA). As per mesh density and porosity of particular unit block structure, reaction force were calculated and this reaction force were used further for calculation of effective stiffness with respect to change in length and enclosed pore surface area.

Compression test were performed on the fabricated specimen through SLS, to find experimental effective stiffness which were calculated against stress vs strain graph at 10 % linear region formed during compression test. The ratio of stress and strain gives effective stiffness for particular structure .We further compare the experimental outcome with numerical analysis result to find deviation in effective stiffness. Based on least percentage of deviation in results of effective stiffness we found square hole unit block is best to fabricate customized scaffold, also square hole unit block possess maximum effective stiffness. The deviation in results in analytic and experimental outcomes, were under the acceptable limit, i.e. In between 8-12%.

SCAFFOLD MODELS	EFECTIVE STIFNESS (M Pa)		DEVIATION (%)
	NUMERICAL	EXPERIMENTAL	
square hole structure	736.35	680.19	8.25
cylindrical cut structure	609.21	541.28	12.54
sphere hole structure	448.07	409.4	9.44

Table 1. Comparison and deviation of results

As per result obtained through comparison of analytic and experimental results we had found square hole unit block possess maximum effective stiffness, and it also proved from least deviation formed through comparison of results. So we use square hole unit block for fabrication of customized scaffold for better inter connectivity of unit blocks, high strength and good porosity.

For linear region extended up to 0.3 mm of displacement we plot stress- strain graph to find effective stiffness for square hole unit block.

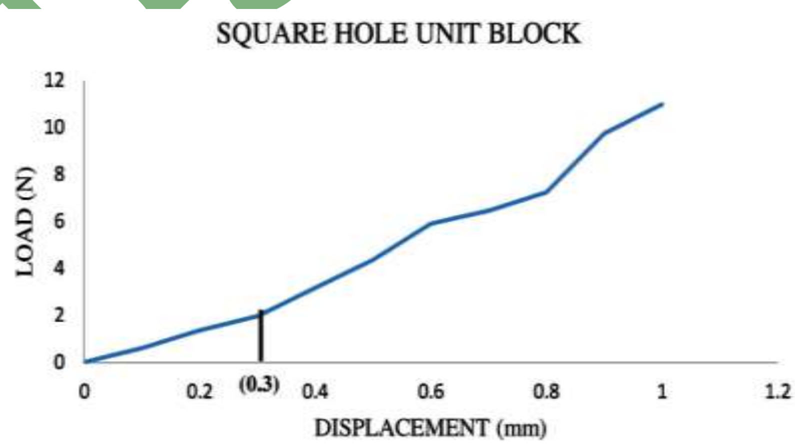

Fig. 5. Load- displacement diagram for square hole structure

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And the resultant stress value for given load and displacement of 0.3 mm, calculated against 10% of strain value i.e.0.012 is 0.000817 Gpa. The ratio of stress and strain value gives effective stiffness of scaffold.

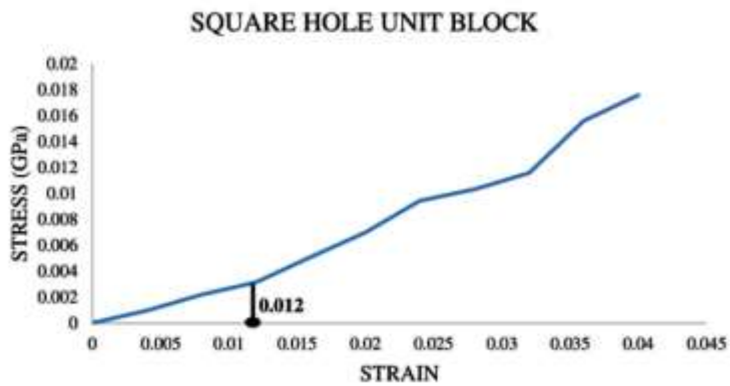

Fig. 6. Stress- strain graph for square hole structure

Conclusion

In this project, a unique CAD tool developed which makes the design and modeling of scaffold easier, reduces lead time and gives better surface finish. We compared the analytic result and experimental outcome for effective stiffness of scaffold, and the least deviation in results shows versatility and reliability of CAD tool.

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References

[1] ASTM F2792-10. Standard terminology for additive manufacturing technologies, copyright ASTM international, 100 Barr Harbor Drive, West Conshohocken, PA 19428.
[2] Bin duan, Min wang, Wen you zhou, Yai Lam Cheung, Zhao Yang Li & William w. Lu 2010, ‘ Three-dimensional nano coposite scaffolds fabricated via selective laser sintering procedure for bone tissue engineering’, Acta Biomaterialia vol. 6 , pp. 4495- 4505.
[3] Cahill, S, Lohfeld ,YT McHugh, PE, 2009, ‘ Finite element predictions compared to experimental results for the effective modulus of bone tissue engineering scaffold fabricated by selective laser sintering, ’ Material science vol. 20, No. 6, pp. 1255- 1262.
[4] Deckard CR, 1988, ‘Selective laser sintering’, Mechanical engineering, Austin; University of Texas at Austin.
[5] Dinis J.C., Morais. T.F. ,Amorim P.H.J., Ruben. R.B., Almeida. H.A., Inforcati P.N., Bartolo P.J. & Silva J.V.L. 2014, ‘Open source software for the automatic design of scaffold structures for tissue engineering application’, Procedia Technology , vol. 16, pp. 1542-1547.
[6] Giantelli S.M., Accoto D.,Trombetta M. & Rainer A., 2014, ‘Current trends in the design of scaffolds for computer- aided tissue engineering’, Acta Biomaterialia, vol. 10, pp. 580- 594.
[7] Goodridge RD, Tuck CJ & Hague RJM, 2012, ‘Laser sintering of polyamides and other polymers’, Progress in material science, vol. 57, No. 2, pp. 229- 267.
[8] Jayanthy parthasarathy, Binil starly & shivakumar Raman, 2011, ‘ A design for the additive manufacturing of functionally graded porous structure with tailored mechanical properties for bio-medical application, ‘Journal of manufacturing process, vol. 13, pp. 160-170.
[9] Kajal Ghosal, Mahima santhakumar Latha & Sabu Thomas, 2014, ‘Poly (ester-amides)- scaffolds for tissue engineering applications’, Europian polymer journal, vol.60, pp. 58- 68.
[10] Leong K.F., Cheah, C.M. & Chua C.K., 2002, ‘Solid freeform fabrication of three- dimensional scaffold for engineering replacement of tissue and organs’, Biomaterial, vol. 24, pp. 2363- 2378.

ISSN: 0976-7126

[11] Lev Podishavalov, Cynthia M. Gomes, Andrea Zocca , Jens Guenster, Pinhas Bar- yoseph, Anath Fischer, 2013, 'Design, analysis and additive manufacturing of porous structurs for bio- compatible micro- scaffolds', Procedia, CIRP5, pp. 247- 252.

[12] Lin Liulan, Hu Qingxi, Huang Xianxu, & Xu Gaochun, 2007, 'Design and fabrication of bone tissue engineering scaffolds via rapid prototyping and CAD', Journal of Rare Earths , vol.25, pp. 379.