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Computer aided design and finite element analysis of bone scaffolds.

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A Dissertation Submitted to the Regional Centre of Excellence in Biomedical Engineering and e-Health (CEBE), University of Rwanda as partial fulfilment of the requirements for the Master's Degree in Biomedical Engineering.

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DECLARATION

I, Martin BYABASHAIJA, declare that this dissertation entitled "**Computer aided design and finite element analysis of bone scaffolds**" is my original work based on research and design and has not been submitted for any other degree or professional qualification.

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CERTIFICATE

This is to certify that the project entitled "**Computer aided design and finite element analysis of bone scaffolds**" is a record of original work done by Martin BYABASHAIJA (Reference number: 220007486), a MSc. Degree student in Biomedical Engineering.

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ABSTRACT

Evolving of computer aided modeling and finite element analysis in current technologies is enabling the design and fabrication of bone scaffolds with the precise specifications as needed to comply with the properties of the damaged or broken bone part to be replaced. 3D designed model allows measured material placement for configuring geometric and porous tissue scaffolds with adapted properties such as mechanical stiffness and biological growth before prototyping and production. Different bone scaffolds have been designed and analyzed to see the results when force (uni-axial load) is applied on them. These scaffolds are made up in different pore size (500mm and 1000mm) and geometry structure (basic, crossed and their offset of 50%). They were designed, analyzed with current technology (computer aided design & finite element analysis) so that we see their correspondence to mimic the natural bone tissue (biomechanical properties) when cells will be grown on them. The basic scaffold showed higher SA/V ratio compared to other scaffolds. These scaffolds and their manufacturing method will be cheap, more effective and it will promote quick recovery compared to existing technologies but also it will have minimum side effects compared to current treatments options.

Keywords: bone; scaffolds; pore size; geometry structure, design, finite element and 3d printing.

LIST OF ACRONYMS

ALP: Alkaline Phosphatase

CAD: Computer Aided Design

FEA: Finite Element Analysis

FEM: Finite Element Method

MSCs: Mesenchymal stem cells

PCL: Poly(ε-caprolactone)

REMCO: Rwanda Engineering and Manufacturing Corporation

SA/V: Surface-area-to-volume

3D: 3 dimensions

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CHAPTER 1. GENERAL INTRODUCTION

1.1 Introduction

The bone is a connective tissue found in the human body and an adult human body is made of 206 bones, these include the bones of the skull, spine, ribs, arms, and legs counting 15% of human body weight. Bones are made up of connective tissue that is calcium-reinforced, as well as specialized bone cells. Bones work with muscles and joints to hold our body together and support freedom of movement. Globally the prevalence of bone fractures is projected to increase nationally from 2.1 million in 2005 to over 3 million fractures in 2025 [1] in America which is very high, leading to the high demand for bone repair or replacement and this becomes our reason for the research.

There have been many ways of solving the bone fracturing problem like bone grafts which is the augment bone repair and regeneration, and other technique are distraction osteogenesis, bone cement fillers, and bone morphogenic proteins which have side effects.

On another side, bone defect repair using the tissue engineering approach is perceived as a better approach because the repair process may proceed with the patient's own tissue by the time the regeneration is complete. Bone tissue development through bone scaffold and cell planting is the focus as a better alternative treatment option that ideally eliminate the previously described issues of current clinically used treatments (i.e., donor site morbidity, limited availability, immune rejection, and pathogen transfer).

Therefore, careful consideration in the design and finite element analysis of a bone implant or scaffold that have strength & accept cell growth is important. And these technologies (design, analysis & 3d printing) [2] that can easily be accessed anywhere for properly treatment for trauma in the skeletal system while not harming the patient is a greater achievement.

This research assessed different 3d designed bone scaffolds with pore size and porosity as well as analyzing their mechanical properties and their structure geometry of basic, crossed, basic offset and crossed offset pores [3].

1.2 Problem statement

The human body's ability to regenerate bone tissues is extremely inefficient and losing human tissue can happen easily due to things like fractures. When a tissue dies or break, it can't be brought back to life and if it's not removed or repaired that affects other areas of the body, such as surrounding bone tissue.

Bone grafts are utilized in a wide array of clinical settings to augment bone repair and regeneration. These transplants are very expensive procedures, and they may result in significant donor site injury and morbidity, deformity, scarring and they are associated with surgical risks as well: bleeding, inflammation, infection, and chronic pain.

Other commonly used bone repair techniques may involve distraction osteogenesis, bone cement fillers, and bone morphogenic proteins. Although the previously mentioned clinical interventions have been shown to improve repair of bone, none possess all of the ideal characteristics: high osteo-inductive and angiogenic potentials, biological safety, low patient morbidity, no size restrictions, ready access to surgeons, long shelf life, and reasonable cost.

This is where bone tissue engineering is useful. By using biomaterial (matter that interacts with the body’s biological systems such as cells and active molecules), functional tissues can be created to help restore, repair, or replace damaged bone of person.

The process of bone tissue engineering involves forming a 3D functional tissue to help repair, replace, and regenerate a bone in the body. To do this in our case, cells and biomolecules are combined with 3d printed bone scaffolds.

Bone scaffold is an important structure that must mimic real bone fibers. The tissue grows on these bone scaffolds to mimic the biological process or structure that needs to be replaced. When these are constructed together, new bone tissue is engineered to replicate the damaged or defected bone tissue.

Therefore, our research focused on designing different bone scaffolds and analysis them to see and select the ones that can fit and maximize the cell growth when planted in the human body.

1.3 Research Questions (Hypotheses)

The following 3 questions are the baselines which guided this study:

1. What type of bone scaffold structure and material needed?
2. What possibility of modeling bone scaffold using computer aided design (CAD)?
3. What are the behaviors of these scaffold when force is applied on them?

1.4 Objectives

1.4.1 General Objective

The main objective is to design and analysis of bone scaffold using computer aided design.

1.4.2 Specific Objectives

- To set the specifications of the bone scaffold (data collection from natural bone).
- To design the different bone scaffolds using computer aided design software.
- To analyze the designed scaffolds using finite element analysis method.

1.5 Study Scope

This study focused on bone scaffold specifications, designing using SolidWorks for computer aided design and analyze the designed models.

1.6 Significance of the Study

The aim of this study was to design bone scaffolds with different geometries and pores size. Then after designed models were analyzed to see how effective they will be when plant in human body when considering their mechanical properties.

1.7 Organization

Chapter one gives the introduction, Chapter two discusses literature review, chapter three gives the research methodology. Chapter four discusses the project results and findings from design and analysis, Chapter five discusses challenges, recommendations, and conclusions from the research study and finally there are references and appendixes.

1.8 Summary

Bone defect or damage is increasing as time goes on and that is the reason why designing and analyzing bone scaffolds using computer aided design is important for us to having faster production of bones development.

CHAPTER 2. LITERATURE REVIEW

This chapter is about what other researchers found out on the design and analysis of bone scaffolds, this narrowed our research in a clear path and having gained knowledge that helped in setting of specifications, design, and analysis of bone scaffolds.

2.1 Scaffold Pore size

One method in tissue engineering for bone regeneration is the creation of three-dimensional (3D) scaffolds with porosity and all restrictions look like the part that must be broken with all the mechanical functions and enables the bone ingrowth [3]. For a bone scaffold to be considered as good scaffold, it has to mimics all the quality of the bone like total porosity, pore size, internal structure, and interconnectivity, as well as mechanical and physicochemical properties [4].

It is clear and have been proved that pore size and structure geometry are important factors in uniform cell proliferation both in the space of scaffolds and in time. Early studies suggested that a minimum pore size of 100 μm enhances bone ingrowth [5], while other investigations have found that an optimal size is in the range of 100–1250 μm [9].

There is a large range of pore size which can help in the cell growth and the larger the pore size the easier the modeling and analysis of the bone scaffold through computer aided design.

2.2 Scaffold Pore geometry

Another feature that influences the rate of bone renewal is the geometry of the porous scaffold [6]. Differences in pore width and curvature of the surface have been revealed to lead to variations in tissue morphology and growth rate. In other words, more tissue is formed because of the smaller vertical spaces between the struts [7]. Similar results were reported with superior cell proliferation happening at the short edges of rectangular pores than at the long edges [8].

Previous studies have suggested that cell proliferation and seeding efficiency is also increased in offset scaffolds because of the higher contact time between the scaffold surface area and the fluid containing cells. Greater mesenchymal stem cells (MSCs) cell proliferation was observed for the basic offset scaffolds compared with higher cell differentiation and Alkaline Phosphatase (ALP) activity in crossed scaffolds. These findings suggest that the basic-offset scaffolds (homogeneous structure) allowed cells to grow homogeneously because of the higher number of anchorage points. Interconnected struts created the angles, which differed from those in basic scaffolds and increased differentiation [9].

They found superior cell differentiation and proliferation efficacy for calcium deposition and ALP activity (up to 50%) for scaffolds with offset values of 50% and 100% [10]. These findings suggest that designing the architecture with different offset values can alter the cell behavior, proliferation, and differentiation.

2.3 Role of porosity

I. In Scaffold permeability

Higher permeability improves the amount of bone ingrowth and inhibits the formation of cartilaginous tissue in the regenerated site [14]. Permeability depends on porosity, orientation, size, distribution, and interconnectivity of the pores. A larger pore size is preferred for cell growth and proliferation because the pores will be occluded later than smaller pores during progressive growth and will therefore provide open space for nutrient and oxygen supply and further vascularization in newly formed bone tissues [15].

II. In Scaffold vascularization

Insufficient vascularity in complex or thick tissues such as bone limits spontaneous regeneration of these parts [16]. A fracture in natural bone produces a hypoxic environment, which leads to upregulation of angiogenesis and eventually creates a vascular network [17]. This process is followed by the differentiation of (MSCs) located in the medullar cavity to cartilage [18]. The newly formed cartilage is then calcified and hardened into bone. Because of the inability of the impermeable inner cartilage to transport nutrients, the cartilage cells start to die, which creates cavities and allows the vessels to invade the cavities and the vascular mesh to develop. Osteoclasts, osteoblasts, lymphocytes and nerve cells also penetrate into the cavity, and the remaining cartilage start to collapse after secretion of osteoid by osteoblasts and osteoclasts, which form the spongy bone [19]. The hypoxic zones actuate the tips of endothelial cells, which behave like oxygen sensors and migrate toward the oxygen-deficient area. Stalk cells begin to sprout and branch to create vessel channels [20].

III. In scaffold mechanical properties

There is a linear relationship between the resistance to mechanical loading and bone density or toughness [21]. The complex heterogeneous and hierarchical structure of bone tissue creates variations in compressive strength and tensile values in different regions of bone [23]. A reduction in bone mass increases the susceptibility to fracture [22]. Cortical bone contains 20% porosity along the transverse axis and has a load bearing capacity of 8–20 GPa parallel to the

osteon direction. Cancellous or spongy bone (>90% porosity) is found next to joints that are highly vascular with young's modulus of 100 MPa, which is lower than that in cortical bone. Therefore, cortical bone generates compact bone which is denser than cancellous bone [24].

IV. In scaffold degradable rate

The pore size plays an important role in the pattern of scaffold degradation. Although greater porosity leads to further permeability, which ultimately results in faster degradation, other parameters such as the homogeneity of pores, morphology and pore size influence the degeneration of porous biomaterials [25]. For example, Wu et al. investigated the *in vitro* degradation rate of 3D porous scaffolds composed of PLGA85/15 (poly (D,L-lactide-co-glycolide)) with a porosity of 80–95% and pore size of 50–450 μm in PBS at 37 °C for 26 weeks. The scaffolds with larger pore size and lower porosity degraded faster than those with smaller pore size and higher porosity. This finding was attributed to the effect of the higher surface area in the scaffolds with larger pore size which increased the diffusion of acidic degradation products during the incubation period and led to a stronger acid-catalyzed hydrolysis [26].

2.4 Design & FEA using Solidworks in Research

Solidworks® is a parametric modeler that uses dimensions, parameters, and relationships to define 3D shapes [11]. It was first introduced in 1995 and becomes one of the leading pieces of software in 3D modelling and analysis [11]. The advancement and the expansion of this software application has extended its applications to various industries and research institutes which use this software in designing, modelling, and simulating stable structures [12]. The software allows engineers and designers to create mathematically solid models and by assigning the favorite material properties, it allows them to simulate and assess the behavior of the designed part using FEM [12]. This software has a wide range of applications such as simulation, motion, flow simulation and many others.

2.5 Summary

The objective of this review was to view the trends in composition studies within the past years and see how further the development of bone scaffolds using computer aided design software (Solidworks) has gone and this has given me direction through my research.

CHAPTER 3. RESEARCH METHODOLOGY

This research was to develop or create a bone scaffold that will help in the development of bone tissue that will be implanted in the body with bone defects created by trauma, infection, tumor resection, skeletal abnormalities, or cases in which the regenerative process is compromised, including avascular necrosis, atrophic non-unions and osteoporosis but still overcomes or withstands them. For the scaffold to be effective, we used better approach in current technologies so that this scaffold fulfills or meets properties needed.

3.1 Research process

Here is the graphic overview for this research from the point of setting specifications to design, finite element analysis and the studying of the results.

3.1 Research requirement

Table 1 shows the specifications of the bone scaffolds that were developed. The parameters that were considered in the generation of the specifications are as follows.

1. Nature and Shape of bone. The bone scaffolds will be for cortical bone which is highly dense and consists of a hierarchical structure, each within a different size scale. The scaffolds will be cylindrical in refer to the shape of long bones. The Maximum Tibia diameter is 24mm and the Length (MTL) of 44cm. The length of adult tibia bones ranged from 35.2cm to 43.6cm with an average of 39.9 ± 2.2cm.

2. Pore geometry

The designed and constructed scaffolds are having circular fibres with pore size of 500 and 1000 μm on each shape and they have four complex structures of porous scaffold by changing the configuration of the deposited fibers and pore size within the architecture of basic, basic-offset, crossed and crossed-offset.

The fibre size used was 400μm which was determined according to the 3d printing nozzle diameter. For the fabrication of the scaffolds, most of the 3d printers with a heated platform and a double drive gear extruder use a 400μm nozzle diameter.

Below is a table with all specifications used in designing the 3d bone scaffold models.

Table 1: Specifications of all Scaffolds

No	Scaffold	B1	B2	B3	B4	C1	C2	C3	C4
1	Structure	Basic	Basic-offset	Crossed	Crossed-offset	Basic	Basic-offset	Crossed	Crossed-offset
2	Scaffold diameter(mm)	24	24	24	24	24	24	24	24
3	Scaffold Height(mm)	11.2	11.2	11.2	11.2	11.2	11.2	11.2	11.2
4	Fibre diameter (mm)	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
5	Pore size (mm)	0.5	0.5	0.5	0.5	1	1	1	1
6	Offset	0%	50%	0%	50%	0%	50%	0%	50%

The scaffold porosity and structure shape were the main point of focus in this research because they are considered as the backbone of the cell proliferation and bone ingrowth. Below are technologies that were involved in this research.

3.2 Research Design Method

3.2.1. 3D modeling

The development of any small structures with internal trusses or pores in model without computer aided design is complicated and impossible. All computer aided design (CAD) models in this research were designed in Solidworks Professional (version 2021). The SOLIDWORKS®

CAD software is a mechanical design automation application that lets designers quickly sketch out ideas, experiment with features and dimensions, and produce models and detailed drawings [13].

Below are basic steps used in designing the bone scaffolds; you open the software and go to the new part open it, go to sketch draw a circle for fibre diameter then extrude it as figure 1, then do linear pattern to have them as many fibres as figure 2 and that was repeated in another plane for us to have basic structure for bone scaffold but to the crossed structure, I used four planes and then repeated those steps to develop the fibres as figure 3 shows us that I had more 2 planes in normal designing features.

The first step was to sketch, a sketch is a basis for most 3D models. Creating a part usually begins with a sketch. A sketch is a 2D profile or cross section. To create a 2D sketch, you use a plane or a planar face.

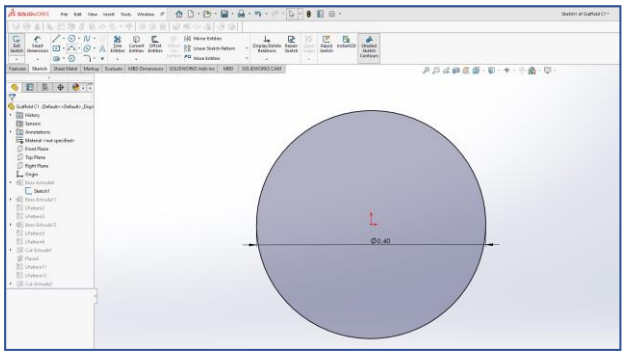

Figure 1: Sketch a Circle for fibre diameter

After sketches completed, creation of the 3D model using extrude boss feature to make a model in z axis was next. A feature is a basic structure block within Solidworks models**.**

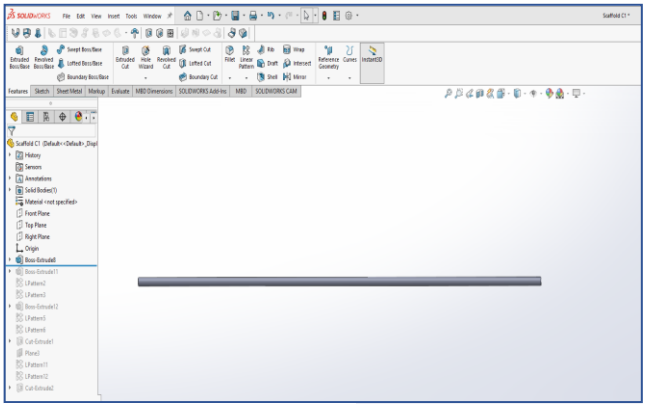

Figure 2: Circle extruded into boss

From the sketches and combination of more features using linear pattern to make a part with the dimensions and material needed gave structure which is a bone scaffold.

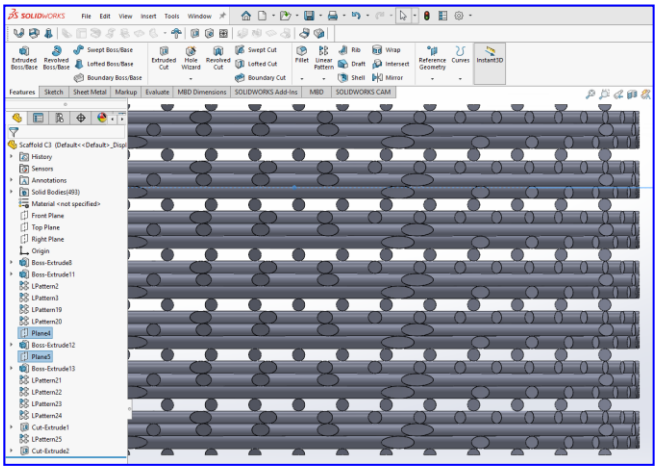

Figure 3: More planes for crossed structure

After all the steps of designing in Solidworks and completing one bone scaffold (B1) then those steps were repeated to do the other seven remaining 3d models.

The first group of four scaffold are shown in Figure 4 to 8. The porous structure of these bone scaffolds was designed using Solidworks having a unit cell with fibre 0.4mm x pore size 0.5mm for four different structure of basic, basic-offset, crossed and crossed-offset respectively.

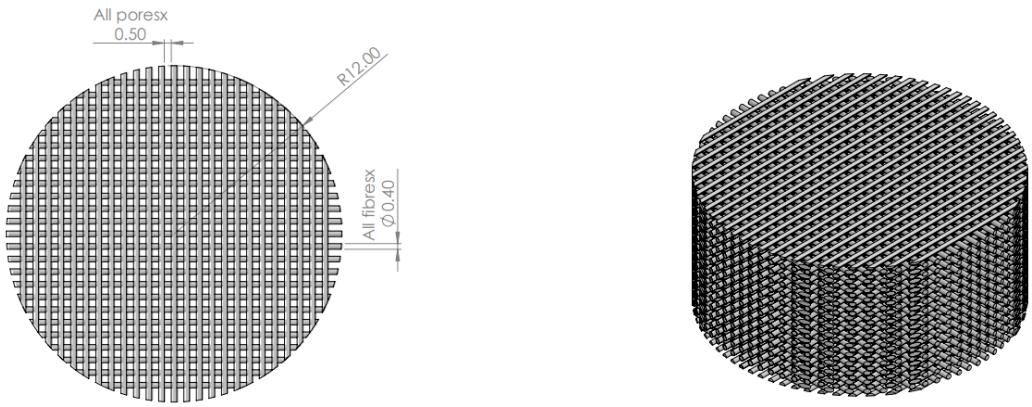

Figure 4: Scaffold B1, Left view: Top & Right view: Isometric

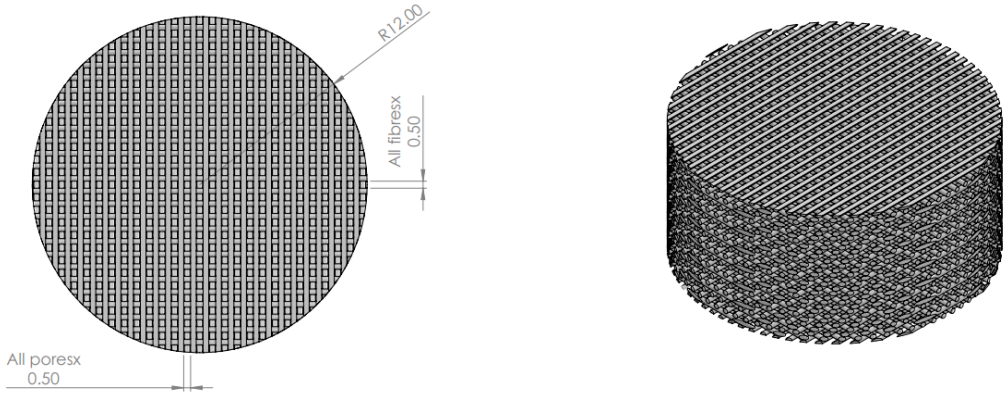

Figure 5: Scaffold B2, Left view: Top & Right view: Isometric

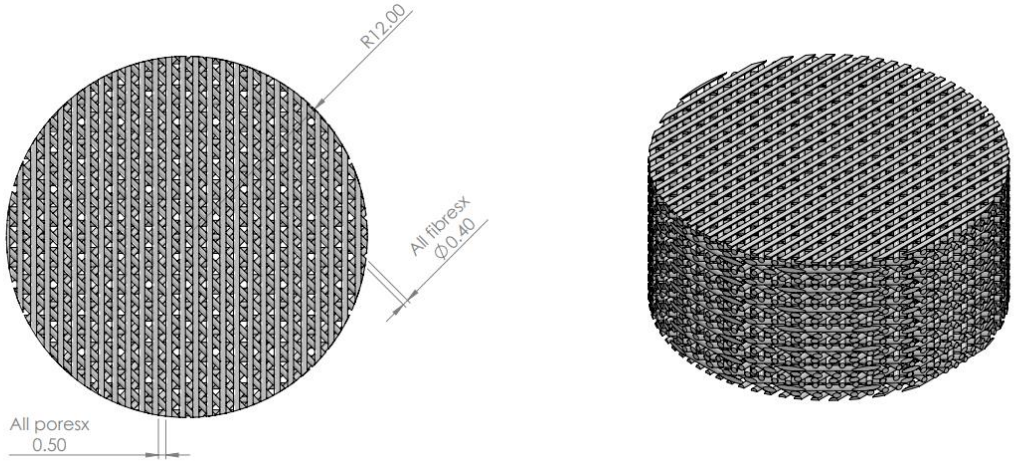

Figure 6: Scaffold B3, Left view: Top & Right view: Isometric

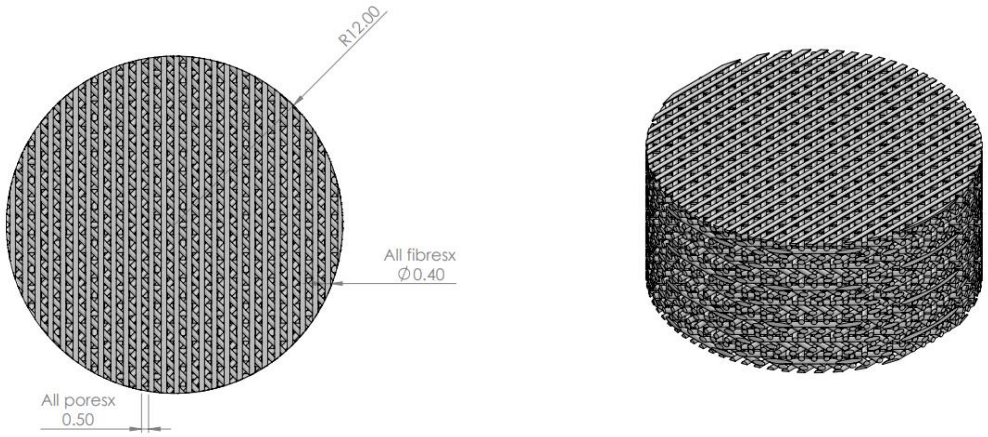

Figure 7: Scaffold B4, Left view: Top & Right view: Isometric

The second group of four scaffolds are shown in Figure 8 to 11**.** The porous structure of the bone scaffolds was designed using Solidworks having a unit cell with fibre 0.4mm x pore size 1mm for four different structure of basic, basic-offset, crossed and crossed-offset respectively.

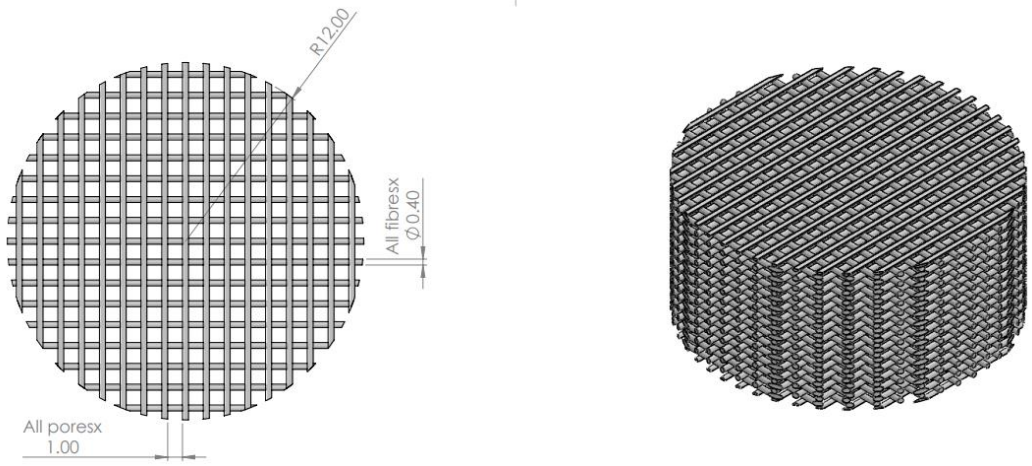

Figure 8: Scaffold C1, Left view: Top & Right view: Isometric

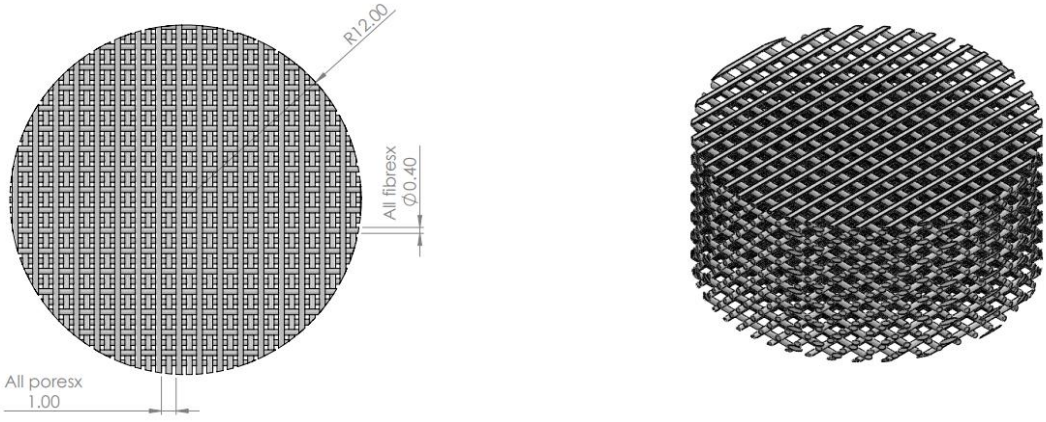

Figure 9: Scaffold C2, Left view: Top & Right view: Isometric

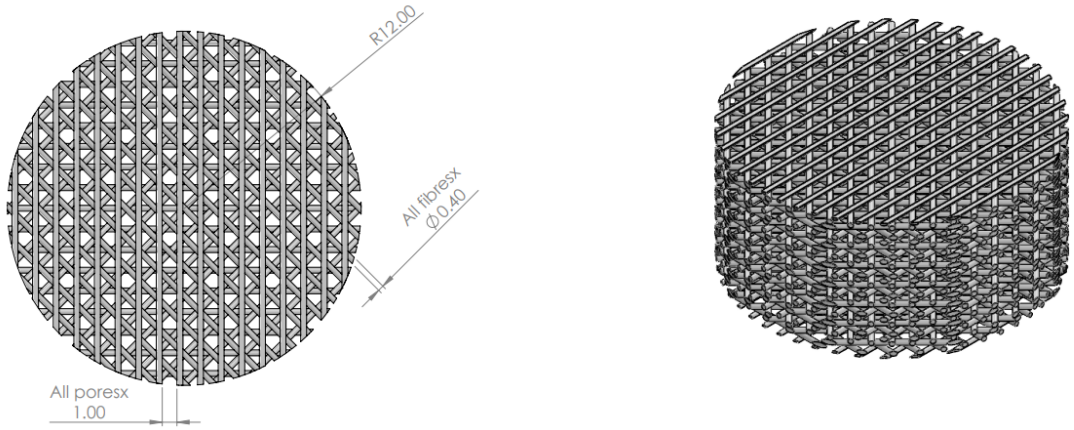

Figure 10: Scaffold C3, Left view: Top & Right view: Isometric

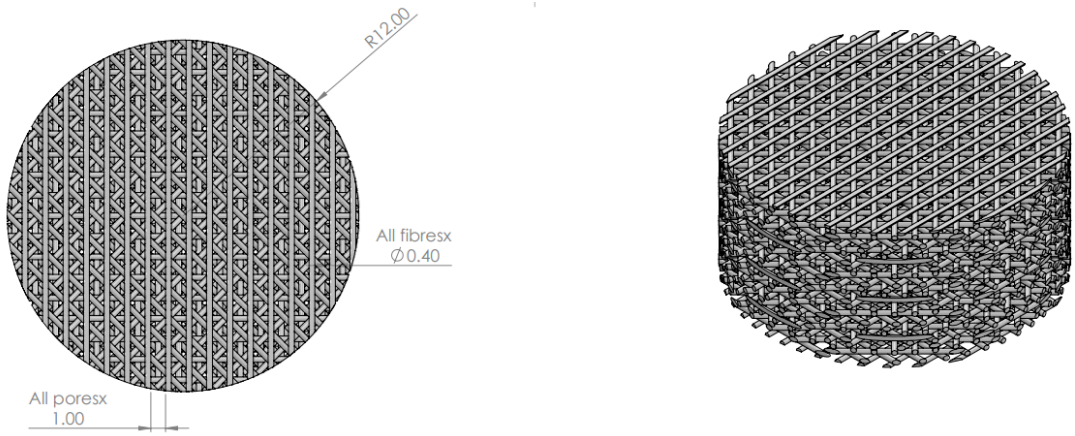

Figure 11: Scaffold C4, Left view: Top & Right view: Isometric

There were eight sample designs used in the simulation analysis and determining the characteristics such as porous volume, volume enclosed, surface area and surface-area-to-volume (SA/V) ratio.

3.2.2. Finite element analysis (FEA)

In the past few years, the finite element analysis (FEA) has been introduced as tool to help in the evaluation of biomechanical behaviors or properties in design models of different human body parts. Finite element analysis (FEA) in this research was done with Solidworks Professional (version 2021) and FEA has showed the stress distribution in the contact area of the implants with cortical bone and around the apex of the implants in trabecular bone.

The below are the steps used during our bone scaffold finite element analysis. The preprocessing steps include defining of geometry of model, meshing, defining boundary conditions, defining material properties, and defining output parameters.

Material properties

The material properties of Polycaprolactone are better properties to be used in an implant of the human body. The main reason is that PCL has long degradable period when used in biomedical applications. In the table 2, we see the mechanical properties of the PCL because they will be our main focus in FEM.

Table 2: Material properties

Name:	PCL
Model type:	Linear Elastic Isotropic
Default failure criterion:	Max von Mises Stress
Yield strength:	7e+07 N/m^2
Tensile strength:	5e+07 N/m^2
Elastic modulus:	3.5e+09 N/m^2
Poisson's ratio:	0.44
Mass density:	1,200 kg/m^3

Force & Fixtures

Model was fixed from the bottom on 39 entities and then the force (6,992.57N) was applied from the top on 39 entities.

Meshing The Models

Meshing is the method to create finite elements and finite elements are shaped by dividing the common geometry with imagined lines, and the components are then associated with each other by stating nodal connectivity at the element boundaries. Table 3 shows the general mesh information used.

Table 3: General Mesh Information

Mesh type	Solid Mesh
Mesher Used:	Standard mesh
Automatic Transition:	Off
Include Mesh Auto Loops:	Off
Jacobian points for High quality mesh	16 Points
Element Size	0.2 mm
Tolerance	0.01 mm
Mesh Quality	High

3.3 Summary

After all steps in the preprocessing of finite element analysis, we ran the process to get the results as they are shown in the following chapter.

CHAPTER 4. THE PROJECT RESULTS FROM DESIGN AND ANALYSIS

In this work, the biomechanical performance of porous scaffolds was designed and evaluated their different structural behavior of the scaffolds. We observed that, effective stresses, strains, and surface-area-to-volume (SA/V) ratio vary depending on geometry structure. It is indicated that effective stresses, strain, surface-area-to-volume (SA/V) ratio not only depends on porosity also depends on pore geometry of scaffold.

4.1 Results

4.1.1 Model results

Table 4: Characteristic Sample design

Model Name	**B1**	**B2**	**B3**	**B4**	**C1**	**C2**	**C3**	**C4**
Design	Basic with Pore size 0.5mm	Basic offset with Pore size 0.5mm	Crossed with Pore size 0.5mm	Crossed offset with Pore size 0.5mm	Basic with Pore size 1mm	Basic offset with Pore size 1mm	Crossed with Pore size 1mm	Crossed offset with Pore size 1mm
Porous Volume (mm^3)	2544.67	1767.97	1771.86	1768.72	1670.2	1134.52	1139.15	1137.32
Volume enclosed (mm^3)	5066.76	5066.76	5066.76	5066.76	5066.76	5066.76	5066.76	5066.76
Surface area, mm^2	26181.6	18352.8	18409.9	18366.7	17213.4	11783.5	11815.7	11822.8
SA/V ratio	0.0971	0.0963	0.0962	0.0963	0.0970	0.0962	0.0964	0.0962

Table 4 shows the characteristics such as porous volume, volume enclosed, surface area and surface-area-to-volume (SA/V) ratio. The SA/V is the basic scaffolds is higher compared from other scaffolds.

4.1.2 Mesh results

Table 5: All scaffold mesh results

Scaffold	B1	B2	B3	B4	C1	C2	C3	C4
Total Nodes	170661	318762	360684	745140	111366	223830	209076	480941
Total Elements	75165	137930	160284	339946	48932	98158	90703	219390
Maximum Aspect Ratio	4.0542	6.9555	6.9555	8.1323	6.6524	10.237	7.4784	6.0879
% of elements with Aspect Ratio < 3	99.9	99.8	99.7	99.7	99.7	99.8	97.8	99.7
Percentage of elements with Aspect Ratio > 10	0	0	0	0	0	0.00408	0	0
Percentage of distorted elements	0	0	0	0	0	0	0	0
Time to complete mesh(hh;mm;ss):	0:00:36	0:00:54	0:00:34	0:00:56	0:00:18	0:00:30	0:00:27	0:00:48

Table 5 shows the results of meshing for the nodes and elements which determine the time of completion which shows that both cross offset takes a long period of time compared to other scaffolds though in the figures basic offset B2 shows high time which is due to the error in solid modeling.

4.1.3 Finite Element Analysis results

Table 6: Finite element analysis results

Type	**Basic**	**Basic-Offset**	**Cross**	**Cross-offset**	**Basic**	**Basic-Offset**	**Cross**	**Cross-offset**
Open size	500mm	500mm	500mm	500mm	1000mm	1000mm	1000mm	1000mm
Title	**Scaffold B1**	**Scaffold B2**	**Scaffold B3**	**Scaffold B4**	**Scaffold C1**	**Scaffold C2**	**Scaffold C3**	**Scaffold C4**

Stress	Max	1.08E+11	3.67E+11	8.84E+12	7.62E+12	7.81E+11	3.86E+11	7.81E+11	8.11E+10
	Min	1.96E+00	3.98E+01	9.62E-01	0.00E+00	3.68E+01	0.00E+00	3.68E+01	2.18E+01
	Yield Strength	7.00E+07	7.00E+07	7.00E+07	7.00E+07	7.00E+07	7.00E+07	7.00E+07	7.00E+07
Strain	Max	1.59E+01	4.02E+01	1.07E+03	9.08E+02	1.04E+02	4.44E+01	1.04E+02	9.60E+00
	Min	5.91E-10	1.90E-08	1.73E-10	0.00E+00	1.72E-08	0.00E+00	1.72E-08	1.21E-08
Displacement	Max	2.85E+03	1.69E+04	4.49E+05	8.20E+14	5.08E+04	2.58E+04	5.08E+04	7.11E+02
	Min	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.00E-03	0.00E+00	0.00E+00	0.00E+00

The results in Table 6 of FEM method are about the stress, strain, and displacement of all designed scaffolds. Figure 12 through Figure 17 show the difference in those parameters for all scaffolds.

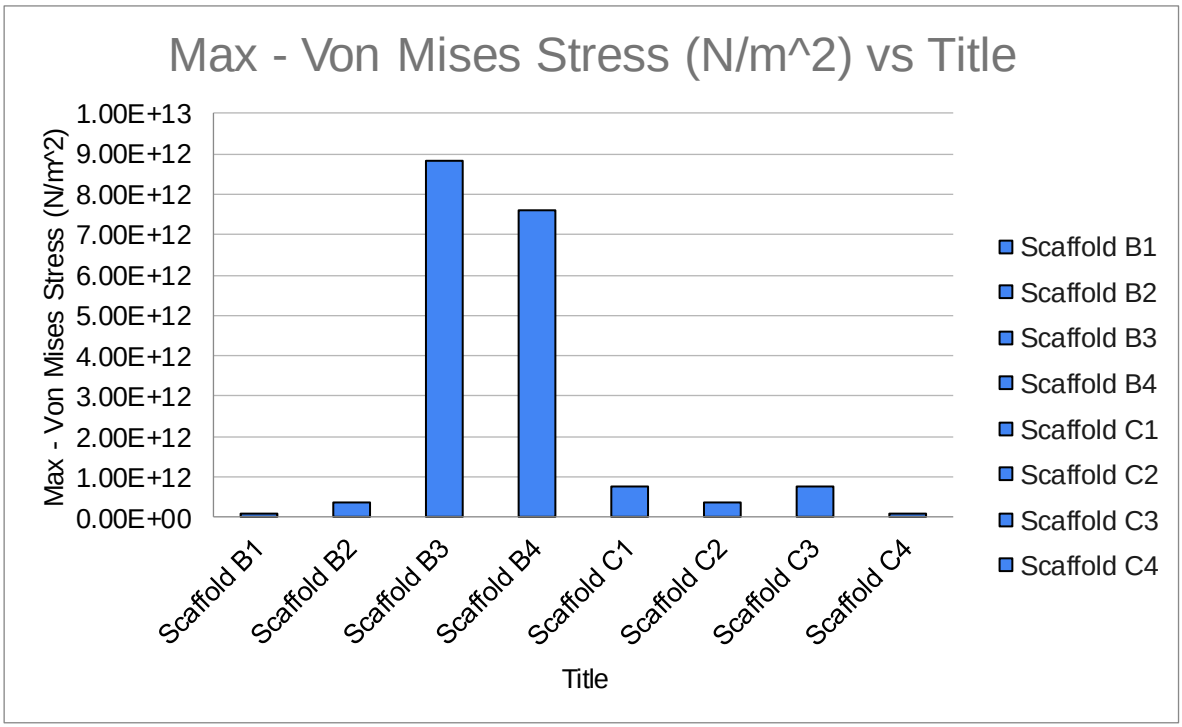

Figure 12: Maximum Stresses of all Scaffolds

Figure 12 shows the difference in the maximum von mises stress of all scaffolds, scaffold B3 & B4 show higher maximum stresses compared to other scaffolds.

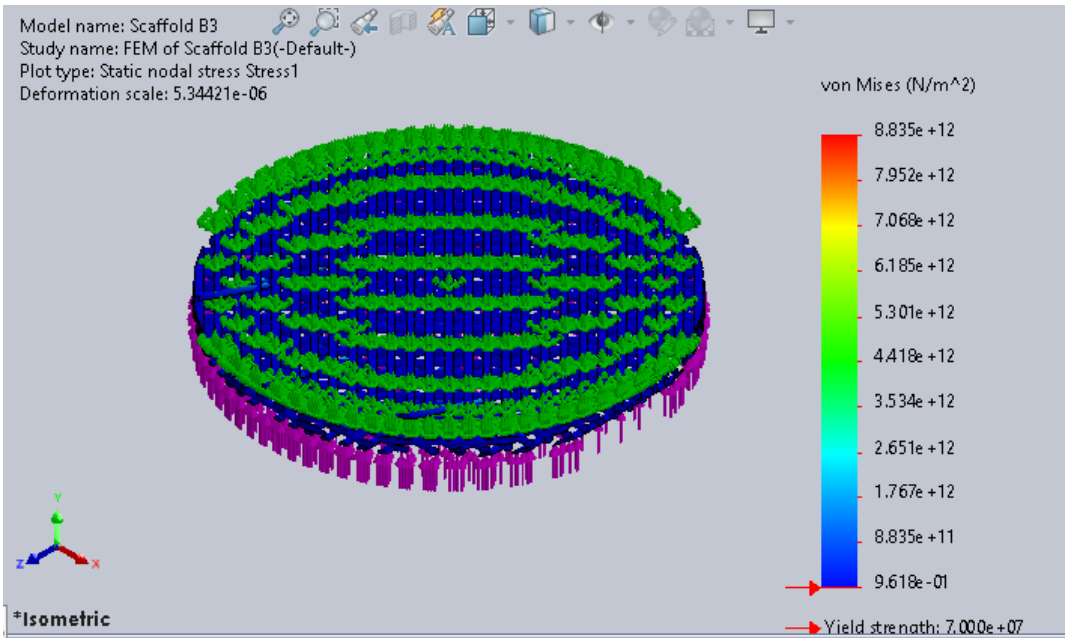

Figure 13: Stress distribution in scaffold B3

Considering the stress distribution on scaffold B3 and B4 as we see in figure 13 with scaffold B3, highness of the stress is due to the end of some fibres not the whole scaffold.

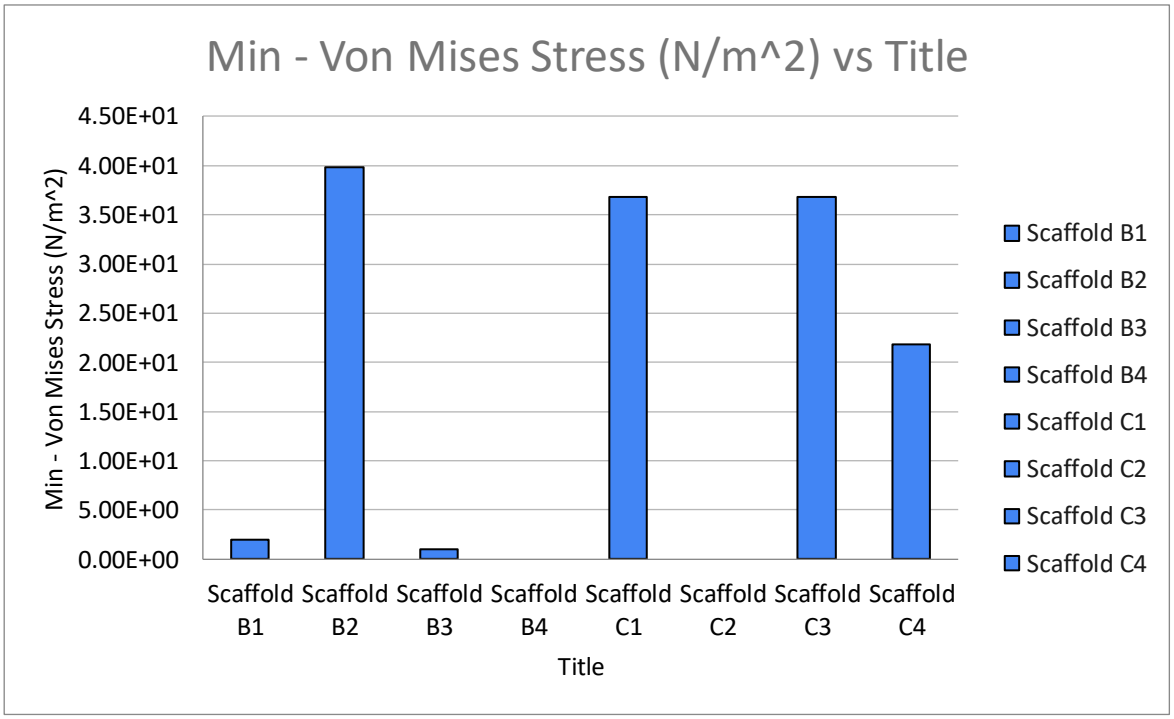

Figure 14: Minimum Stresses of all scaffolds

Figure 14 shows the difference in the minimum von mises stress of all scaffolds, scaffold C2 & B4 show lower minimum stresses compared to other scaffolds. But even the highest of the minimum stress is still very lower compared to the yield strength of the material.

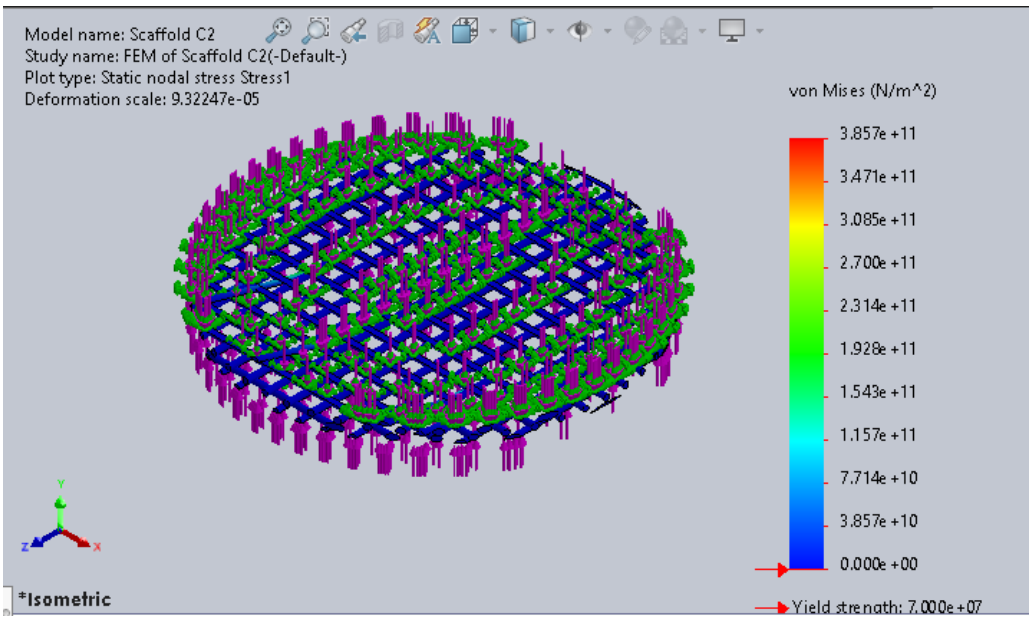

Figure 15: Stress distribution in Scaffold C2

A closely observation to Figure 13 of stress distribution in B3 which has maximum stress and Figure 15 of stress distribution in C2 which has minimum stress, they all show that almost every area is in the range of the minimum stress which even lower compared to yield strength.

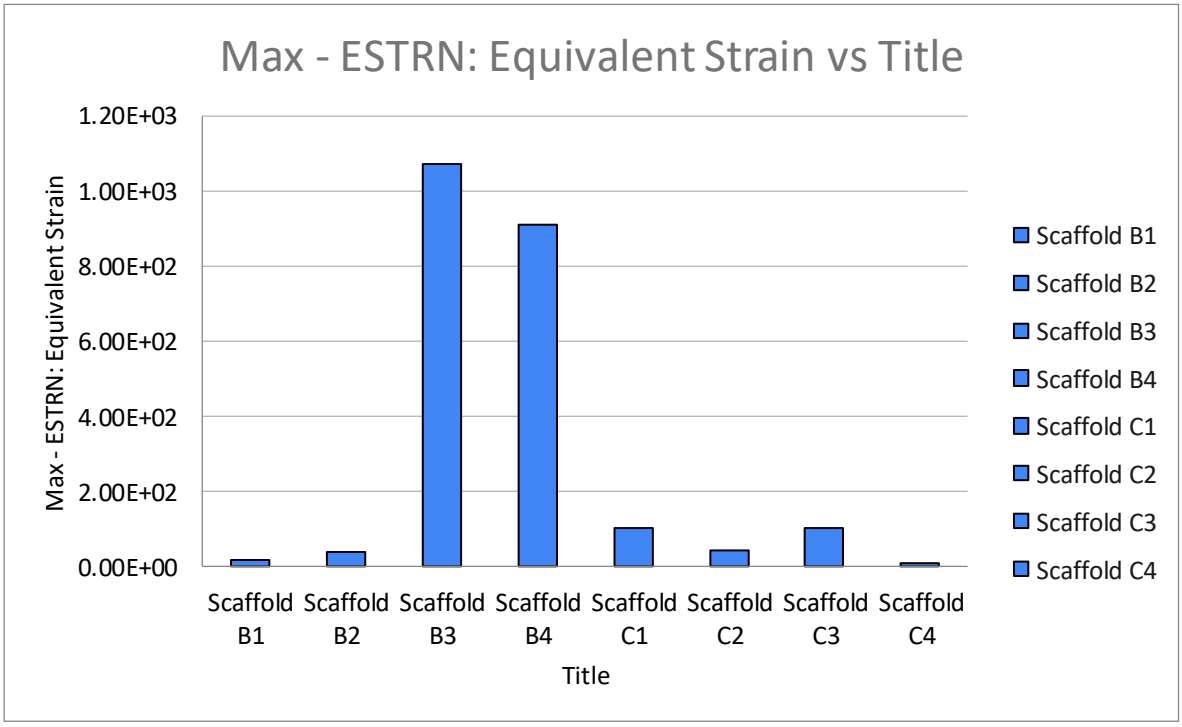

Figure 16: Maximum strains of all scaffolds

Figure 16 shows the difference in the maximum strains of all scaffolds, scaffold B3 & B4 show higher maximum strains compared to other scaffolds.

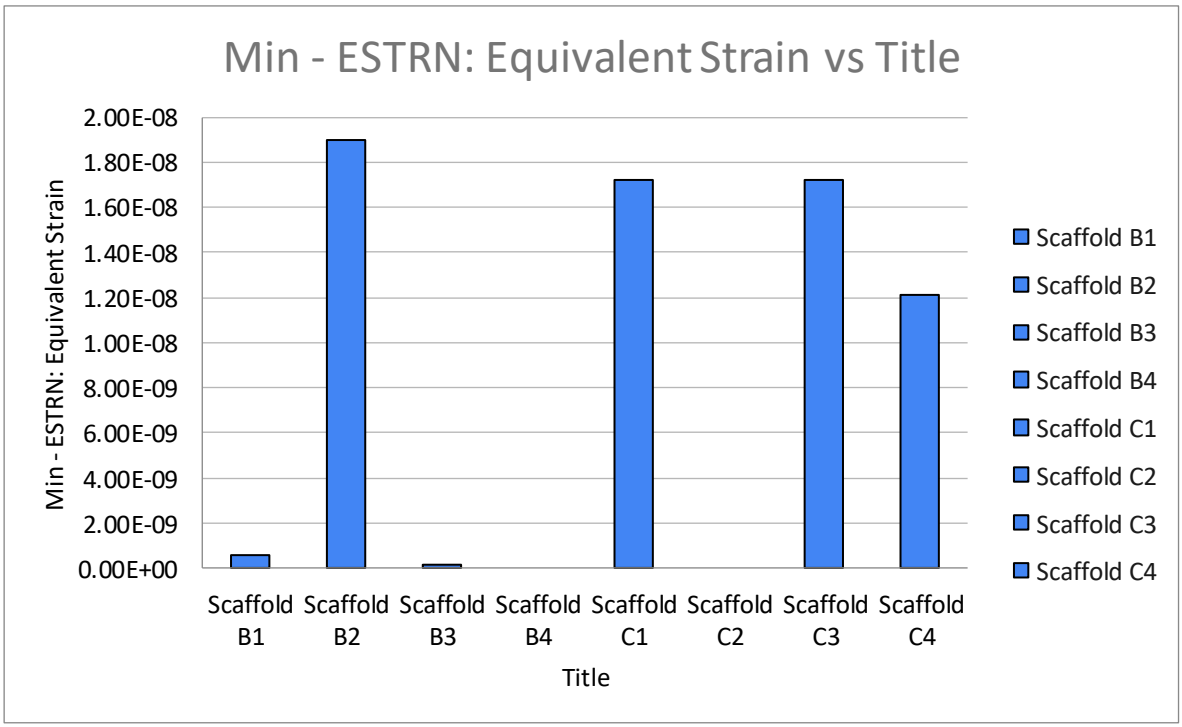

Figure 17: Minimum strains on all scaffolds

Figure 17 shows the difference in the minimum strain of all scaffolds, scaffold B4 & C2 show lower minimum strains compared to other scaffolds.

4.1.4 Summary

The tables and figures above showed the results got after designing and finite element analysis using solidworks and conclusion on the results is going to be high lighted in the following chapter.

4.2 Discussion

This study enlightened more on another alternative then using bone graft and other old treatment of damaged bone tissue. Bone tissue is the solidest tissue in the musculoskeletal system, yet it is prone to damages as an outcome mainly of trauma. Fortunately, it has self-healing capability without leading to scar formation for the majority of injuries. Unfortunately, this capacity of bone is limited to defects with sizes smaller than critical size, a defect length generally exceeding an L/D ratio of 2–2.5 associated with the affected bone, in addition to other factors such as age, location, as well as biomechanical conditions. For large bone defects or cases of compromised degenerative processes, intervention is necessary generally through the use of grafts [1].

This study found out that it is possible to design bone scaffold with any structure needed as two different porous structures (500mm and 1000mm) and with different geometry structure (Basic, crossed and their offset of 50%) of Poly(ε-caprolactone) material were modeled in SolidWorks, the only thing was to change from default to customized settings to be able to designed tiny fibers. The CAD model of scaffolds was obtained by repeating 4x4x4 along the x, y, and z-axis using their unit cells of each structure. A fixed unit cell size for all the scaffold models with circular fiber diameter of 400 μm with pore sizes of 500 and 1000 μm on each shape. There are other studies that have proven the possibility of designing and printing bone scaffolds

Scaffolds produced with synthetic polymers are useful tools for bone grafting. Therefore, the current study aimed at testing the capacity of 3D-printed PLA scaffolds as potential bone grafting structures. With this aim, we first fabricated and characterized scaffolds/grafts fabricated using 3D printing technique, and compared scaffold properties with those of native trabecular bone tissue harvested from immature bovine [1].

This study during the design phase, it identified that SA/V in the basic scaffolds (B1 & C1) is higher compared to other scaffolds with (0.0007 - 0.0009) difference but that won't make a big difference and that both cross offsets took a long period of meshing to complete from (48-56) seconds compared to other scaffolds with (36-27) seconds but 54 seconds for B2 is an error due edge fiber (solid modeling).

This study did finite element analysis on stress, strain and displacement of all designed scaffolds which were found to be tolerable like the stresses we considered minimum stresses (9.62E-01 - 0.00E+00) which are lower compared to yield strength (7.00E+07) of the material and maximum stresses was neglected due to the observed made on figure 1 and 2 which show that these stresses are bought by the errors for edge fiber (solid modeling) but the all scaffolds are in blue color which are lower and strain & displacements are all minimum the slight change are due error of edge fibers. But apart from scaffolds with basic structure performed or proved to be better than other scaffolds.

The limitation in our study was unusual raising of parameters due to deformation of the side fiber edge as even other studies demonstrate Indeed, stress shielding raises from the mismatch in stiffness between scaffolds and host bone that causes an undesirable load transfer between surfaces in implanting sites [2]. It is from this point I recommend that in future work, the

modifications of the scaffold design should be done to protect fibers on edges from experiencing higher stresses by building a solid wall and then 3d printing should be done to continue with our research to evaluate the cell growth on these designed bone scaffold using the Polycaprolactone material so that there would be validation of the FEA results. In-vitro and in-vivo testing for biomechanical properties will also be done to verify the rate of bone growth.

CHAPTER 5. CONCLUSION AND RECOMMENDATION

5.1 Conclusion

This study presented a modeling of two different porous structures (500mm and 1000mm) and with different geometry structure (Basic, crossed and their offset of 50%) of Poly(ε-caprolactone) material and their FEA have been performed to simulate the compressive behavior under uni-axial load. Assessment of all eight scaffolds' compressive stresses, strain, porosity, surface area and volume have been discussed. Porosity and SA/V ratio depend upon the geometry structure for a constant volume. The basis with pore size of 500mm is recommended as the suitable candidate over other scaffolds due to its higher SA/V ratio and on the point of stresses all scaffolds have a minimum stress compared to the yield strength.

5.2 Recommendations

For future work, the modifications of the scaffold design should be done to protect fibres on edges from experiencing higher stresses by building a solid wall and then 3d printing should be done to continue with our research to evaluate the cell growth on these designed bone scaffold using the Polycaprolactone material so that there would be validation of the FEA results. In-vitro and in-vivo testing for biomechanical properties will also be done to verify the rate of bone growth.

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APPENDICES

Appendix 1: Full results of FEA of all scaffolds

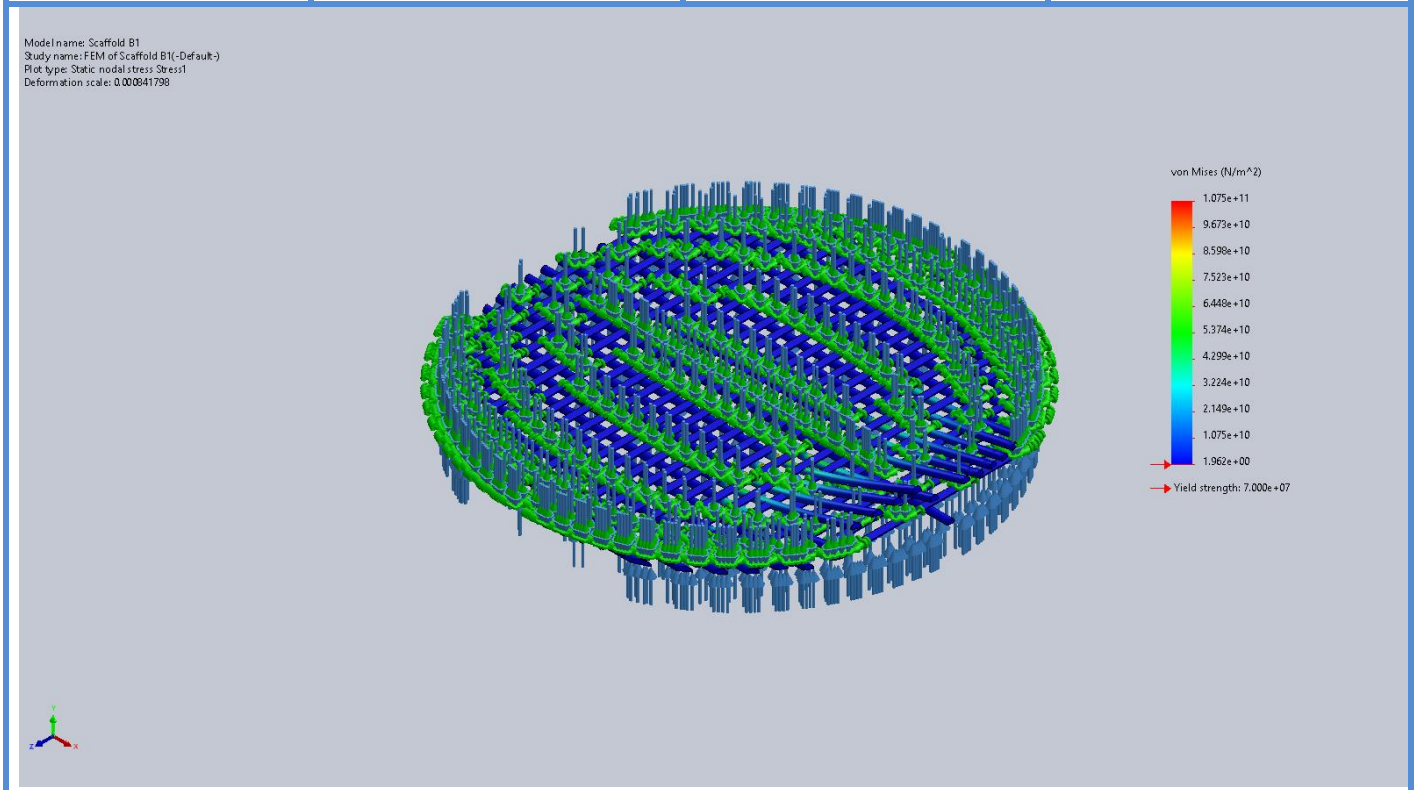
1. FEA study results of scaffold B1
2. FEA study results of scaffold B2
3. FEA study results of scaffold B3
4. FEA study results of scaffold B4
5. FEA study results of scaffold C1
6. FEA study results of scaffold C2
7. FEA study results of scaffold C3
8. FEA study results of scaffold C4

Appendix 2: 2d drawings of all scaffolds

1. 2d drawing of scaffold B1
2. 2d drawing of scaffold B2
3. 2d drawing of scaffold B3
4. 2d drawing of scaffold B4
5. 2d drawing of scaffold C1
6. 2d drawing of scaffold C2
7. 2d drawing of scaffold C3
8. 2d drawing of scaffold C4

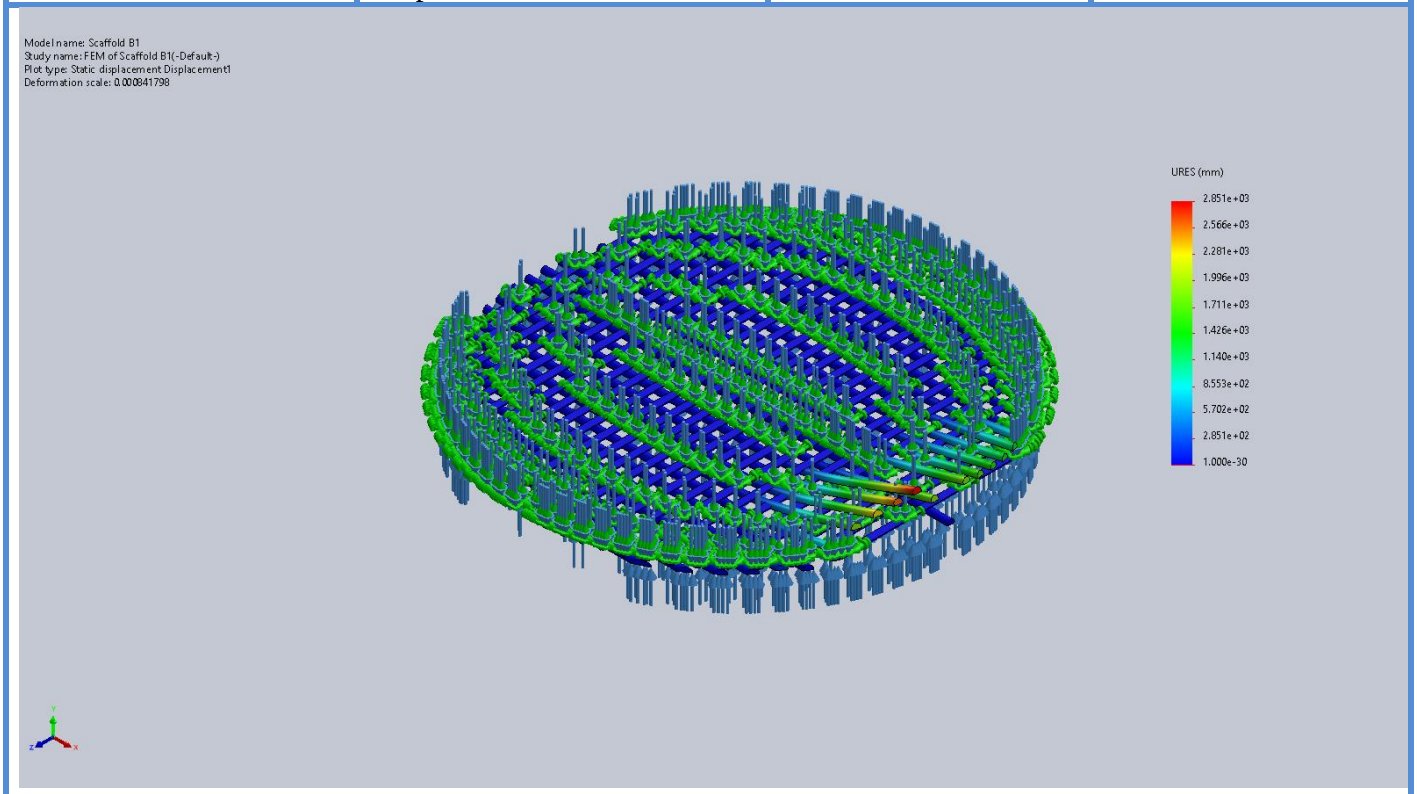
FEM Study Results of Scaffold B1

Name	Type	Min	Max
Stress1	VON: von Mises Stress	1.962e+00N/m^2 Node: 29278	1.075e+11N/m^2 Node: 160479



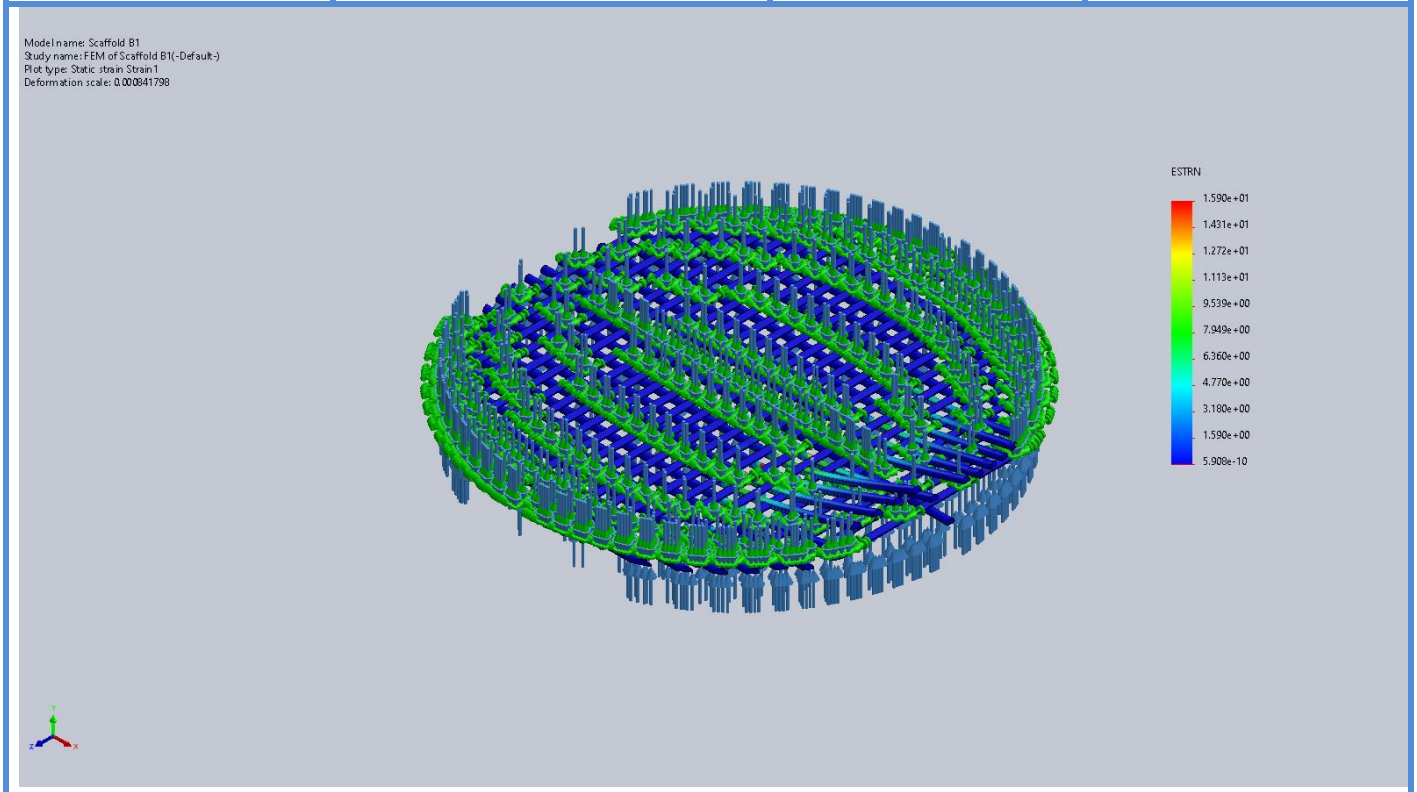
Scaffold B1-FEM of Scaffold B1-Stress-Stress1

Name	Type	Min	Max
Displacement1	URES: Resultant Displacement	0.000e+00mm Node: 4369	2.851e+03mm Node: 110730



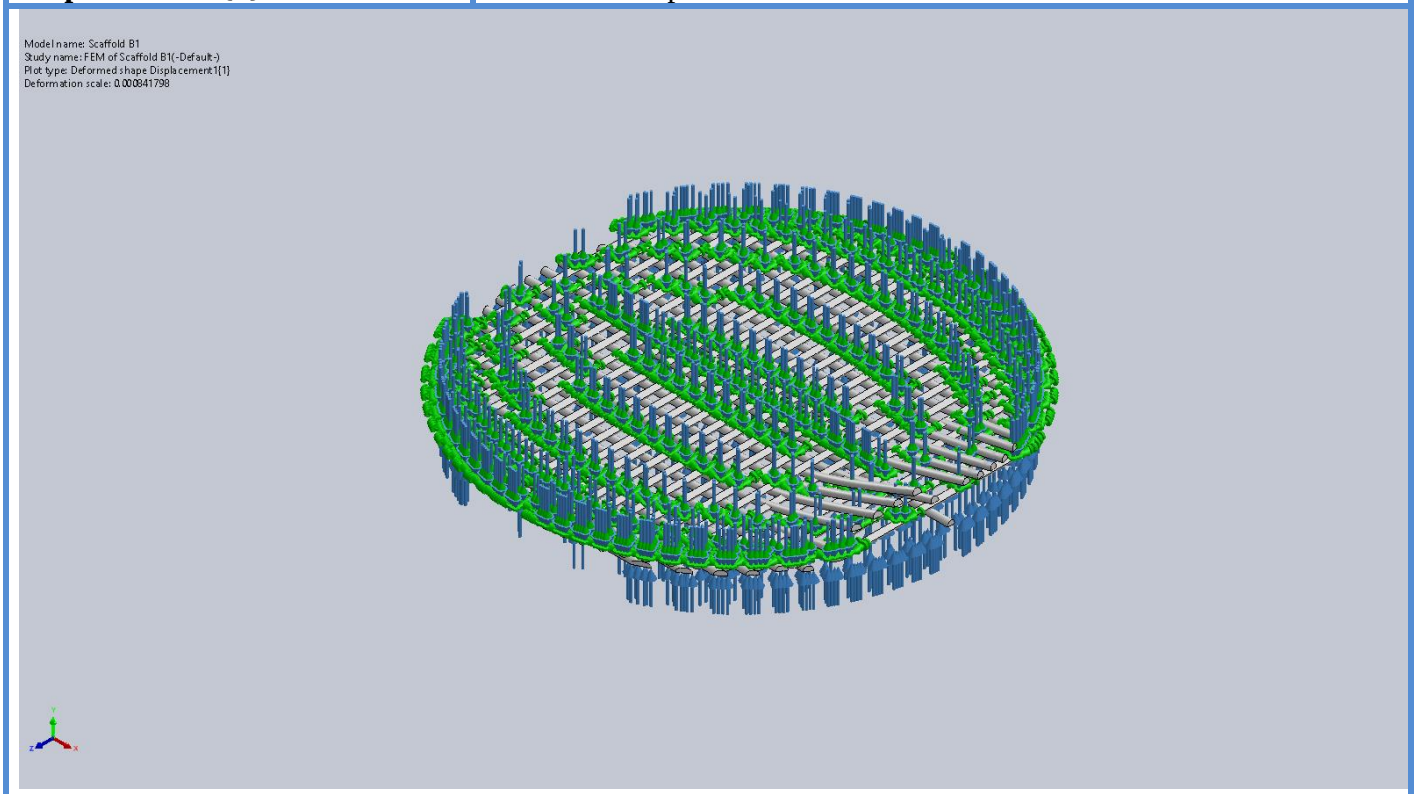
Scaffold B1-FEM of Scaffold B1-Displacement-Displacement1

Name	Type	Min	Max
Strain1	ESTRN: Equivalent Strain	5.908e-10 Element: 68576	1.590e+01 Element: 69304



Scaffold B1-FEM of Scaffold B1-Strain-Strain1

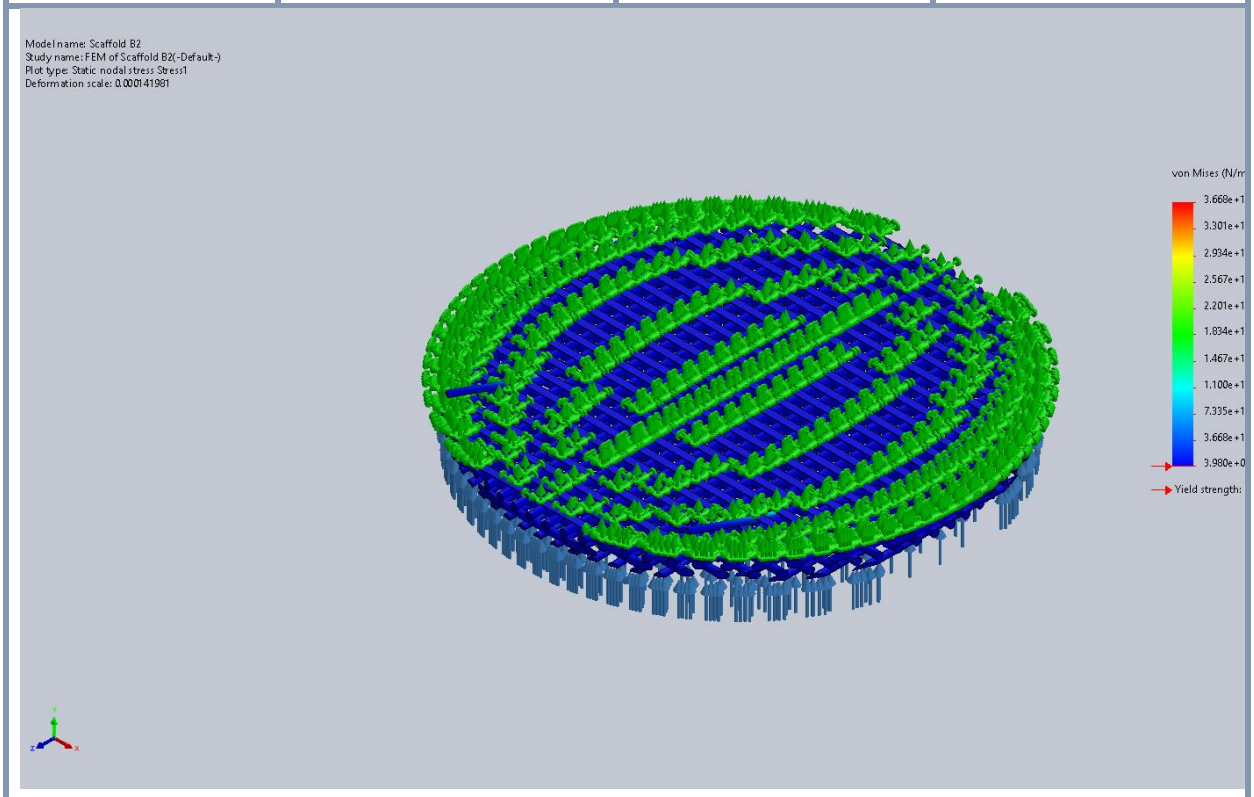
Name	Type
Displacement1{1}	Deformed shape



Scaffold B1-FEM of Scaffold B1-Displacement-Displacement1{1}

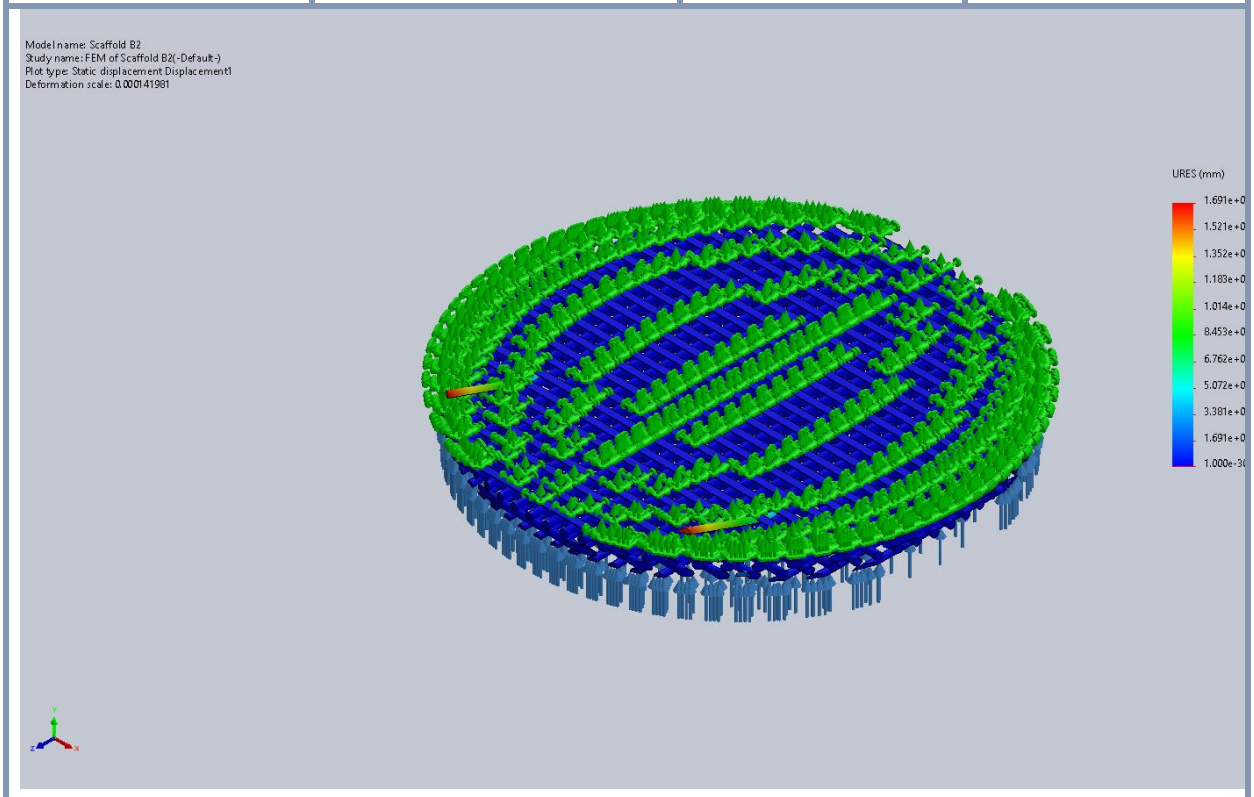
FEM Study Results of Scaffold B2

Name	Type	Min	Max
Stress1	VON: von Mises Stress	3.980e+01N/m^2 Node: 89100	3.668e+11N/m^2 Node: 201271



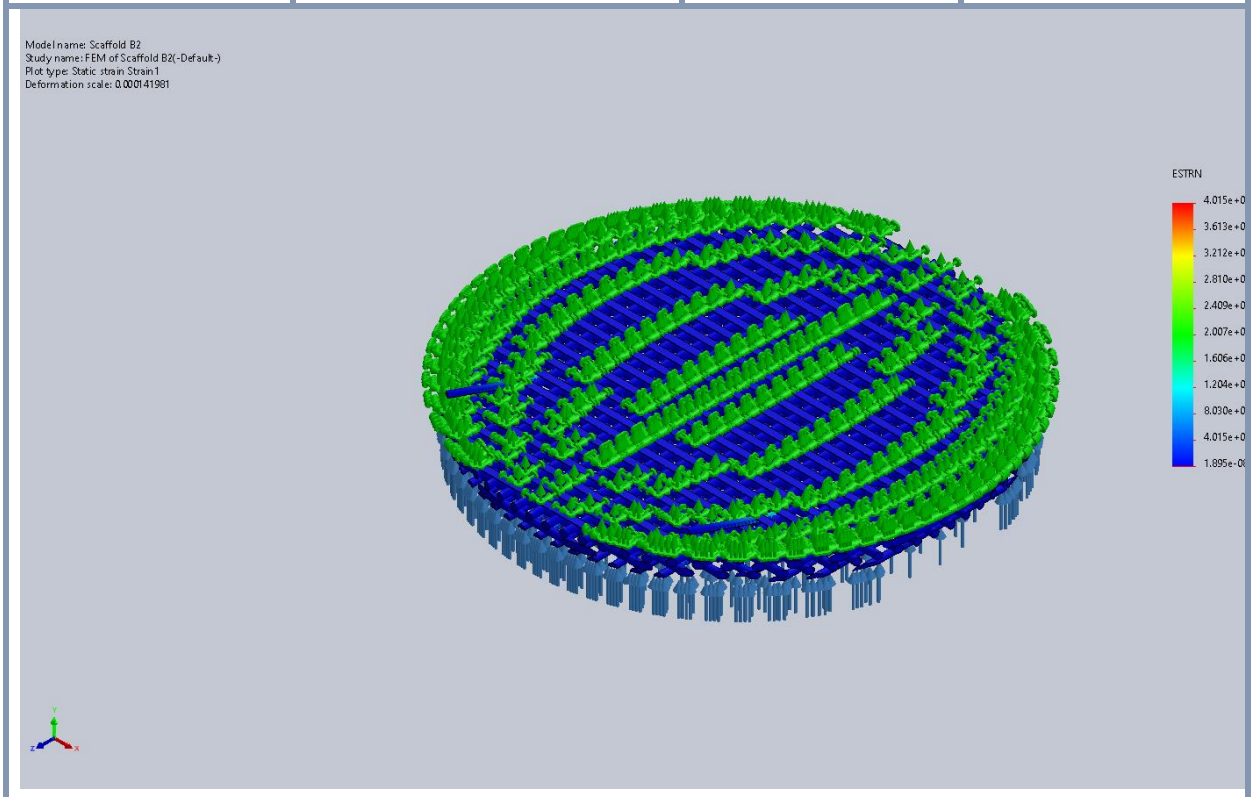
Scaffold B2-FEM of Scaffold B2-Stress-Stress1

Name	Type	Min	Max
Displacement1	URES: Resultant Displacement	0.000e+00mm Node: 3181	1.691e+04mm Node: 201526



Scaffold B2-FEM of Scaffold B2-Displacement-Displacement1

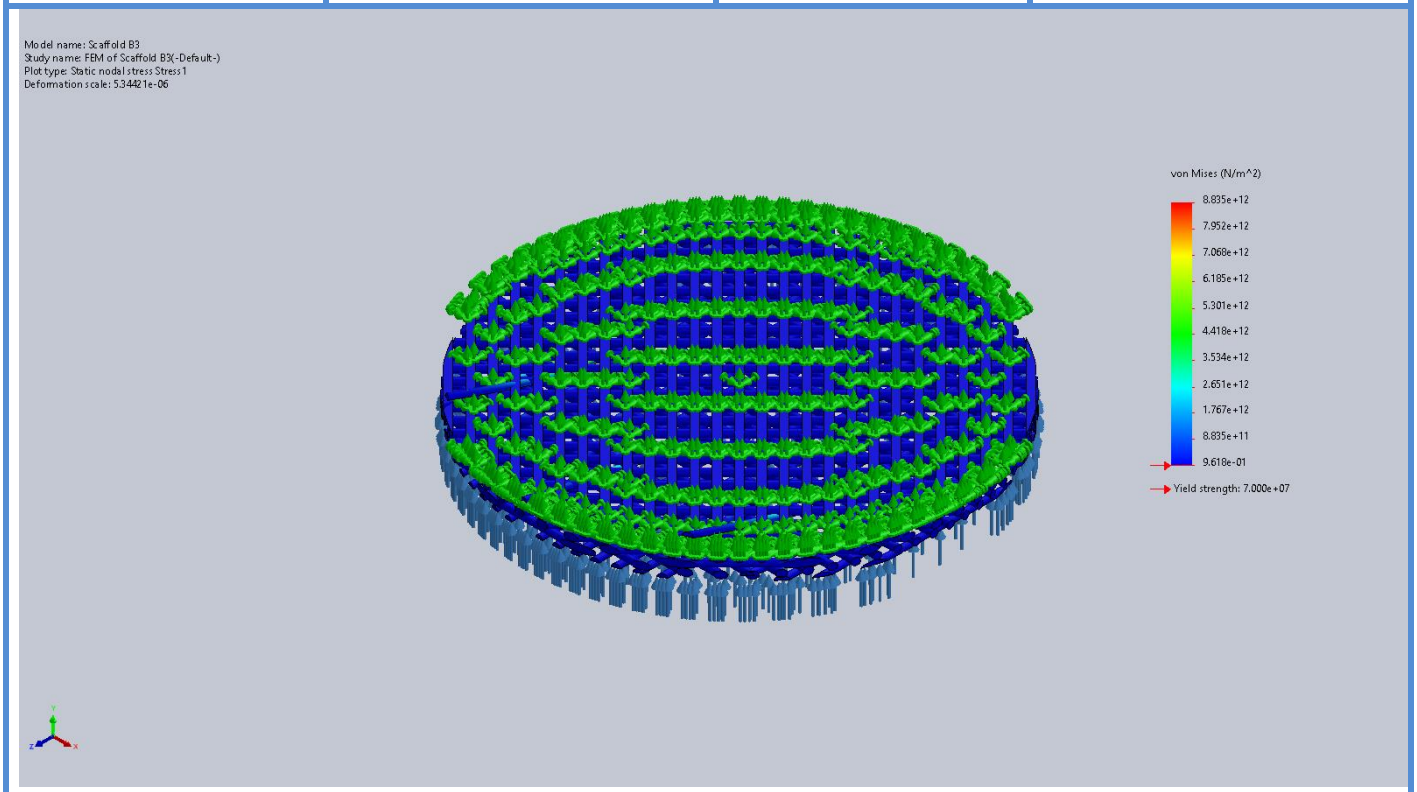
Name	Type	Min	Max
Strain1	ESTRN: Equivalent Strain	1.895e-08 Element: 37348	4.015e+01 Element: 122349



Scaffold B2-FEM of Scaffold B2-Strain-Strain1

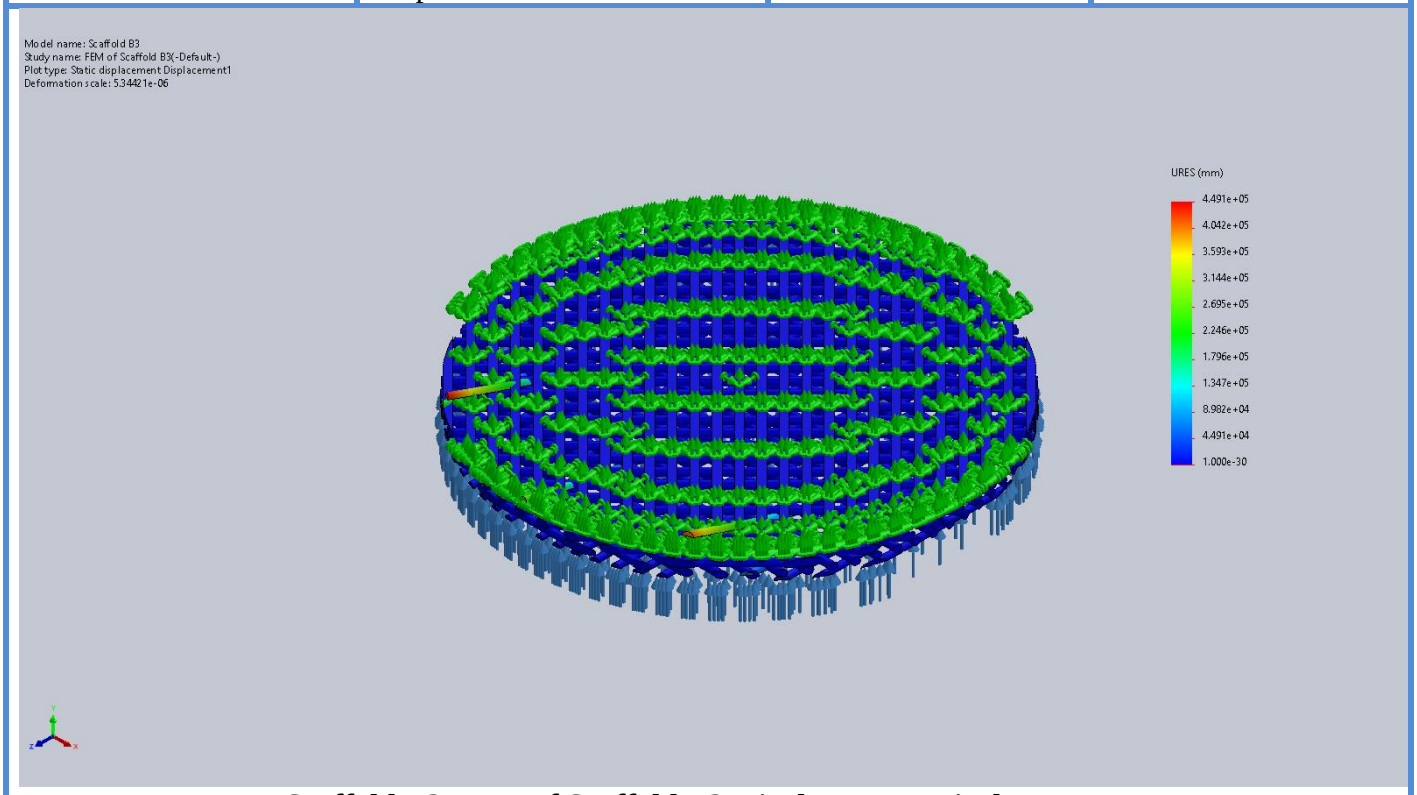
FEM Study Results OF Scaffold B3

Name	Type	Min	Max
Stress1	VON: von Mises Stress	9.618e-01N/m^2 Node: 352636	8.835e+12N/m^2 Node: 43164



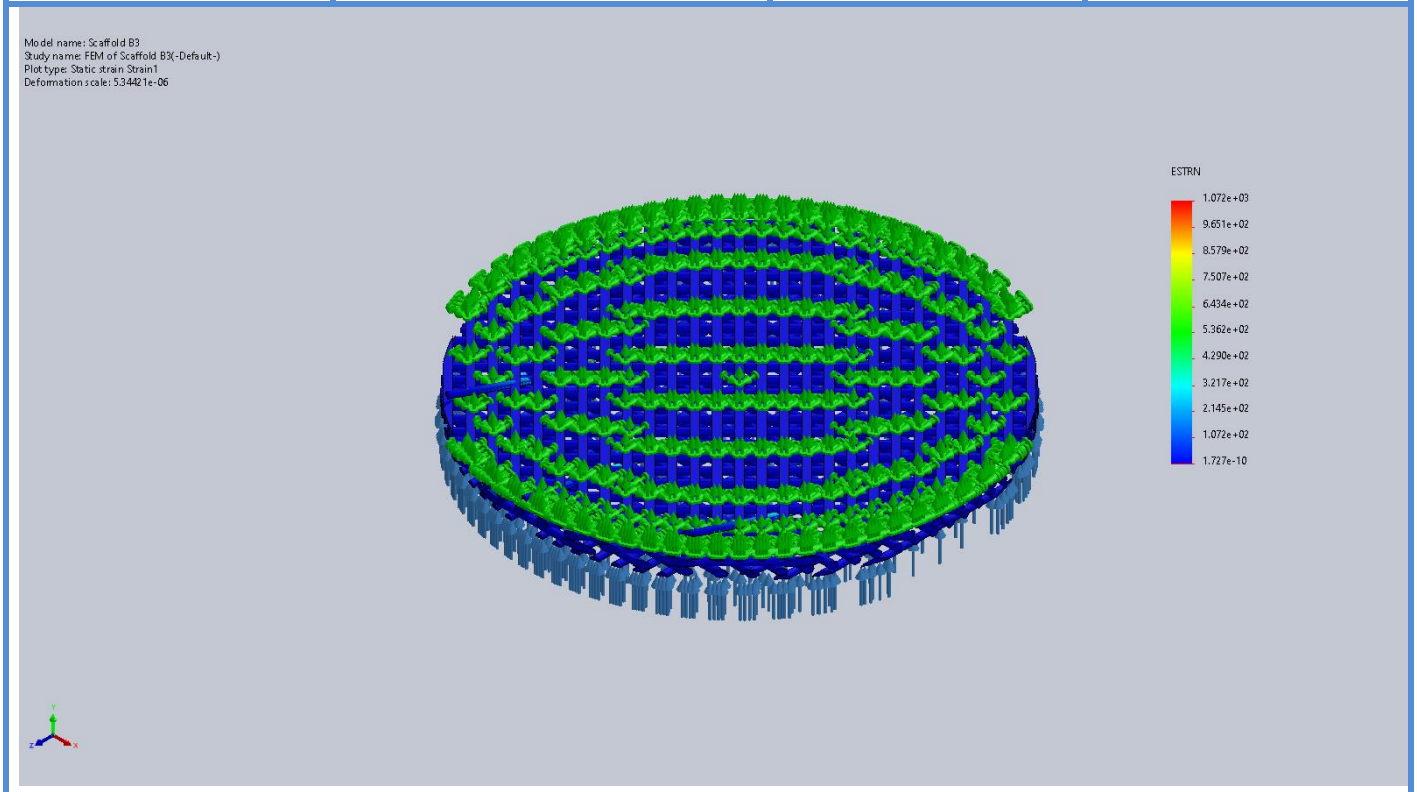
Scaffold B3-FEM of Scaffold B3-Stress-Stress1

Name	Type	Min	Max
Displacement1	URES: Resultant Displacement	0.000e+00mm Node: 1	4.491e+05mm Node: 43423



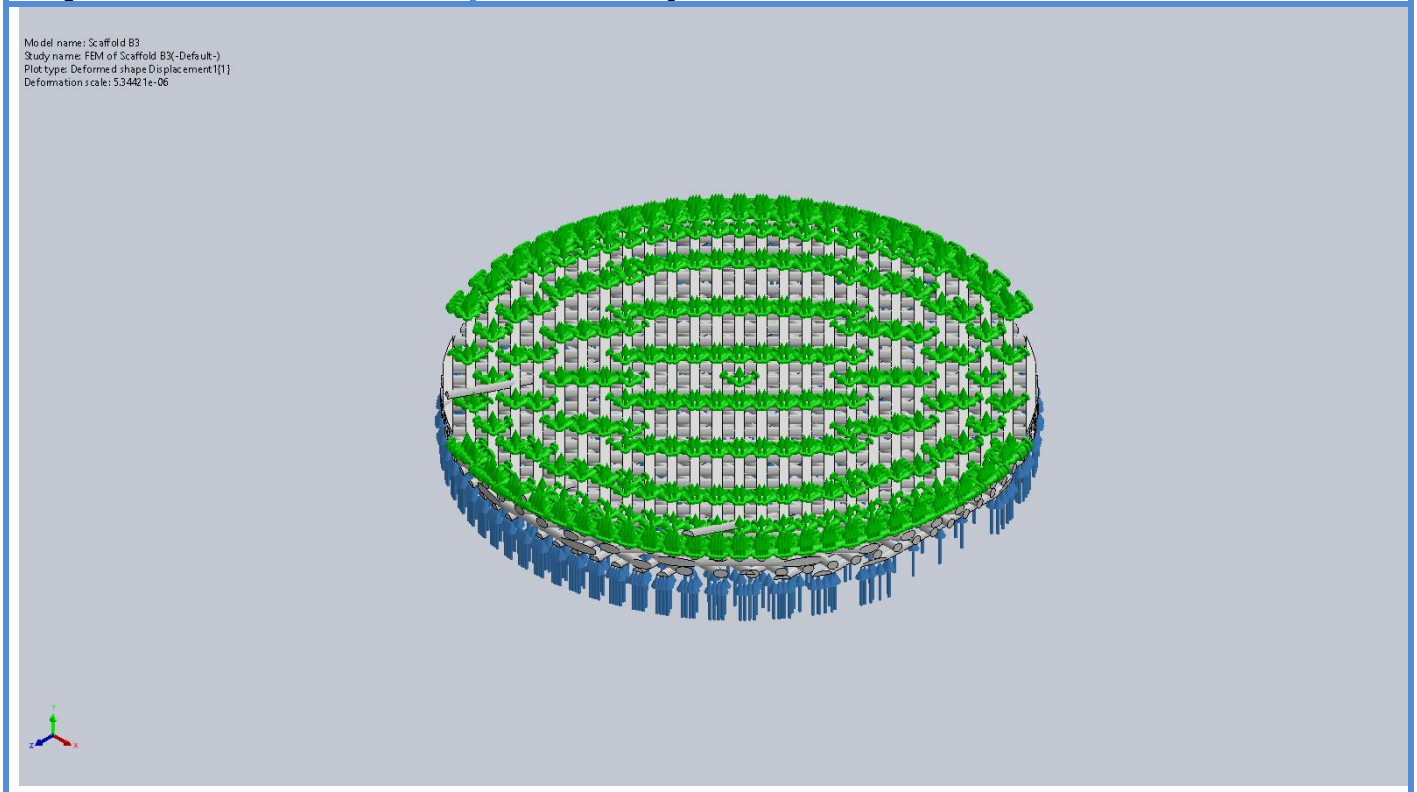
Scaffold B3-FEM of Scaffold B3-Displacement-Displacement1

Name	Type	Min	Max
Strain1	ESTRN: Equivalent Strain	1.727e-10 Element: 156034	1.072e+03 Element: 20900



Scaffold B3-FEM of Scaffold B3-Strain-Strain1

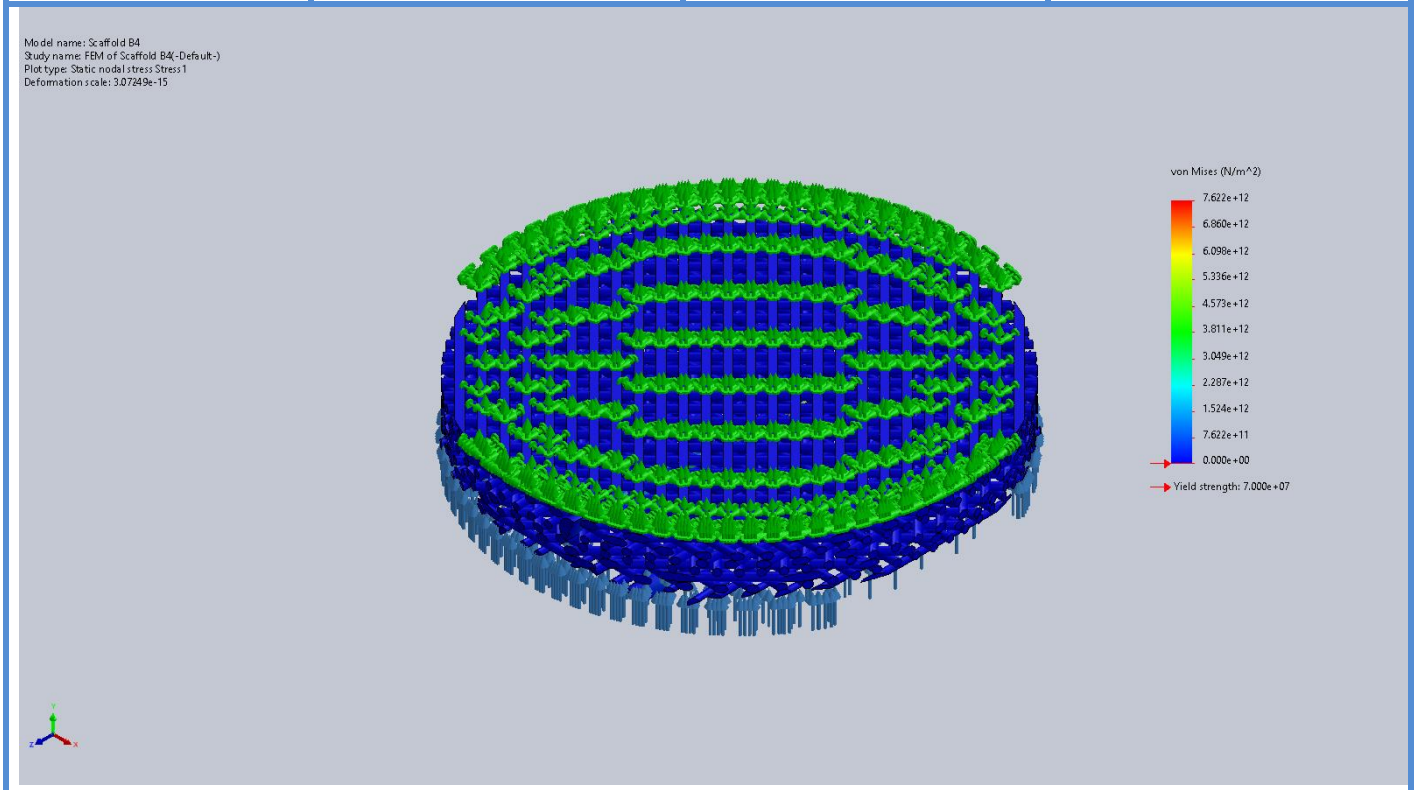
Name	Type
Displacement1{1}	Deformed shape



Scaffold B3-FEM of Scaffold B3-Displacement-Displacement1{1}

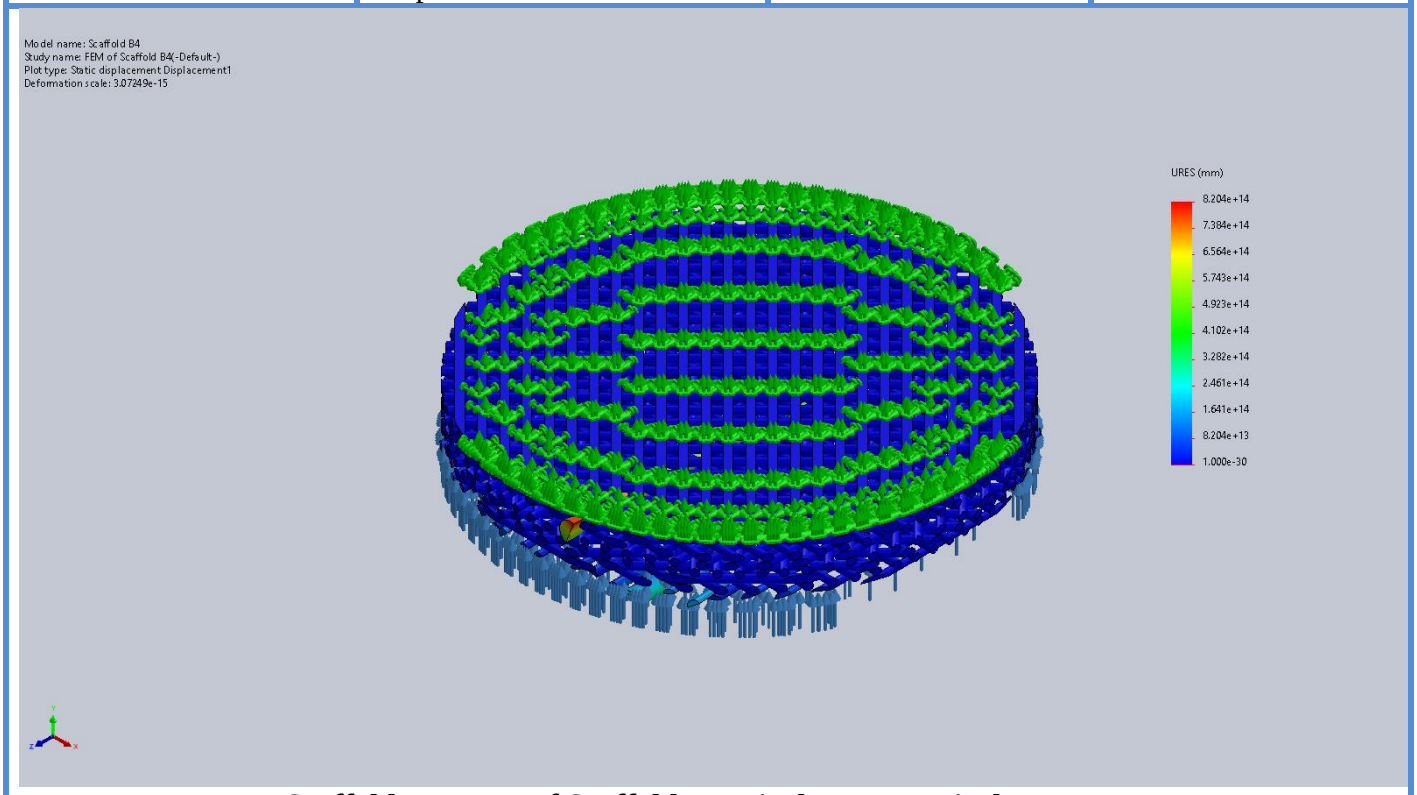
FEM Study Results of Scaffold B4

Name	Type	Min	Max
Stress1	VON: von Mises Stress	0.000e+00N/m^2 Node: 1	7.622e+12N/m^2 Node: 73333



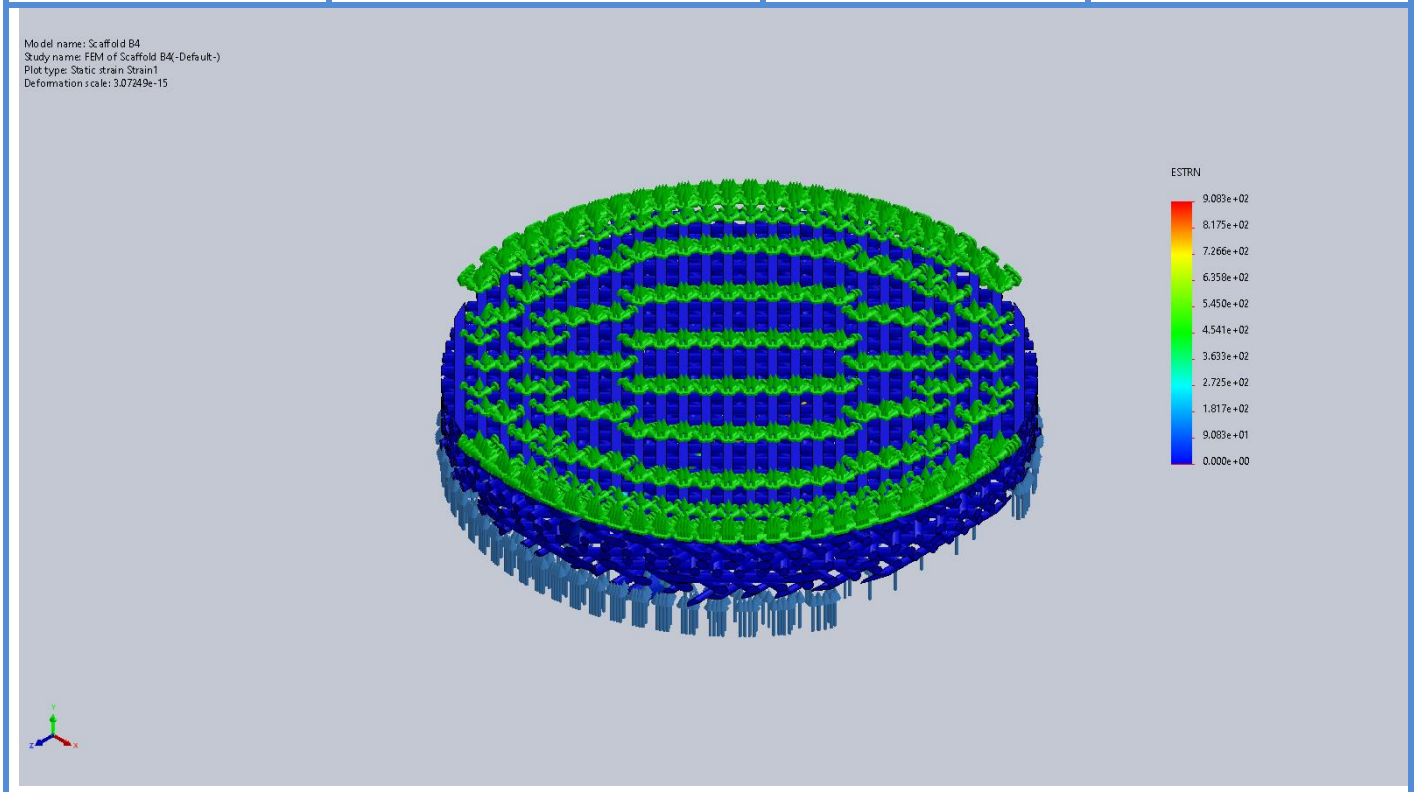
Scaffold B4-FEM of Scaffold B4-Stress-Stress1

Name	Type	Min	Max
Displacement1	URES: Resultant Displacement	0.000e+00mm Node: 1	8.204e+14mm Node: 73748



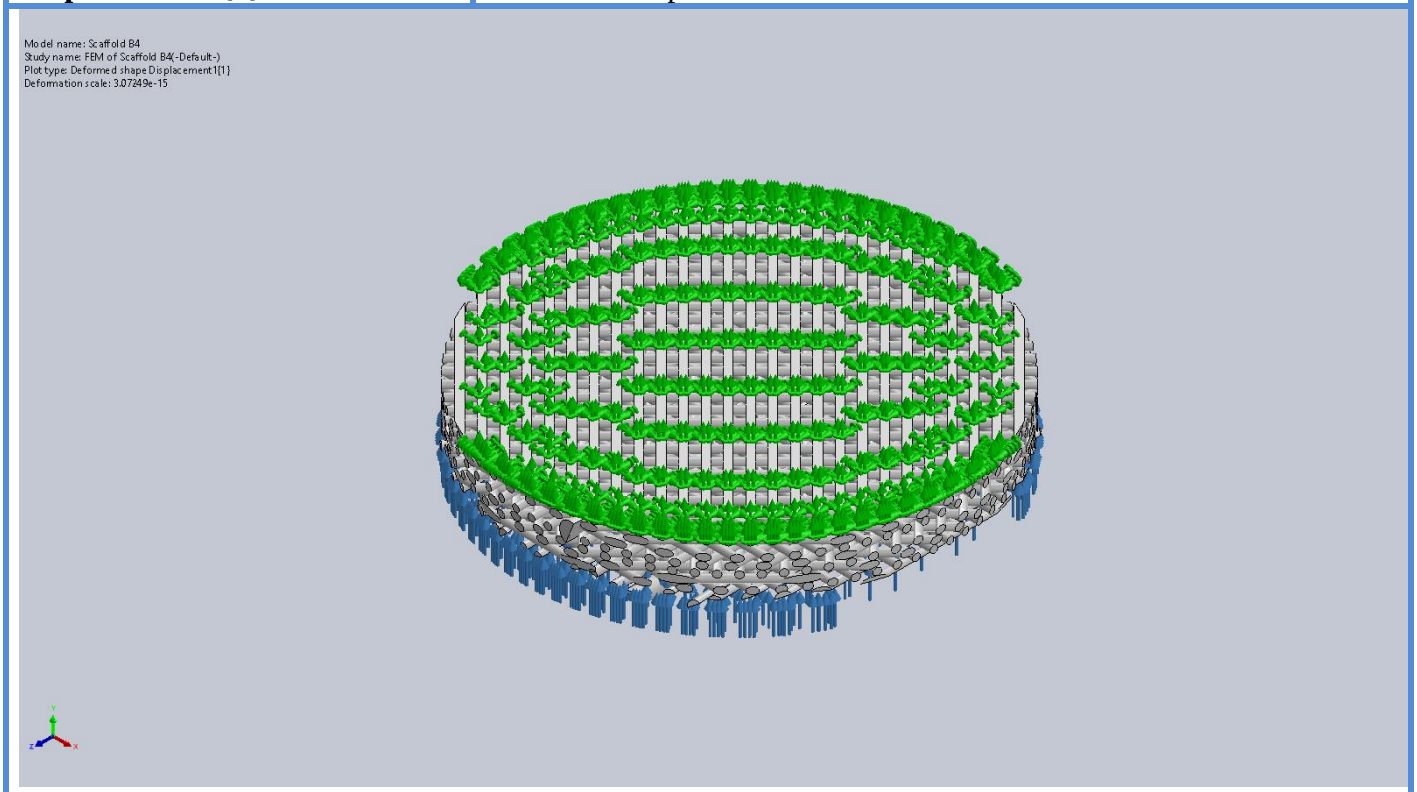
Scaffold B4-FEM of Scaffold B4-Displacement-Displacement1

Name	Type	Min	Max
Strain1	ESTRN: Equivalent Strain	0.000e+00 Element: 1	9.083e+02 Element: 30282



Scaffold B4-FEM of Scaffold B4-Strain-Strain1

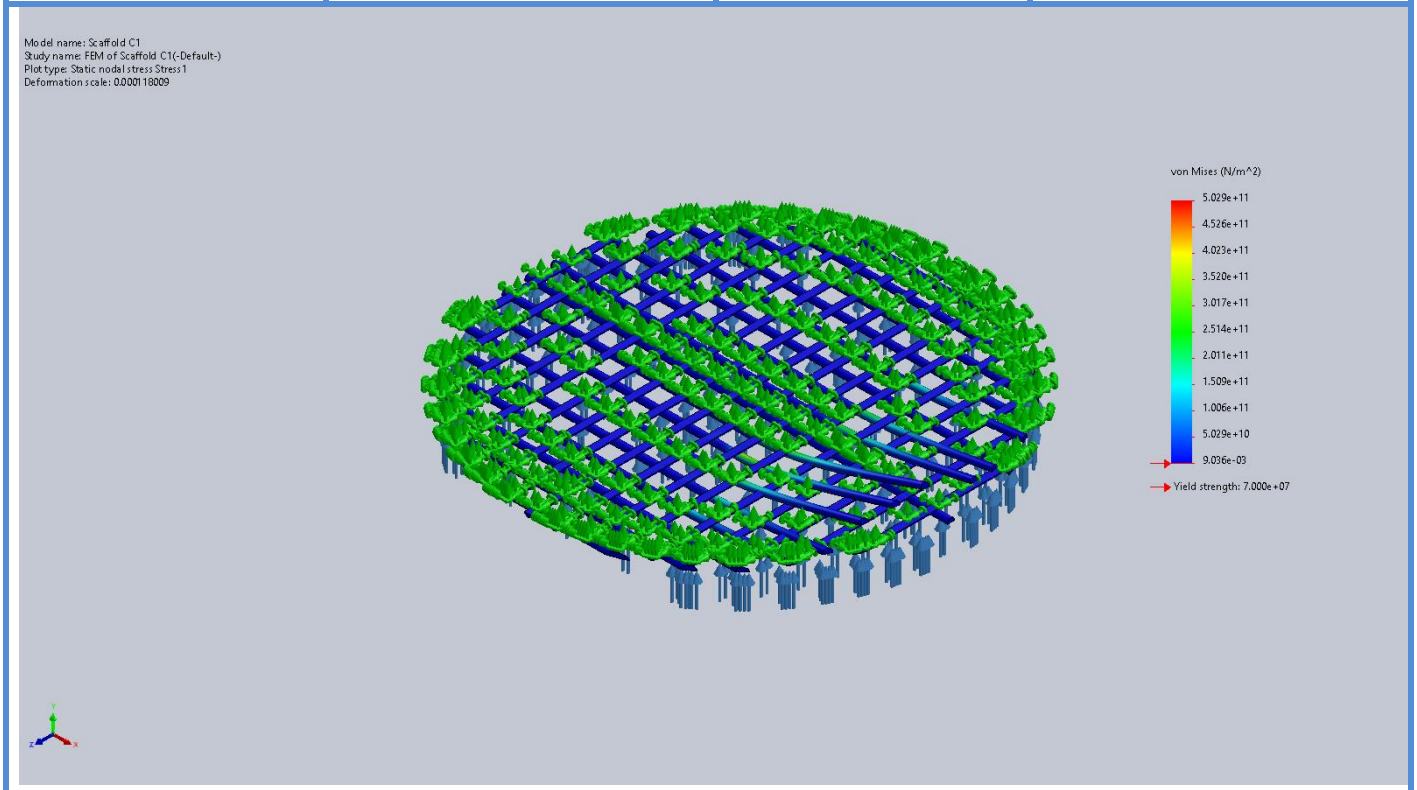
Name	Type
Displacement1{1}	Deformed shape



Scaffold B4-FEM of Scaffold B4-Displacement-Displacement1{1}

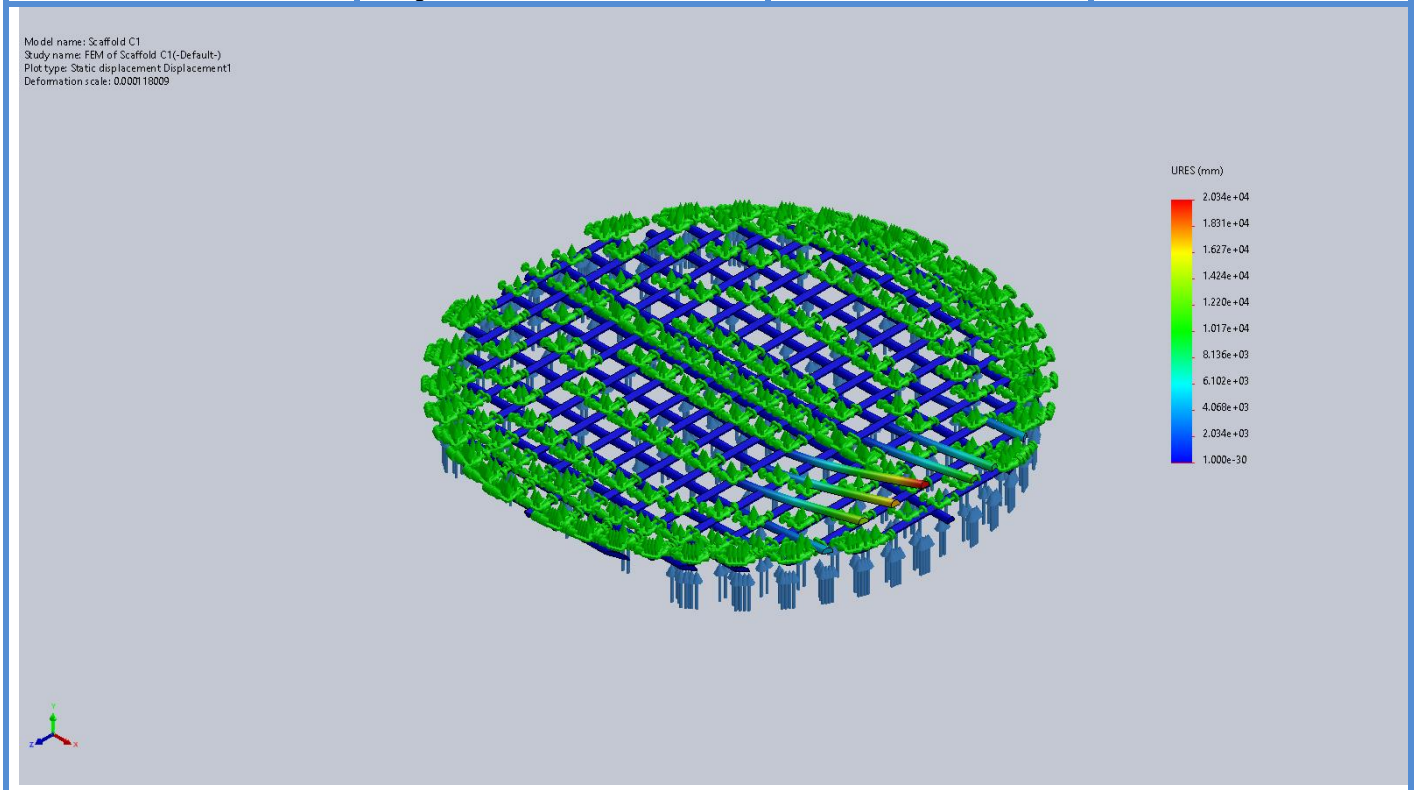
FEM Study Results of Scaffold C1

Name	Type	Min	Max
Stress1	VON: von Mises Stress	9.036e-03N/m^2 Node: 87457	5.029e+11N/m^2 Node: 35673



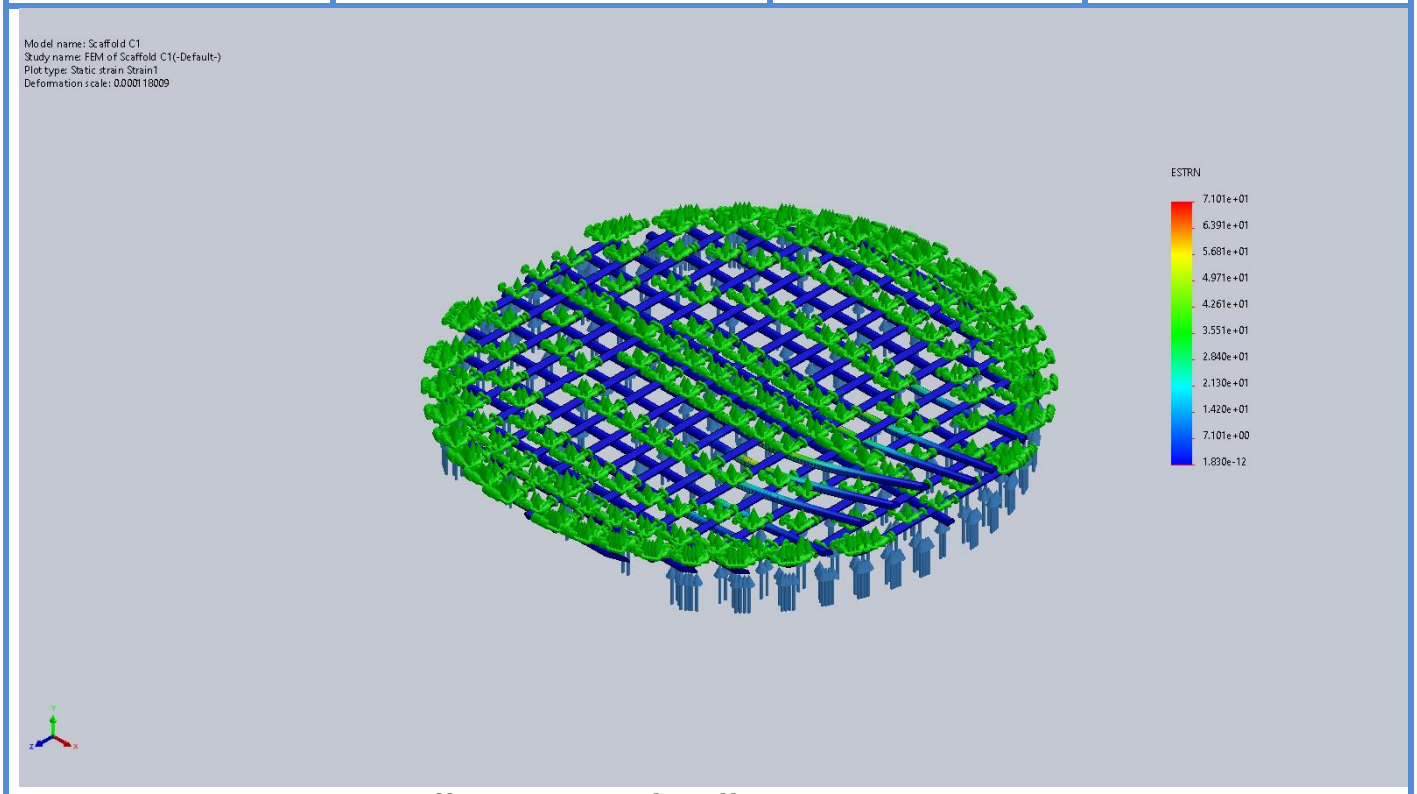
Scaffold C1-FEM of Scaffold C1-Stress-Stress1

Name	Type	Min	Max
Displacement1	URES: Resultant Displacement	0.000e+00mm Node: 1	2.034e+04mm Node: 47237



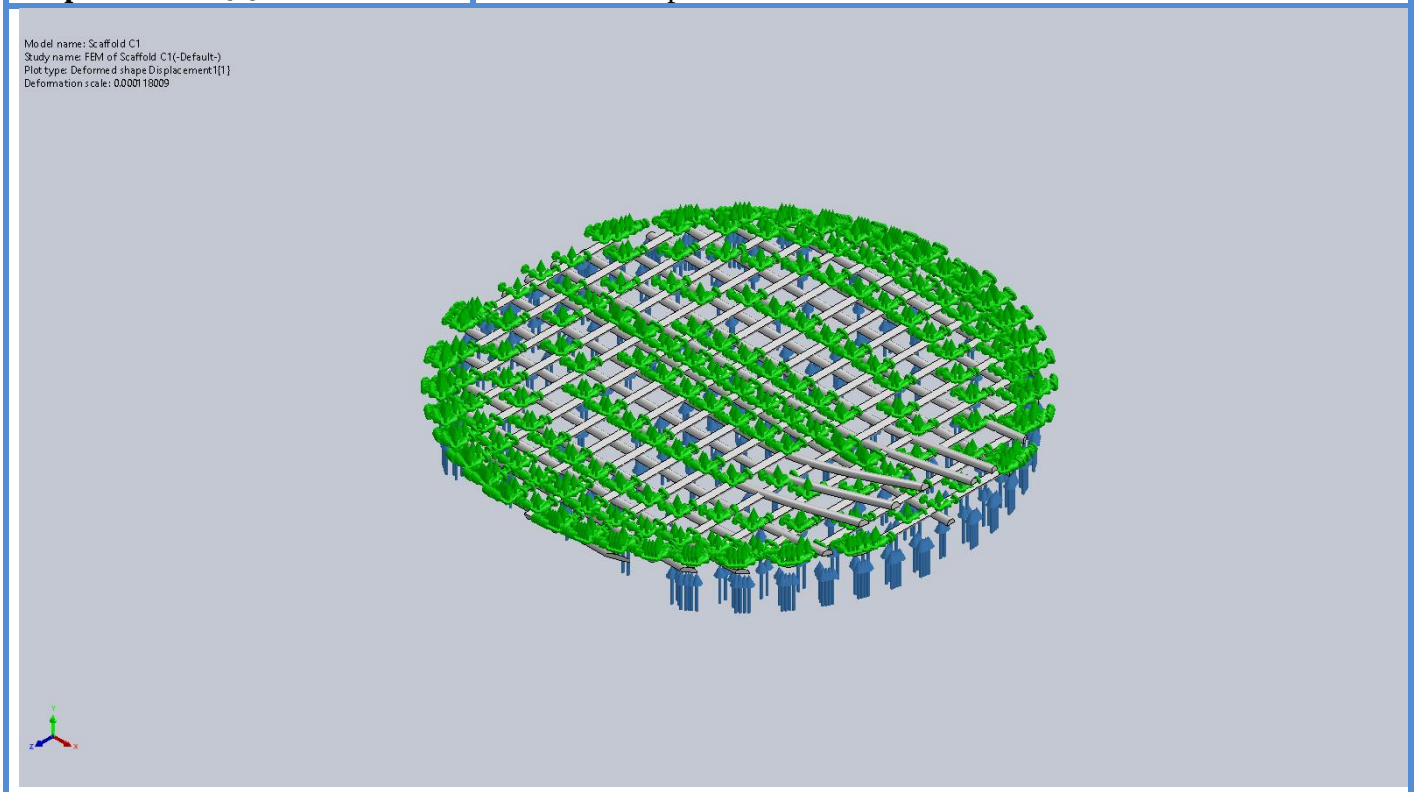
Scaffold C1-FEM of Scaffold C1-Displacement-Displacement1

Name	Type	Min	Max
Strain1	ESTRN: Equivalent Strain	1.830e-12 Element: 37903	7.101e+01 Element: 15080



Scaffold C1-FEM of Scaffold C1-Strain-Strain1

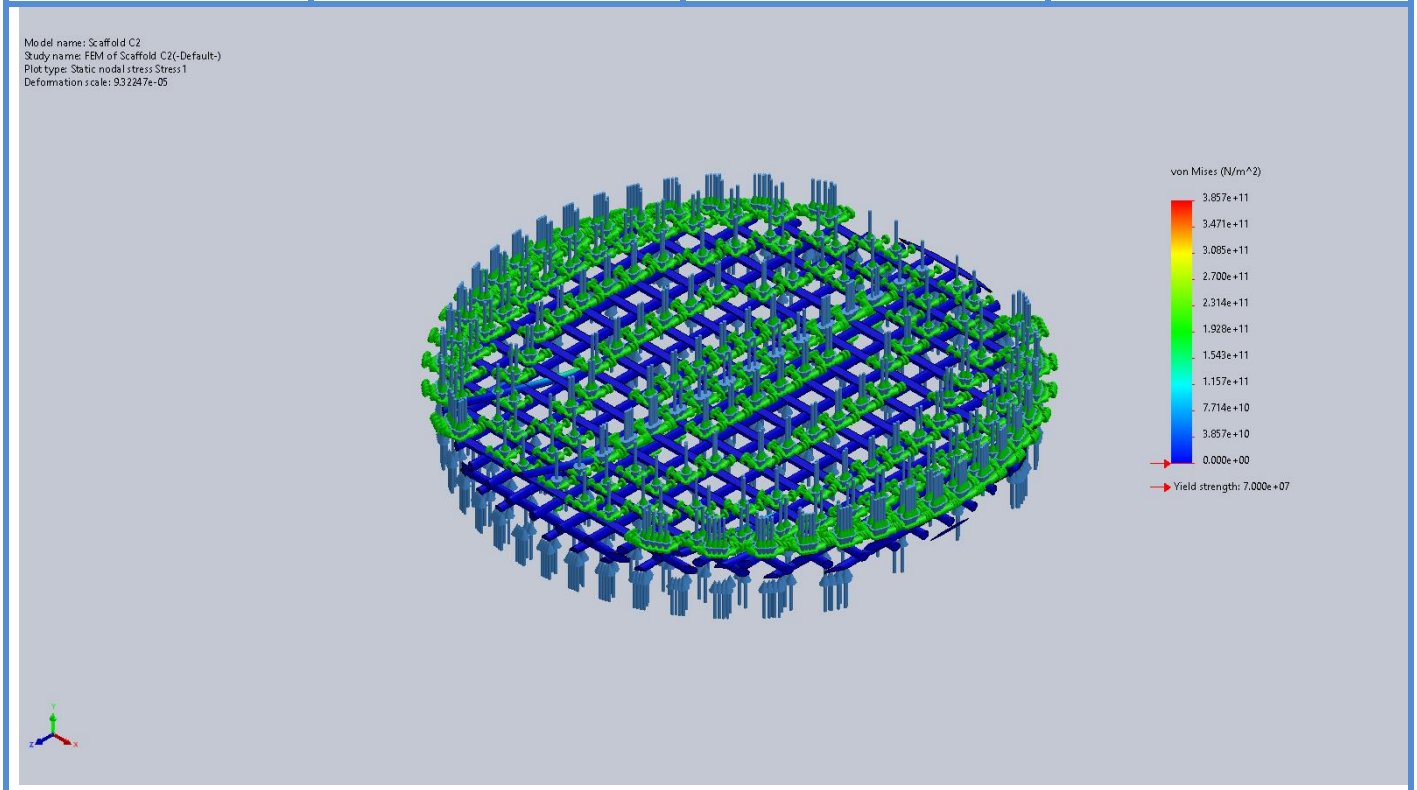
Name	Type
Displacement1{1}	Deformed shape



Scaffold C1-FEM of Scaffold C1-Displacement-Displacement1{1}

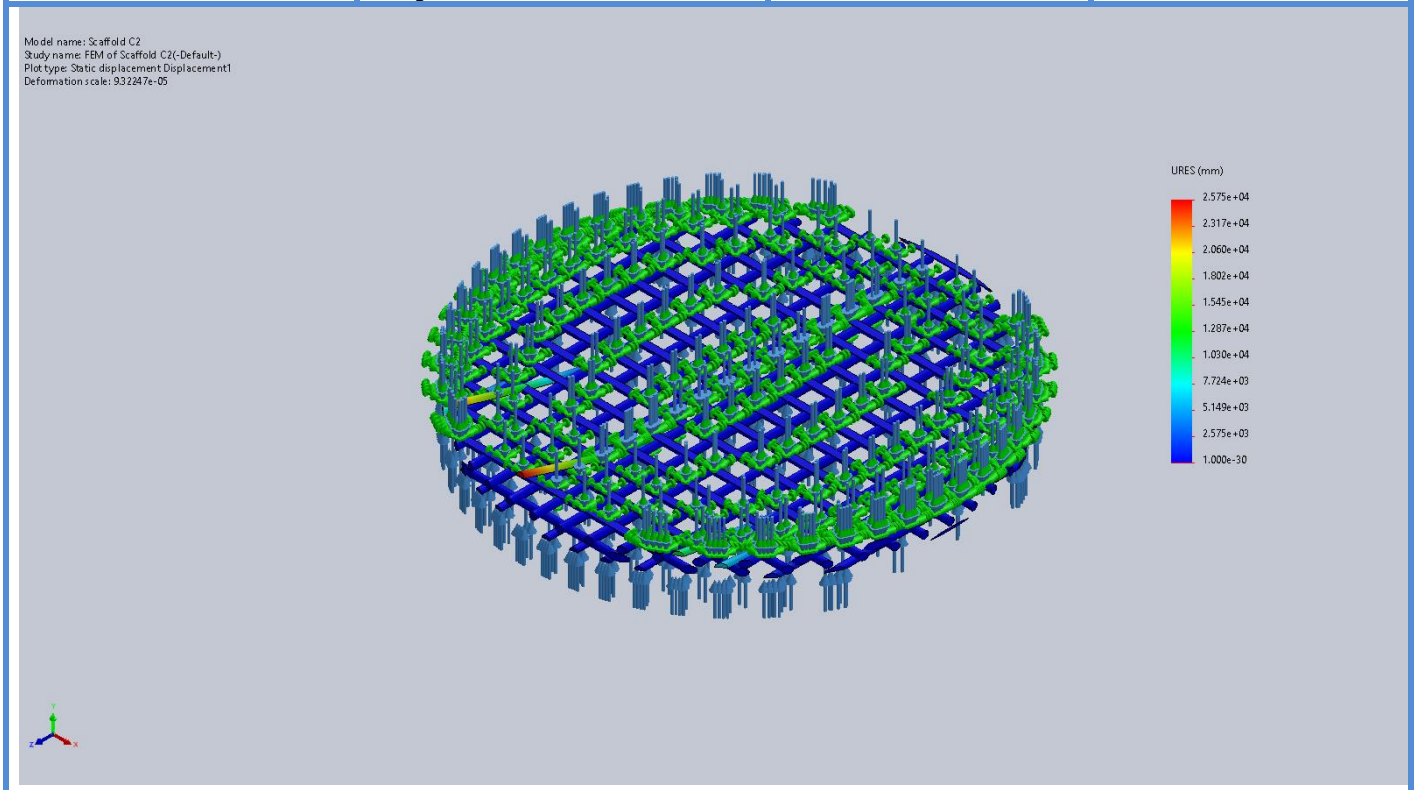
FEM Study Results OF Scaffold C2

Name	Type	Min	Max
Stress1	VON: von Mises Stress	0.000e+00N/m^2 Node: 107313	3.857e+11N/m^2 Node: 45625



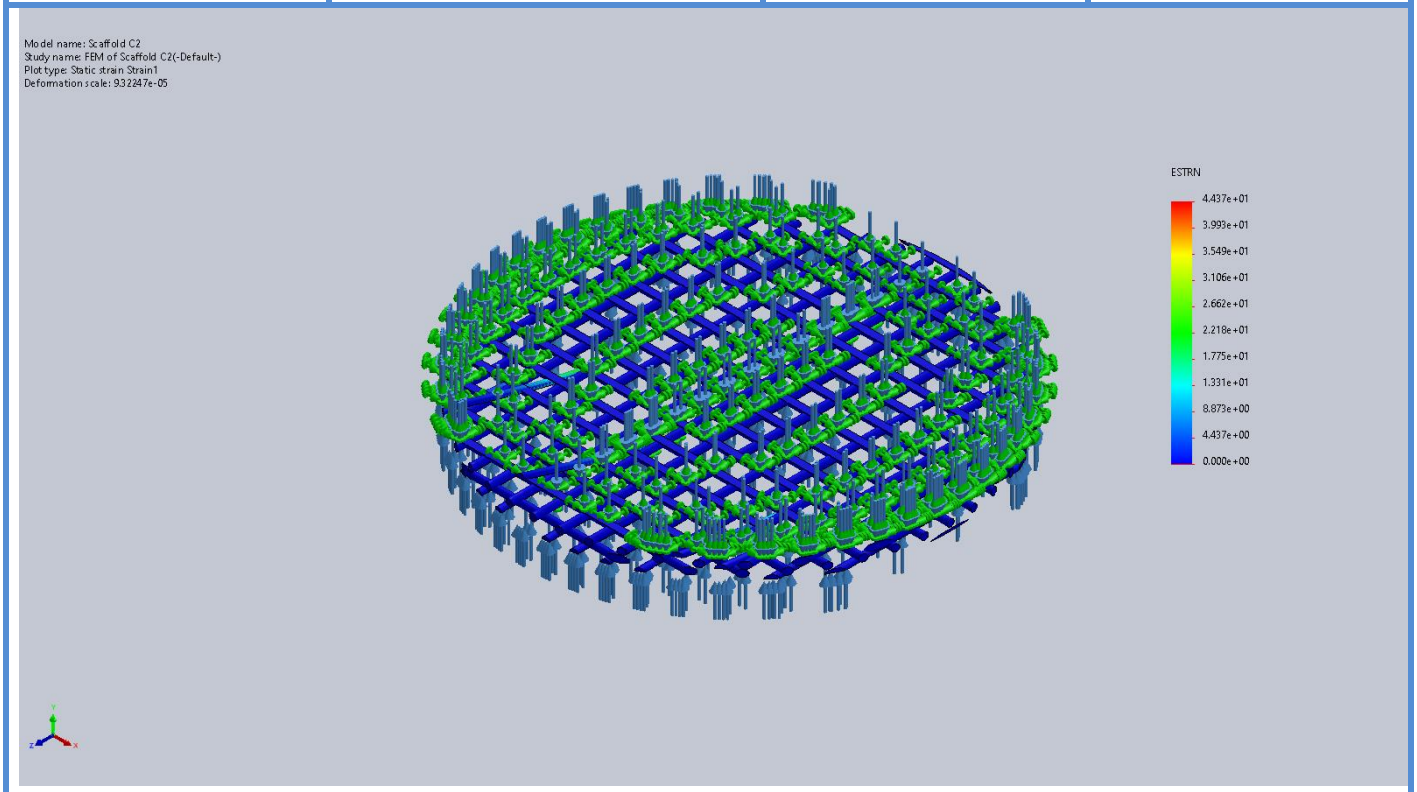
Scaffold C2-FEM of Scaffold C2-Stress-Stress1

Name	Type	Min	Max
Displacement1	URES: Resultant Displacement	0.000e+00mm Node: 4637	2.575e+04mm Node: 10538



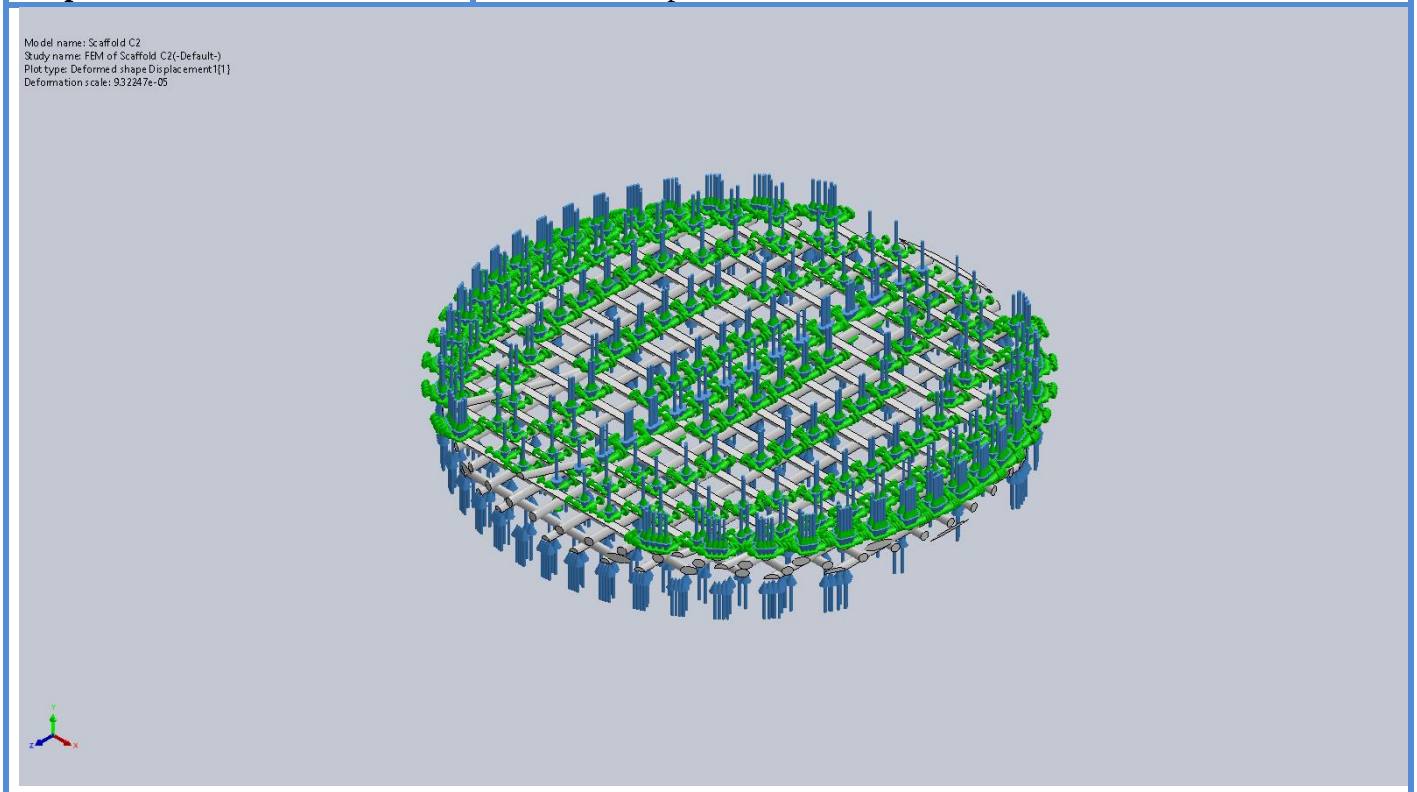
Scaffold C2-FEM of Scaffold C2-Displacement-Displacement1

Name	Type	Min	Max
Strain1	ESTRN: Equivalent Strain	0.000e+00 Element: 47002	4.437e+01 Element: 5718



Scaffold C2-FEM of Scaffold C2-Strain-Strain1

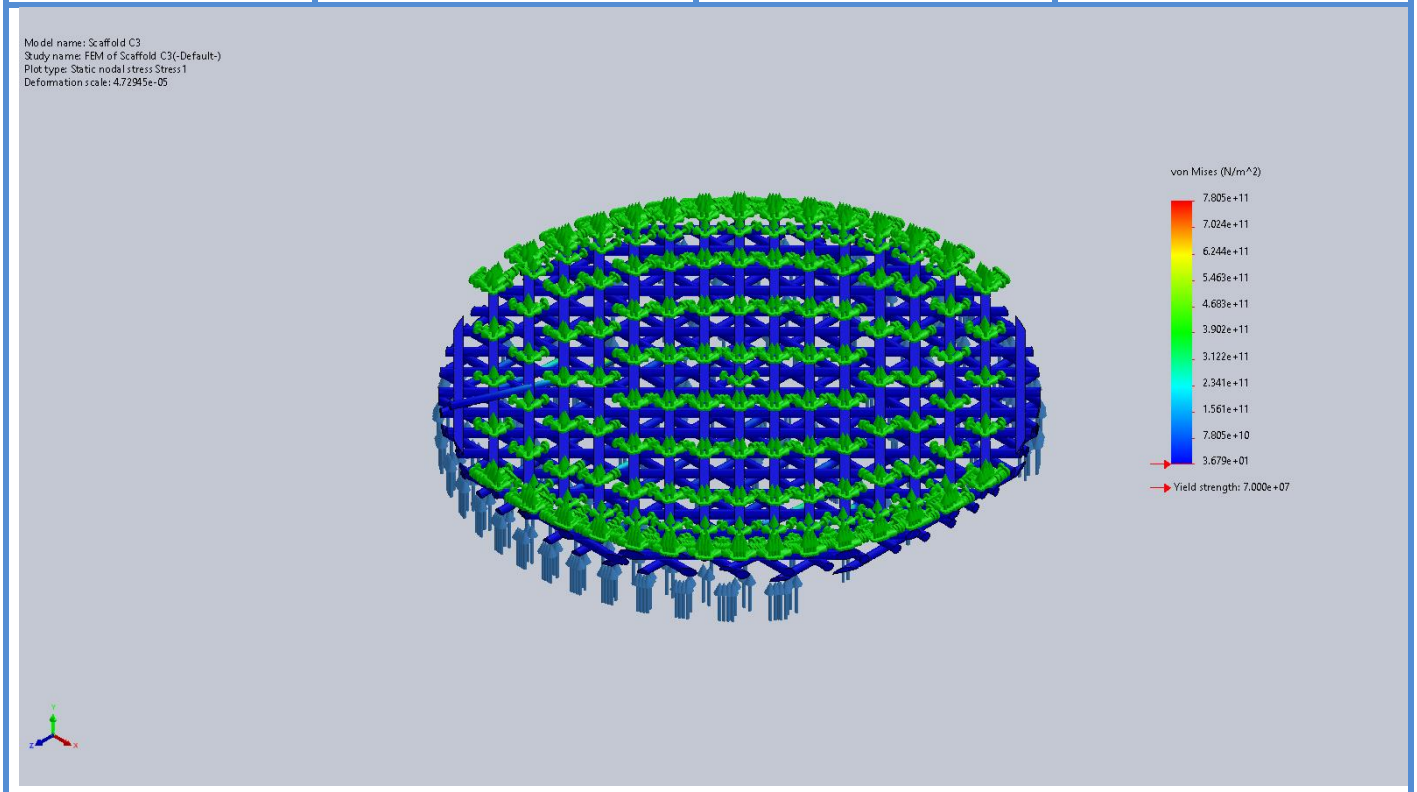
Name	Type
Displacement1{1}	Deformed shape



Scaffold C2-FEM of Scaffold C2-Displacement-Displacement1{1}

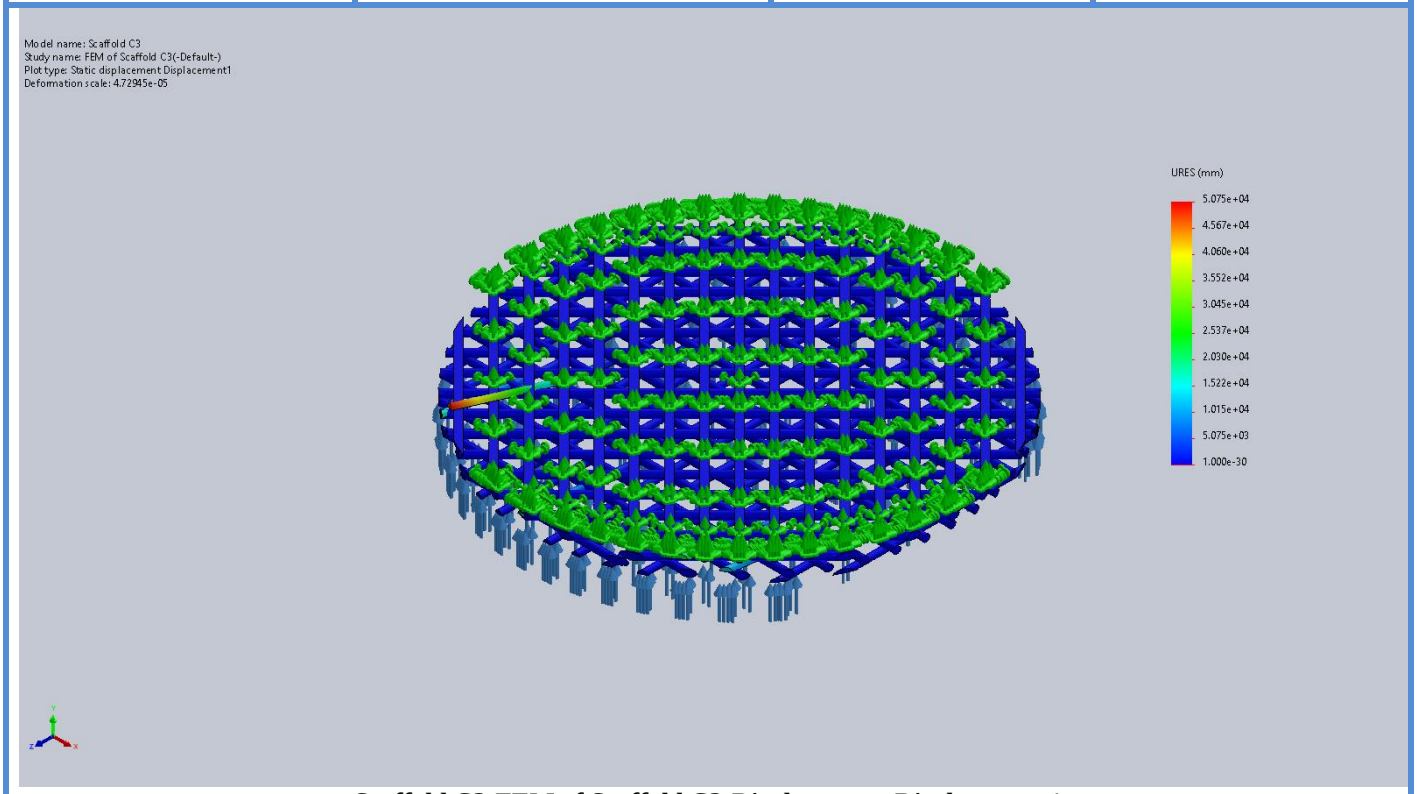
FEM Study Results of Scaffold C3

Name	Type	Min	Max
Stress1	VON: von Mises Stress	3.679e+01N/m^2 Node: 6267	7.805e+11N/m^2 Node: 107624



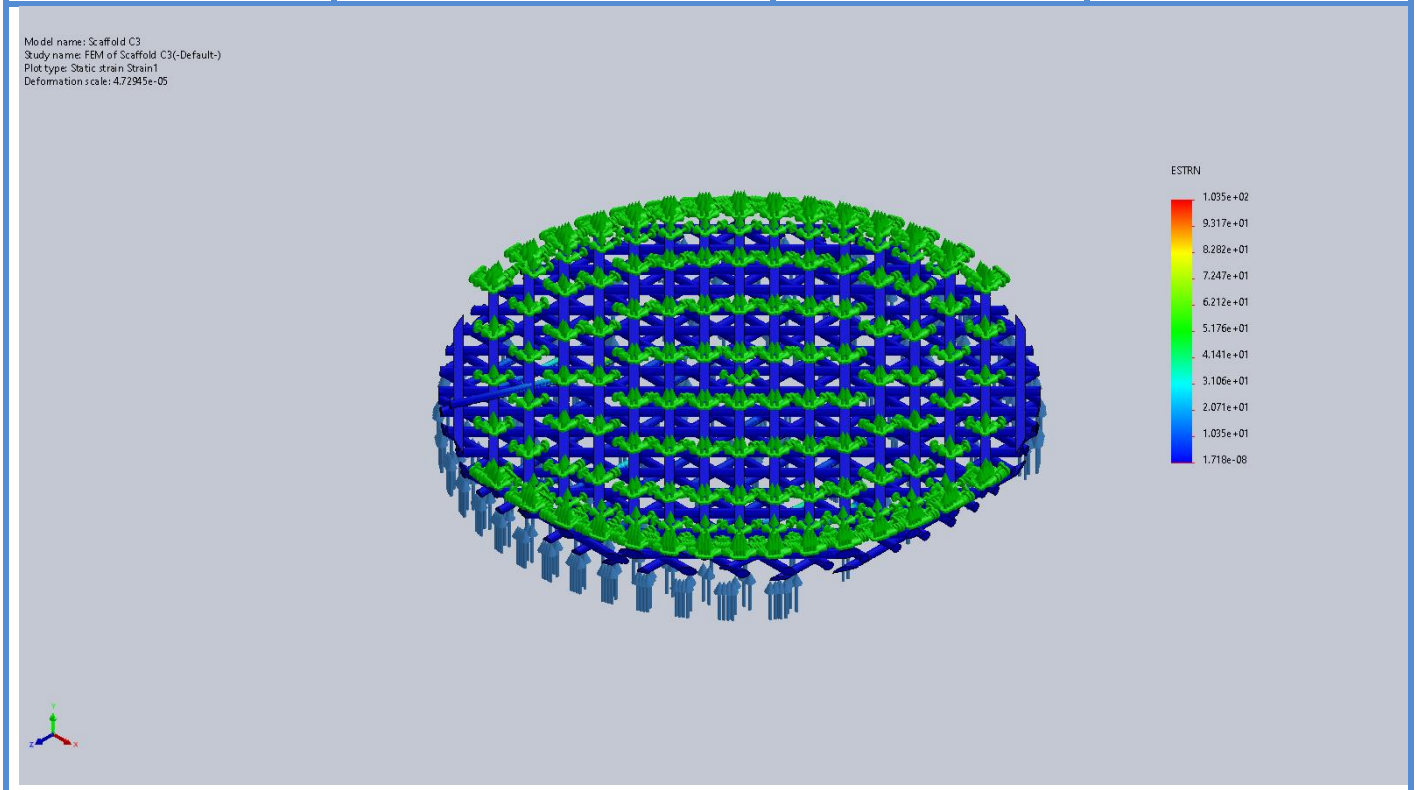
Scaffold C3-FEM of Scaffold C3-Stress-Stress1

Name	Type	Min	Max
Displacement1	URES: Resultant Displacement	0.000e+00mm Node: 4486	5.075e+04mm Node: 107889



Scaffold C3-FEM of Scaffold C3-Displacement-Displacement1

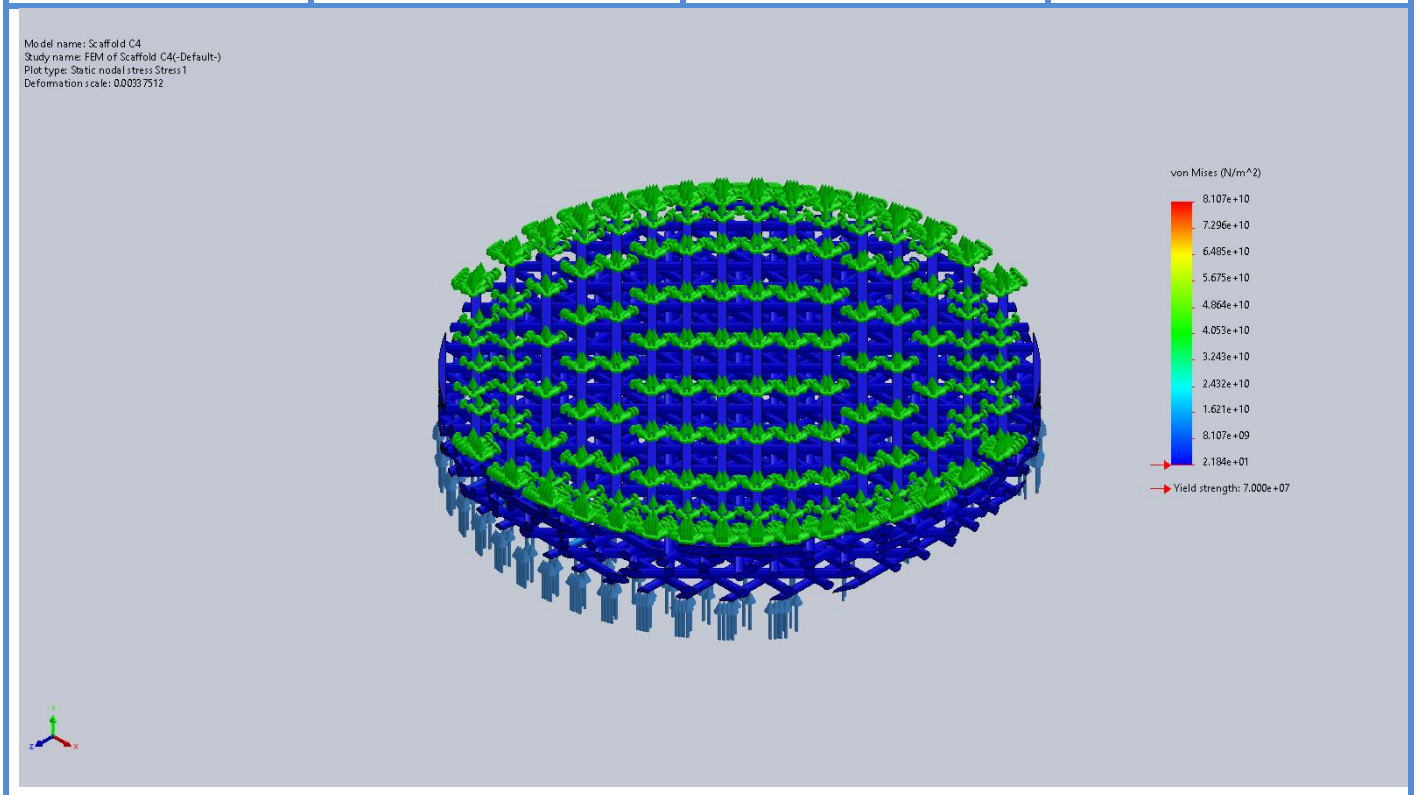
Name	Type	Min	Max
Strain1	ESTRN: Equivalent Strain	1.718e-08 Element: 2338	1.035e+02 Element: 46639



Scaffold C3-FEM of Scaffold C3-Strain-Strain1

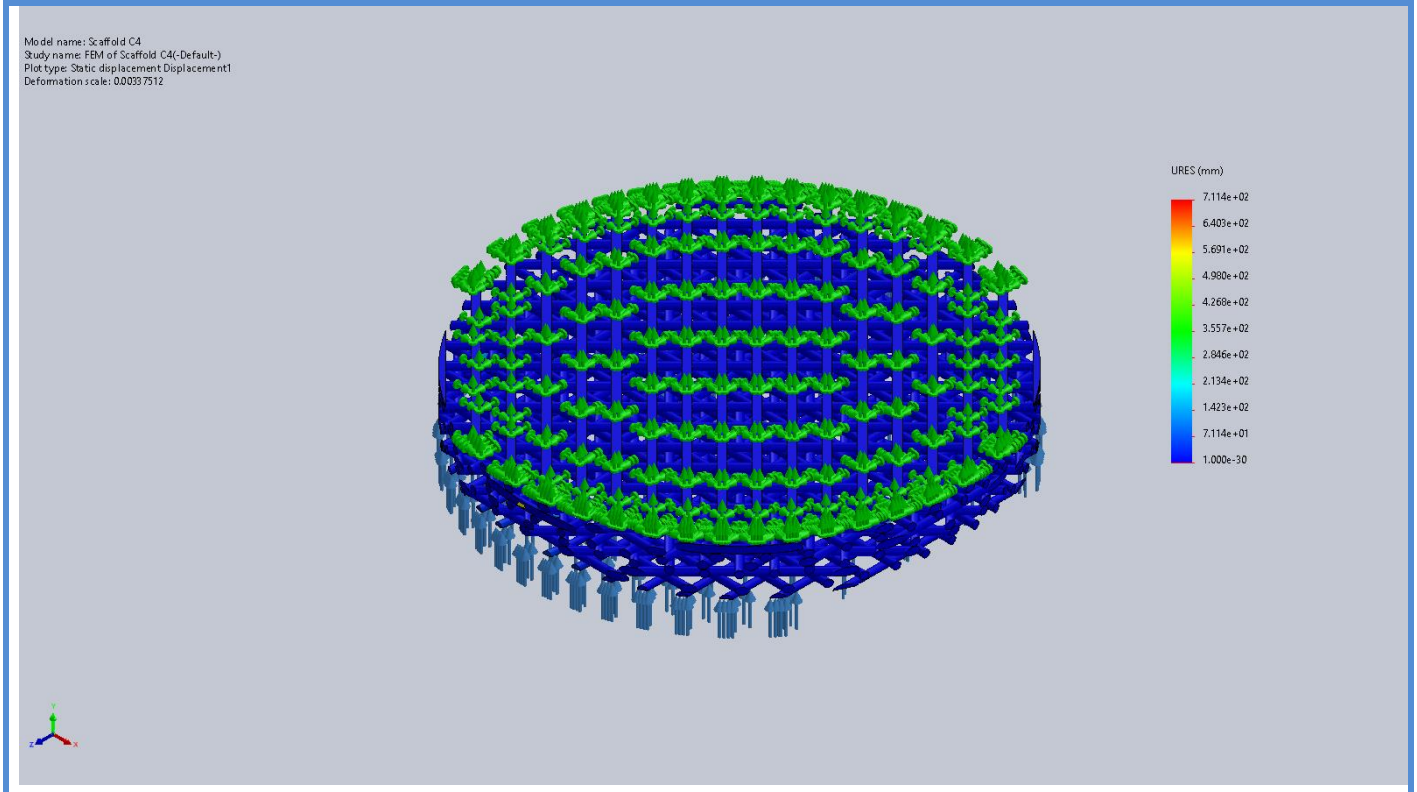
FEM Study Results of Scaffold C4

Name	Type	Min	Max
Stress1	VON: von Mises Stress	2.184e+01N/m^2 Node: 443534	8.107e+10N/m^2 Node: 119422



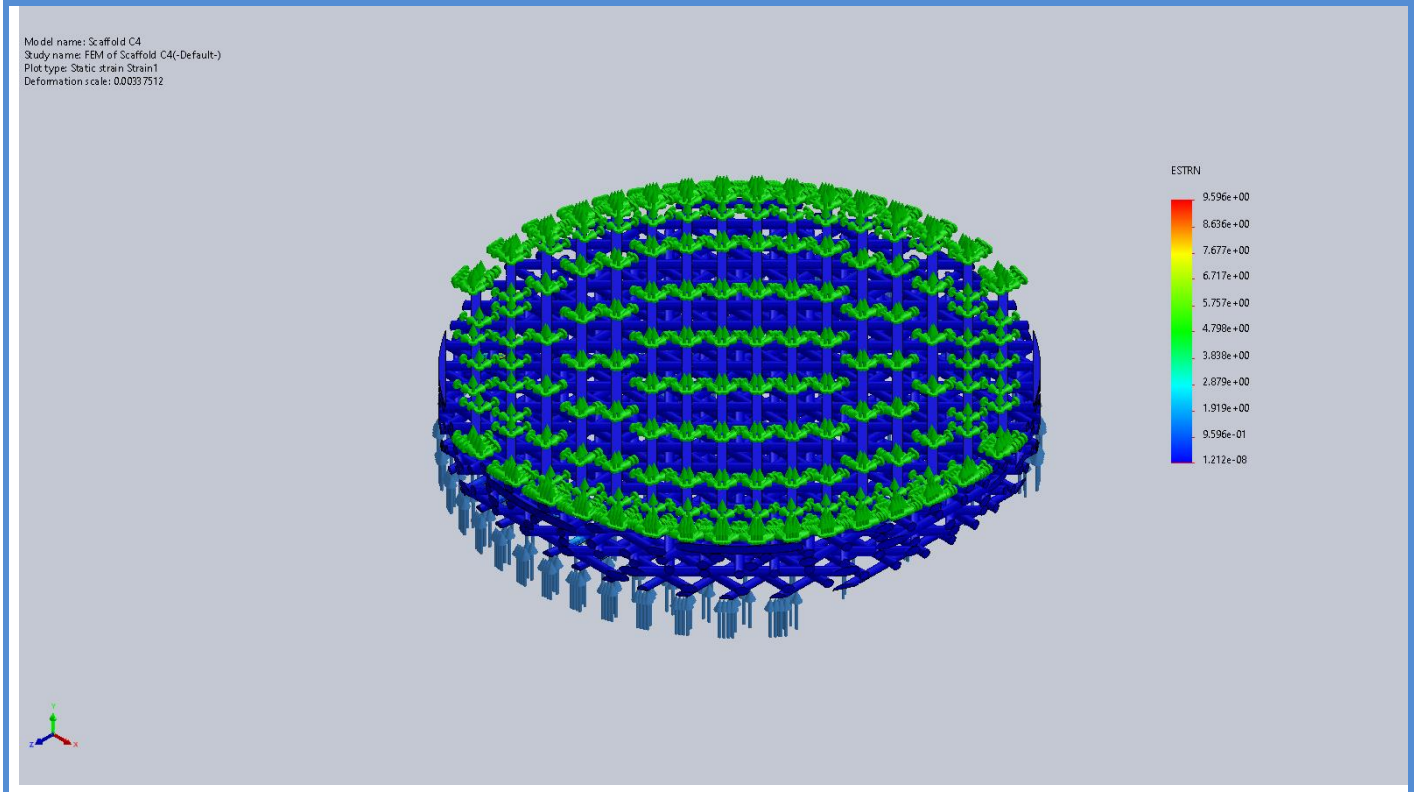
Scaffold C4-FEM of Scaffold C4-Stress-Stress1

Name	Type	Min	Max
Displacement1	URES: Resultant Displacement	0.000e+00mm Node: 61419	7.114e+02mm Node: 117758



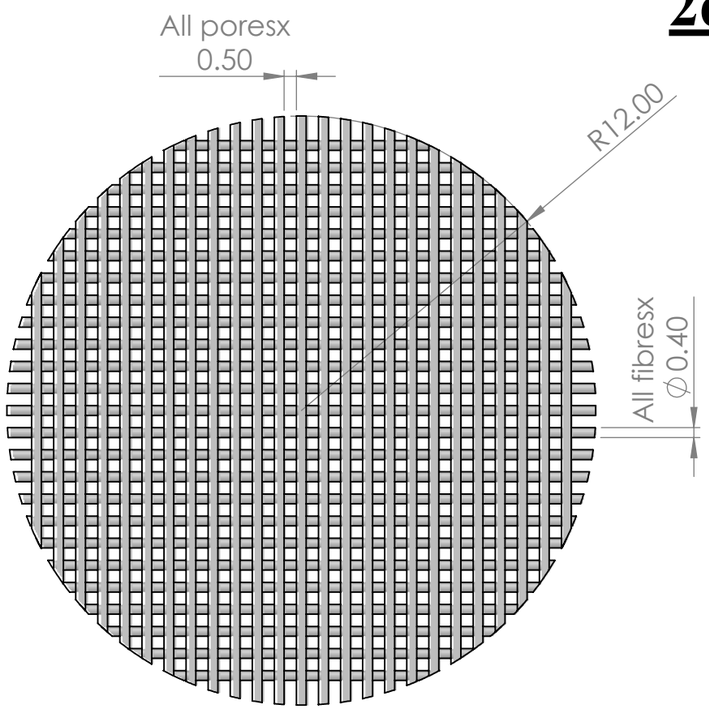
Scaffold C4-FEM of Scaffold C4-Displacement-Displacement1

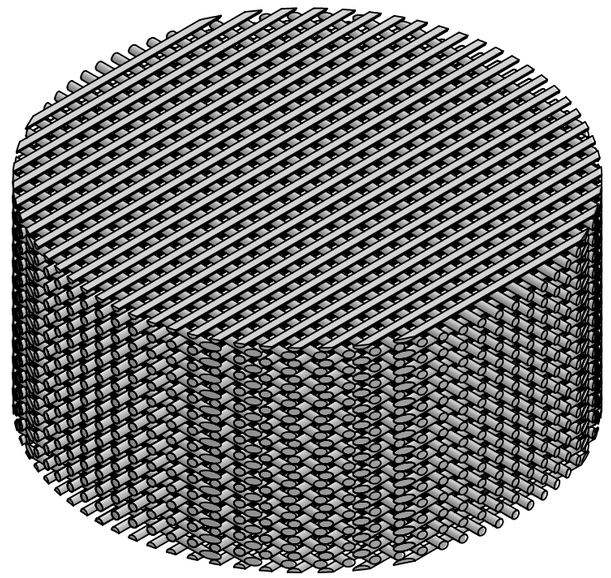
Name	Type	Min	Max
Strain1	ESTRN: Equivalent Strain	1.212e-08 Element: 37474	9.596e+00 Element: 54543

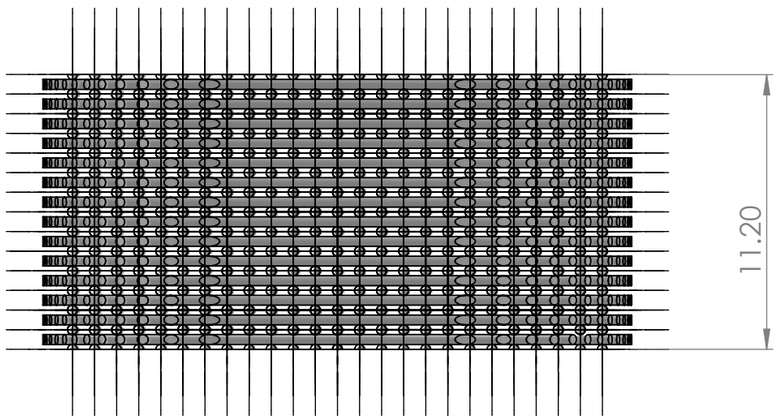


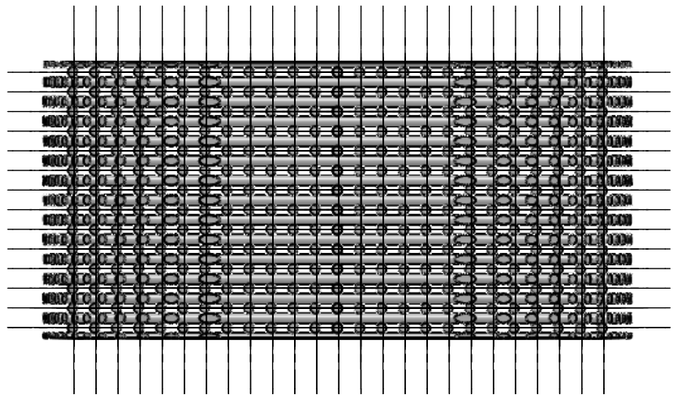
Scaffold C4-FEM of Scaffold C4-Strain-Strain1

2d drawing of scaffold B1



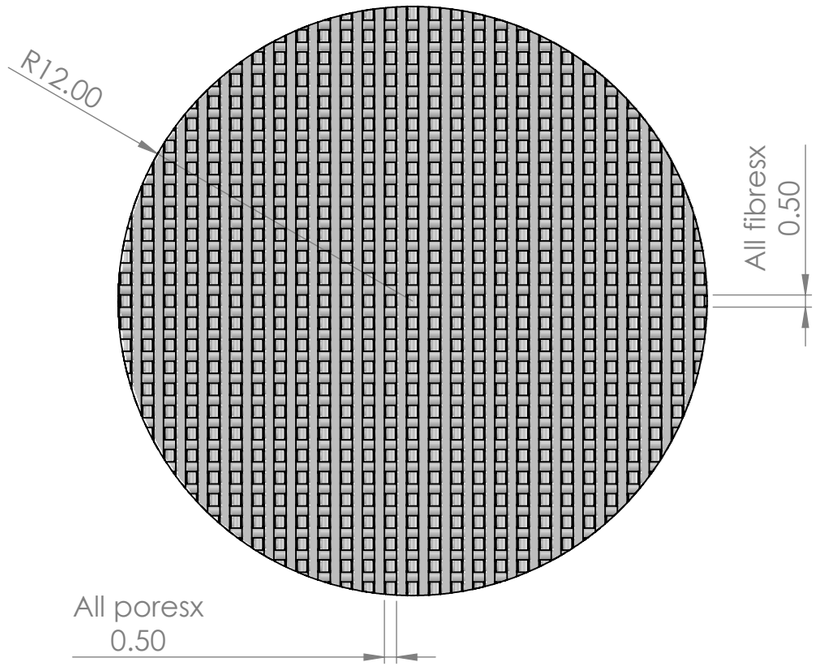


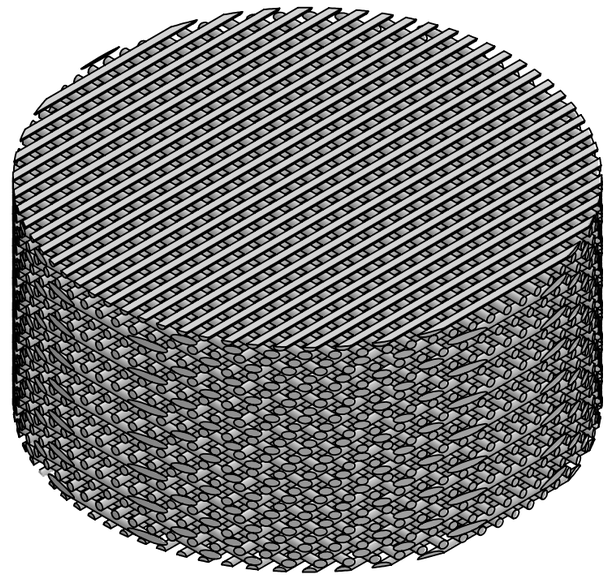


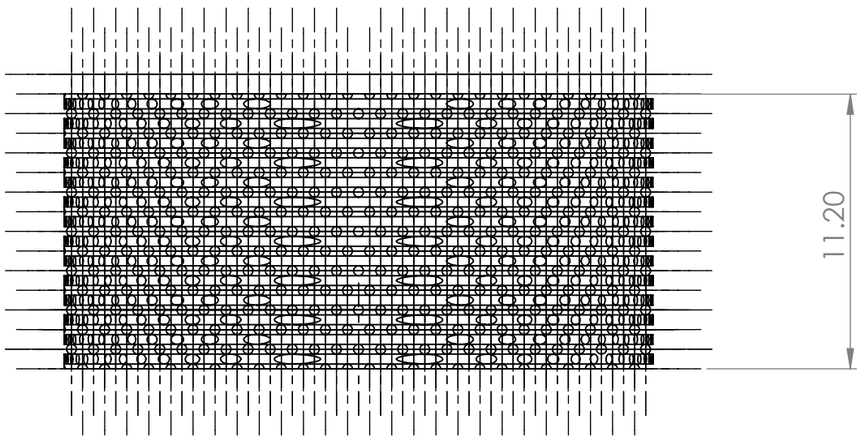


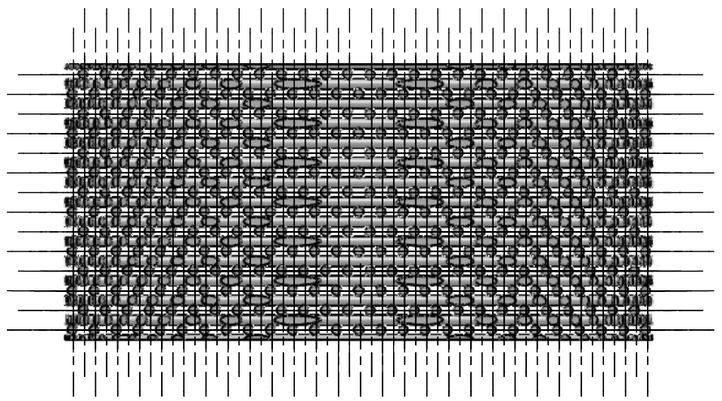
UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:		FINISH:			DEBURR AND BREAK SHARP EDGES		DO NOT SCALE DRAWING / REVISION
	NAME	SIGNATURE	DATE				TITLE: Scaffold B1
DRAWN	Martin						
CHK'D							
APPV'D							
MFG							
Q.A				MATERIAL: PCL			DWG NO. A3
				WEIGHT: 3.12 grams			SCALE:2:1 / SHEET 1 OF 1

2d drawing of scaffold B2



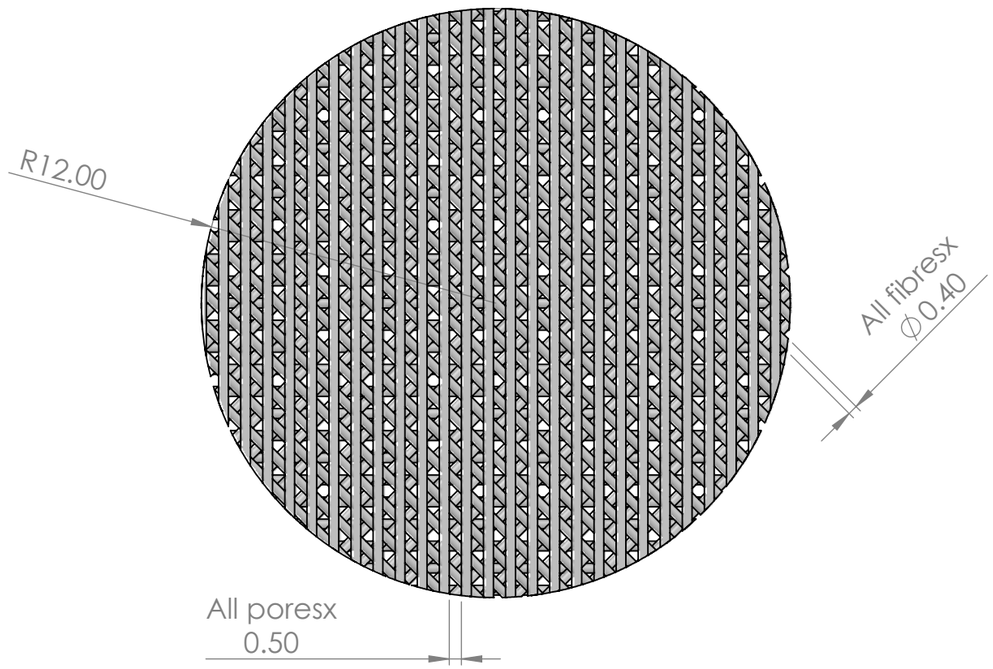


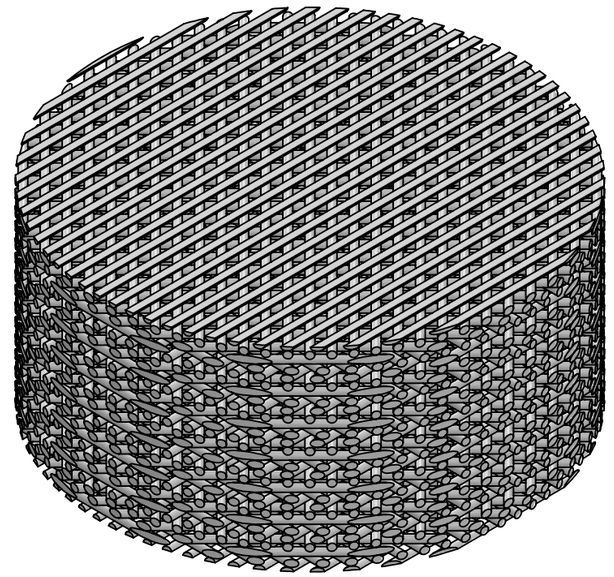


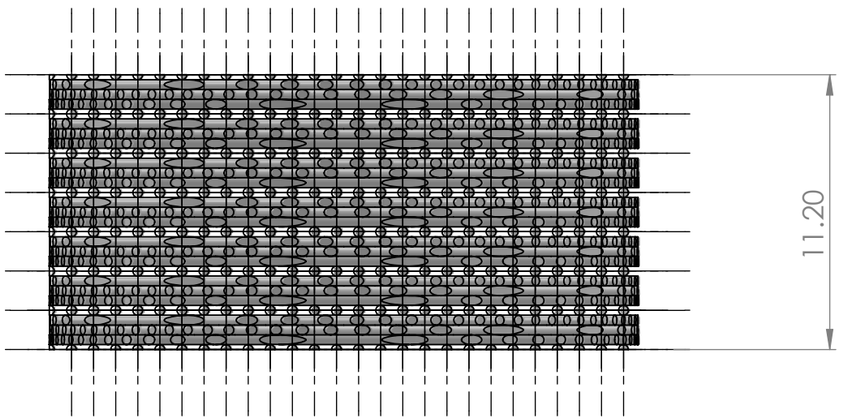


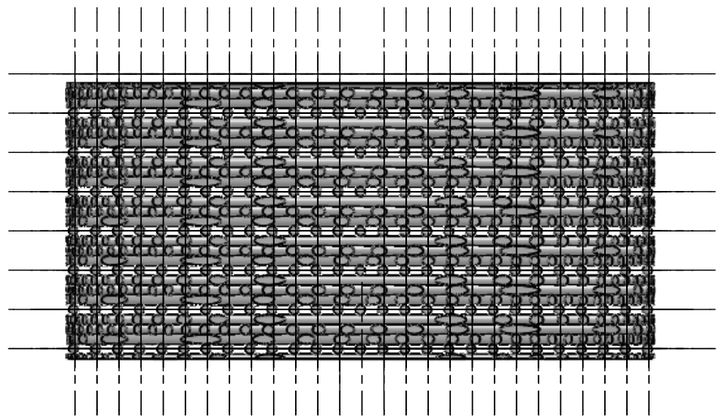
UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:		FINISH:			DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION
	NAME	SIGNATURE	DATE			TITLE: Scaffold B2	
DRAWN	Martin						
CHK'D							
APPV'D							
MFG							
Q.A				MATERIAL: PCL		DWG NO.	A3
				WEIGHT: 2.19 grams		SCALE:2:1	SHEET 1 OF 1

2d drawing of scaffold B3



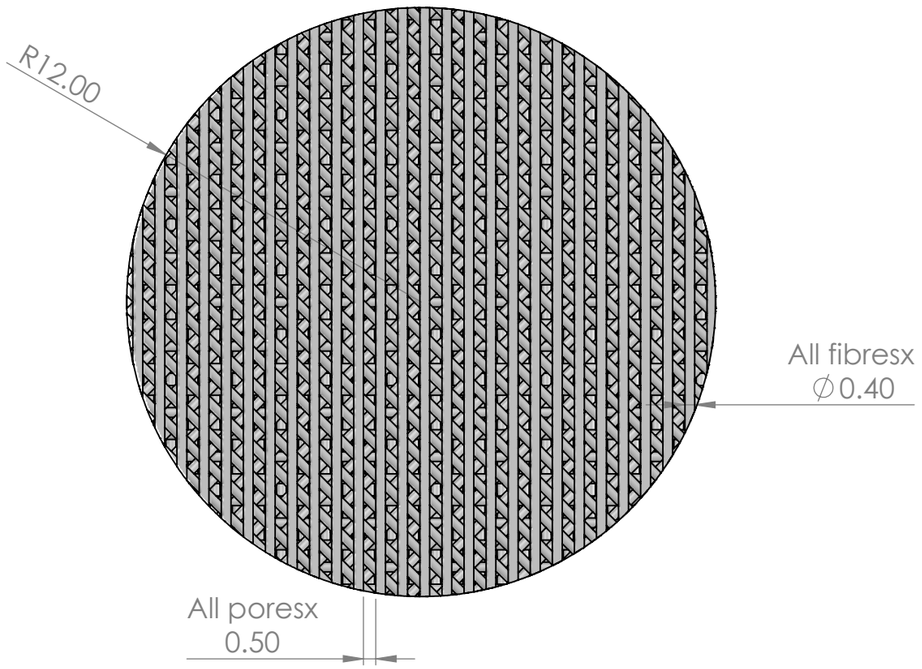


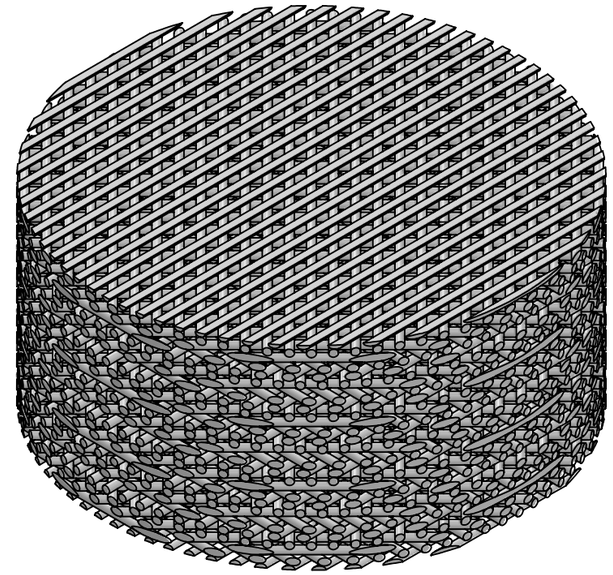


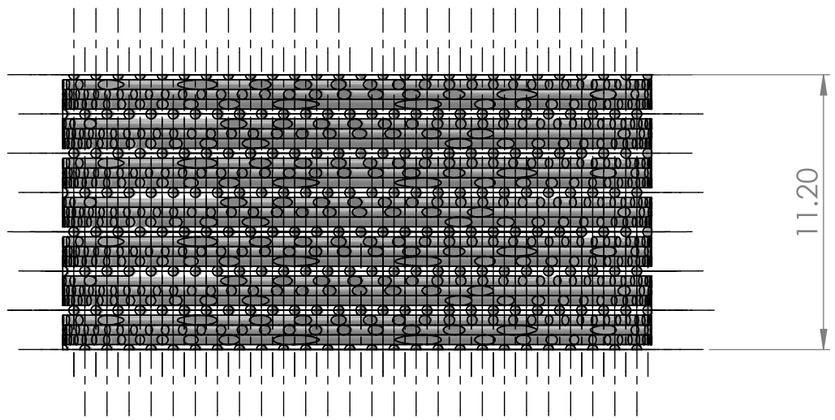


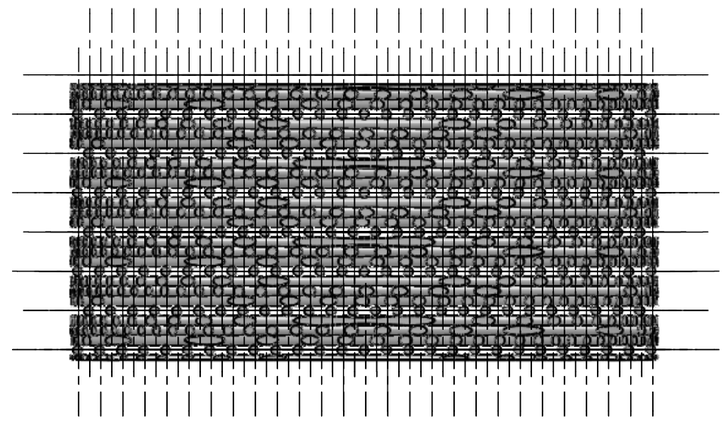
UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:		FINISH:		DEBURR AND BREAK SHARP EDGES		DO NOT SCALE DRAWING	REVISION
	NAME	SIGNATURE	DATE			TITLE: Scaffold B3	
DRAWN	Martin						
CHK'D							
APPV'D							
MFG							
Q.A				MATERIAL: PCL		DWG NO.	A3
				WEIGHT: 2.20 grams		SCALE:2:1	SHEET 1 OF 1

2d drawing of scaffold B4



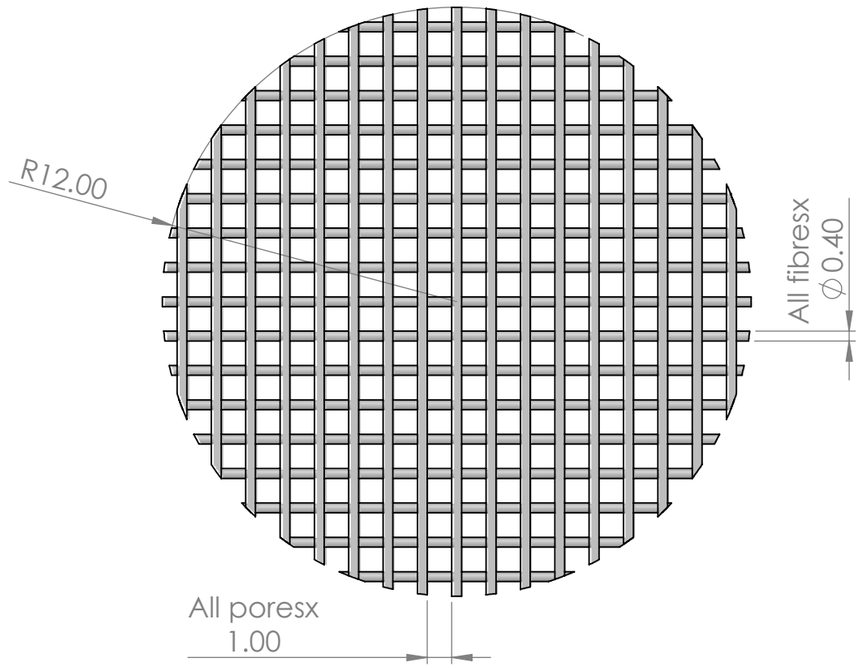


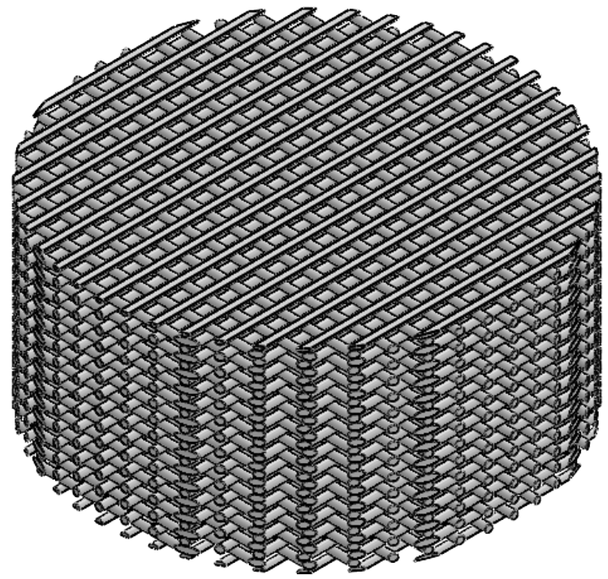


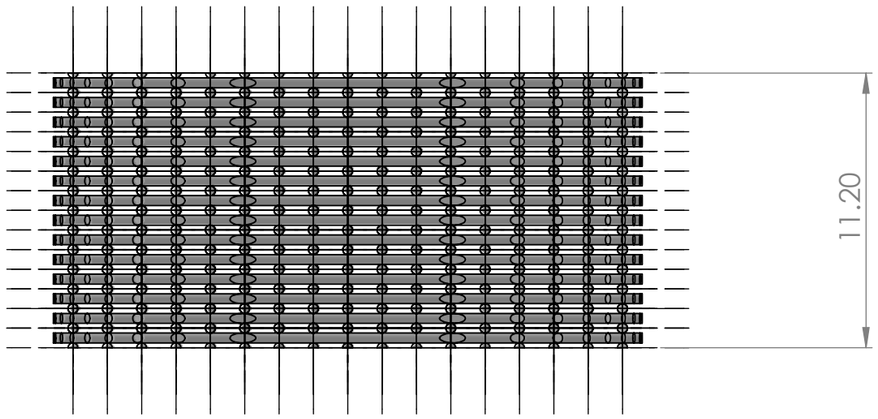


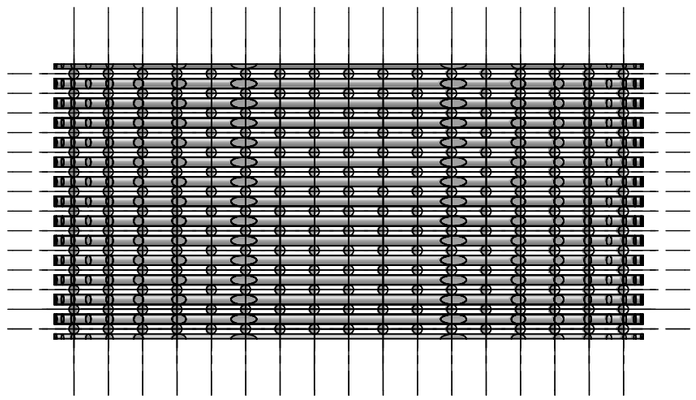
UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:		FINISH:		DEBURR AND BREAK SHARP EDGES		DO NOT SCALE DRAWING	REVISION
	NAME	SIGNATURE	DATE			TITLE: Scaffold B4	
DRAWN	Martin						
CHK'D							
APPV'D							
MFG							
Q.A				MATERIAL: PCL		DWG NO.	A3
				WEIGHT: 2.19 grams		SCALE:2:1	SHEET 1 OF 1

2d drawing of scaffold C1



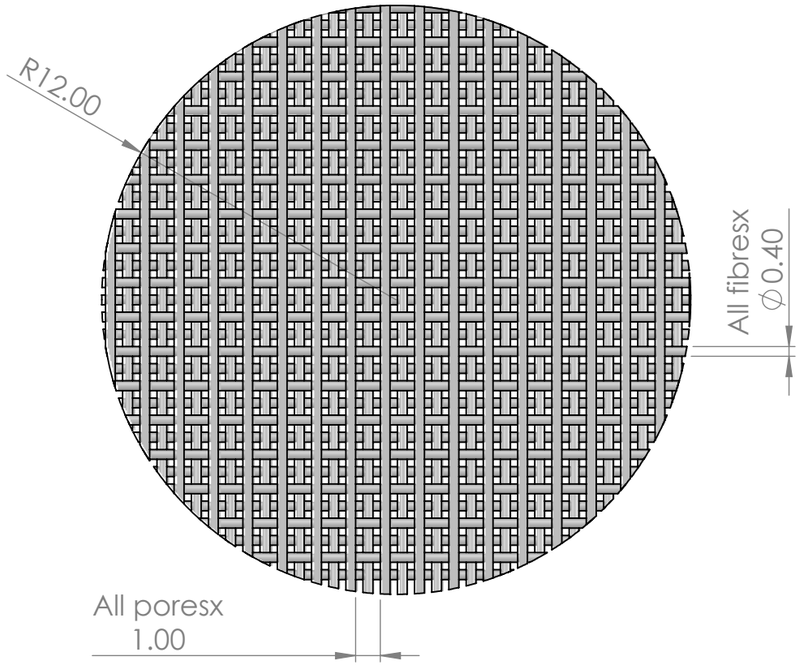


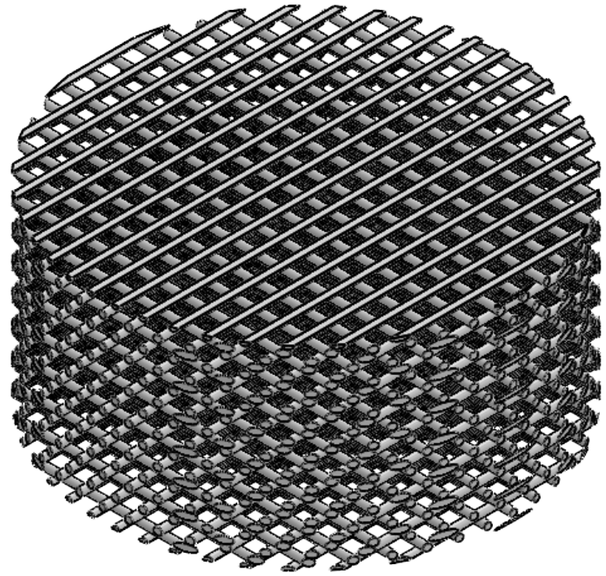


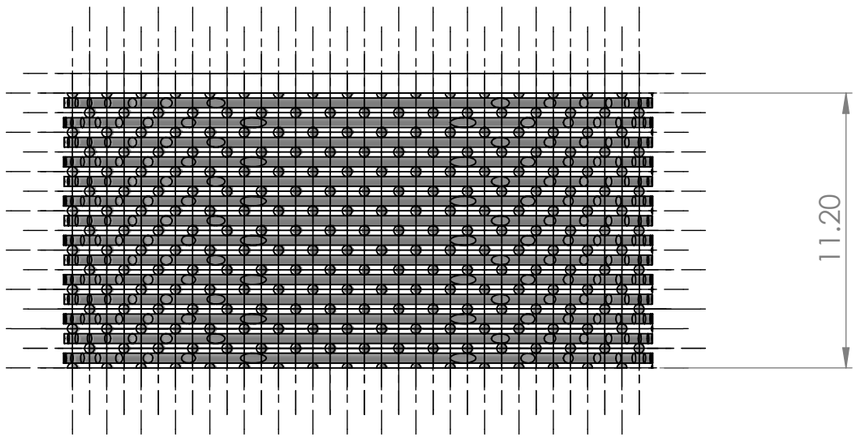


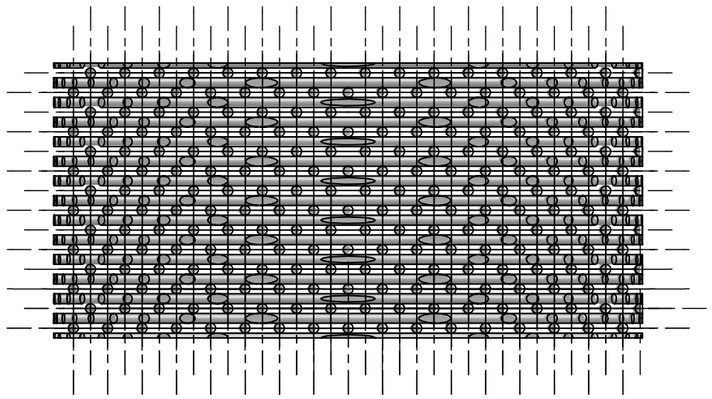
UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:		FINISH:			DEBURR AND BREAK SHARP EDGES		DO NOT SCALE DRAWING / REVISION
	NAME	SIGNATURE	DATE				TITLE: Scaffold C1
DRAWN	Martin						
CHK'D							
APPV'D							
MFG							
Q.A				MATERIAL: PCL			DWG NO. A3
				WEIGHT: 2.07 grams			SCALE:2:1 / SHEET 1 OF 1

2d drawing of scaffold C2



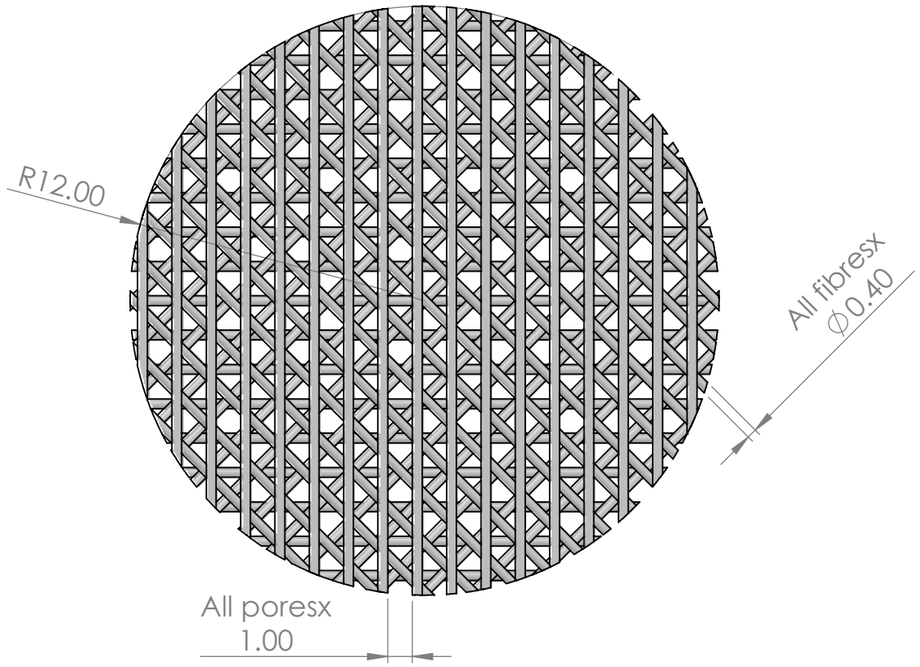


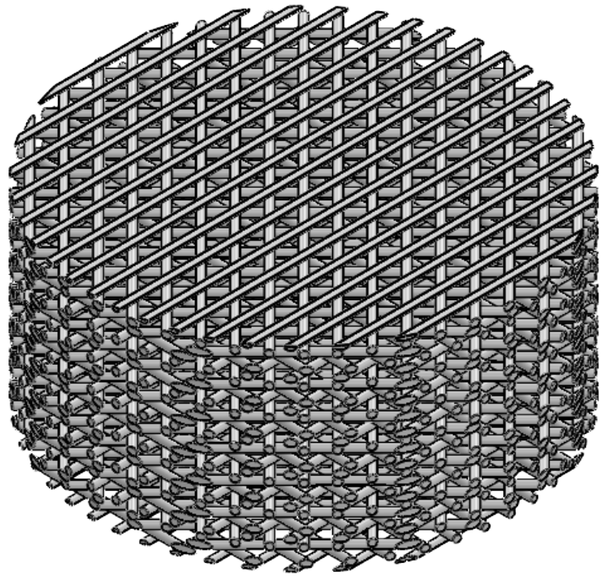


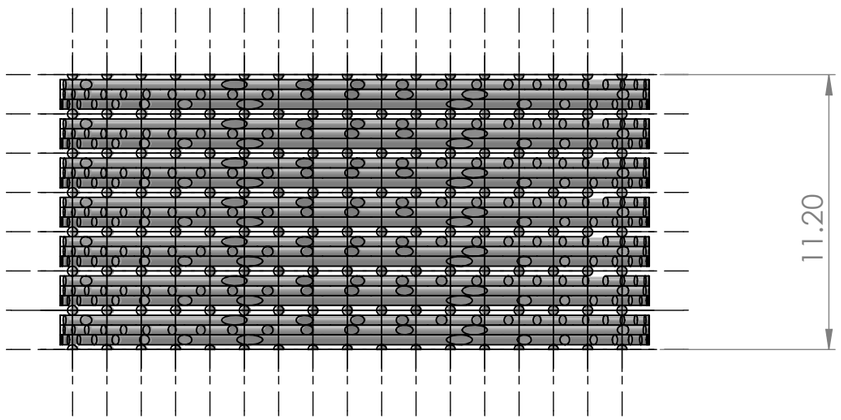


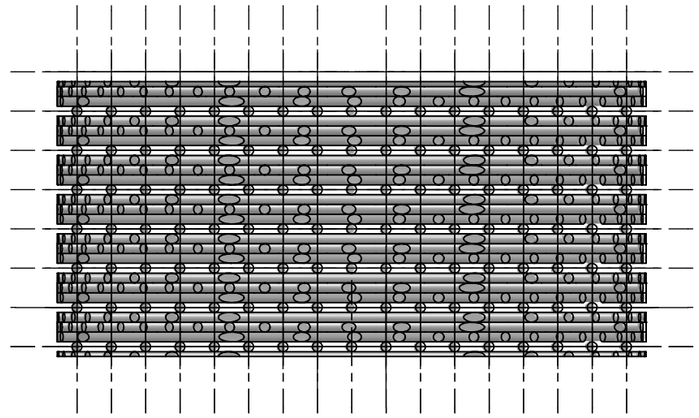
UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:		FINISH:		DEBURR AND BREAK SHARP EDGES		DO NOT SCALE DRAWING	REVISION
	NAME	SIGNATURE	DATE			TITLE: Scaffold C2	
DRAWN	Martin						
CHK'D							
APPV'D							
MFG							
Q.A				MATERIAL: PCL		DWG NO.	A3
				WEIGHT: 1.41 grams		SCALE:2:1	SHEET 1 OF 1

2d drawing of scaffold C3



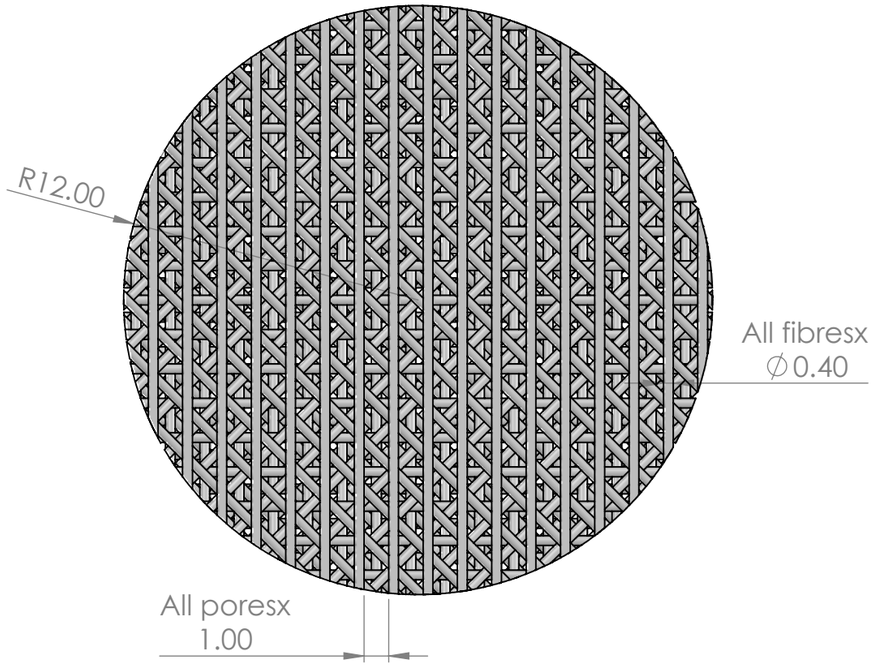


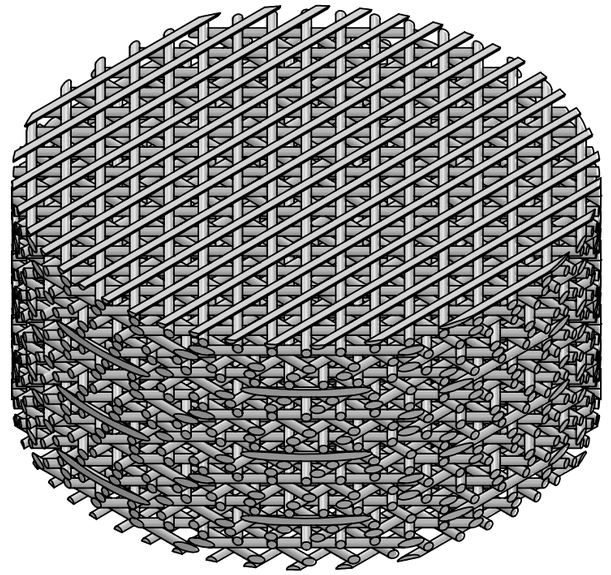


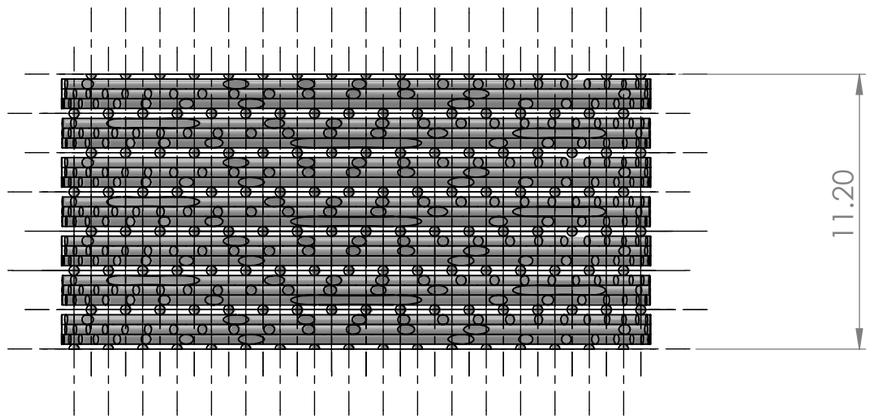


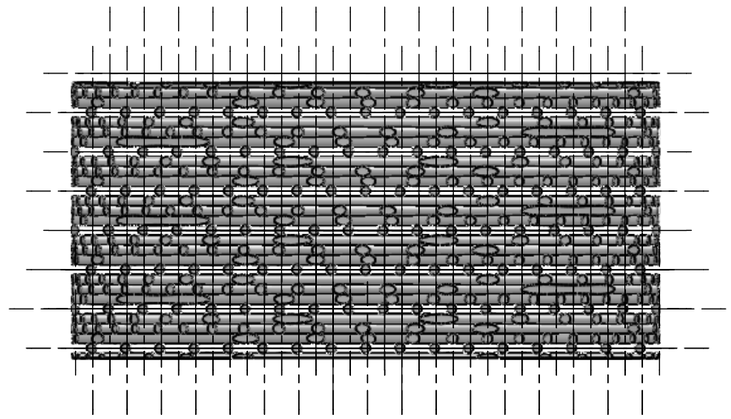
UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:	FINISH:		DEBURR AND BREAK SHARP EDGES		DO NOT SCALE DRAWING	REVISION	
	NAME	SIGNATURE	DATE				TITLE: Scaffold C3
DRAWN	Martin						
CHK'D							
APPV'D							
MFG							
Q.A				MATERIAL: PCL		DWG NO.	A3
				WEIGHT: 1.41 grams		SCALE:2:1	SHEET 1 OF 1

2d drawing of scaffold C4









UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:	FINISH:		DEBURR AND BREAK SHARP EDGES		DO NOT SCALE DRAWING	REVISION	
	NAME	SIGNATURE	DATE			TITLE:	
DRAWN	Martin					Scaffold C4	
CHK'D							
APPV'D							
MFG							
Q.A				MATERIAL: PCL		DWG NO.	A3
				WEIGHT: 1.41 grams		SCALE:2:1	SHEET 1 OF 1