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DESIGN STUDY OF ANATOMICALLY SHAPED LATTICE SCAFFOLDS FOR THE BONE TISSUE RECOVERY

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Abstract. *The current major scaffold design concepts for bone tissue recovery are characterized by labyrinthine design. Their main shortcomings are low level of permeability for new growing tissue, poor design adaptability in regard to particular anatomy and required biomechanical conditions during recovery, as well as very demanding post processing after free form fabrication. In contrast to the most of the existing solutions, latticed scaffold design does not try to imitate the trabecular structure and rejects the labyrinthine concept. It is characterized by simple 3D latticed support structure, which provides a high level of permeability for the new growing tissue cells, and in the same time a proper level of bio-adhesiveness. In addition, its design is easy to manage in order to make it follow the particular anatomical shape and at the same time provide the required elastic properties and structural strength. The paper presents a part of design concept proving process, which is related to stress analysis of the anatomically shaped lattice scaffold design. The aim of the analysis was to identify functional relation between design parameters and elastic properties of the scaffold. The established relations are crucial for getting optimal values of elastic properties of scaffold that are required in a specific trauma-fixation case. The design study shown in the paper was done for the case of lattice scaffold anatomically shaped to the upper part of proximal diaphyseal trauma of rabbit tibia. Design parameters which were altered within the design study were lattice's struts cross-sectional area, density of the struts and angle of the struts intersection. The analysis showed that structural flexibility of latticelike scaffold may easily be changed through modification of three selected design parameters. In this way, it is confirmed that the proposed type of scaffold has an important capability to adapt its elastic properties to the required values, while being able to keep its great permeability and geometrical consistency to the particular anatomy of trauma region.*

1 INTRODUCTION

For more than 15 years of research, numerous design concepts [1-7] of scaffolds that are aimed for the bone tissue recovery have been developed. However, there are still challenges to overcome in an effort to optimize design of the bone tissue scaffolds. Those challenges arise from the two opposite groups of requirements. The demands of the first group are:

- to provide maximal permeability of the scaffold volume for the new growing tissue cells,
- to ensure biocompatibility with native tissue,
- to control biodegradability of the scaffold and
- to maximize simplicity of the scaffold fixation and implantation.

The demands of the second group are:

- to achieve the high level of bio-adhesiveness of the scaffold structure elements,
- to provide high level of geometrical, i.e. anatomical consistency (*congruency*),
- to manage the mechanical properties of the scaffold (e.g. structural strength and stiffness) to ensure required deformations and
- to ensure high level of design manufacturability.

One of the very important demands is to find the design which is capable of being changed easily, in order to ensure the required deformations of the scaffold and bone graft. This deformation is crucial for stimulation of the ossification process inside the bone graft but also between the native tissue and graft. In the cases of large traumas, where it is necessary to temporarily or permanently substitute the missing piece of the bone, the scaffold has to hold the bone graft, but also to enable load transfer through its struts. In accordance to that function, it is very important to be able to manage the mechanical properties of the scaffold by changing its design. Depending on type of trauma and fixation frame that is selected, surgeon should choose and implant a proper scaffold. Besides the fact that scaffold design should coincide to anatomy of traumatized or missing piece of the bone, it should also provide proper biomechanical features, e.g. structural stiffness.

A number of studies are reported in literature that are related to investigation or optimization of elastic properties and structural strength of scaffolds, fabricated using various additive technologies. Most of them are performed on idealized or unit cell scaffold structures, subjected to axial loading, with or without comparison with experimental results. Just a moderate number of studies are taking into account realistic, physiological loading conditions and the whole bone-scaffold-fixation frame assembly. In [8] three titanium scaffolds of different porosity were subjected to finite element analysis (FEA), and the results were compared mutually and with experimental ones. While FEA proved to be a good technique for prediction of elastic properties of the scaffold, the results were notable different from experimental ones. The reason for this lays in the fact that the real geometry of the scaffold, which was produced using a rapid prototyping technique, was quite different than idealized scaffold geometry used in FEA. Similar results were obtained in [9], where polyamide and polycaprolactone scaffolds, fabricated using selective laser sintering were subjected to tensile and compression tests as well as to FEA. In [10] both representative volume elements of scaffold and both representative volume elements of bones were subjected to FEA. A good overview of the studies present in literature so far is given in [11]. In this paper, the suitability of open-porous titanium scaffolds to act as bone scaffolds is tested. A number of scaffold designs with variable porosity were subjected to axial compression up to the occurrence of structural failure, and the results were compared to numerically obtained ones. Moreover, in aforementioned study the scaffolds were custom designed to fit a large missing part of femoral bone, and FEA was performed to predict the behavior of all designs variations under physiological loading conditions.

In all the papers the tendency was present to establish correlations between scaffold design parameters and its elastic properties. Effective porosity was often used as an universal scaffold design feature, while structural modulus was most often used to characterize resulting elastic properties of the scaffolds.

The main goal of the studies described in this paper was to prove that elastic properties of the lattice scaffold may easily be changed to achieve the required mechanical properties, while keeping its permeability and other favorable features of lattice design described in the next chapter.

2 LATTICE SCAFFOLD DESIGN CONCEPT

Anatomically shaped latticed scaffold (in further text abbreviation ASLS will be used) is a new design concept of scaffold aimed to hold implanted bone graft. It is designed in a way to provide high level of permeability, maximal geometrical congruency to particular anatomy, manageable design, simple and efficient fixation and high level of manufacturability. One of the most important objectives of this kind of scaffold is to enable orthopaedic treatment of large scale trauma and to ensure thorough bone tissue recovery. Striving to that goal, the imperative was to create design which is easy to change and consequently easy to tune its elastic properties and structural strength. Having this feature the ASLS design could be tailored for required fixation case i.e. for required load distribution between fixation and traumatized bone region.

Briefly, ASLS consists of two groups of simple struts (Figure 1). The struts in the first group follow the geometry of outer wrapping surface of the bone but they also follow the geometry of inner wrapping surface (near the medullary cavity). These *wrapping struts* form outer and inner surrounding support of the latticelike structure, which is characterized by densely interlaced lattice. Yet, this wrapping lattice is still sparse enough to enable easy penetration of vascular and nerve tissue/structures/ to the interior of the bone graft, ensuring the preconditions for bone tissue growth. The struts of the second group are located in the space of (future) spongy bone and they connect wrapping lattice structures providing required strength of the scaffold as a whole.

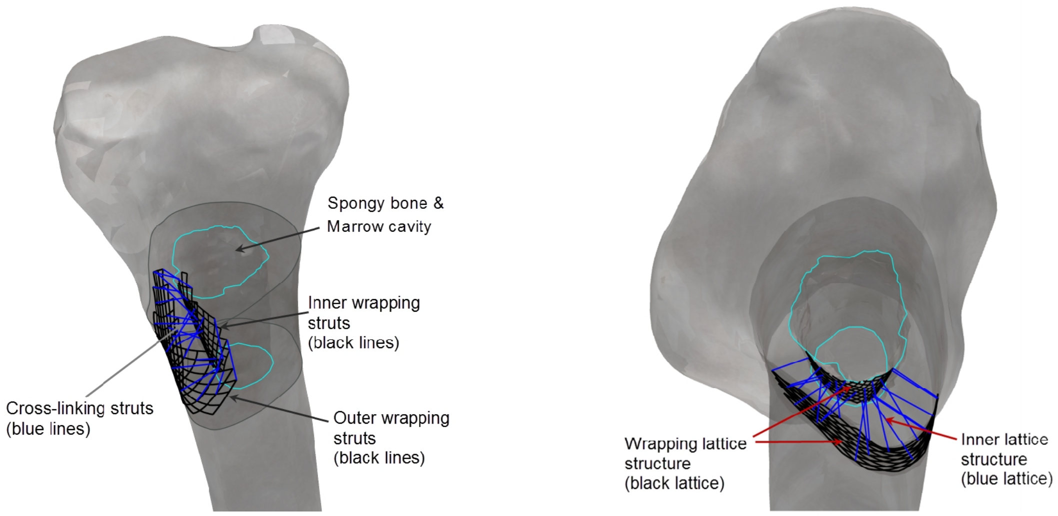
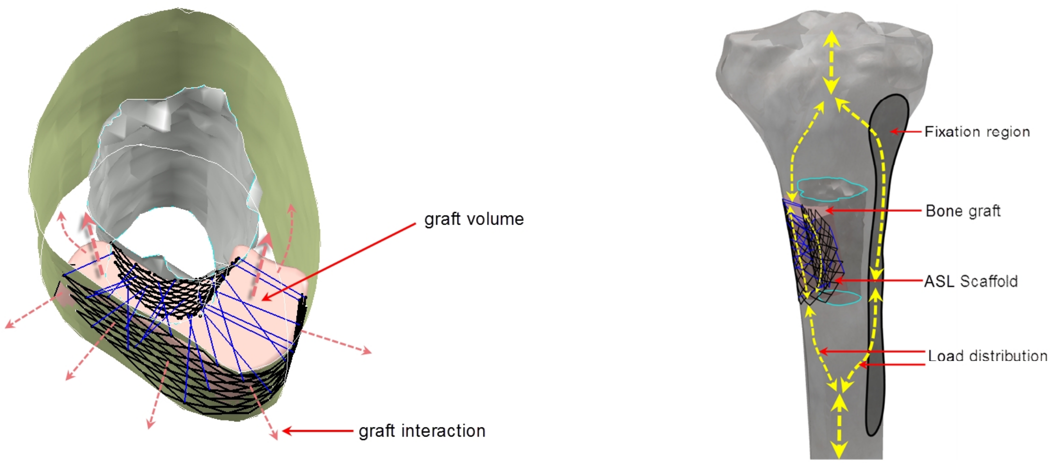


Figure 1: Design concept of ASLS (Anatomically Shaped Lattice Scaffold)

The second group of the struts is called *inner structure of cross-linking struts* and it is characterized by sparsely interlaced lattice than wrapping ones. Low density of the inner structure is designed to assure easier and deeper vascularization and innervation of the bone graft (Figure 2-a). In addition, low density of the ASLS inner structure enables free transformation of the bone graft into the bone tissue as well as its interconnection to the neighboring healthy bone tissue and muscles. Furthermore, due to the bioadhesive process the cross-linking struts become the carriers and highways for cells colonization (*ossification center-lines*) .



a) b)

Figure 2: Bone graft insertion (a) and load distribution schema (b)

Another, very important feature of the ASLS design is its ability to withstand a component of the mechanical load, which is required to convey by the traumatized bone in order to keep ossification process within the bone graft active (Figure 2-b). Main component of the mechanical load will be transferred via fixation structure. This requirement imposes optimization of the ASLS design according to the trauma and fixation case and consequently in regard to the load that ASLS has to withstand (Figure 2-b). In the following chapter a short study is described, which was performed in order to prove that elastic properties of the proposed lattice scaffold design may easily be adjusted to the required structural stiffness, which will enable expected range of displacement. Design flexibility is achieved by modification of principal design parameters, such as lattice's struts cross-sectional area, density of the struts and angle of struts intersection.

3 DESIGN STUDIES

For the purpose of present and future design studies, two models of ASLS were created. Both ASLS samples were designed to match anatomical shape of the upper part of proximal diaphyseal trauma of rabbit tibia (Figure 3).

The first model was designed to wrap the whole bone's tube in the defect region (Figure 4). The main purpose of this model (in further referred to as *fully wrapped scaffold*), was to study the sensitivity of elastic properties of lattice design to change of principal design parameters. Compared to usual scale of the defect found in orthopaedic practice, this scaffold model may be considered too large and unfeasible.

The second model, showed in Figure 5, is congruent to the realistic shape of bone defect (Figure 3), and is based on CT images of rabbit tibia. This model was subjected to a load case that approximately represents physiological loading after the surgery. Then the sensitivity study similar to first one was performed, in which the struts angle was changed and the response of bone-scaffold assembly obtained.

Figure 3: ASLS for proximal diaphyseal trauma of rabbit tibia

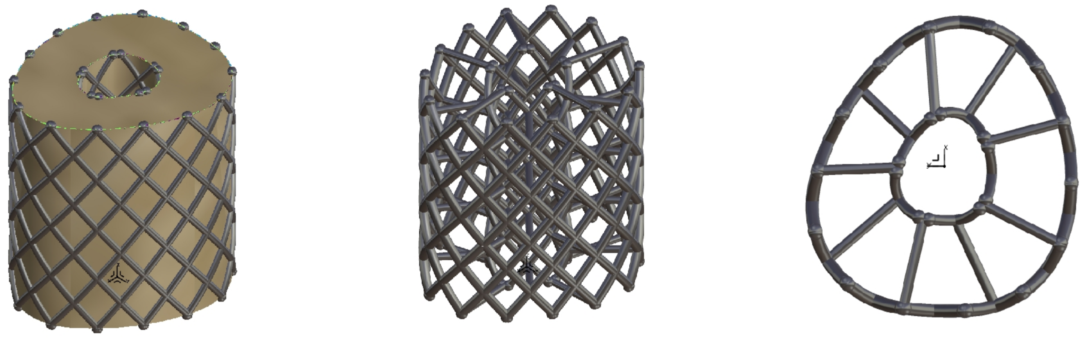


Figure 4: ASLS for complete envelopment of the bone – fully wrapped ASLS

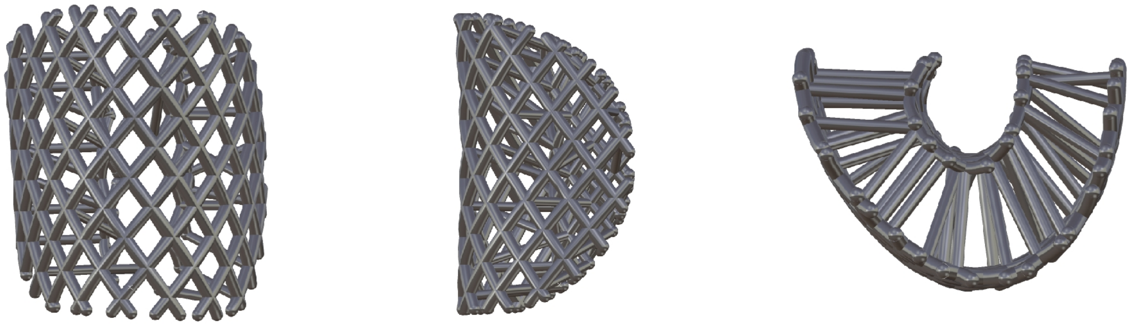


Figure 5: ASLS for realistic bone defect (D = 8m)

3.1 Sensitivity study of fully wrapped ASLS design elastic properties to principal parameters changes

In order to study the sensitivity of elastic properties of *fully wrapped* ASLS design (Figure 4) to variations of major design parameters, finite element model was built and positioned between two very stiff cylindrical bodies with parallel inner surfaces. It was then subjected to axial compression, with the force acting on one of the surfaces, the other one being fixed. Frictionless contact was defined between the scaffold and two other bodies, using multipoint constraint approach. Such boundary conditions have been chosen in order to minimize their effect on scaffold deformation, so that the changes in stress-strain field may be correlated only to changes in principal design parameters. The values of three different design parameters (density of the struts, lattice's struts cross-sectional area and angle of struts intersection) were changed during the study. In this way, a total of seven scaffold instances, driven by parameters values given in Table 1, were created (Figure 6).

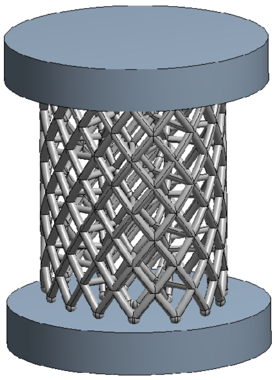
Scaffold porosity, defined according to Eq. (1), was also used, as derived parameter describing scaffold geometry.

$$\text{Scaffold porosity} = \left(1 - \frac{V_{str}}{V_{circumscribed}}\right) \times 100\% \tag{1}$$

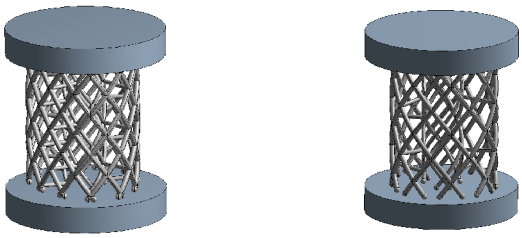
where V_{str} is the effective volume of scaffold struts and $V_{circumscribed}$ is the volume of approximately cylindrical body circumscribing the scaffold (490.8mm^3).

Instance No.	Struts density [mm^{-1}]	Struts diameter [mm]	Struts cross-sectional area [mm^2]	Struts angle [°]	Struts effective volume [mm^3]	Porosity
1	0.67	0.4	0.16	52	56.31	0.885
2	0.53	0.4	0.16	52	46.1236	0.906
3	0.43	0.4	0.16	52	36.7678	0.925
4	0.67	0.32	0.1024	52	38.94	0.921
5	0.67	0.48	0.23	52	80.42	0.836
6	0.67	0.4	0.16	32	53.2	0.892
7	0.67	0.4	0.16	72	55.82	0.886

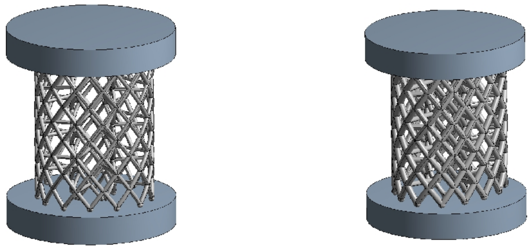
Table 1: Fully wrapped ASLS instances used in the study, and corresponding parameter values.



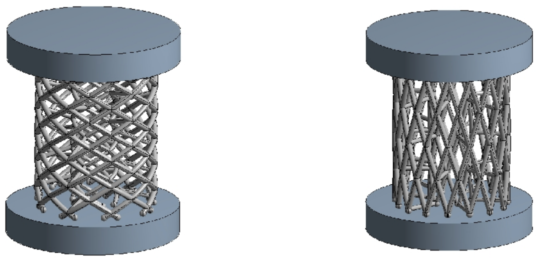
Instance1



Instances 2 and 3, variable struts density



Instances 4 and 5, variable struts cross-sectional area



Instances 6 and 7, variable struts angle

Figure 6: Instances of fully wrapped ASLS, obtained by change of principal design parameters.

Maximal axial displacement $\mathbf{u_x}$ and maximal equivalent Von-Misses stress $\boldsymbol{\sigma_{VM}}$ were monitored as output quantities, as well as structural stiffness $\mathbf{K_S}$ (Eq. 2) and structural modulus $\mathbf{E_S}$ (Eq. 3):

$$K_S = \frac{F}{\Delta l} \tag{2}$$

where F is the axial load and Δl is the change of initial scaffold length,

$$E_S = \frac{F \cdot l_0}{A \cdot \Delta l} \tag{3}$$

where l_0 is the initial scaffold length (10mm) and A is the area of the front surface of approximately cylindrical body circumscribing the scaffold (49.08mm).

Linear elastic material model was used to represent elastic behavior of the scaffold. Scaffold was supposed to be built from Arcam Ti6Al4V titanium alloy, characterized by typical values of Young's modulus (120GPa), Poisson's ratio (0.36), yield strength (950MPa) and ultimate tensile strength (1020MPa). Hypothetic, extremely stiff, material was used to model the bodies between which the scaffold is pressed, with Young's modulus set to 1×10^6GPa. Each of FE model instances was meshed with 10 node quadratic tetrahedron elements, using average global edge length of 0.2mm. Depending on instance, mesh size varied from 47000 to 105000 elements. Finite element model of the fifth instance is shown in Figure 7.

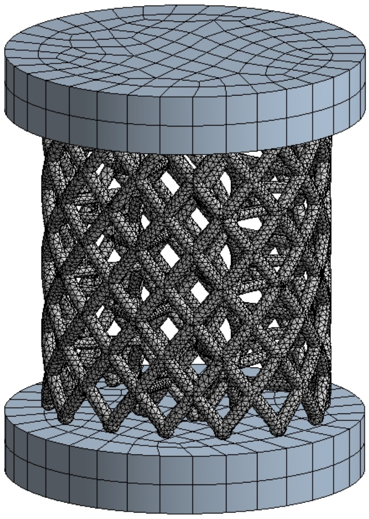


Figure 7: Finite element model of fully wrapped ASLS.

In order to check if nonlinear behavior is present in scaffold compression, large deflection effects were initially considered in the analyses and five different load intensities were applied: 20, 40, 60, 80 and 100N. As it may be seen from Figure 8, resulting structural stiffness of the scaffold, was found to be nearly independent of load intensity, so the study was continued using load intensity of 60N, which was chosen as a representative one in case of long bones of the rabbit.

Typical results of the analyses conducted within the study, are shown in Figure 9. Complete set of maximal values of axial displacement and equivalent Von-Misses stress, as well as values of structural stiffness and structural elasticity, obtained numerically for all instances, is given in Table 2. Maximal values of stress in the scaffold are in all cases well below yield strength of titanium alloy (950MPa).

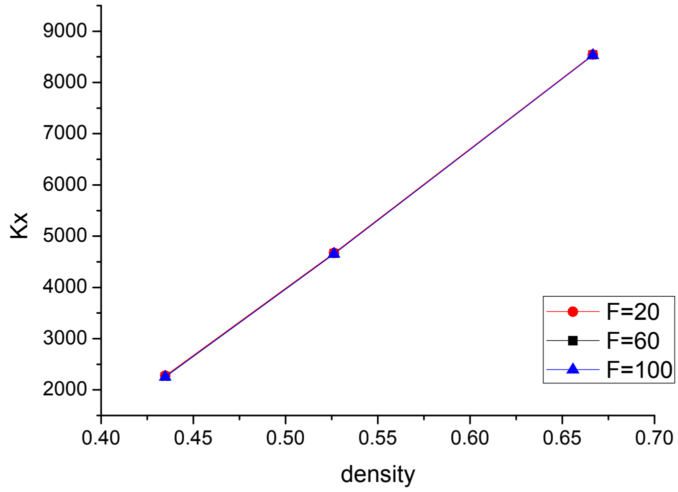


Figure 8: Structural stiffness of fully wrapped ASLS, calculated at three different load intensities. The independence of stiffness from load intensity confirms nearly linear behavior of the structure.

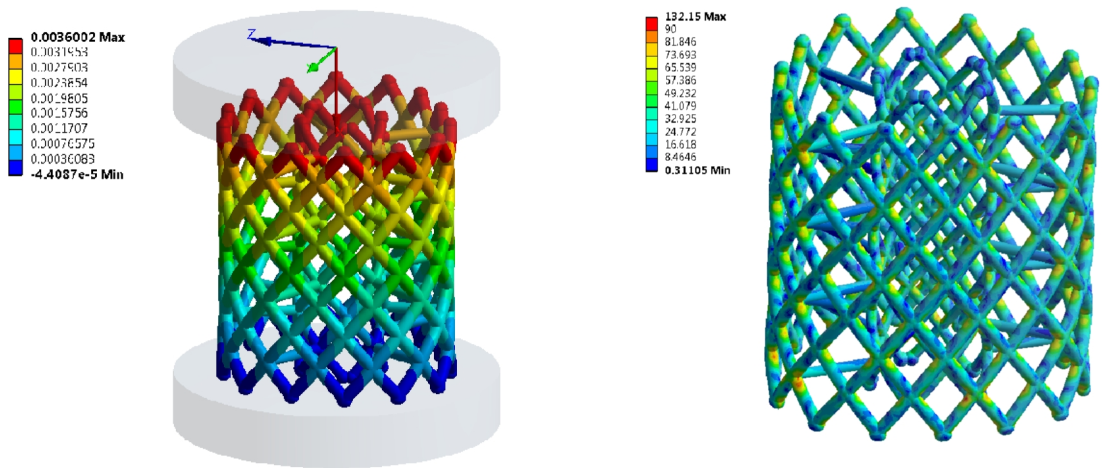


Figure 9: Resulting fields of axial displacement $\mathbf{u}_x$ and equivalent Von-Misses stress σ_{VM}, for instances 5 and 1 respectively.

Instance No.	$u_{x\ max}$ [mm]	K_S [N/mm]	E_S [N/mm^2]	$\sigma_{VM\ max}$ [N/mm^2]
1	0.00703	8537.0	1739.4	132.15
2	0.01287	4662.8	950.0	217.25
3	0.02652	2262.1	460.9	350.46
4	0.01447	4145.5	844.6	230.16
5	0.00360	16665.9	3395.7	212.42
6	0.03614	1659.8	338.2	278.81
7	0.00282	21282.0	4336.2	63.42

Table 2: Output values resulting from design study of fully wrapped ASLS design and calculated quantities.

Based on the complete set of results, sensitivity of structural stiffness and modulus to principal design parameters was estimated. Figure 10 shows that a nearly linear correlation exists between struts density and structural modulus. Correlation between struts cross-section area and structural modulus is a bit further from linear one (Figure 11), while the one between structural modulus and struts angle is noticeably nonlinear (Figure 12).

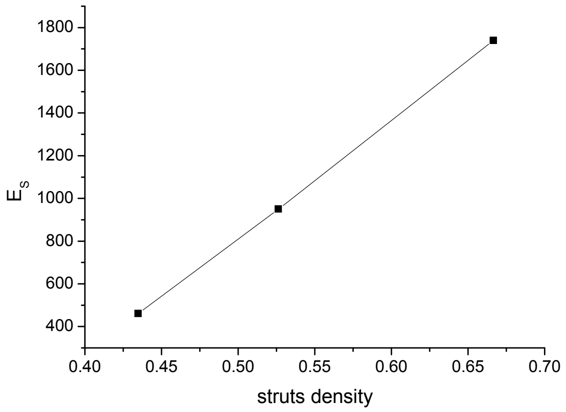


Figure 10: Sensitivity of structural modulus $\mathbf{E_S}$ to change of struts density.

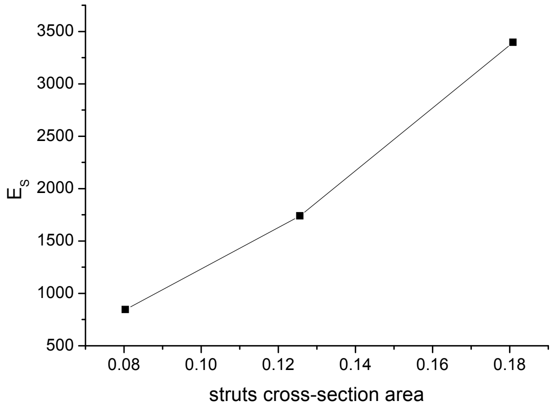


Figure 11: Sensitivity of structural modulus $\mathbf{E_S}$ to change of struts density.

In an attempt to find an universal design parameter that could be used to predict the value of structural modulus of lattice design scaffold, correlation between structural modulus and porosity was also observed. When all the instances were considered, a meaningful correlation could hardly be established, as dispersion of modulus values was very large. But, when the instances 6 and 7, which were obtained by change of struts angle, were not considered in regression analysis, a very close linear fit with a large value of R^2 was obtained (Figure 13). This fact, together with correlation shown in Figure 10, proves that the value of struts angle has very large effect on structural modulus of lattice scaffold and that the correlation between those two is highly nonlinear.

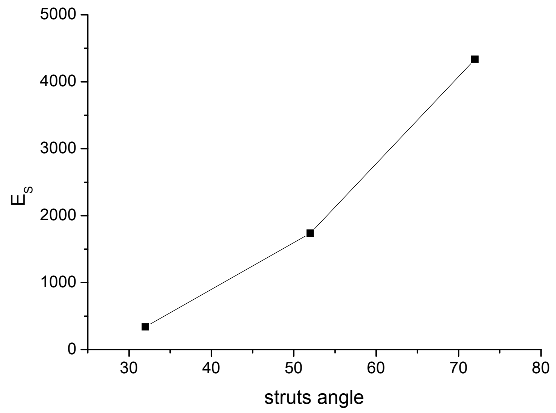


Figure 12: Sensitivity of structural modulus $\mathbf{E_S}$ to change of struts angle.

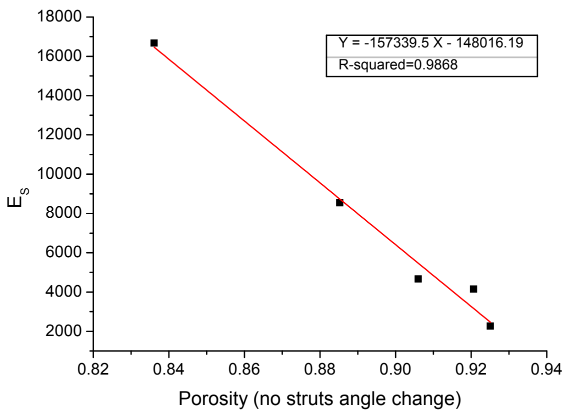


Figure 13: Sensitivity of structural modulus $\mathbf{E_S}$ to change of porosity (instances with changed struts angle are not considered).

3.2 Sensitivity study of realistic shape lattice scaffold elastic properties to change of struts angle

Scaffold shape and loads are never as ideal as shown in previous study, in which they were deliberately simplified to explore the mechanical behavior of fully wrapped ASLS design. To get a step closer to reality, a more realistic scaffold was modeled and assembled with a model of rabbit tibia segment, based on CT images. Three assembly instances were created, with variable struts angle (Figure 14).

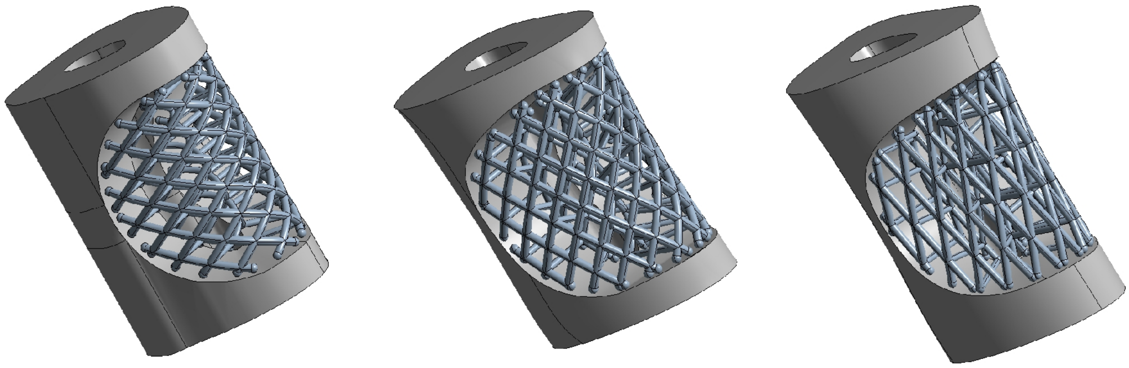


Figure 14: Three instances of bone segment-scaffold assembly, in which struts angle was modified to take representative values of 32°, 52° and 72° respectively.

Scaffold material was defined in the same way as in the previous study, and bone material was set to be linear elastic, characterized by mid value of Young's modulus reported in literature [12] for rabbit tibia (22GPa), typical reported Poisson's ratio (0.33) and ultimate tensile strength (195MPa). Fixation of the scaffold to the bone was approximated by bonded contact between neighboring surfaces of the two components. To approximate the axial load acting on the bone, one of the frontal surfaces of the bone was fixed, while equally distributed load of 60N was applied to the other (Figure 15).

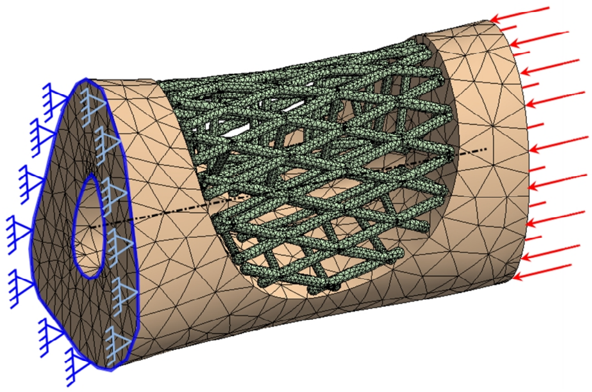


Figure 15: Finite element model of bone segment-scaffold assembly. Boundary condition and load shown in the picture are defined on front surfaces of the bone segment.

Typical results of the analyses conducted within the study, are shown in Figure 16 and Figure 17.

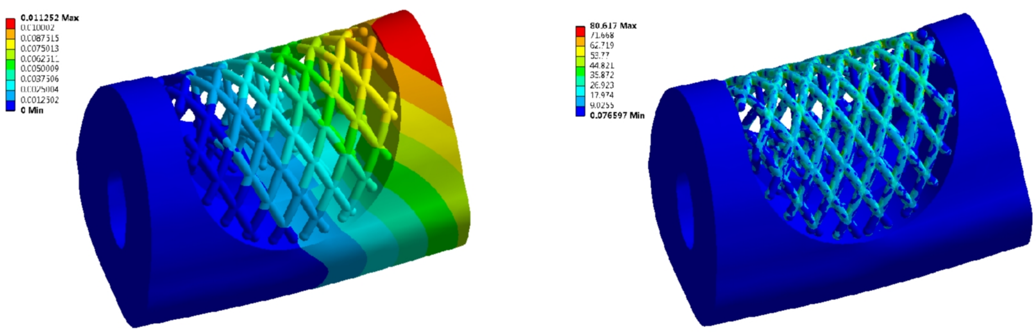


Figure 16: Total deformation and equivalent stress field on bone segment - scaffold assembly. Struts angle is set to 32°.

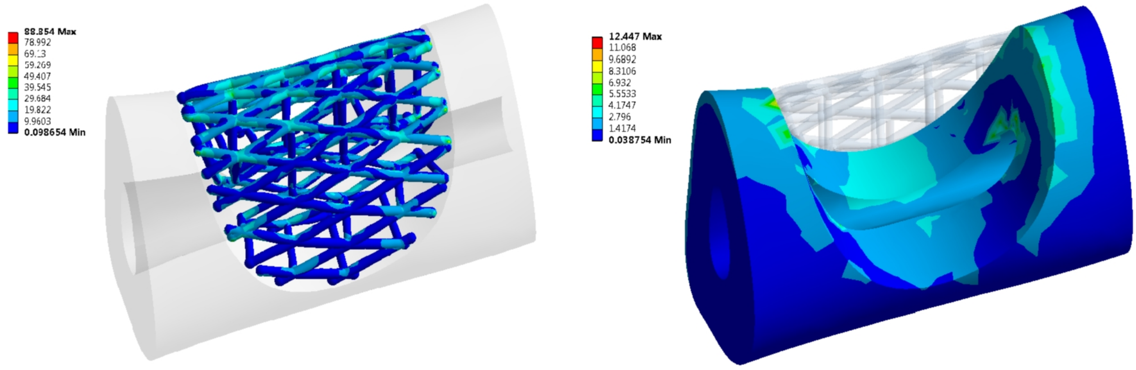


Figure 17: Equivalent stress field on bone and scaffold shown separately. Struts angle is set to 72°.

From previous images it may be seen that maximum value of equivalent stress in the scaffold (88.8MPa at struts angle of 72°) is much lower than Yield strength of titanium alloy (950MPa). The same is true for maximal stress in the bone (12.5MPa at struts angle of 72°), which is well below ultimate bone strength (195MPa). Correlation between struts angle and defect length dilatation obtained during the study is shown in Figure 18.

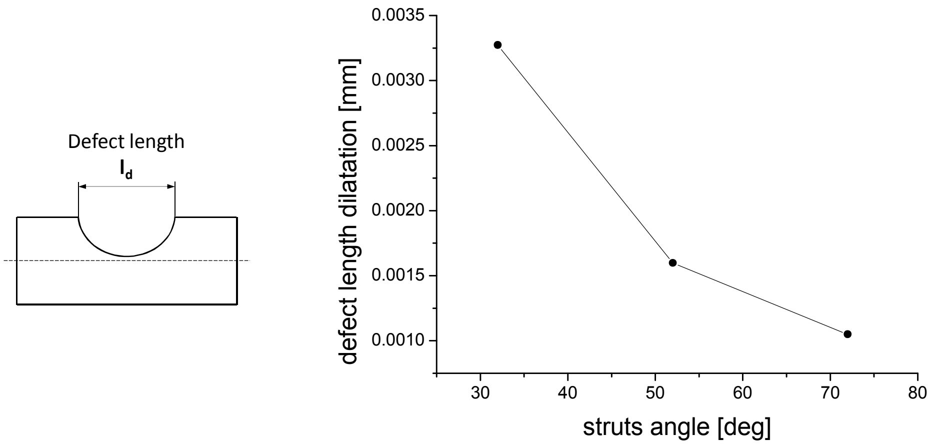


Figure 18: Bone defect length dilatation vs. struts angle.

As in the previous study, conducted on the fully wrapped ASLS design, it is obvious that struts angle is the design parameter which has a major influence on elastic properties of lattice scaffold. Moreover, the correlation between struts angle and structural stiffness of the scaffold is noticeably nonlinear, which is probably due to the fact that axial compression of the struts starts to dominate over other deformation modes as struts direction gets closer to load axis (in this case at struts angle of 90°).

4 CONCLUSIONS

Design studies described in the paper showed that the design concept of *anatomically shaped lattice scaffold* enables the easy control of scaffold's stiffness by changing the three main design parameters: density and cross-sectional area of the struts and angle of struts intersection. In current research a scaffold design was studied that was anatomically shaped according to the upper part of proximal diaphyseal trauma of rabbit tibia. Furthermore, the design study helped to determine functional relationships between these three design parameters and mechanical properties of the scaffold structure. Knowing these dependencies, it is much easier to properly customize the design of ASLS and to pair it with a fixation frame, in order to ensure a proper load distribution between fixation and scaffold as well as to keep the ossification process active inside the bone graft. Thus, it may be concluded that customization of ASLS design to the particular anatomy of a traumatized piece of the bone as well as to the requested load distribution, improves tissue recovery.

Finally, the results of these design studies call for the research of new materials, which will have to be equivalently strong as titanium, but will be characterized by controllable biodegradability.

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