Novel approach to generic parametrized lattice scaffold model design

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Abstract— **In order to create a personalized scaffold design, multiple data and information are needed: 3D scan of the bone, load conditions, placement of the scaffold in relation to the part of the bone that must be recovered/healed etc. Besides previously mentioned prerequisites for scaffold design, certain global guidelines should be observed in order to achieve desired scaffold mechanical properties: difference in results between the numerical analysis and mechanical testing of the scaffold (determined as percentage), trends that indicate how changes in geometry affect the mechanical properties of the scaffold (determined by structural optimization), etc. Some of previously mentioned guidelines were observed by multiple researchers through the development of generic or personalized scaffold designs, which can be used for mechanical or finite element analysis testing, but up to this point, no studies have produced a generic lattice scaffold model that can be used for structural optimization. Because of this, the goal of the study is to develop a flexible and robust parametric model of a generic lattice scaffold design that may be used in structural optimization. Parametric scaffold model developed in this study is meant for long bones recovery/healing and is in tablet form (with flat tops and bottoms) so that it can be used more easily in mechanical testing. It can change the diameter, density, and angle of its struts, with the possibility to modify its overall dimension at the same time, making the model flexible and robust (thus applicable to structural optimization).**

I. INTRODUCTION

Scaffolds are artificial porous or lattice-like structures that encompass grafts and provide mechanical support while guiding the growth of bone tissues in fracture regions, which they occupy [1]. Bone scaffolds are intended for fractures where a large part of the bone is missing, thereby making a natural recovery process difficult [2]. The outer surfaces of personalized scaffolds follow the anatomical shape of the bone, while the inner structures can be very complex, because of which additive manufacturing (AM) is a suitable choice for scaffold production.

Because scaffold can be personalized, depending on the individual it is made for, and because of their crucial part in bone recovery, it should mimic (as closely as possible) mechanical properties of the bone it is made for (flexibility, strength, etc.). In addition, scaffold should withstand any loads it may be exposed to. This is why it is important to test the scaffold before using it. Process of mechanically testing every scaffold before getting the one that meets the mechanical requirements is very time-consuming and can be costly. This is why numerical analysis is a better choice, as it eliminates the need for a large number of mechanical tests, so it is a much faster (and cheaper) solution.

For determining the mechanical properties trends of lattice and porous scaffolds, a generic parameterized scaffold CAD model can be used. This model needs to be fully flexible and robust, so various combinations of scaffold dimensions can be regenerated, without any interventions from the designer. All of this would allow multiple lattice sample designs of different geometrical parameters to be created easily and more importantly in a way that samples are comparable between each other by the basic structure of their geometrical elements, which is important for mechanical testing. In addition, through structural optimization, trends that indicate how changes in geometry affect the mechanical behavior of a scaffold could be determined. This would give greater insight to the designer on how scaffold geometry parameters should be adapted with respect to the desired mechanical properties. Also, this kind of generic parameterized lattice scaffold model would allow for a bidirectional connection to be used between the FEA software and the CAD software, which is crucial for an expeditious structural optimization. The goal of this study is to create such a generic parameterized lattice scaffold CAD model, which is flexible, robust, and thus could be used for structural optimization to determine the mechanical properties of the scaffold.

II. STATE OF THE ART

There are multiple approaches to designing scaffolds and based on them the resulting scaffold concepts can be separated in to two basic groups: porous scaffolds and lattice scaffolds. It is evident that a greater number of studies are based on porous scaffolds, while the number of lattice designs is significantly lower, due to complexity of their design process.

When designing scaffolds different CAD methodologies can be employed. It is possible to design scaffolds by using unit cells (micro-architectures), where multiple units can be combined into a single macro scaffold model [3]–[7]. A different approach would be to design the entire macro scaffold model as a single structure ([2], [8]–[11]). Both unit cell and macro approaches can also be designed with different methodologies. Inside the unit cell or macro scaffold bounding box (volume), structures can be created with Boolean operations (by subtracting volumes from the base model [3], [9]) or by wireframe design ([2], [3], [8]). Topology optimization can also be applied in scaffold design in order to optimize the scaffold geometry to certain load conditions [1]. When analyzing different studies ([2], [5], [8], [9], [12]), it is clear that certain repeating design parameters can be identified, such as scaffold:

- pore size/ strut diameter,
- pore density/ number of struts,
- strut angle and
- overall size (height, width, or diameter).

Naturally, the methodology (unit cells, macro scaffold, personalized shape, etc.) and geometry of the designs differ, but global parameters present in the design process can be identified.

As mentioned earlier, the scaffold must meet specific mechanical requirements in order to be applicable in medical practice. The mechanical behavior of porous scaffolds has been evaluated by mechanical testing ([5], [6], [9]–[15]) and structural analysis in numerous studies ([3], [4], [6], [10]–[13], [15]–[17]), which have defined basic trends that show how geometrical ([6], [9], [13]–[15]) and production ([4], [10]–[12]) parameters influence the overall mechanical behavior of a scaffold.

The same can be done for lattice scaffolds ([2], [7], [8]), but due to their design complexity, less data regarding their mechanical properties exists. Because of which this study focuses on developing a generic parametrized scaffold design.

III. METHODOLOGY

In this study, a generic parametrized lattice scaffold model design has been developed, which is flexible and robust and thus represents the prerequisites for future studies determining the mechanical propertied of lattice scaffolds. Flexibility and robustness of the scaffold model is ensured through the use of simple CAD features, such as sweep and circular pattern (which can be easily edited/changed), as well as through elements of the scaffold itself and shapes of those elements. There are 8 elements of the scaffold model: outer struts (green elements on the Figure 1); inner struts (yellow elements on the Figure 1); base struts (grey elements on the Figure 1); cross struts (blue elements on the Figure 2); top outer rim (bigger red element on the Figure 3); bottom outer rim (bigger red element on the Figure 3); top inner rim (smaller red element on the Figure 3); bottom inner rim (smaller red element on the Figure 3). The scaffold model is symmetric with respect to the horizontal plane, which intersects it at half height (Figure 4);

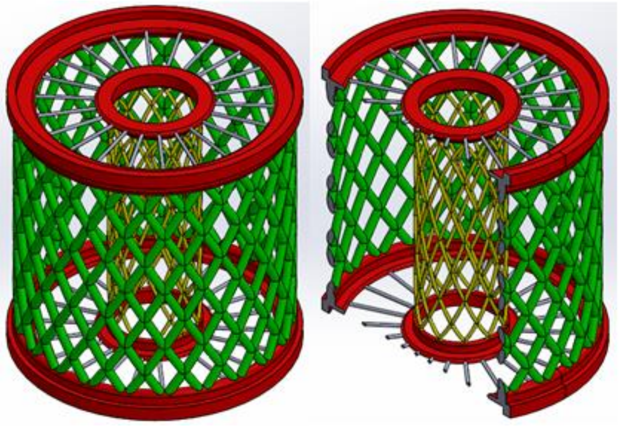

Figure 1. Generic parameterized lattice scaffold model (outer, inner, and base struts)

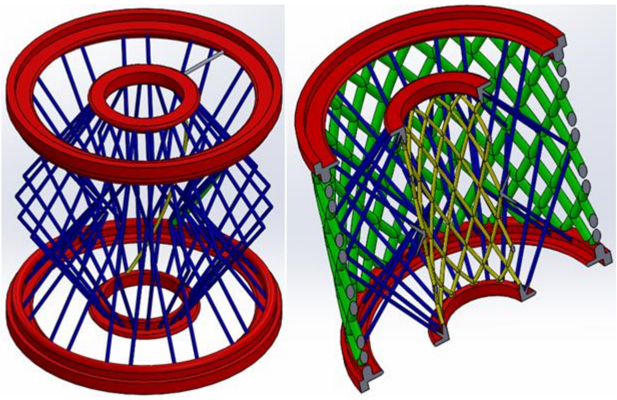

Figure 2. Generic parameterized lattice scaffold model (cross struts)

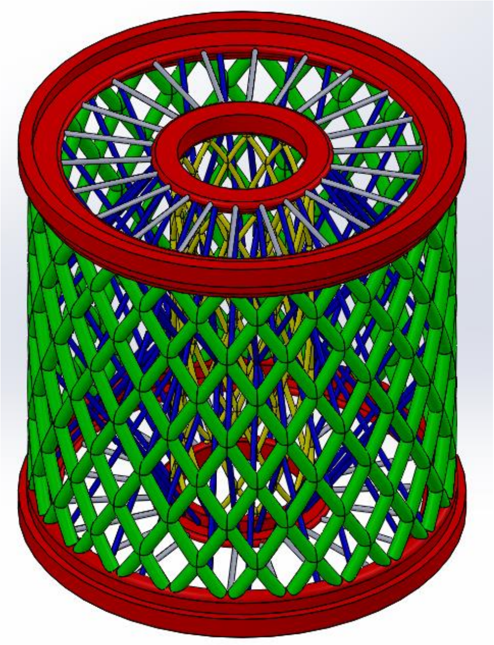

Figure 3. Generic parameterized lattice scaffold model

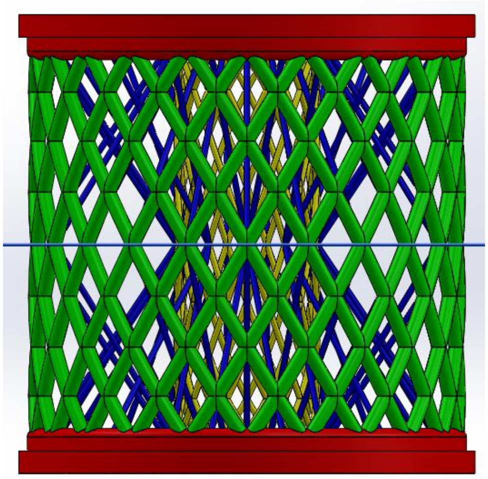

Figure 4. Symmetry of generic parameterized lattice scaffold model

All the different strut elements take on the main role of the scaffold – to carry given loads in the most optimal way so the proper deformation of the scaffold is provided [2]. However, this role is not equally shared between different strut elements, as outer struts carry the majority of the load, so their diameter needs to be larger than the diameter of other struts. In addition, outer struts and inner struts need to keep the bone graft in the area between them, so the density of their distribution needs to be optimal – dense enough to keep the bone graft between them, and not dense enough to make the scaffold stiff, which would result in non-optimal deformation of the scaffold under the required loads. Base struts connect outer and inner rims, and cross struts connect outer struts to the top/bottom inner rims, as well as inner struts to top/bottom outer rims. In previous versions of the scaffold design ([2], [8]) , all of the rims had simple circle for their cross section. In the first version of the novel scaffold design (Figure 5), the circle cross section on the top/bottom inner/outer rims made it hard to find the optimal design of the parametric model, in which the ends of the struts always connect in the same juncture points (Figure 6).

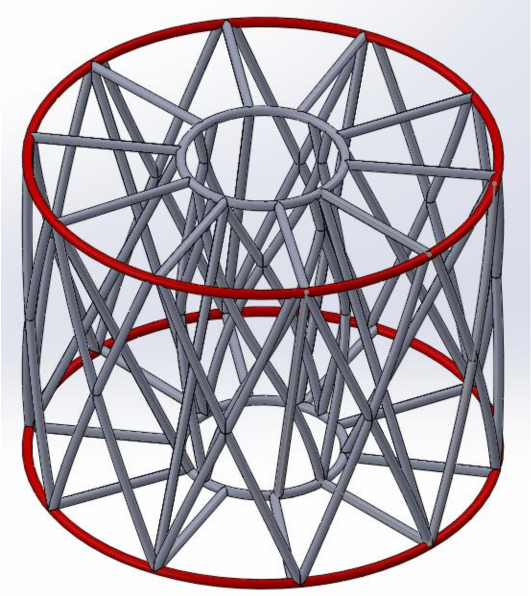

Figure 5. First version of generic parameterized lattice scaffold model (circular rims)

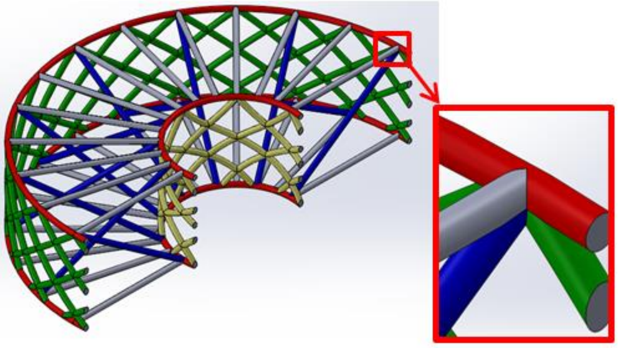

Figure 6. Ideal junction points of generic parameterized lattice scaffold model

Often, there would be struts with ends that ended few millimeters apart of the points in which all other struts end (Figure 7), which also resulted in different unwanted surfaces appearing on the scaffold model. This made it impossible to create a valid parametric model for the structural optimization. Because of this, rims were made so the struts would “flow into” the rims (Figure 8), thus eliminating the need for accurate struts end juncture points.

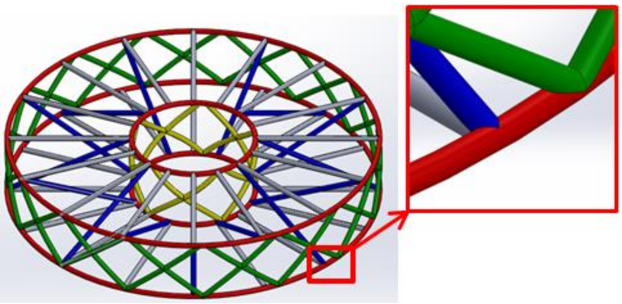

Figure 7. Non-ideal junction points of generic parameterized lattice scaffold model

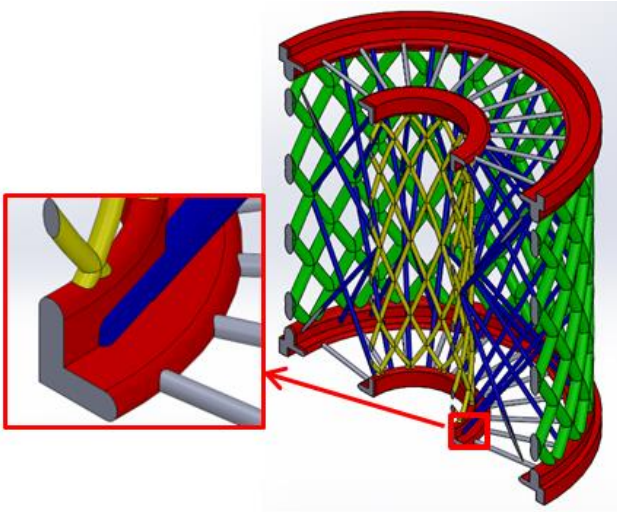

Figure 8. Rims in valid generic parameterized lattice scaffold model

Parametric scaffold model needs to have multiple parameters that will provide the needed variety of the different strut elements, as well as parameters that determine the overall size of the scaffold. All needed parameters were observed and included in the proposed parametric scaffold model. Parameters were divided into two groups: primary parameters and secondary parameters. Primary parameters, such as angle of outer/inners struts, diameter of outer/inner/base/cross struts, distance between outer/inner struts, are used in majority of the literature as parameters for creating general shape and dimensions of the scaffold. Secondary parameters were added so the structural optimization of the scaffold model can be fully analyzed. Some of the secondary parameters used in the developed parametric scaffold are: rim diameters (defines the diameter of the circle used as a base for the sweep feature), scaffold height, number of struts elements, etc.

Developed parametric model has been tested by using it in some basic filament analysis tests. It was concluded that with different parameter combinations, the model can successfully regenerate, which means that it is eligible for further use in previously explained ways (for optimization, mechanical testing, etc.)

IV. CONCLUSION

In this study a design methodology for a generic parametrized lattice scaffold model has been showcased. The model has been designed in such a way that it is flexible and robust, which has been checked through successful regeneration of models featuring multiple combinations of structural parameters values. This model allows for future structural optimization studies and mechanical tests to be conducted, which means that the result of this study is an important step in determining the effects that the geometry of lattice structures has on a scaffolds' mechanical properties.

Figure 9. Different parametric sets of generic parameterized lattice scaffold model

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