

## DESIGN OF NON-UNIFORM TRUSS STRUCTURES FOR IMPROVED PART PROPERTIES

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### Summary

This paper discusses generation of lattice structures with non-uniform shape and their optimization in a computer aided design (CAD) model of an exemplary part. Feasibility of encapsulating the whole process within one off-the-shelf CAD suite is analyzed. A method of design of lattice structures of variable density is proposed. A series of finite element method (FEM) analyses leading to achieving improved structures is presented.

**Keywords:** ultralight, lattice structures, additive manufacturing, design for manufacture, parametric optimization

### Projektowanie nieregularnych struktur kratownicowych z uwzględnieniem ich właściwości

#### Streszczenie

W artykule przedstawiono tworzenie nieregularnych struktur kratownicowych. Prowadzono proces optymalizacji z użyciem modelu CAD na przykładzie przyjętego elementu. Ustalono możliwość realizacji zadania za pomocą jednego niezmodyfikowanego narzędzia projektowego. Opracowano metodę tworzenia nieregularnych struktur kratownicowych. Wykonano analizę z zastosowaniem metody elementów skończonych, umożliwiających opracowanie modeli stanowiących podstawy do poprawy właściwości elementów struktury kratownicy.

**Słowa kluczowe:** konstrukcje ultralekkie, kratownice, wytwarzanie przyrostowe, optymalizacja parametryczna

## 1. Introduction

Significant growth of Additive Manufacturing (AM) technology in the last three decades allows production of parts with complex geometry. Such a feat means that designer is less restricted by technological issues when considering the form of his designs – he could focus on function. When considering parts in weight-critical applications, even one of nature's most impressive structures could be copied: bone with its lattice composition giving it strength and rigidity while ensuring the most effective use of all material [1, 2].

It is also important to observe, that the medical industry also shows great interest in such structures due to their superior bone in-growth properties.

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Together with favorable weight/performance ratio this enables much better endoprosthesis applications [3].

While stochastic processes already have been used for generating of porous materials in the past, controlled, generated periodic structures have been presented, having superior properties at low relative densities [4, 5]. The ability to control all parameters and properties of created structures and fabrication in a one step process that made designers turn to AM, was enabled. Today this idea is proven for many specific processes and a wide array of materials from polymers like nylon to metallic superalloys. Specific research on generating and optimization of truss structures in parts is however, far from completeness. Although similar principles have been already applied by civil engineers on a routine basis [6], these new possibilities still leave the traditional mechanical engineers' toolset somewhat inadequate and incomplete.

The main problem restricting the use of civil engineering derived methods is that they mostly assume pivotable joints linking the trusses while in AM they are rigid. Other restrictions concern the available geometry of truss structures, available by AM. This concerns mostly angle of vertical unsupported structures which is limited. These considerations limit design and optimization options available for the designer [3].

## 2. Background on ultralight truss structures

Coming up with a lattice design that would be as sophisticated as bone tissue is beyond human ability. Because of that, up to date, most lattice structures used are regular – basing on patterned primitives, using the same cell and truss sizes and forms throughout the whole part. There are some tools available, enabling generation of more sophisticated truss structures based on CAD geometry. By outputting generic files (mainly STL) however, limiting any future modification possibilities [5]. Similarly add-ons of specialized software allowing FEM-based optimization, including multi-scale, of designed internal structures are not suited for CAD-output [6]. Finally, not finding appropriate tool, one decides to build own specific software tools from scratch to fulfill his needs [7]. Fortunately, current CAD systems offer enough robust tools enabling creating and optimizing more advanced forms of lattice structures by adaptation of external common software techniques to cad – generated geometry. This paper discusses the possibilities of alternating lattice density by modification of feature oriented, parametric CAD structures on given way.

Current research on truss structure design for AM is very limited as can be seen in the few cases of reported implementation. There are basically two approaches – the continuous truss approach (i) and unit cell approach (ii). In (i) a truss of desired parameters is treated as a primitive and patterned to fill the space encompassing the part to be filled. Subsequently the resulting structure has

to be truncated, since in most cases it exceeds the part's boundaries. In (ii) the patterned entity is a voxel containing the lattice's unit cell. This method is preferred by specialized tools' developers, but when using mint CAD systems both are competitive.

Another consideration is the shape of the truss and their spatial arrangement in context of the part in its supposed load conditions. This is where the unit cell approach allows greater design elasticity. Guidelines on appropriate form of structure to utilize are present in many publications. For best mechanical properties, generally keeping a structure stretch-dominated and avoiding low angles (ie. trusses close to perpendicular towards loads) is recommended [5, 8].

In order to ensure the best performance with minimum mass it the best approach is to optimize the structure. There are three basic types of truss structure optimization: size, shape and topology. Size optimization bases on modification of the form of the trusses' cross-sections, by altering their dimensions or figure. Shape optimization takes the location of nodes into consideration, while topology remains constant. Topology influences the connection of the nodes by the trusses. It is generally advised to run all three types of optimization in parallel [6]. Considering how mechanical design is handled, it is often achieved by multi-scale optimization, but this method is not directly supported by typical CAD systems.

### 3. Sample creation

In order to fulfill the aim of this research, a simple beam has been proposed to be taken into consideration (Fig. 1.). As one of the subjects to be tested was the performance of off-the-shelf CAD system in such application, CATIA V5 has been selected for completeness. It offers all needed components:

- advanced parametric modeler,
- built-in FEM module of suiting capabilities,
- built-in optimization suite,
- robust STL exporter for shop floor transport.

Even though CATIA also extensively supports scripting for all of these modules, the aim was to restrain as much from development as possible [9].

The selected method for populating the part with internal lattice was the continuous truss approach. The form of the structure selected was a series of grates. Similar shape has been proposed for endoprosthetics [10]. The considerations, that were taken into account when selecting the specific type of structure, were collected in Table 1.

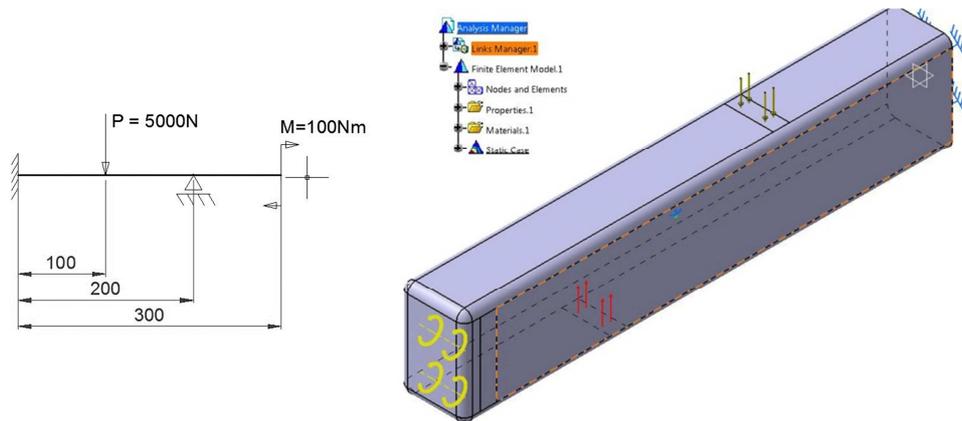
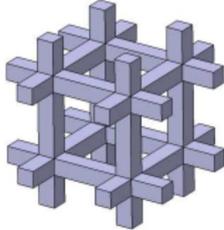
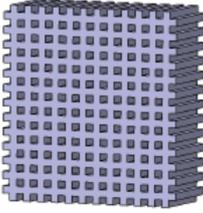
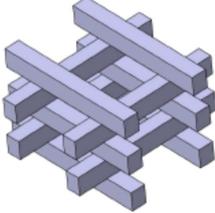


Fig. 1. The scheme of the modelled beam and solid model supported and loaded in CATIA V5 FEM

Table. 1. Considerations for selecting a specific type of internal lattice

Criterion	Structure 1	Structure 2	Structure 3
Representation			
Description	Continuous trusses of unrestricted cross-section placed along the axes of a Cartesian axis system, multiplied	Foam-type periodic structure, orthogonal plane-type elements, multiplied	Grate-type structure, continuous truss of rectangular cross-section, without overlaps
Pattern operations	3, each along two directions	2, along one direction each	2, along two directions each
Structure properties	Allows for easy control of porosity, biggest optimization potential, uses up most computer resources	Removing support material may be an issue, some optimization potential, uses up least resources	Sufficient optimization potential, acceptable computer resources requirements

As can be observed, computer performance play a significant role when planning to the use the CAD-generated lattice structure. Since modern CAD-systems do not handle data of patterned geometry in an efficient way, these operations are a strong limitation. A mid-tier PC with 8GB of RAM running Windows 7 became unstable when trying to update a pattern operation with over

2500 entities. Switch to a 64 GB machine allowed generating structures consisting of 8000+ entities, but it was still a time consuming process. Probably with the right custom-scripted functions this bottleneck could be removed, but it is important to point out that typical CATIA configuration is not particularly suited for designing and handling parts containing large truss structures. Moreover one should point on the fact, that comparing to concurrent integrated CAD/CAM system CATIA V5 wins competition mostly, when performance is the main criterion. Therefore CATIA V5 is commonly used to model complex structures in architectural, aerospace, marine and mechanical applications.

The spacing between parallel trusses (shape) was controlled by parametric sketches, set-up in anticipation of the loads that would be present in the FEM analysis. The parameters controlling the shape of the sketches would then be subject of optimization using the Simulated Annealing Algorithm. The goal of this optimization was to search for an case of minimal weight while trying to reach displacement and maximum von Misses stress in the structure below a set level. At the same time parameters were limited so that the structure would always ensure removing supporting material in a fabricated part. It means critical, vertical positions of truss beams remain.

The CATIA V5 workbenches used for this case study were: Part Design (solid modeling), Wireframe Design (node locations), Generative Structural Analysis (meshing & FEM), Product Engineering Optimization (optimization).

#### **4. Parametric FEM optimization and results discussion**

The model consisted of a constant number of 576 trusses in order to ensure correct model topology even with minimum spacing between trusses. Most of the time however some 30% of these elements were truncated in entirety. The outer layer of the model was also skinned with a thin skin element to ensure proper propagation of loads onto the lattice structure. The spacing of the trusses was controlled by two sketches with 14 parameters selected for optimization.

The model was set to mesh itself by using the automatic OCTREE Tetrahedron mesher with 1.5 mm size and sag up to 1 mm. This generated nearly 890.000 elements in FEM analysis of a randomly selected case. The material selected for analysis was typical steel with properties as presented in Table 2. Such properties are easily achieved with Selective Laser Melting of steel powder. It is also important to notice at this point that these calculations are of strictly benchmarking type.

FEM analysis of the solid model and model with uniform truss structure provided the level of reference for optimization (Fig. 2). Target for maximum deflection was set at 0.01 mm and target maximum von Misses stress at 30 MPa.

Table 2. Steel properties for the FEM module

Properties	Steel
Young's modulus	200 GPa
Poisson's ratio, $\nu$	0,266
Density, $\delta$	7860 kg/m <sup>3</sup>
Yield strength, $R_{po.2}$	250 MPa

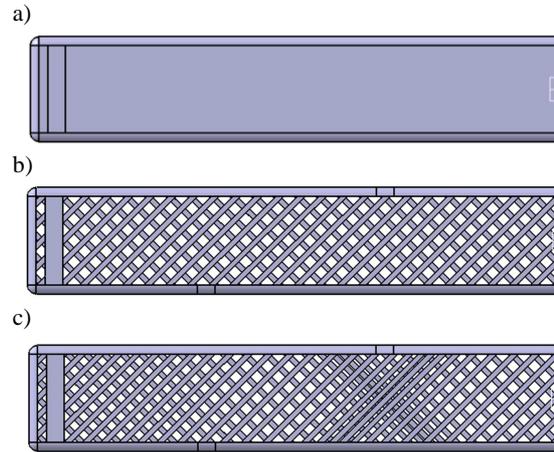


Fig. 2. Design process: a) solid model, b) model with uniform internal structure, c) model with non-uniform internal structure

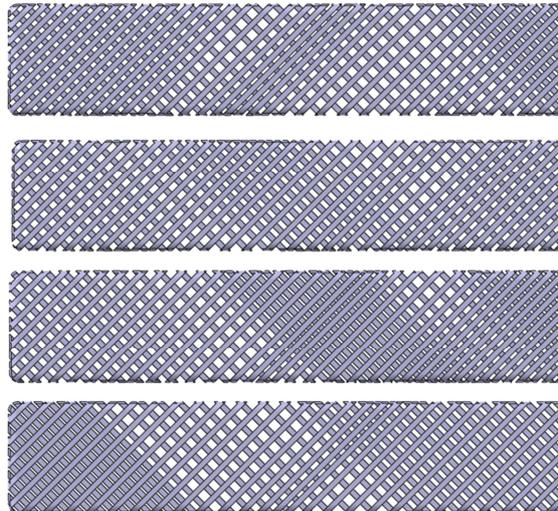


Fig. 3. Selected cases from the optimization process along with best found solution (uppermost)

The resulting procedure took up to 50 min. per iteration (Fig. 4). About ten of which were taken by model updating with new parameters, ten for meshing and up to 30 min for solving the FEM case. This meant that optimization with a target duration of 48 h only resulted in 48 valid generations. In a real-world scenario the calculations would need respectively more time on a preferably much more powerful workstation, but even with the limited number of generations the results are satisfactory. A selection of individuals produced by optimization von is shown in Fig. 3. Collected results presented on a graph are shown in Fig. 4.

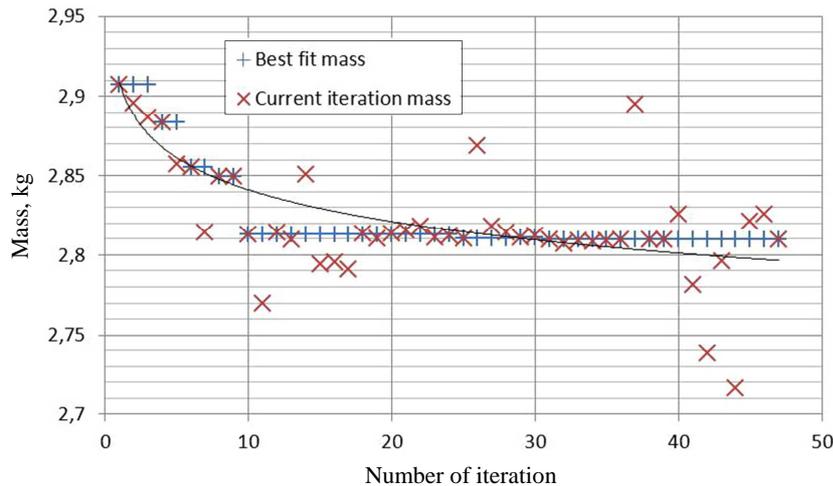


Fig. 4. Optimization results with exponential fit line for Best fit; Note that many of the more light-weight iterations were not the best sit since they missed optimization criteria by too large margin

The resulting best case had a weight 19% higher than the uniform (minimum density) structure, yet presented nearly 50% smaller maximum displacement and 50% smaller maximum von Misses stress.

## 5. Conclusions

CATIA V5 has proven to be an appropriate tool for incorporating all areas of design and optimizing truss structures for small scale and with certain restrictions.

Current CAD systems introduce a limitation on patterned structures' complexity by sub-optimally handling data. This enforces the designer to abandon pattern operations and instead use workarounds. These alternate

methods however need to take CAD-associativity into consideration, as it is very important for the robustness of the whole model. It is suggested to utilize the system's scripting functionality to develop appropriate tools for populating solids with truss structures. But even without programming skills, design of such parts is possible.

Another problematic area is the truncation of elements that had to be calculated by the system in the first place. Such approach is counterproductive and it is very much advised to develop methods for creating conformal structures, that would follow the part's geometry.

As for today, direct-to-STL may be a better option for creating especially large elements with lattice internal structures if non-parametric design is acceptable.

Shape optimization has proven to be no problem whatsoever to CATIA V5. And since in the given case it relies on the same principles as size optimization, both of these methods should be used in parallel.

Today the biggest challenges lie in proper modeling and topological optimization of internal lattice structures for parts with the use of parametric CAD.

The accuracy and repeatability of generative methods, as discussed in [11] should be also pointed as a significant technological problem of rapid manufactory and prototyping.

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