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Generative design of a large-scale nonhomogeneous structures

Jelena Djokikj*. Jovana Jovanova**

* Ss. Cyril and Methodius University in Skopje, Faculty of Mechanical Engineering, Ruger Boskovikj No.18, 1000 Skopje, North Macedonia (e-mail: jelena.djokikj@mf.ukim.edu.mk.

** Delft University of Technology, Faculty of Mechanical, Maritime and Materials Engineering, Mekelweg 5, 2628 CD Delft, Netherlands (e-mail:j.jovanova@tudelft.nl)

Abstract: The digitalization of the product design process has become the new norm in the engineering design with the development of different CAD software, design analyses tools, and rapid prototyping techniques. More holistic approaches in the product design analyses include modeling of the manufacturing technologies and the entire logistics regarding the product life-cycle. Advanced design techniques have paved the way for engineers and designers to create new innovative products with unique functionalities or entirely change the shape of an existing traditional product. Generative and parametric design methods have established themselves in the recent years with benefits regarding material use and sustainability, but mostly with the development of the additive manufacturing technologies. They enable concepts like application driven design to become feasible, in this case lightweight structures while still maintaining structural integrity. In this work, an application driven design of non-homogeneous structure with tailored response to different external load conditions is presented. The structure design constraints in size and expected load capacity result in nonhomogeneous structure with optimal material distribution and structure mechanical response.

Keywords: design methodology, generative design, parametric design, CAD modeling, smart design of large-scale structure, nonhomogeneous structure.

1. INTRODUCTION

Advanced design techniques are constantly evolving capturing more and more physics-based features into their algorithms allowing for more realistic engineering designs. 3D CAD software platforms have become the norm in product design, offering a lot more than just straightforward digitalization of the drawing process itself (Roucoules et al. 2020). CAD modelling platforms are constantly upgraded with algorithms to support the designer in the design process using topology optimization (Meng et al. 2020), generative design and parametric design (Briard et al. 2020, Ricotta et al 2020). These features can support design products with innovative functionalities and unique shapes, not possible to be derived in any other way. The developments in the design field have been extensively supported by the developments in the manufacturing and logistics. The digitalization of the entire product life cycle has become part major player in the Industry 4.0 era (Kritzinger et al. 2018) and digital twins in manufacturing.

Manufacturing techniques have been digitalized as well, using precise digital machines able to perform multiple tasks in different scales: from milling and drilling, over casting and extrusion, to additive manufacturing (AM). AM developments in the last decade have opened up all industries for new product designs (Thompson et al. 2016). AM technologies are pushing the boundaries of possible shapes and forms for end products, which has been one of the main constraints in engineering design. The possibility of fabricating complex 3D shapes with different materials and even combination of materials and functional grading can push the creative limits of engineers and designers beyond imaginable only few years ago. One of the main constraints in additive manufacturing has been the product size. However the advances in recent years show that this can be overcome as the manufacturing techniques mature and develop further.

Design of metamaterials and lattice structures enabled by additive manufacturing have provided features not found in nature to be manufactured and used in engineering product design. Patterned shapes for light weight structures continue to gain attention. Nonhomogeneous structures can provide tailored structure response based on expected external loads, resulting in optimal design shape and tailored structure properties. Design for additive manufacturing (DfAM) has become a topic of interest as it combines the product shape and it manufacturability in single design framework (Vaneker et al. 2020). Taking in consideration the manufacturing constraints in the design process reduces the time from initial design to prototype (Djokikj et al. 2019).

In this paper a design framework for nonhomogeneous large scale structures is presented taking in consideration external loads combinations and AM constraints. This framework is beneficial for an application driven design of large scale structures as it combines the parametric design, evaluation and design optimization by generative approach. AM opens numerous possibilities for large scale design and this framework will create re-applicable designs to multiple

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specific scales and different external loading conditions. The benefit of this framework is that the structure can be optimized based on the performance requirements of each specific case study. Truss structures, support structures, cranes and port structures, floating structures and other traditionally mega steel-based structures can be designed in a novel way using this framework and allow for smart design and multi-functionality on the large-scale.

The remainder of the paper is as following: Section 2 shows the design framework and the main elements that are part of the process of designing large-scale structures taking in consideration the AM technology. Section 3 focusses on the parametric design, explaining the used principles and constrains applied in the design of the cell unit. Section 4 presents the results of the conducted finite element analysis (FEA), which are used as inputs for the generative design algorithm. Section 5 focuses on the generative design of the large-scale structure and the possibilities that are revealed by this kind of approach. The last section 6 concludes the work and further research plans are discussed.

2. DESIGN FRAMEWORK

The design of large-scale structures is still quite traditional and conservative when it comes to the design process, the material choice and manufacturing. However with the developments in additive manufacturing, the size ceiling is pushed further and further, and the large scale structures can benefit from the advances in the available design techniques.

This requires a different design framework from the traditional one, including the size, external loads and the manufacturing technology considerations. In this work we propose an application driven design framework shown in (Fig. 1) that begins from understanding the application and the expected loading ending with a design ready for fabrication using AM technology.

By integrating the external expected loads into the framework, the structure is designed in optimal manner and tailored to respond to the environment as expected not exceeding deformations and maximum stresses. The main phase in this design framework is the *parametric design* step. In parametric design the goal is to design with the same but variable design parameters. This requires definition of the parameters and their variability which leads to straightforward and relatively easy redesign of the structure geometry. Almost endless shape and geometry possibilities are possible in redesigning the problem with new parameters if needed. In our case the structure is segmented and the design parameter is the segment size and the number of segments. Based on these 2 parameters the structure geometry is generated. The designer makes the decision of the number of segments used and the complexity of the geometry of each segment. This also includes the AM technology constraints such as minimum possible wall thickness.

The *FEA* are conducted in order to analyse the stress distribution in cells with different geometry. The outcome of the FEA is applied in the optimization process in order to achieve the most appropriate cell geometry, also called *generative design*.

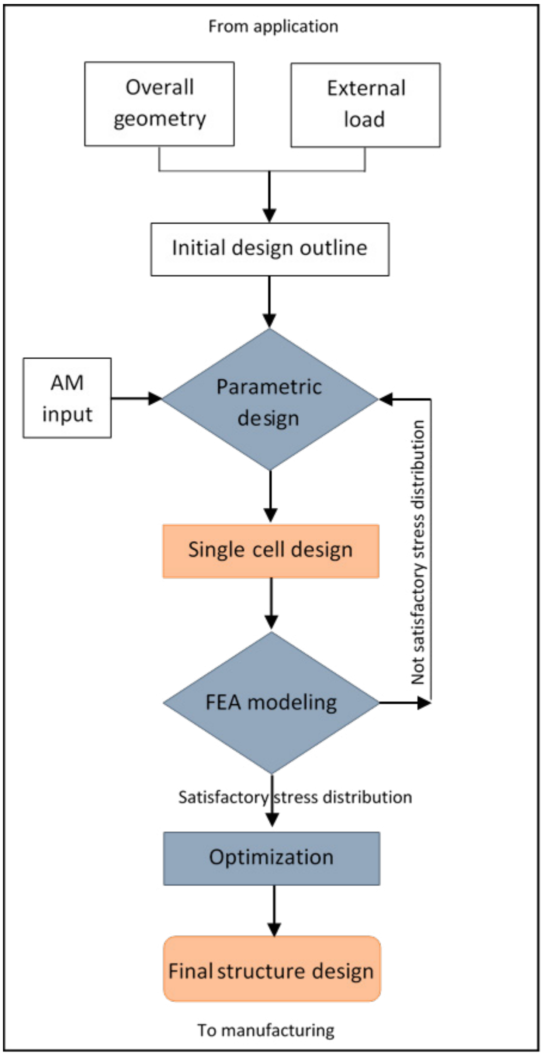


Fig. 1. Application driven design framework for non-homogeneous large-scale structures

We use the parametric layout, but automate the variations in parametric choice based on the loading conditions. For a large-structure design, the generative design approach is used to choose the cells with the appropriate cell geometry among a predefined number of cells in a structure, based on the external loading conditions (Fig 2).

The parametric design is used in determining the number of cells in the structure and overall shape of the structure based on the specific application and the AM constrains. Although, the generative design is used to determine the complexity of the cell geometry based on the external loading conditions and AM constrains. The algorithms runs until an optimal solution is reached with regards to maximum allowable stress and deformations.

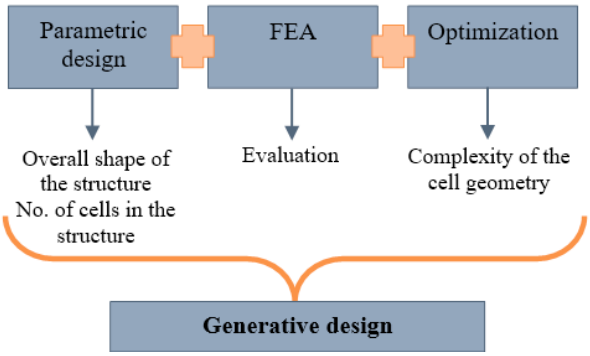


Fig. 2. Generative design for optimal structure tailoring

Application driven structure design can potentially enable for optimal structure, minimum material use, onsite fabrication and no need for transportation from manufacturing location to the actual structure location. The structures designed in this manner can be further developed into smart structures by adding sensors for structural health monitoring and/or smart materials in critical segments serving as actuators. The programming of the structure can be tailored for specific loads or combination of loads. Integrating variable material properties (energy absorption, compliance, actuation, etc.) into the shape generation can increase the design space and open up for application driven smart large-scale multi-material structures design.

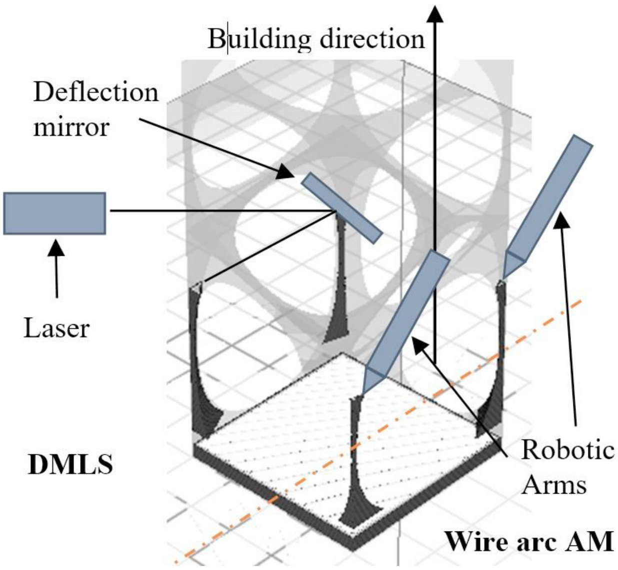


Fig. 3. Graphic representation of possible fabrication technics (left – powder based process, DMLS; right - Wire Arc AM)

AM considerations are taken into account since the structure of this complexity in the geometry and size is only reasonable to be fabricated using AM. Another advantage of the AM, important for this specific case is that each structure is one of a kind, which is the advantage of these technologies. AM constraints regarding the minimum wall thickness and detail are applied in the early stages of the design process, and also as limitations to the parametric and generative algorithms.

Two AM processes are proposed as possible for this kind of structure, direct metal laser sintering (DMLS) and wire arc AM, since the used material is expected to be metal (Fig. 3).

DMLS can be restrictive in the size matters (due to the restricted bed size), but the output is with higher quality than that the wire arc AM. Then again, wire arc AM has no restrictions in size, is flexible process allowing fabrication on site. In conclusion when the complexity of the design is concerned both processes are acceptable. Which process is chosen at the end will depend on the structure's application

3. PARAMETRIC STRUCTURE DESIGN

This approach for parametric design can produce variation of structure designs quickly. For designers this approach is very useful as they can get unique 3D models of structures based on the parametric input variations. However additional analyses are needed for the structure response in order to confirm the structure expected behaviour. Then the designer goes into an iterative process of fine tuning the design based on the loading requirements.

In this paper we propose initial cell parametric design that is essential part of lattice large-scale structure. The geometry of the cell is designed parametrically which means that range of parameters are used to define the cell (Fig. 4). This states that anywhere in the design process the designer can go back to the initial design and change some of the input parameters. The cell size is fixed (10x10x20 mm), which can refer to 1x1x2 m in reality. The scaled size is to avoid large data, which is important for the later steps (FEA and generative design).

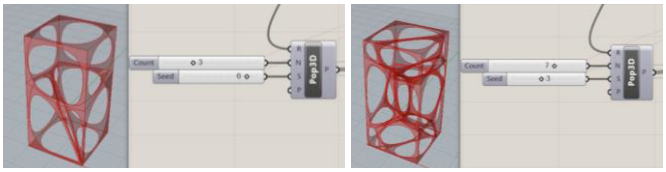

Count 3
Seed 6
Count 7
Seed 3

Fig. 4. Parametric design of single cell

To define the unit cell size and complexity, in this work Rhinoceros (Rhino) 6 and its graphical algorithm editor Grasshopper is used (Fig. 4). As a plug-in for Rhino, Grasshopper is integrated with the robust and versatile modelling environment. This platform allows designers high level of control over the structure design (Akos at al. 2014).

The proposed cell design is inspired by nature and applied by the Voronoi tessellation (Fig. 5). The Voronoi diagram is an example of leading trends in parametric design. The Voronoi Tessellation describes a system of the self-organization of biological structures visible on the wing of a dragonfly, the turtle shell, honeycomb or the shell of a sea urchin (Nowak et al. 2015). As a result, this tessellation promotes the heterogeneity and strategic distribution of material properties (Oxman, 2010). The Voronoi tessellation partitions the surface of the CAD model into cells using the vertices of the model (lattice points) as "seeds" or "generators," such that for each seed there is a corresponding cell consisting of all points closer to that seed than to any other (Goswami et al. 2019).

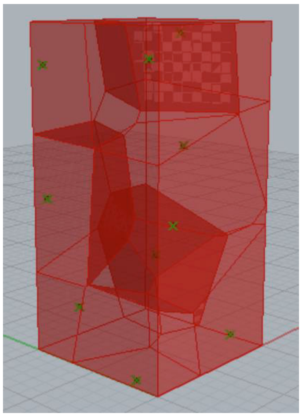


Fig. 5. 3D Voronoi tessellation for latttice design

The nonhomogeneous large-scale structure is built by addition of number of cells (Fig. 6). The cells can be added in all directions. The different geometry cells combinations are in order to achieve maximum functionality (structural integrity, stability, strength, energy absorption, etc.) with minimum material mass.

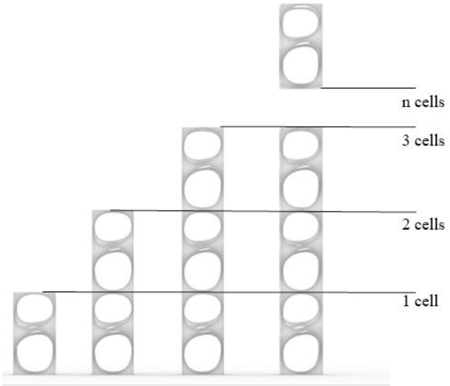
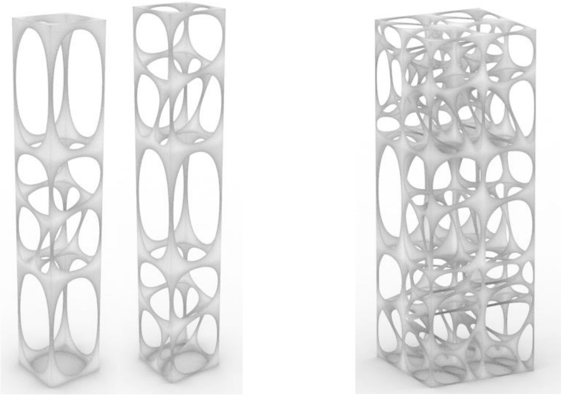


Fig. 6. Building structure by adding number of unit cells (1 cell, 2 cells, 3 cells and n-cells)

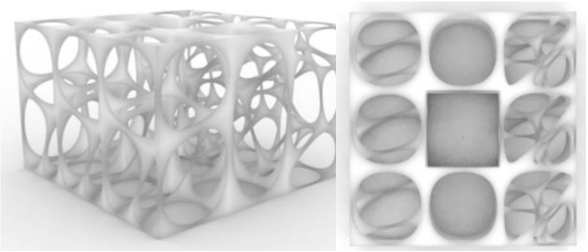
The different cells arrangements result in various structure designs which expands the functionality of the structure itself. Few combinations of the upscaling are presented in Figure 7.

In order to be able to scale up the structure modelling, when it comes to size, number of unit cell, distribution in combination to complex loading, we propose an automated generative design approach.



a) Column 1x1x3, different cells combinations (1 cell in width/depth, 3 cells in heigh)

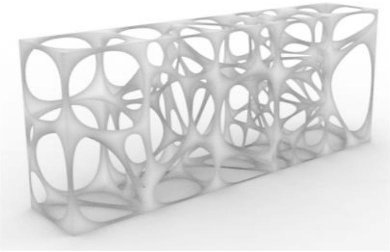
b) Column 2x2x3, different cells combinations (2 cells in width/ depth, 3 cells in height)



Isometric view

Top view

c) Box 3x3x1 (3 cells in width/depth, 1 cell in height) with hole inside



d) Wall 5x1x1 (5 cells in width, 1 cell in depth/height)

Fig. 7. Scaling up by addition of cells in multiple directions

4. UNIT CELL & STRUCTURE ANALYSIS

The advantage of this design approach is that the design can be tailored to respond in a certain way based on the input loads and the geometry of the structure. Different unit cell designs under the same external load conditions demonstrate different stress distribution (Fig. 8). This can help understand the possibilities and variations to get closer to an optimal design solution.

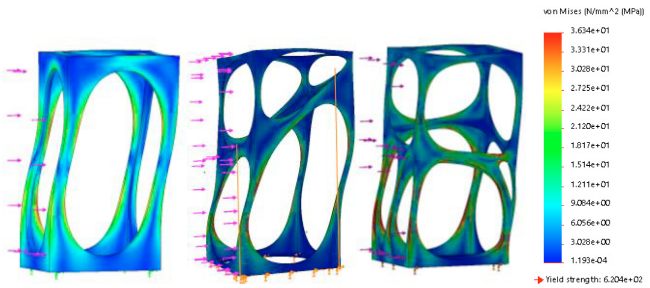


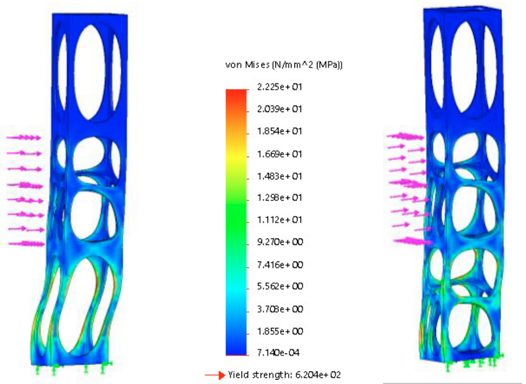
Fig. 8. Different geometry unit cell stress distribution (left – one count; middle – two counts; right – three counts)

We analysed different cell geometries with the same material under the same loading conditions, side force of 1N (Fig 8). In Fig. 8, results of the analysis are presented with one scale showing their stress distribution. Maximum stress for the left cell is 36.34 MPa, for the middle cell 50.29 MPa, and for the right cell is 136 MPa. It is evident that the third cell has highest value, but still all the values are within the material's stress constraint, which is 620.4 N/mm^2. From the stress distribution, it can be concluded that different application can benefit from different material distribution. Displacement analysis of the same cells is presented in the Table 1. It is evident that the least displacement is noted in the first cell which corresponds to the results from the maximum stress analysis. So if the application needs a stiffer structure then the local unit cell can be tailored with one count. If the application expects local impact loading and potential energy absorption can prevent the structure, then the unit cell with 3 counts can be positioned at the impact load expected position.

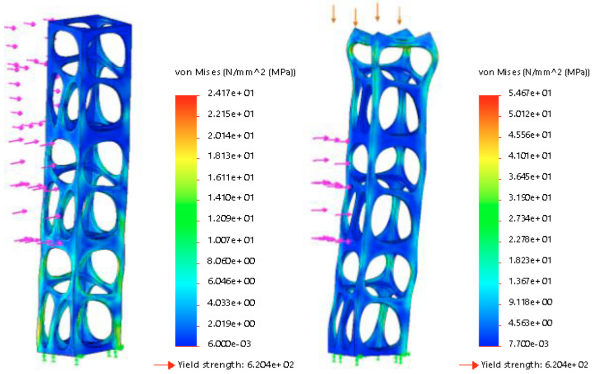
Table 1. Displacement along X and Y axis

	1 count	2 counts	3 counts
Max [mm] (along x)	1.609 e-03	2.251 e-03	4.291 e-03
Min [mm] (along x)	1.597 e-03	2.174 e-03	5.927 e-04
Max [mm] (along y)	1.266 e-02	8.975 e-03	1.358 e-02
Min [mm] (along y)	1.594 e-06	8.671 e-07	1.544 e-06

Once we go to higher number of unit cells then the complexity of the shape and the possibilities for parametric design increase. In the case of a structure built from 3 unit cells the structure response to the same loading conditions is different. FEA analyses was also applied on structures beam-like column, consisted of 3 cells added on top of the other. In Figure 9-a structures with cells with different geometries are put under same loading conditions, 1N. It is evident that if pressure/force is applied in the middle section, the highest stress value of 22.25 MPa is noticed in the first cell. This is why in the second example, the first cell is substitute with cell with more complex geometry. The new structure responds more stable to the applied loading conditions, and the maximum stress value is 16.64 MPa.



a) One loading condition for 3 cells structure with different geometries



b) Two loading conditions

Fig. 9. Stress distribution as a result of different loading

In Figure 9-b, the same two structures are put under different multiple loading. The first example, under lateral loading achieves maximum stress of 24.17 MPa. In the second example, when the loading is from top and side, the maximum stress is much higher, reaching 54.67 MPa. The value may not be very high, but the deformations on the top cell are quite big. In this case, it is suggested that the top cell should be with more complex geometry, allowing it to absorb the load and to avoid fatal deformations or even cracks.

5. GENERATIVE STRUCTURE DESIGN

Parametric design is great for simple loading solutions and intuitive parametric choice. However to be able to optimize the best shape with multiple variable inputs, a generative design approach is needed. Within the design framework that we proposed, we parametrically design the unit cell which shape can vary depending on the input parameters with the possibility to multiply in width, depth or height. Then we apply generative design (Fig. 10) in order to choose the best cells geometry based on the external loading conditions which results with optimal structure design. The cell geometry corresponds to multiple loading conditions of various directions and magnitudes.

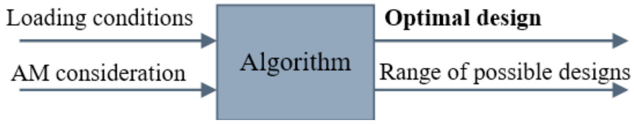


Fig. 10. Proposed generative approach

The distribution of shear-stress lines and surface pressure is embodied in the allocation and relative thickness of the vein-like elements built into them. If the structure needs to carry concentrated load in particular area then this unit cell will be designed with multiple thicker walls. If part of the structure is not critical in caring the external load, the unit cell in these sections will be lighter. Also if overall structure response requires localized compliance or localized energy absorption the distributed unit cells will be tailored to the expected structure behaviour with optimum geometry shape. Additionally, AM constrains as minimum wall thickness, overhangs and bridges are taken into considerations. Voronoi tessellation can adapt to different input parameters, so this also one of the main reason why it was chosen for these application. Applying the generative approach presented in Figure 10, resulted with numerous structure designs.

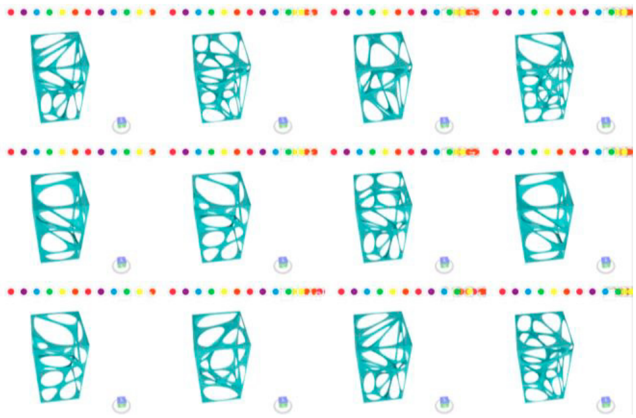


Fig. 11. Range of possible designs by the generative algorithm

In Figure 11, some of the results from the generative approach are presented. For the generative design the interactive evolutionary algorithm, Biomorph was used. Biomorph is a plug-in for Rhino Grsshopper created by Harding and Brandt-Olsen, inspired by the pioneering work of Dawkins, who was the first to implement this latter approach, using computation and a selection interface to evolve. As Harding and Brandit-Olsen explain, once Biomorpher is launched, the user may select a population size, single-point crossover and random mutation rate. Selecting these parameters depends on the problem in hand, which can vary dramatically depending on the nature of the parametric model itself, the (unknown) search space and the sensitivity of the mapping between genotype and phenotype. (Harding, J. and Brandt-Olsen, C., 2018).

Important thing is that the Biomorpher records the evolution history and displays this to the user, including optional performance data. As the solution space could be completely unknown when initialising a search, there is potential to steer evolution towards undesirable paths – indeed, this is inevitable for any wide design exploration. With this in mind, some way to return to previous generations and begin a new search branch becomes important (Harding, J. and Brandt-Olsen, C., 2018).

The generative design does not interfere with the designs work since at the end of the process offers a range of designs that satisfy the input parameters, allowing the designer to choose the suitable structure design.

In Figure 12, seven examples of different structures are presented as result of the different inputs in the generative design algorithm. All the structures are consisted of three 1x1x2 m cells, making them 6m in height. The first structure has no external loads, so its geometry is clean and simple offering the necessary stability and use of minimum material. It is used as connector to other elements. In all the other examples force of 100 N is applied. The second structure is an example of a stricter that has relatively small force/pressure applied to the second (middle) cell. The third structure has a small top load/pressure applied to the third (top) cell, so one cell with complex geometry is enough to reduce the stress. The forth structure has side or frontal force/pressure applied in the first (bottom) cell. The fifth structure is an example of a structure that has top force/pressure applied to the third (top) cell. The geometry complexity is increased for the both cells (Fig. 12) in order to have better stress distribution and less deformations. The sixth structure has side or frontal force/pressure applied to the second (middle) cell, the first cell is with same geometry in order to offer more structural stability. The last, seventh, structure has side or frontal force/pressure applied on the first (bottom) and the third (top) cell. It is understandably that these examples can be widen to horizontal beams caring a load, even further for support plate or 3D structure.

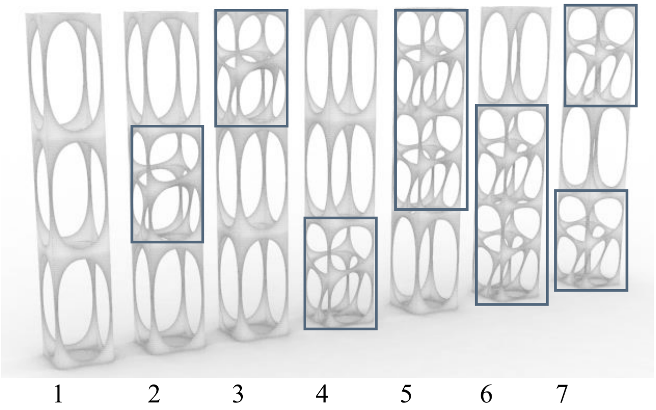


Fig. 12. Example of different cell geometries based on the different loading conditions

The optimal solution can be stated with different design constraints, based on the application. Certain walls can be designed with stability constraint from buckling, others can be designed with allowable flexibility. This allows this algorithm to be application driven and each design to be optimal and unique. By expanding this algorithm with multi-material properties, the structures can be programmed to act in certain way based on external loading. This type of high level integration in the design process enables local design intervention for overall structure programmable response. By controlling the materials and the spatial control locally features such as energy absorption, flexibility, stiffness, crack prevention and others can be achieved. This is beneficial for multifunctional structures and optimal stress distribution

6. CONCLUSIONS

Design of a large structures is a major engineering challenge itself, but it gets even more complicated in the case of a non-homogenous structure. However the advantages offered by these structures span from material reduction, stability, energy absorption, local compliance. With the new advancement in the additive manufacturing and engineered materials, the design possibilities for large scale structures expand.

In order to make beneficial advances in CAD design modelling for the large structure applications, in this work we proposed a generative design framework. The framework allows for parametric design of unit cell based on Voronoi tessellation for the latttice structure design. Then the structure is optimized based on expected external loads, the manufacturing constraints and the application constraints. The generative design offers freedom in the design process, generating all feasible optimal solutions, allowing the designer to choose the most suitable structure design.

Future research plans include application driven designs and multiple case studies including small scale prototyping. The final goal is to design and fabricate a large scale structure with additive manufacturing on site with tailored properties. This will allow the mega metal structures industries to utilize on advanced design techniques, engineered materials and additive manufacturing.

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