3D Printing of High Strength and Multi-Scaled Fragmented Structures

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Our research aims to push the limits of 3D printing towards the structural design and optimization. Additive manufacturing has an unique feature which is printing multi-faced complex geometries as easy as simple ones. Therefore additive manufacturing creates the chance of producing really small scaled complex forms. In a structural network, it can be easily understood that the more geometric variations to respond stress, the more adaptive structure will become to respond structural needs. The structural reaction is to be fictionalized by procedural operations and analysis that will be a tool to design multi-scaled fragmented structures. Those operations is to use the structural analysis and material reactions. Their iteration with the overall geometry will form the geometric generations. However the verification of the generations as outcomes of a real 3D printer is crucial. To verify, the precision of additive manufacturing should be sensitive enough that the structural element will function as it's simulated in computer with the algorithm. The sensitivity is important because, even couple of micro-sized problems can cause bigger ones in the structural element itself. The combination of all these variables can enable an initial geometry, to be able to adapt the stuructural needs in every additive generation.

Keywords: *Additive Manufacturing(AM), Structural Optimization, Selective Laser Sintering(SLS), Structural Design, Shape Grammars, Design Computation*

INTRODUCTION

Additive manufacturing (AM) processes include products that are built on layer by layer basis, by way of sectional cuts. AM technique has different aspects when we compare it with other fabrication or prototyping processes such as CNC based systems, moldings, plastic molten etc. Usually there are number of steps between the digital design model and the end manufactured product. In additive manufacturing, we can talk about direct itranslation from the CAD geometry to the machine as a guide to built accordingly. As a result of this working flow, by using the same data of instructions, 3D printing has acquired another distinctive face. A 3D printing machine uses same information which is layering on top of each other to generate any geometry. It could be a simple box or a complex, multi angled, multi sized, tessellated geometry(Berman,2012).

Therefore, this face of additive manufacturing is framing the basis of this project. Thanks to the AM technologies there is a chance to fabricate limitless procreations of a geometry. Thus, the shape could be manipulated into a new one that is adaptive and self-generative to become more customizable in structural manners. A geometry as such, could be modeled in a computer with a generative algorithm to adopt the predefined structural conditions. Since the machine has flexibility to produce any geometry at any complexity levels, our research also will try to seek the best co-relation of between digital and physical models inputs for a high strength structure.

ALGORTIHMIC RESEARCH

High strength structures can be seen in many ways in nature. Some of them can be, tree branches, leaf veins, blood vessels, respiratory system etc. But when we zoom in these examples a bit more, it can be perceived that they are multi-scaled fragmented structures(Rayneau-Kirkhope, Mao, Farr,2012). Theoretically these fragmented generations can be applied infinite times and as result of that, a fractal in 2-3 dimensions could have infinite generations. In order to assess the use of these geometrical models for the design of architectural components an generative algorithm is required. This algorithm, should have the capacity to encode complex geometries and/or as a tool to generate complex geometric forms starting from a simple shape(Fasoulaki,2008).

In our research one of our goal is to unleash the potential of rule-based design to create 3d architectural structural elements. Therefore rules could interpreted in a different way that is reproducing new geometries. At this point adaptation of the generated geometries to the starting ones is crucial. In this work this adaptation is going be based on size. The algorithm is consisted of as following:

1-Subdividing Initial Geometry

The internal circulation process starts with an adaptive subdivision. It's adaptive because it understands the geometry and scales down the geometry to maintain a coherent geometrical relation between the overall geometry and the discritised component. Scaling factor is also determined by the subdivision number it can be formulated as follows:

- *Divide base edge length with subdivision number and reach number "X"*
- *Divide X with base edge length and reach scaling factor. After reaching scaling factor smaller geometry is copied side by side and on top of each other.*

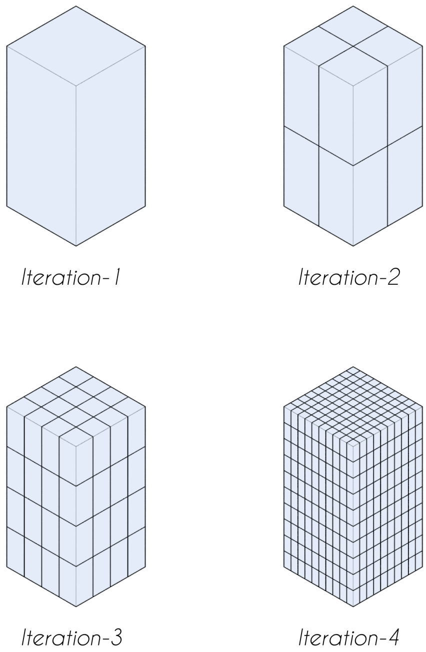


Figure 1
Series of Subdivision Iterations

2- Stress Detection

In the next step, at each stage of the subdivision iterations, structural loads are going to be simulated. In the diagrams above structural analysis are done according to the subdivision. For the load and the support inputs, the geometry itself was used. This simulation for the diagrams was done in *Rhinoceros*(software) by using *Millipede* which implements topology optimization methods for structural optimization is an add-on for *Grasshopper*(visual scripting interface for Rhinoceros.) Topology optimization methods are to solve material distribution problems by generating optimal topology results. Within these methods each element is addressed as a design variable that are allowed changes in density(homogenization) or solid-void(bi -directional evolutionary structural optimization).(Brackett,Ashcroft,Hague,2011) Figure 2 shows the colours on a simple geometry according to the stress level.. (Minimum stress is black, Maximum stress is red.) The material is selected as concrete but it could also be changed according to the geometry or the technology.

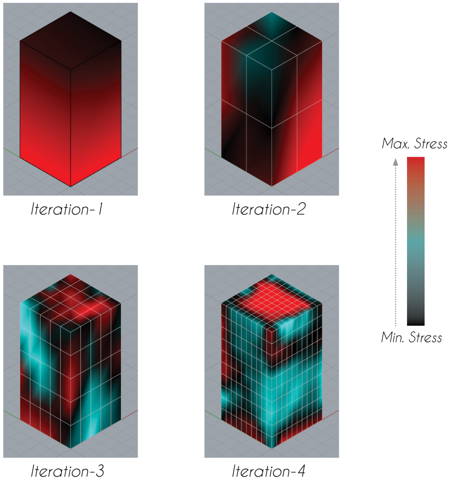


Figure 2
Series of Load Detection on Faces

3-Stress Subdivision

As a methodology a conditional is defined by filtering the subdivisions according to their stress. The conditional is splitting geometries into two: *Below the average stress* and *Above or equals to the average stress*. In our research we benefit from Shape Grammar as a theoretical source to subdivide and decompose geometries within smaller fragmentations. Shape grammars were introduced as a generative computational method for rule based design by George Stiny and James Gips in 1971. A shape grammar is a container of geometric shape rules and a mechanism for selection and process of the rules. These rules consist of spatial trasformations -i.e. move, rotate, scale, mirror that allowing one shape to be a part of smaller one. (Stiny and Gips 1972) The output faces of our stress subdivision methodology, the ones that are carrying less than the average stress are filtered to exist only in that iteration. The ones that are carrying more than the average or equals to the average proceeds to the next iterations in the geometry. And then the same subdivision operation starts again for the first subdivided components that advances to the next iteration. But this time distributed stress is going to determined the subdivision numbers. The faces which remains in the equation is going to address the crossing subdivided geometry in the first step.

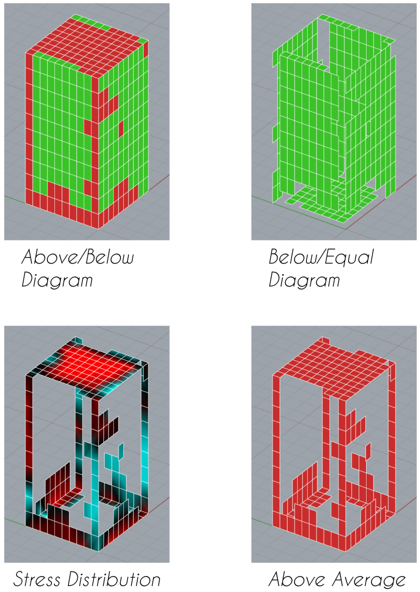


Figure 3
Series of Stress Subdivision

Methodologically the structural data will be synthesized in an algorithm formed by the different inputs

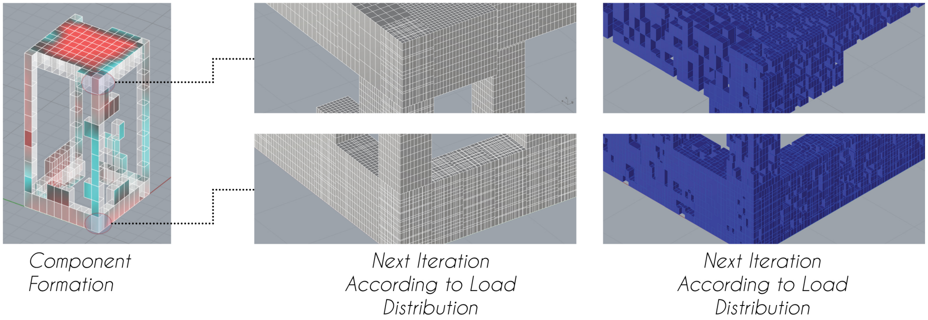


Figure 4
Next Iteration of Subdivision Operation

that define it. As similar as the shape grammars left hand is going understand the loads and left hand is going to feed the right hand for culling operations. The response of the geometry to structural loads it will be tested according to the structural requirements incorporated in the algorithm. Since it is impossible to get precise outputs without considering the material properties, in order to increase the efficiency of the algorithm, parameters representing material properties will be inferred and considered on the research. It can be easily understood that we need to test the static performance and aesthetics of the design solutions generated by the algorithm. As similar as the shape grammars left hand is going understand the loads and left hand is going to feed the right hand for culling operations.

TECHNOLOGY

There are different 3D printing methods that were developed to proceed AM operations to understand how these different basic processes are been applied to building materials and manufacturing processes. Since this research promises for number of iterations that are scaling down the geometries into sand size. The material also needs to be able to manufactured sand size. Therefore in this research manufacturing method is chosen to Selective Laser Sintering(Hollister, Das,and Brock,2004). SLS is a technique that uses laser as power source to form solid 3D objects.

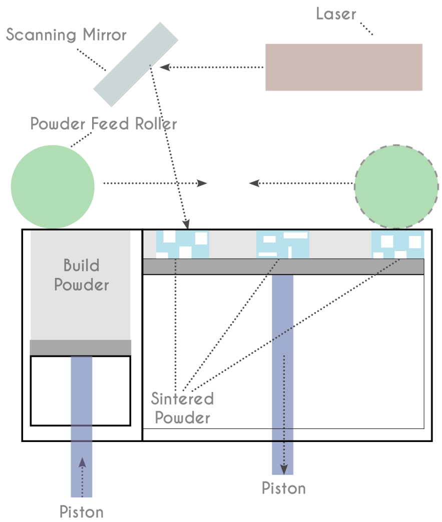
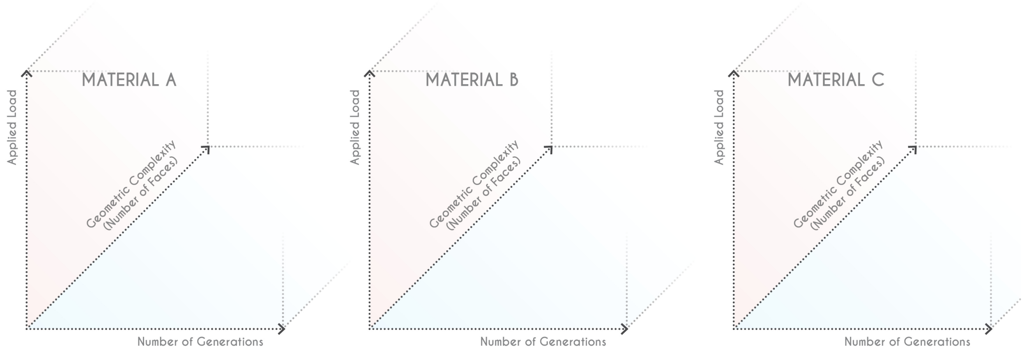


Figure 5
Selective Laser Sintering Work-flow Diagram

SLS constructs structures from 3D CAD data by sequentially fusing given areas in a powder bed, layer by layer, via a computer controlled scanning laser beam. The powder formulation is based on material selection. Because according to the material the size and the behavior of its processed version will be dif-

Figure 6
Representative matrix of possible generations for different materials.



ferent. As long as the material can be formulated into a powder for production, there is no limit on the selection. However, powder information is an important step in 3D printing because the powder material can cause major volume fraction on the final geometry(Utela, Strorti, Anderson and Ganter,2008).
Another important reason why a structure might fail at a point, rather than geometry or perfection level of fabrication, can be the material properties. Different materials will have different features and behaviors according to geometries that they are applied on. In order to sharpen the precision level of the algorithm, different materials and their properties should be in the equation(Schirber,2012). To achieve the optimal to respond to a certain design aspect and structural element, each output should be forced to the failure points by being subjected to the loads. The reasons of failures can be exposed, analyzed and solved according to which properties are required. The solutions that will be concluded from the results of physical outputs, will feed the algorithm. So that essentially, each examination of a 3D printed structural element will be links of a feedback loop between algorithm and physical entities of the algorithm

CONCLUSION

To sum up, our research aim to push the limits of 3D printing towards the structural concerns. Additive manufacturing has a unique feature which printing multi-faced complex fractals can be printed as easy as simple geometries. The feature of additive manufacturing creates the chance of producing really small scaled fractals. It can be easily understood that the more iterations are performed into the structural network the stronger it will become. Therefore this performance can lead an algorithm that will be a tool to design multi-scaled fragmented structures. The algorithm will be fed the structural analysis and material reactions. Their integration with the overall geometry will form the generations. However the verification of the generations as outcomes of a real 3D printer is crucial. To verify, the precision of additive manufacturing should be sensitive enough that the structural element will function as it's simulated in computer with the algorithm. The sensitivity is important because, even couple of micro-sized problems can cause bigger ones in the structural element itself. As a result, the combination of all these variables can enable a structure, to be more adaptive every additive generation.

REFERENCES

Berman, B 2012, '3-D printing:The new industrial revolution', *Business Horizons*, 55, p. 1
Brackett, D, Ashcroft, I and Hague, R 2011 'TOPOLOGY OPTIMIZATION FOR ADDITIVE MANUFACTUR-

ING', *Proceedings of the solid freeform fabrication symposium*, Austin, pp. 348-362
Fasoulaki, E 2008, *Integrated Design: A Generative Multi-Performatiove Design Approach*, Master's Thesis, MIT
Partee, B, Hollister, SJ and Das, S 2004 'Fabrication of Polycaprolactone Bone Tissue Engineering Scaffolds Using Selective Laser Sintering', *Manufacturing Engineering and Materials Handling Engineering*, California, pp. 525-535
Rayneau-Kirkhope, D, Mao, Y and Farr, R 2012, 'Ultralight Fractal Structures from Hollow Tubes', *Phys. Rev. Lett.*, 109, p. 204301
Stiny, G and Gips, J 1972 'Shape Grammars and the Generative Specification of Painting and Sculpture', *Information Processing 71*, Amsterdam, pp. 1460-1465
Utela, B, Storti, D, Anderson, R and Ganter, M 2008, 'A review of process development steps for new material systems in three dimensional printing (3DP)', *Journal of Manufacturing Processes*, 10(2), pp. 96-104