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Master's degree
Parametric Design in Architecture

UNIVERSITAT POLITÈCNICA DE CATALUNYA
BARCELONATECH
School of Professional & Executive Development

Stress Lines Additive Manufacturing (SLAM)

Babur SAGLAM, Juan SANCHEZ

Abstract

Although MA has been highly evolved over the last decade, especially in recent years, problems with resistance testing remain constant when the model's behavior is required to be the best. As part of an Additive Manufacturing improvement, this document contains information about a method used to optimize the behavior of the structures found in the 3D printed models and how this method can be used to ensure greater stiffness depending on the direction of the applied loads over a model or structure and the supports. The proposed strategy is based on experimental previously made tests derived from the computational design using a parametric structural engineering tool which provides analysis.

Keywords: Additive manufacturing, stress lines, optimization, supports, 3d printing, isocurve.

1. Introduction

In spite of the great advantages that AM offers us, it is also true that it has its own advantages and risks, which in some cases make the process to reach the production of an object more expensive. One of these challenges and the most important one is to make sure that at the end of the object it has good properties.

During conventional AM processes, in which the material is deposited in layers, the results produced tend to generate a great change in its structure and properties, that is, anisotropic elements are generated with different ductility that varies according to the forces applied. This anisotropy causes negative effects on the model and puts its durability at risk, since in some cases, depending on the orientation of the printed filament, it can reduce its resistance capacity by up to 50%, according to Mueller.

Due to the above, alternatives have been looked at in which durability, resistance and AM converge to obtain a better performance of the model, which is why Stress Lines Additive Manufacturing (SLAM).

1.1 Definitions

1.1.1 Additive Manufacturing (AM)

AM is a name to describe the process of creating an object by building it one layer at time, whether the material is plastic, metal, concrete, etc. It is the opposite of subtractive manufacturing (figure 1) or 3D milling, in which an object is created by cutting a solid block of material until the final product is complete.

Technically, AM can refer to any process where a product is created by building something up, such as molding, but it typically refers to 3D printing.

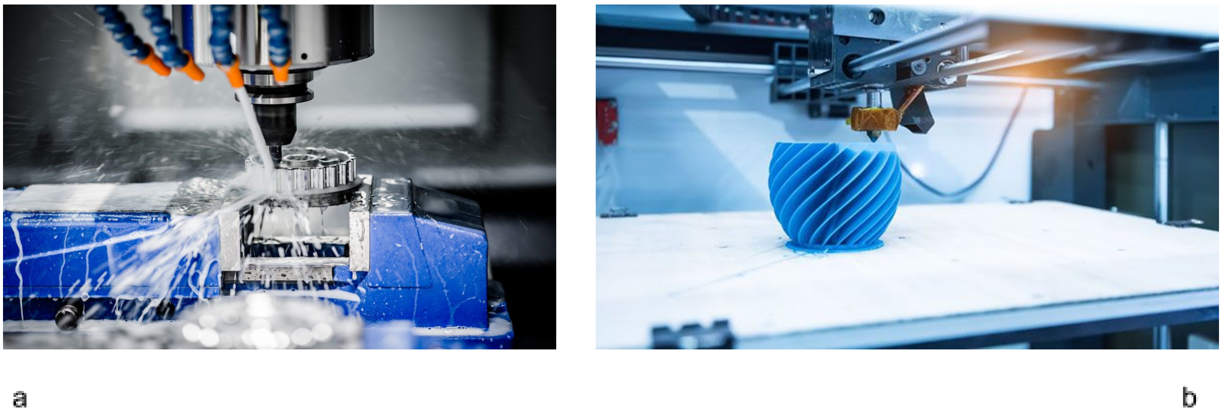


Figure 1: (a) Subtractive Manufacturing process, (b) additive manufacturing process [https://smithindustriesltd.com]

1.1.2 Principal Stress Lines

Principal stress lines (figure 2) are pairs of curves that indicate trajectories of internal forces and therefore idealized paths of material continuity, naturally encode the optimal topology for any structure for a given set of boundary conditions. Although stress line analysis has the potential to offer a direct, and geometrically provocative approach to optimization that can synthesize both design and structural objectives, its application in design has generally been limited due to the lack of standardization and parameterization of the process for generating and interpreting stress lines.

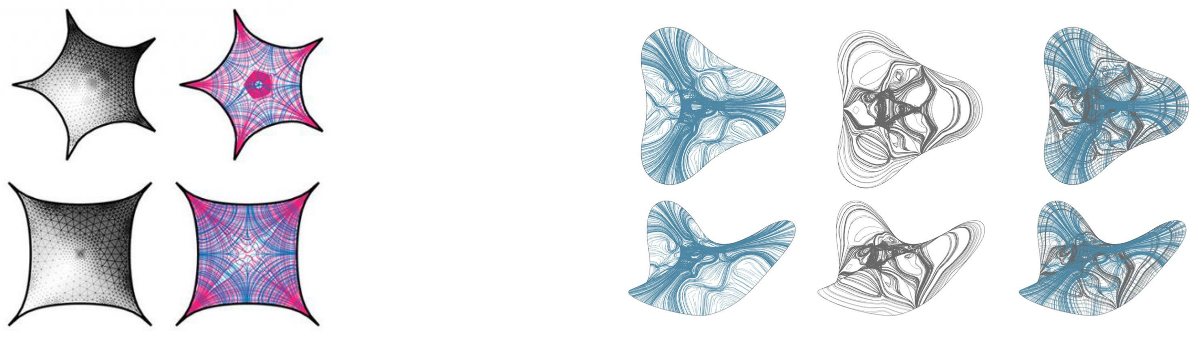


Figure 2: Principal stress lines [http://digitalstructures.mit.edu]

1.1.3 Stress Lines Additive Manufacturing

Typical AM processes produce anisotropic products with strength behavior that varies according to filament orientation, thereby limiting its applications in both structural prototypes and end-use parts and products.

SLAM (figure 3) was developed as a high-performance fabrication method capable of producing specimens that accurately convey both geometry and the structural performance expected of the specimens' geometry and intended application.

Figure 3: SLAM [http://digitalstructures.mit.edu]

2. State of the art

2.1. Additive Manufacturing Along Principal Stress Lines by Tam, Kam-Ming Mark and Caitlin T. Mueller.

According to the research done by Tam, Mark and Mueller in the field of digital manufacturing, they present a new process that reconsiders the AM techniques that are used today. In their paper they propose a method using Fused Deposition Modelling (FDM) in which they add material explicitly along the three-dimensional principal stress trajectories, or stress lines, of 2.5-D structural surfaces.

During their process they used a robot that allows the movement in 6 directions called *KUKA KR6 R900 sixx* (figure 4) which was created specifically for the realization of the studies and the impression of the form derived from the use of a method of dynamic relaxation.

The results obtained were relatively successful according to the tests made in which they added different kinds of loads, however they add that there is a certain margin of imperfection and imprecision that will decrease as they improve and make it more standardized.

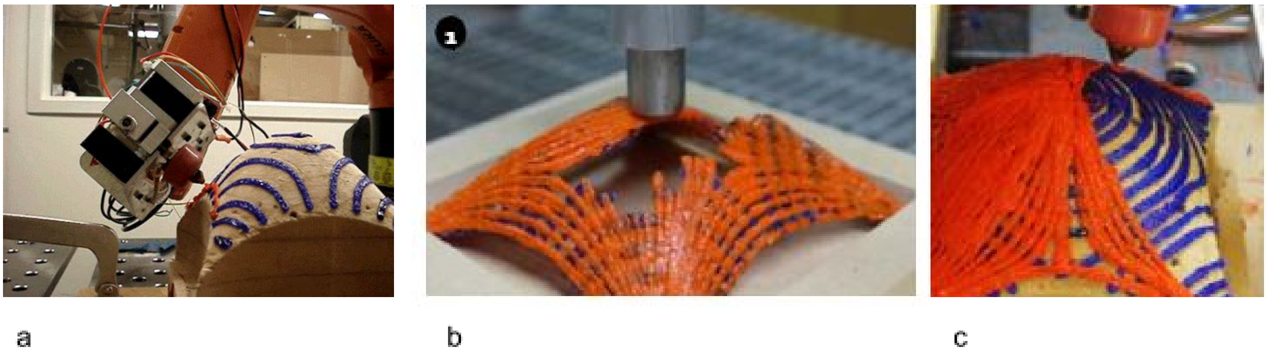


Figure 4: (a) *KUKA KR6 R900 sixx* robot, (b) loading testing failures, (c) filament extrusion [Tam, Kam-Ming Mark and Caitlin T. Mueller. “Additive Manufacturing Along Principal Stress Lines.” (June 2017)]

3. Hypothesis

Based on the knowledge about stress lines and their effects that these can generate in structures, we want to prove that by following the model along these lines it is possible to improve the behavior of a model by printing in a different way its structure through AM. We are taking as a basis the fact that corrugations provide greater structural stability to replicate it with Stress Lines.

All the physical tests will be done in an empirical way and derived from the use of computational software plug-ins (Karamba, Millipede).

3.1. Initial experiment

For our first test, our objective was to obtain stress lines by applying random forces on a random surface and study the behavior and differences that the structure had when printing the original shape and then the one that followed the stress lines.

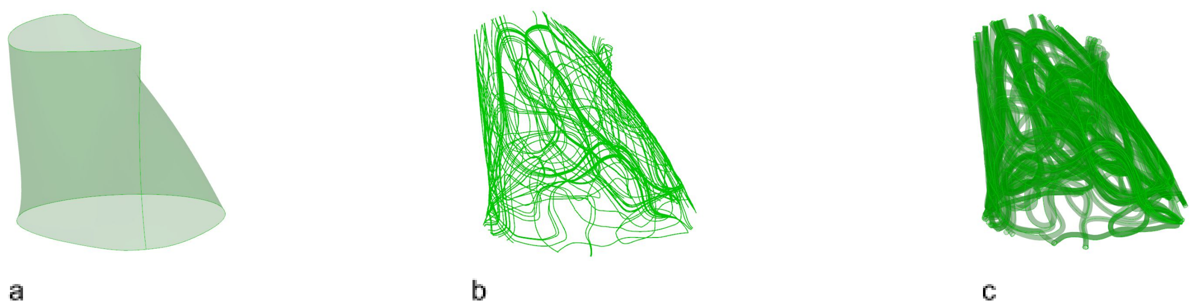


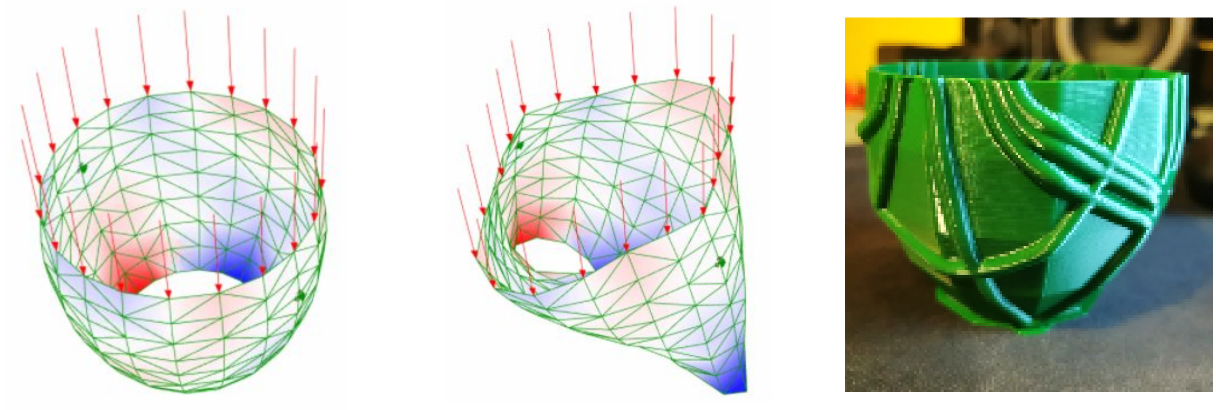
Figure 5: (a) Original shape, (b) principal stress lines in the surface, (c) lines with thickness

As a result of printing the model with the stress lines made corrugations, we obtained a shape that at first sight and with simple tests was more stable regarding its rigidity. The amount of stress lines can vary by changing force parameters and loads.

Figure 6: Final result of our first attempt to get corrugations that follow the stress lines on the surface

3.2. Second attempt

By applying forces on the -z axis over the top of our structure we can get an approximation of the behavior it will actually have without applying the corrugations on the stress lines. The red colored part indicates the most critical parts where the element works in compression, on the contrary, the blue one is tension.



a b c

Figure 7: (a) Forces applied on the structure, (b) exaggeration of the deformation, (c) final result of our second attempt to get corrugations that follow the stress lines on the surface

3.3. Third attempt

During our third attempt, the way of analyzing the model had some changes. We used a structural analysis and optimization component for grasshopper (millipede) which allows linear elastic analysis of frame and shell elements in 3d, 2d plate elements for in plane forces, and 3d volumetric elements.

The shape of the model was replaced by a cylinder that later allowed us to perform the corresponding tests in a feasible and accessible way.

We started by giving the cylinder a support at one end (figure 8) on the XZ plane, allowing movement in x,y and z and blocking Rx, Ry and Rz.

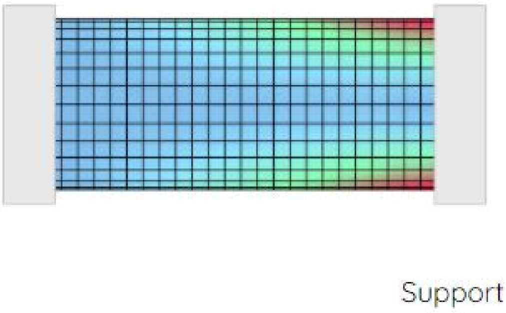


Figure 8: Cylinder fixed with support

After fixing the support it is necessary to add a load. For this case a load was added on a solid which in terms of the plug-in turns out to be a load in the -z direction.

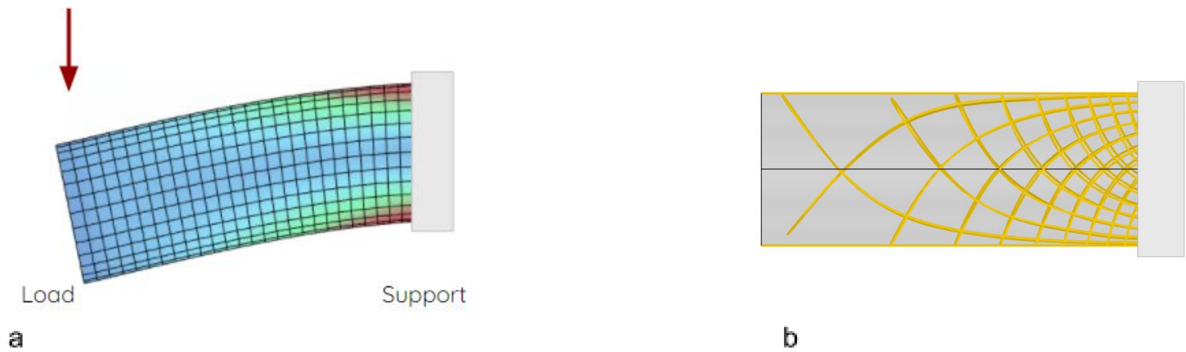


Figure 9: (a) Load applied in -Z and exaggeration of the deformation, (b) stress lines generated from the applied force

4. Physical experimenting phase

For our final physical experiment we used an implementation of "millipede" load simulation, we received the principal stress lines. With these lines we created a corrugated cylinder, and for comparison we created another corrugated cylinder with isocurves. To compare on equal terms, we calculate the length of principal lines and isocurves to make them same. The last one is a non corrugated plain cylinder.

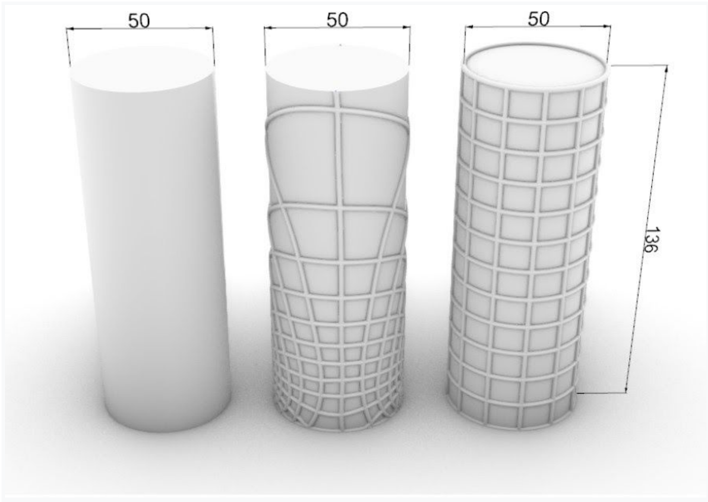


Figure 10: Plain cylinder, corrugated with principal lines and corrugated with isocurves

4.1 .Additive manufacturing specifications

4.1.1. Printing settings applied to all 3 test objects. Spiralic (vase) mode selected:

- Material PLA/PHA
- Modulus elasticity :2,960 MPa
- Tensile strength: 61.5 MPa
- Density: 1,24 gr/cm3
- Nozzle size: 0.8mm
- Operation Temp: 205 C
- Layer height: 0.2mm
- Base height: 0.7mm

4.1.2. Printing settings applied to all 3 test objects. Spiralic (vase) mode selected:

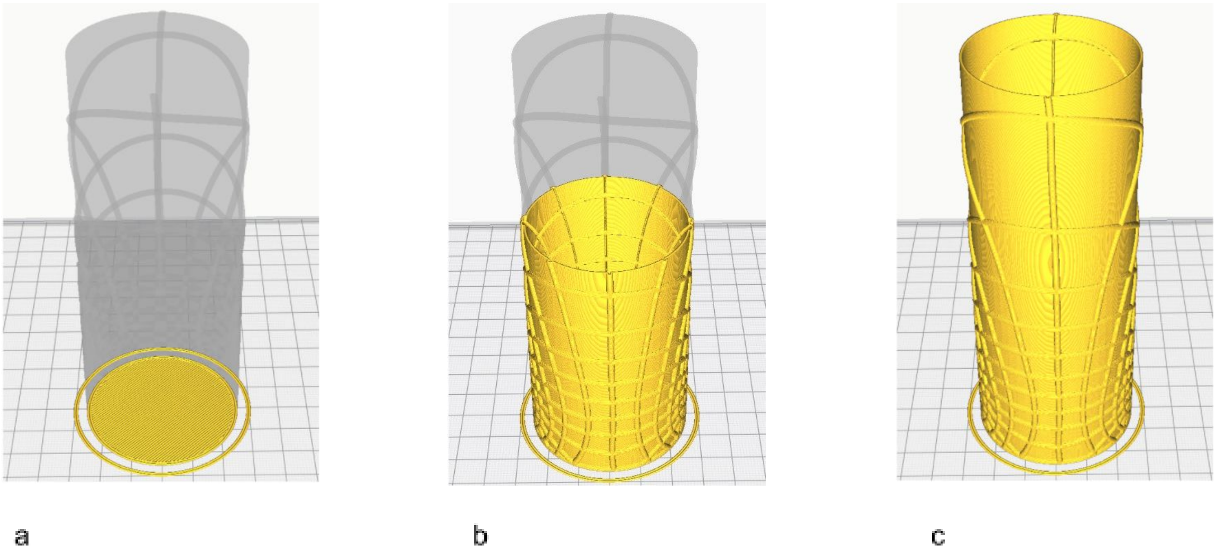


Figure 11: Printing simulation process before manufacturing

4.1.3. Printing settings applied to all 3 test objects. Spiralic (vase) mode selected:

Figure 12: Printed test objects with integrated base and load supports

5. Measuring and Calculations

After fixing the test objects, 1.5kg loads incrementally added and measured the bending deformation of cantilever effects.With these assets, we created a displacement graph.

Figure 13: Loading and measuring the test objects

5.1. Printing settings applied to all 3 test objects. Spiralic (vase) mode selected:

Figure 14: All the test objects failed from lower end bottom

5.2. Displacement graph

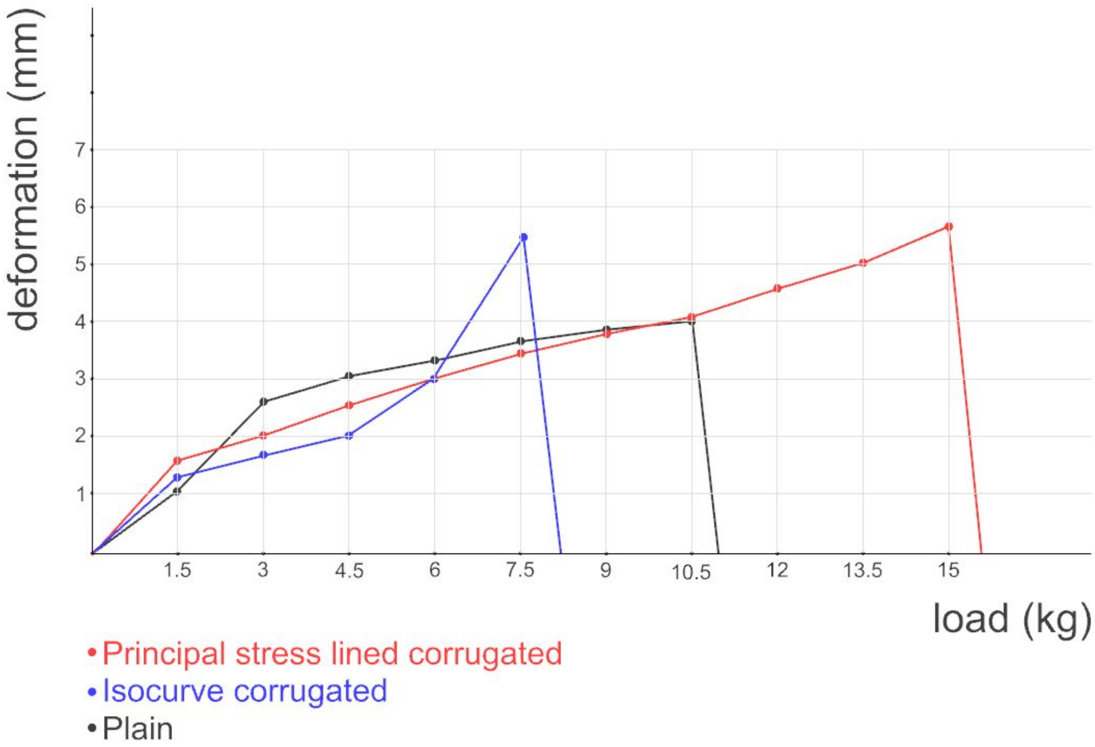


Figure 15: Graph comparing the difference in the behavior of the three tests

6. Conclusion

With the final results, Our cantilever rigidity test.We can see the clear winner is a corrugated piece with principal stress lines. Doubtfully non corrugated piece, stranded longer compared to iso curved corrugated one.We believe that this happened due to support elements.For being sure, we need to make more experiments and compare them.

Overall, with given precise supports and loads to a design element, principal stress lines show us a good method for making corrugated design pieces for better rigidity and less material usage.

For taking this idea to a higher level, we believe that it will be much better using 100% infilled fully corrugation (solid pipe) for better stiffness and rigidity.

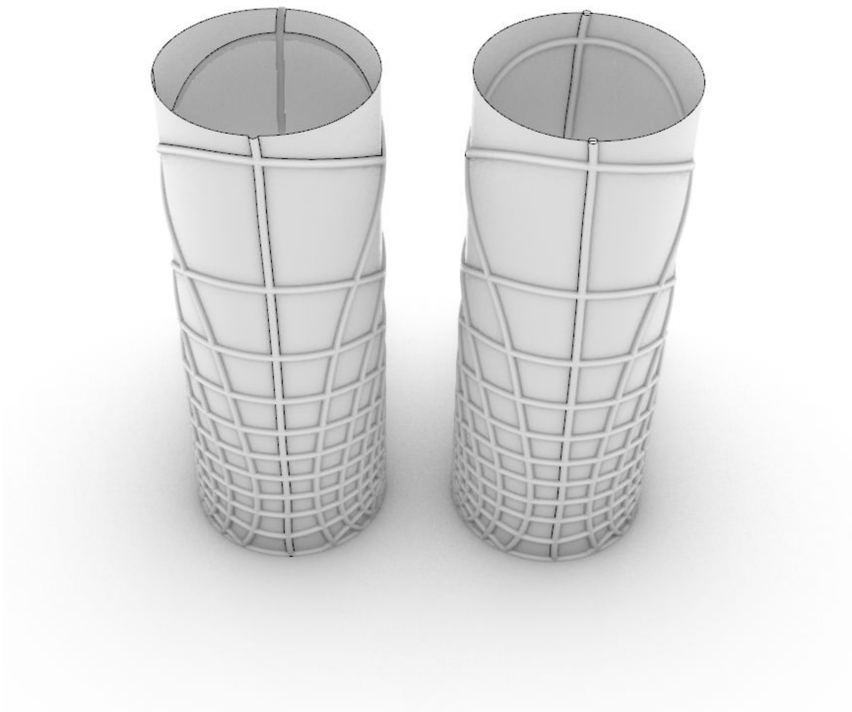


Figure 16: Left, corrugated with PSL. Right, corrugated with %100 infilled PSL pipes

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References

[1] K.M Tam and C. T. Mueller, "Additive Manufacturing Along Principal Stress Lines." *3D Printing and Additive Manufacturing* 4, 2 (June 2017): 63–81 © 2017 Mary Ann Liebert, Inc

[2] K.M. Tam, J. R. Coleman, N. W. Fine, C. T. Mueller, "Stress lines additive manufacturing (SLAM) for 2.5 D shells", Massachusetts Institute of Technology.

[3] J. Feng, J. Fu, Z. Lin, et al. "A review of the design methods of complex topology structures for 3D printing". Vis. Comput. Ind. Biomed. Art 1, 5 (2018)

[4] J.B. Khurana, T.W. Simpson and M. Frecker, "Structurally intelligent 3D layer generation for active-z printing", 2018

[5] J. Podroužek, M. Marcon, K. Ninˇcevi´c and R. Wan-Wendner, "Bio-Inspired 3D Infill Patterns for Additive Manufacturing and Structural Applications", Department of Structural Engineering, Ghent University, 9052 Ghent, Belgium

[6] S. Bialkowski, "GPGPU Accelerated Structural Optimisation Utility For Architects", Lodz University of Technology