# Adaptive Variable Stiffness with Strategically Arranged Materials

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## Abstract

By designing materials with variable stiffness, structures can adapt to various functional requirements. This paper presents variable stiffness explored in two case studies relying on an architected material approach that involved gradient pattern differentiation and freeform printing using thermoplastic polymers (TPE). The differentiated cell pattern had gradients from high to low density of cells, which facilitate variable stiffness. Numerical and experimental studies showed the potential for application of materials with variable stiffness in adaptive structures.

## Keywords

adaptive structure, robotic 3D printing, variable stiffness

Considering adaptive structures as being capable to respond dynamically to changing requirements by employing material design strategies that facilitate reconfiguration, two cases have been explored, in which reconfiguration is achieved by architecting the material using computational design and robotic 3D printing techniques (Fig. 1).

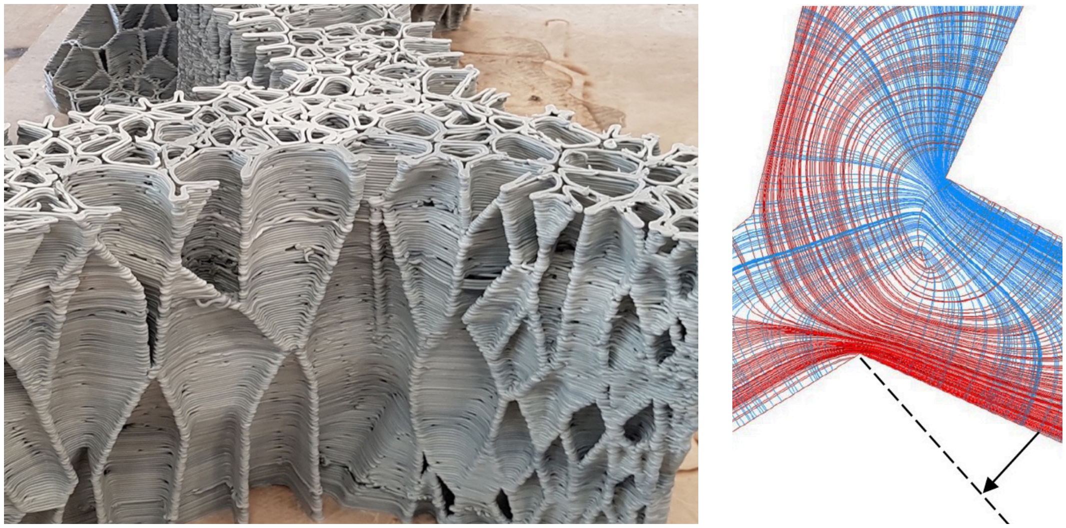

FIGURE 1 Fragment showing the flexible back of the chaise longue and respective structural analysis

Additive manufacturing technologies are enabling fabrication of cellular materials with complex architectures (Schaedler and Carter, 2016). By tailoring the material architecture to specific requirements i.e. by varying cellular architecture, material properties can be customized. In the presented architected material approach, mechanical and physical properties of the structure inform the inner multiscale design. The material has a differentiated cellular pattern allowing for a gradient from high to low density of cells with the purpose of achieving variable stiffness. The control of deformation is based on varying density of cells with variable size, which is based on functional requirements related to how much the overall shape should deform or not. The variable density results from structural requirements, material properties, and extrusion thickness that determine local buckling and elastic deformation.

## Material design

Several cellular patterns were developed in order to identify material behavior as well as printability (fig. 1 and 2). The angles of the cells are constrained to 45 degrees in relation to the printing bed in order to reduce material use and printing time. The final cellular architected material approach involved a differentiated pattern consisting of 3D Voronoi cells of various sizes. This implies that the control of stiffness is differentiated thus non-uniform (with some areas being stiffer than others). The advantage of the Voronoi cells is that the cells can gradually change in size from big to small and vice versa. Thus the stiffness can gradually increase or decrease, which contrasts uniform distributions where units could change in size step by step, and therefore the stiffness would increase or decrease incrementally, not gradually. Another advantage is that the Voronoi cell pattern can be printed with continuous tool paths.

FIGURE 2 Chaise longue shape change from lying down (left) to sitting (right) obtained by tuning the stiffness through variable material deposition

The gradual distribution of stiffer and less stiff areas is following structural analysis results (Fig. 1 and 2). The stress lines resulting from structural analysis are transformed into a point cloud that is used to generate the centre points of the Voronoi cells. Since the cell density determines the global and local stiffness, which is also influenced by the stiffness of the material, the points in the data field are increased or decreased to achieve the required local and global density variation. From test prints, it was determined that for the chaise longue 3000 cells would create the required global and local stiffness of the material system. Cell density distribution follows the structural analysis and stiffness is tuned according to simulated stresses. Furthermore, the points are placed strategically so that the edges of the cells are within the printing angle tolerances. While the global density distribution is according to the previous described stiffness requirements, the exact placement is based on the printing angle requirements.

## Case studies

The developed architected material has been tested on a chaise longue (Fig. 2) and the developed Design-to-Robotic-Production (D2RP) approach has been scaled up for a Mars habitat (Fig. 3). Both feature adaptive stiffness for facilitating functional requirements.

The chaise longue features a flexible behaviour: The more weight is placed on the back support, the more it deforms, until equilibrium is achieved. When the position changes from upright to reclined position, the stress distribution changes and more weight is positioned on the back support. In order to achieve such range of behaviours, the weight distribution is mapped onto the surface of the chaise longue, which informs local and global cellular patterns. More weight requires higher density of smaller cells to achieve higher degrees of stiffness and vice versa. The objective in this case was to generate a stable chaise longue with a controlled flexible behaviour while using minimal material. Thus larger or smaller cell densities are placed according to the desired stiffness, in order to create softer or stiffer areas where needed.

This approach has been investigated with respect to its feasibility for large scale structures in a project for an underground Martian habitat developed in response to a call for ideas initiated by the European Space Agency (ESA). The proposed idea was to 3D print on top of a Martian concrete layer (Wan et al., 2016) of an underground habitat, a silicon-based sealing layer that allows operation of the life support system. While the layers of soil covering the Martian habitat provide protection against radiation and large temperature fluctuations, the concrete ensures structural stability. The sealing layer printed on top of the concrete facilitates the implementation of pressurized environmental control. Due to the variable stiffness of the architected material, this layer facilitates other functionalities related to the use of the space (Fig. 3) as well. Depending on the specific activities i.e. sleeping, socializing, or working, areas designated for those activities are cushioned or stiffened accordingly.

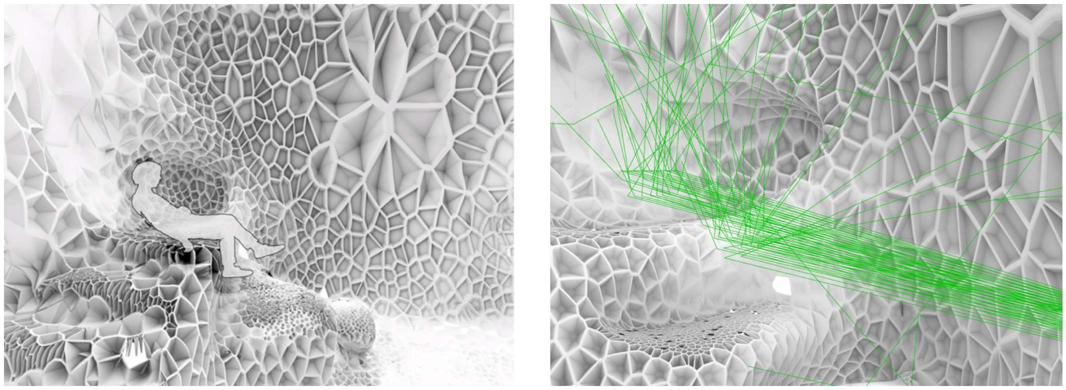

FIGURE 3 Multi-functional adaptive mesh (left) with acoustic properties tested for scattering effects (right)

This is achieved, after performing the structural analysis, to understand the tensile and compressive forces at stake, so that specific stress lines can be used to inform a point cloud, which is the basis of the Voronoi structure. The present study model has been achieved by populating the fragment with 5000 points for experimental purposes. The point cloud is also informed by the functionality of the space. The horizontal surfaces have a higher cell density for creating surfaces to walk, lie, sit or sleep on and some areas are less stiff than others in order to provide cushioning for comfort. In addition to functionalities related to activities, the point cloud is informed by acoustic requirements. According to the acoustic analysis (fig. 3), the surface tectonic based on the Voronoi logic contributes to acoustic comfort. The pattern facilitates sound scattering, preventing sound waves from mirror-bouncing phenomena, which might result in echoing. This capacity of the surface to scatter sound is obtained in addition to the tactile qualities achieved through variable stiffness.

## Design-to-Robotic-Production

D2RP links computational design to robotic production. While the D2RP approach in the first case study involved use of the required process and material, the D2RP approach in the second case study involved scaling up design to building scale and emulation of the process (fig. 3, 4 and 5). The involved additive and subtractive processes were reproducing the excavation and the reinforcement processes on Mars but employed materials were different. The milling procedure in EPS was designed in such a way that material removal was gradual along a continuous toolpath (fig. 4 and 5). The continuous path approach was implemented in the additive D2RP process as well only using TPE with glass fiber reinforcement instead of Martian concrete. To avoid having to print a supporting structure, the cells design obeyed the aforementioned 45-degree inclination rule.


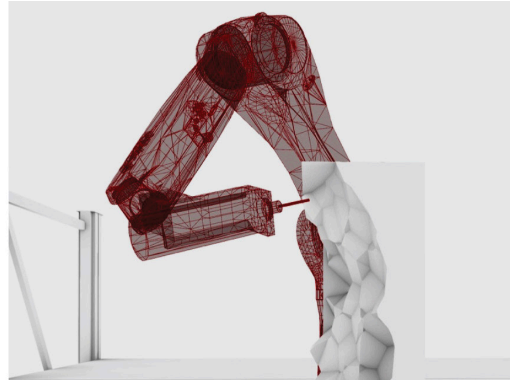

FIGURE 4  Robotic path optimization for subtractive D2RP

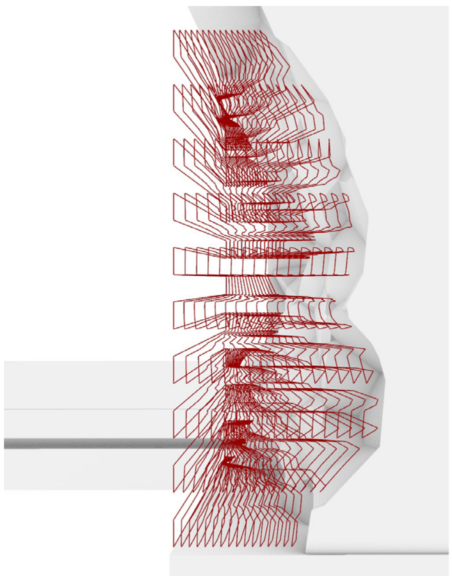
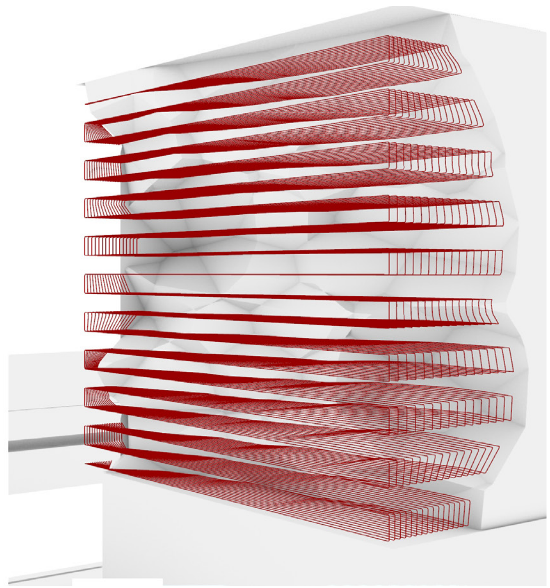

FIGURE 5  Required toolpaths for creating surface tectonics

## Conclusion

Numerical and experimental tests have shown that stiffness variation is feasible and the use of architected materials with variable stiffness facilitates structural adaptation. In the presented case, the developed architected material ensures variable stiffness through the gradient pattern differentiation. The material is customisable and the 3D printing process allows for mass customisation of products.

Future work will further investigate feasibility of this approach for large scale structures. In particular the integration of various functionalities required for indoor environments involving not only furnishing as presented in this paper but also sensor-actuator networks for environmental control will be of particular relevance.

## Acknowledgements

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