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Cellular and Topology Optimization of Beams under Bending: An Experimental Study

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Abstract

Design for Additive Manufacturing (AM) includes concepts such as cellular materials and topology optimization that combine the capabilities of advanced computational design with those of AM technologies that can realize them. There is however, limited experimental study of the relative benefits of these different approaches to design. This paper examines these two different approaches, specifically in the context of maximizing the flexural rigidity of a beam under bending, while minimizing its mass. A total of 23 beams were designed using commercially available cellular design, and topology optimization software. The Selective Laser Sintering (SLS) process was used to manufacture these beams with Nylon 12, which were then tested per ASTM D790 three-point bend test standards. The effect of varying the size and shape of cells on the flexural rigidity was studied using 15 different cellular designs. These results were then compared to six different topology optimized beam designs, as well as three solid and hollow baseline beams. These preliminary findings suggest that topology optimized shapes underperform their cellular counterparts with regard to specific stiffness, and that stochastic cellular shapes deserve deeper study.

Introduction

In several applications, a main focus of design is towards volume and mass reduction while improving structural performance. Topology and cellular design optimization are two popular approaches used to achieve these goals. Topology optimization is a free form design approach that aims at finding optimal distributions of material within a domain for a given set of objectives and constraints [1]. It has therefore been known to lead to new and unanticipated designs that typically outperform conventional low weight designs [2, 3]. Cellular structures consist of a unit cell (combination of material and space) that is repeated in space to create a larger structure. It is difficult or even impossible to manufacture these complex geometries using traditional manufacturing processes. Additive manufacturing helps us accomplish the manufacturing needs for topology and cellular optimized designs and the marriage of new design tools with AM process technologies has a large potential for impacting several industries.

Studies have been done for manufacturing topology optimized structures using Additive Manufacturing processes. Cellular structures are another weight reduction solution which have been widely studied. The repeating lattice structures provide better structural properties in some contexts, when compared to baseline designs [4]. The organic nature of the structures have extensive applications in the biomedical and aerospace industry for making implants and light-weight aircraft structures [5]. Using this technology, aerospace companies like Airbus and

Bombardier have been able to reduce the weight of components significantly without compromising structural rigidity [5].

A key question from a practical standpoint is as follows: *how well do the predictions of design optimization software hold up in practice*? This is the question this work seeks to address in a small way, by way of examining the performance of the software in the context of the 3-point bend test. Altair Inspire was used to perform topology optimization for maximizing the stiffness with varying mass percentages. The objective of this study was to maximize the flexural rigidity of beams while minimizing relative density. The beams were printed using Selective Laser Sintering (SLS), which is an Additive Manufacturing (AM) processes used for polymers. The primary advantage of SLS is that it does not require support structures for printing which has multiple advantages including printing complex geometries with high resolution, reduced post processing time since there are no supports to be removed, high build rate and good mechanical properties [6]. Test were performed using a 3-point bend test setup. Topology optimization and cellular structure generation were used for designing 24 beams made out of Nylon 12. In the following section, the specific methods used to design these beams is discussed in more detail. This is followed by a discussion of the experimental setup for the 3-point bend test, and the results obtained from these tests. The paper concludes with a discussion of the conclusions and insights gained from this study.

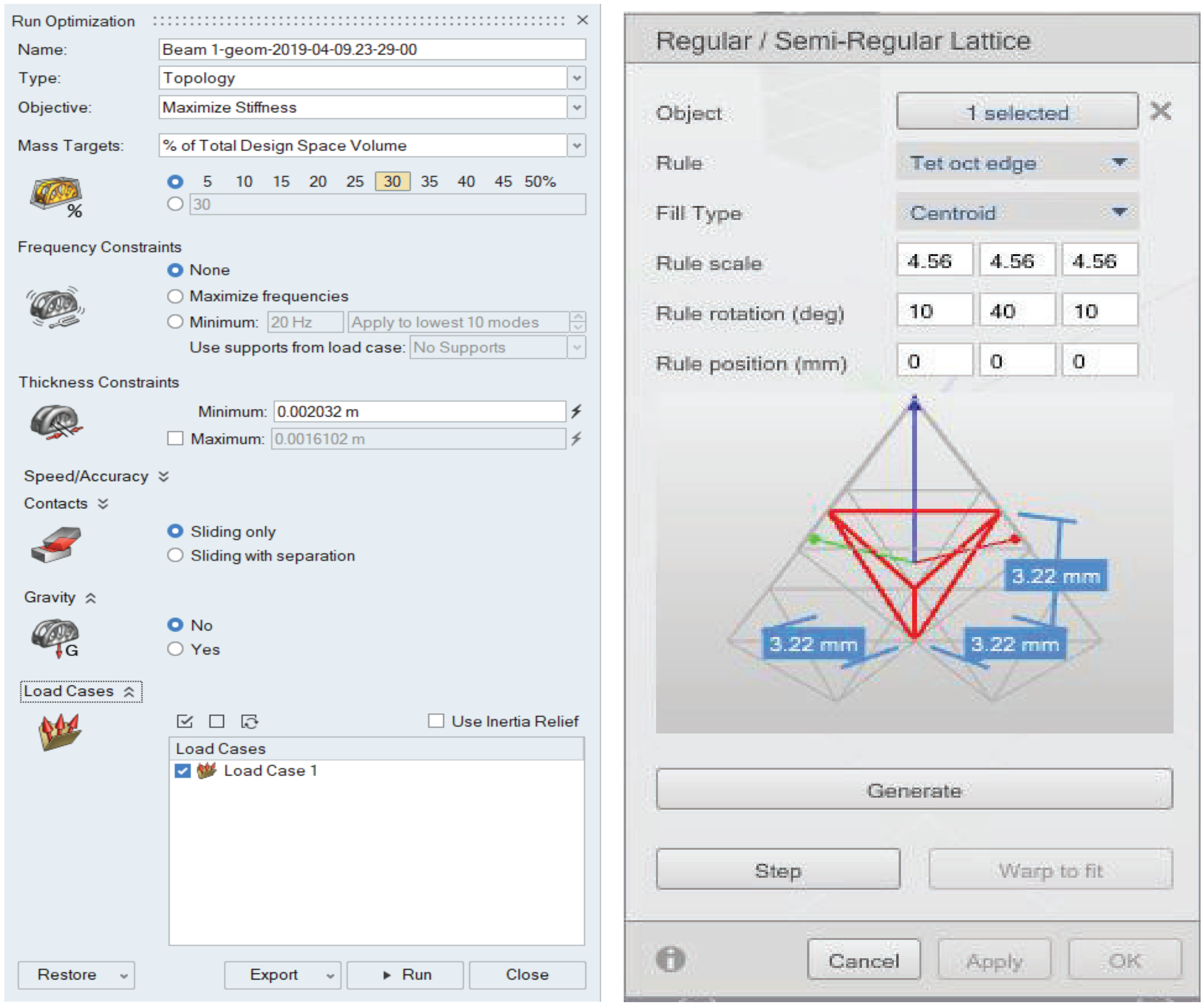
Design Methods

For this study, three baseline beams were used for comparison in a 3 point bend setup: a solid cuboid, a hollow cuboid, and a hollow cylinder. For the hollow cylinder the inner radius is 0.67 times of outer radius, this is the optimum ratio for a cylindrical beam under bending [7]. For the hollow cuboid the thickness is 10% of the total width. The dimensions of the baseline beams are listed in Table 1.

Table 1. Baseline Design Parameters

Name	Length (in)	Breadth (in)	Height (in)	Diameter (in)
Solid Cuboid	7.2	0.45	0.45	N/A
Hollow Cylinder	7.2	N/A	N/A	Outer: 0.45 Inner: 0.30
Hollow Cuboid	7.2	0.45	0.45	N/A

In addition to the baseline solid and hollow beams, two different commercial software packages were used for design optimization: SolidThinking's Inspire software was used for topology optimization, and nTopology's Element was used for cellular material design. User interfaces of both software packages are demonstrated in Figures 1a and 1b, respectively. Each of these approaches is discussed below in turn.



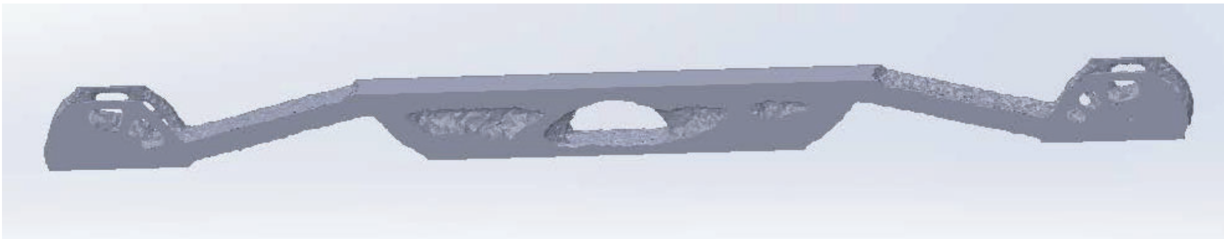
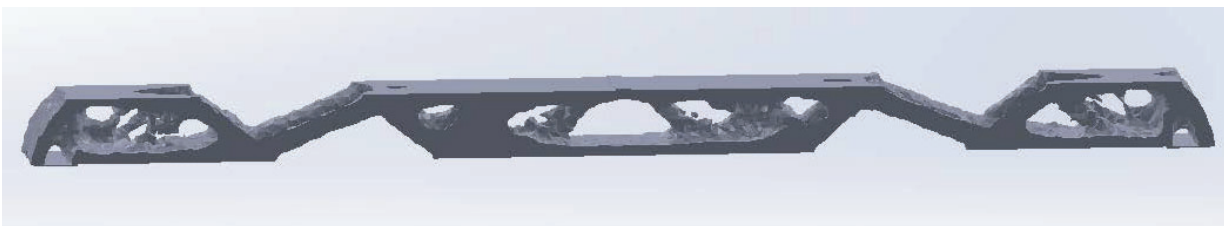
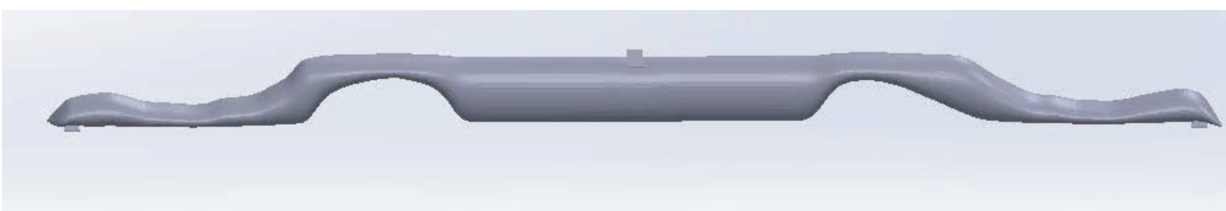
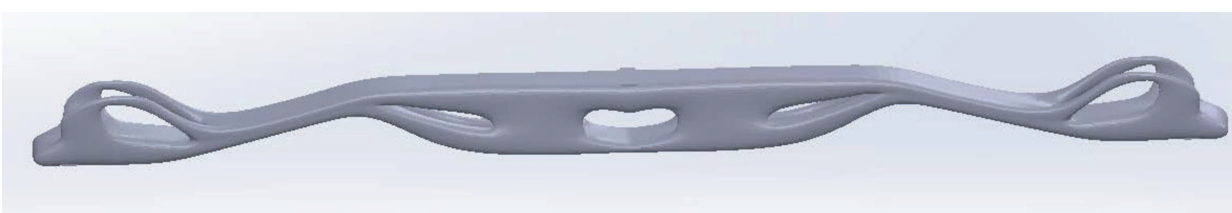
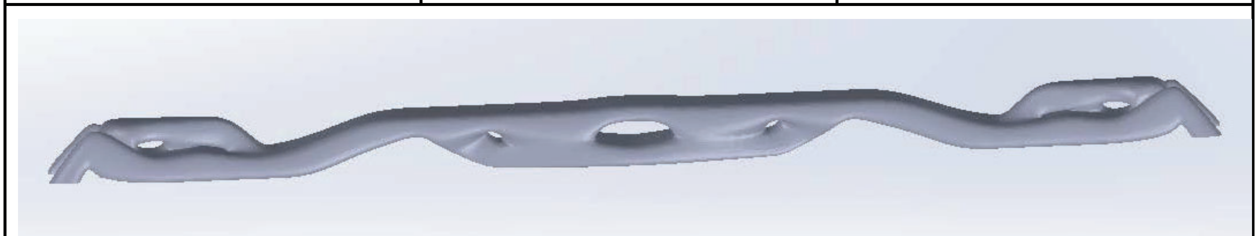
(a) (b)

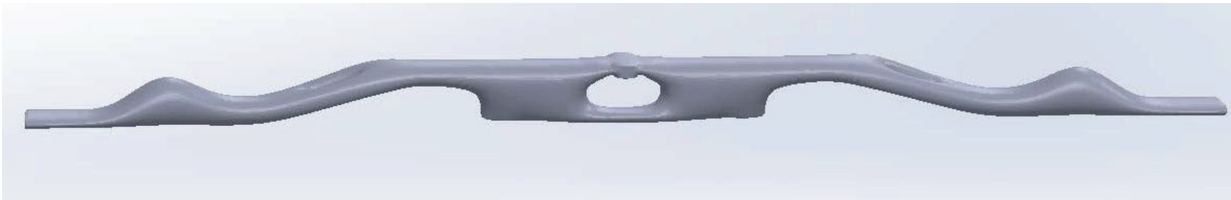
Figure 1. (a) SolidThinking Inspire topology optimization user interface, and (b) Cellular structure generation tab in Element nTopology

<u>Topology Optimization</u>

A total of six designs, shown in Table 2, were created with the Inspire software, beginning with a solid beam and a 150N applied load corresponding to the 3 point bend setup with roller supports. Exclusion zones were defined around contact of the load and the supports, so as to ensure regions available for contact were not subject to optimization. These beams varied in percentage of mass retained and whether the PolyNURBs tool was used to smoothen the geometry. This was done to study the effects of this smoothing on the resulting performance of the beam.

Table 2. Topology Optimization Design Parameters

Name	**Mass Retained**	**PolyNURB**
TopOpt 1	25	No
		
TopOpt 2	30	No
		
PolyNurb 1	25	Yes
		
PolyNurb 2	30	Yes
		
PolyNurb 3	35	Yes
		

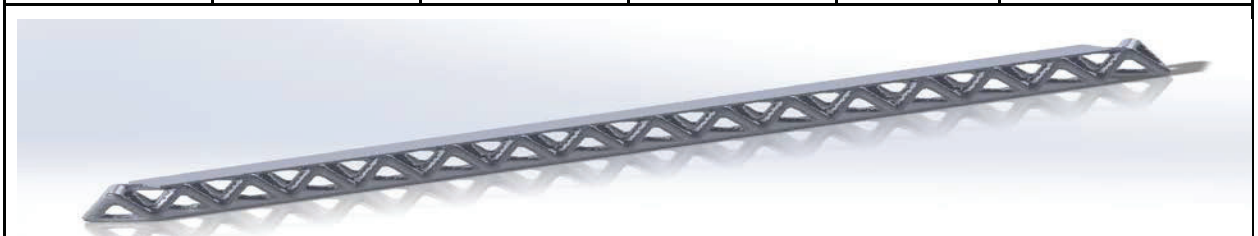
PolyNurb 4	30	Yes
		

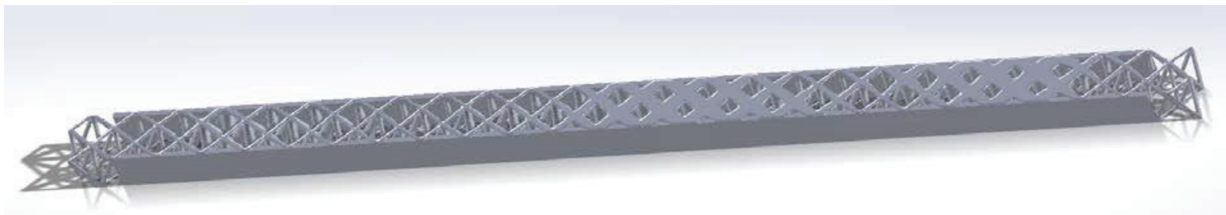
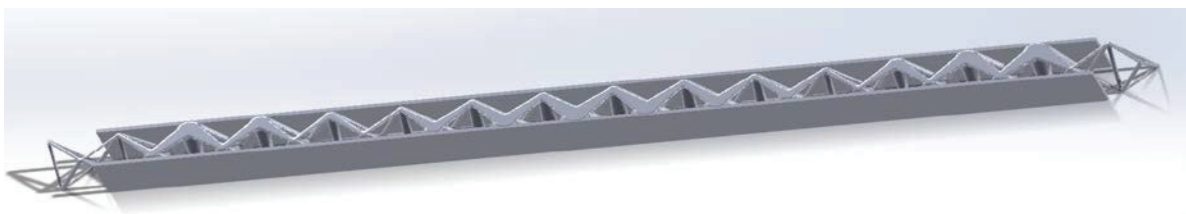
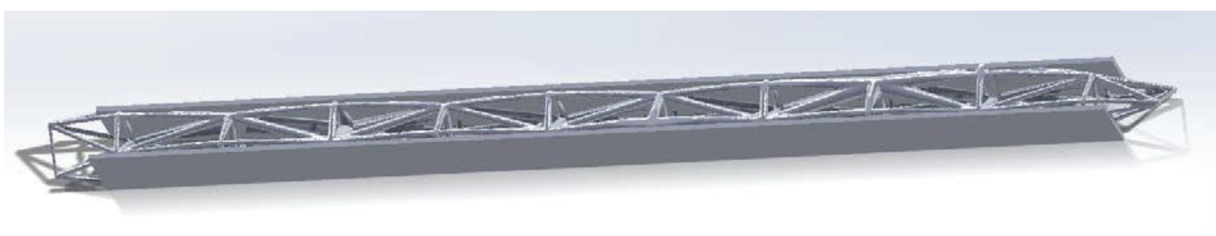
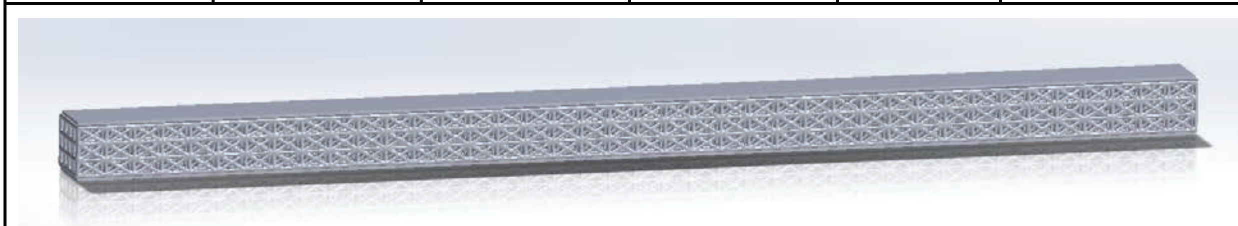
Cellular Design

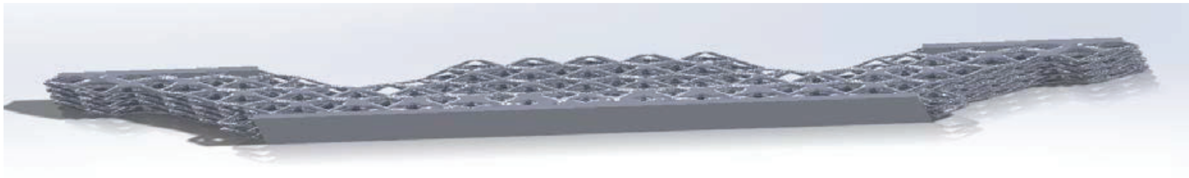
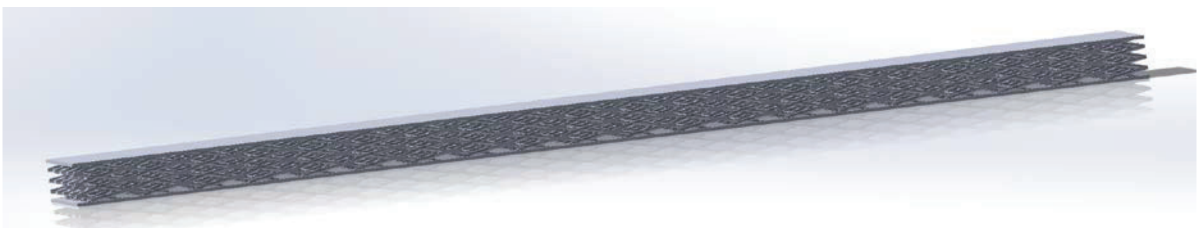
Cellular structures were created by importing the baseline solid cuboid into the nTopology Element software. A total of 14 cellular designs were created, with a 1mm thick sandwich panel added to the top and bottom – these are shown in Tables 3 and 4. The panels span the length of the beam including the overhang and have a width identical to the bounding box cross-sectional dimensions of each of the beams. This panel was added due to the irregular surfaces of the topology and cellular structures to allow for a flat surface to make testing more accurate.

Of the 14 cellular beams, eight had periodic tessellations with different unit cell shapes and member thicknesses as shown in Table 3. Two of these eight designs had periodic tessellation with tet octet edge unit cell and were optimized for our loading conditions using the Pro version of the Element software. The remaining six beams (from the original 14), were generated with stochastic lattices using various combinations of modifier points and surface modifiers which the designer to vary the size of the stochastic cells, and their distribution along the length and cross-section. The range of designs generated with this approach are shown in Table 4. The seed value for the underlying stochastic algorithm that generates these shapes was kept constant for all stochastic designs (Figure 2).

Table 3. Periodic Cellular Design Parameters

Name	Cell Shape	Cell Size (x, mm)	Cell Size (y, mm)	Cell Size (z, mm)	Optimized or Thickened?
Tet Oct 1	Tet Octet Edge	10	40	10	Uniformly Thickened (3mm)
					

Tet Oct 3	Tet Octet Edge	30	10	10	Uniformly Thickened (3mm)
					
Tet Oct 4	Tet Octet Edge	6	20	6	Optimized
					
Tet Oct 5	Tet Octet Edge	10	40	10	Optimized
					
Tet Oct 6	Tet Octet Edge	30	10	10	Optimized
					
Cuboid	Cuboid with cross members on side	40	4	3.28	Uniformly Thickened (1mm)
					
Optimized	Cubic Centroid	20	4	4	Optimized

Beam					
					
Lattice Sandwich Panel	Cubic Centroid	20	4	4	Uniformly Thickened (1mm)
					

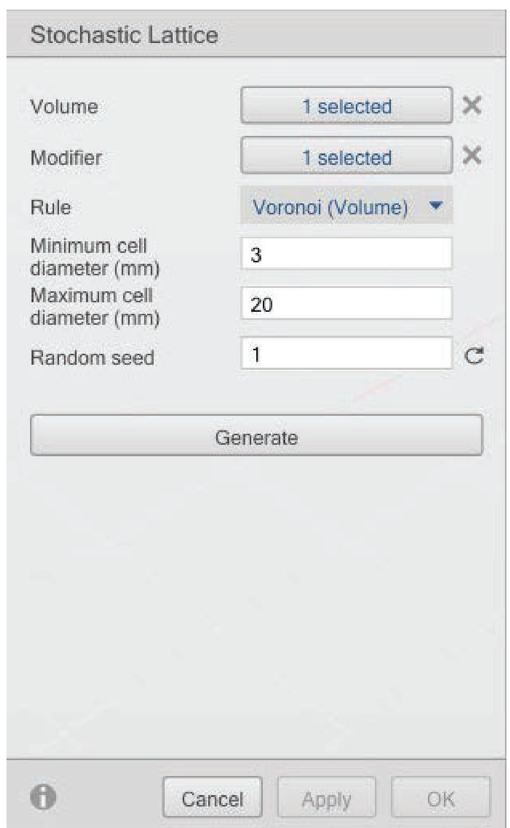
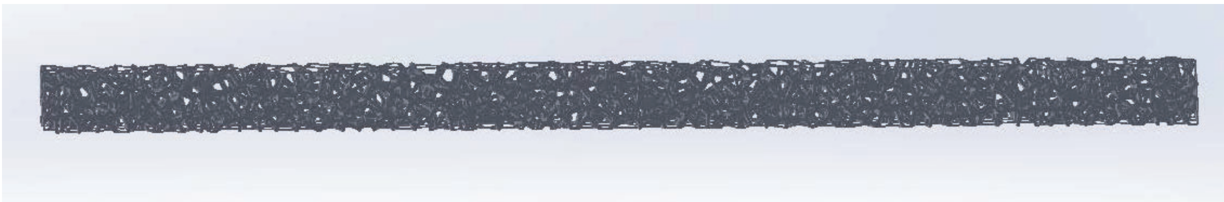
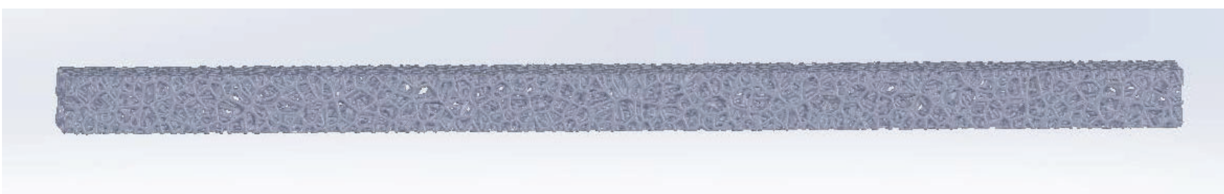
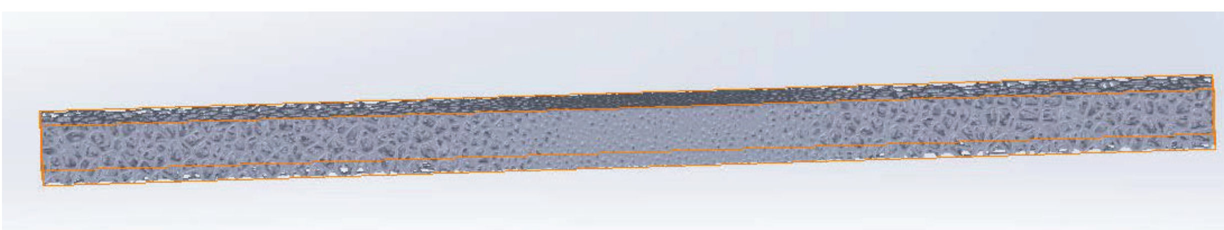


Figure 2. Stochastic structure generation tab in Element nTopology

Table 3. Stochastic Design Parameters

Name	Min Diameter	Max Diameter	Modifier
Dense Bottom 1	3	20	Surface
			
Dense Bottom 2	2	10	Point
			
Dense Bottom 3	2	10	Surface
			
Dense Center	1	10	Point
			
Stochastic 1	1	3	Point
			
Stochastic 2	1	2	Point

The material used to fabricate the beams was Nylon 12 (PA2200) printed on an EOS Formiga P110. The tensile modulus, tensile strength and density were used as the input material properties for the beam optimization, and are summarized in Table 5.

Table 5. Material properties of Nylon 12 used in this study [8]

Property	Value	Unit
Tensile Modulus Z-Direction	1650	MPa
Tensile Strength Z-Direction	42	MPa
Flexural Modulus	1500	MPa
Density	930	kg/m^3

Experimental Setup

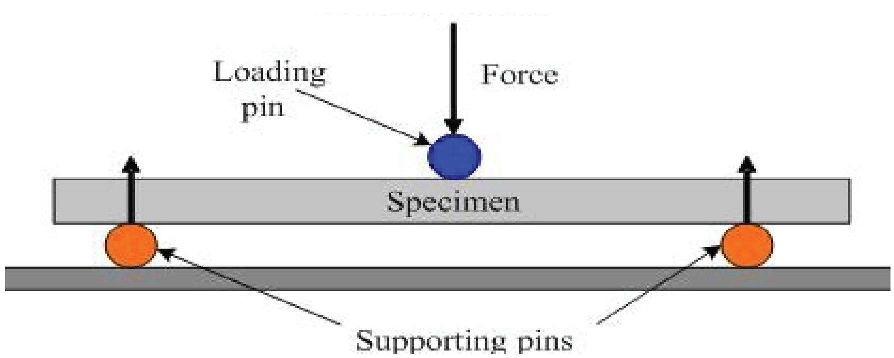


Figure 3. 3-point bend test setup per ASTM standards [9].

In engineering mechanics, flexure or bending characterizes the behavior of a slender structural element subjected to an external load applied perpendicular to the longitudinal axis of the element. A flexure test produces tensile stress in the convex side of the specimen and compression stress in the concave side, this creates an area of shear stress along the midline. To ensure the primary failure comes from tensile or compression stress the shear stress must be minimized, this is done by controlling the span to depth ratio (span length divided by the height/width of the specimen). All beams were designed in this work for a span to depth ratio of 16:1 per ASTM D790-17 standards [10], and the test setup used is shown in Figure 4. Additionally, in concurrence with the test standard, the overhang length for the beam on either side of the supports was set to be 10% of the span length.

Figure 4.Test setup used for this study

The flexural test measures the force required to bend a beam under 3-point loading conditions. In this study, as the cross section of these beams are different from a uniform cross section for which an area moment of inertia *I* may be readily computed, an effective flexural rigidity (E^*I^*) is instead used as the primary criterion for comparison between beam designs. Thus, while there is no specific *E* (elastic modulus) and *I* value that is computable for these beams, the product E^*I^* may be assessed from relating beam deflection at an applied load to derive this measure. The relative density is the density of the test beam by the density of a solid beam of identical dimensions and the relative flexural rigidity is the flexural rigidity of the test beam by that of a solid beam of identical dimensions.

Results and Analysis

Figure 5 shows the load-displacement responses of all 23 beams – while comparing these curves is misleading, since each beam has a different mass, it is still noteworthy that the stochastic cellular beams show a wider range than the periodic ones, and that topology optimization solutions are confined to a relatively narrow range at the bottom. The solid box, as expected shows the highest load bearing capability, and is also among the stiffest and the hollow box and hollow cylinder show similar behavior. Figures 6 through 8 are isolated load-displacement plots for each of the three design strategies employed in this work: topology optimization, periodic cellular materials, and stochastic cellular materials, respectively.

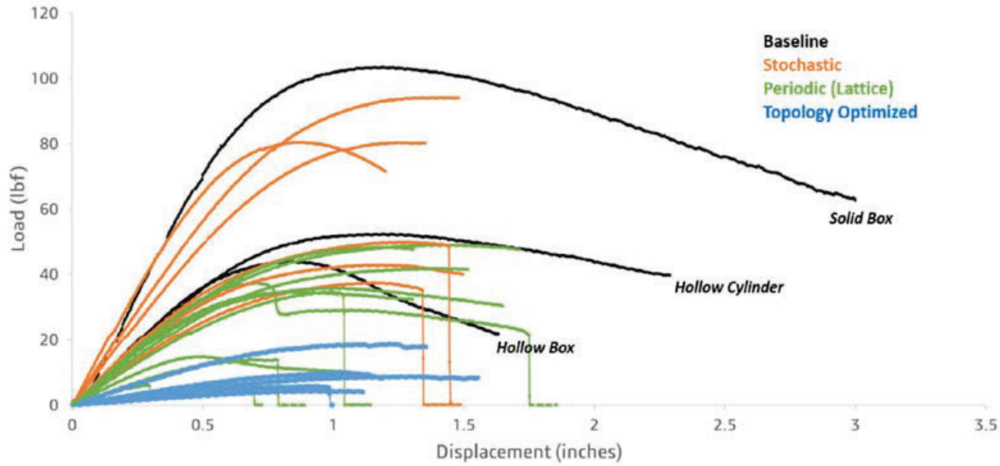


Figure 5. Load-displacement plots for all beams tested, color coded by high level design strategy

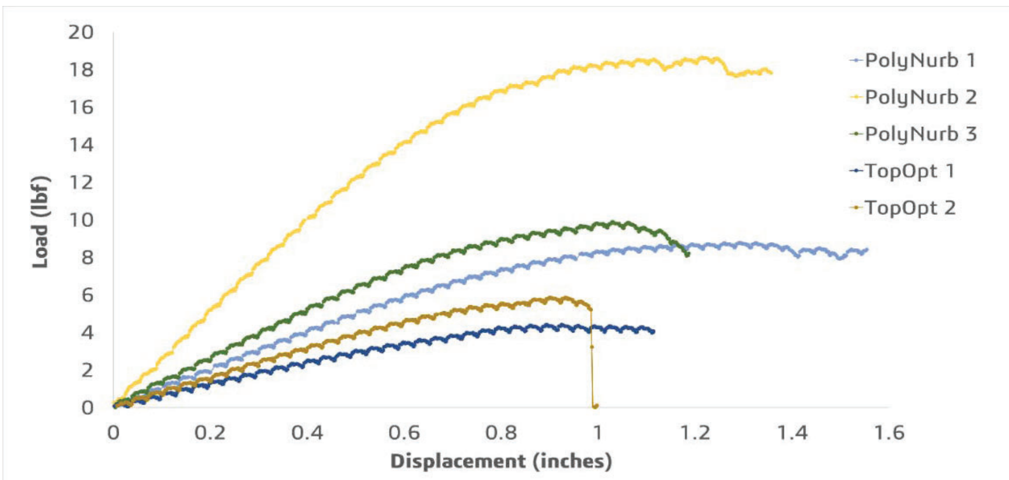


Figure 6. Bending load-displacement response of topologically optimized beams only

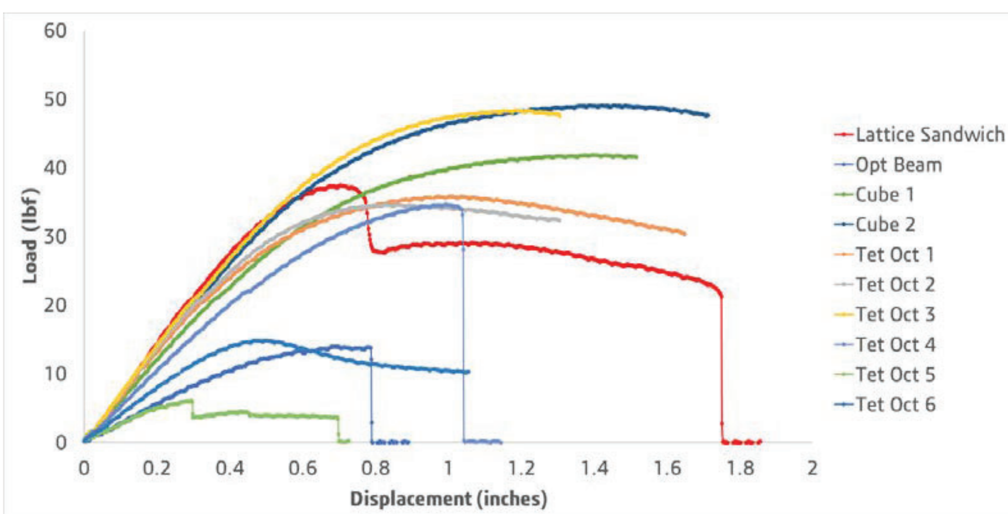


Figure 7. Bending load-displacement response of periodic cellular beams only

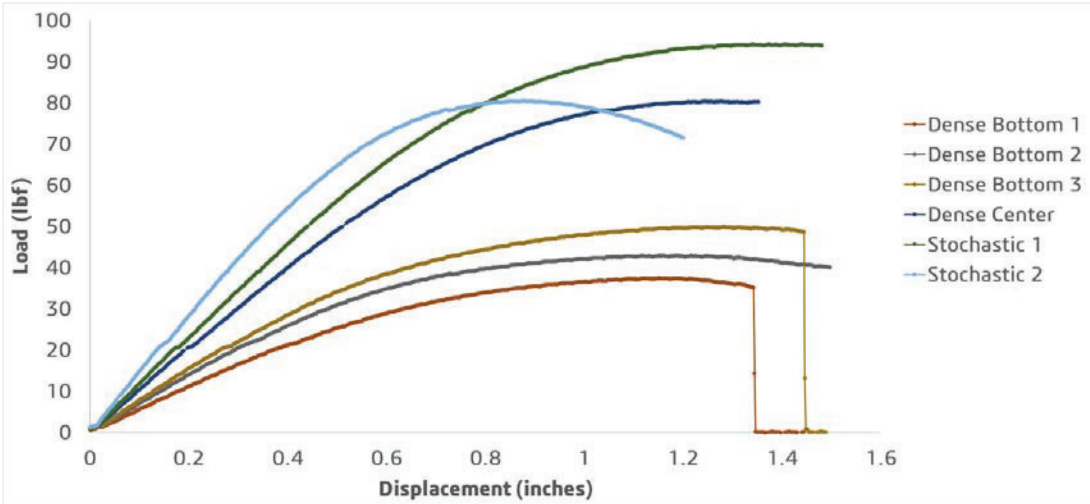


Figure 8. Bending load-displacement response of stochastic cellular beams only

To enable meaningful comparisons between these beams, we must isolate the contribution of mass from the estimated quantities of interest – for this work, the two parameters of interest are flexural rigidity, and the maximum bending stress experienced in the beam. Figure 9 shows the effective flexural rigidity plotted as a function of relative density, where relative density is the mass of the designed beam divided by the mass of its solid bounding (enveloping) box. Therefore, the solid beam has a relative density of 1.

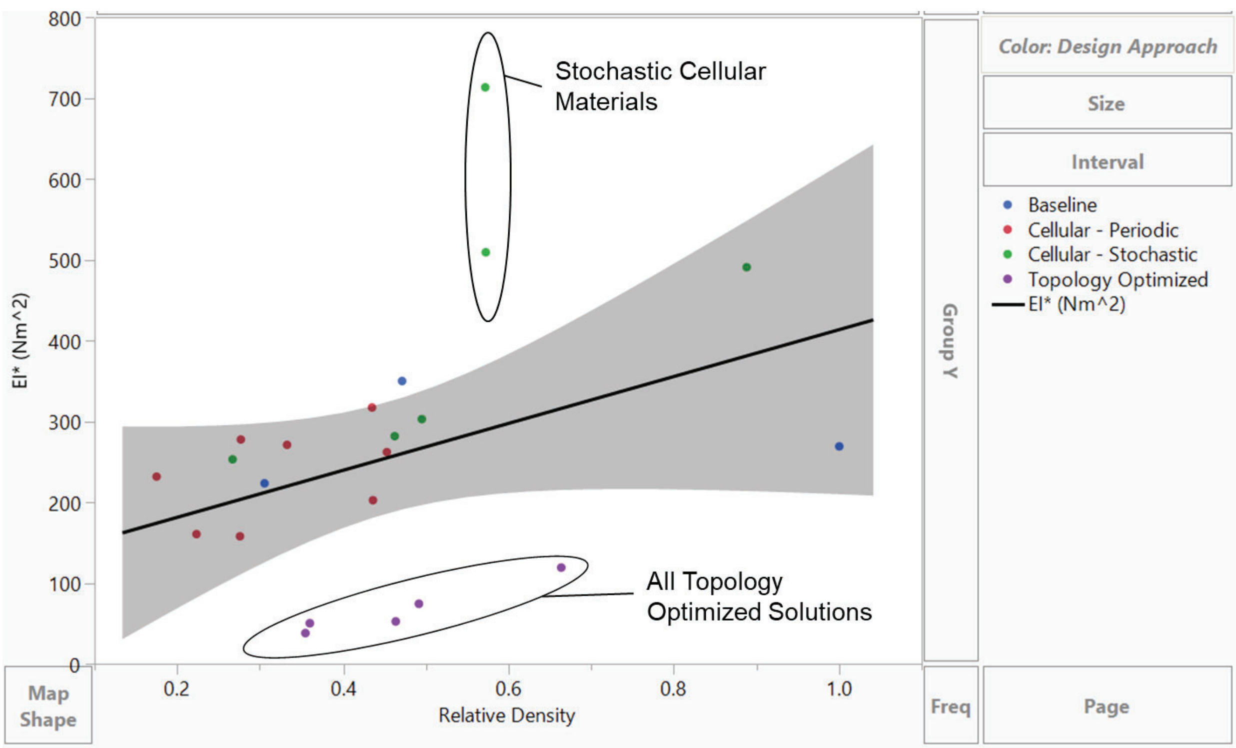


Figure 9. Effective flexural rigidity (E*I*) plotted as a function of relative density of the beam, with solid beam representing a relative density of 1

As can be seen in Figure 9, the topology optimized beams, despite being optimized with the objective of maximizing stiffness at different mass fractions, greatly underperform the beams populated with cellular structures. Further, the stochastic cellular materials once again display a wide range of results, including two designs that have rigidity measures far higher than the majority of periodic and stochastic designs. Plotting the maximum bending stress (estimated at the peak load experienced by the beam) against relative density, as shown in Figure 10, shows similar trends. The stochastic 2 design (see table 3), which is a graded stochastic geometry in a hollow box, showed an ability to withstand very high peak loads for its relative density in comparison to the other solutions.

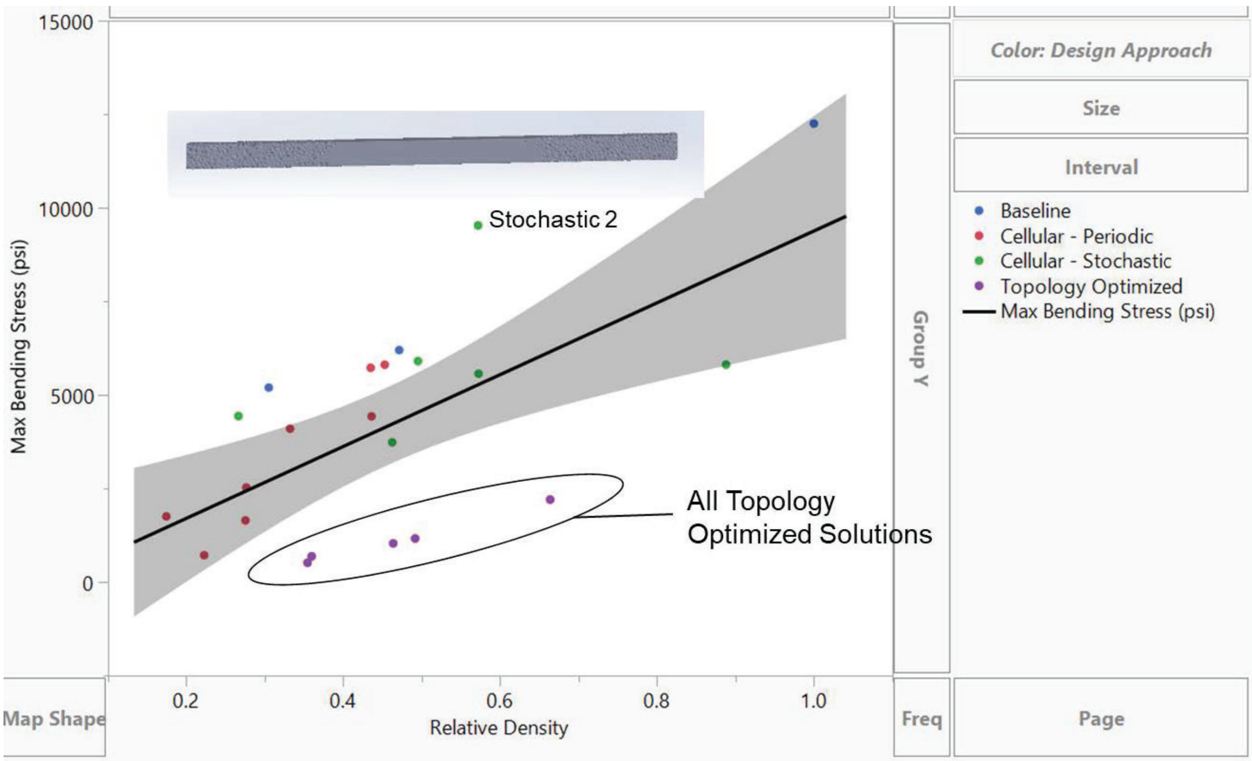
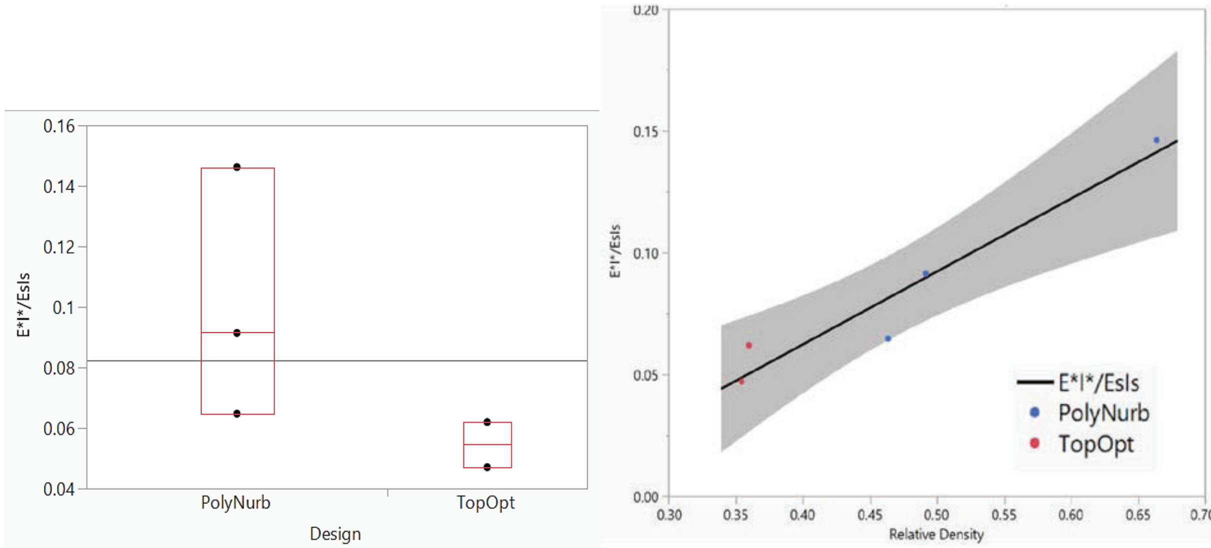


Figure 10. Maximum bending stress (estimated at the peak load experienced by the beam) plotted as a function of relative density of the beam

A final study of interest was to examine the effect of PolyNURBs on the bending response. PolyNURBs is a feature in the Inspire software that enables smoothing of faceted geometries that are typical of topology optimization software outputs. As can be seen in Table 2, the topology optimized designs selected for the study included 3 geometries that were smoothened with PolyNURBs, and 2 that were printed as optimized, with all facets intact. While this represents a very small sample size, a comparison of the geometric efficiency of the flexural rigidity was performed. Following Berger et al. [11], the geometric efficiency is estimated as a dimensionless ratio of the effective flexural rigidity discussed before, divided by the flexural rigidity of an equivalent solid beam, and expressed as (E^*I^*/EI). As can be seen in Figure 11a, smoothing a faceted geometry does have the effect of increasing the geometric efficiency of its bending rigidity, and also its maximum bending stress, as seen in Figure 12a. However, when plotted with respect to relative density (Figures 11b and 12b), it is apparent that the improvements are essentially emerging from an addition of mass that is typical with smoothing applications. Thus we may conclude that smoothing functions do improve the solution (at least in the context of maximizing stiffness and peak load per unit mass) but do so only at the expense of increasing mass of the structure.



(a) (b)

Figure 11. Geometric efficiency of flexural rigidity: (a) as a comparison between PolyNURBs and the faceted topology optimized solution, and (b) versus relative density

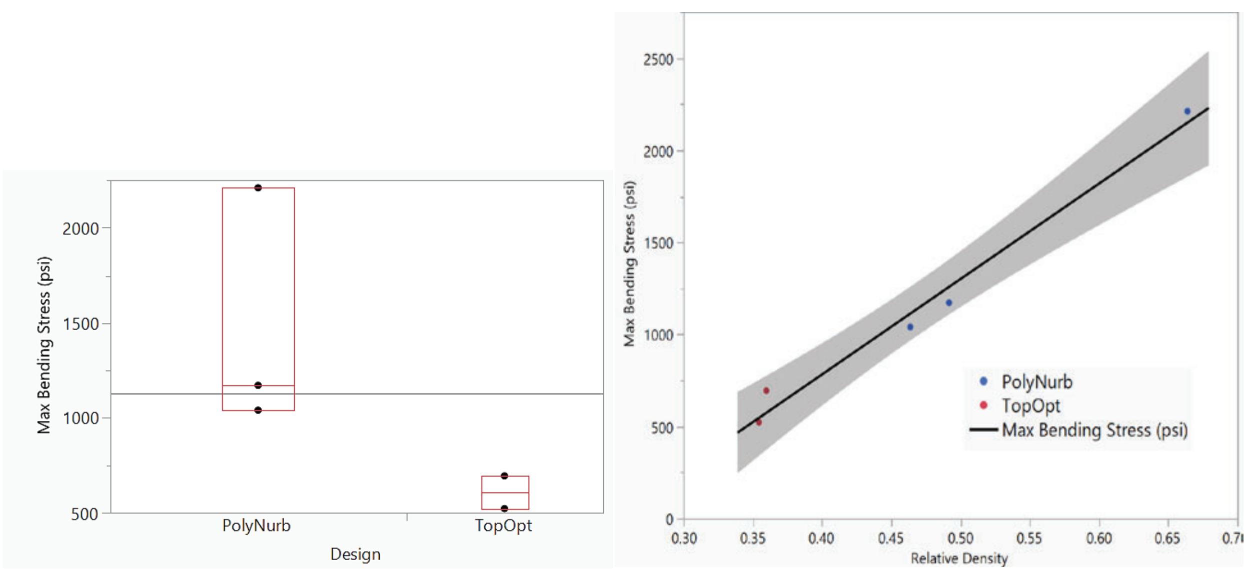


Figure 12. Maximum bending stress (a) as a comparison between PolyNURBs and the faceted topology optimized solution, and (b) versus relative density

Discussion

Topology optimization and cellular materials represent two exciting avenues for design enabled by AM. However, much work is needed to validate the results of using these design software solutions, and identifying trade-offs and risks in implementing supposedly optimized designs. In this rather limited, and preliminary work, an effort has been made to demonstrate how the application of these software solutions to well-studied problems such as the 3-point bend test may elucidate practical aspects of implementing these optimization software without relying on more complex, component level design.

The reader is cautioned against necessarily interpreting from this study that topology optimization solutions will underperform lattice based structures in bending – in fact there is computational evidence suggesting the opposite [12]. The use of two different software packages is also complicated by their own assumptions – however the experimental results do suggest that there is perhaps a loss of redundancy with topology optimization when these parts are fabricated and tested, that is not observed as much with cellular materials. Ultimately, this work hopes to make the case for greater experimental study of optimized geometries, be they via topolo

Acknowledgements

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