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Topology optimization through stiffness/weight ratio analysis for a three-point bending test of additive manufactured parts

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Abstract. Topology Optimization (TO) is a technique that allows for increasingly efficient designs and its objective is to maximize the performance of mechanical systems or structure in a variety of fields. Attempts to employ TO for parts manufactured with conventional methods such as casting, forging, injection moulding, CNC machining and the like could not lead to desired optimum results due to the existing manufacturing constraints regarding geometrical complexity. Currently, additive manufacturing (AM) techniques allow the fabrication of more complex shapes which in principle will lead to improved performances through application of the TO concept. This study focuses on structural optimization of additive manufactured parts of thermoplastic parts based on analysis of the stiffness/weight (mass) ratio for a beam subjected to a three-point bending load. The experimental work is done on optimization of parts manufactured by Fused Deposition Modelling (FDM) technology and finally compared with an identical model manufactured using Polyjet 3D printer. Different TO software are compared to conduct the optimization, and a module of SolidWorks 2018 from Dassault Systems is chosen for the topology optimization for the final experiment. The study focuses on the results on stiffness/mass ratios, paying attention to the influence of different printing parameters on the test results. An increase of stiffness/weight ratio of 31.7% was predicted by software while experiments showed an increase of just 27.04%.

1. Introduction

Topology optimization is a type of structural optimization that is used as a tool or technique in areas that need reduction of weight in a component by optimal distribution of mass (weight) and hence leads to improved stiffness to weight ratio. The optimization technique produces shapes by removal of materials from regions where the component shows low levels of stress under loading conditions. Such shapes can be complex and hence difficult to manufacture using the traditional manufacturing techniques. With the current opportunities provided by additive manufacturing, however, the difficulty of fabrication of complex shapes is not an issue, and hence topology optimized design can be realized. As additive manufacturing is a technology that is not yet fully mature, it requires detailed studies of several aspects to understand the material behavior under loading conditions. In this introduction, a brief literature review is reported to understand the previous work on material characterization of additive manufactured parts and also on topology optimization.

In order to perform a proper topology optimization, the optimization software needs to rely on material properties verified for each additive manufacturing strategy. In Akessa et al. [1], for instance, a study was conducted to characterize the mechanical properties of ABS-M30 material using rectangular samples that were subjected to 3-point bending tests. The samples were manufactured by varying the air gap, raster width and raster angle. A similar study was reported by Gebisa and Lemu [2] in which the effects of varying the FDM process parameters on the flexural properties of ULTEM 9085 were investigated. The objective of this study was to consider all possible combinations of parameters; air gap, raster width, raster angle, contour number and contour width.

According to other recent studies carried out by Domingo-Espin et al. [3], anisotropic material properties should be considered when using FEA simulation of FDM parts exceeding the elastic region limit. From this study, conclusions were achieved using tests and simulations of an “L” shaped cantilever beam with bending and torsion for polycarbonate materials. Furthermore, dynamic properties were studied as described by Domingo-Espin et al. [4], where a simple prismatic part was loaded using a dynamic mechanical analysis (DMA). Results showed that the building parameters, namely nozzle diameter, number of contours and distance between rasters can control the elastic behavior of the FDM manufactured part, being the number of contours the most influential parameter. Test parameters, such as amplitude, frequency and temperature, showed a great influence on the damping capacity of the part.

Creep behaviour of polycarbonate (PC) parts manufactured using FDM process were studied by Salazar-Martín et al. [5] using experimental method focusing on the effect of three process parameters: (1) part build orientation, (2) raster to raster air gap, and (3) number of contours. The study was conducted on the primary and secondary creep behaviour. It was found that increasing the density of the sample, by increasing number of countours and reducing air gap, causes creep strain to decrease. The study also shows the significance of arranging the deposited filaments in the same direction the sample is loaded. The influence of FDM manufacturing parameters on mode I fracture properties has been recently studied by Sedigi et al. [6] to explore how a part can hold deformation energy beyond elastic limits, taking into account plasticity and crack locations.

Other additive manufacturing techniques have been studied to understand the influence of manufacturing parameters on material properties. For example, Morales-Planas et al. [7] studied the influence of different manufacturing parameters such as part orientation on mechanical properties of Multi Jet Fusion PA12 focused on achieving the right design for watertightness, strength and tolerances. Once material properties are well studied, a topology optimization can be performed taking into account these values and a literature review on topology optimization is provided.

A review on topology optimization was performed by Hassani et al. [8] already in year 1998 and is continuously reviewed due to the growth of software and hardware developments. For example, Campbell et al. [9] provided a review of numerical optimization techniques for meta-device design for optical materials. In this paper, the literature review focused on lightweight design considering topology optimization needs for the best stiffness to weight ratio. Gebisa and Lemu [10] reported a case study on topology optimized design for additive manufacturing. An engine bracket was topologically redesigned to reduce its weight considering fabrication in AM. The study results show that topology optimization is a powerful technique to reduce the weight of a structural product while maintaining the design requirements if additive manufacturing is considered.

Faskhutdinov et al. [11] reported a study done on the topology optimization of a jet engine part with Selective Laser Melting (SLM) technology where the process of TO is described. The optimization is the process of choice of the best option imaginable. That decision is done based on some dependent values (design data) and a target function. The values of design data are found at which the target function has a minimum. While there may be a number of targets, one will have to have priority on others, as not all of them may be compatible. Then, topology optimization allows finding an optimal material distribution in a given design space under the certain loads and boundary conditions. Recently, Wang et al. [12] worked on lightweight design for robots by integrating topology optimization and parametric system optimization using TOSCA software. Their target was to maintain the deformations of the end-effector of a serial painting robot reducing the mass of components.

The objective of the work reported in this article is to conduct topology optimization of 3D printed parts of thermoplastic materials for improved stiffness to mass ratio using both experimental test (3-point bending test) and optimization software.

2. Materials and Methods

2.1. Three-point bending test

A three-point bending test is defined as a starting point for the topology optimization reported herein. This is because tensile tests are not adequate as they provide a uniform stress distribution across the section of the specimen and therefore the optimization is limited to a reduction of cross section. Three-point bending test is relatively simple to conduct in a common laboratory facility. It creates different stress values across the thickness of the specimen and provides room for topology optimization.

In this study, the stiffness to mass ratio is used as a parameter of optimization. Stiffness for a constant section specimen of a simple supported beam under transverse load is theoretically calculated as follows based on pure bending:

$$k = \frac{F}{y} = \frac{48EI}{L^3} \tag{1}$$

where k is stiffness, F is applied force, y is displacement in loading direction, E is Young modulus, I is section inertia and L is span length. For the same beam loading, maximum stress (σ) is obtained at the middle of the specimen and theoretically expressed as follows:

$$\sigma = \frac{FLh}{8I} \tag{2}$$

where h is section height of the specimen.

Theoretical equation for stress does not include stress concentrations near supports but test is defined to obtain fracture on lower parts of specimen. Therefore, in classical engineering optimization, increasing inertia will improve stiffness and at the same time reduce maximum stress avoiding plasticity and fracture with the exception of stress concentration effects if new shapes involve sharp edges.

2.2. Simulation software for topology optimization

Software for topology optimization is growing very fast together with the rapid increase in computational speed and hardware capacity. As a result, many modelling and simulation tools are incorporating topology optimization modules in their software package. In this study, a module of SolidWorks 2018 from Dassault Systems is chosen for the topology optimization. The software allows the definition of boundary conditions similar to the three-point bending test setup and provides design rules to select surfaces that should be defined as design features and non-design features. The design features are subjected to material removal if not contributing to load sharing while the non-design features should be kept as they are in initial design, regardless of the stress level acting on them. The software also allows the definition of other rules such as the optimization criteria. The optimization criteria in this case is defined based on the best stiffness to mass ratio with a load of 50 N, considering the material anywhere in the beam remains within the elastic region.

2.3. Additive fabrication and testing machine

Fortus 450mc machine from Stratasys (Figure 1(a)), FDM technology, is chosen to fabricate original and optimized parts using ABS – M30 material. According to the material data, the density is around 1040 kg/m3, Young's modulus between 2180 and 2230 MPa and yield strength between 26 and 31 MPa with elongation at break between 2 and 7%, depending on the orientation of the part (Table 1) [13]. For model slicing and machine control, the pre-processor software of the machine, Insight® 12.2, was used. Raster and contour width were set to 0.4064 mm with just one contour and 0 mm air gap between contours. Two orientations were chosen, flat and edge and for each orientation two angles 0º and 45º were chosen.

Optimized parts required support material for overhanging areas. The FDM process of the machine uses support material referred to as SR20, which dissolves at 70±3 °C and removed from the manufactured part. The solvent is a water solution with additions of sodium hydroxide and sodium carbonate. Two sample designs, i.e. rectangular samples and optimized samples were printed and tested. Four variations with different parameters where designed for each sample, and three specimens for each variation were tested. In other words, a total of 12 + 12 = 24 ABS specimens were tested.

Table 1. Properties for ABS- M30 and Verowhite (from [13] and [14]).

	Density [kg/m^3]	Young's modulus [MPa]	Yield stress [MPa]	Elongation at break [%]
ABS-M30	1040	2180-2230	26-31	2-7
Verowhite	1170	2000-3000	50-65	10-25

In order to compare the results with another printing technology, the identical designs were manufactured using an Objet30 Prime machine from Stratasys (Figure 1 (b)) which is based on Polyjet technology. This machine cures acrylic liquid by using ultraviolet lamps which can provide high accuracy with layers of 0.015 mm. The material used for this study was VeroWhite [14]. According to the material manufacturer, this material has the material properties given in Table 1. A total of 10 + 10 = 20 samples from Verowhite material were manufactured with the same manufacturing conditions to check repeatability. Finally specimens where tested using three-point bending test on an Instron 5985 (Figure 1 (c)) where displacement and force where recorded. Span length for the beam supports was set to 100 mm with a velocity of 1mm/min.

Figure 1. Machines used for additive manufacturing machine and testing (a) Fortus 450mc FDM machine (b) Objet 30 Prime Polyject machine and (c) Instron 5985 tensile test machine.

3. Results and discussion

The original geometry considered for this project is shown in Figure 2, where two small extensions were provided to a rectangular beam to avoid falling from the three-point bending supports. Theoretical calculation are provided with equation (1) and equation (2) ignoring these extensions. From theoretical calculations, the following values are obtained: mass, m = 20.8 g, stiffness, k = 640 N/mm (at E = 2000 MPa) and stress, $\sigma = 1.875$ MPa (for F = 50 N), which is below 26 MPa for the lowest yield stress and without considering stress concentration effects.

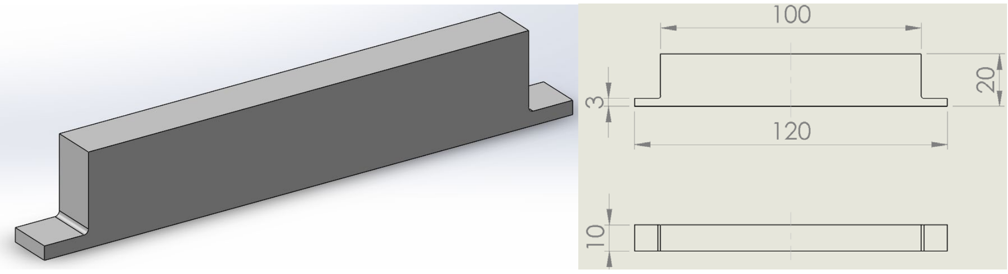

Figure 2. Original geometry to be optimized for a three point bend.

Once the samples are defined, topology optimization was performed to achieve an improvement in the stiffness/mass ratio. Figure 3 (a) shows the optimized model, i.e. after removing unwanted material but with sharp edges. Then, a smooth optimized geometry is generated (Figure 3 (b)) upon generating soft cure transitions. In this optimization process, the mass is reduced from 20.8 g down to 9.1 g. Since the section is not constant or of regular shape, theoretical calculations are not possible for stiffness and strength.

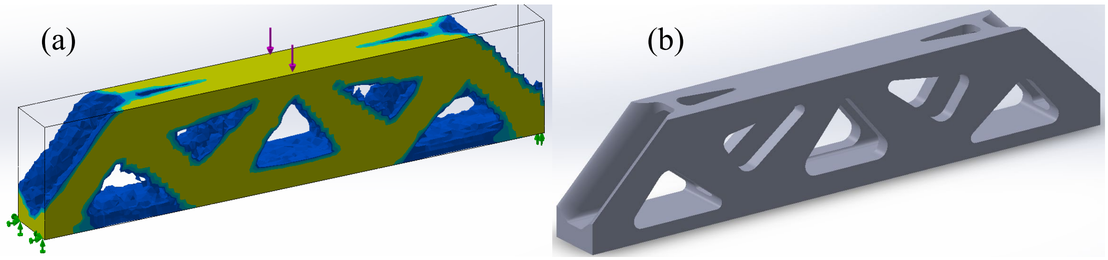

Figure 3. Optimized part (a) with rough surfaces as optimized and (b) smoothed surface geometry created base on optimized shape.

The original and the optimized parts are then manufactured with both machines. Figure 4 (a) shows the specimen manufactured using ABS-M30 material and SR20 support. After the support material is removed, the specimen is three-point bending tested as illustrated in Figure 4 (b).

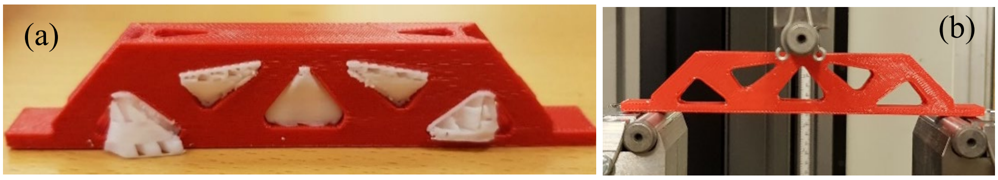

Figure 4. Optimized part (a) as manufactured with material support material and (b) under three-point bending test.

The same procedure was repeated for the specimens fabricated from Verowhite material. Object30 Prime allows fabrication of parts which are closer to CAD geometry as it allows much smaller layer thickness. This means, it is possible to get a smoother surface in this case compared with that of Fortus 450mc machine. As shown in Figure 5(a), the fracture started from the top connection between front and bottom face but low friction led to sliding of the test sample (Figure 5(b)) with conditions dissimilar to the case in topology optimization, which is defined with ideal conditions where the load is placed in the middle and lower supports are always in the same place. Figures 6(a) and (b) show von Mises stress distribution for the original design and the optimized shape, respectively. In both figures, stress is much higher at the load point (middle of the beam) and at the support points (locations of boundary conditions), thus attention is paid to points in the lower part of the middle section of the specimen where fracture is expected to happen.

Figure 5. Optimized structure tested with unstable sliding support.

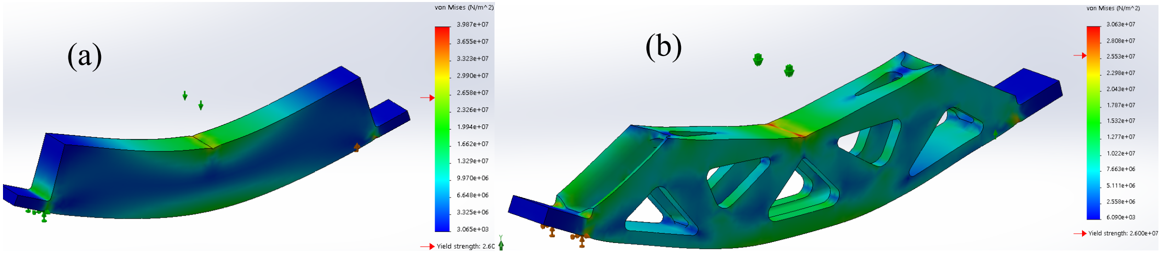

Figure 6. von Mises stress for 1 mm displacement for (a) original shape and (b) optimized shape.

Finally, Figure 7 shows results for all ABS-M30 tests for both original and optimized designs for each fabrication condition. The difference in stiffness to mass ratio for all orientations ranged from 18590 to 20830 N/m/g for original part and from 23460 to 26960 N/m/g for optimized parts. Comparison of all scenarios is provided in Table 2.

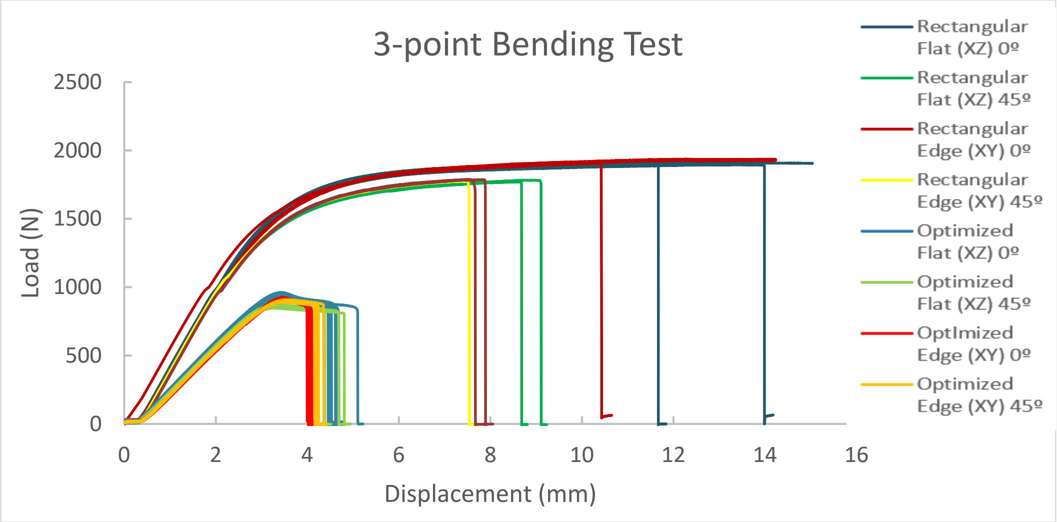

Figure 7. Test results for several printing directions for Fortus 450mc.

Analyzing all scenarios, it can be observed that the increase in stiffness to mass (k_y/m) ratio varies from 12.61% increase in the worst case to 45.03% in the best case. The achieved average increase in stiffness to mass ratio is 27.04%. This is very important since the layer orientation of real complex 3D components cannot be controlled for each location and therefore it is important to expect that improvement is achieved for any combination of orientations. Table 3 gives summarized values of the average mass, loads, displacements and stiffness.

Table 2. Stiffness comparison of ABS-M30 for different scenarios.

	Stiffness to mass (k_y/m) ratio (N/m/g)				
	Average value	Lowest value	Highest value	Worst case optimization	Best case optimization
Rectangular	1.975E+04	1.859E+04	2.083E+04	2.083E+04	1.859E+04
Optimized	2.509E+04	2.346E+04	2.696E+04	2.346E+04	2.696E+04
k_y/m increase after optimization	27.04%	26.19%	29.43%	12.61%	45.03%

Table 3. Average values for each sample design.

	Mass (g)	Max. load (N)	Displ. at max. load (mm)	Load at 1 mm displ. (N)	k_y (N/m)	k_y/m (N/m/g)
Rectangular	19.71	1847	10.06	389.2	3.892E+05	1.975E+04
Optimized	8.87	906	3.43	222.6	2.226E+05	2.509E+04

Furthermore, fracture is also analyzed for each specimen and fabrication orientation. Figure 8 shows fractured parts from edge fabrication ((a) and (b)) and flat fabrication ((c) and (d)). For each sample shown, the upper part is 0º and the lower part is 45º. Original parts are shown on the left and optimized parts on the right. Fracture is complete for flat orientations while fracture is produced on the bottom of the specimen (as expected) for edge manufactured components.

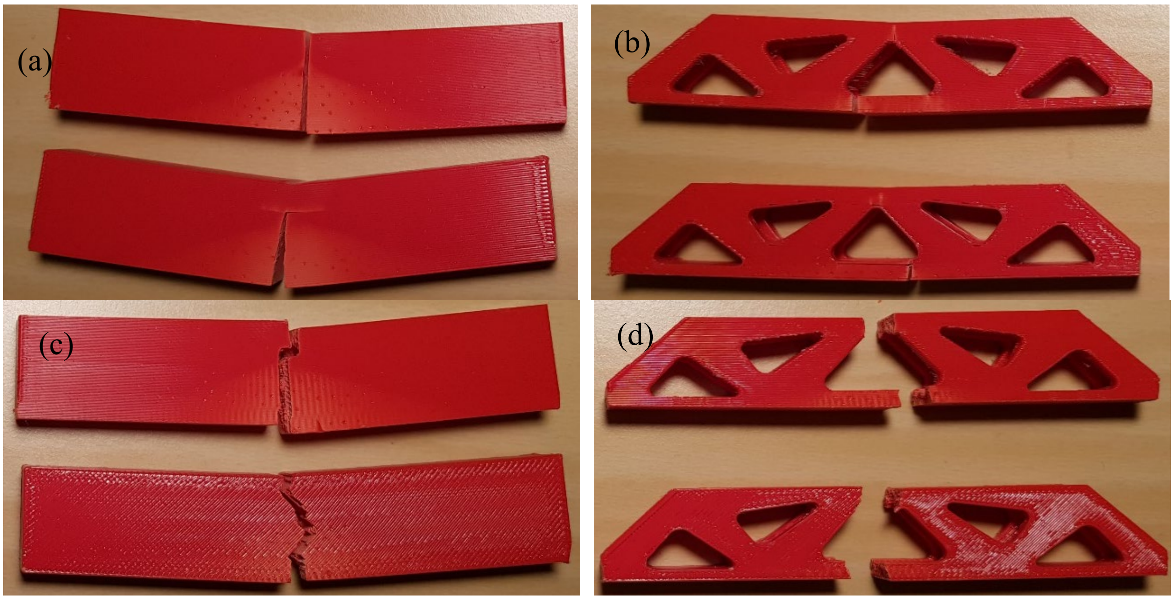

Figure 8. Fracture of original samples (left a and c) and optimized samples (right b and d).

Results are compared with predictions made by optimization software. In the simulations for optimization, a Young´s modulus of 1526 MPa was used for a better fitting to test data. 3D tetrahedral elements of side length 1 mm were used to obtain 12 elements per each mm^3 with 4 Jacobian points for each element. Therefore, for the original shape a total of 130087 nodes and 187218 elements were used to be eliminated during the optimization process and to define the light weight structure. However, the importance of optimization simulations is the reduction of weight using reliable material data. As given in Table 2, this varies depending on the material orientation. Comparison of the stress results of the optimized model with the original model is given in Table 4. This comparison shows that optimization software (FEA) resulted a 31.7% improvement in stiffness to mass ratio (with the same Young's modulus) while average results for the 3-point bending tests gave a 27.04% improvement. These percentage improvements between the simulation approach and experimental test approach have no significant difference.

Table 4. Comparison of FEA simulations with tests.

	Stiffness to mass (k_y/m) ratio (N/m/g)		
	FEA (E =1526 MPa)	3-point bending test (average)	Difference
Rectangular	2E+04	1.975E+04	1.25%
Optimized	2.634E+04	2.509E+04	4.75%
Improvement of k_y/m after optimization	31.7%	27.04%	

The work was repeated using another printer having better resolution. In this case, 10 samples for original design and 10 samples for optimized design were manufactured using Verowhite material and an Object30 Prime printer. For the last samples of Verowhite material, the support was not mechanically removed after solvent exposition for 24 hours in order to avoid possible damage to the structure. The weight of components is shown in Figure 9. Average values of each printing direction are taken for ABS-M30 samples. The weight of the Verowhite original design is very close to the computer aided design weight of 24.10 g considering density of 1170 kg/m^3 while ABS-M30 designs do not reach the expected density due to accuracy in layers and trajectories.

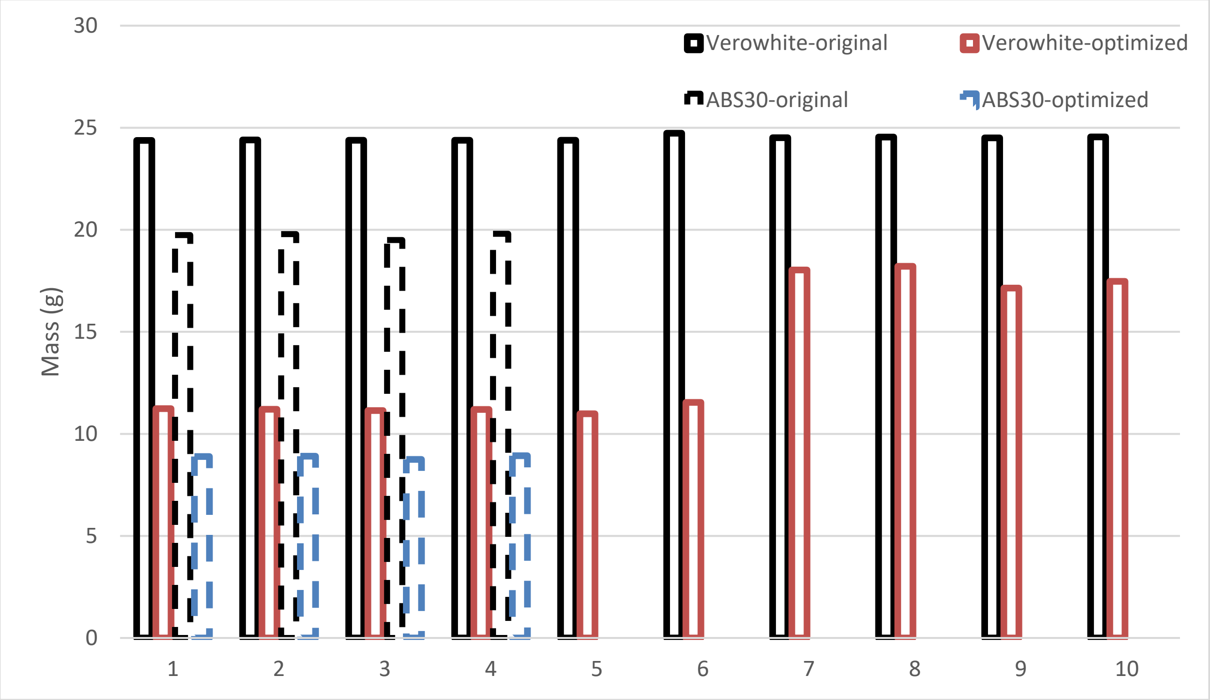

Figure 9. Mass comparison for Verowhite and ABS-M30.

On the other hand, Verowhite optimized shapes do not show any improvements in the stiffness to mass ratios as shown in Figure 10. A possible reason for this can be the sling of the Verowhite components that place the load in a point far from the center of the specimen due to a surface that looks like a polished surface. If focused on the original structures, the curves are very similar for ABS-M30 and Verowhite if the weights are normalized. The ABS 30 model, however, has shown improvement in stiffness to mass ratio. In both cases, for ABS-M30 and Verowhite, the optimized shape can take less deformation and less energy when compared to original designs.

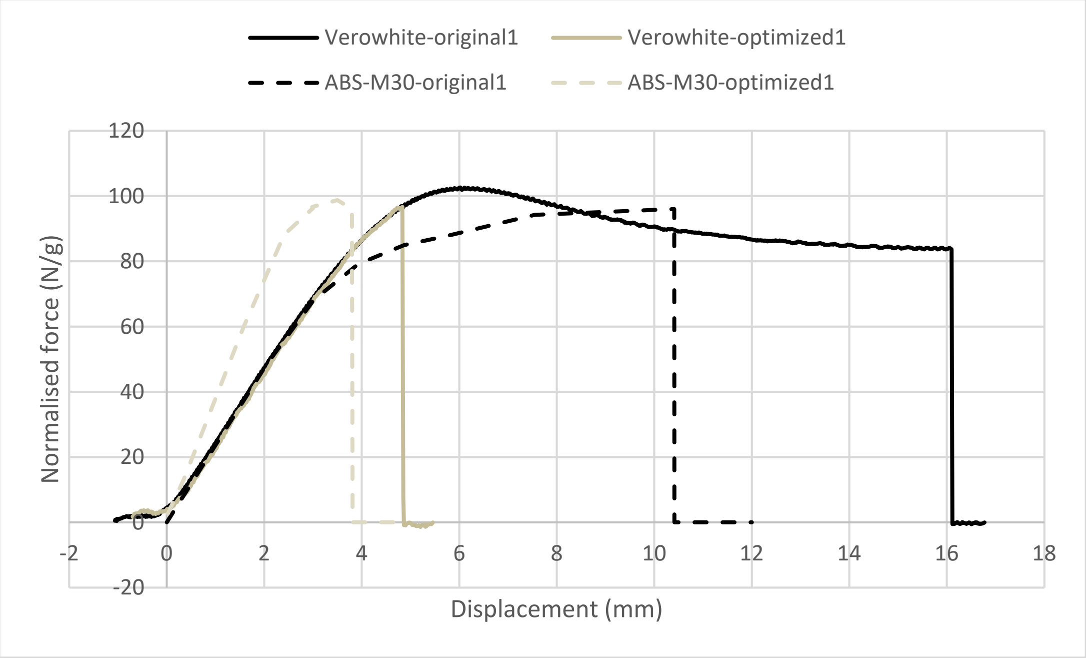

Figure 10. Comparison Verowhite to ABS-M30.

4. Conclusions

In this paper, a study focusing on topology optimization of additive manufactured part using Fortus 450mc (FDM technology) and Polyjet Object30 Primeis machines is reported. The selected part is tested using three-point bending test. The optimization targets maximum (improved) stiffness to mass ratio. It is observed that the obtained stiffness to mass ratio varies with printing orientation. For the ABS-M30 FDM manufactured parts, the topology optimized part under three-point bending test resulted in an average improvement in stiffness to mass ratio of 27.04%, worst case improvement of 12.61% and best case improvement of 45.03%. Similar design geometry was used to compare the optimized part performs by using Verowhite material printed in a Polyjet Objet30 Prime machine. It is observed that the part manufactured by Polyjet Objet30 Prime machine gives better accurate geometry compared with ABS-M30 using FDM Fortus 450mc. The part manufactured using Verowhite showed no improvement in stiffness to mass ratio. One reason for this lack of improvement is the glossy surface of the manufactured part when the support material is removed. The sliding of the test specimen under the three-point bending supports due to the glossy surface led to inaccuracies in the test results. It has also been observed that the optimized shapes provide a lower fracture displacement and absorb less energy when compared to original shapes.

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