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BIOMIMETIC CELLULAR STRUCTURES FOR TURBINE SYSTEM COMPONENTS

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Abstract: The research aim is to investigate cellular structures inspired from nature, in order to improve the internal structural resistance of turbine system components (e.g. hydroelectric and gas turbine blades, OGV-Outer Guide Vanes, nacelles, gearboxes) with reduced mass. The investigations were conducted at laboratory level, utilizing two 3D printing technologies to acquire the desired cellular structures which were further tested for tensile, bending and impact resistance. The first selected technology was Fused Deposition Modelling with Continuous Filament Fabrication to obtain 3D printed parts, which can be reinforced with continuous carbon, glass, or Kevlar fibers. The second technology used is Digital Light Processing 3D printing, which uses photopolymer liquid resin that cures under digital light source. The main motivation of utilizing the 3D printing technologies is the desire of implementing rapid prototyping in the final manufacturing of the turbine system components with structural topological optimization and improved structural and dynamic efficiency through biomimetic inspired structures. Conventional polymeric composite manufacturing technologies are sometimes restrictive in the geometries they can produce, and there is a chance that additive manufacturing can step in and help create internal structures that could not be obtained through conventional manufacturing methods. New developed structural architectures could be manufactured for a specific application through 3D printing which allows for a high level of customization parameters, including the possibility to use continuous carbon, glass and Kevlar fiber to create the geometrical pattern. All these, combined with conventional composite manufacturing technologies, could lead to obtain better end results.

Key words: 3D printing, biomimetic, structure, turbine system

1. INTRODUCTION

Emerging technologies of additive manufacturing (AM) have revolutionized important areas such as aerospace and energy by replacing classical technologies for the development of advanced composite structures with automated processes that can achieve complex shapes in a short time and with low associated costs. Although additive manufactured structures are at a place where composite materials were, in the first stages of introducing them to key industrial areas, the industry is quickly building up means of validating the additive manufactured structures.

One such subject of interest, that has seen great interest in the research community, are the development of complex cellular structures, most of them inspired from nature which are now possible thanks to the capabilities of AM technologies to reproduce complex geometries with ease and great accuracy.

In the studied paper [1], the authors characterize both experimentally and numerically three classes of non-traditional 3D filling models at three scales as an alternative to the classical models of 2D filling in the context of additive manufacturing and structural applications. The investigated 3D filling models are biomimetic in nature and include gyroid, Schwarz D and Schwarz P structures. They are not only known from nature, but also arise from topological numerical optimizations. A classic 2D hexagonal model was used as a reference.

The mechanical performance of 14 cylindrical specimens at compression is quantitatively related to rigidity, maximum deformation and weight. Digital image correlation provides accurate surface measurements and information about the periodic states of the deformation field at the surface of the test-pieces. The associated variability, which is inherent in the production and testing process, was evaluated for 3 identical Gyroid samples. The nonlinear model of the material for preliminary FEM analysis is based on the results obtained from the tests of the tensile test samples with 3 different strategies of sections layer by layer, horizontally. 3D filling patterns are generally useful when the extrusion orientation cannot be aligned with the orientation of the construction and the main deformation field, i.e. in the case of generative design, such as the branched structure presented or any complex shape and boundary condition.

Fig. 1. Transition from a column to branch structures, [1]

A transition from the classical column to the branched (organic) structures is shown in figure 1, for which a FEM linear model was iteratively run while removing the material in the areas least subjected to mechanical deformations in the piece. This example can be interpreted as a roofing support and serves as a motivation for further analysis of various filling options. In additive manufacturing rarely use filling densities close to 100%.

Also in their paper, research shows methods by which additive manufacturing also opens the door for optimizing the local filling density based on the fields of real deformations and performance requirements, i.e. to manipulate the thickness of the filling wall or the size of the filling feature to obtain a uniform distribution of mechanical stresses (figure 2). This mapping can be fully automated and integrated into the CAD and digital manufacturing process.

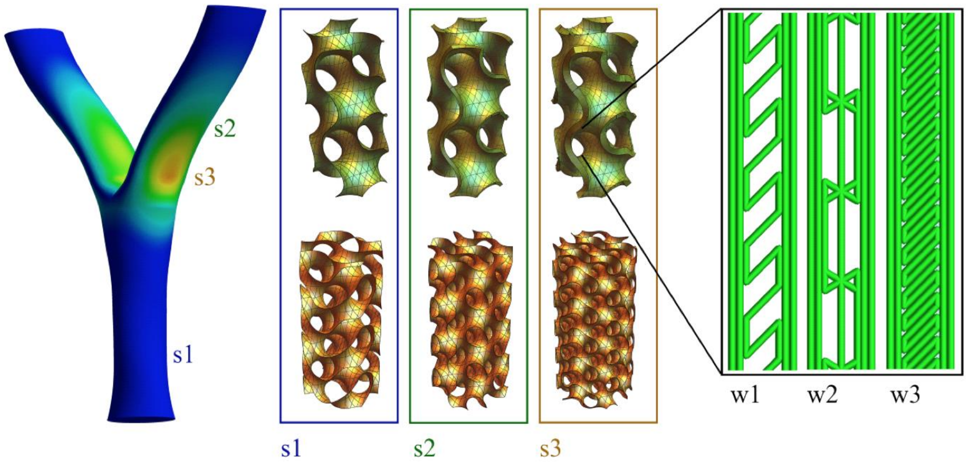


Fig. 2. The principle of scalar optimization using an ordinary gyroid geometrical network, mapped to the levels of mechanical stresses (s1 to s3) by manipulating the thickness of the 3D filling wall or the density of 3D filling. Wall density can be further adjusted by variation of the wall filling pattern (w1 to w3), [1]

Other innovative ways, of bioinspired sandwich cores, come from [2] that follows a different path of generating such structures using a MATLAB code, based on equations that compute an isosurface. As well as the structures presented from the previous research paper, a high level of interest was identified for triply periodic minimal surfaces (TPMS). TPMS exhibit a zero-mean curvature for any points, given they are locally minimized for surface area withing a chosen boundary [3]. Such structures have been found within sea creatures [4] and even butterfly wings, [5,6].

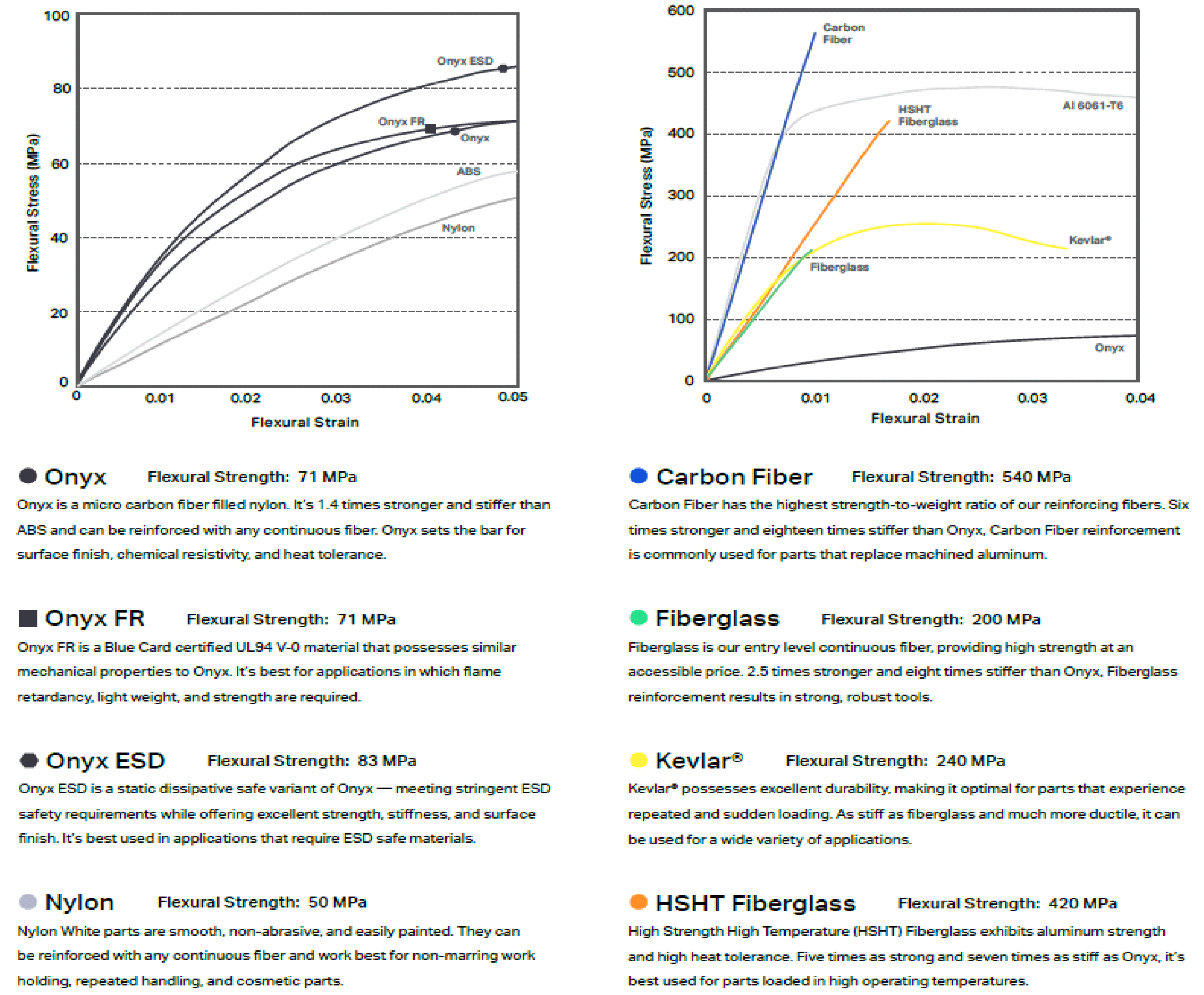
2. MATERIALS AND METHODS

2.1 Manufacturing Conditions

The present study took first steps into developing 3D printed cellular sandwich structures which goals are to offer more versatility for areas where classic composite sandwich structures are used. This would allow the development of more complex 3D geometry sandwich cores, instead of their 2D nomex and aluminum honeycomb core precursors. In the next chapters, the manufacturing technologies and materials used, as well as the test campaign and its results, will be detailed.

The test specimens were manufactured using two different technologies because of the constraints each technology brings together with it:

- Markforged X7 Industrial series machines are based on FDM technology, having as a base material a nylon filled with 42% chopped carbon fiber that they call Onyx. The new technology that they bring on the table, is a second active printing head, that allows the deposition of reinforced continuous carbon, Kevlar or glass fiber, either separately or to reinforce the Onyx printed part.
- The Photocentric's LC Magna 3D printer is based on DLP technology and uses photopolymer resin as a base material, with a broad variety of such resins that are suited for certain applications.



● **Onyx** Flexural Strength: 71 MPa

Onyx is a micro carbon fiber filled nylon. It's 1.4 times stronger and stiffer than ABS and can be reinforced with any continuous fiber. Onyx sets the bar for surface finish, chemical resistivity, and heat tolerance.

■ **Onyx FR** Flexural Strength: 71 MPa

Onyx FR is a Blue Card certified UL94 V-0 material that possesses similar mechanical properties to Onyx. It's best for applications in which flame retardancy, light weight, and strength are required.

◆ **Onyx ESD** Flexural Strength: 83 MPa

Onyx ESD is a static dissipative safe variant of Onyx — meeting stringent ESD safety requirements while offering excellent strength, stiffness, and surface finish. It's best used in applications that require ESD safe materials.

● **Nylon** Flexural Strength: 50 MPa

Nylon White parts are smooth, non-abrasive, and easily painted. They can be reinforced with any continuous fiber and work best for non-marring work holding, repeated handling, and cosmetic parts.

● **Carbon Fiber** Flexural Strength: 540 MPa

Carbon Fiber has the highest strength-to-weight ratio of our reinforcing fibers. Six times stronger and eighteen times stiffer than Onyx, Carbon Fiber reinforcement is commonly used for parts that replace machined aluminum.

● **Fiberglass** Flexural Strength: 200 MPa

Fiberglass is our entry level continuous fiber, providing high strength at an accessible price. 2.5 times stronger and eight times stiffer than Onyx, Fiberglass reinforcement results in strong, robust tools.

● **Kevlar®** Flexural Strength: 240 MPa

Kevlar® possesses excellent durability, making it optimal for parts that experience repeated and sudden loading. As stiff as fiberglass and much more ductile, it can be used for a wide variety of applications.

● **HSHT Fiberglass** Flexural Strength: 420 MPa

High Strength High Temperature (HSHT) Fiberglass exhibits aluminum strength and high heat tolerance. Five times as strong and seven times as stiff as Onyx, it's best used for parts loaded in high operating temperatures.

Fig. 3. Markforged X7 available 3D printing materials

The Markforged system is equipped with two nozzles – one for storing nylon or other types of plastic infill and one for carbon fiber, Kevlar or fiberglass reinforcement filament. After the initial infill operation, the reinforcement is "pinched" in place whenever necessary - around the perimeter of the part, for example, or around the perimeter of the holes.

The "Fused Filament Fabrication" (FFF) or simply put, FDM printing process is incredibly adaptable – however, it doesn't work for every plastic. As a result of the constraints required to precisely extrude plastic from a small nozzle, traditional plastics originally optimized for injection molding cannot be used. However, the printable plastics cover a massive range of compositions, printing constraints and material properties. To find the right material, the requirements of the applications with the properties of the materials with which it can be printed must be chosen.

In addition to thermoplastic printing, Markforged also adapts the FFF process to print non-plastics. In the manufacture of continuous filament (CFF), an FFF printer with a second specialized nozzle places continuous carbon fiber, fiberglass, or Kevlar® in a part. In figure 3, one can see more details on the current available 3D printing materials.

The 3D DLP printers use a digital projector screen to emit an image of a layer over the entire printing bed, polymerizing all points simultaneously.

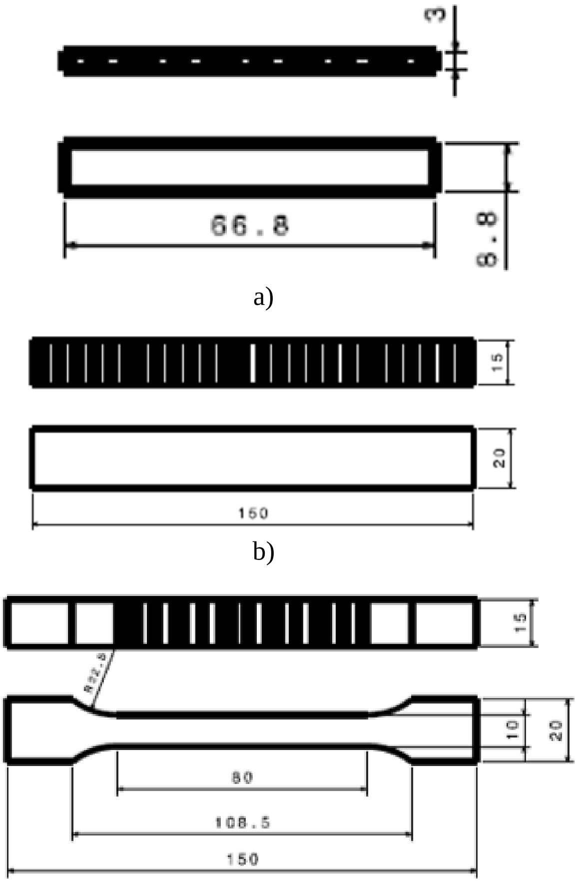
DLP technology [7] has as its main element the DMD (Digital Micromirror Device) chip – a matrix of micro-mirrors used for fast spatial modulation of light. The rapid switching of these micro-mirrors between the lenses that direct light to the bottom of the bowl establishes the coordinates in which the liquid resin polymerizes in the given layer. Since the projector is a digital screen, the image of each layer is composed of square pixels, resulting in a three-dimensional layer consisting of small rectangular cubes called voxels. For each cross section of the 3D CAD model, the UV light emitted by a projector is modulated and projected through the chip onto the surface of the polymer resin in the construction tank. Each individual micro-mirror of the DMD chip projects pixels from the cross-section of the 3D model. Under the action of UV light, photoreactive liquid resin (sensitive to ultraviolet light) solidifies into successive layers. Since the entire cross-section is projected in a single exposure, the construction speed of a layer (section) is constant regardless of the complexity of the geometry. Whether you print a simple piece or simultaneously 10 complex pieces, the printing speed remains constant.

2.2 Design of sandwich cores

As previously mentioned, the present research study consisted in taking first steps towards the first phase of development and integration of biomimetic cellular structures. The approach was towards the present utilization of sandwich core materials, which is to reduce mass by offering similar mechanical properties of the final part. In this respect four type of cellular structures were designed (Table 1) and developed by means of additive manufacturing, using FDM and DLP technologies described in the previous section. All static and dynamic mechanical testing samples were designed through CATIA V5 integrating structures that were inspired by biomimetics. Biomimetics represents the application of existing biological methods and systems in nature to the design of engineering systems and modern technologies and is the way to solve technical problems through models, systems, or elements in nature.

Static regime mechanical tests were performed using a Instron 5982 model mechanical testing machine. Tensile tests were performed according to ASTM D638 [8] while the three-point bending test specimens with a length of 150 mm, a width of 20 mm and a thickness of 15 mm (including the thickness of the sandwich layers), were performed according to ASTM C393 [9]. Dynamic mechanical analysis (DMA) was performed on Discovery DMA 850 equipment according to ASTM D5023, having the test specimen geometry of 66.8 mm length, 8.8 mm width and 3 mm thickness, having the sandwich panels of 0.4 mm in thickness. All the samples are presented in figure 4.

The tensile test specimens, have the geometry represented in figure 4c. Like the other two test specimens, it has a thickness of 0.4 mm for the sandwich panels.



a)

b)

c)

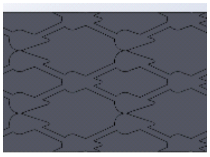
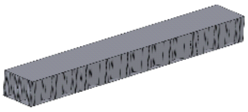
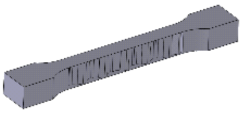
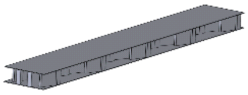
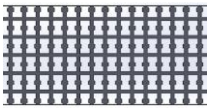
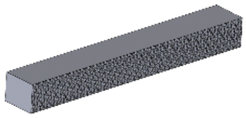
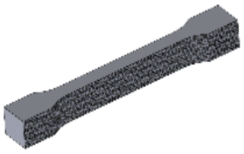
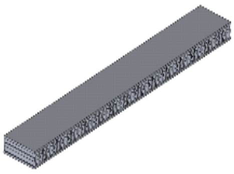
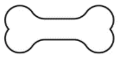
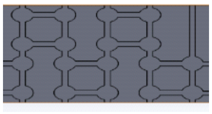
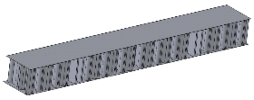
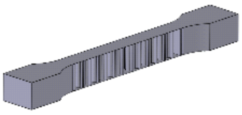
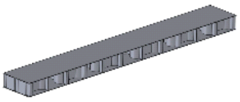
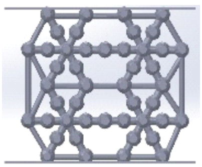
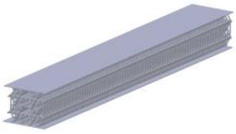
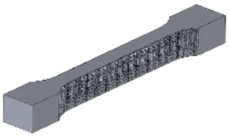
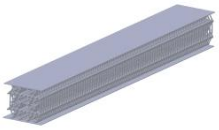
Fig. 4. Overall geometries of the tested samples; a) DMA; b) Three-point bending; c) Tensile

For this research, 75 test specimens were 3D printed. Each of these test pieces were designed based on a biomimetic model, namely: water drop, bone and snowflake. More details regarding the sample geometry, manufactured quantity and materials used are found in table 1, table 2 and figure 5.

2.3. Material Properties and Manufacturing Conditions

The materials used in this study consisted of Onyx, a nylon-based material in which composition there is 42% carbon-chopped microfibers for the Markforged X7 3D printer and a photopolymer resin marketed by Photocentric as “Photocentric Daylight Magna High Tensile Resin”. The DLP technology obtains from the afore mentioned resin, samples with an isotropic character and thus the printing direction does not bring considerable changes in the final resistance of the part. In the case of additive manufacturing technology by FDM, the final sample has an anisotropic character due to the adhesion between the printed layers. For this reason, the laying on the printing bed has a significant role in the final strength of the piece.

Table 1. Test specimen geometries

Biomimetic models	Cellular structure	Three-point bending specimens	Tensile specimens	DMA specimens
 Tear Drop				
 Vertical Bones				
 Horizontal Bones				
 Snowflake				

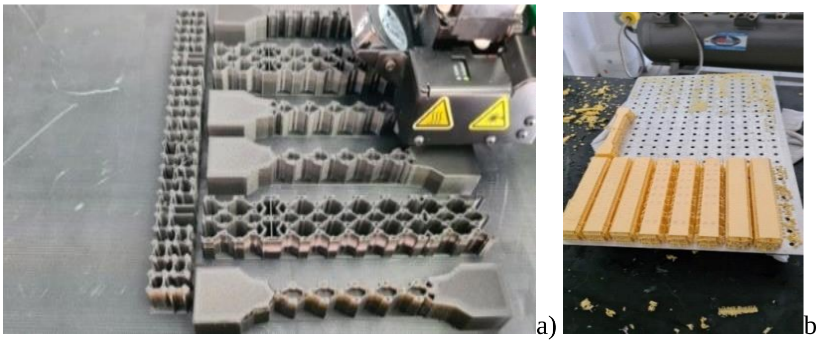

a) b)

Fig. 5. 3D printing of samples on a) Markforged; b) LC Magna Photocentric

Table 2. Test specimens code and materials

Cod	Test	Material	Name
L	Tensile	Onyx	Tear Drop
LI	Three-point bending	Onyx	Tear Drop
LRI	Three-point bending	Daylight High Tensile	Tear Drop
O	Tensile	Onyx	Horizontal bones
OI	Three-point bending	Onyx	Vertical bones
RFI	Three-point bending	Daylight High Tensile	Snowflake
RL	Tensile	Daylight High Tensile	Tear Drop
RO	Tensile	Daylight High Tensile	Horizontal bones
ROI	Three-point bending	Daylight High Tensile	Horizontal bones
VRO	Tensile	Daylight High Tensile	Vertical bones
VROI	Three-point bending	Daylight High Tensile	Vertical bones
RDO	DMA	Daylight High Tensile	Horizontal bones
VRDO	DMA	Daylight High Tensile	Vertical bones
DL	DMA	Onyx	Tear Drop
DO	DMA	Onyx	Horizontal bones
RDL	DMA	Daylight High Tensile	Tear Drop

Thus, emphasis is placed on the optimal placement of additively manufactured test specimens on the printing bed of the Markforged X7 printer, which was decided on prior expertise on this 3D printer, taking into account also, the guide developed by the Markforged developers.

In Table 3, data on the materials used in this study are available from the manufacturer datasheets.

Table 3. Material properties

Properties	Daylight High Tensile	Onyx
Density [g/cm^3]	1.16	1.2
Viscosity [cPs]	980	-
Flexural strength [Mpa]	95	81
Tensile modulus [Mpa]	3060	1400
Flexural modulus [Mpa]	2200	2900
Ultimate tensile strength [Mpa]	81	36
Impact strength notched izod [J/m]	22.7	330

3. RESULTS AND DISCUSSION

Three-point bending test results are plotted as mean values of each tested core cellular configuration in figure 6. Results show a significant difference between each core concept. Here, the tear drop concept has recorded the best results of all the concepts tested. What is interesting to see is that all of the concepts, 3D printed with liquid photopolymer resin show a significantly higher flexural strength in static 3-point bending compared to Onyx core cellular developed configurations. The tear drop sandwich core concept exhibits more than twice the flexural strength of the second best VROI concept (Vertical bones concept) both developed using Daylight High Tensile photopolymer, as can be seen in figure 7. On the other hand, the L concept (Tear Drop) developed using Onyx material exhibits the highest ductility.

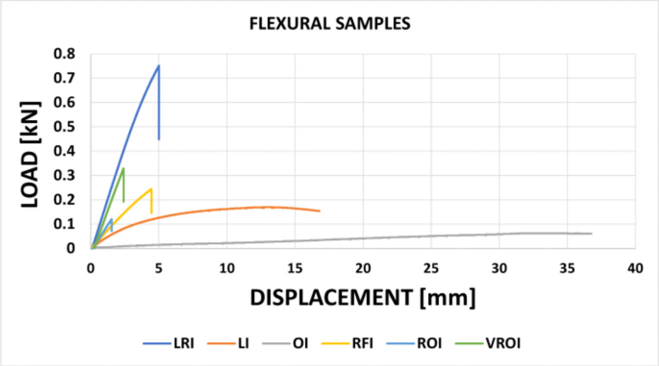


Fig. 6. Load displacement curves from three-point bending tests

Tensile tests results reported in figure 8 indicate that, again, the tear drop concepts exhibit the best results. From the tensile test samples, a similar behavior is observed for all concepts in the early stages of the test. These can be seen in figure 8 being represented by thresholds that show the gradual propagation of defects occurring in cellular structures until the moment of critical failure of the test specimens. The difference is that this time, it is the concept 3D printed with Onyx that surpasses the liquid resin 3D printed tear drop.

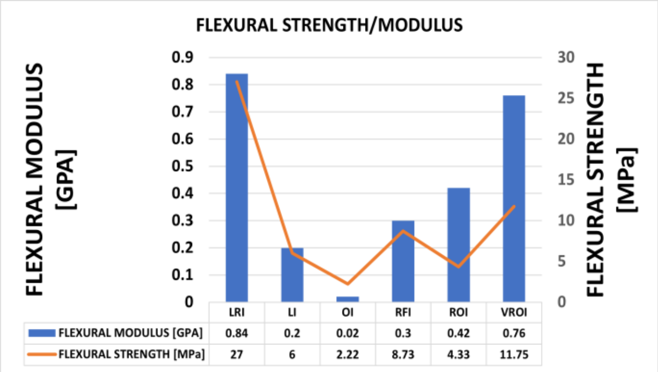


Fig. 7. Flexural strength/ modulus of the specimens

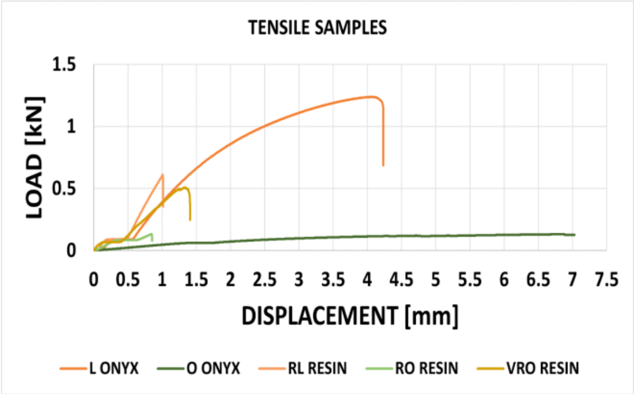


Fig. 8. Load displacement curves from tensile tests

For the rest of the concepts, the liquid resin 3D printed samples still behave better than the Onyx ones. The high performance of the tear drops specimen's 3D printed with Onyx is due to the elasticity of the core, allowing for more deformation than the liquid resin 3D printed tear drop core specimens. This is clearly seen in figure 9, given the fact that the liquid resin 3D printed tear drop has a higher tensile modulus which makes it stiffer than the Onyx 3D printed one.

To get a more efficient comparison of the mechanical characteristics of the sandwich core structures, a strength to mass ratio analysis is plotted in figure 10. It was determined for both tensile and flexural specimens. This analysis can give more insight on how each core behaved:

- For the flexural tests, two of the best cores are the ones 3D printed with liquid photopolymer resin;

- In tensile tests, the Onyx exhibited the best results due to its high elasticity;
- Overall, the best concept is the tear drop core sandwich cellular structure.

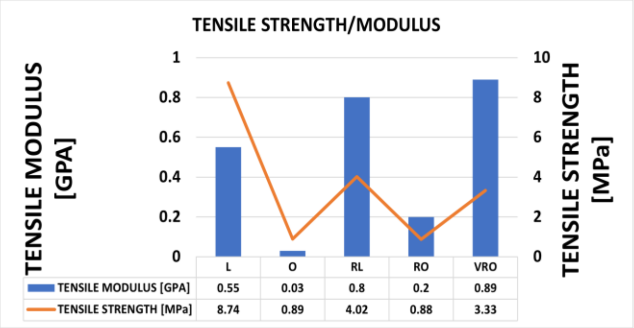


Fig. 9. Tensile strength/ modulus of each developed cellular concept

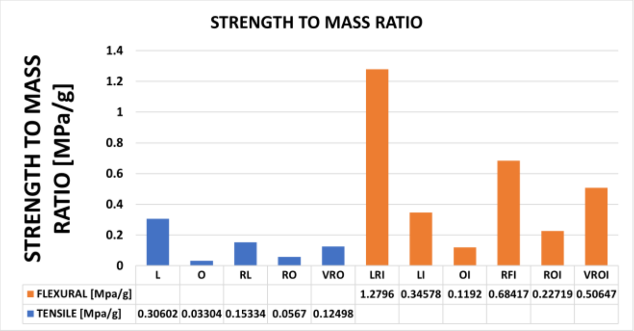
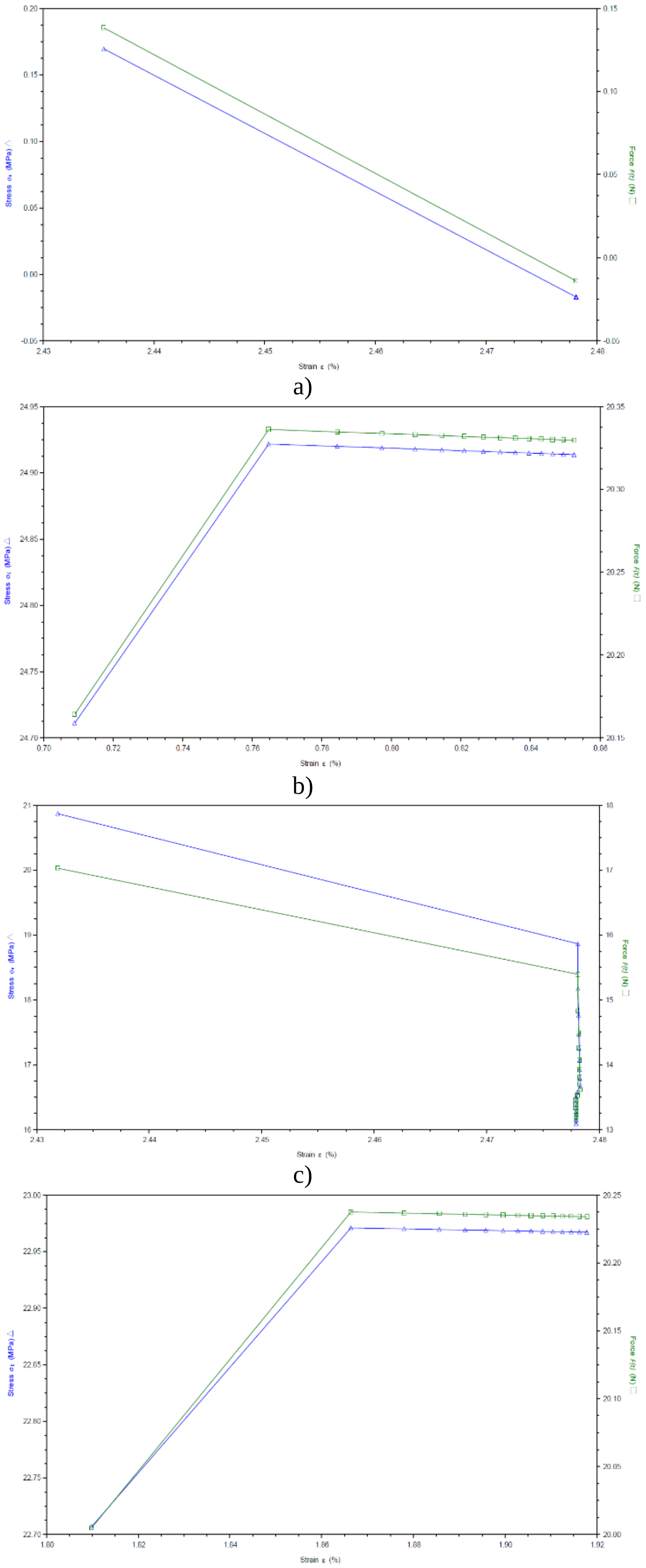


Fig. 10. Strength to mass ratio of each developed cellular concept

A dynamic mechanical analysis of cellular structures was performed, with samples containing isolated parts of previously tested structures to observe their singular behavior, rather than in the network. The module used in the test was the three-point bending module and a maximum deformation of 5 mm was chosen as input data, a value chosen on the basis of the previously performed mechanical tests. The results are highlighted in figure 11. The behavior of concepts RDO, VRDO, DO and RDL is similar to what we have seen in the initial mechanical tests. DMA sample, RDO, has the same failure characteristics as the sample ROI. The Onyx 3D printed tear drop sample, LI, shows a similar behavior with its homologue DL tested on DMA. One can clearly see that the maximum force at which failure begins to install in the single cell is about 0.18 kN for both, while the elasticity of the material is present in both plotted graphs, allowing for a substantial deformation before critical failure occurs. For the DMA tested sample DO, when compared to its homologue OI, the behaviors do not match. The reason is the poor network connection of the cellular structure which is the result of 3D printing limitations and CAD complexity.

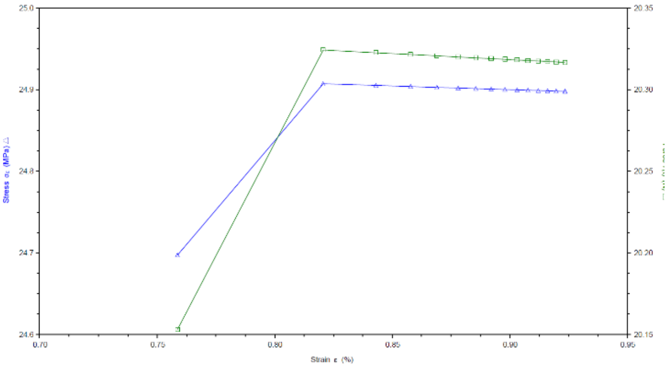


a)

b)

c)

d)



e)

Fig. 11. DMA a) RDO-Horizontal Bones Resin; b) VRDO-Vertical Bones Resin; c) DL-Tear Drop Onyx; d) DO-Horizontal bones Onyx; e) RDL-Tear Drop Resin

4. CONCLUSIONS

The main purpose of the research was to make first steps in the characterization of new sandwich core structures, based on biomimetics and show the potential of 3D printing them for specific applications. The ability of the Markforged X7 industrial series 3D printer, of manufacturing such cores out of carbon, glass or Kevlar fiber, will improve the mechanical behavior of the next, optimized core cellular structures. The aim is to integrate such structures with carbon fiber reinforced polymer face plates and reduce the need of post processing the sandwich structures, while significantly reducing the mass of the final component.

The study is indeed at an early stage, and many more aspects need to be addressed in order to better understand and optimize the development of 3D printed sandwich cores. It could be clearly seen from the flexural and tensile tests that the cellular structures show a nonhomogeneous behavior from one 3D printing material to another. This means that future developments of such cores have to take into account a specific matrix of constraints that will help identify the right sandwich core for each application intended to be implemented.

In the case of three-point bending specimens, 2 distinct behaviors were observed, namely a linear behavior until failure, at which point it occurs suddenly with the reaching of the maximum force and another type of behavior, ductile that does not show a breaking point of the test specimens and continues to deform with a decrease in the applied force. These two behaviors are given strictly by the material used due to the elastic ability of the onyx to deform without breaking, thus in the case of additive manufactured liquid resin specimens, the LR concept showing the best flexural resistance while in the case of test specimens manufactured additively from Onyx LI has the best resistance to bending. It can be concluded that the concept integrating the tear drop geometries has higher resistance compared to the other concepts, both flexural and tensile.

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