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Evaluation of cellular structures for structural impact absorption: Numerical analysis.

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Abstract: Cellular structures are easily found in natural materials with high mechanical performance, i.e., low weight and high mechanical strength. In recent years, additive manufacturing technologies have evolved, allowing the manufacturing of complex geometry components with high impact energy absorbing capacity such as cellular structures. For this reason, nowadays it is possible to find companies exploring these structures for collision protection elements as, for example, in sport personal protective equipment. This work presents computational tools for the design of products based on cellular structures and some considerations for their numerical simulation when subjected to impact loadings. In addition, this work also comprises a short overview on types of cellular structures that present reasonable-to-good resistance to impact loading, of which some are numerically evaluated using the finite element method.

Keywords: Cellular structures, structural impact.

INTRODUCTION

Materials with cellular structure are easily found in nature, such as wood, cork, plant tissue, bone tissue, etc. This is because biomaterials are mechanically more efficient, i.e., they have greater mechanical strength together with minimal body mass. The internal structure of wood is a good example, it has an exceptional high performance to resist bending and crushing loads.

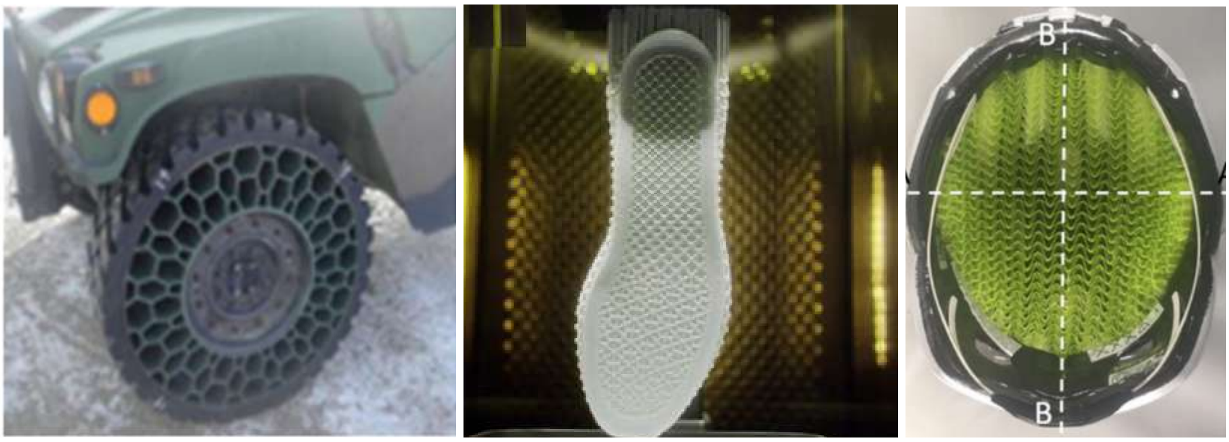
In recent years, cellular structures in biomaterials are being used as inspiration for development of new materials with similar structures, especially due to their mechanical properties and lower weight. This makes these materials attractive for specific applications as for example shock energy absorption, thermal insulation, high resistance to repetitive loads, stability, among others, involving lower cost in certain cases.

These cellular structures are already commonly used (macro scale) in lattice structures in civil constructions, it is seen in structures made of bars and beams [1] and even bridges explore lattice structures because of the good mechanical strength and low mass. However, the application of these structures in a smaller scale was unachievable since traditional manufacturing methods are not able to manufacture parts with such complexities or fabricate them with many defects as porosity, cracks, material pullout and accumulation, misalignment and even microstructural changes that ended up decreasing the resistance of these materials [2].

With technological improvements in the manufacturing area, new alternatives have emerged to solve these obstacles, such as additive manufacturing technologies that allow the fabrication of structures with high geometric complexity, such as cellular structures, allowing to explore the potential of these structures in several applications.

Therefore, nowadays is already being explored the introduction of cellular structures in mechanical components and products that involve a high absorption of impact energy, mechanical damping and even comfort together with a considerable reduction in mass [4], as for example in soles of custom-made shoe [5], protective sports helmets [6] and even on military car tires that doesn't s use an inner tube [5,7] as shown in Fig. 1.

In helmets, for example, they are used as an internal material for impact damping, leading to a greater chance reduction of skull fractures and brain injury in accidents, when compared to a standard helmet. In addition, it was possible to verify in impact tests [6] that conventional helmets do not have good results in oblique impacts, opposite the helmet that had cellular structures and was able to more satisfactorily absorb the impact.



(a) **(b)** **(c)**

Figure 1 – Examples of cellular structures: (a) in a car tire, (b) in the sole of shoes and (c) in a helmet.

CELLULAR STRUCTURES FOR IMPACT APPLICATIONS

Cellular structures for mechanical applications

There are several types of cell structures that can be explored in mechanical design to obtain a better structural response. For example, cell structures based on mathematical formulations can be introduced in various applications by adjusting their mechanical properties through various parameters such as density, geometry and material, etc., to obtain more efficient structures depending on the application.

Although cellular structures have great structural efficiency when compared to solid structures, it is not that simple to recognize which cellular structure has better performance than others for a specific application. It is necessary to identify the loading conditions to verify which structures are prone to obtain good results in the impact loading tests.

The types of loads in cellular structures according to [3] can be classified into: gravity loading, compression, torsion, tension, bending, shear and even a combination of some of these loads. Besides, other important factor [3] is the loading direction (which can be classified as uniaxial, biaxial or multiaxial) and the application period, that is, how it is applied along time (slow increase, impact, constant over a long period of time or cyclical). Having defined the characteristics of the load to be applied to the mechanical structure (type, direction and period of application), it is possible to choose which structure will present the best performance.

Analyzing some of the cellular structures found in nature, it can be observed that some of them have a better performance for mechanical stresses with specific load characteristics. In addition, these cellular structures end up having other non-structural advantages such as storage space, thermal and acoustic regulation. Table 1 shows some natural cellular structures and their respective loads.

Table 1 – Natural cellular structures and the loads they support [3].

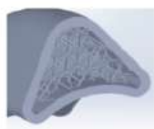
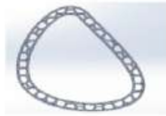
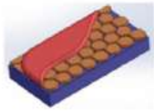
Loading Conditions			Natural Model	Cellular Material Design			
Type	Direction	Duration		Tessellation	Elements	Connectivity	Schematic Diagram
Gravity (Self-Weight)	Uniaxial	Creep	Honeybee nest 	Periodic—Unary—Edge-to-Edge—Regular	Surface	Hexagonal prism, surfaces connect edges	
Compression	Hydrostatic	Dynamic, Fatigue	Venus flower basket [75] 	Hierarchical-Overlaid	Beam	Corner vertices and across faces	
Bending	Variable	Dynamic	Toucan beak [78] 	Stochastic	Closed cell foam and lattice struts	Stochastically distributed faces and vertices	

Table 1 – Natural cellular structures and the loads they support [3] (continued).

Bending	Distributed (surface pressure load)	Static (Stable)	Amazon waterlily leaf [66] 	Branching	Beam	Along edges defined by branching pattern	
Compression	Pressure, Variable	Impact	Pummelo [79] 	Stochastic	Surface	Stochastically distributed faces	
Shear	Hydrostatic	Static (Stable)	Ray [67] 	Periodic—Unary, Edge-to-Edge—Regular Hierarchical—Overlaid	Surface (tiles)	Faces	
Compression	Uniaxial—Variable	Impact	Abalone shell [80,81] 	Periodic—Unary, Edge-to-Edge—Regular Hierarchical—Overlaid	Surface (tiles)	Faces	
Compression	Uniaxial—Variable	Impact	Mantis shrimp [82] 	Periodic—Unary—Overlapping	Beam (fibers)	Fibers stacked along a helical twist	

Generation of cellular structures

Disregarding the software that allows the development of more complex cellular structures, some structures as lattices can be generated manually or using mathematical formulations [8]. To create cell structures manually the most common methods are the use of beams and truss structures, it commonly results in structures with simpler geometry as shown in Fig. 2. By this method, the structures can be easily parameterized, so it is easier to implement than others.

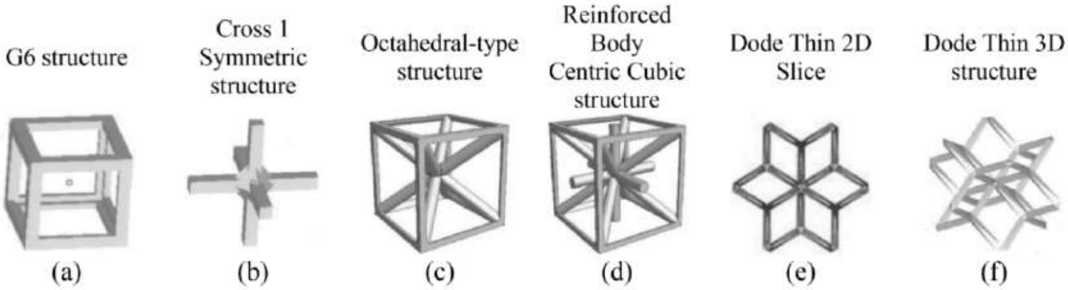


Figure 2 – Example of structures made manually [8].

With mathematical formulations, it is possible to create cell structures with different patterns by using different algorithms. Unlike manual structures, these structures can explore more complex geometries which are a subset of hyperbolic surfaces. Some examples of mathematical formulations are: nodal approximation, variation level set approaches, and Weierstrass formulas [8]. Figure 3 shows some examples.

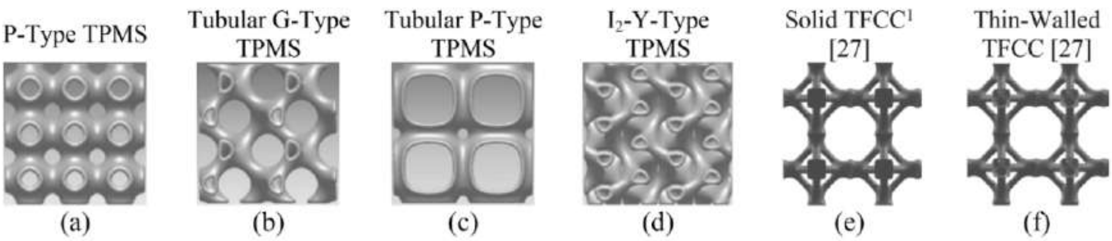


Figure 3 – Example of structures made by mathematical formulations [8].

Triply periodic minimal surfaces (TPMS) are a non-intersecting 3D surface characterized by a zero value of mean curvature at each point. TPMS are used to design regular structures with crystalline symmetry [9]. TPMS structures are defined by:

$$ki = 2\pi * \frac{ni}{Li} \qquad \text{(with i = x,y,z)} \qquad (1)$$

Where k_i are the TPMS function periodicities, n_i are the numbers of cell repetitions in directions x, y and z and L_i are the absolute sizes of the structure in those directions. [10]

And TFCC is a topology-optimized face center cube [11]. Where the face center cube consists of a sort of rearrangement of the atom.

Furthermore, to be able to compare the structures performance, it is necessary that they have approximately the same mass and that they were made of the same material. In that way, relative density is a good parameter to select the best structures even when there are different types of lattices. Relative density is expressed as:

$$\frac{\rho^*}{\rho s} \qquad (2)$$

Where $\rho *$ is the density of the cellular structure and ρs is the density of the material that structures are made. The relative density is calculated depending on the geometry of the structure. On the examples below, it has beam-based structures that assume function of the ratio of the thickness of the member over its length (t/l) [3]:

$$\text{Honeycomb: } \frac{\rho^*}{\rho s} = c1 * \frac{t}{l} \qquad (3)$$

$$\text{Open cell foam: } \frac{\rho^*}{\rho s} = c2 * \left(\frac{t}{l}\right)^2 \qquad (4)$$

Where c1 and c2 are constants. In case of more complex structures, it can be computed directly from the CAD software or can be measured experimentally once manufactured. And, with relative density, it is possible to predict a mechanical response for certain properties, this relation is called by “Scaling Laws”. In that way, these properties are geometry dependent, but can be used in the absence of analytically derived relationships.

For example, the effective modulus can be expressed by:

$$E *= c * Es * \left(\frac{\rho^*}{\rho s}\right)^n \qquad (5)$$

Where E* is effective modulus of cellular structure and E_s is effective modulus of the solid material. In this way, if the same material and the same loadings are used and the tests have the same parameters, the effective modulus may be adequate to compare different cell structures and to determine which is more suitable.

Is it important to mention that scaling laws ignore the variation of parameters, i.e., even changing thickness of walls or changing cell sizes, different structures can have the same relative density. Figure 4 shows two different lattices with the same relative density [3].

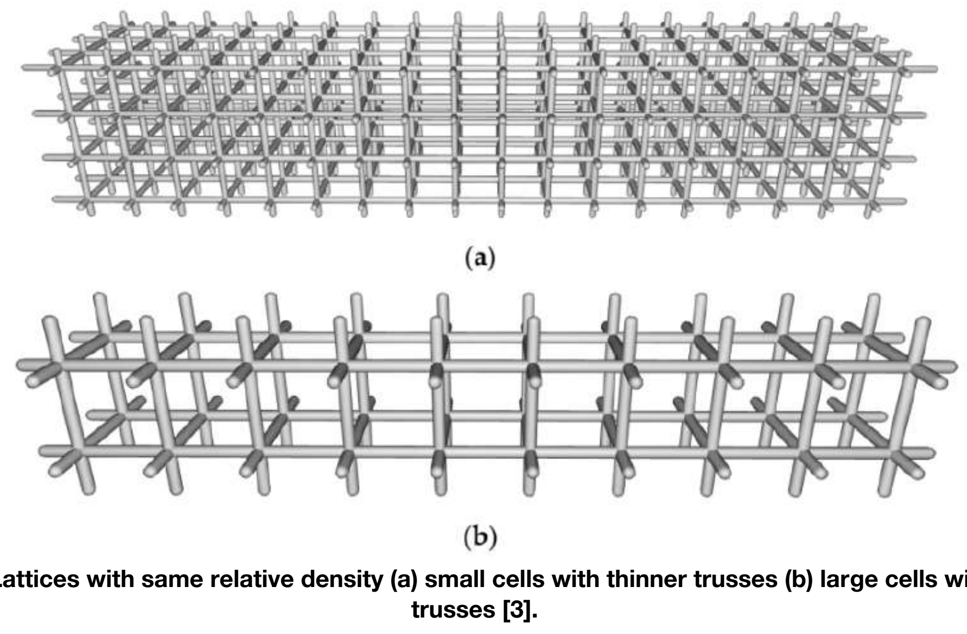


Figure 4 – Lattices with same relative density (a) small cells with thinner trusses (b) large cells with thicker trusses [3].

Empirical methods for evaluating performance of cellular structures

Regarding empirical methods, it is worth mentioning that there is no standardized method to measure the performance of cellular structures, either for all types of loads or for a specific one. Therefore, in order to have the desired performance, specific research is needed where specimens are subjected to certain loads to evaluate their performance.

So, it is possible to find scientific research in which various types of cell structures are empirically evaluated in order to find those with better performance according to the type of load. For example, several cellular structures are designed based on geometric patterns and, from tests (experimental or computational), it is possible to find the most promising structures in terms of impact energy absorption. Figure 5a below shows the computer simulation of the 3-point bending test of a solid beam, which was filled using different patterns of cellular structures to verify which of those present better bending performance. Fig. 5b shows one of these filling patterns that showed excellent results [3].

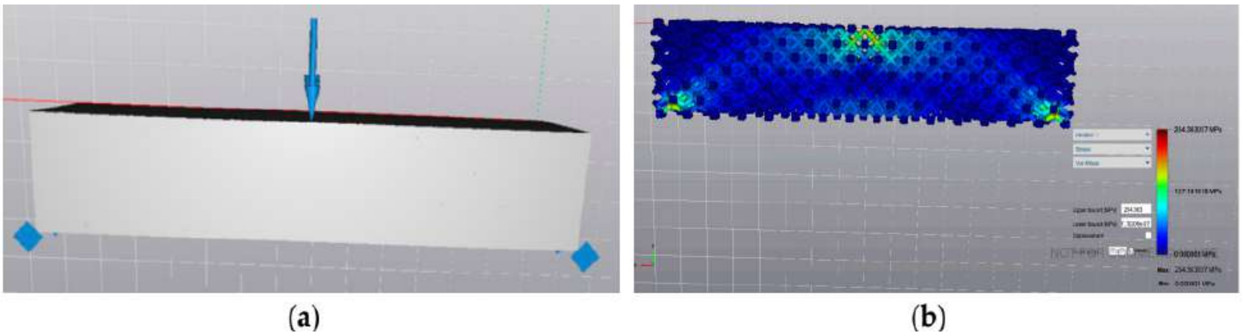


Figure 5 – Example of computational test: (a) object being tested (b) and one of the alternatives of cellular structures. [3]

With empirical methods, it is possible to determine cellular structures with best response to certain loadings, Fig. 6 shows results for 3-point bending tests of a beam and comparing in different relative densities. The displacement was used for an effective flexural rigidity (EI)*, with I = area moment of inertia. This quantity was normalized with respect to the flexural rigidity E_sI of a solid beam constructed with material Es [3].

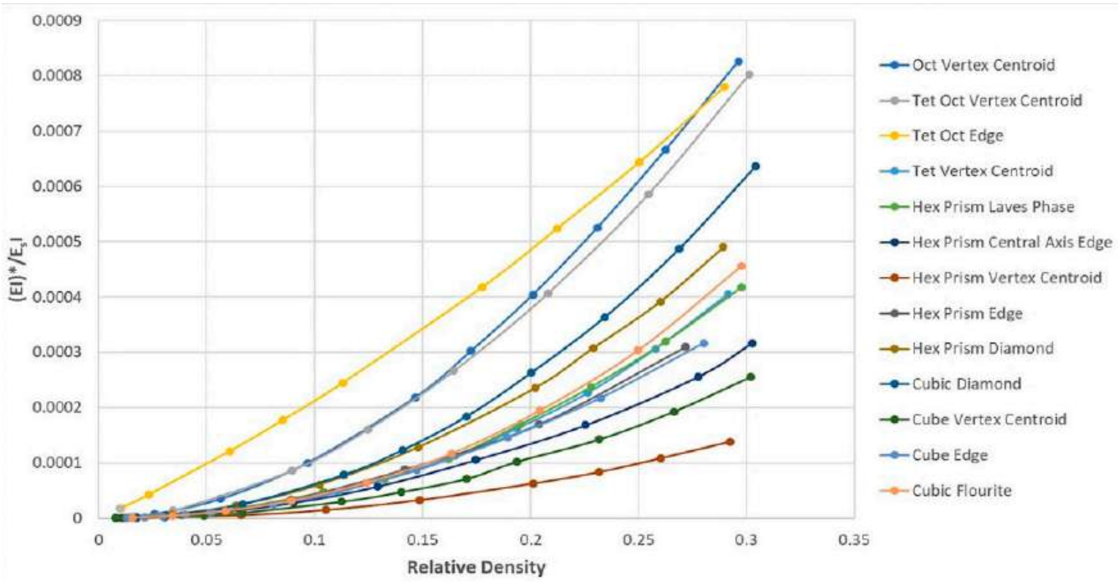


Figure 6 – Graph with different cellular structures across a range of relative densities [3].

COMPUTATIONAL TOOLS FOR DESIGNING CELLULAR STRUCTURES

Nowadays, it is possible to find in the international market commercial codes that allow the creation and implementation of a wide diversity of cellular structures into components and products. This is only possible with the development of manufacturing techniques, particularly the emergence of additive manufacturing technologies, that allow the manufacture of increasingly complex products. In Table 2 are presented some examples of Computer-Aided Design (CAD) software that allow the design of products with cellular structures.

Table 2 – Commercial software that allows the creation of cellular structures.

Software	Company	Website
nTopology	nTopology	ntopology.com
Materialise 3-matic	Materialise	materialise.com/en/software/3-matic
AUTODESK® WITHIN	Autodesk	withinlab.com
WITHIN MEDICAL	Autodesk	autodesk.com/products/within-medical
AUTODESK® NETFABB®	Autodesk	autodesk.com/products/netfabb
Altair Inspire™	Altair	altair.com/inspire

It is already possible to find products that use cellular structures made using these software on the market. Due to the many benefits (good shock absorption, high surface area, good strength-to-weight ratio), projects involving these structures are even more common to create products that can perform better mechanically.

Figure 7 shows a product designed with the aim of reducing mass and overcoming some of the restrictions of additive manufacturing when topology optimization is used, i.e., optimizing the structures with variable density [12].

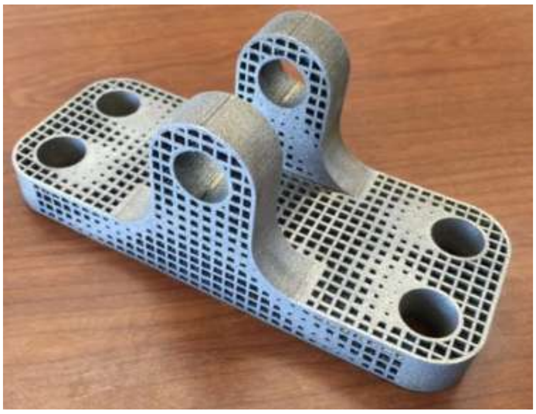


Figure 7 – Use of cell structures together with topology optimization [12].

Cellular structures are also used as a supporting structure to prevent failures caused by residual stress in laser powder bed metal additive manufacturing. Figure 8 shows the design of a part in CAD with the support made with cellular structures [13].

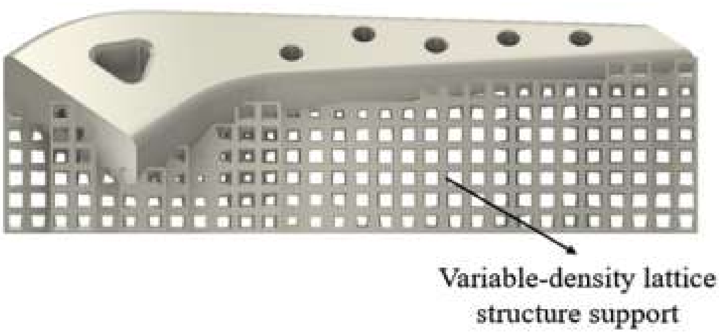


Figure 8 – Support made with cellular structures [13].

These structures can even be used to produce implants more similar to human bones in case of surgery to repair accidents as shown in Fig. 9 [14].

Figure 9 –Implants used in medical surgery [14].

STUDY CASE: CAE ANALYSIS OF CELLULAR STRUCTURE SUBJECTED TO IMPACT LOAD

In this work, the nTopology software was used for the elaboration and design of cellular structures. In this software, the modeling of cellular structures is done through block programming as shown in Fig. 10.

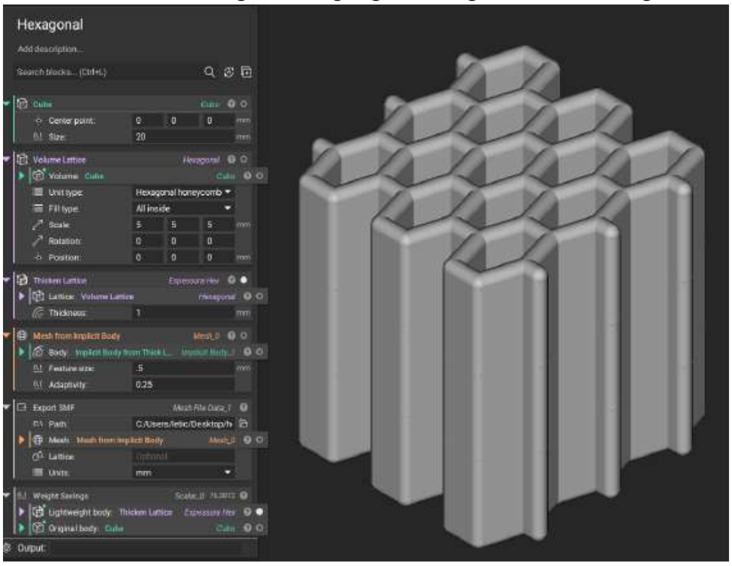
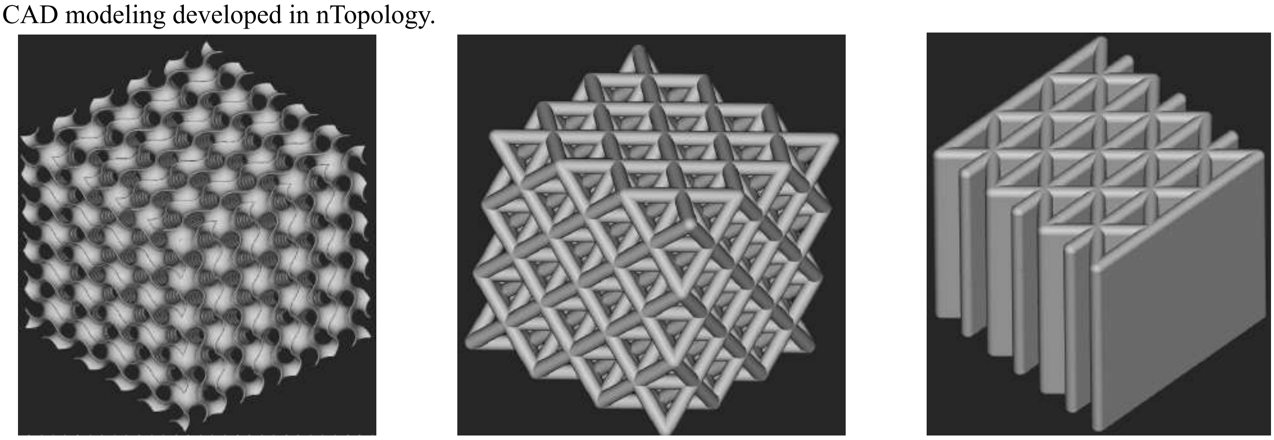


Figure 10 – Block programming used to create the cellular structure.

For the elaboration of the cellular structures, the “lattice” option was used, which allows the generation of different types of lattice structures. In Fig. 11, it is possible to see some of these structures built from a 20x20x20mm cube, all CAD modeling developed in nTopology.



(a) **(b)** **(c)**

Figure 11 – 3D modeling of cellular structures using nTopology software: (a) Walled TPMS Gyroid, (b) volume lattice octet and (c) volume lattice triangular honeycomb.

After CAD modeling, numerical simulation can be initiated in the model. nTopology software counts on with a CAE module to perform Finite Element Analysis (FEA) in the CAD model already created. Simulations were all performed in a honeycomb hexagonal cube specimen. Computer aided engineering (CAE) allows practicing mechanical tests on virtual prototypes, reducing the time for product development, having physical results even without carrying out experimental tests, foreseeing any consequence of geometry changes in the product performance.

Initially, nTopology software was used for CAE. CAE simulations were made considering just one cell of a hexagonal honeycomb structure to save time processing. After some tests, it was possible to verify the lack of more complex tools in the software. CAE simulations in nTopology code are limited to linear elastic materials and FE implicit analysis, so it was not possible to create, for instance, a rigid object or include contact mechanism.

In that way, CAE analysis was initiated in Abaqus, a FE software more specific for CAE simulations for scientific research so counting with more diversity of tools (explicit analysis, contact mechanism, rigid bodies, non-linear materials with strain rate sensitivity, etc.) that allows a more accurate FE analysis and more precise results. It is worth mentioning that to perform the numerical simulations, smaller specimens were used to reduce the processing time of the results.

Performing the first tests in Abaqus, some problems impede the completion of the test, problems related to the large quantity of elements and event time that leads to an extremely long processing time. To solve these problems, "mass scaling" strategy was implemented. With this strategy, it was possible to reduce the processing time by modifying artificially the density of the material, but care must be taken to not influence the mechanical event results. So, it was possible to accomplish the test, but it was still time consuming and the process was not complete as seen in Fig. 12.

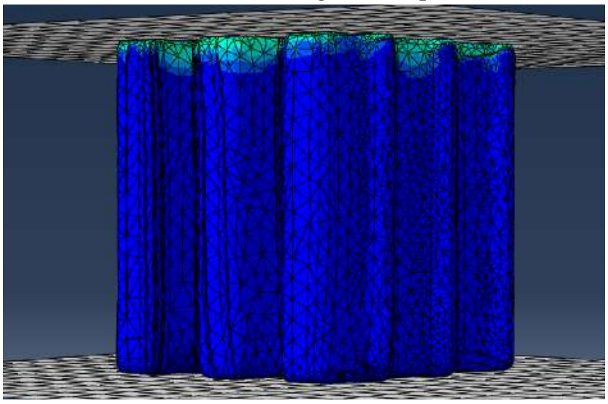
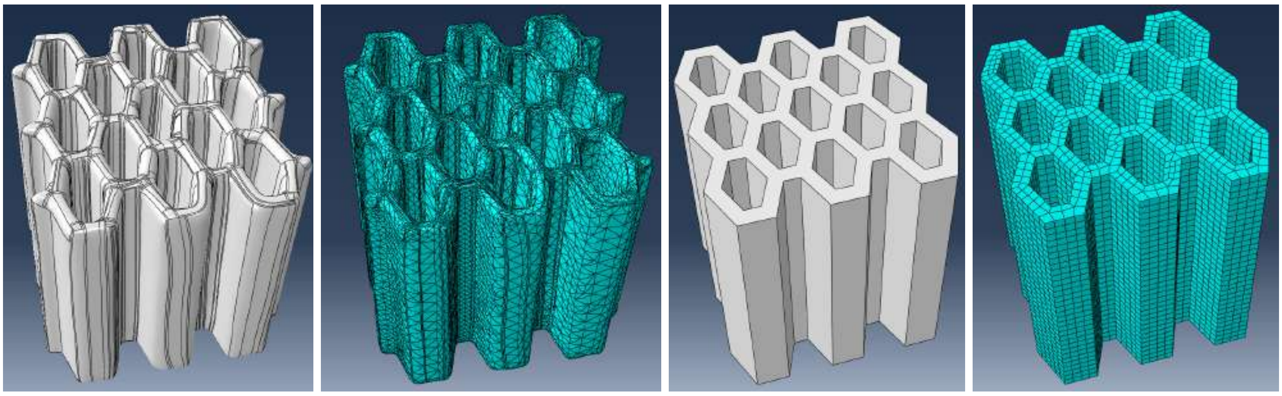


Figure 12 – Numerical simulation using mass scaling.

Even after this change, results were not satisfactory, so the CAD geometry was modeled in other software (Fusion 360 software) to smooth the corners of the CAD model, allowing it to create less complex meshes to reduce the software processing time. A large quantity of elements leads to longer processing times, at the same time, more complex elements (non-linear material) require more complex equations to solve the problem. Figure 13 shows the difference between nTopology and Fusion 360 cellular structures.



(a) (b) (c) (d)

Figure 13 – (a) Original Cellular structure made in nTopology (b) and respective mesh; (c) Cellular structure made on Fusion 360 software (d) and the mesh with less complex elements.

Using the cellular structure performed in the Fusion 360, it was possible to obtain satisfactory results even without the use of mass scaling. Below Fig. 14 shows the numerical impact test of the honeycomb hexagonal cell structure.

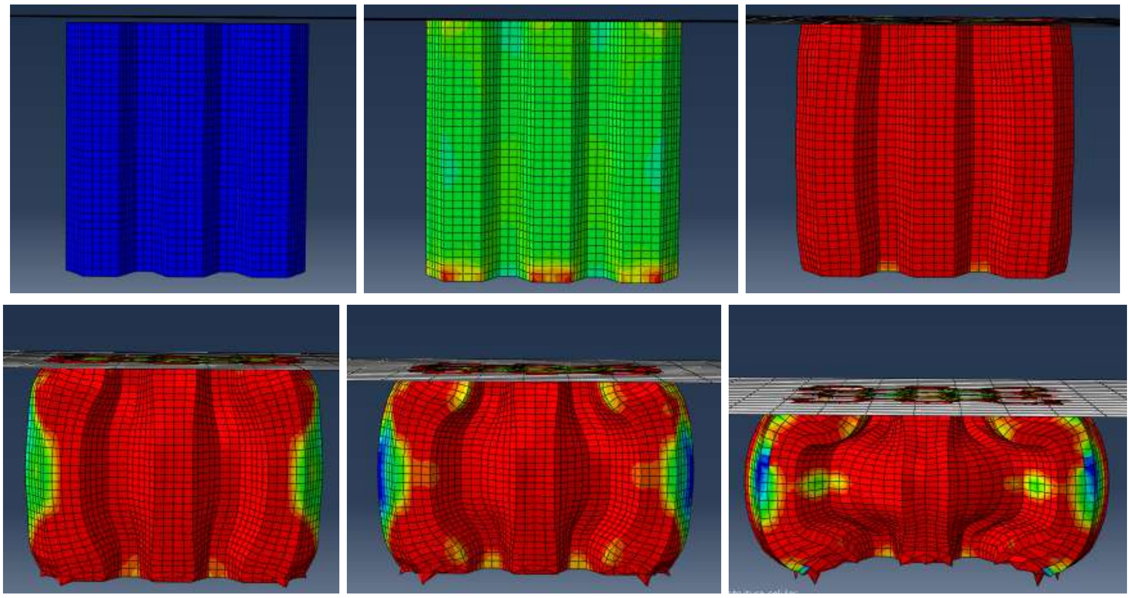


Figure 14 – Numerical simulation accomplished in Abaqus with hexagonal honeycomb.

From the numerical analysis, some response data can be obtained from the test. Figure 15 shows the velocity of the rigid body that compressed the cell structure (rigid body represents the rigid plates of the testing machine). Velocity is constant before contact with the rigid plate, but, after contact, the velocity decreases almost linearly since the weight of the object (mass = 30 kg) is much greater than the resistance offered by the cellular structure.

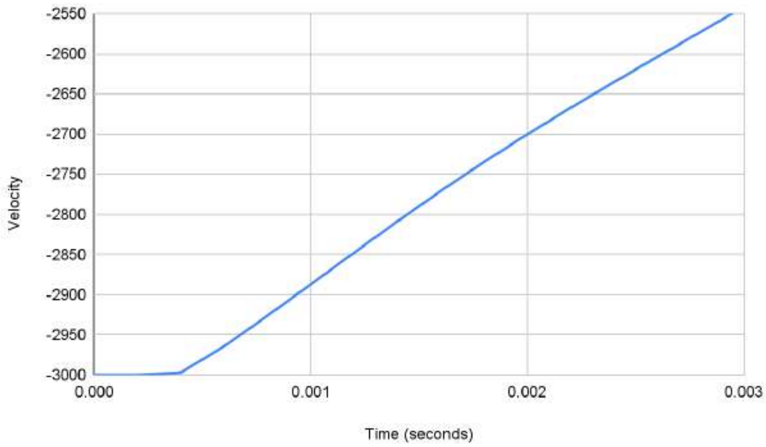


Figure 15 – Velocity x time graph of numerical analysis.

And Fig. 16 represents the force applied during the analysis. The test was performed with an elasto-plastic material. At the beginning of the impact, the applied force increases linearly for a period of time (elastic regime), after which the plastic regime of material is reached and the force falls slightly.

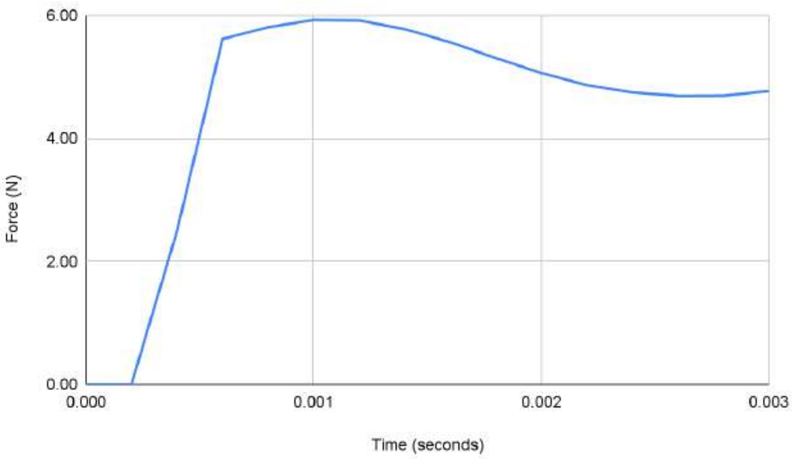


Figure 16 – Force x time graph of numerical analysis.

CONCLUSIONS

It is clear how important cellular structures are becoming for the present market, whether to create products with a good strength-to-weight ratio, for excellent shock absorption properties, or for diverse other advantages. The advancement of manufacturing techniques such as additive manufacturing technologies and the emergence of specific software to design cellular parts was essential for the increasing implementation of more complex geometries in common products such as cellular structures.

However, it is important to highlight the deficit that new software to design cellular structures still have in terms of CAE simulation tools, particularly when dealing with more specific and simulations of average complexity. In this sense, the use of traditional CAE software is needed to amend this deficit. In addition, it is necessary to reduce the size of the cellular specimens to carry out the numerical simulations, since larger structures demand very long processing times, impeding processing in home computers.

Finally, it is expected that with the advancement of present technologies, more advanced software and faster computers will emerge and they probably will allow dealing numerically with more complex parts requiring less processing time than currently is needed. Thus, more specific research in this direction can be explored.

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