27th ABCM International Congress of Mechanical Engineering
December 04-08, 2023, Florianópolis-SC, Brazil

COB-2023-1395
3D NUMERICAL SIMULATION OF CARBON FIBER COMPOSITES WITH ADDITIVE MANUFACTURING STRUCTURAL CORE FOR INDUSTRIAL APPLICATIONS

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Abstract. *This study aims to assess the feasibility of using 3D printed materials as structural cores in composite materials through numerical simulations. Composite materials and metal 3D printing have shown promise in various applications due to their strength, stiffness, and low weight. Nevertheless, complex and expensive manufacturing processes limit their use. 3D printing with polymers provides a cost-effective alternative for producing complex geometries with precision. It also allows for material selection to tailor properties.*

Numerical simulations using the finite element method investigated the mechanical properties of different configurations of 3D printed materials as structural cores in composites with carbon fiber and resin reinforcement. The results show promising data, but it is necessary to evaluate the conditions with caution when interpreting simulation results compared to real-world conditions. Further studies are needed to evaluate practical performance in specific applications.

In conclusion, this study demonstrates the potential of using 3D printed materials as structural cores in various industries. The cost-effectiveness, precision, and versatility of 3D printing make it an attractive option for manufacturing tailored composite materials.

Keywords: *Composites, Additive manufacturing, Finite Elements, Carbon fiber, Industrial applications, numerical simulations*

1. INTRODUCTION

The history of composite materials dates back centuries, with evidence of their use by ancient Egyptians in the manufacturing of bricks made from a combination of straw and clay. Natural composites, such as bone and wood, which combine cellulose and lignin, existed even before that period. In the mid-20th century, a new category of materials known as composites emerged, developed through the field of multifunctional materials engineering. These materials utilize polymers reinforced with glass fibers, driven by the demands of the aerospace, automotive, and biomedical industries for lighter and stronger materials (Callister, 2019; Ashby et al., 2019).

In addition to topology optimization, additive manufacturing (AM) plays a crucial role in the pursuit of lighter forms. AM, also known as 3D printing, enables the fabrication of complex geometries with greater ease and efficiency compared to conventional methods. One of the most widely used methods is Fused Deposition Modeling (FDM), which involves the extrusion of heated polymeric filaments to create three-dimensional objects (Godec et al. (2022).

The primary objective of this study is to investigate the performance of complex structures with a core manufactured through AM and coated with carbon fiber using numerical simulations. Different core densities and compositions will be evaluated to analyze how these variations affect the geometry's performance under operating conditions. This research aims to contribute to the development of lighter and stronger composite materials with potential applications in various engineering fields and industrial sectors.

2. STRUCTURE MODELING

To study the effect of carbon fiber-reinforced structural core geometries manufactured through AM, sandwich panels with dimensions of 150mm x 50mm x 20mm were chosen. Carbon/epoxy laminations with a total thickness of 2mm will be used as reinforcement, as shown in Figure 1.

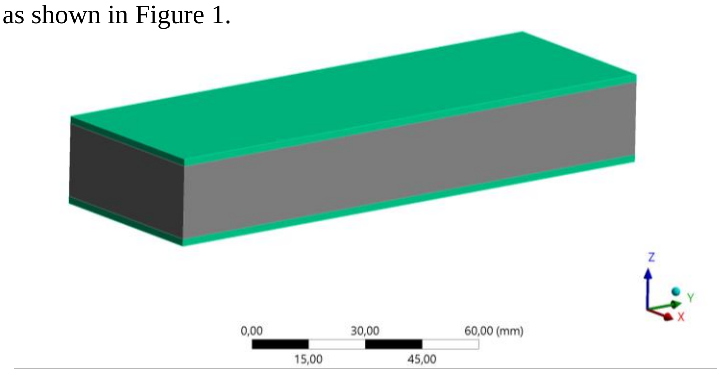
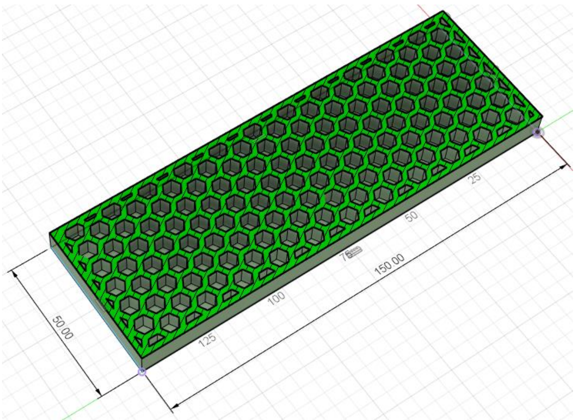
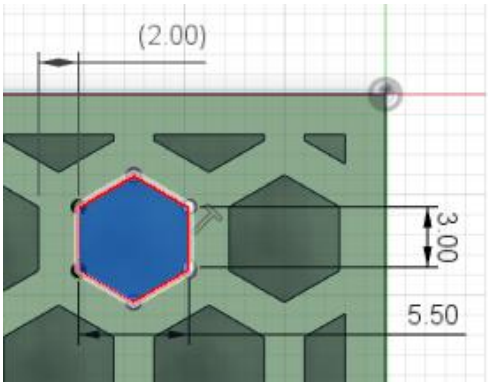


Figure 1. Geometry details

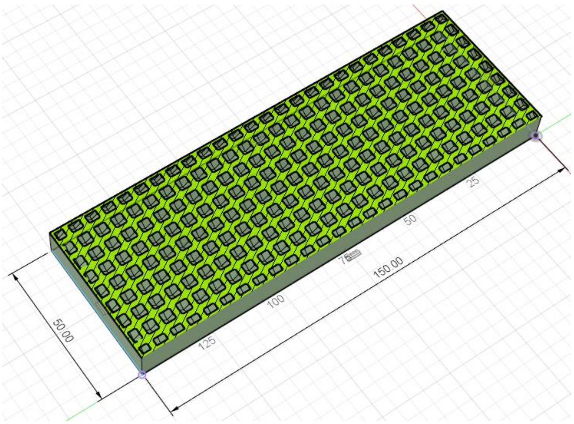
For the core composition, three distinct filling patterns were employed: Solid, honeycomb, and 3D hexagonal (Figure 2). Additionally, variations in the core fill percentage of 12.5%, 25%, 50%, and 100% were investigated. The 3D filling pattern consists of a complex and alternating formulation, resembling the arrangement of two hexagonal profiles in the XY and ZY directions, resulting in a geometry akin to a crystal with hexagonal faces. The choice of higher fill percentages aims to explore a comprehensive range of material behavior and assess the advantages of increasing the core density. This investigation seeks to provide insights into the structural performance and optimization of fiber-reinforced carbon composite geometries manufactured using additive manufacturing techniques.



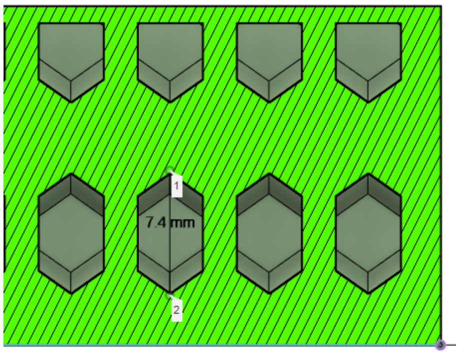
a) Honeycomb infill



b) Honeycomb details



c) 3D Hexagon infill



d) 3D Hexagon details

Figure 2. Geometry infill shapes

2.1 Numerical modeling

For the calculations involving the panel structure, the ASTM C393 standard, which is specific for rectangular cross-section sandwich panels, was employed. Regarding the shear stress calculations of the core, the following equation was used:

$$\tau_c = P / (d + t_c) * b \tag{1}$$

$$\sigma_f = P L / 2t * (d + t_c) * b \tag{2}$$

Equations 1 and 2 relate the parameters P, d, L, and t_c, where P represents the maximum applied load, d is the panel thickness, L is the length between supports, and t is the thickness of the faces. The maximum deflection (△max), known from test data, is used in Eq. (3) to determine the structural stiffness. The following equations describe the variables D and U, which represent the flexural and shear stiffness of the sandwich panel, respectively, while G is the shear modulus of the core, as represented in Eq. (4) and (5).

$$\triangle max = (P L\hat{}3 / 48D) + (P L / 4U) \tag{3}$$

$$D = E1 * t1 * E2 * t2(d + c)2 \, b / 4(E1t1 + E2t2) \tag{4}$$

$$U = G(d + c)\,\hat{}2 \, b / 4t_c \tag{5}$$

When a sandwich panel with a structural core is subjected to bending, its deflection consists of two distinct parts. The first part is the deflection resulting from bending, which is influenced by the stiffness of the faces. The second part is the deflection caused by shear, which depends on the stiffness of the core used in the structure's fabrication (Bitzer, 1997).

The geometries and their respective variations were simulated under bending conditions using a three-point bending test, as depicted in ASTM C393 standard (Figure 3). For the loading condition, a monotonic load of 10kN was applied to the top plate surface. The lower cylinders are fixed, but they have contacts with the plate that allow sliding and free bending of the specimen, preventing face yielding and intracell buckling outside the area of interest (VITALE et al., 2016; DANIEL, 2002; PETRAS; SUTCLIFFE, 1999).

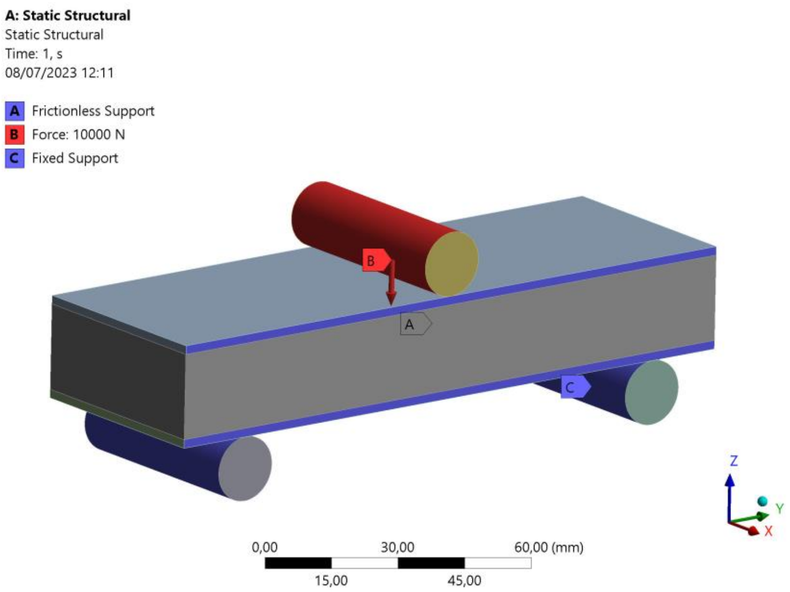


Figure 3. Boundary conditions

2.2 Materials

Tests were performed to obtain data regarding the mechanical properties of the polymer core material used. According to ASTM D638 standard, Type I specimens with a thickness of 3.2mm, a length of 50mm, and a width of 165mm were prepared as shown in Figure 4. The material properties were assumed to be orthotropic since different strengths exist in the plane of core printing (XY) and the plane of contact between the printing layers (Z).

For the selection of characteristics of the fibrous reinforcement that will coat the polymer-based printed core, composites made from unidirectional or bidirectional reinforced laminates were evaluated due to their superior structural efficiency (Callister, 2019). An important characteristic of the composite is its increased strength when the applied force is parallel to the fiber direction. Therefore, the directional arrangement of the fibers in the part is crucial to achieve the best possible properties for each specific loading condition.

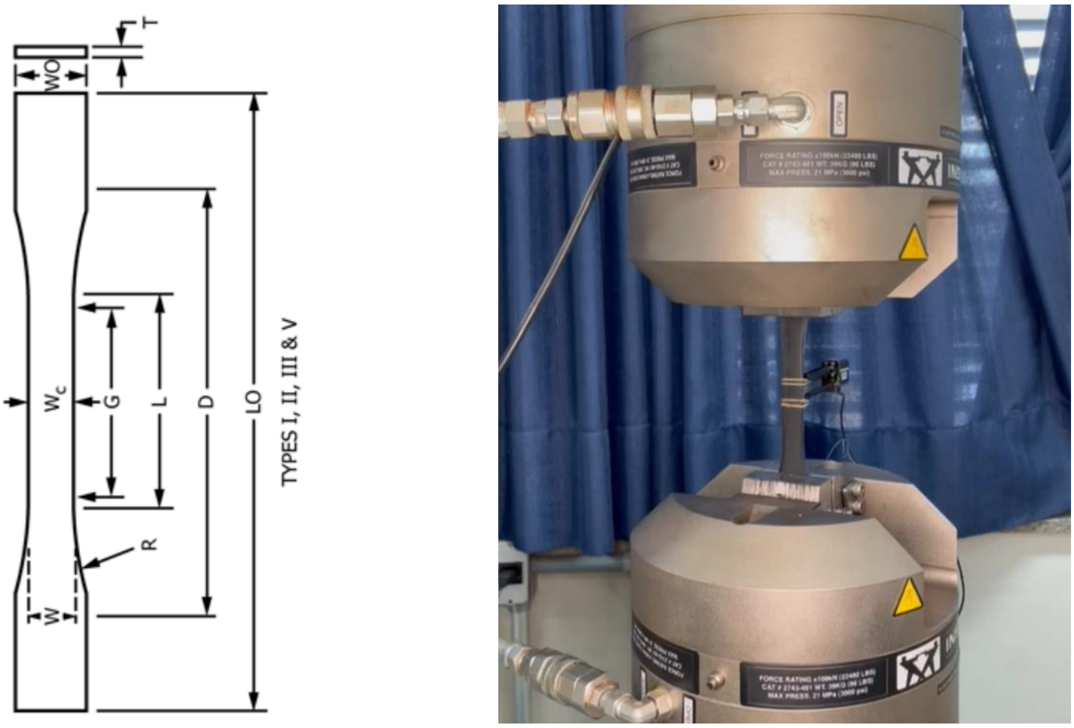


Figure 4. ASTM D638 test

Table 1 – Mechanical properties of materials

Composite Properties	ABS	Carbon Fiber
Young Modulus X direction [GPa]	1,57	59,16
Young Modulus Y direction [GPa]	1,57	59,16
Young Modulus Z direction [GPa]	3,54	7,5
Poisson’s Ratio XY	0,37	0,04
Poisson’s Ratio YZ	0,37	0,3
Poisson’s Ratio XZ	0,37	0,3
Shear Modulus XY [MPa]	572,52	3300
Shear Modulus YZ [MPa]	1290,34	2700
Shear Modulus XZ [MPa]	1290,34	2700
Density (g/cm^3)	1,53	1,451

3. RESULTS AND DISCUSSIONS

Through the simulation of panels with varying densities, it was observed that carbon fiber reinforcement has a strong influence on the total deflection of the panel, significantly increasing its stiffness and reducing the overall displacement. As shown in Figure 5, it can be observed that the panel's fill density strongly affects its displacement response. For panels manufactured using additive manufacturing (AM) without carbon reinforcement, the difference between a 50% fill density and 100% fill density is barely noticeable when evaluating the total displacement, where for Carbon+Full-infill it was possible to observe a displacement of 0,38872 mm, in comparison, the Carbon+3D_Hex had a displacement of 0,51029 and 0,60859 mm for Carbon+Honeycomb. For a better visualization of the infill effects on displacement, given that higher infill results in greater mass, a mass vs. displacement graph can be seen in Figure 6.

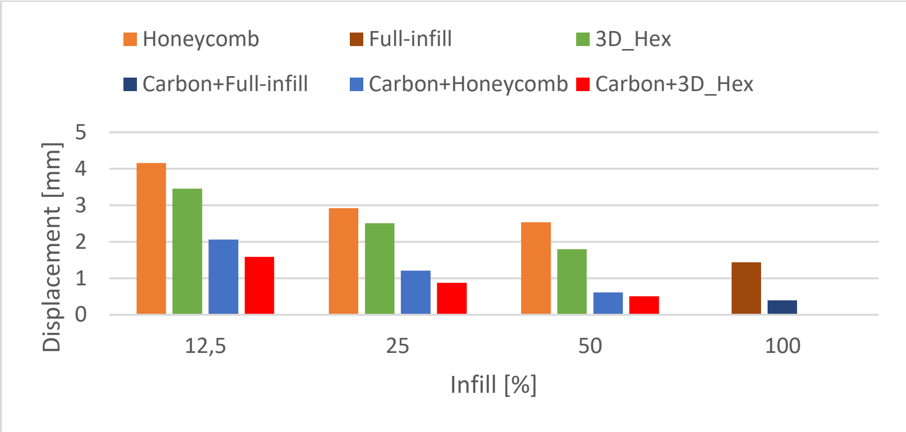


Figure 5. Displacement analysis using different types of infill's, materials, and shapes.

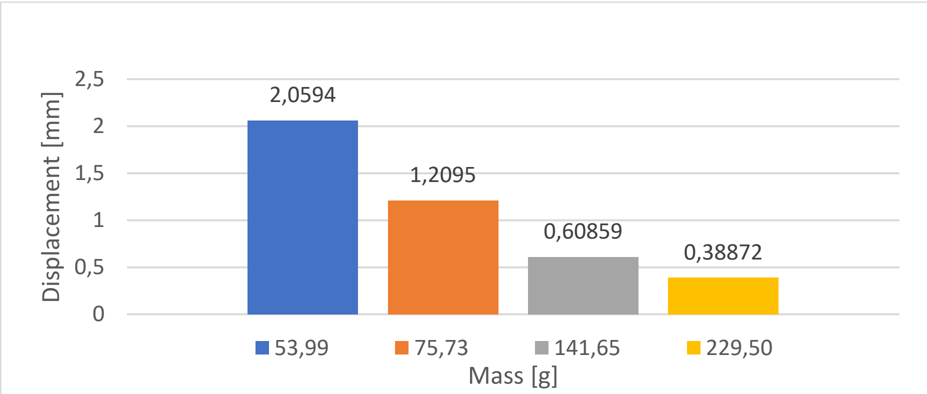


Figure 6. Influence of mass effect on displacement of Carbon-Honey infill.

From the stress-strain data observed in the geometries shown in Figure 7, it can be inferred that we have greater deformation when there is no fibrous reinforcement. The reduction in observed stresses is due to the densification of the printed core in the case where there is no carbon fiber in the panel. With the application of reinforcement in the geometry, it is possible to observe that although carbon fiber reduces deformations, there is an increase in the maximum observed stresses, indicating a non-uniform distribution of the stress field in the geometry due to poor distribution at the contact interface.

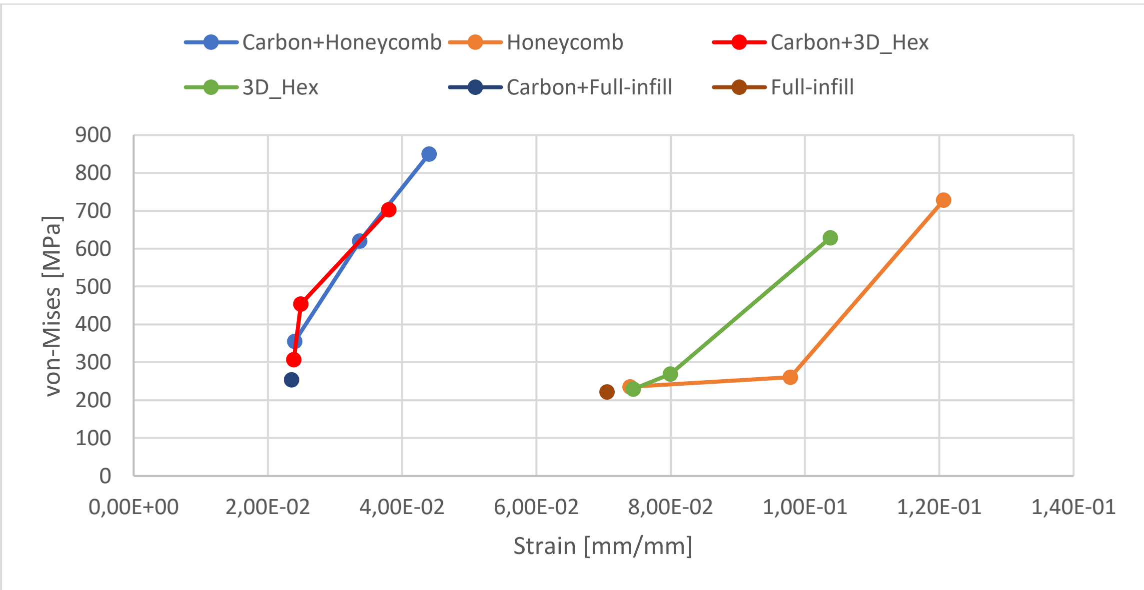


Figure 7. strain curve in different types of material configurations.

From the evaluation of the stress field observed in Figure 8, it can be inferred that as the densification of the core manufactured by AM occurs, there is a greater distribution and uniformity in the stress field. Another point of attention is the performance of the filling, where lower stresses can be observed in the proposed 3D filling compared to the traditional honeycomb. For all filling cases, an equivalent volume percentage was used to ensure that there are no significant differences in the total mass of the panels when comparing the two variable filling cases.

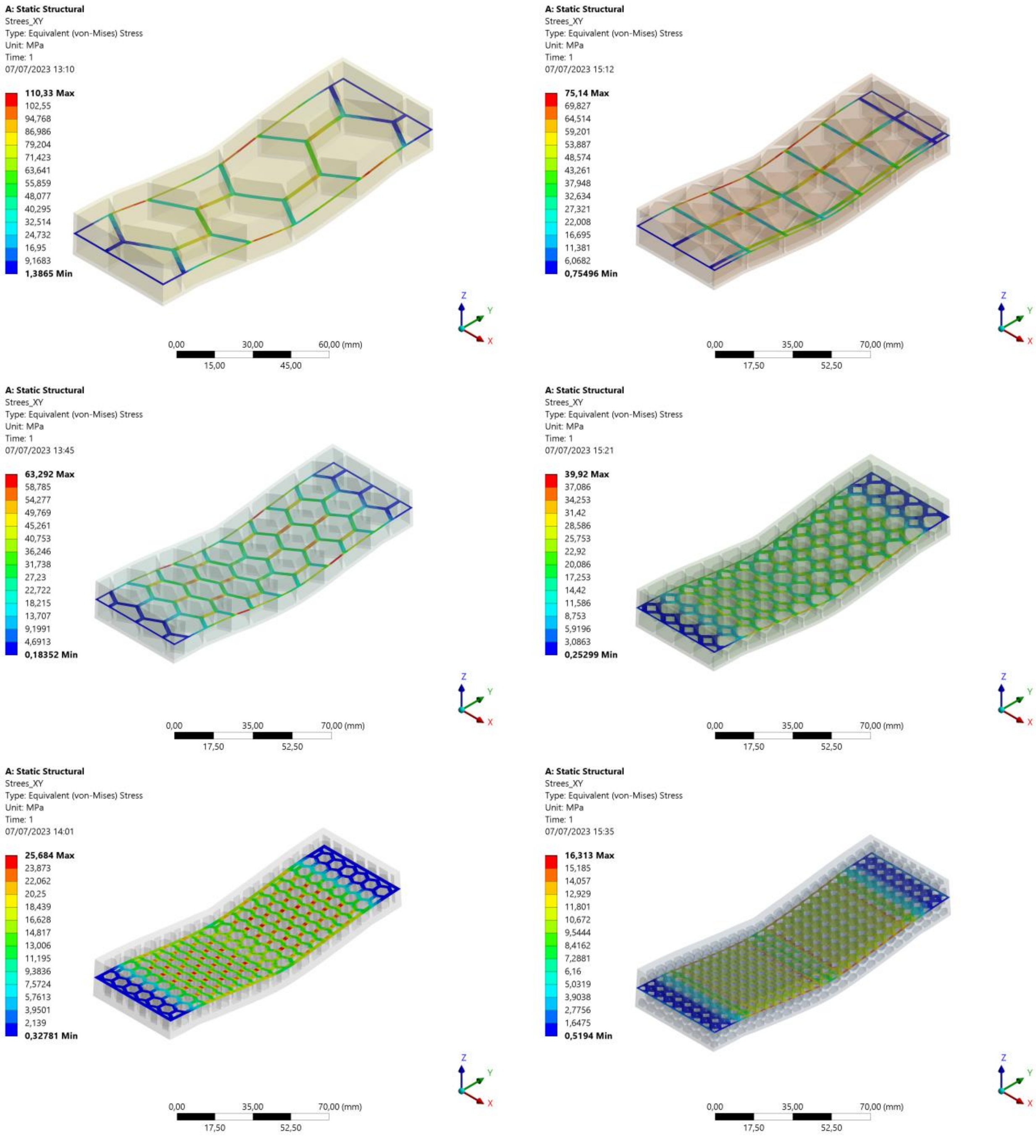


Figure 8. Equivalent von-Mises on XY plane of different shapes and infill's.

The 3D filling exhibits greater interconnectivity among its geometries, reducing the total deformation observed (Figure 9). Due to the improved distribution of stress field and core densification, fillings above 12.5% show greater uniformity due to better distribution and replication of their geometry.

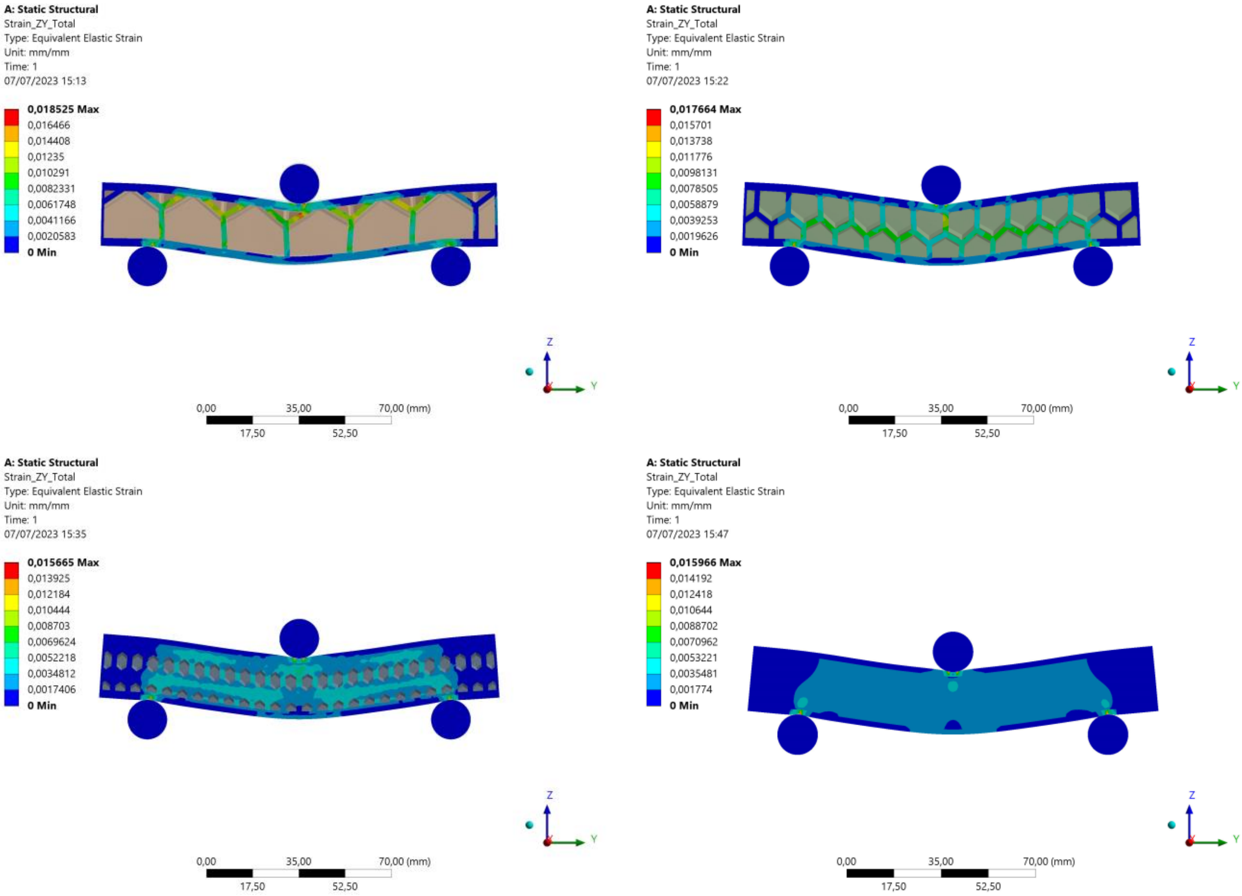


Figure 9. Equivalent total strain in different types of infill

Based on the data observed with different core geometries and density variations (Figure 10), an analysis of the total mass of the fillings was conducted to guide the selection of the filling percentage for each application. In this regard, considering the distribution of stress field and total deformation of the panels, when the total mass of the structure is a critical parameter in the design, fillings of 50% show mechanical results that are very close to those of 100%, providing a more balanced option when considering the trade-off between the total mass of the structure and its mechanical response.

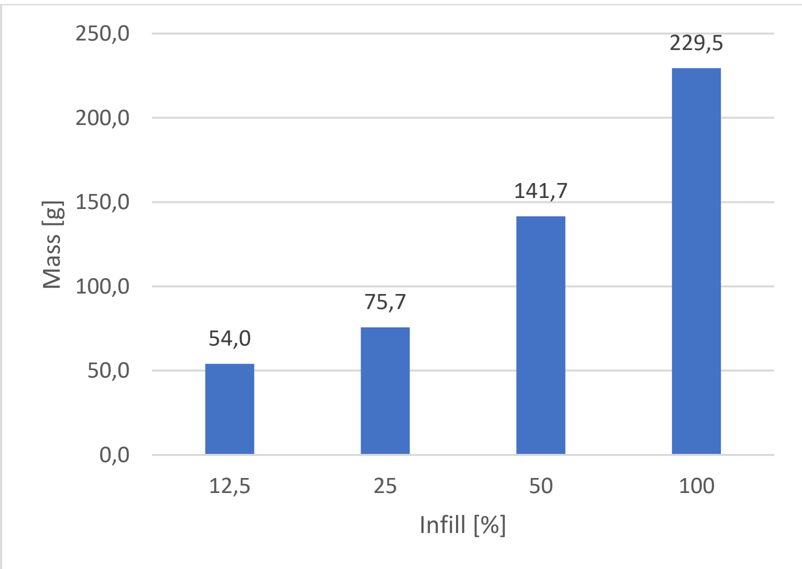


Figure 10. Analysis of mass based in infill density.

4. CONCLUSIONS

The main objective of this study was to investigate the performance of structures with a core manufactured through AM and coated with carbon fiber using numerical simulations. Through the evaluation of the results, it can be concluded that the densification of the core significantly enhances the mechanical response of the fabricated geometries. Different core densities and compositions were evaluated to analyze how these variations affect the geometry's performance under operating conditions. The application of a hexagonal 3D filling showed superior results compared to the 2D filling studied, expanding the possibilities for applications in more complex geometries due to its interconnectivity and more uniform distribution of stress field.

Despite the good performance achieved using carbon fiber reinforcement, it is still necessary to evaluate the results with caution, considering the interaction and adhesion between the fibrous material and the printed core, which may be prone to delamination or poor adhesion due to processing defects.

With these considerations, this research contributes to the development of lighter and stronger composite materials, with potential applications in more complex geometries, serving various areas of engineering and industrial sectors.

5. ACKNOWLEDGEMENTS

The authors would like to thank CAPES (Coordination for the Improvement of Higher Education Personnel) and FAPDF (Foundation for Research Support of the Federal District) for their financial support, as well as the Experimental and Computational Mechanics Group (GMEC) for their technical assistance in conducting this research.

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