Bioinspired structures for core sandwich composites produced by fused deposition modelling

J Bru¹, M Leite¹,², AR Ribeiro¹,³, L Reis¹,³, AM Deus³,⁴ and M Fátima Vaz¹,³

Abstract
Sandwich panels are widely used in many engineering applications where saving weight while maintaining high strength and stiffness is required. The most common core structure in sandwich panels is the two-dimensional regular hexagonal cell shape, denoted as Honeycomb. In recent times, bioinspired materials and structures have become increasingly attractive to researchers, as they provide adequate functional properties. The goal of the present work is to study two new bioinspired structures aimed at improving the performance of sandwich panel cores. Among all the large amount of structures that nature provides, two novel cores inspired in the structures of enamel and of bamboo were chosen. The compressive and flexural properties of these two innovative cellular structures were assessed and compared with the classic honeycomb. All the arrangements were numerically simulated for different relative densities. The fused deposition modelling technique enables to print selected samples in polylactic acid that were experimentally tested in compression and in bending. Results show that the mechanical properties depend strongly on the core geometry, on the relative density and on the cell thickness distribution. A satisfactory agreement was found between finite element results and experimental data. For the same relative density, the bioinspired natural structures proposed in the present study are potential competitors with the traditional core structures in what concerns strength, stiffness and energy absorption.

Keywords
Bioinspired structures, sandwich panels, mechanical testing, fused deposition modelling, finite element method

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Introduction
Geometrical configurations of natural materials have inspired authors to mimic the natural structures, giving rise to the concept of bioinspired materials.¹⁻⁴ As biological systems have been optimized by nature over millions of years of evolution, they are expected to provide good functional performance. Several works have explored the relationship between structure and properties in biological materials.¹⁻⁴

Bioinspired or biomimetic designs have been motivated by natural structures, such as nacreous shells,⁵ turtle shells,⁶ byssal threads,⁷ bamboo,⁸ beetles,⁹ woodpecker beaks,¹⁰ horns,¹¹ squids,¹² dentin–enamel junctions and enamel.⁸

Among natural materials, bamboo and enamel show interesting mechanical features. Bamboo presents a microstructure with a graded distribution of fibres in the longitudinal and radial directions, which confer excellent strength–weight and stiffness–weight ratios.⁸,¹² The volume fraction of fibres decreases across the cross-section of the bamboo culm, which may be regarded as a hollow tube.¹² The outside regions have higher fibre densities than the inside regions, meaning that the exterior zones have higher strength than the interior ones.¹²

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Enamel is the hardest and one of the most durable tissues of the body.\textsuperscript{13} In the structure of enamel, the hydroxyapatite crystallites are organized and bundled together by organic molecules into larger scale structures, designated as ‘keyhole-shaped’ enamel rods.\textsuperscript{13}

In recent years, focus has been placed in structural design, and a significant effort has been carried out to develop lightweight high-performance structures, with high specific stiffness and strength and superior energy absorption capacity.\textsuperscript{14} Composite sandwich panels are among the structures that fulfill these requirements and are extensively used in automobile, aerospace and train industries, as well as in maritime applications.\textsuperscript{1,15–17}

Sandwich panels are made of two thin skins bonded to a thick and light core. While the face sheets provide flexural stiffness and strength to the sandwich composite, the core plays an important role, as it contributes to the flexural stiffness, to the out-of-plane shear and compressive strength of the panel.\textsuperscript{14} The most common cores are made of two-dimensional or three-dimensional cellular materials, designated, respectively, by honeycombs and foams.\textsuperscript{1} Periodic hexagonal cellular structures are among the most used honeycomb cores.

Cellular structures and sandwich panels have been increasingly investigated.\textsuperscript{18–22} There is a growing interest in exploring other structures that might enhance the shear response, load-bearing and energy absorption ability of the lightweight structures.\textsuperscript{18,21,23–25} New core designs have been proposed in order to replace the more common honeycomb hexagonal structure.\textsuperscript{21,23,26,27} In particular, two new core designs, specifically lotus and hexagonal honeycomb with Plateau Borders, have been recently proposed by Araujo et al.\textsuperscript{26} and compared with the regular hexagonal honeycomb. The new arrangements presented stiffness, strength and energy absorbed that made them competitive with the traditional core structures for the same density.\textsuperscript{26}

Current developments on large-scale computation and advanced manufacturing techniques, such as additive manufacturing, enable the design of cellular structures with complex geometrical features. Among the additive manufacturing processes, fused deposition modelling (FDM) is one of the least expensive methods, which makes it one of the most commonly used\textsuperscript{28–30} in the FDM method, a part drawn in a CAD file is built layer by layer, due to the extrusion of a material controlled by suitable software. The nozzle or head moves into the X–Y plane until the material is deposited in the entire plane, after which the head moves vertically in the Z plane to deposit new layers, so that the part can be built. Several materials may be used in the FDM process, including polylactic acid (PLA) which is a biodegradable aliphatic polyester.\textsuperscript{26} As FDM deposits material directionally, the result is a part that has an anisotropic behaviour, for example in the strength and stiffness.\textsuperscript{29,31,32}

Despite the enormous potential of bioinspired structures in optimizing lightweight structures, few studies are available in the literature, and these structures have not been fully explored in terms of modeling and fabrication.\textsuperscript{8,27,33–35}

In the current work, two novel bioinspired core structures are proposed, designated by Bamboo and Enamel, which were adapted to mimic the features of the natural materials, bamboo and enamel. The two novel structures are compared with the regular hexagonal honeycomb denoted by Honeycomb. The FDM process was used to fabricate several core plates with different arrangements in PLA. Four densities were studied in the case Enamel and Honeycomb, while for Bamboo two graded structures were taken into account. The mechanical properties and failure behaviour were analysed through three-point bending (3PB) and compression tests, either experimentally or with finite element (FE) models. The failure mechanisms of the cores under bending and compression tests were identified, and conclusions regarding the mechanical behaviour of the studied materials/structures were drawn.

Materials and methods

Materials

The three different configurations, Honeycomb, Enamel and Bamboo are shown in Figure 1. All the samples were drawn with the 3D CAD program Autodesk Inventor 2016. The samples were built symmetrically with approximately the same size. For the compression tests, the dimensions of the specimens were around $136 \times 118 \times 10 \text{ mm}^3$, while for the 3PB test, the dimensions were approximately $140 \times 65 \times 10 \text{ mm}^3$.

The Enamel structure was constructed with a keyhole-shape in resemblance with the literature data.\textsuperscript{13} Both Honeycomb and Enamel (Figure 1(a) and (b)) are non-graded structures, as they possess the same geometric characteristics in the entire samples. These arrangements are characterized, respectively, by the parameters $t$, $l$, and $t$, $r$, as exhibited in Figure 1. The radius $r$ of the Enamel structure was calculated to give the same internal area as the one exhibited by the Honeycomb cells for $l = 10 \text{ mm}$.

The Bamboo structure was inspired by the micro-architecture of bamboo vascular bundles, which could be mimicked by a connecting network of hexagonal lattices, where the use of varying thicknesses in the same sample leads to a graded structure. The configuration, Bamboo$_{L}$, may be considered to be a longitudinal graded structure, as the thickness of the struts changes from $t_1$ to $t_4$ in the $X_2$ direction (Figure 1(c)), whereas in Figure 1(d), a transversal graded structure, Bamboo$_{T}$, is presented with a thickness variation from $t_1$ to $t_4$ along the $X_1$ direction. Both Bamboo structures possess differences of...
the wall-cell thickness, being thicker in the outside walls than in the inside walls. The design strategy was to study separately the longitudinal and the transversal graded structures. An alternative that was not followed would be to decrease or increase the cell thickness in all six sides of a cell.

For each configuration, the relative density was measured by the CAD software Autodesk Inventor 2016, by calculating the ratio of the area occupied by the solid divided by the area of the entire structure, as defined by previous authors.\(^1\)

For each of the configurations, Honeycomb and Enamel, four relative densities were studied, while for the graded structures, Bamboo_L and Bamboo_T, two geometries were considered with approximately the same relative density (Table 1).

All the parameters and the corresponding relative densities are indicated in Table 1. The samples will be

Table 1. Geometric parameters and relative density for the three arrangements.

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<thead>
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<th>Relative density</th>
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<td>2.3</td>
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<td>2.2</td>
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</table>

Figure 1. Schemes of cellular configurations: (a) Honeycomb, (b) Enamel, (c) Bamboo_L and (d) Bamboo_T.
denoted by the geometry type followed by a number which corresponds to the different relative densities or to a particular distribution thickness as defined in Table 1.

Selected samples, namely Honeycomb_4, Enamel_4, Bamboo_L_1 and Bamboo_T_2, were chosen to be printed by FDM, as they present approximately the same relative density. The drawing files were processed by the software CURA, after which specimens are printed in an Ultimaker 3 device where the object is built layer by layer until the part is completed. The material used was PLA, delivered by ESUN. The extrusion temperature was 210 °C and the layer thickness was 0.15 mm. The built plate temperature was 80 °C. All parts were created at room temperature, as the printer has no closed chamber. The printer speeds to make the inner and outer walls were, respectively, 40 mm/s and 30 mm/s.

**Finite element modelling**

The numerical simulations were carried out using the software Abaqus version 6.14-1, to evaluate the mechanical behaviour of the specimens subjected to bending or to compression loadings. Isotropic behaviour in material properties was considered as simplifying assumption. Figure 2 exhibits the assemblies for simulating both types of tests.

In the compression simulations, the cellular structure was kept between two parallel plates. The lower plate was fixed, while the upper plate was moving down until a displacement of 10 mm was achieved.

For the 3PB bending simulations, the structure was held between the two lower supports, which were fixed, and a movable upper support. The final displacement of the upper support was 2.5 mm. The support span was taken as 80 mm for all bending tests.

A contact interaction between the structure and supports with a friction coefficient of 0.2 was selected.

The cell wall material used in the simulations was PLA. The most relevant PLA properties for the current study were density, Young’s modulus, Poisson’s ratio and yield stress, which were taken, respectively, as $\rho = 1252 \text{ kg/m}^3$, $E = 1.5 \text{ GPa}$, $\nu = 0.36$ and $\sigma_y = 20 \text{ MPa}$, from a previous work.

Elements of type C3D20R, i.e. 20-node quadratic brick, reduced integration, were used in the cell wall mesh.

A convergence study was performed in order to assign the mesh size for each configuration. The convergence criterion was set as less than 7% changes in the highest von Mises stress. After mesh refinement, the number of elements, for example in the Enamel_2 model for compression, was 11,132, while for bending, 32,041 elements were defined.

The simulations allow obtaining several features, such as load–displacement curves, that were obtained from the reaction force of the upper support or plate, as a function of the displacement of the elements beneath the same support. The stiffness, $K$, was evaluated as the slope of the linear region of the load–displacement curve, and the energy absorbed, $E_a$, until maximum load was also calculated. The maximum stress $\sigma_{\text{max}}$ allows for the evaluation of the strength of a cellular structure.

**Experimental tests**

Compression and 3PB tests of the FDM printed samples, namely Honeycomb_4, Enamel_4, Bamboo_L_1 and Bamboo_T_2, were conducted on an Instron 3369 universal testing device with a load cell of 10 kN and a cross-head speed of 2.5 mm/min, using the Bluehill Software. The load was measured by the machine load cell.

Figure 3 exhibits the experimental set-up for both tests. Three samples were experimentally tested for each configuration.

The compression tests were carried out according to the procedure defined by ASTM D695 – 15 (Standard Test Method for Compressive Properties of Rigid Plastics), while the 3PB tests followed ASTM C393 (Standard Test Method for Flexural Properties of Sandwich Constructions).

The load–displacement curves, the initial stiffness and the energy absorbed were obtained. The failure mode of each configuration was assessed.

**Results**

**Finite element analysis of compression tests**

Figure 4 shows the von Mises stress distributions for all the configurations studied under compression.

Compared to Enamel, the Honeycomb samples (Figure 4(a) to (d)) attain higher stresses, and more deformed cells are found at zones of the specimen perpendicular to the applied loads. The Enamel configurations show higher values of stresses and deformations closer to the upper plate with a pyramidal shape zone of cells with lower stress (Figure 4(e) to (h)). The localization of the maximum stress does not...
depend on the relative density for the Honeycomb and Enamel configurations.

The graded structures, Bamboo_L, clearly exhibit a high stress zone at the mid-section of the specimen (Figure 4(i) and (j)), which corresponds to the cells with lower thickness. In particular, the highest stress is found in the middle cell. The Bamboo_T arrangements present higher stresses in cells in the middle of the sample (Figure 4(k) and (l)), but there is no a pronounced effect of localization as in the Bamboo_L configuration.

The load–displacement curves obtained by FE analysis are shown in Figure 5. The curves of Figure 5 show a linear part followed by a nonlinear
zone which may be associated to the damage of the structure.

In the two non-graded structures, Honeycomb and Enamel, an increase in density causes an increase in the mechanical strength for the same displacement. For these two arrangements (Figure 5(a) and (b)), there is a large increase in the load when the relative density increases from Honeycomb_3 to
Table 2. Relative density and FE results for compression tests.

<table>
<thead>
<tr>
<th>Geometry</th>
<th>(\bar{\rho})</th>
<th>(\sigma_{\text{mod}} (\text{MPa}))</th>
<th>(K/\bar{\rho}) (N/mm)</th>
<th>(E/\bar{\rho}) (J)</th>
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<td>Honeycomb_1</td>
<td>0.086</td>
<td>512.46</td>
<td>208.37</td>
<td>6.39</td>
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<tr>
<td>Honeycomb_2</td>
<td>0.106</td>
<td>339.49</td>
<td>318.64</td>
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<td>Honeycomb_3</td>
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<td>290.70</td>
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<td>206.26</td>
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<td>57.79</td>
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Bamboo_T_2 presents a higher value of maximum stress in comparison with the non-graded structures Honeycomb_4 and Enamel_4 (Table 2).

Making an analysis of Table 2, one may infer that for densities of 0.1 and 0.22, the highest energy is absorbed by the Honeycomb structures, while for the density of 0.12, the Enamel configuration prevails. The Bamboo_T_1 allows energy absorption values close to the ones obtained with the same relative density Honeycomb_4. This was also observed with respect to the maximum stress values.

**Finite element analysis of 3PB tests**

The von Mises stress distributions obtained for all the configurations studied under flexural testing are shown in Figure 6, where one can observe that maximum stress is reached where the cellular structures contact with the three supports for all the cases considered.

Simulations undertaken with the Enamel structures (Figure 6(e) to (h)) reveal that for the same displacements, the stresses attained in the Enamel structures are lower than the ones achieved in the Honeycomb arrangements for the same relative density. Once more the localization of the maximum stress does not seem to depend on the relative density, in the Honeycomb, Enamel and Bamboo arrangements.

The flexural load–deflection curves obtained by FE analysis are shown in Figure 7. Both Honeycomb and Enamel arrangements reveal a large increase in the load when the relative density increases from Honeycomb_3 to Honeycomb_4 and from Enamel_3 to Enamel_4 (Figure 7(a) and (b)).

Honeycomb is the arrangement that can reach the highest load value, among all the configurations. In comparison with the other two arrangements, Enamel does not have a good response to bending loadings, given the lowest values of the load attained. In middle range of the load values are the Bamboo structures, for which Bamboo_L provides higher loads for the same deflection in comparison with Bamboo_T. The two Bamboo_L configurations, which have the same relative density, do not exhibit the same load–displacement curves, in opposition to Bamboo_T which present overlapping curves. These results show the influence of the different thickness distributions on the load-bearing ability of these configurations.

Table 3 shows FE results for 3PB tests obtained for the three configurations, where the parameters were scaled to the relative density. As the density increases, there is a decrease in the maximum stress attained in the Honeycomb structures. Taking a closer look at Table 3, one can observe that the Honeycomb configurations present the peak values of stresses for relative densities of 0.1, 0.12, while for the density of 0.22, the highest value was found with the Enamel configuration. For the same relative density, the Honeycomb...
arrangement possesses highest stiffness and highest energy absorption in comparison to Enamel.

The graded structure, Bamboo_L_1, sustains higher stresses, with almost the same stiffness and energy absorbed than Honeycomb_4, which has almost the same density.

Experimental compression tests

FDM specimens, Honeycomb_4, Enamel_4, Bamboo_L_1 and Bamboo_T_2, were experimentally tested under compression and the respective load–displacement curves are presented in Figure 8(a). The FE simulation curves are re-plotted in Figure 8(b) for comparison. There is the same trend in experimental and simulation results. The arrangements Honeycomb_4 and Enamel_4 are the ones that sustain higher load values. The other configurations carry lower loads, as both seen in experiments and numerical simulations. In general, the values obtained in experiments are larger than the ones attained in numerical simulations.

Table 4 shows the slope of the linear region of the load–displacement curves, $K$, and the energy absorbed until maximum load, $E_a$, scaled to the relative density, for the curves of Figure 8. The arrangements Honeycomb_4 and Enamel_4 display the highest stiffness and energy absorbed in comparison with the other structures.

Figure 9 shows the samples after the compression test, making possible a visual inspection analysis of failure. The Honeycomb_4 sample presents localization of deformation at mid-section cells, which is in accordance with the literature. Enamel_4 shows high deformation of cells at the bottom of the specimen. Both Bamboo structures exhibited failure at mid-section cells. As expected, the graded structure, Bamboo_L_1, reveals an inner layer of highly deformed cells at the mid-section of the specimens, which corresponds to the lower thickness cells layer. In the compressed Bamboo_T_2 specimen, there are a larger number of cells deformed, but the deformation is not so high, or not as concentrated as in the case of Bamboo_L_1.

Experimental 3PB tests

Figure 10 and Table 5 gather the experimental results for the samples printed by FDM tested under 3PB tests. Load–deflection curves present the same trend in simulations and in experiments. Higher values of load, of $K/\rho$ and of $E_a/\rho$ are attained with the arrangement Honeycomb_4, followed by the graded Bamboo structures and by Enamel_4.

Images of the failed specimens after flexural testing are shown in Figure 11. Honeycomb_4, Enamel_4 and Bamboo_L show the same failure pattern with fracture initiation below the middle support, at the face opposite to the contact. In Bamboo_T, a different failure pattern was observed, with the cell walls opening into two halves.
Figure 7. FE load–displacement curves of bending tests of the four structures: (a) Honeycomb; (b) Enamel; (c) Bamboo_L and (d) Bamboo_T.
Discussion
This work presents new insights in the developing field of biologically inspired design. Bio-based materials have become increasingly appealing to researchers in recent times, as they offer innovative possibilities in the development of lightweight structures. Some natural structures do combine hierarchical architecture with gradients in structural features and consequently on properties, which can be quite useful in a range of applications. In effect, the pursuit of ideal structures with low density, high stiffness and high strength is one of the purposes of structural design. To achieve this goal, one can take advantage of new technological tools that make easier the task of creating and fabricating structures with complex shapes. Driven by several concerns, from environmental preservation to sustainability, researchers have recently attempted to propose new bio-inspired structures that have the potential to compete with hexagonal geometries. As the out-of-plane properties of the hexagonal honeycombs are not exceptional, nature-based structures have been introduced in an attempt to overcome this handicap. While the present paper is a first approach in the field of bioinspired structures, more comprehensive work needs to be performed to establish the set of advantages presented by these structures over the traditional hexagonal configurations.

In the present work, two new cellular configurations, Enamel and Bamboo, were studied and compared with the regular hexagonal honeycomb. The mechanical response of such configurations is not

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<th>( \sigma_{\text{max}} \bar{\rho} ) (MPa)</th>
<th>( K / \bar{\rho} ) (N/mm)</th>
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Table 3. Relative density and FE results for bending tests.

Figure 8. Comparison of (a) experimental and (b) FE results for compression tests.
simple to predict, as several factors are involved, besides geometry, namely density and thickness distribution. The authors in the present study have chosen to evaluate the mechanical behaviour both with finite element analysis and with experimental mechanical testing, making use of FDM to produce specimens with selected configurations.

Honeycombs formed by regular hexagonal cells have been extensively used in core sandwich panels due to its good mechanical properties. In the compression of honeycombs, there is an initial linear phase followed by a second step in which the structure deforms by elastic buckling (elastomers) or by plastic collapse (plastic materials), depending on the cell wall material. In this case, there is a localized plastic collapse of some cell walls, where the local stresses attain values superior to the yield stress. The damage propagates into the specimen in the form of bands of collapsed cells. Moreover, the vertices or triple joints are regions with a high level of local stresses. In recent times, the purpose of many researchers has been, as stated previously, to explore optimal cell structure designs, by changing, for example, the cell angles of the honeycombs, which would reduce stress concentration. This idea was the basis for the present authors to propose an Enamel-based structure.

The mechanical behaviour of two-dimensional cellular structures depends on two main mechanisms of deformation, namely bending and stretching. The prevalence of each mechanism depends on several factors, such as the type of loading. In general, when a honeycomb is subjected to in-plane loads, such as compression, the deformation is dominated by bending because the cell walls bend. When loaded along out-of-plane direction, such as in flexural bending, the stretching of the struts/cell walls occurs with the axial extension or compression of the cell walls. Besides these two mechanisms of deformation, bending and

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**Table 4. Relative density, FE and experimental results for compression tests.**

<table>
<thead>
<tr>
<th>Geometry</th>
<th>$\rho$</th>
<th>$\sigma_{\text{max}}/\rho$ (MPa)</th>
<th>$K/\rho$ (N/mm)</th>
<th>$E/\rho$ (J)</th>
<th>$K/\rho$ (N/mm)</th>
<th>$E/\rho$ (J)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Honeycomb_4</td>
<td>0.229</td>
<td>206.26</td>
<td>1981.54</td>
<td>11.95</td>
<td>1957.69 ± 78.31</td>
<td>16.35 ± 0.73</td>
</tr>
<tr>
<td>Enamel_4</td>
<td>0.222</td>
<td>224.64</td>
<td>1925.99</td>
<td>7.09</td>
<td>1732.08 ± 34.64</td>
<td>10.39 ± 0.51</td>
</tr>
<tr>
<td>Bamboo_L_1</td>
<td>0.205</td>
<td>245.18</td>
<td>1544.05</td>
<td>5.97</td>
<td>1414.32 ± 45.26</td>
<td>8.57 ± 0.32</td>
</tr>
<tr>
<td>Bamboo_T_2</td>
<td>0.243</td>
<td>222.21</td>
<td>1724.78</td>
<td>10.03</td>
<td>1215.73 ± 51.07</td>
<td>6.83 ± 0.28</td>
</tr>
</tbody>
</table>

**Figure 9.** Failure behavior of (a) Honeycomb, (b) Enamel, (c) Bamboo_L and (d) Bamboo_T, after compression tests.
stretching, other effects influence the mechanical response of cellular solids, such as the behaviour type of the cell wall material, which may be ductile or brittle.

The effect of the core geometry into the mechanical properties was evaluated in the present study by compression and flexural loading, for the two non-graded structures, Honeycomb and Enamel. Both structures exhibited bending-dominated deformation of the cell walls under in-plane loading of compression. The application of flexural loads, i.e. out-of-plane conditions shows the presence of cracks in the cell walls due to stretching. However, PLA being a brittle material at room temperature, fracture tends to occur prior to plastic deformation.

The density effect was evaluated for Honeycomb and Enamel structures with four different values of densities. As the density increases, the Honeycomb and Enamel arrangements exhibited the same trends, as the maximum stress decreases, the stiffness rises and the energy absorption also tends to increase, when the specimens are subjected to compression loading. Enamel arrangements prevail in attaining higher strengths, the other parameters being stiffness and energy absorption of the same order of

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**Table 5. Relative density, FE and experimental results for bending tests.**

<table>
<thead>
<tr>
<th>Geometry</th>
<th>$\bar{\rho}$</th>
<th>$\sigma_{\text{max}}/\bar{\rho}$ (MPa)</th>
<th>$K_f/\bar{\rho}$ (N/mm)</th>
<th>$E_a/\bar{\rho}$ (J)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Honeycomb_4</td>
<td>0.229</td>
<td>85.31</td>
<td>593.77</td>
<td>1.73</td>
</tr>
<tr>
<td>Enamel_4</td>
<td>0.222</td>
<td>85.97</td>
<td>144.01</td>
<td>0.45</td>
</tr>
<tr>
<td>Bamboo_L_1</td>
<td>0.205</td>
<td>98.60</td>
<td>508.26</td>
<td>1.22</td>
</tr>
<tr>
<td>Bamboo_T_2</td>
<td>0.243</td>
<td>89.89</td>
<td>302.43</td>
<td>0.87</td>
</tr>
</tbody>
</table>

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**Figure 10.** Comparison of (a) experimental and (b) FE load–deflection curves for 3PB tests.
magnitude than the ones achieved by the Honeycomb configuration.

However, the same varying density Enamel arrangements, when subjected to flexural loadings, provide low load-bearing capacity. Despite a few exceptions, Enamel displayed a lower maximum stress, stiffness and energy absorption in comparison with Honeycombs when subjected to 3PB. The failure zones were precisely at the joints with lower angle as shown in Figure 11.

The effect of the cell thickness was evaluated with two graded structures, Bamboo_L and Bamboo_T with approximately the same relative density. Under both compressive and flexural loadings, Bamboo_L provided higher strength than the two graded structures with comparable relative density, revealing to be a promising core structure. The failure modes of the two Bamboo structures are different, showing a clear localization of deformation in a form of band for Bamboo_L. On the contrary, there is no formation of localized deformation bands in the case of Bamboo_T.

It is worth mentioning that a satisfactory agreement between the experimental results and the numerical predictions was found for the load–displacement response, failure mode and stress distribution.

It is interesting to note that in compression testing, experimental values are higher than the ones obtained by FE, while during flexural testing, simulation results are superior to the experimental ones. These tendencies were previously observed.26,39

The differences in values obtained numerically and experimentally may be attributed to the manufacturing process. The struts are formed by the external contours and an inner infill. For thin struts, the infill zone is reduced, and the struts get very strong due to the outer contours. Compression of stronger struts leads to higher experimental values. Under flexural loadings, the two contours separate each other for lower loads than if there was a unique wall.

In fact, FDM produces compact struts, but also air gaps were observed in the case of graded structures. The presence of air in low thickness struts was probably due the difficulties of FDM to produce homogeneous struts with lower thickness.

Although the structures studied in the present paper show promising results, there was no a unique configuration with ideal properties of strength, stiffness and energy absorbed.

Figure 11. Failure behavior of (a) Honeycomb, (b) Enamel, (c) Bamboo_L and (d) Bamboo_T, after 3PB tests.

Conclusions

In this paper, the concept of bioinspired materials based on Bamboo and Enamel structures has been applied. The mechanical performance was investigated with the finite element method and experimental testing of compression and flexural bending. A satisfactory agreement was found between FE and experimental results in the case of PLA specimens fabricated by FDM.

The mechanical properties showed a strong dependence on the core geometry, on the relative density and on the cell thickness distribution.

Under compression, Enamel arrangements provide good responses, exhibiting values of loads of the same order of magnitude than the ones achieved by the Honeycomb configuration. However, under flexural loading, the Enamel configuration showed low load-bearing capacity, even for the highest relative density.

The results suggest that the bioinspired structures have a potential in the development of novel sandwich panel cores, where strength, stiffness and energy absorption are major concerns. The outcomes of the investigation show
that the properties of cellular solids may be changed throughout controlling and manipulating their topology.

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