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LOW VELOCITY IMPACT RESPONSE OF 3D PRINTED SANDWICH PANELS WITH TPU CORE AND PLA FACES

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Sandwich panels are used in the automotive and aerospace industries due to their superior mechanical properties. Cellular structures, especially those with a negative Poisson's ratio (auxetic behaviour), lead to a very good energy absorption capacity, making them suitable as cores for sandwich structures. In this study, the mechanical behaviour and impact energy absorption properties of some 3D printed sandwich panels with cellular cores are investigated through experimental tests at low impact speed. Using the fused deposition modelling (FDM) rapid prototyping method, three types of sandwich panels with different cores (re-entrant 0 degrees, re-entrant 90 degrees and hexagonal) were fabricated. The panels were made of two different materials, the core from TPU (thermoplastic polyurethane) and the faces from PLA (polylactic acid). The faces were bonded to the core with a two-component adhesive. These panels were subjected to low-speed impact tests at an impact energy of 10 J. The upper faces were not damaged because the core has an elastic behaviour and allows the cell walls to deform without yielding. The entire impact energy was absorbed through the deformation of the core walls. The sandwich panel with re-entrant 0 degrees core proves to have the most elastic behaviour leading to the highest displacement obtained during impact. The re-entrant 90 degrees core has the most rigid behaviour as the highest value of the impact contact force during testing was obtained.

Keywords: re-entrant honeycomb core, sandwich panels, 3D printing, low velocity impact, energy absorption

1. Introduction

Sandwich panels, which contain faces of composite materials and a foam core or different structures, are widely used in light construction, especially in the aerospace industry, due to their superior advantages over conventional structures. Among these advantages are the high strength-to-weight ratio, improved stiffness

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and weight, thermal and acoustic insulation, as well as high-energy absorption capacity [1].

Sandwich panels consist of two thin faces, at the top and bottom of the panel, separated by a light and relatively thick core. The lightweight core connects the faces with little weight gain, but gives the sandwich panel high flexural stiffness and buckling resistance. The complexity of the materials and architecture of sandwich panels is constantly increasing due to the increasing demand to improve the structures, thermal insulation or heat transfer performances for a wide range of engineering applications. It was shown recently that the multifunctional performance of sandwich structures can be improved by modifying the architecture of the cell core. Recent developments in advanced manufacturing technologies, for example additive manufacturing (3D printing) and laser cutting, have enabled the fabrication of architected cell cores that were impossible to manufacture by conventional manufacturing processes such as extrusion, milling, casting [2].

The structural performance and energy absorption capacity of a sandwich panel mainly depends on the properties of the material from which it is made and the geometric characteristics of the faces and the core. Among all the cell topologies for the core of the sandwich panel architectures, the hexagonal honeycomb has been commonly used and analyzed as the cell core. Sandwich panels with conventional honeycomb cores are rigid, light and absorb high impact energy, and are used for various applications [3], [4]. However, they have some problems due to their closed-cell architectures, including gas retention, which leads to low thermal conductivity and moisture trapping. Moisture trapped in closed cells leads to increased weight and a change in the center of gravity, a problem that can be solved by using open cell cores. More recently, auxetic cores have been examined due to their unusual deformation mechanisms for which Poisson's ratio is negative. Auxetic cellular materials present a number of technical advantages, such as shear strength, increased indentation resistance, increased absorption energy. Moreover, auxetic structures show synclastic deformation and have better acoustic properties compared to their conventional counterparts [5], [6].

Mechanical and physical testing of polymers and composites is essential for determining material properties for use in: design and analysis, quality control, meeting performance requirements and optimizing manufacturing processes. These tests are particularly important in industries such as: aerospace, automotive, consumer goods, medical and defense [7]. Mechanical testing of composite materials made from different polymers involves the evaluation of key mechanical parameters such as strength and stiffness. Common standardized mechanical tests for polymer composite materials include tensile (stretch) tests, flexural tests, and impact tests [8].

Tensile tests are an essential aspect in the evaluation of the mechanical properties of materials, and as they are standardized, through quasi-static test methods material properties are established. Numerical simulations use mathematical and computational methods to model this behaviour, providing engineers and researchers with detailed insight before physical tests are performed. With the evolution of computer technologies, numerical simulation has become an essential tool in the field of engineering, offering an efficient and accurate approach in studying the behaviour of materials [9].

The bending test measures the force required to bend a beam-type specimen. Three-point bending tests are generally performed and used for rigid and semi-rigid materials, as resins and fiber-laminated composites [10].

The impact test is designed to determine how a specimen made of a known material, such as polymers, ceramics, or other composite materials, responds to a suddenly applied stress. The impact test is explicitly used to evaluate the hardness, brittleness, toughness, crack sensitivity and resistance of materials to dynamic loading [11], [12].

Additive manufacturing, also known as 3D printing or rapid prototyping, has emerged as a revolutionary technology that is redefining the manufacturing landscape in various industries. The importance and industrial use of additive manufacturing (AM) has increased in recent years. In addition, the number of AM system manufacturers tripled between 2013 and 2016. Beginning in 2014, Airbus integrated printed parts into the A350 XWB aircraft. Another example is a German supplier to the automotive industry, which produces more than 40,000 plastic parts for customers. These examples highlight the growing acceptance and benefits of AM methods [13].

The increase in the use of additive manufacturing (AM) methods results from the improvement of production methods and special customer requirements. In some cases, the economic efficiency of AM methods exceeds the economic efficiency of traditional production methods. AM methods help to produce small batches or realize individualized and complex geometries in a cost-effective way. The benefits of AM methods result from the short and largely digital process chain. Compared to a milling processing chain, no complex programming takes place [13].

Additive Manufacturing (AM) is one of the pillars of Industry 4.0 listed by the Boston Consulting Group, and it is considered a promising production process that allows the rapid manufacture of products with full functionality. It appears as a technical lever for product innovation and sustainability, as it brings opportunities both through the possibility of creating complex products and through the lower consumption of resources compared to traditional production processes [14, 15].

This paper presents the low velocity impact response of sandwich panels with auxetic and non-auxetic core structures. Three types of cores were used: hexagonal, re-entrant with cells parallel to the z-axis and re-entrant with cells oriented at 90 degrees to the z-axis, designed using CATIA V5 software and made using 3D printing method. For these topologies, low speed impact tests were performed in order to obtain their mechanical properties.

The energy absorption capacity of a sandwich panel is affected by its geometry (length, width and thickness), the relative density, the properties of the base material used for the construction of the panel, the topology of the cells that form the core. This study focuses specifically on the energy absorption capacity of sandwich panels made through rapid prototyping. The main dimensions of the sandwich panels, length, width, face thickness and core thickness, were kept constant throughout the study.

In the first part of this paper, aspects related to the design and production of sandwich panels are presented. In the second part, after performing the low-velocity impact testing the experimental results are analysed and commented. The influence of the core structure on the damage of the samples is also discussed.

2. Material and Methods

2.1 Materials

The design of the sandwich panels for the impact tests was carried out using the CATIA V5 design software. The CAD file was saved in STL format, and later with the Ultimaker Cura software, the G-code required for the 3D printer was generated. The dimensions of sandwich panels, including length *a*, width *b*, face thickness t_s, core thickness t_c, are shown in Fig. 1. Fig. 2 shows the 3D models for sandwich panels, notated further as PS1, PS2, and PS3.

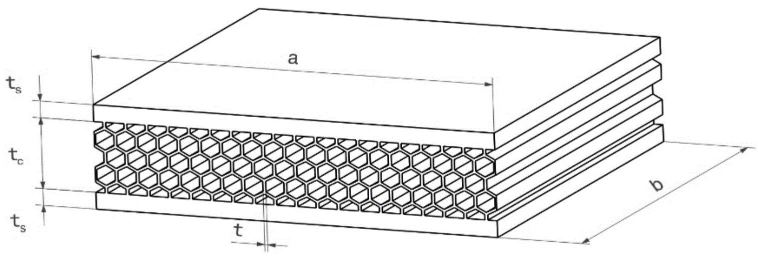
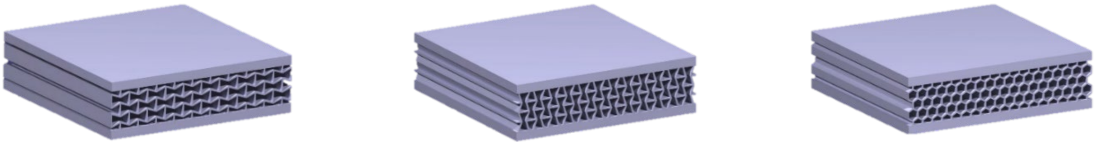


Fig. 1. Sandwich panel geometry.

The dimensions of sandwich panels, for all three topologies (Fig. 2), namely re-entrant 0 degrees, re-entrant 90 degrees and honeycomb, are the following: length *a* –110 mm, width *b* – 110 mm, uniform wall thickness *t* – 0.8 mm being the same for all three cores, core neight t_c – 21 mm and face thickness t_s – 5 mm.



a) b) c)

Fig. 2. Topologies of sandwich panels: a) re-entrant core 0 degrees (PS1), b) re-entrant core 90 degrees (PS2), c) regular hexagonal core (PS3)

The sandwich panels were made by 3D printing. The printer model is Ultimaker S5 Pro Bundle, and it uses FDM (Fused deposition modeling) technology. The materials considered for the fabrication of the sandwich panels are: Ultimaker PLA Green 1608 (2.85 mm, 750 g – spool weight, print temperature 195 – 240°C) and Ultimaker TPU 95A Blue 1334 (2.85 mm, 750 g – spool weight, print temperature 225 – 235°C).

The printing parameters for panels with TPU core and PLA faces are:

- For the core: 100% infill density, print bed temperature 60°C, layer height 0.2 mm, extruder type AA 0.4, print temperature 225°C, print speed 25 mm/s;
- For the faces: 15% infill density, print bed temperature 60°C, layer height 0.2 mm, extruder type AA 0.4, print temperature 205°C, print speed 70 mm/s.

To create the sandwich panels, the PLA faces were glued to the TPU core using a two-component Mitre Apel adhesive based on cyanoacrylate. Table 1 shows the printing time for each type of TPU core, the amount of material used, and for the PLA faces, the duration and amount for a set of two plates.

Table 1

Printing time and material quantity

No.	Description	Printing time	Material quantity
1.	Re-entrant auxetic core 0 degrees_	18h 26min	129 g
2.	Re-entrant auxetic core 90 degrees	18h 29min	132 g
3.	Honeycomb core	18h 22min	139 g
4.	Faces	8h 46min	145 g

2.2 Experimental Set-up

To characterize the behaviour of the 3D printed sandwich panels, several low velocity impact tests were performed using an INSTRON impact tower, model Ceast 9340, presented in Fig. 3. The tests were conducted in accordance with the ASTM D3763-18 standard [16]. Special attention was given to centering the specimens on the steel support, so that the impactor would strike exactly in the center. Additionally, the height adjustment of the specimen support was done carefully to avoid influencing the clamping force exerted by the pneumatic clamping system. Excessive force would crush the specimens at the clamping area, while insufficient force would result in slippage between the specimen and the support, thereby affecting the test results.

After creating several sandwich panels with honeycomb and auxetic re-entrant cores in two configurations, multiple impact tests were conducted to study their behaviour. Using the control software for the impact tower, several parameters were set, including the impact energy. Based on this energy and the mass of the drop system, the drop height and impact velocity were calculated. Several tests were conducted for an impact energy of 10 J.

Fig. 3. Drop tower INSTRON Ceast 9340.

3. Results for the impact tests

The graph presented in Fig. 4 shows the variation of impact force over time for the sandwich panel with re-entrant 0 degrees TPU core. An approximately linear increase can be observed in the first portion, reaching a peak force of 1207.03 N at 3.5 ms. After reaching the first peak, the force slightly decreases to 1025 N due to the indentation and cracking of the upper face in the impact area, followed by another peak of 1225.49 N at 6.7 ms, and then a slow decline. Compared to the PLA sandwich panel, it registers lower impact force values, due to the much more elastic behaviour of the core, being similar to that of synthetic rubber.

In Fig 5, the graph shows the variation of impact force over time for the sandwich panel with re-entrant 90 degrees TPU core. Similar to the previous panel, an almost linear increase can be observed in the first part, with small oscillations due to the deformation of the core walls.

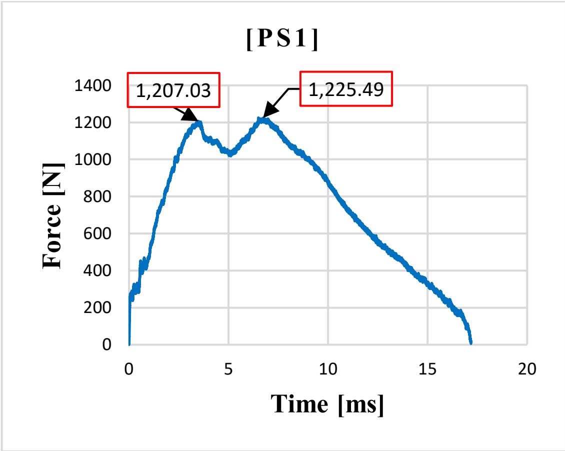


Fig. 4. Variation of impact force over time for the PS1 panel with TPU core.

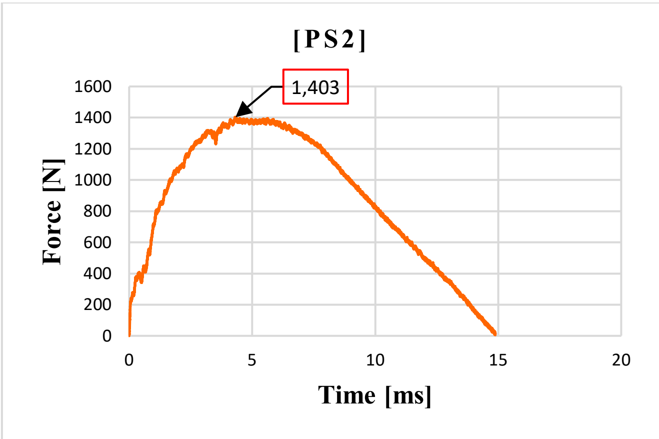


Fig. 5. Variation of impact force over time for the PS2 panel with TPU core.

The maximum force is reached at 4.3 ms and registers a value of 1403 N, followed by a linear decline.

In Fig. 6, the graph shows the variation of impact force over time for the sandwich panel with honeycomb TPU core. Similar to the previous panels, an approximately linear increase can be observed in the first part, with small oscillations due to the deformation of the core walls. The force reaches a maximum of 1086.32 N at 2.5 ms, followed by a sharp decline indicating some damage event, immediately followed by an increase until it reaches a value of 1168.69 N at 5.4 ms.

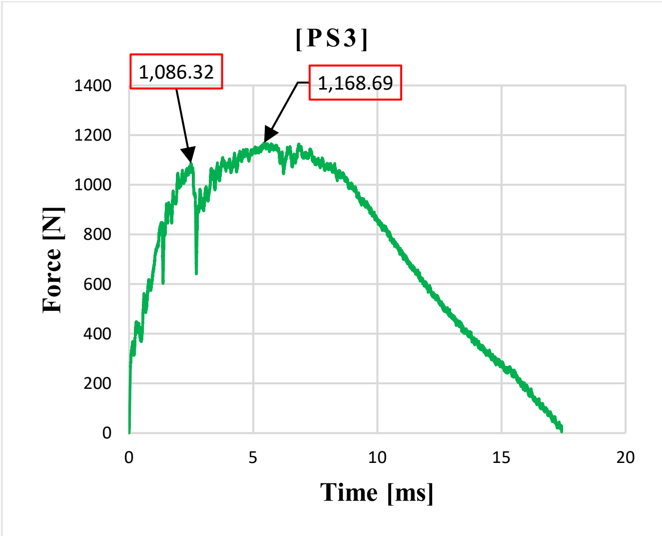
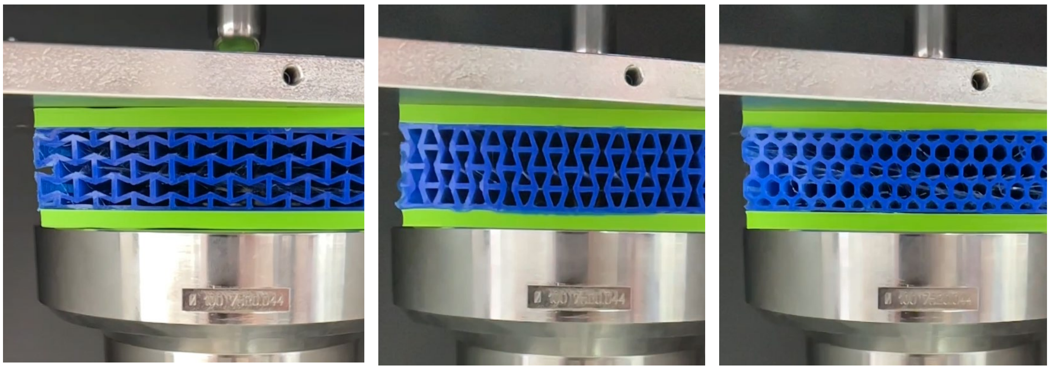


Fig. 6. Variation of impact force over time for the PS3 panel with TPU core.

In Fig. 7, the sandwich panels with TPU core during impact tests at an energy of 10 J are shown. The upper faces were not perforated because the core has an elastic behaviour and allows the honeycomb walls to deform without breaking. Almost the entire impact energy was consumed by the deformation of the core cell walls.



PS1 PS2 PS3

Fig. 7. Sandwich panels with PLA faces and TPU core during impact tests.

The figures below present a comparison between the three types of panels with TPU core. The following graphs are depicted: force – time (Fig. 8), force – displacement (Fig. 9), energy – time (Fig. 10), speed – time (Fig. 11). It can be observed that the panels exhibit a very similar behaviour, which is attributed to the material of the cores. A slight difference is noticed for panel PS2, which records a higher force compared to PS1 and PS3, as well as a smaller displacement. These types of sandwich panels demonstrate surprisingly good recovery. Following the impact tests, the faces of the sandwich panels were not damaged.

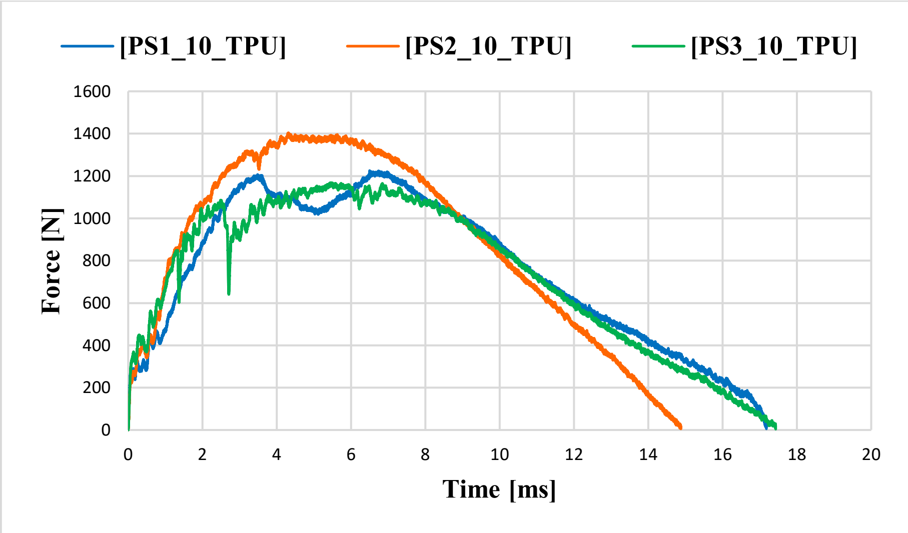


Fig. 8. Comparison of impact force variation over time for all types of cores.

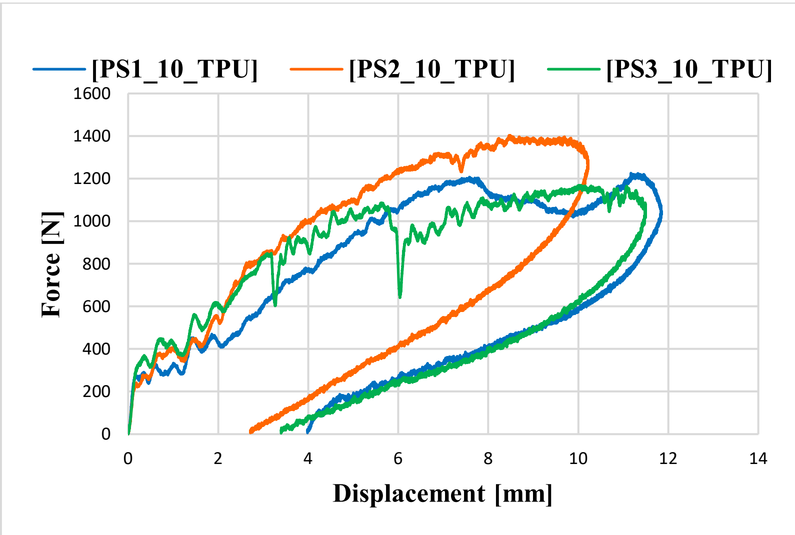


Fig. 9. The variation of impact force with impactor displacement for all types of cores.

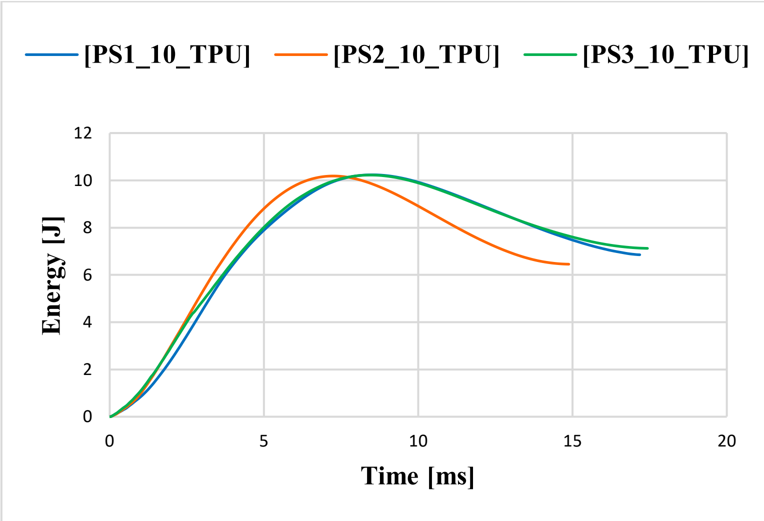


Fig. 10. The variation of absorbed energy over time for all types of cores.

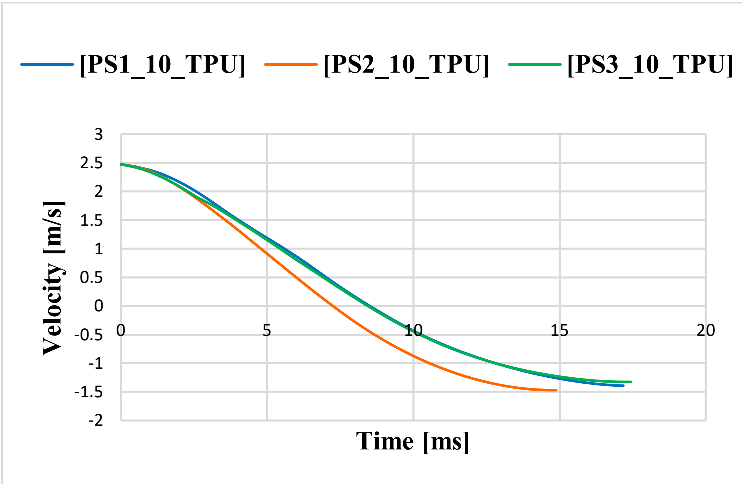


Fig. 11. The variation of the impactor's velocity over time for all types of cores.

4. Discussion and conclusions

The sandwich panel PS2 with a re-entrant 90 degrees core proves to have a stiffer behaviour than the other two panels, reaching a maximum force of 1400 N at 10 J impact energy, and the impact event took place only 15 ms, a shorter time than for the other two panels. On the other hand, the recovery of the PS2 panel is superior to PS1 and PS3, as the remanent displacement is the smallest, of about 2.8 mm. At this level of impact energy, the upper face of all three panels was not damaged. However, for PS1 with re-entrant 0 degrees core the cells near the impact zone were damaged. This can be observed from the impact force variation over time

(Fig. 4) that presents two force peaks slightly above 1200 N. These forces have somehow a higher value than for the PS3 regular honeycomb core panel (Fig. 6). The PS2 with re-entrant 90 degrees core has the most rigid behaviour with the highest value on the impact contact force (Fig. 5) and lowest remanent deformation (Fig. 9). In all, for a low level of impact energy, the re-entrant cores are a good alternative compared to the regular honeycomb core.

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