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Sustainable sandwich structures made from bottle caps core and aluminium skins: A statistical approach

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ABSTRACT

This work further investigates the manufacture and characterisation of a sustainable sandwich panel made from aluminium skins and a recycled thermoplastic bottle cap core, an innovative concept proposed in a previous paper. A full factorial design based on Design of Experiments (DoE) and Analysis of Variance (ANOVA) techniques has highlighted the complex influence of three manufacturing parameters (type of polymeric adhesive, adhesive layer thickness layer and core packing topology) on the absolute and specific physical and flexural properties of the panels. The ANOVA revealed that the use of higher amount of epoxy polymer led to enhanced panel strength and stiffness. The cell packing topology, however, did not provide a significant effect on most panel properties. Discarded bottle caps have proven to be a promising lightweight and inexpensive honeycomb component for structural applications.

1. Introduction

Sandwich panels consist of two sheets of rigid material connected by a soft and thick core, which can be chemically or mechanically bonded. A variety of core materials can be used in sandwich structures, from polymeric foams to honeycomb lattices [1]. The use of polymeric foam can help to reduce the structural weight and improve insulating properties, while honeycombs are more suitable for enhanced load bearing capabilities. The main advantage of sandwich panels consists in their high specific flexural stiffness, due to the core thickness and the reduced weight. Light-weighting and high strength are the main characteristics that make these materials suitable for aerospace applications [2].

Hexagonal honeycombs are the most common cellular cores used in structural applications [3], and different core topologies with 2D and 3D arrangements have been tested to optimise the mechanical performance of sandwich panels, assessing the effect of internal (e.g. geometry) and external factors (e.g. temperature, load rate) on panel properties [1,3–5]. Circular cell honeycombs are worthy of a particular mention. These core structures, discussed in technical open literature since the 1960s [1] and investigated at length by Chung and Waas [6], can be used in a variety of applications, such as oil transport in on- and off-shore facilities, and structural applications in sandwich plates [7]. Circular cell honeycombs have been hailed as a very promising core topology to enhance the stiffness and strength of a structure. Oruganti and Ghosh [8] have found that panels with circular cell honeycombs feature a significantly higher stiffness when compared with similar cores made from hexagonal honeycomb cells, due to the higher cell wall buckling loading. Lin et al. [9] have observed similar results, with enhancements of the deformation, strength and yield stress in circular cell cores depending on the cell packing. Different cell packings have been previously used to optimise the strength and stiffness of the resulting sandwich panel (Fig. 1). Hu et al. [10] have compared two circular cell packings, the cubic and the hexagonal ones (see Fig. 1.a and .b, respectively); the configurations present different angles between the adjacent lines that connect the centres of neighbouring tubes. Circular honeycombs with hexagonal packing show a significant higher energy absorption capacity (23%) and better performance under out-of-plane loads than circular honeycombs in cubic packing because of the higher number of restrictions (i.e., the number of adjacent cells in direct contact - 6 for hexagonal packing vs. 4 for cubic packing). A more restricted structure prevents the cell wall buckling and promotes the plastic deformation, leading to a more efficient energy absorption configuration.

The adhesive layer must guarantee an efficient skin-core load transfer, and the enhancement of the structural stiffness can be also

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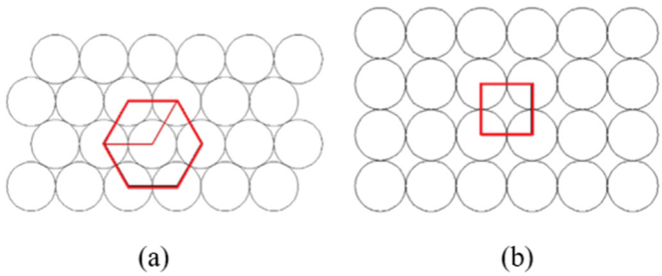

Fig. 1. Two circular honeycomb topologies: hexagonal (a) and cubic packing (b) [10].

achieved by applying surface treatments of the skins, or by controlling the amount of adhesive. The use of surface primers on metallic skins can provide moisture and corrosion protection, and – at the same time - enhance the chemical bonding between the surface of the skin and the polymeric adhesive [11]. Moreover, a mechanical pre-processing of the metallic skins based on abrasion with sandpaper tends to remove the passive oxide layer adsorbed on the surfaces, and that enhances the chemical interaction between the skin and the adhesive and increases the surface roughness [12]. Higher quantities of adhesive tend to correlate with an improved mechanical performance of the structures [13–16]. The quality of the adhesion is mostly attributed to the amount and the distribution of the adhesive layer. Okada and Kortschot [13] have found that larger and more regularly distributed adhesive fillets tend to enhance the energy absorption capacity. The presence of more uniformly distributed regular fillets is correlated to higher amounts of adhesive, which are able to form a meniscus near the cell walls [14]. Jen et al. [15] have assessed the performance of three different adhesive levels (400, 700, and 1000 g/m^2) on the fatigue behaviour of bonded aluminium honeycomb sandwich beams. The structures with the highest amount of adhesive showed the best fatigue life performance.

Sustainability is now one of the main concerns when developing innovative structural materials. The increasing costs of landfills in addition to new regulations for the disposal of end-of-life materials (such as the EU directive for vehicles [17]) impose the development of new solids with easy recyclability, and the use of eco-friendly components in manufacturing. An example of sustainable tubular honeycomb core is the structure proposed by Cabrera et al. [18]. This sandwich panel is composed by a tubular honeycomb made of polypropylene and bonded onto a polypropylene skin with a polypropylene (PP) based adhesive, creating therefore an *all-PP* structure. The use of a single-phase material facilitates the recyclability of the core and the structure, which could be melted in a single step. The overall mechanical performance of *all-PP* structures is considered adequate when compared to a similar structure made from glass fibre skins. Another type of sustainable sandwich structure is the one made from bottle caps (recycled tubular honeycomb core) and embedded in sandwich structures, as trialled in a previous work by the authors [19]. Polypropylene caps are used to close soft plastic bottles in a variety of beverages but cannot be recycled with the PET bottles, and that results in a more expensive recycling process. Moreover, recycled PP tends to possess less strength and stiffness due to the rupture of the PP polymeric chains [20,21]. Our previous work [19] described the manufacturing of a sandwich panel made of aluminium skins and a bottle cap core bonded with epoxy polymer adhesive. The orientation of the bottle caps (single direction and/or alternated caps) and the use of adhesive between the caps were the fundamental design parameters of the concept. The panels with the alternated bottle caps configurations showed a 20% higher strength compared to the structures with the single aligned caps. The adhesive between caps and the adjacent cells contributed to a further enhancement of the panel strength between 24% and 33%.

The potential re-use of the PP bottle caps is very appealing, since their disposal is very damaging for the environment and wildlife. The estimated amount of bottle caps annually disposed of in landfills is around 320,000 t [22]. Bottle caps have been ranked amongst the top ten items polluting the oceans [23]. In 2007 only, the annual production of PET bottles in Brazil was around 9 billion units [24]. However, there is a large difference in terms of PET and PP recycling rates in different countries. In the US, the recyclability of PET is around 25%, while for PP items is up to 9% only [25]. In Brazil, the recyclability rates of PET and PP were respectively 42% and 9% in 2016 [26]. These figures highlight the urgent need of innovative designs of sustainable products, potentially based on the use of recycled bottle caps.

The present work is focused on the development of a sandwich panel based on aluminium skins and a sustainable core made of bottle caps. The promising findings obtained in the previous research [19] stimulated further investigations on bottle cap panels by testing new architectural designs to improve mechanical properties. A Full Factorial Design was used to identify the effects on the mechanical and physical responses of the panels upon modifications of the bottle caps cells packing (hexagonal and cubic packing), the type of polymeric adhesive (epoxy and polyester adhesive), and the average thickness of the polymeric adhesive (0.8 and 1.5 mm). The mechanical properties considered here are the flexural strength, flexural modulus, skin stress, core shear modulus, core shear stress, and bulk density of the core/sandwich panel.

2. Methodology

2.1. Materials

Sandwich panels were manufactured using a pair of aluminium sheets connected to a core of polypropylene bottle caps by polymeric adhesives. The aluminium sheets (brushed aluminium type ISO 1200 [27] with 0.5 mm thickness, see Fig. 2.a) were sourced from *Barro Preto Metais* (Brazil). Two thermoset polymers were evaluated: an epoxy (Renlam M-1 resin type with Amine-based hardener type - HY 951) and a polyester (Polylyte resin type with MEK hardener type), both supplied by Huntsman (Brazil). Tensile, compressive and flexural strength and

Fig. 2. Aluminium skins (a), Wash Primer components (b) and disposed bottle caps (c) used for sandwich panel manufacturing.