Oliveira, P. R., Bonaccorsi, A. M. S., Panzera, T. H., Christoforo, A. L., & Scarpa, F. (2017). Sustainable sandwich composite structures made from aluminium sheets and disposed bottle caps. *Thin-Walled Structures*, *120*, 38-45. https://doi.org/10.1016/j.tws.2017.08.013

Peer reviewed version

Link to published version (if available):
10.1016/j.tws.2017.08.013

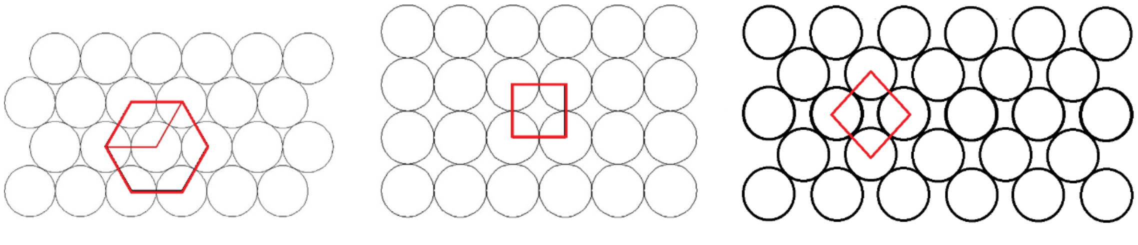
SUSTAINABLE SANDWICH COMPOSITE STRUCTURES MADE FROM ALUMINIUM SHEETS AND DISPOSED BOTTLE CAPS

Abstract: *This work describes the development of a sustainable and low-cost sandwich composite structure made from aluminium skins and bonded to a tubular core with epoxy resin. The core is made from disposed plastic bottle caps. An analysis of variance (ANOVA) has been performed to determine the significance of the orientation of the bottle caps in the core, the use and type of adhesive over the bulk density and the mechanical properties of the sandwich panels. The results show that a core topology made from an alternated orientation of the bottle caps provides an enhancement of the resistance in the face skins and the core. The use of the epoxy adhesive between adjacent bottle caps also gives an increase of the maximum resistance of the panel.*

Key words: *Sandwich composites, bottle caps waste, tubular honeycomb, analysis of variance.*

1. INTRODUCTION

Sandwich structures are made from high-bending stiffness external skins bonded onto high transverse shear and low strength cores, such as foams or honeycombs [1]. The main structural features of sandwich composites are their high specific bending stiffness, strength, and favourable compressive behaviour, which are all characteristics that make them suitable for aerospace applications [2]. A variety of materials have been developed and evaluated as sandwich cores, with the hexagonal honeycomb cells made from aluminium and stainless steel being the most common ones [3]. In recent years the use of alternative core geometries and materials has also been evaluated. One of the most recently developed core topologies is the circular cell honeycomb, also called the tubular honeycomb (TH). THs have been used for different applications, ranging from supporting oil transport infrastructure in on and offshore facilities, to energy absorbing sandwich plates [4]. A significant body of research [4-9] has shown the advantages of using tubular honeycombs to enhance the mechanical performance of sandwich panels. Oruganti and Ghosh [5] have shown the intrinsic stiffness and strength enhancement of TH structures due to the geometrical constraints associated with the deformation of cylinders. Hu *et al.* [6] have also given evidence of the improved energy absorption capability of tubular honeycombs, and their generally adequate mechanical performance under out-of-plane loads. Different geometries of THs have been considered in previous work (Figure 1). The main difference between these packing topologies is the angle between the centres of the adjacent tubes [4]. The angles for the orthotropic, hexagonal, and cubic geometries are 45º, 60º and 90º, respectively.



(a) (b) (c)

Figure 1. Three tubular honeycomb geometries: (a) hexagonal, (b) cubic, and (c) orthotropic [4].

Polymeric tubes as core materials are present in the market, and one example is the tubular sandwich structure from the *Plascore Company*. This material consists of stacked tubes made from polyetherimide and joined by thermal bonding [3]. Another example of tubular core present in open literature is the one within the sandwich structure proposed by Cabrera, Alcock, and Pejis [9]. The specific sandwich panel is fully made from polypropylene (PP) sheets, tubular cores and adhesive layers made of, resulting in an *all-PP* sample. The structure has been designed to be recycled in a single process, since all the components are made from the same material. The overall mechanical performance of this composite has been deemed adequate, when compared against reference samples made from glass fibre laminate skins and cores. Sustainability is one of the main challenges and requirements to develop future materials and structures that need to comply with EU directives for life cycle [9] [10]. A possible way to further address the recycling of waste material for structural applications (albeit secondary), is the re-use of bottle caps. Caps made of polypropylene (PP) are used to close PET bottles, and cannot be recycled together with the PET material since the polypropylene has a higher melting point than the PET. Moreover, recycled PP has less performant mechanical properties due to the rupture of polymeric chains, which leads to a reduction of the tensile strength and the Young's modulus [11]. The use of differentiated recycling processes also causes a lower degree of re-use of the bottle caps compared with the bulk PET material (9% for PP vs. 25% for PET of the total recycled material in the US [12]). In 2012, the annual production of PET bottles in Brazil was close to 562,000 tonnes [13]. It is therefore evident to identify some alternative routes to re-use the plastic caps, and their application as constituents for sandwich composite materials can potentially be a very attractive one. Cabrera, Alcock, and Pejis [9] have highlighted that polypropylene tubular cores achieve a moderate strength and high specific properties, besides being able to provide a new recycling route for the PP waste. Moreover, the closed surface presented by one side of the cap can favour the adhesion between core and skins, depending on the direction of adjacent bottle caps.

The purpose of this work is to investigate the feasibility of using polypropylene bottle caps assembled in a cubic packing as a core material, and the mechanical performance of sandwich panels made with this particular core. The cubic packing for the bottle caps core was chosen because of its intrinsic easy manufacturing process. The sandwich panels have skins made of aluminium and are bonded with epoxy polymer adhesive. Two groups of experiments have been carried out to identify the effects of two manufacturing parameters on the mechanical and physical properties of these panels: (i) the position of the bottle caps and (ii) the bonding between the adjacent caps. The sets of experiments have been performed following a Design of Experiment (DoE) technique to relate the production parameters to changes in the bulk density, flexural stiffness, elastic modulus, skin stress and core shear modulus.

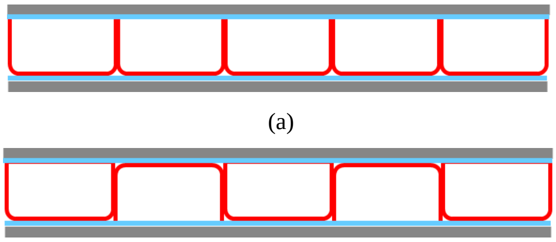
2. MATERIALS AND METHODS

2.1. Composite Materials

The sandwich composites have been made with aluminium skins, bottle caps as polymeric core and epoxy polymer as adhesive. The epoxy resin (Type MX14, Amine-based hardener type HY951) was supplied by Huntsman (Brazil). The aluminium sheets (type ISO 1200 [14] with 0.5 mm thickness) were sourced from Alumiaço (Brazil). The disposed polypropylene bottle caps were obtained from *Coca-Cola*® soft drink bottles. The caps were washed and dried at room temperature for 24h to remove any dirt from the disposal process.

2.2. Statistical Analysis

An Analysis of Variance (ANOVA) was conducted to verify the significance of the response of the two experimental factors used in the DoE [15,16]. The factors were considered in two independent groups of experiments, one group for each factor assessed. The use of individual groups of experiments was considered because those factors were judged to be independent from each other. No interaction effect is therefore assessed in this work. The first group of experiments tested two configurations for each orientation of the bottle caps: the first related to the caps placed along the same direction, the second along an alternated pattern (Figures 2.a and 2.b). The second group of experiments helped to understand the effectiveness of using an adhesive between the bottle caps. For this particular case three levels of experiments were considered: the presence of the bottle caps without adjacent connection, the bottle caps connected with hot melt as adhesive, and the caps bonded together with epoxy polymer. Three-point bending tests were used to determine the bulk density, flexural stiffness, elastic modulus, skin stress and the equivalent core shear modulus. The other factors related to the materials selection and the manufacturing processes were kept constant. These constant factors were the type of resin (Epoxy resin type MX14), the resin fraction (equivalent to an adhesive layer with 1 mm thickness), the resin mixture time (2 min), the cure time of the samples (10 days at room temperature, approximately at 22ºC), type of aluminium sheet used (type ISO 1200 [14] with 0.5 mm thickness), honeycomb packing (cubic), and type of bottle cap (from Coke bottles, diameter of 30.52 mm and height of 12.4 mm). Table 1 summarises the experimental factors and the levels investigated in the two sets of experiments. The Analysis of Variance (ANOVA) provides the significance of each experimental factor on the responses (physical and mechanical properties) based on a confidence interval of 95%. The software Minitab 17 [17] was used for the treatment of the data and the analysis of the results.



(a)

(b)

Figure 2. Schematic views of bottle caps oriented along a single (a) and alternate directions (b).

Table 1. *Experimental conditions*

Experiments	Evaluated Factor	Levels	Samples
1st set of Experiments	Bottle caps Orientation	Same direction (Fig 2.a)	8 (4 in each replicate)
		Alternated Directions (Fig 2.b)	8 (4 in each replicate)
2nd set of Experiments	Adhesive between bottle caps	Without	From the most favourable level of the 1st set of experiments
		Hot melt adhesive	8 (4 in each replicate)
		Epoxy resin reinforcement	8 (4 in each replicate)

2.3. Fabrication and testing

The sandwich structure was produced in two steps. The external side of the aluminium sheet was first covered by a plastic layer to avoid resin leakage. The covered aluminium sheet was then inserted in a mould and adjusted to fit. The epoxy resin and the hardener were mixed for nearly 2 minutes and then spread over the uncovered aluminium surface located inside the mould, this to create a uniform adhesive layer with an estimated thickness of 1 mm. Finally, the bottle caps were placed by hand in sequence over the facings according to the orientation. The resin was cold cured under a 3.5 kPa pressure for 24h. The same process was repeated for the second skin (Figure 3). Figure 4 shows the sandwich plate with the dimensions for the flexural test. The specimen size (242 x 92.1 x 14 mm) was based on those specified in the ASTM C393 standard for long beam samples [18]. Four samples were produced per experimental level (see Table 1), with two replicates adopted for a total of 32 samples. During the first group of experiments no lateral connection between the adjacent bottle caps was used. For the second set of experiments the adjacent bottle caps were however connected using different techniques. The first lateral (sideways) connection method consisted in using hot melt glue between the bottle caps prior to the assembly of the sandwich panels. The second method consisted in spreading some epoxy polymer on the lateral surface of the caps with a wood stick. This operation was performed inside the mould, and the polymer layers created with these techniques helped to generate an additional lateral reinforcement.

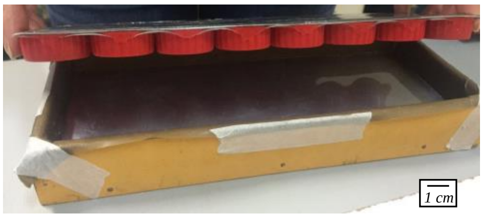


Figure 3. *Second part of sandwich manufacturing process: first face with bottle caps being inserted in the mould with second face with epoxy resin*

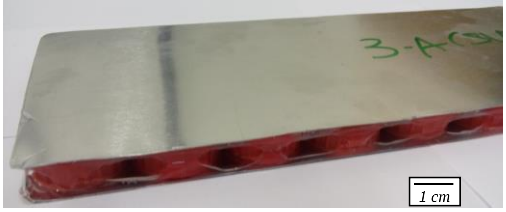


Figure 4. *Sandwich plate made with bottle caps core*

The sandwich plates were tested using a classical three-point bending (3P) loading for sandwich panels following the ASTM C393 standard [18]. Three-point bending tests can provide a rapid estimation of the flexural strength and stiffness of sandwich panels with readily available testing procedures. The 3P bending rig used in our work had a span length of 150 mm and cross head velocity of 6 mm/min, again as recommended by the ASTM C393 standard [18]. The samples were tested using a Shimadzu AGX machine with 100 kN load capacity (see Figure 5).

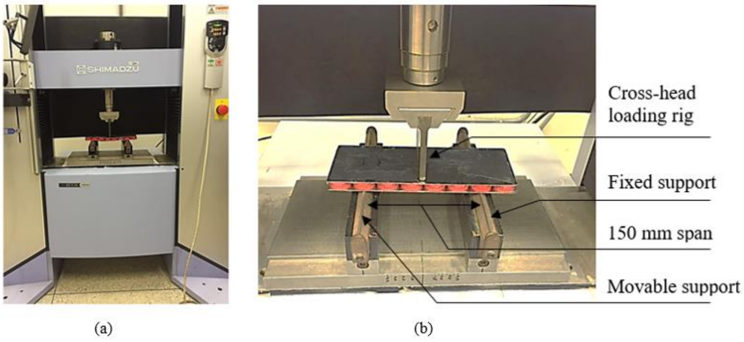


Figure 5. *Shimadzu Universal testing machine (a) and detail of 3P test rig (b)*

The parameters corresponding to the response of the DoE were the flexural stress and the flexural modulus (σ_f and E_f, according to ASTM D790 [19]), the core shear modulus (G_f, calculated following the ASTM D7250 protocol [20]), and the core shear ultimate and skin stresses (F_s^{ult} and σ [18]). The bulk density was determined by weighting each sample using a *Marte BL3200H* scale (ASTM D792-13 [21]). The core shear ultimate stress and the skin stress were calculated based on Equations 1 and 2 (ASTM C393 [18]):

$$F_s^{ult} = \frac{P_{max}}{(d+c)*b}\ [MPa] \tag{1}$$

$$\sigma = \frac{P_{max}*S}{2*t*(d+c)*b}\ [MPa] \tag{2}$$

In these equations P_{max} is the maximum force prior to failure (in N), S is the span length, t is the nominal skin thickness, d is the sandwich thickness, c is the core thickness (obtained from $c = d - 2*t$), and b is the sandwich width. All lengths are in mm. The core shear modulus was calculated using the sets of equations presented below (Equations 3 to 6):

$$D = \frac{E_{skin}*(d^3-c^3)}{12}\ [N-mm^2] \tag{3}$$

$$U_i = \frac{P_i*(S-L_1)}{4*\left(\Delta - \left(\frac{P_i}{96*D}*(2*S^3)\right)\right)}\ [N] \tag{4}$$

$$G_i = \frac{U_i*(d-2*t)}{(d-t)^2*b}\ [MPa] \tag{5}$$

$$G_f = \frac{\sum_{i=1}^{10} Gi}{10}\ [MPa] \tag{6}$$

Those equations are only appropriate if the elastic moduli of the skins are previously determined, and if both skins are identical (ASTM D7250 [20]). The flexural stiffness (D) is first calculated, with E_{skin} being the Young's modulus of the skin (see Equation 3). The shear rigidity (U_i) and the core shear modulus (G_i) are calculated for a series of ten applied forces evenly spaced up to maximum force (see Equations 4 and 5). In those equations P_i is the force level considered (in N), L_1 is the load span length (for 3PB test, $L_1 = 0$) and Δ is the beam mid-span deflection (in mm) at each force level considered. When the mechanical response of the sandwich panel is approximately linear the overall core shear modulus (G_f) can be calculated from the values obtained at all force levels (see Equation 6). The flexural strength and modulus are calculated using Equations 7 and 8 (ASTM D790 [19]):

$$\sigma_f = \frac{3*P_{max}*S}{2*b*d^2}\ [MPa] \tag{7}$$

$$E_f = \frac{S^3*m}{4*b*d^3}\ [MPa] \tag{8}$$

For equation (8), the slope coefficient m (in N/mm) that indicates the slope of the initial straight-line portion of the load deflection curve is required.

A microhardness test was carried out on the bottle cap samples to characterise the hardness H_V of the core material. Square samples of 10 mm of side (Figure 6) were tested using a Mitutoyo MVK-G1 machine. The material shear (τ_{max}) and tensile stress (σ_{max}) can be extracted by using the Tresca criterion shown in Equations 9 and 10 [22]. The elastic modulus of the material (E) was determined from Equation 11 (see Giménez *et al.* [23]).

$$\sigma_{max} = \frac{H_V}{3} \tag{9}$$

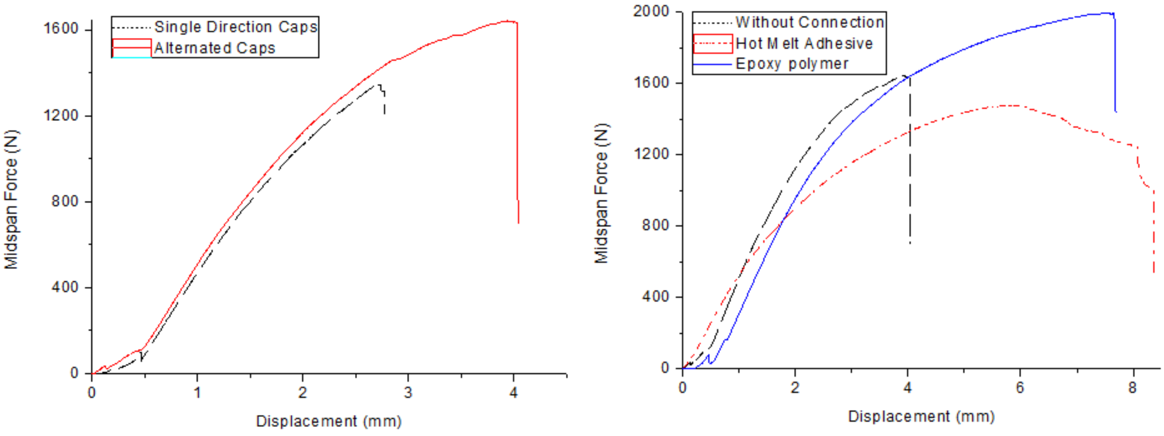
$$\tau_{max} = \frac{H_V}{6} \tag{10}$$

$$E = H_V * 20 \tag{11}$$

Figure 6*. Bottle caps samples used in the microhardness test*

3. RESULTS

Table 2 shows the average values of the investigated parameters calculated using Equations 1 to 8. The values in the brackets correspond to the standard deviation of the calculated means. The first group of experiments (Experiment #1) indicates that the sandwich panels made with the alternate oriented bottle caps topology had the highest average values. The second group of experiments (Experiment #2) allowed to evaluate the types of connections, but only for the cores made with the caps in alternated directions, since this level featured the most promising mechanical properties in Experiment #1. Figure 7 shows some examples of the mid-span force vs displacement of the different types of panel topologies tested. Although both the single and alternate caps directions show a very similar overall stiffness (Figure 7a), the sandwich panel with alternate caps featured the highest strength and toughness. The use of the hot melt adhesive provided a reduction of the sandwich panel stiffness (Figure 7b). On the other hand, the hot melt adhesive contributed to a slight improvement of the panel toughness. Sandwich panels with adjacent caps connected with the epoxy polymer featured a higher strength and toughness than the samples with no connection.



(a) (b)

Figure 7*. Flexural mid-span Force vs. Displacement plots of Experiment #1 (a) and Experiment #2 (b).*

Table 2. *Mean Results and standard deviation values obtained during the sandwich flexural tests for each condition.*

Responses	Same bottle cap orientation	Alternate bottle cap orientation	Alternate bottle cap connected with hot melt adhesive	Alternate bottle cap connected with epoxy polymer

Maximum Force (N)	1249.17 (81.67)	1515.17 (125.92)	1395.97 (108.69)	1874.55 (130.29)
Core shear stress (MPa)	0.497 (0.038)	0.596 (0.061)	0.530 (0.045)	0.769 (0.065)
Skin stress (MPa)	74.49 (5.84)	89.42 (9.12)	79.99 (6.68)	115.38 (9.69)
Shear Modulus (MPa)	29.54 (4.68)	33.58 (5.35)	17.88 (1.92)	32.04 (6.59)
Flexural Modulus (GPa)	2.01 (0.31)	2.31 (0.30)	1.57 (0.14)	2.49 (0.15)
Flexural strength (MPa)	15.343 (1.409)	18.20 (2.181)	15.89 (1.584)	24.26 (2.41)
Bulk Density (kg/m^3)	514.62 (7.75)	510.42 (9.21)	493.02 (10.53)	532.04 (10.41)

In the Analysis of Variance (ANOVA) it was assumed that no interaction occurred between the bottle caps orientation and the connection factors. Table 3 illustrates the P-Values obtained for each investigated response. The P-values in bold are those below 0.05, and they are indicators of the presence of significant effects. The value of 'R^2 Adjust' was also obtained to show how well the statistical model predicts the responses from new observations. Higher values of R^2 (adj) imply models of greater predictability. The R^2 (adj) value for bottle cap orientation varied from 76.49% to 92.34%. For the bottle cap connections, the R^2 ranged from 73.65% to 79.45%. These values indicate a satisfactory adjustment of the data to the model. Tukey and Fisher tests were performed for the results of the Experiment #2 to compare the average values in each condition and identify the statistically significant levels. This comparison test was carried out since three levels were assessed during the Experiment #2, and ANOVA was not able to report which level is significantly different from the others [16].

Table 3. *P-Values for each response*

Responses	Bottle caps orientation	Bottle caps connection
Maximum Force (N)	**0.010**	**0.007**
Core shear stress (MPa)	**0.028**	**0.006**
Skin stress (MPa)	**0.028**	**0.006**
Shear Modulus (MPa)	0.269	**0.008**
Elastic Modulus (GPa)	0.227	**0.004**
Flexural strength (MPa)	0.061	**0.006**

The average values of the microhardness and the predicted mechanical properties (Eq. 9, Eq. 10, and Eq. 11) are shown in Table 4. The strength and the stiffness values show a good agreement with analogous results reported in open literature [24].

Table 4. *Characterisation of core material by microhardness test.*

Parameters	Values
Hardness (MPa)	**50.3**
Elastic Modulus (GPa)	**1.01**
Tensile strength (MPa)	**16.7**
Shear Strength (MPa)	**8.4**

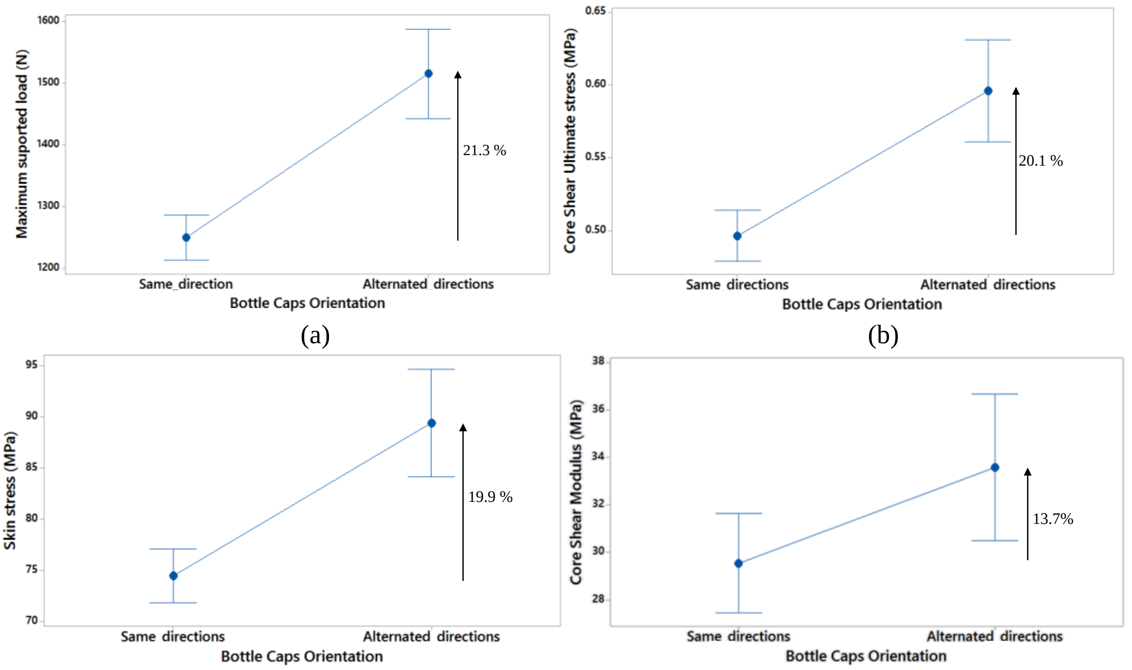
4. DISCUSSIONS

4.1. Bottle Caps Orientation

Table 2 shows that the alternated caps topology had a higher flexural strength compared to the one with the caps along the same direction. Further evidence to that conclusion is given by the graphs in Figure 8, which provide a comparison of the mean values and standard deviations in the two tested levels for all measured responses. However, according to the P-Values shown in Table 3 the bottle caps orientation has a significant effect only on the maximum bending force, core shear stress and skin stress. The P-Value for the flexural strength (0.061) was slightly above 0.05, which may indicate a significant effect if a lower confidence interval is considered.

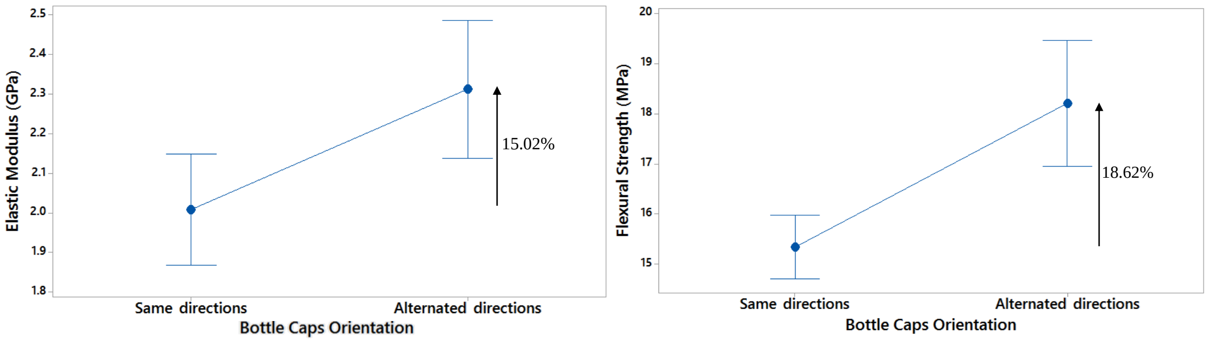
The flexural modulus was significantly lower than the Young's modulus of the aluminium. This discrepancy can be attributed to a reduced adhesion between the smooth aluminium surface and the epoxy used to bond the skins to the bottle caps core. Therefore, early delamination prevented full contribution of the aluminium to the mechanical performance of the sandwich panels. The results were significantly dependent upon the core and the adhesives used, with the flexural modulus being quite similar to the modulus of the epoxy [25]. It is possible in principle to apply surface treatments and prevent the premature delamination caused by the reduced adhesion. These treatments of the aluminium surface range from chemical (primer finishing) to mechanical (sandpapering), in addition to mechanical fastening between the skins and the polymeric core.

The higher values observed for the alternated bottle cap orientations may be justified by the distribution of the contact area between the bottle caps and the aluminium facings. It is a well-known fact that the bonding between metallic sheets and sandwich cores is a critical aspect for the mechanical performance of sandwich plates [26]. The bottle cap provides a larger contact area with the aluminium sheet because of the closed side. The core made from single direction caps provides an asymmetric connection with the facings. A lower mechanical performance, in terms of maximum force, can therefore be attributed to the presence of a reduced contact area between the core and skin on the open surface of the caps.



(a) (b)

(c) (d)



(e) (f)

***Figure 8**. Effect plots for the maximum force (a), core shear stress (b), skin stress (c), shear modulus (d), Flexural Modulus (e), and Flexural strength (f).*

Figure 9 shows an example of a failed sandwich panel with a core along a single direction. One can observe the presence of a delamination failure occurring on the face connected to the open surface of the bottle caps. This is a clear indication of the presence of a reduced contact and bonding area.

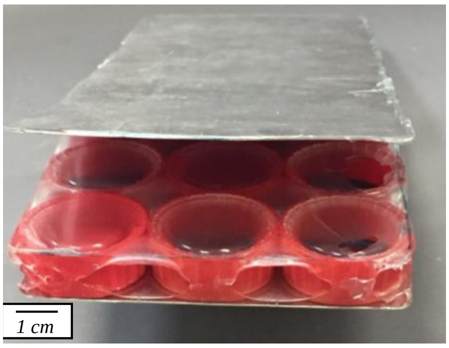


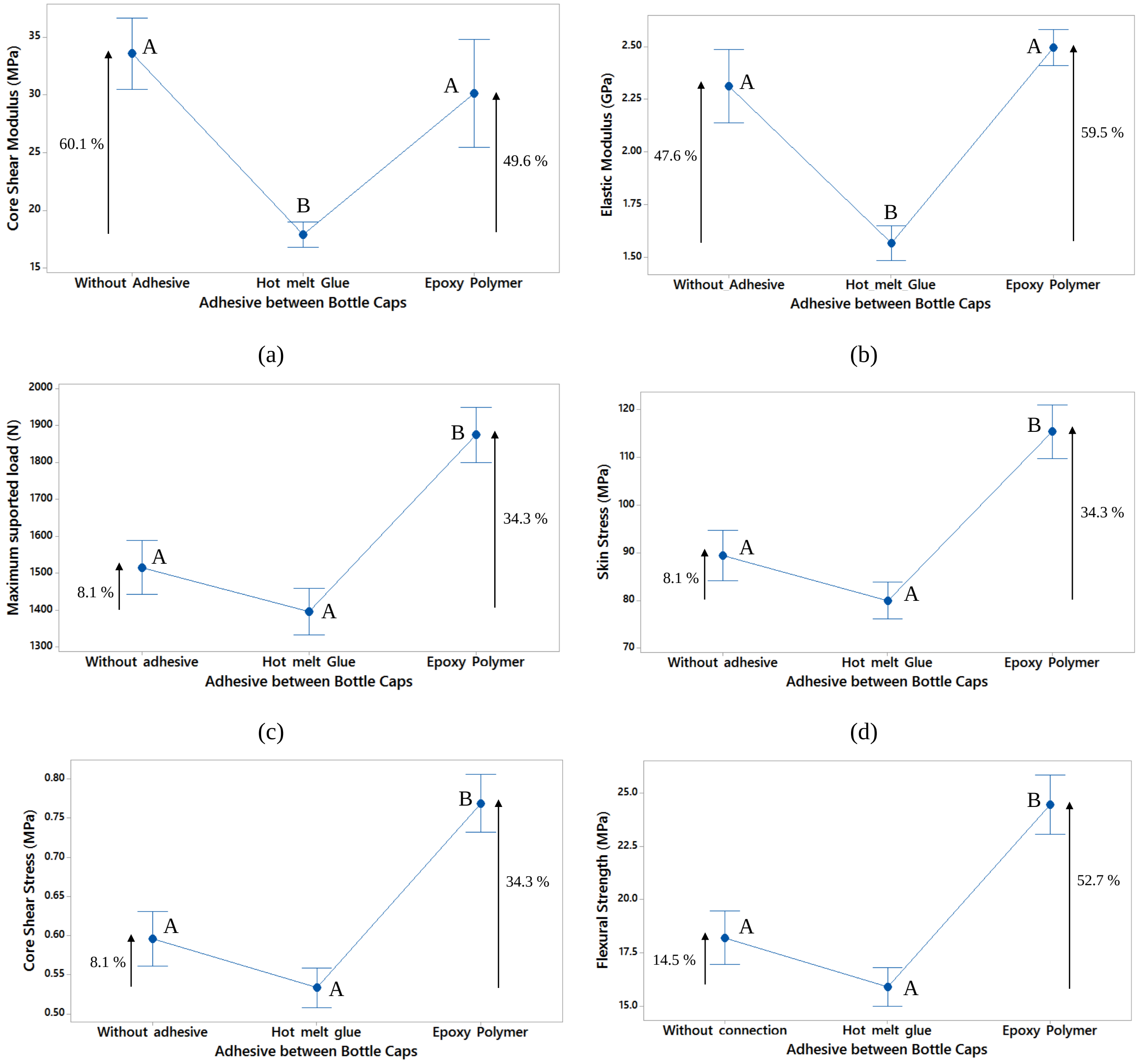
***Figure 9**. Failed Bottle caps sandwich samples with evident delamination on cap side with open end.*

Delamination led to a shear failure of the core in the region between the adjacent bottle caps (Figure 10). The same failure pattern was observed in all samples with single direction caps. The higher force carried by in samples with the core made from bottle caps in alternate directions can be therefore attributed to the enhanced contact area with the two skins. Considering that the core shear stress, skin stress and flexural stress are dependent on the maximum force, the same conclusion can be extended to these mechanical parameters.

***Figure 10**. A bottle caps sandwich sample with core shear failure between the adjacent caps.*

4.2. Connection of Bottle Caps

A set of P-values lower than 0.05 (Table 3) indicate that all the mechanical parameters were significantly affected by the type of connection used. The highest mechanical performance of the sandwich panels was obtained for lateral connections with the epoxy. Figure 11 shows the mean values and standard deviation plots for the mechanical results assessed using the second experiment.



(a) (b)

(c) (d)

(e) (f)

***Figure 11**. Effect plots and comparison of the average results from various tests for the shear modulus (a), flexural modulus (b), maximum load (c), skin stress (d), core shear stress (e) and flexural strength (f).*

Tables 5 and 6 show the Tukey and Fisher matrices related to the comparison of the mean values. In these matrices, two levels that are not considered statistically different share a letter. The letters shown in Tables 5 and 6 are also presented in Figure 11. The comparison shows that the use of the hot melt adhesive had a major influence on the shear and the elastic moduli (see Table 5), causing some significant reductions of these engineering constants (12.7% and 32.3%, respectively). The reduced rigidity presented by the hot melt adhesive is the likely reason for the presence of a lower panel stiffness under bending deformations. The temperature of the hot melt glue is close to 130ºC [27], and this can partially affect the thermoplastic microstructure, since the melting temperature of the polypropylene is around 160ºC [24]. In contrast, the Tukey and Fisher tests did not identify significant differences between the averages of those responses when the epoxy was used. This fact may be attributed to the similar composition between the sandwich composites with and without the epoxy polymer connection in adjacent caps. In the two classes of sandwich panels the amount of epoxy was almost the same.

Table 5. *Tukey and Fisher comparison test matrix for Shear Modulus and Flexural Modulus.*

	Levels	Matrix
Adhesive between Bottle Caps	Without adhesive	A
	Epoxy polymer reinforcement	A
	Hot melt adhesive	B

Table 6. *Tukey and Fisher comparison test matrix for Maximum Load, skin stress, core shear stress and flexural strength.*

	Levels	Matrix
Adhesive between Bottle Caps	Without adhesive	A
	Hot melt adhesive	A
	Epoxy polymer reinforcement	B

The comparison of the average results for the remaining parameters showed a significant increase in the mechanical response when the epoxy was used between adjacent bottle caps (see Table 6). The majority of the epoxy-connected samples did not present a visual shear failure between adjacent bottle caps. However, only one specimen from all tested samples reinforced with epoxy resin presented the previous failure mode (out-of-plane shear failure between bottle caps). That observation evidences a significant enhancement of the shear strength provided by epoxy resin between bottle caps. The failure of the reinforced panels was mainly due to the delamination of the aluminium skin. Figure 12 shows two examples of tested panels with the core made from the epoxy-connected caps. It is seen from the figure that the core is almost intact after the test. The use of the hot melt adhesive did not significantly change the other parameters. A small reduction of the average values however occurred, indicating that the hot melt adhesive did not act as expected to enhance the mechanical performance of the sandwich structures (see Figures 11.c to 11.f).

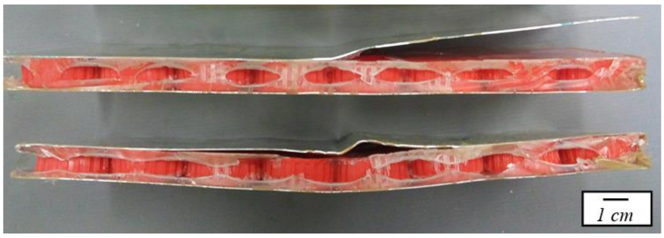


Figure 12*. Tested Bottle caps sandwich samples with no visible shear failure.*

4.3. Comparisons with other sandwich materials

Table 7 compares the best setup condition (alternated orientation for bottle caps connected with epoxy resin) with a sandwich composite with tubular polypropylene core and polypropylene skins manufactured following the guidelines of Cabrera, Alcock, and Pejis [8]. The core density and some composite mechanical properties were compared between the two configurations. For a meaningful comparison, we have evaluated the specific properties (i.e., the ratio between each mechanical property and the composite bulk density). It is noted that all the mean values of the mechanical parameters obtained for the sandwich panel produced in this paper were superior to those achieved by the tubular core panel in [8]. Positive percentages mean that the properties of the sandwich bottle cap panels are higher. Despite the higher density of the panel with the bottle caps (0.532 g/cm³), the higher specific properties show the overall high specific mechanical performance, and the feasibility of using the proposed bottle-cap sandwich panel configuration for secondary structural applications that require low-cost lightweight materials.

Table 7. *Comparison between the proposed sandwich composite and the sandwich composite with tubular core manufactured in [8]*

Response	Alternate bottle cap orientation with epoxy connection	PP composite [8]	Percentage Variation
Core Bulk Density (g/cm³)	0.1875 (0.0070)	0.120	56.25%
Composite Bulk density (g/cm³)	0.532 (0.104)	0.195	172.82%
Flexural rigidity (N-m²)	280.75 (10.53)	54.81 (2.21)	412.23%
Specific Flexural Rigidity (x 10^{-6} N-m/g)	**527.73 (19.80)**	**281.07 (11)**	**87.75%**
Shear stress (MPa)	0.77 (0.07)	0.27	184.81%
Specific Shear Stress (N-m/g)	**1.45 (0.12)**	**1.3**	**4.33%**
Skin Stress (MPa)	115.38 (9.69)	24	380.73%
Specific Skin stress (N-m/g)	**216.87 (18.22)**	**123.08**	**76.21%**

5. CONCLUSIONS

This work has introduced a concept sandwich structure composed of aluminium skins and a core consisting of bottle caps connected by epoxy polymer. The design concept may provide a possible route to reuse disposed bottle caps that possess a lower degree of recyclability than their PET bottles, due to the higher melting temperature of the PP and its reduced performance after recycling. Statistical analyses (ANOVA and Comparison Mean Tests) were performed to identify the effect of the bottle cap orientation and the methods used to connect the caps on the mechanical performance of the sandwich panels. The bottle caps oriented along alternate directions provided a larger contact area with the external skins. The samples with that particular core exhibited enhanced mechanical properties under 3P bending loading, especially in terms of maximum force, shear and skin stresses. In addition, the use of an epoxy to connect the adjacent bottle caps provided a further increase of those mechanical parameters. That effect was however not observed when a hot melt adhesive was used for this purpose. The elastic and shear modulus appeared to be independent of the geometry and the connection methods used. In summary, this work featured a feasible approach to reuse domestic waste in a lightweight composite material, which can be used for secondary structural parts in engineering applications.

ACKNOWLEDGMENTS

The authors would like to thank the Brazilian Research Agencies, CAPES, CNPq and FAPEMIG for the financial support provided.

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