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TRANSVERSE FASTENING REINFORCEMENT OF SANDWICH PANELS WITH UPCYCLED BOTTLE CAPS CORE

P. R. Oliveira[1], L. J. da Silva[2], T. H. Panzera[2], G. G. del Pino[3], F. Scarpa[4]

[1]Department of Sustainable Systems Engineering – INATECH, Albert-Ludwigs-Universität Freiburg, Freiburg im Breisgau, Germany.
[2]Centre for Innovation and Technology in Composite Materials (CIT^{e}C), Department of Mechanical Engineering, Federal University of São João del Rei (UFSJ), São João del Rei, Brazil.
[3]Department of Mechanical Engineering, State University of Amazonas, Manaus, Brazil.
[4]Bristol Composites Institute (ACCIS), University of Bristol, UK.

Abstract: *This work describes the use of transverse reinforcement in eco-friendly sandwich panels made from aluminium skins and a core of upcycled bottle caps. The Design of Experiments technique identifies the effect of the position of the metal rivets on the panel. The results show a moderate increase in strength and a significant enhancement of the sandwich panel stiffness when the rivets are placed on the upper skin, with a remarkable improvement in terms of the core shear modulus. The use of metal rivets has also increased the specific mechanical strength and stiffness of the panels, which highlights the effectiveness of the transverse reinforcement in bottle caps panels.*
Keywords: *sandwich composite; transverse fastening; tubular honeycomb; bottle caps waste; design of experiment (DoE).*

1. Introduction

Sandwich panels are structural components made from bonding two stiff rigid plates to a thick and soft core [1]. One of the main characteristics of sandwich panels is their excellent strength-to-weight ratio, which makes this structural element suitable for lightweight and resistant structures in aerospace and vehicle frames [2]. A variety of materials can be used as panel skins, from metals to composite laminates. A wide range of core materials is also available, such as polymer foams, wood (e.g. balsa wood) [1], and different types of honeycombs, the latter being perhaps the most widespread used type of sandwich core [3]. The most common honeycombs are those with hexagonal cells, which feature high-energy absorbing capacity and lightweight configurations. In recent times, however, a new core cell configuration emerged: the honeycomb with tubular circular cells (i.e., the tubular honeycomb [4]).

Tubular honeycombs (THs) act as a sandwich panel core in a range of applications, from fuel transport to structural load bearing element. THs have been used since the early 60s to replace cores made of balsa wood [1]. Oruganti and Ghosh [5] have found that the circular cell can enhance the panel stiffness compared to honeycombs made with hexagonal cells. The deformation strength and yield stress can increase up to 20% [6] depending on the cell packing (hexagonal or cubic packed cells). Hu et al. [7] have observed that the energy absorbing capacity in THs could be increased by 23% by adopting a hexagonal packing of circular cells compared to a cubic one, due to the greater number of adjacent cell constraints (6 in hexagonal packaging vs. 4 in the cubic). The hexagonal packing could prevent cell wall buckling and reduce the deformation of the structure.

Recent investigations of sustainable honeycombs aim to reduce environmental impact and to increase the recyclability of structures. Cabrera, Alcock, and Pejis [8] proposed the development of a sustainable tubular honeycomb by creating a sandwich panel fully composed of PP (polypropylene) in the skins, core and adhesive. The use of PP components aims to facilitate the recycling of the panel in a single process. The mechanical responses of the panel under flexural loads were adequate, and that highlighted the feasibility of using thermoplastic materials to build the panel. Recently, Oliveira et al. [9, 10] have also proposed a circular thermoplastic core based on bottle caps as circular cells. The use of discarded bottle caps as a sandwich panel core was motivated by the need to recycle large annual disposal quantities of bottle caps in landfills (~320,000 tonnes) [11]. The bottle caps are made of polypropylene and cannot be recycled together with the polyethylene terephthalate (PET) plastic bottles. The difficulty of recycling bottle caps has created a large gap in the recycling rate of the two bottle components. For example, amongst the polymers recycled in Brazil, 42% are PET-based plastics, while only 9% of them are made of PP [12]. This scenario is not different in other countries, such as the USA, with a recycling rate of 25% for PET and 9% for PP [13]. In the United Kingdom, 13 billion units of plastic bottles are produced annually, but the caps are among the ten most scattered items on British beaches found during cleaning works, which highlights the difficulty of the recycling routes for caps [14].

Two previous works were carried out to identify the effects of the geometry, packing topology and bonding of aluminium bottle caps panels. Oliveira et al. [9] reported that the use of bottle caps placed in alternate directions increased the panel strength by 20% compared to individually oriented caps. Intra-cap connections with epoxy adhesive also provided increasing panel strength up to 33%. The authors also investigated the effects of the type and amount of adhesive (epoxy and polyester) and the cell packing system (hexagonal and cubic) on the mechanical properties of aluminium bottle caps panels [10]. Thick epoxy polymer adhesives increased the flexural strength and the stiffness of the panel by 55%. In addition, the core shear modulus and the elastic modulus increased approximately 8 and 13%, respectively. Cell packing did not substantially affect the panel strength; however, the cubic packing provided the highest mechanical performance, which contrasts with other results in open literature about tubular honeycombs [5-7].

The reinforcement of sandwich panels can be also achieved by using cross-sectional fasteners that prevent early delamination of the skin. In that case, it is recommended to use screws and rivets for the transverse support. Stainless steel and aluminium are some of the materials recommended because of their high strength and low susceptibility to corrosion [15]. Sapozhnikov and Shakirov [16] have evaluated the use of rivets and screws as reinforcement of the polymer bonding. The use of rivets of 4.5 mm diameter increased the resistance of the specimens under shear by up to 10%. Smaller rivet diameters reduced the stress concentration, despite the difficulty of fixing those to the structure. The main failure modes observed were skin cracks and rivet rupture due to shear loads. Other failure modes mentioned by Matteis and Landolfo [17] include the inclination of the rivet under skin shear load and the skin delamination (similar to wrinkling failure). The failure modes were divided by the authors in fragile and ductile, the latter being recommended.

The main problem related to transverse fastening is the drilling with the consequent generation of stress concentrators. Khoran et al. [18] evaluated the effect of the drilling parameters and the diameter of the drill on the damage of sandwich panels with glass fibre reinforced polymer (GFRP) skins and various cores, such as balsa wood and corrugated/non-corrugated polyvinyl chloride (PVC) foams. The authors found that the intermediate values for drill diameters (up to 7 mm) and cutting speed (up to 1600 rpm) lead to reduced delamination coefficients. Rezende et al. [19] have studied the influence over the burr height and the thrust force of the drill geometry, feed rate, and the use of a pilot hole when drilling a panel made of aluminium skins and polyethylene foam core. The authors found that higher feed rates reduce the thrust force due to the reduced material stiffness at higher speeds. The use of the pilot hole, on the other hand, increases the burr height, affecting the delamination of the panel.

Despite its demonstrated improved stiffness, mechanical fastening has not been extensively explored to develop lightweight sandwich panels. Therefore, this work discusses the effects of transverse reinforcements on honeycomb bottle caps, a proposal for an eco-friendly core for sandwich panels to help provide an alternative route for the disposal of bottle caps. The position of the rivets in the skins is assessed using a statistical analysis based on a full factorial design (DoE, design of experiments) and analysis of variance (ANOVA). The use of rivets can take advantage of the closed surface of plastic bottle caps, reducing the delamination to aluminium skin. The metallic components also provide good mechanical performance to the bottle caps panels, despite increasing their ecological footprint and hindering the panel recycling, for which alternative skins and bio-based adhesive are recommended [20]. The mechanical and physical responses, such as flexural modulus, core shear strength and modulus, skin stress, and their weight-specific properties determined by the equivalent density are evaluated to obtain the best reinforcement design for lightweight secondary structures in transportation facilities, as cargo bays and truck floors.

2. Materials and methods

2.1. Composite materials

The material of the face skins is brushed aluminium (ISO 1200 H14) [21] with 0.5 mm thickness. The aluminium sheets are treated with a bi-component wash primer (Sherman-Williams) that combines a primer 045 and a catalyst 051. An epoxy adhesive supplied by Huntsman is prepared by mixing the Renlam-M and HY951 parts at 10:1. The disposed caps from Coca-Cola^{TM} soft drink bottles are made of polypropylene [22]. The caps are obtained with local recyclers, washed and dried for 24 hours at room temperature. The aluminium rivets used in this work have a diameter of 3 mm and a length of 10 mm. The properties of the aluminium skin, epoxy polymer and bottle caps were determined by the authors in previous studies [9,10] and are summarised in Table 1. Bottle caps properties are determined from the converted Vickers hardness of a 10 mm square sample extracted from upper surface of bottle caps [9].

Table 1. Mechanical properties of the individual panel components [9,10].

Components response	Aluminium skin	Epoxy polymer	Bottle cap
Tensile strength, MPa	105.7	48.27	16.7
Elastic Modulus, GPa	35.34	2.25	1.01
Shear Strength, MPa	-	-	8.4
Compressive strength, MPa	-	80.46	-

Hardness, MPa	-	-	50.3

2.2. Design of experiment (DoE)

Three DoE factors investigate the effect of the transverse reinforcement provided by the rivets associated to their location: the rivets placed on (i) the upper, (ii) the lower and (iii) on both skins sides (Table 2). Figure 1a shows a schematic drawing of the rivets positions. The first two configurations are based on the use of rivets on skins subjected either to tensile or compressive loads during the flexural test. Rivets are placed in all caps whose closed surfaces are in full contact with the skin (half of the caps). Twelve rivets are applied, and this corresponds to half of the caps being fixed to one of the skins. The third set of rivets on both skins considers half of the total rivets (six rivets) on the upper skin and the other half (six rivets) on the lower skin (Figure 1b). The rivets are distributed in both skins around the peripheral area to avoid the delamination of the skins under bending. Panels without rivets manufactured by Oliveira *et al.* [10] are used as reference baseline.

Table 2. Factor and its levels investigated in this work.

Factor	Level
Transverse reinforcement	Without rivets (reference condition investigated in [10])
	Rivets on upper skin (under compression - see Fig. 1a)
	Rivets on lower skin (under tensile - see Fig. 1a)
	Rivets placed on both skins (see Fig. 1b)

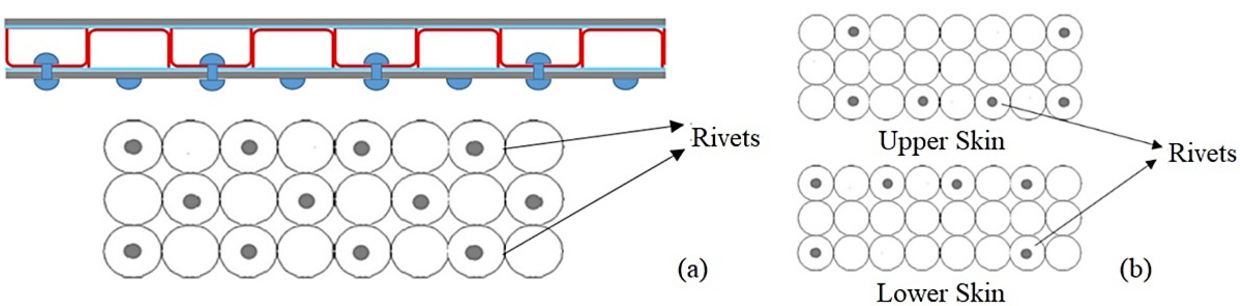


Figure 1. Lateral view and rivets distribution scheme at single skin (a) and distribution of rivets in both skins (b).

The mechanical responses (skin stress, core shear stress, core shear modulus, flexural modulus) have been determined by three-point bending tests, besides determining the equivalent density to obtain specific properties. The following factors have been maintained constant [10]: the type of adhesive (epoxy polymer), the cubic packing system and the adhesive thickness (1.5 mm).

Other manufacturing parameters have been considered based on previous work [9]: the polymer blending time (2 minutes); curing time (7 days at room temperature, approximately 22ºC); the aluminium skin type (brushed aluminium ISO 1200 [21] with 0.5 mm thickness); orientation of bottle caps (alternate bottle caps); use of intra-cap connection with the polymer; and type of bottle caps (from Coca-Cola® bottles, with 30.5 mm diameter and 12.4 mm height). Four samples are produced per condition (excluding the reference condition, manufactured in previous study [10]) considering two replicates, resulting in 24 specimens. The data have been analysed using ANOVA, with the significant levels affecting the responses determined within a 95% confidence interval [23] by the Minitab software.

2.3. Manufacturing and testing

The manufacturing procedure to bond each skin to the core consists of two steps. First, the aluminium surfaces are sanded (600 mesh-size). The sanding is followed by acetone cleaning and spraying of the wash primer. The outer skin surface is protected with a plastic film to prevent resin leakage and placed in a wood. Subsequently, the epoxy adhesive is prepared and spread on the aluminium surface to create a uniform adhesive layer. The bottle caps are placed on the aluminium sheet following packing and orientation previously determined in [9, 10]. The mould is closed with a lid and a cold pressure of 3.5 kPa is applied for 24h. The partially manufactured sample is subsequently removed from the mould and drilled at the specific locations using 3mm steel drill bits. The rivets are then applied using a rivet gun. The second skin is attached to the panel following the same manufacturing steps previously described. The compaction time is 24h, followed by a cure time of 7 days at room temperature. Typical samples have 246.5 × 91.5 × 13.5 mm^3 size. The dimensions are based on the guidelines from ASTM C393 standard [25].The mechanical properties were determined via three-point bending (3PB) performed using a Shimadzu AGX universal testing machine with 100kN load capacity. The test followed the guidelines of ASTM C393 standard [25] considering a crosshead speed of 4 mm/min and a span length of 150 mm.

The 3PB test results in the load vs. displacement curve. Mechanical properties are then calculated from the maximum load before failure and geometrical parameters. The investigated responses are the flexural modulus (E_f, according to ASTM D790 [26]), the core shear modulus (G_f, calculated according to ASTM D7250 [27]), and the core shear and skin stresses (F_s^{ult} and σ, always in accordance with ASTM C393 [25]). The equivalent density is calculated by weighing each sample using a precision scale and determining the sample volume (ASTM D792-13 [28]). The weight-specific properties are obtained by the ratio between the responses and the density.

3. Results

Table 3 shows the average results and standard deviations of the bending test and Table 4 presents the statistical analysis including ANOVA, normality (Anderson-Darling) and homogeneity (Bartlett) tests. ANOVA reports the significance of factors based on P-Values (probability values), which indicate whether a factor or interactions may affect a particular response. P-Values obtained from the ANOVA lower than 5% indicate that the factor affects significantly the response within a 95% confidence interval. Significant effects are assessed using effect plots that show the means for each value of a categorical variable. A line connects the points for each variable; however, they are not considered to be scatter plots [23]. Additionally, the R^2-adjusted values represent the adjustment of the analysed data to the statistical model. Higher values of R^2 (adj) (closer to 100%) indicate models with higher confidence to predict results from new observations. The R^2-adjusted presented here varies between 88.3% and 92.5% and indicates adequate adjustments of the data to the model. ANOVA findings are only valid when the response data follow a normal distribution and the variances are homogeneous. Therefore, two statistical tests, the Anderson-Darling (AD) and Bartlett tests are also conducted to verify respectively the normality and homogeneity of the data. The P-Values obtained in the Anderson-Darling and Bartlett tests should be greater than 5% to indicate that the response data follow the normal distribution and that the variances are homogeneous, which is verified for all responses, validating the ANOVA conclusions.

Table 3. Average experimental results with standard deviation (in parentheses) for the experiment proposed in this work.

	Maximum load, N	**Core shear stress, MPa**	**Skin stress, MPa**	**Core shear modulus, MPa**	**Flexural elastic modulus, GPa**	**Density, kg/m³**	**Specific core shear stress, N.m/g**	**Specific skin stress, N.m/g**	**Specific core shear modulus, N.m/g**	**Specific elastic modulus, 10³ N.m/g**

Without rivets [10]	2,111.1 (73.7)	0.9 (0.03)	129.3 (5.0)	29.6 (3.0)	2.8 (0.2)	589.3 (14.2)	1.5 (0.05)	219.3 (6.9)	50.3 (5.0)	4.8 (0.4)
Rivets on upper skin	2,299.4 (93.9)	1.0 (0.04)	144.8 (6.0)	52.4 (6.0)	4.0 (0.2)	620.9 (3.0)	1.6 (0.1)	233.2 (9.8)	84.4 (9.5)	6.4 (0.4)
Rivets on lower skin	2,282.8 (114.1)	1.0 (0.05)	143.9 (7.7)	43.8 (4.3)	3.5 (0.2)	620.5 (4.2)	1.5 (0.1)	230.8 (12.2)	70.4 (6.9)	5.7 (0.3)
Rivets on both skins	2,307.0 (94.8)	1.0 (0.04)	143.5 (6.5)	38.4 (4.3)	3.2 (0.3)	615.3 (4.3)	1.6 (0.1)	233.2 (9.6)	62.4 (6.7)	5.1 (0.5)

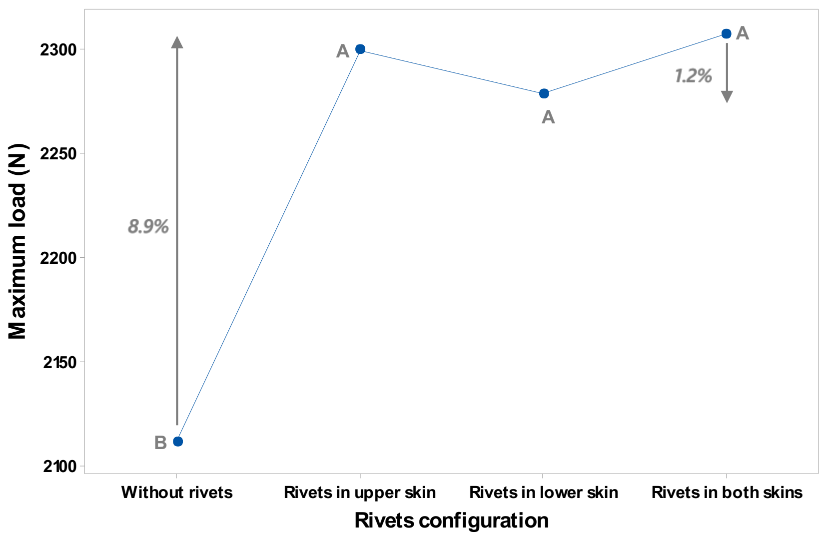
Table 4. ANOVA results for the experiment proposed in this work

	Maximum load	**Core shear stress**	**Skin stress**	**Core shear modulus**	**Flexural elastic modulus**	**Specific core shear stress**	**Specific skin stress**	**Specific core shear modulus**	**Specific elastic modulus**
ANOVA (P-values ≤ 0.05)	**0.010**	**0.013**	**0.013**	**0.014**	**0.018**	**0.024**	**0.024**	**0.016**	**0.025**
R^2-adjusted (%)	92.45	91.61	91.61	91.33	89.95	88.48	88.48	90.62	88.33
AD test (P-values ≥ 0.05)	0.400	0.304	0.304	0.525	0.191	0.754	0.754	0.551	0.422
Bartlett (P-values)	0.202	0.849	0.849	0.559	0.913	0.645	0.645	0.439	0.796

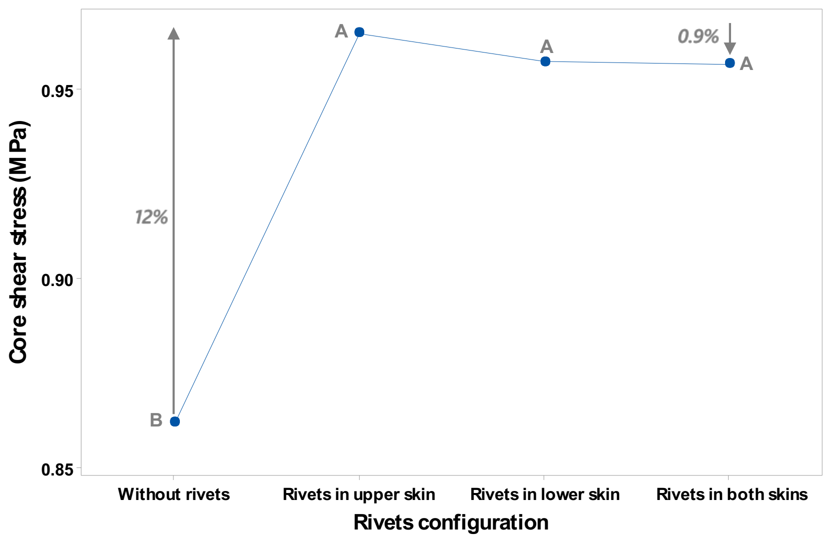
ANOVA is able to identify the effect of significant factors; however, it does not indicate which levels most affect the response. In this context, the Tukey test is used to compare the effects between different levels for each response-variables [23]. The Tukey test identifies which levels are statistically different from the others based on a 95% confidence interval. Levels with similar mean values share a letter or a group of letters, e.g. A/AB, while different mean values display different letters. The responses based on the strength, stiffness, and density of the panel are independent of each other, for this reason, they can present different Tukey letters for the same level of the investigated factor.

3.1. Maximum load, core shear and skin stress, and specific properties

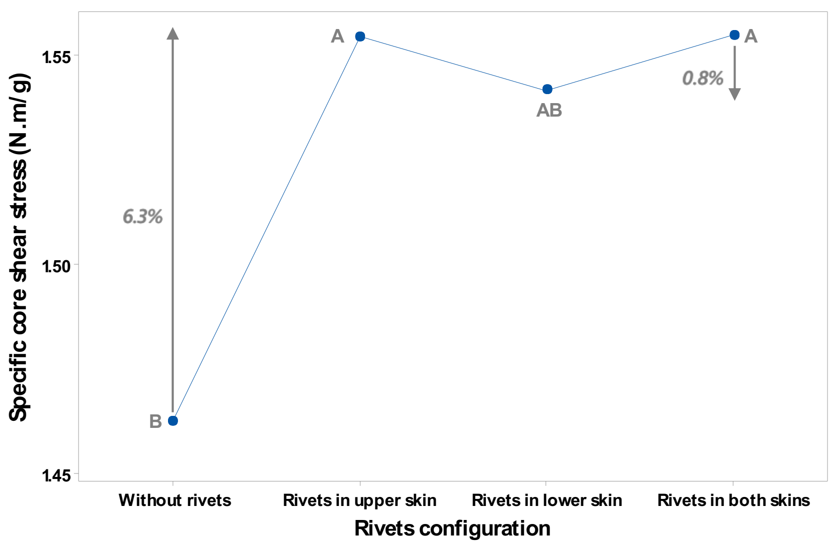
Figure 2 shows the effect plots of the maximum flexural load and related responses, such as core shear stress and skin stress, including the Tukey test. The core shear stress and skin stress follow similar behaviour, as evidenced in Tables 3 and 4, since they are dependent on the maximum load before failure. All absolute properties show an increase in their mean (average) values when transverse reinforcement is applied, indicated by different letters in the Tukey test for reference condition without rivets (Group B) and riveted conditions (Group A). The rivets located on the upper skin subjected to compressive load provided the highest mechanical performances with enhancements varying between 8.9 and 12% for the analysed responses. The variation of the maximum strength and the related variables in relation to the rivets position is around 1%, without significant distinction between the reinforcement levels. The results of the specific core shear and skin stress are shown in Figure 2c and 2e. The behaviour in this case is similar to the ones observed for the absolute properties. The specific responses have their average values increased by 6.3% when the panel is reinforced with rivets. The variations of the absolute and specific panel strength are also similar to the increase in shear load strength found in open literature due to the use of rivets [15]. The different rivet locations do not appear to provide significant changes (all reinforced conditions share a letter A). Slight reductions (0.8 to 0.95%) are obtained when the rivets are added to the lower skin (Group AB), which is also similar to the reference condition (Group B).



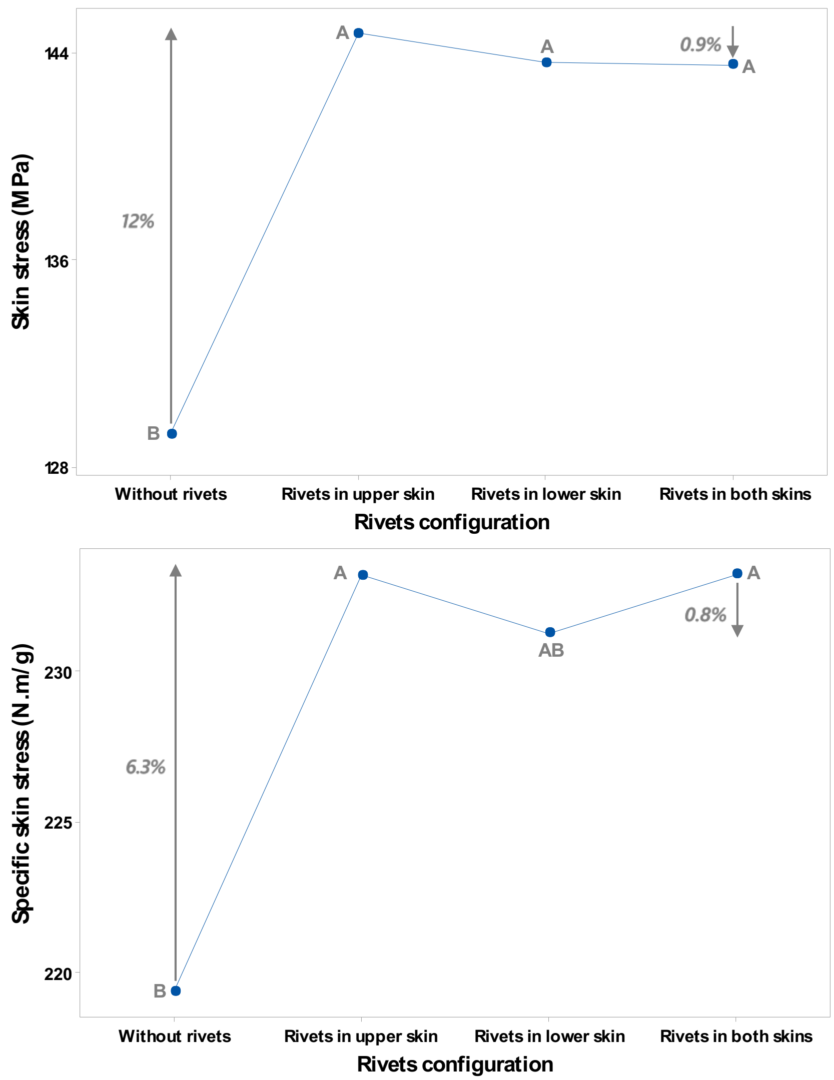
(a)


Core shear stress (MPa)
0.95
0.90
0.85
12%
0.9%
A
A
A
B
Without rivets
Rivets in upper skin
Rivets in lower skin
Rivets in both skins
Rivets configuration

(b)


Specific core shear stress (N.m/g)
1.55
1.50
1.45
6.3%
0.8%
A
AB
A
B
Without rivets
Rivets in upper skin
Rivets in lower skin
Rivets in both skins
Rivets configuration

(c)



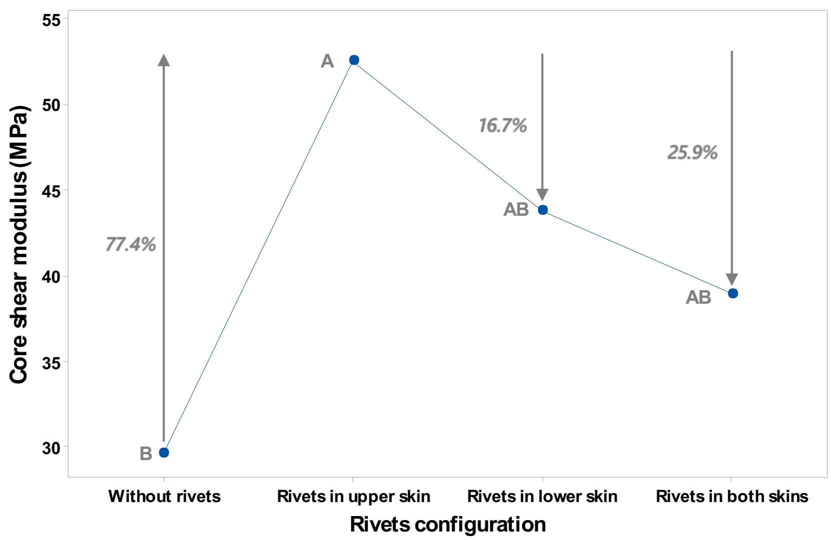
(d)

(e)

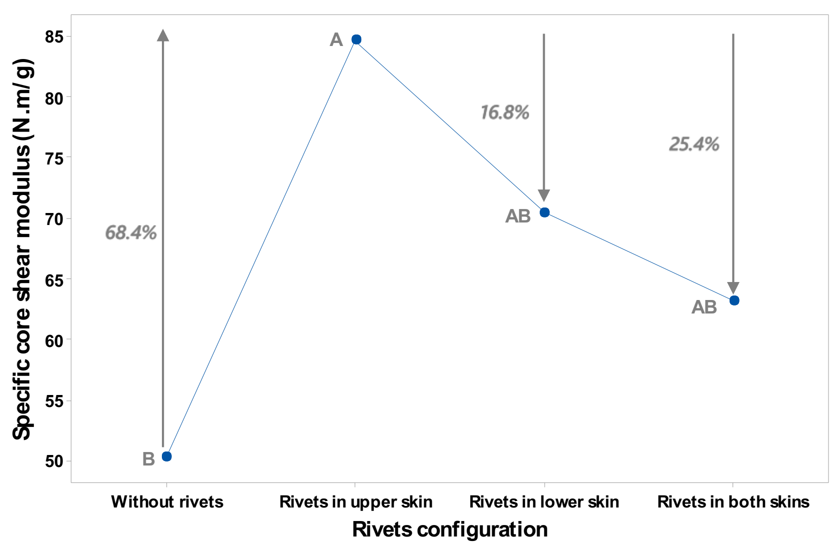
Figure 2. Effect plots of the mean (average) for the maximum load (a) and the absolute and specific core shear stress (b,c) and skin stress (d,e).

3.2. Elastic modulus, core shear modulus, and their specific properties

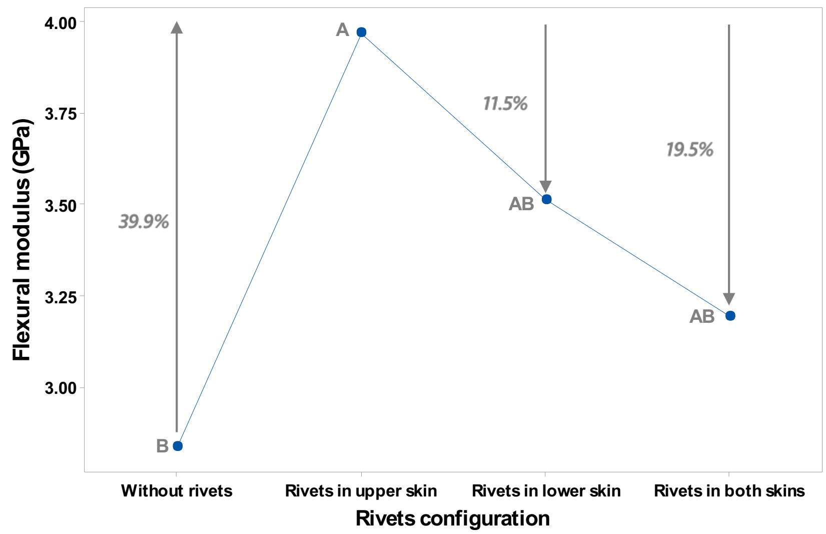
Figure 3 shows the effect plots related to the mean (average) of the core shear and flexural modulus, and their specific properties. The main advantage obtained by incorporating the rivets consists in the substantial increase of the elastic properties of the sandwich panels. Significant increases of 77% and 68% occur for the absolute and specific core shear modulus in panels made with rivets placed on the upper skin (Group A). The panels manufactured with rivets placed on the lower skin and on the two skins show similar averages to upper skin reinforced and unreinforced panels by sharing both letters (Group AB). They exhibit a reduction of the absolute and specific core shear modulus by approximately 16% and 25% when compared to the analogous values from panels with rivets on the upper skin. The flexural modulus also features a significant increase compared to the baseline condition (both levels exhibit different letters in Tukey's test) when the rivets are fixed on the upper skin (40% increment for the absolute value and 33% for its specific property). On the contrary, reductions between 11% and 19% are observed in the case of rivets placed on the lower plate, and on both the panel skins. Tukey test show significant changes between the pristine condition (Group B) and those with the rivets on the upper skins (Group A). This is a clear indication of the effectiveness of the transverse reinforcement.



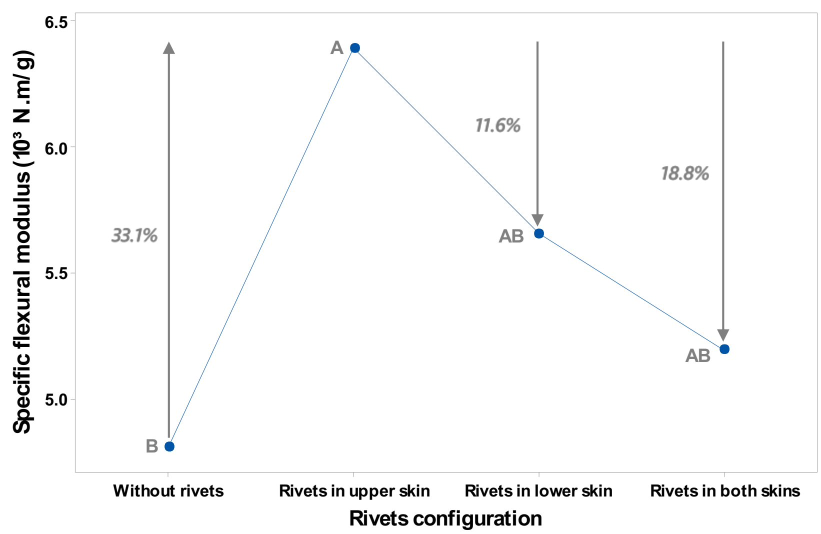
(a)



(b)



(c)



(d)

Figure 3. Effect plots for the mean (average) of absolute and specific core shear modulus (a,b) and flexural modulus (c,d).

4. Failure analysis

The most common failure mode observed in bottle cap panels without rivets is the delamination of the upper aluminium skin [10]. The increased strength and stiffness in panels made with rivets on the upper skin is attributed to the reduction of the delamination between the skin and the thermoplastic core. The rivets prevent the sliding of the adjacent bottle caps under shear loads. This effect contributes to a progressive failure of the sandwich panel without premature core rupture. This failure mode leads to localised bending on the upper skin under compression, where a central delamination (wrinkling-like failure) is present (Figure 4). The main cause of this failure is the reduced bond strength between the adhesive and the aluminium surface. In this case, the bonding is very dependent on the rivets, and their position has a significant effect on this outward buckle featured by the aluminium sheets under compression.

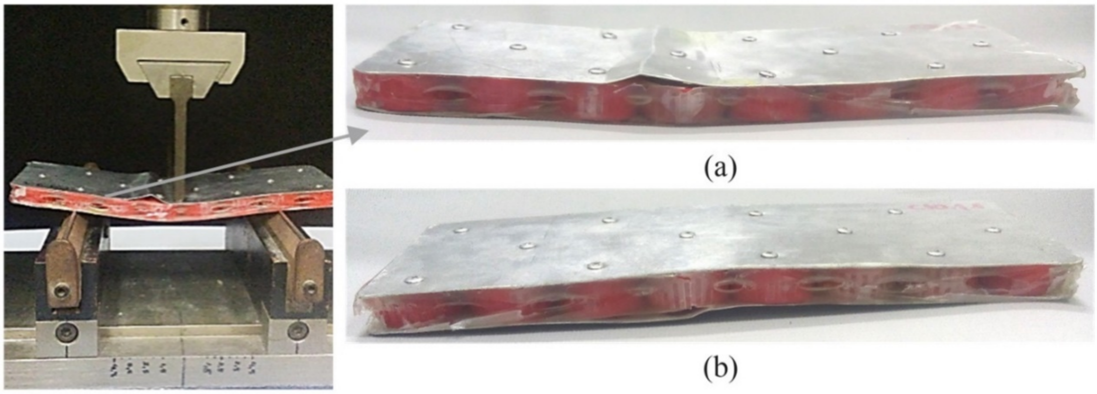


Figure 4. First failure mode for single side rivet panels: wrinkling-like failure of reinforced (a) and unreinforced upper skin (b).

A second failure mechanism is due to the failure of the lower skin under tensile loads (Figure 5). Samples made with rivets in both skins do not exhibit wrinkling failure. On the contrary, these samples show a greater bonding between the core and the skins and provide the highest flexural maximum load together with the panels made with rivets on the upper skin only. The skin strength in the experiments is within the value of the ultimate tensile stress of the aluminium sheet (110-145 MPa [29], Table 3). Therefore, the skin in the sandwich panel has developed a partial or total failure under the tensile loads during bending. Three stages of skin failure are observed (Figure 5). The first stage consists in the wall pressure exerted by the bottle caps on the skin, which induces the skin necking near its ultimate tensile strength (Figure 5a). The second stage is based on the initiation of the crack and its propagation along the contours of the bottle caps (Figure 5b) until the total skin failure, resulting therefore in the third stage, i.e. the failure of the sandwich structure (Figure 5c). All samples have shown similar crack propagation patterns, being the crack tangential to the cell walls in contact with the skin. The origin of these cracks is due to the initial reduction of the thickness due to pressure of the cell walls, which increases the local stress beyond the ultimate tensile stress of the aluminium. This mechanism is not observed in the reinforced panels with the rivets placed on the lower skin only (which is subjected to tensile loads), due to the lower bonding between the upper skin and the adhesive. In this case, the outward wrinkle failure occurs before any crack could propagate on the lower skin.

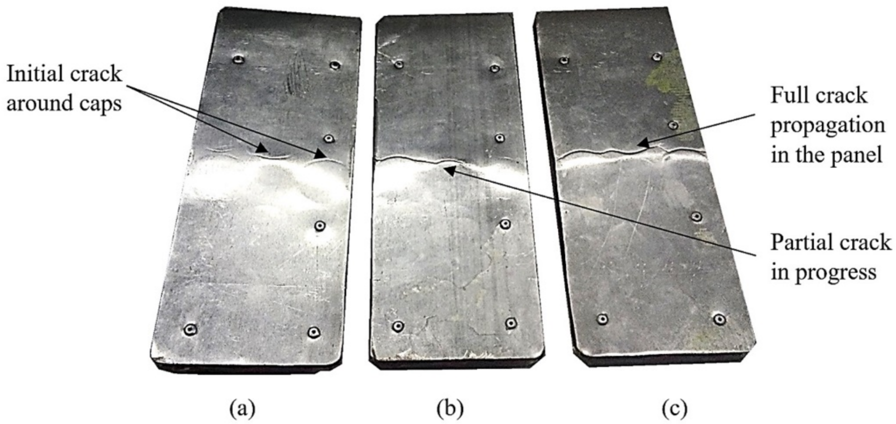


Figure 5. Second failure mode for transversally reinforced sandwich panel: partial (a) or total rupture of lower skin (b).

5. Comparative analysis

Table 5 presents a comparison between the present work and previous studies performed without rivet reinforcement [9, 10]. The mean values of all the evaluated properties are presented with their standard deviations in parentheses. It is possible to observe a substantial increase of all the absolute and specific responses. The main increases of the specific properties are observed for the core shear modulus (68.4%) and the elastic modulus (33.1%) in comparison to the unreinforced condition investigated in previous research in same testing conditions [10]. The comparison with the design with the reduced adhesive amount (1.0 mm adhesive layer [9]), tested at slightly different cross-head displacement rate (6 mm/min), also suggests that the reinforcement of the proposed rivets increases specific properties from the lightweight design. These results indicate that the use of transverse reinforcement enhances the specific strength and stiffness of the sandwich panel despite higher panel density, contributing to obtain structures that are more efficient.

Table 5. Comparative analysis between the sandwich panels with bottle caps core studied by this research group.

Mechanical Response	**Oliveira *et al.* [9] (1.0 mm adhesive)**	**Oliveira *et al.* [10] (1.5 mm adhesive)**	**Rivet reinforced panel tested in present study**

Maximum load, N	1874 (130.0)	2111.1 (73.5)	2299.4 (93.9)
Core shear stress, MPa	0.8 (0.06)	0.9 (0.03)	1.0 (0.04)
Skin stress, MPa	115.0 (9.7)	129.3 (5.0)	144.8 (6.0)
Core shear modulus, MPa	32.0 (6.6)	29.6 (3.0)	52.4 (6.0)
Elastic modulus, GPa	2.5 (0.15)	2.8 (0.2)	4.0 (0.2)
Flexural strength, MPa	24.3 (2.4)	27.2 (1.3)	31.0 (1.4)
Bulk density, kg/m^3	532.0 (10.4)	589.3 (14.2)	620.9 (3.0)
Specific core shear stress, N.m/g	1.4 (0.11)	1.5 (0.05)	1.6 (0.1)
Specific skin stress, N.m/g	216.2 (18.2)	219.3 (6.9)	233.2 (9.8)
Specific core shear modulus, N.m/g	60.0 (11.1)	50.9 (5.0)	84.4 (9.5)
Specific elastic modulus, x 10^3 N.m/g	4.7 (0.28)	4.8 (0.4)	6.4 (0.4)
Specific flexural strength, N.m/g	45.7 (4.5)	46.0 (1.5)	50.4 (2.1)

6. Conclusions

The effects of the aluminium rivets on sandwich panels made of aluminium skins and recycled bottle caps core have been investigated. The flexural modulus, core shear strength and modulus, skin stress, and their specific properties are measured using three-point bending tests. The use of rivets placed on the upper skin enhances all the mechanical responses, especially the absolute and specific elastic properties, such as the core shear modulus by 77.4% (68.4% for its specific counterpart) and the flexural modulus by 39.9% (33.1% the specific value). The absolute (and specific) core shear stress and skin stress of rivet reinforced panels show an increase of 12% (6.3%) and 12% (6.3%) respectively. A wrinkling-like effect is observed in panels with rivets in only one skin, while panels with rivets on both skins exhibit enhanced bonding to the skin. Sandwich panels with rivets on the two skins also provide higher core shear and skin stresses, but their elastic properties are reduced from 20% to 26%. This indicates that the reinforcement provided by the upper skin rivets plays an important role in the stiffness of the bottle cap panels. Further modifications related to the sustainability of the components, such as the use of alternative bonding (e.g. bio-sourced polymer or thermoplastic adhesive), and skins (e.g. laminates from renewable fibres), can help to improve the environmental performance of the proposed design.

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Declaration of conflicting interests

The authors declare that they have no conflict of interest.

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