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COMPRESSIVE AND FLEXURAL BEHAVIOR OF FIBERGLASS/POLYURETHANE SANDWICH PANELS: EXPERIMENTAL AND NUMERICAL STUDY

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The mechanical properties of sandwich panels with a polyurethane core and fiberglass face layers produced by a continuous lamination process have been studied. Tensile, compression and shear tests were performed on isolated face layer materials. Using a nonlinear finite-element model, the mechanical behavior of the sandwich panels in flatwise compression, edgewise compression, and bending was simulated, and a good agreement with experiments was found to exist.

1. Introduction

Sandwich panels are composed of a thick core and thin face layers (skins). They are suitable for many applications, including motor vans, in which thanks to the good thermal insulation properties, they prevent the deterioration of perishable food products by helping one to maintain them under controlled temperatures [1].

Sandwich face layers are sometimes made of a composite material, e.g., fiberglass [2, 3]. Fiberglass can be produced, e.g., by the widely used continuous lamination, which allows a large production scale, providing the repeatability and reliability in the process. The sandwich core is often made of a polymeric material, in particular, a polyurethane (PU) foam, which is commonly manufactured by the closed mold injection process, with the faces already positioned at the bottom and top of the mold. The density of the foam, its cellular pattern, and foam growth are influenced by its formulation and the production process [4].

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In general, the composite face layers provide sandwich panels with most of their physical/mechanical properties [5]. Li et al. [6] analyzed face layers produced with 3D fabric sewing jute yarns having configurable structures using Kevlar fiber threads and found that the compressive and flexural strengths were, 7.7 and 3.8 times, respectively, higher than those of blank composites without 3D fabrics. Khan et al. [7] showed that the core can also affect the buckling load of these panels, and reported a 6% increase in it with addition of 5% Al_2O_3 reinforcement to the PU core.

Many experimental and numerical studies have been devoted to sandwiches, but only a few of them have assessed the nonlinear effects of these structures [8]. Jamil et al. [9] modelled sandwich panels with a PU core and aluminum skins. The PU was modelled as an isotropic elastoplastic material exhibiting a strain-rate dependence and obeying the Cowper–Symonds power law. Abbasi et al. [10] performed a numerical simulation of sandwich panels with a PU foam. They used a crushable-foam model to simulate the nonlinear behavior of their core, and found a maximum 7.5% difference between numerical and experimental results. But this required a great number of input parameters.

Foam-based sandwiches are highly complex because of the nonlinear effects and damage mechanisms associated with static and dynamic loadings [11-12]. Ignatova and Sapozhnikov [13] investigated the mechanical behavior of a foam under indentation loads considering it as a compressible hyperelastic solid. Xie et al. [14] analyzed the flexural behavior of sandwich panels with a foam core subjected to a concentrated load.

Our work aimed to assess the influence of face layer material on sandwich panels consisting of a polyurethane core and glass-fiber reinforcements (short fibers or bidirectional fabrics) in their face layers. Nonlinear numerical simulations by finite-element method (FEM) were carried out to estimate the mechanical response of the panels to various loads and to investigate its reliability for an initial assessment of different types of panels.

2. Materials and Methods

2.1. Materials and the manufacturing process

The composites for sandwich face layers were produced using a polyester resin (of standard 10.335 from Reichhold) and an E-glass-fiber reinforcement being either random short fibers (P243; nominal weight: 775 g/m²) or a 0°/90° bidirectional woven fabric (LT0530; nominal weight 900 g/m²). The continuous lamination process used to produce the composite face layers/skins is illustrated in Fig. 1a. Briefly, it consists of the following steps. There is a long conveyor belt on which two nonstick films slide, and, between them, a composite with a specified thickness is produced. First, the resin/catalyst is entered, and then the reinforcement (a mat or fabric) is introduced into it. Short fibers are added from the rovings when a mat is used. These constituents are compressed between the films and are heated to 60°C when passing through an oven. After laminating and near-complete curing, the composite is stored at 23°C to finalize the release of the residual styrene monomer. The final composite thicknesses were 1.9 and 1.2 mm in the cases of short fibers and fabric, respectively.

A PU was injected by a 3.4-kW Transtécnica injection machine with an air mixer in its head. Using a 1.0×2.5-m frame, fiberglass face layers were placed in a mold in such a way as to obtain a 64±1-mm-thick PU core. The frame was positioned in the mold base with mechanical restrictions at its ends to guarantee the desired thickness and properties of the core. A mixing ratio of 1.23:1 (isocyanate:polyol) was used, and the PU was injected and kept in the mold for ≈2 h to minimize dimensional or density variations, incomplete cavity filling, voids, irregular cell sizes, and contraction. The overall curing time was 72 h, and the final foam density was 40 kg/m³. Figure 1b shows the equipment used to assemble the panels used to make specimens. After curing, the panels were cut using a circular saw and sanded to the desired shape of specimens for various tests. It is also worth mentioning that small voids were observed in the PU core. These voids are considered normal in this type of manufacturing process but have to be controlled.

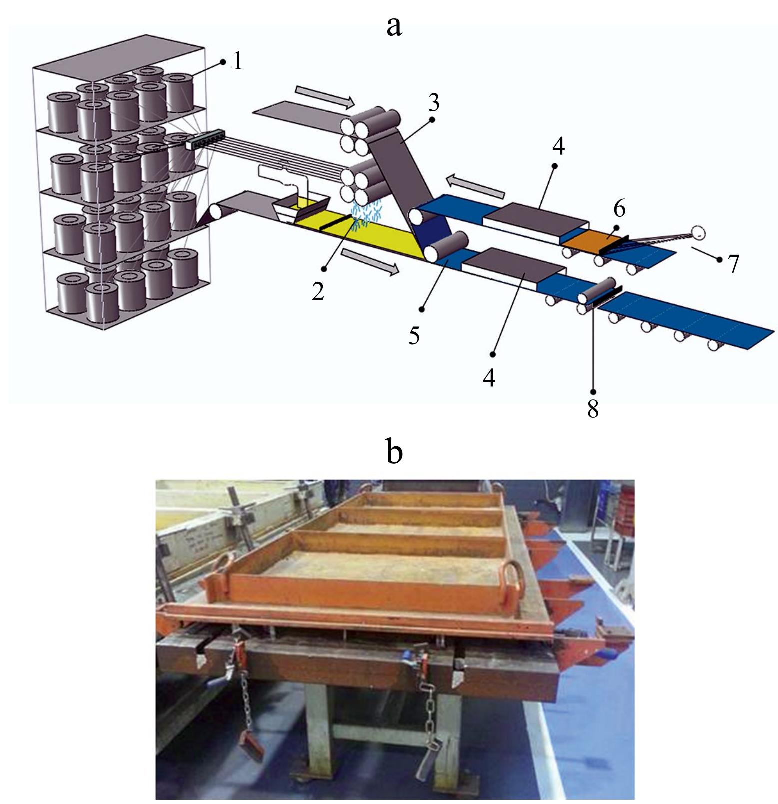

Fig. 1. (a) Continuous lamination process of short-fiber and fabric composites for panel faces, and (b) a mold for producing sandwich panels.

2.2. Physical / mechanical tests

The evaluation of face layers included physical and mechanical testings. First, the weight content of glass fibers was determined by burning, according to ASTM D5630. For mechanical tests, an Instron universal testing machine, model 3382, equipped with a 5-kN load cell, was used. The tensile tests were carried out on rectangular 175-mm-long and 25-mm-wide specimens at a deformation rate of 2 mm/min, according to the ASTM D3039 standard. The compression tests were performed, according to the ASTM D6641 standard, on rectangular and tabbed 140-mm-long and 12-mm-wide specimens at a deformation rate of 1.3 mm/min. The in-plane shear tests were performed, according to the ASTM D7078 standard, at a deformation rate of 2 mm/min. The specimens had a double V-shaped notch at the center, machined to necessary dimensions. Three to five specimens per type of reinforcement were used for each test.

The mechanical tests of sandwich panels were carried out in the same equipment. The core compression tests were performed following the ASTM C365 standard, which can be used for both continuous (e.g., foams) or discontinuous cores. The tests were performed on finished sandwich panels, instead of an isolated core, to avoid using a different non-representative method to obtain an isolated foam. Specimens of dimensions 50×50 mm were tested at a deformation rate of 10 mm/min. The tests were performed for both types of sandwiches — with short-fiber and fabric face layers — although these tests give the compressive strength and elasticity modulus of core. The edgewise compression tests of the 500×140-mm panels were performed, according to the ASTM C364 standard, at a deformation rate of 5 mm/min.

Finally, bending tests were performed on the panels according to the ASTM C393 standard to determine the core shear properties. The specimens were 140 mm long and 70 mm wide, and the deformation rate was 20 mm/min. The maximum core shear stress and the maximum stress on face layers were calculated from the maximum load and geometric characteristics of the sandwiches.

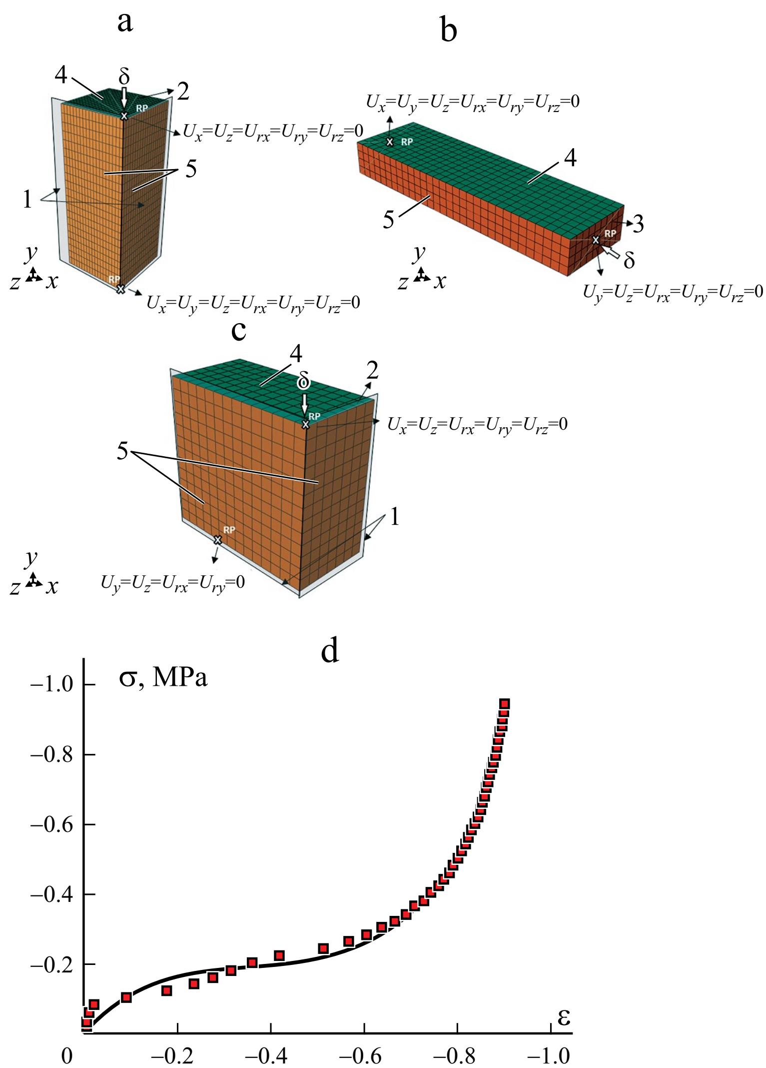

Fig. 2. FE models with reference points (RPs) simulating the core compression (a), and longitudinal (edgewise) compression (b) and bending (c) of sandwich panel, and the stress vs. strain diagram $\sigma - \varepsilon$ of core compression (d): experimental points (■) and the simulation by a fourth-order (N) Ogden model (——).

2.3. Structural analysis of sandwich panels

The properties of composites (face layers) were analyzed by the MECH-Gcomp software [15]. The reference data for the analysis came from experimental tests carried out by the manufacturer. To calculate the elastic modulus E_1 , the Halpin–Tsai approach was used for the composite with short fibers. The calculated elastic modulus was compared with that obtained in the mechanical test.

The numerical simulations of the sandwich panels were performed using the FEM and the commercial AbaqusTM/ Version 6.14 program. A 3D model was used. The face layers were initially modeled using the estimated elastic constants and later calibrated with the actual results of tests. The random composite was considered quasi-isotropic, but the composite with a bidirectional fabric — orthotropic, with the same properties in the 0 and 90° directions. A tie-type constraint was used at the contact between skins and core. Cohesive elements were not used because the failure occured mainly at the core.

TABLE 1. Physical and Mechanical Properties of Fiberglass Composites of Sandwich Faces

Property/Material	Fiberglass	
	Short fibers	Fabric
Fiber weight fraction W_f, %	39 ± 0.6*	54 ± 1.4
Maximum tensile strain, %	1.26 ± 0.09	1.15 ± 0.08
Tensile strength, MPa	100 ± 7.8	146 ± 6.2
Longitudinal elastic modulus, GPa	8.0 ± 0.3	13 ± 0.5
Maximum compressive strain, %	0.83 ± 0.04	0.43 ± 0.01
Compressive strength, MPa	173 ± 8.5	150 ± 7.6
Maximum shear strain, %	1.61 ± 0.04	1.83 ± 0.08
Shear strength, MPa	43 ± 4.8	34 ± 3.6

*Standard deviation.

Figures 2a-c show the mesh, boundary conditions, and loads used for core compression, longitudinal (edgewise) compression, and bending modeling, respectively. Reference points (RPs) were employed to represent the support and indenter boundary conditions. For core compression, the top and bottom surfaces (interfacing the skins) were connected to the RPs using coupling type constraints. No displacements and rotations were allowed at the lower and the upper RPs, except for the maximum imposed displacement δ = 50 mm along the y axis. For the longitudinal compression, the face layers in the y - z plane were connected to the RPs using the same constraint, and the maximum imposed displacement δ along the x axis was 2 mm.

For the bending test, the RPs were connected to the edges along the z axis. Displacements along y and z axes and rotations about the x and y axes were allowed neither at the lower nor the upper RP, except for the maximum imposed displacement δ = 50 mm along the y axis. The results of reaction forces and displacements were obtained at the RP. The foam core was modeled using a hyperelastic model, hyperfoam, implemented based on the actual stress–strain diagram $\sigma - \varepsilon$ of the PU foam obtained in the core compression test (Fig. 2d). Fitting of the experimental data was performed using a fourth-order (N) Odgen model [16], which is also shown in this figure.

In the simulations, the mesh for the panel core was built with 8-node linear C3D8R elements, with reduced integration, and for the panel face layers (modeled as skins) — with 4-node linear S4R elements with reduced integration. The mesh convergence in compression was studied for three sizes of the element, namely, 5, 3, and 1 mm, with their total numbers of 5415, 8303, and 23826, respectively. The results with the 1-mm elements did not significantly differ from those with the 3-mm ones. Therefore, the 3-mm elements were taken for all analyses. The same procedure was also performed for the other loading conditions. For core compression, a standard mesh with 3-mm elements, altogether 8303 elements and 8800 nodes were used. For bending, a standard mesh with 5-mm elements, altogether 1470 elements and 1680 nodes, were employed. For the longitudinal compression, a standard mesh with 8-mm elements, altogether 10944 nodes and 11340 elements, were utilized.

3. Results and Discussions

3.1. Physical and mechanical properties of fiberglass face layers

Table 1 presents the physical and mechanical characteristics of the composites of panel face layers. The fiber volume fraction (V_f) was higher in the case of fabric than short fibers, which, together with the fact that the fabric fibers were continuous and aligned, led to better mechanical properties for the fabric face layers.

Table 1 also shows a higher tensile strength and longitudinal elastic modulus and a lower maximum tensile strain for the woven composite, both showing a brittle behavior. The elastic modulus obtained with the Mech-G (analytical) was

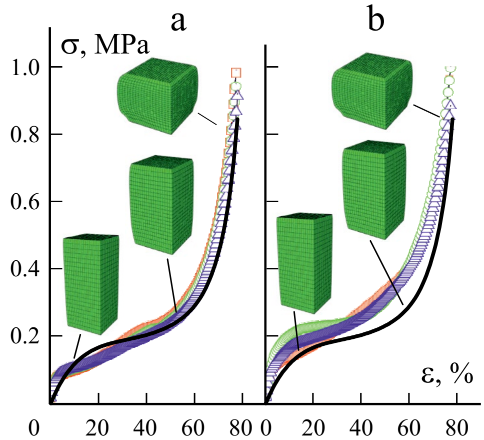

Fig. 3. Experimental (—□—, —○—, — Δ—) and calculated (——) and longitudinal compressive stress–strain diagrams $\sigma - \varepsilon$ of panels with short fibers (a) and a bidirectional fabric (b): samples 1 (—□—), 2 (—○—), and 3 (— Δ—).

7.98 GPa for the short fibers, which was very close to the measured value. It is also seen that the composite face layers with short fibers had higher of 12% compressive strength and 49% maximum strain than that with fabric. But the shear strength of the face layers with fabric was 21% lower than that of the short-fiber composite even when the fiber content was increased. This can be explained by the fact that the short fibers were randomly oriented in many directions, including the ±45° ones, but the fabric fibers were oriented only at 0 and 90°.

3.2. Comparison numerical and experimental results for sandwich panels

Figure 3a, b shows the compressive stress–strain diagrams of sandwich panels with short fibers and fabric, respectively. Three well-defined characteristic zones can be seen in the diagrams: an initial linear elastic zone, a zone associated with collapse of cells at an almost constant stress, and a zone of increased core density, where the stress increases exponentially. This behavior is common of polymer foams [17]. Comparing Fig. 3a with Fig. 3b, it can be seen that the compression behavior of the panel core has not been significantly affected by the face material. Some dispersion of experimental data among samples is observed, especially in the cell collapse region, due to morphological variations in the foams. Considering these results, a similar response can be expected for cores in various tests. Figures 3a, b also show the deformed shapes of panels in compression. Greater deformations are seen in the densification phase of core, and the deformed shapes are similar for the two face layer types analyzed.

Owing to the great number of parameters that influence the mechanical response of sandwich panels, their computational modeling is complex, and there are only a few models capable of accurately predicting this behavior [18]. The simulations reported here will focus on the first and second zones of deformation diagrams of the sandwich panels, which correspond to the working range of this material in the automotive sector. Figure 3 shows the numerical compressive stress–strain diagram which will agree with experimental data.

The maximum compressive loads of sandwich panels, with faces layers containing short fibers and a fabric, obtained experimentally were 10,367 ± 966 and 11,851 ± 2,633 N, respectively, but the corresponding simulated ones were 10,933 and 13,366, respectively, showing a good agreement. Results of such an analysis depend more on face layer than core properties, in general, such studies are performed on panels whose one end is free, but the other one allows arbitrary displacements and rotation [19].

Although a perfect adhesion between face layers and the core was assumed in the model used, it was also able to capture the maximum buckling load. The debonding between face layers and core in tests occurred due to the large

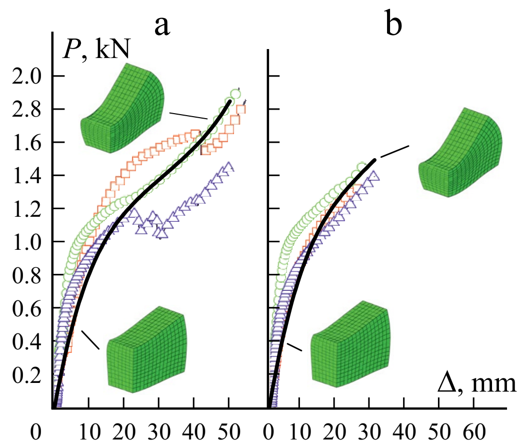

Fig. 4. Experimental (—□—, —○—, — Δ—) and calculated (▬▬) flexural load–displacement diagrams $P-\Delta$ of panels with short fibers (a) and a bidirectional fabric (b): samples 1 (—□—), 2 (—○—), and 3 (— Δ—).

difference in their elastic moduli, which increased the shear loads in the interface region. This effect is detrimental to the overall performance of such panels, and engineering undertaking have to be adopted to tackle this issue [20]. In automotive applications, sandwich panels under similar loading conditions are assembled with both their ends restricted, so that the face layers cannot detached from the core in this region, which is critical in terms of debonding. Compression tests, which are easy to perform and provide reliable results, can be used to evaluate this adhesion in sandwiches and their overall failure [21]. Other failure modes, such as core shear, face layer shear, and face layer crush have not been observed in the sandwich panels studied [22].

Figure 4 shows the load–deflection diagrams and deformed shapes of panels obtained in 3-point bending tests, where greater dispersion in results can be observed. In general, the load increased linearly with deflection until the core began to fail under compression and, especially, shear stresses. The panels with woven face layers (Fig. 4b) showed a behavior similar to those made with short fibers (Fig. 4a). For the most part, the panels showed, a nonlinear behavior due to the highly nonlinear deformation of core. Since the deformations of beam faces were much smaller than those of core, the nonlinearity of face layers could be disregarded to simplify the numerical model [23].

A macroscopic failure of sandwich panels in bending can occur by detachment of the upper face layer, compressive failure of the upper face layer, and/or core failure by shearing. In the first case, the shear stress at the interface between the upper face layer and core surpasses the adhesion strength at this interface. In the second case, the compressive stress in the upper face layer surpasses its compressive strength. In the third case, the shear stress of core exceeds its shear strength. In the bending tests performed in this study, face layer detachments, i.e., adhesive failures, were observed. This detachment could be minimized by adding reinforcement elements connecting the face layers and core [24].

When comparing the experimental and numerical results in bending, a similar pattern was observed, but the numerical values were lower. The differences may be explained by the fact that the adhesion between face layers and the core was considered perfect in the numerical model, but it was not such in test samples, and also by the imperfect agreement with the hyperfoam model. The deviation is expected to be smaller for larger panels, since the deflection then is distributed over a larger area and the panels behave more like the classic Euler beam, minimizing the effect of core shearing.

In Table 2, the mechanical properties of sandwich panels with the two types of face layers are presented. The compressive strengths of core were very similar for both of them. In longitudinal compression, the strength of panels with a fabric was by about 14% higher, even though the fabric-reinforced face layer had a lower thickness and a lower compressive strength. This can be explained by the fact that the resistance to buckling increases with growing elastic modulus of face layers [25].

TABLE 2. Mechanical Properties of Sandwich Panels

Property/Material	Fiberglass	
	Short fibers	Fabric
Parallel-plate compressive strength, MPa	0.954 ± 0.0337*	0.967 ± 0.0697
Maximum longitudinal compressive strain, %	1.01 ± 0.08	1.00 ± 0.09
Longitudinal compressive strength, MPa	1.134 ± 0.103	1.346 ± 0.998
Maximum deflection, mm	53 ± 2.1	28 ± 2.1
Maximum flexural load, N	1742 ± 259.9	1398 ± 72.5
Maximum core shear stress, MPa	0.19 ± 0.03	0.15 ± 0.09
Maximum face stress, MPa	4.97 ± 0.74	6.38 ± 0.33

*Standard deviation.

It is also seen that the deflection and the maximum flexural load were higher for the panel with face layers with short fibers. Therefore, in bending, the influence of face thickness was critical when optimizing the performance sandwich panels. Furthermore, the panel with face layers containing short fibers reached a maximum core shear stress 21% higher than that with fabric face layers, but the maximum face stress was 28% lower. When considering the standard deviation, it becomes apparent that there were no significant differences between the maximum shear stress in the core. However, as regards the maximum face layer stress, the panels with fabric face layers tended to be superior, which may be attributed to the higher tensile strength of the fabric composite.

The mechanical performance of the sandwich panels studied was also compared with that of similar structures investigated in the literature. The failure modes and general results observed in our study were found to be compatible with those reported by Khan et al. [26], who reviewed the recent advances in sandwich structures based on PU foam cores. Henao et al. [27] investigated sandwich panels made of an E-glass (800 g/m^2 [0/90] fabric of thickness 0.24 mm with a fiber volume fraction of 55%) and a PU core. In 3-point bending, the maximum core shear stress was 0.16 MPa, which is a value intermediate between those found in our work. They also performed edgewise compression tests and obtained a strength of 8.9 MPa, which is ≈ 6.6 times higher than the strength found here. This discrepancy corroborates the premature buckling failure observed for our samples. Abdi et al. [28] studied sandwich panels with chopped glass fibers/polyester composites as face layers and a PU foam as the core material and obtained, that, in 3-point bending, the maximum core shear stress and face layer stress were 0.67 and 33 MPa, respectively.

4. Conclusions

In this work, sandwich panels with a PU foam core and polyester/E-glass fiber face layers, either as short fibers (random reinforcement) or a bidirectional fabric, were produced and investigated in parallel-plate compression, longitudinal compression, and bending. The physical and mechanical properties of the different face layers were determined by physical and mechanical tests. The panels were produced by continuous lamination and had different thickness and fiber content, depending the type of reinforcement used. The thinner 0°/90° fabric-reinforced face layer, but with a higher fiber content, showed a higher tensile strength and modulus, but lower compressive and shear strengths.

Finite-element simulations were performed to reproduce the mechanical tests carried out on the sandwich panels. The numerical simulations showed a good agreement with experimental results in all the loading cases studied. The hyperelastic foam model used presented a good fit with the nonlinear experimental curves deformation diagrams in compression and bending of sandwich panels. The results obtained also confirm the importance of performing isolated characterization tests on the face layers and core of the panels for their more reliable numerical analyses.

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REFERENCES

1. H. Fahrzeugbau, Sandwichelemente für den fahrzeugbau: aufbau, fertigung, montage, anwendung. Landsberg/Lech: Verl. Moderne Industrie (2006).
2. B. D. Agarwal, L. J. Broutman, and K. Chandrashekhara, Analysis and Performance of Fiber Composites, John Wiley & Sons, New Delhi (2006).
3. ASTM INTERNATIONAL, D3878-16. Standard terminology for composite materials, West Conshohocken (2016).
4. R. P. Torreira, Isolamento térmico, Fulton Editora Técnica, São Paulo (1980).
5. K. Djama, L. Michel, A. Gabor, and E. Ferrier, "Mechanical behaviour of a sandwich panel composed of hybrid skins and novel glass fibre reinforced polymer truss core," Compos. Struct., **215**, 35-48 (2019).
6. Z. Li, X. Wei, Z. Gao, et al., "Manufacturing and mechanical characterization of polyurethane resin based sandwich composites for three-dimensional fabric reinforcement," Mater. Today Commun., **24**, No. 101046 (2020).
7. T. Khan, O. A. Aydın, V. Acar, et al., "Experimental investigation of mechanical and modal properties of Al_2O_3 nanoparticle reinforced polyurethane core sandwich structures," Mater. Today Commun., **24**, No. 101233 (2020).
8. S. Sayahlatifi, G. H. Rahimi, and A. Bokaei., "The quasi-static behavior of hybrid corrugated composite/balsa core sandwich structures in four-point bending: Experimental study and numerical simulation," Eng. Struct., **212**, No. 110361 (2020).
9. A. Jamil, Z. W. Guana, W. J. Cantwell, et al., "Blast response of aluminium/thermoplastic polyurethane sandwich panels – experimental work and numerical analysis," Int. J. Impact Eng., **127**, 31-40 (2019).
10. M. Abbasi and A. A. Nia., "High-velocity impact behavior of sandwich structures with AL faces and foam cores – Experimental and numerical study," Aerosp. Sci. Technol., **105**, 106039 (2020).
11. K. Bey, K. Tadjine, R. Khelif, et al., "Mechanical behavior of sandwich composites under three-point bending fatigue," Mech. Compos. Mater., **50**, 747-756 (2015).
12. M. Özen., "Influence of stacking sequence on the impact and postimpact bending behavior of hybrid sandwich composites," Mech. Compos. Mater., **52**, 759-766 (2017).
13. A. V. Ignatova and S. B. Sapozhnikov, "Two-scale modeling of the mechanical behavior of a composite foam," Mech. Compos. Mater., **51**, 655-660 (2015).
14. Z. Xie, Zhibin Li, and J. L. You, "An approximate solution to the plastic response of clamped sandwich beams under concentrated loading," Mech. Compos. Mater., **52**, 359-368 (2016).
15. URL: http://www.ufrgs.br/mechgcomp/ (reference date: 20/Oct/2020).
16. URL: http://130.149.89.49:2080/v2016/index.html (reference date: 18/Dez/2020).
17. M. Mohamed, S. Anandan, Z. Huo, et al., "Manufacturing and characterization of polyurethane based sandwich composite structures," Compos. Struct., **123**, 169–179 (2015).
18. M. Sadighi and S. A. Hosseini, "Finite element simulation and experimental study on mechanical behavior of 3D woven glass fiber composite sandwich panels," Compos. B. Eng., **55**, 158–166 (2013).
19. J. R. Correia, M. Garrido, J. A. Gonilha, et al., "GFRP sandwich panels with PU foam and PP honeycomb cores for civil engineering structural applications: effects of introducing strengthening ribs," Int. J. Struct. Integr., **3**, No. 2, 127–147 (2012).
20. V. Vadakke and L. A. Carlsson., "Experimental investigation of compression failure of sandwich specimens with face/core debond," Compos. B. Eng., **35**, No. 6–8, 583–590 (2004).
21. A. C. Manalo, "Behaviour of fibre composite sandwich structures under short and asymmetrical beam shear tests," Compos. Struct., **99**, 339–349 (2013).
22. N. A. Fleck and I. Sridhar, "End compression of sandwich columns," Compos. Part A Appl. Sci. Manuf., **33**, No. 3, 353–359 (2002).

23. A. Mostafa, K. Shankar, and E. V. Morozov, "Influence of shear keys orientation on the shear performance of composite sandwich panel with PVC foam core: numerical study," Mater. Des., **51**, 1008–1017 (2013).
24. L. Wang, W. Liu, L. Wan, et al., "Mechanical performance of foam-filled lattice composite panels in four-point bending: experimental investigation and analytical modeling," Compos. B. Eng., **67**, 270–279 (2014).
25. W. N. Yeh and Y. E. Wu, "Enhancement of buckling characteristics for sandwich structure with fiber reinforced composite skins and core made of aluminum honeycomb and polyurethane foam," Theor. Appl. Fract. Mech., **15**, No. 1, 63–74 (1991).
26. T. Khan, V. Acar, M. R. Aydin, et al., "A review on recent advances in sandwich structures based on polyurethane foam cores," Polym. Compos., **41**, No. 6, 1–46 (2020).
27. A. Henao, M. Carrera, A. Miravete, and L. Castejón, "Mechanical performance of through-thickness tufted sandwich structures," Compos. Struct., **92**, 2052–2059 (2010).
28. B. Abdi, S. Azwan, M. R. Abdullah, et al., "Flatwise compression and flexural behavior of foam core and polymer pin-reinforced foam core composites and sandwich panels," Int. J. Mech. Sci., **88**, 138–144 (2014).