MODIFIED EXPANDED CORK CORE SANDWICH STRUCTURE WITH IMPROVED PERFORMANCE

Paulo J. R. O Nóvoa[1,2], Albertino J. C. Arteiro[1], and António T. Marques[1, 2]

[1]Department of Mechanical Engineering (DEMec), Faculty of Engineering - University of Porto (FEUP), R. Dr. Roberto Frias s/n, 4200-465 Porto , Portugal
Email: prnovoa@fe.up.pt, aarteiro@fe.up.pt, marques@fe.up.pt, Web Page: http://www.fe.up.pt
[2]Composite Materials and Structures Research Unit (UMEC), INEGI, FEUP Campus, Rua Dr. Roberto Frias 400, 4200-465 Porto, Portugal
Email: prnovoa@inegi.up.pt, marques@inegi.up.pt, Web Page: http://www.inegi.pt/

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Abstract
Considering the growing interest for strong rigid lightweight structures the present work investigates the use of commercially available black corkboards as core material in composite sandwich structures. In addition to a commercial low density product, a modified material developed at laboratory scale, containing polymeric pillars, is also considered, as a design strategy to improve through-thickness and shear performances. The face-sheets were glass fiber reinforced epoxy resin infused laminates, and a polyurethane structural adhesive was used to assemble the structure. The sandwich structures are evaluated with respect to three-point bending and four-point bending, to assess both flexural and shear behaviors. Although the core modification method resulted in a large increase of bulk density, the density increase of the sandwich structure was attenuated by the dominant contributions from the other components. Low core shear strength was the cause of failure in both flexural loading geometries, but the modified core failure occurred at an 80% higher stress value. The estimated core shear modulus was 70% higher for the modified core. The sandwich density increase is outweighed by the increase in performance of the modified core, so that both absolute and specific property improvements result.

1. Introduction

Composite sandwich panels exhibiting both high specific strength and stiffness constitute important alternatives for lightweight structures, as these grow in demand. Cork agglomerates and derivatives have been attracting some interest as possible renewable source-based alternatives to traditional core materials, particularly, synthetic polymer foams. The focus on cork agglomerates is increased due to their retention of particularly desirable properties found in natural cork, such as high flexibility, elasticity, compressibility, and recovery, resulting in natural material based products with excellent energy absorption capacity. These properties underline a potential to act as an interesting core material choice for sandwich structures, particularly when impact phenomena are anticipated. Conversely, cork agglomerates generally exhibit higher densities compared to commercial polymer foams.

Black expanded corkboards (BEC) constitute a particular type of cork agglomerate in a lower density range, which could lead to cork based sandwich structures with enhanced overall specific properties. However, standard BEC products are designed for acoustic and thermal insulation applications in construction [1, 2], with structural integrity not being paramount. In fact, the absence of an added binder in its composition contributes to the low bulk density feature, but this low natural binder content also reduces the inter-particle bond strength. They are manufactured with lower quality cork grades [3], and commercial applications are mainly found in insulation for ceiling, external and internal walls, and flooring systems.

Previous research addressing the use of cork agglomerates as core materials, have focused either on commercial products [4 - 10] or lab-scale materials based on cork granules and alternate binders [5]. There is still scarce research addressing the use of BEC products in attempting structural composite structures. Lakreb *et al.* studied sandwich panels with BEC core and pine wood veneer face-sheets [11], and some of the present authors have assessed BEC core composite sandwich structures with respect to bending/shear and impact performances [12]. The later study exposed the expected material low internal bonding strength.

The present work investigates the use of commercially available black corkboards as core material in sandwich structures, and attempts to improve its performance through a simple reinforcing strategy, taking advantage of the materials' rugged morphology, with a high content of internal macroscopic voids. The method consisted of drilling the core panel with 2.5 mm diameter vertical holes according to a simple pattern, and filling them with the adhesive material prior to sandwich assembly, thus introducing a network of reinforcing adhesive pillars. The additional sandwich components were analogous those used in previous works of this research group [9, 10, 12-14], simplifying the recognition of changes in performance ascribed to core modifications – face-sheets were +/-45º glass fiber fabric reinforced epoxy resin laminates produced by resin infusion, and the sandwich structure was assembled using a polyurethane structural adhesive.

The sandwich structure was evaluated with respect three-point bending, and four-point bending following a standard test method, and a procedure and which also allowed measuring core shear properties. The results were analyzed to determine how effective the through-thickness BEC reinforcing scheme was, with respect to both overall sandwich and core performances.

2. Experimental

All sandwich structures were manufactured using the same facing material, core thickness, and adhesive layer thickness and material. The glass fiber reinforced polymer (GFRP) face-sheets are similar to those used in previous investigations [9, 10, 12-14]. This research focused mainly on the core material.

2.1. Materials

The fiber reinforced face-sheets were produced using as matrix, a very low viscosity (170 mPa.s) two component Biresin® system (Sika®, Germany) based on epoxy resin CR83 and amine hardener CH83-6, particularly suited for infusion and injection processes.
The reinforcing phase was Multifab® (Lintex®, PRC) EBX 600, a double biaxial (±45°) E-glass fiber fabric, with areal weight of 612 $g.m^{-2}$ considering the contribution from polyester yarn stitching.
The core materials were based on a 12 mm thick expanded insulation cork board with bulk density of 100 $kg.m^{-3}$ (AISOL™ - Amorim Isolamentos S.A., Portugal) – a product developed for insulation in construction applications containing wide distribution of coarse granules in the 5 to 20 mm range. Characteristic properties supplied by the manufacturer can be found in reference [1].
The face-sheets were adhesively bonded to the core using a structural bi-component polyurethane resin system recommended for sandwich construction - SikaForce®-7710 L100 (Sika®, Germany). The two adhesive components consist of respectively filled polyols, and isocyanate derivates, which should be mixed in a 100:19 mass ratio.

2.2. Manufacturing

Sandwich structure face-sheets, with 370×90 mm^2, were cut from a *ca.* 1 mm thick fiberglass/epoxy laminate, produced by vacuum infusion, consisting of two layers of ±45° biaxial fabric - *i.e.*, a four-ply laminate.

Two BEC-based cores were used: neat BEC consisting of the commercial product, and a modified adhesive pin-reinforced BEC. Fabrication of the modified core involved drilling a square array of 2.5 mm diameter holes with neighboring centers 14 mm apart from each other. Each hole was then filled with the polyurethane adhesive, which was allowed to cure before sandwich assembling. The bulk density of the modified BEC increased drastically to *ca.* 260 $kg.m^{-3}$, *i.e.*, more than 150 %.

The face-sheets were bonded to the cores using the bi-component polyurethane-based adhesive. After assembly, weight was evenly distributed on top of the sandwich structure so that a constant pressure was applied throughout the adhesive curing/bonding stage, and adhesive layers with nearly constant and equal thicknesses resulted along each of the sandwich bonded surfaces. A structure with a nominal thickness of 15 mm was obtained, from which the specimens for flexural testing were cut. Each sandwich panel generated two specimens. Several panels were manufactured for each core type.

2.3. Flexural mechanical testing

Three- and four-point bending tests were performed with an Instron® (USA) model 4208 electromechanical universal testing machine, using a 5kN load cell. The bending tests were performed according to methods in ASTM C 393 [15] and ASTM D 7250 [16]. In order to obtain correct deflection values throughout the linear elastic region, a dial gage was used to measure displacement of the lower face-sheet up to 10 mm.

Sandwich specimens with nominal dimensions of 350 × 40 mm^2 (length × width), were tested in both loading geometries. Three-point bending was performed with a span length of 200 mm, with loading roller and supports' diameters of 15 mm and 20 mm, respectively. Four-point bending was performed using the third-point loading configuration (Fig. 1), with the outer span length (L) set to 300 mm, and 20 mm diameter rollers were used for both loading and supporting rollers. In both tests, hard polyurethane blocks were placed between the loading rollers and the specimen to distribute load and prevent early core compression collapse. Loading was applied at a constant speed of 5 $mm.min^{-1}$ for both loading geometries.

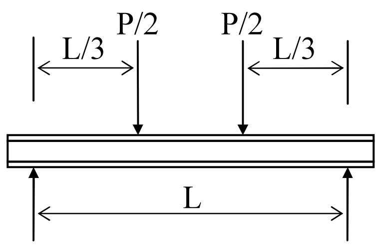

Figure 1. Third-point loading configuration in four-point bending test.

Each specimen was loaded in both configurations. Odd numbered specimens were loaded in three-point bending up to 4 mm midpoint deflection, and then unloaded and allowed to rest, before being loaded in four-point bending up to failure. Even numbered specimens were loaded in the reverse order – *i.e.*, up to 4 mm midpoint deflection in four-point bending, and until failure in three-point bending.

3. Results and discussion

Throughout three-point bending testing the localized mid-span loading lead, as expected, to noticeable compression of the low modulus BEC core, but it ultimately failed by shear. Images of specimens under test, after core shear failure, for both BEC and modified BEC structures are presented in Fig. 2. In four-point bending, core shear failure was again observed as depicted in Fig 3.

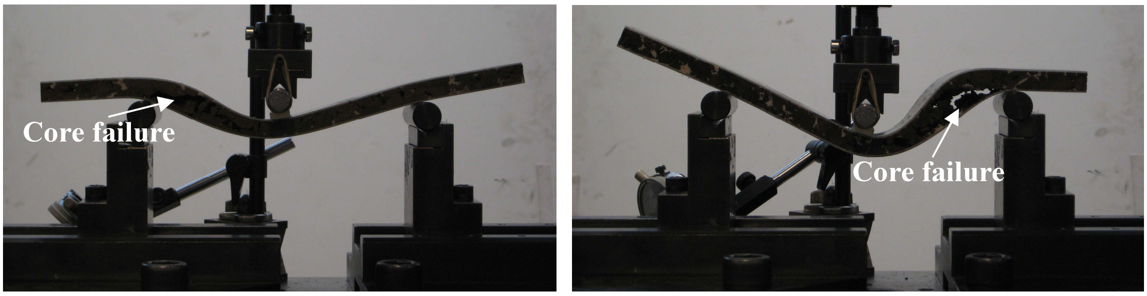

Figure 2. Three-point bending tests after core shear failure for neat BEC (left) and modified BEC (right) based sandwich structures.

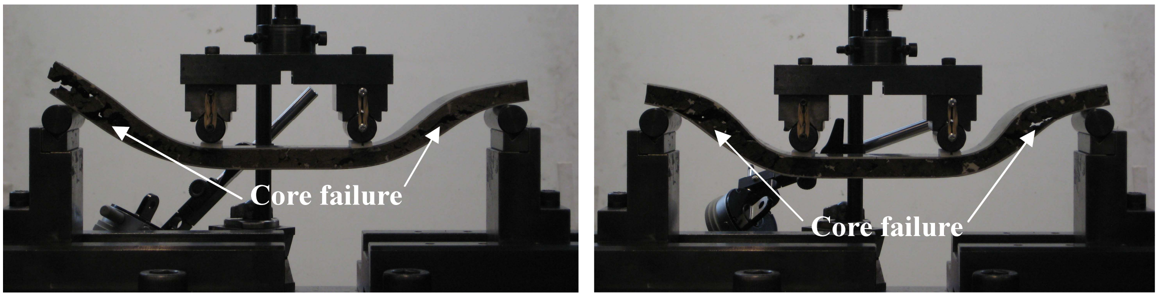

Figure 3. Four-point bending in third-point loading configuration, after core shear failure for BEC (left) and modified BEC (right) based sandwich structures.

Load vs. deflection curves of representative specimens, for both three-point and four-point bending are presented in Fig. 4. These curves, where deflection is based on cross-head displacement are only meant to qualitatively show overall flexural behavior up to failure. All loading curves are characterized by clear maximums, but failure is more catastrophic in 3-point bending for both core materials. Loading in 4-point bending results in a smoother load loss after failure onset, which can be interpreted as failure progressing at a lower rate. Is also evident that the modified BEC core results in a structure with greatly improved performance. The average maximum values for displacement, load, core shear stress and face-sheets bending stress, are given in Table 1. The results show that for each core material both loading geometries resulted in similar values for maximum core shear, and face-sheet bending stresses, but as observed above, low core shear strength led to structure failure, and bending stresses on facings remained far below the laminate ultimate bending stress. The reinforced BEC core failed at values (τ_{av} ~242 kPa) about 80% higher relative to BEC (τ_{av} ~134 kPa). Although maximum stress values occurred at similar deflections irrespective of geometry or material, the experimental curves show that catastrophic failure is delayed to higher deflections for reinforced BEC.

The values for sandwich flexural stiffness (D) and transverse shear rigidity (U) - and core shear modulus (G) - were determined in accordance with ASTM 7250 standard practice [16], which relies on the simultaneous solution of the sandwich displacement general expression for two different loading conditions. The calculation was performed using the displacement behavior up to a midpoint deflection of 4 mm, *i.e.*, the maximum value at which each test that was not carried until failure, was interrupted before unloading (*cf.* 2.3. Flexural mechanical testing). The results are presented in Table 2.

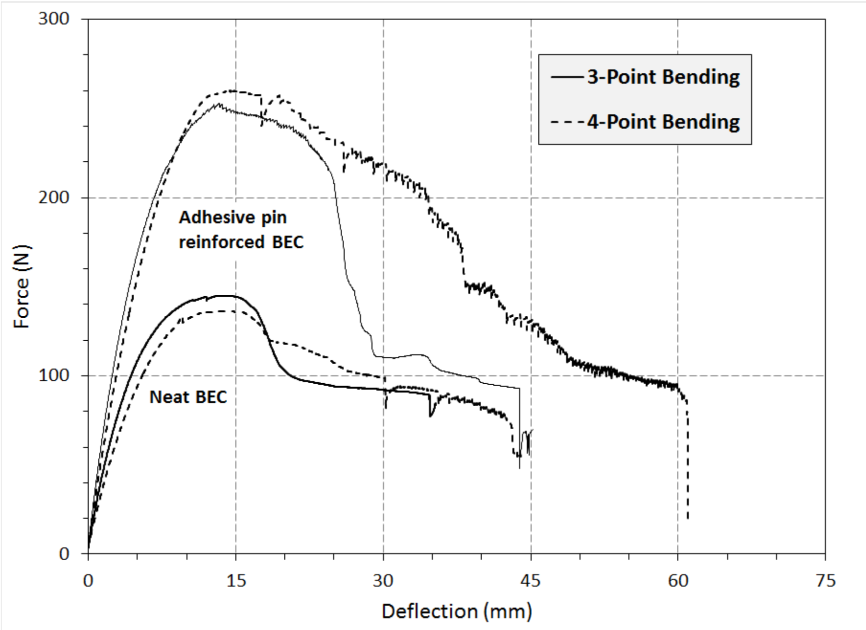

Figure 4. Load vs. deflection curves from three-point and four-point bending tests of representative sandwich structure specimens with both BEC based cores.

Table 1. Flexural average properties at maximum load.

Sandwich core material	Loading geometry	Deflection (mm)	Load (N)	Facing bending stress (MPa)	Core shear stress (kPa)
Neat BEC	3-point	14.4	145	12.9	131
	4-point	14.5	136	13.8	138
Pin reinforced BEC	3-point	13.4	253	19.3	238
	4-point	14.8	260	20.0	245

Table 2. Results based on application of ASTM D7250 practice.

Sandwich core material	Sandwich structure properties		Core property
	Flexural stiffness, D ($MN.m^2$)	Transverse shear rigidity, U (kN)	Shear modulus, G (MPa)
Neat BEC	55.4	1.20	2.15
Pin reinforced BEC	58.4	2.07	3.72

Both structures show similar flexural stiffness, as it expected that core contribution is marginal (*ca.* 5% increase with modified BEC). The value obtained for neat BEC is identical to the one previously obtained, where a sandwich structure with a 16 mm thick BEC core was studied [12]. The results show an increase in core shear modulus in excess of 70% for the modified BEC material compared to that of neat BEC. Although the modified core material has a much higher density (*cf.* 2.2. Manufacturing), the core material contribution to the sandwich structure density is much lower than that of face-sheets and adhesive layers combined. In fact, the experimentally determined densities for neat BEC and modified BEC based sandwich structures are *ca.* 430 kg.m^{-3} and *ca.* 540 kg.m^{-3}, respectively – *i.e.*, a 25% increase. Therefore, considering the increase in core shear modulus, there is still almost 40% net gain in specific shear modulus.

4. Conclusions

Composite sandwich structures using both neat and adhesive pin reinforced black expanded corkboard as core materials were manufactured and studied with respect to bending/shear mechanical behavior. The main conclusions can be summarized as follows:

- The core modification resulted in an bulk density increase from 100 kg.m^{-3} to 260 kg.m^{-3} - *i.e.*, an increase in excess of 150 % - which translated in 25% increase for sandwich structure density;
- Flexural testing in both three- and four-point bending resulted in core shear failure for both structures, but the modified core failure occurred at a shear stress *ca.* 80% higher;
- Core shear moduli were estimated based on a standard practice, with the modified core showing a 70% increase;
- In spite of the clear detrimental effect of core modification on core bulk density, when sandwich properties are considered, density increase is outweighed by the measured increases of values for both core shear strength and modulus, and therefore not only absolute but also specific (*ca.* 40%) improvement is achieved.
- The value obtained for shear modulus of black expanded corkboard was 2.2 MPa, reproducing that obtained in a previous work with the same material but different thickness [12].

In future works we expect to validate the obtained shear properties by preferred methods such as those described in ASTM C273 [17]. Other perforation geometries and reinforcing methods shall also be addressed.

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