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Low velocity impact and flexural performance of sandwich structures with cork and polymer foam cores

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Abstract

The core material plays an important role in the static behavior of sandwich structures, but particularly in their dynamic behavior. Cork with its unique flexibility, elasticity and compressibility properties is an excellent natural energy absorber and motivates the study of its incorporation in sandwich construction. In this work, flexural and impact behaviors of sandwich structures with fiberglass/epoxy face sheets, different cork based core materials, and PMI, PU and PVC foam cores are experimentally studied by four-point bending and low velocity impact, and compared. Flexural properties of cork based structures are lower than those of structural polymer foams for the geometries explored in this work. Core indentation was the single collapse mode observed in this study; therefore, further studies including other specimen geometries for four and three-point bending are required to evaluate other collapse modes and understand the full behavior of cork under flexural loading. Damage tolerance exhibited by cork core structures subject to low velocity impact make cork an improved core material, particularly for sandwich structures likely to regularly suffer low velocity impact events. Ongoing work on cork based core materials modified with a nanoporous gel, and with a dispersion of carbon nanotubes in the bonding layer, is briefly mentioned.

Keywords: Cork; Sandwich structure; Polymer foam cores; Low velocity impact; Flexural; Damage;

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1. Introduction

Knowledge of constituent material properties is important in defining a composite structure for a given application and in understanding how that structure will respond to the various stimuli likely to be imposed on it [1]. In many applications, sandwich structures with laminated face sheets are used because of the well-known advantages of this kind of construction. The face sheets are loaded primarily in tension or compression to resist bending while the core resists the shear stresses [2]. However, core materials play an important role not only in the static behavior of sandwich structures, but particularly in its dynamic behavior.

The inherent unique qualities of flexibility, elasticity and compressibility of cork, excellent mechanical properties for impact situations, make it an excellent, natural energy absorber and motivate the study of its incorporation in sandwich construction. Review of the literature shows already some research studies [3-7] regarding the characterization and improvement of cork's static properties, namely when integrated in a sandwich structure. However, there is a lack of

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information in terms of low velocity impact behavior of cork core sandwich structures. So, in order to take advantage of cork's natural ability to resist low velocity impact loading, it is necessary to further evaluate the reliability of cork as the core of sandwich structures, testing not only its static properties, but also its damage resistance and tolerance.

In this work, four-point bending and low velocity impact tests were performed on specimens from sandwich constructions based on different core materials. In order to evaluate the benefits of using specially designed cork agglomerates instead of standard ones, two different cork agglomerates were tested. One was specially developed by Amorim Cork Composites S.A. for polymer composite sandwich construction applications which, according to the manufacturer, shows improved bonding characteristics not seen in other cork agglomerates. The other was a general purpose cork agglomerate, used for example, in wall boards and coverings. These customary cork agglomerates are typically slightly heavier than those designed for sandwich construction, and don't have any surface treatment to improve bonding characteristics. Three polymer-based foams – polymethacrylimide (PMI), polyurethane resin (PUR), and polyvinyl chloride (PVC) − were also tested as core materials for comparison.

2. Experimental

All sandwich structures were constructed using the same facing material, core thickness, and adhesive layer thickness and material. The parameter under study was the core material.

2.1. Materials

A very low viscosity (170 mPa.s) two component Biresin® system (Sika®, Germany) based on epoxy resin CR83 and amine hardener CH83-6 was used as matrix for the sandwich facings. The reinforcement for the laminates used as sandwich facings was a multiaxial E-glass fibre fabric. The material was Multifab® (Lintex®, PRC) E BX 600, a double biaxial (±45°) fabric with areal weight of 612 g.m^{-2}, which includes the contribution from polyester yarn stitching.

The core materials included two types of cork agglomerates and three rigid polymer foams. The cork based cores included a general purpose coarse grain ($\phi \leq$ *ca.* 5 mm) cork agglomerate, used for example, in wall boards and coverings (SEDACOR, Lda., Portugal), and CoreCork™ NL25 (Amorim Cork Composites S.A., Portugal) – a product developed for composite applications, with finer grain and narrower size distribution, lower density (250 kg.m^{-3}) and a surface treatment to improve adhesion.

The polymer based rigid foams were: Rohacell® FX (Evonik Industries, Germany), a closed-cell rigid polymer foam based on PMI which does not contain any CFC's; Airex® C70.75 (Airex® AG, Switzerland) a closed cell cross-linked foam based on an interpenetrating polymer network of PVC modified with aromatic amides containing no CFC's, with nominal density of 80 kg.m^{-3}, negligible water absorption, excellent resistance to chemicals, with a fine cell structure offering an excellent bonding surface, and combining excellent stiffness and strength to weight ratios; a rigid polyether-based PUR foam (Polirígido, S.A., Portugal) with low density and good thermal and sound isolation properties.

A highly structural two-component, fast-curing polyurethane assembly adhesive − SikaForce®-7888 L10 (VP) (Sika®, Germany) − was used to bond the face sheets to the core materials. The adhesive components are a mixture of filled polyols and isocyanate derivatives, respectively, which must be mixed in a 1:1 volume ratio.

2.2. Manufacturing

The sandwich structures were produced obtaining separately the fiberglass/epoxy laminate face sheets, by vacuum infusion, preparing the core, and bonding them together using the structural adhesive. Each fiberglass/epoxy facing had two layers of ±45° biaxial fabric. Two large laminates (*ca.* 2000×600 mm^2) were obtained by vacuum infusion, from which 600×450 mm^2 face sheets were cut. These were bonded to 12 mm thick core material pieces using the two-component polyurethane-based adhesive. After assembly, weights were uniformly distributed over the sandwich structure to assure that a constant pressure was applied throughout adhesive curing/bonding, and ensuring that the adhesive layer had approximately constant thickness along each of the sandwich bonded surfaces. The resulting structures had a nominal thickness of 15 mm, from which specimens for impact and four point bending were cut.

2.3. Mechanical Testing

In this work, four-point bending and low velocity impact tests were performed on sandwich specimens.

2.3.1. Flexural testing

The four-point bending tests were conducted according to ASTM C 393-00 [8], in an Instron testing machine. Four sandwich specimens were tested for each sandwich construction. Specimens had 350 mm length × 30 mm width. The span length was 300 mm. Load was applied at a constant rate of 5 mm/min, using a third-point loading configuration (Fig. 1). The loading rollers had a diameter of 20 mm and load was measured using a 5 kN load cell.

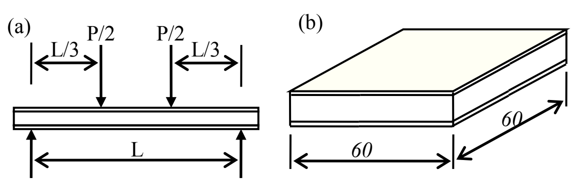

Fig. 1. (a) Third-point loading configuration for four-point bending tests, according to ASTM C 393-00, and (b) low velocity impact specimens.

2.3.2. Impact testing

At the moment the work was being performed, no standard regarding low velocity impact testing of sandwich structures was available – ASTM International's Committee D30 was developing a proposed new standard ASTM WK30231 which later resulted in standard ASTM D7766 / D7766M-11, "Practice for Damage Resistance Testing of Sandwich Constructions" [9]. Considering the available information at the time, low velocity impact tests were therefore carried out based on standards for polymers and laminates, such as ASTM D 5628 – 96 [10], ASTM D7136 / D7136M – 05 [11], ASTM D7137 / D7137M – 05 [12] or Airbus AITM1-0010 [13], for example, and with the restrictions imposed by the testing equipment.

Specimens with dimensions 60 × 60 mm^2 (*cf.* Fig. 1) where used for low velocity impact testing. The tests were carried out in a Rosand IFW 5 HV testing machine, at impact energies of 10 J, 15 J, 20 J, 25 J, 30 J (three specimens per sandwich structure) and 40 J, using a 3.774 kg mass impactor with a 16 mm diameter hemispherical tip. The impact energy was obtained changing the drop height, as summarized in Table 1.

Table 1. Impact conditions for low velocity impact testing

Impact energy [J]	Impact height [m]	Impact velocity [m.s^{-1}]
10	0.270	2.30
15	0.405	2.82
20	0.540	3.26
25	0.675	3.84
30 (3×)	0.811	3.99
40	1.081	4.60

Each specimen was fixed with a pneumatic lever arm with a reversible ring, using a clamping pressure of 3 bar (a higher clamping pressure could compress excessively those core materials with lower through-thickness resistance, namely the PUR foam and cork agglomerates). The test was performed capturing the impactor after the first strike, so that a second strike wouldn't occur.

3. Results and Discussion

3.1. Flexural tests

The flexural testing results for the sandwich specimens with polymer foam- and cork-based core materials are shown in Fig. 2 and Fig. 3, respectively. The displacement at yield, load at yield, core shear stress at yield and facing bending stress at yield for each sandwich construction are summarized in Table 2.

In this study, PMI foam and modified PVC foam core sandwich specimens showed the best performance under flexural loading, as their level of local compression was substantially smaller than that exhibited by other sandwich specimens (*cf.* Fig. 4). Furthermore, these sandwich structures withstand similar maximum loads, as can be seen in Table 2.

Specimens with PUR foam were the weakest under flexural loading, exhibiting high local compression beneath the loading pads and the lowest maximum load (*cf.* Fig. 5).

The sandwich structures with cork agglomerates, both NL25 and standard ones, exhibited similar behavior under flexural load. Both agglomerates exhibited pronounced lack of local compressive strength, conducting to considerable local compression (*cf.* Fig. 6). However, the standard agglomerate exhibited a slightly higher maximum load when compared with the NL25 agglomerate, as one can see in Table 2.

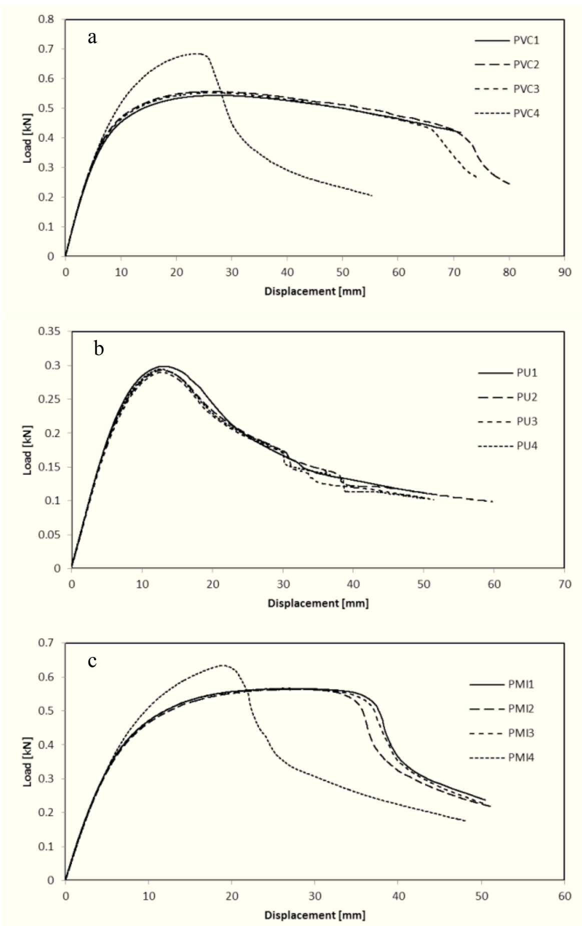

Fig. 2. Load-deflection curves from four-point bending tests for sandwich structures with polymer foam-based core materials: (a) Airex® C 70.75 modified PVC foam, (b) PUR foam, and (c) Rohacell® PMI foam.

Table 2. Four-point bending test results at yield points

Core material	Displacement	Load	Core shear stress	Facing bending stress
	[mm]	[kN]	[MPa]	[MPa]
PVC	26.8	0.585	0.722	48.1
PUR	13.0	0.294	0.361	24.0
PMI	25.3	0.582	0.721	48.1
NL25	13.7	0.372	0.434	28.9
Cork (standard)	16.6	0.416	0.456	30.4

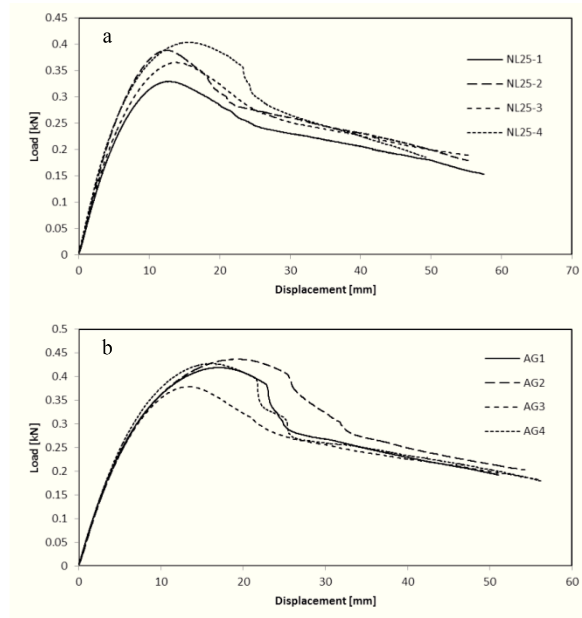

Fig. 3. Load-deflection curves from four-point bending tests for sandwich structures with cork-based core materials: (a) NL25 cork agglomerate and (b) standard cork agglomerate.

Fig. 4. Sandwich specimens during four-point bending testing: modified PVC foam (left) and PMI foam (right) cores.

Fig. 5. Sandwich specimen with PUR foam core during four-point bending testing.

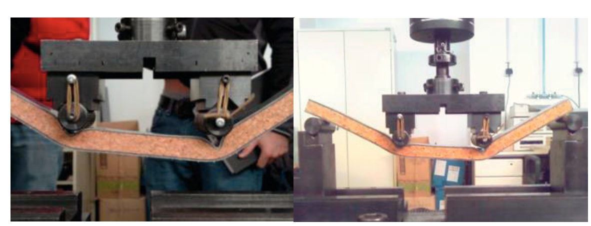

Fig. 6. Cork core-based sandwich specimens during four-point bending testing: NL25 (left) and standard cork (right) cores.

3.2. Impact tests

The force-time plot histories of the sandwich specimens impacted at 15 J, 25 J, and 40 J are shown in Fig. 7. The standard cork and NL25 cork agglomerate core specimens are referred as AG*i* and NL25-*i*, respectively. Similarly, PMI*i*, PU*i* and PVC*i* refer to PMI, PUR and modified PVC foam core specimens, respectively.

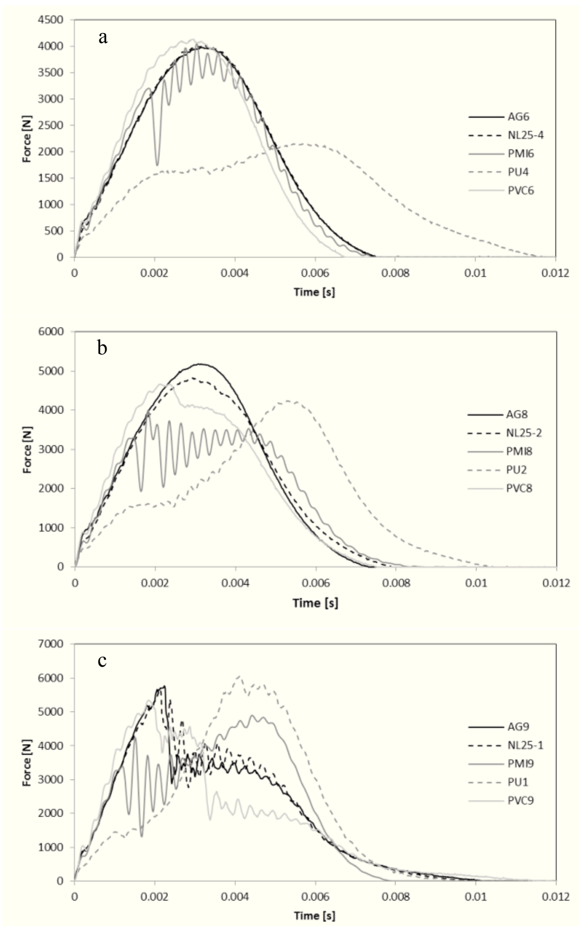

Fig. 7. Force-time plot histories of sandwich specimens subjected to low velocity impact: (a) 15 J, (b) 25 J, and (c) 40 J energy levels.

Low velocity impact testing showed that sandwich specimens with PUR foam core material exhibit the worst low velocity impact behavior of all tested specimens. Generalized core crushing and matrix cracking is observed at all impact energies.

For impact energies below 15 J, PMI, PVC and cork based sandwich specimens exhibited similar behavior. However, for intermediate impact energies, between 20 J and 25 J, cork based specimens exhibited considerable smaller externally visible damage area, even though some matrix cracking may occur, as shown in Fig. 8 (a) and (b). On the other hand, specimens with PVC foam core (which exhibit similar peak force) showed the largest damage area and had permanent indentation. However, as seen clearly in Fig. 8 (c), the worst damage scenario occurred with specimens with PMI foam core, which exhibited considerable matrix cracking, permanent indentation, considerable core damage and extensive face-to-core debonding.

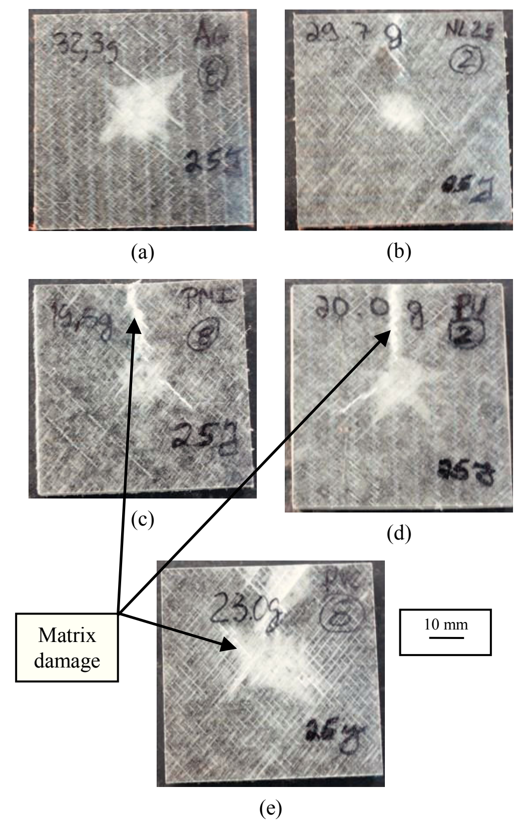

Fig. 8. Specimens impacted at 25 J: (a) standard cork agglomerate (AG), (b) NL25, (c) PMI, (d) PUR and (e) modified PVC. Cork based specimens clearly show less damage than other sandwich specimens.

For impact energies above 30 J, PVC and cork based sandwich specimens also exhibited fiber failure. Furthermore, for the highest energy level (40 J), penetration of the front facesheet may occur. In spite of sandwich specimens with PMI foam core did not exhibit front face penetration and fiber failure, the permanent indentation observed is enormous, as well as core damage and face-to core debonding.

4. Conclusions

Similarly to what was found in other studies [3-7], cork based structures' four-point bend flexural properties for the geometries explored in this work are lower than those of structural polymer foams. Since core indentation was the unique collapse mode observed in this study, further studies including other specimen geometries for four and three-point bending may be useful to evaluate other collapse modes, following the approach proposed by Rice et al. [14], for instance. Such an evaluation may help to understand the full behavior of cork under flexural load, including if its sandwich structures' flexural properties are enhanced when indentation is avoided.

The excellent properties of flexibility, elasticity, viscoplasticity and compressibility of cork make it an improved core material, particularly for sandwich structures likely to regularly suffer from low velocity impact events. At the moment, the authors of the present work are carrying out studies on flexural and low velocity impact behavior of sandwich structures with cork based core materials impregnated with a nanoporous gel, and with a dispersion of carbon nanotubes in the bonding layer. Those studies may indicate if the natural ability of cork to be used as a core material can be further improved, in order to optimize cork based core materials performance in sandwich construction.

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