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Dynamic Response of Green Sandwich Structures

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Abstract

Synthetic fibre-synthetic foam core sandwich composites are widely used for many structural applications due to their superior mechanical performance and low weight but the limited end of life disposal options and environmentally friendly character are currently envisaged as barriers to their continued development. The objective of this article is to analyse the suitability of using agglomerated cork as core material in sandwich structures to be used in applications where energy absorption due to low velocity impacts can be of importance. Green sandwich specimens with flax/epoxy face sheets and agglomerated cork as core have been manufactured and their response to low velocity impacts has been compared to the results obtained with similar specimens using traditional synthetic core. This study shows that the peculiar deformation mechanisms of cork can allow to tailor the damage extension through-the-thickness thus providing in principle a better damage tolerance after impact.

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Keywords: Polymer matrix composites; Sandwich structures; Natural fibres; Low velocity impact; Cork

1. Introduction

The need for sustainable materials with the aim to alleviate the environmental impact of engineering materials and increase their end of life disposal options has definitely stimulated, over the last two decades, a resurgent interest in natural fibres as reinforcement in polymer matrix composites [1,2]. Also sandwich structures cannot be considered exempt from these environmental concerns, especially if one considers their increasing use in aerospace, marine,

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automotive and transportation fields, dictated by the enhanced flexural stiffness and lightweight coupled with additional benefits related to the specific application, such as thermal and acoustic insulation, ease of forming, fire retardation. Typically, sandwich structures for these applications use thin laminated face sheets bonded to synthetic honeycomb or foam cores. Cork is a natural cellular material obtained from the bark of the oak (*Quercus suber L.*) and is periodically harvested from the tree, usually every 9–12 years and is therefore a renewable resource [3]. Cork exhibits several interesting properties, namely low density, reduced permeability to liquids and gases and thermal insulation properties in addition to a peculiar mechanical behaviour characterized by nonlinear elasticity, exceptional compressibility without fracture, and unusual dimensional recovery capability, which gives rise to outstanding energy absorbing performance [4,5]. These properties can be ascribed to the three-dimensional structure of cork that may be described as an array of closed prismatic, on average hexagonal cells stacked base-to-base making rows oriented in the radial direction of the tree and assembled side by side, forming a honeycomb-type structure [5].

A major concern that still hinders a much more widespread usage of sandwich composites is their susceptibility to damage due to impact loading and therefore cork and its products, such as agglomerated cork, are envisaged as ideal core materials for sandwich structures. The successful application of sandwich structures depends on an in-depth characterization and understanding of the sandwich constituent materials (face sheets, core, and adhesive), and also of the whole structure under quasi-static and dynamic loading scenarios. In this regard, studies on cork and related sandwich structures are available in literature, but they are mainly focused on quasi-static properties, such as in compression, tensile and shear [6-8]. On the contrary, the response of cork and resulting sandwich structures to impact loading has received considerably less attention, including some studies on low velocity impact [9-12], ballistic response [13], dynamic crushing behaviour [14] or blast wave response [15].

It is to be noted that in most studies sandwich structures based on agglomerated cork were characterized by skins made of carbon fibre reinforced polymers or aluminium, thus not allowing a full exploitation of the environmentally friendly character of cork. The aim of the present work is to analyse the response to low velocity impact of green sandwich panels consisting of flax/epoxy face sheets and two different types of core materials, namely agglomerated cork and Rohacell 110WF rigid foam, for comparison purposes. This sandwich construction, based on flax/epoxy skins and agglomerated cork as core material, has been already investigated by Mancuso et al. [16] who reported results of an extensive and detailed characterization of the flexural behaviour of such structures intended as structural components of small sailing boats, without addressing the response to impulsive loadings.

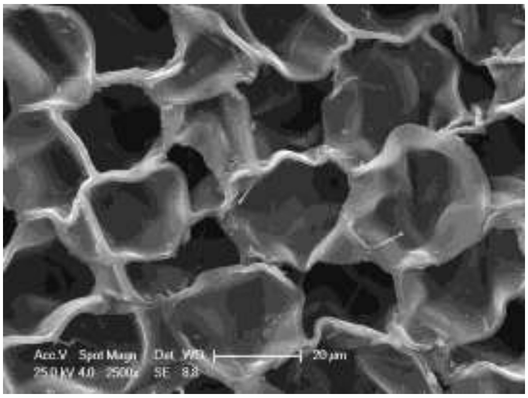
2. Materials and methods

The unidirectional prepreg material system (FLAXPREG UD 180) based on epoxy matrix with a fibre areal weight of 180 g/m^2 was supplied by Lineo. The face sheets were manufactured with a quasi-isotropic configuration [+60/0/-60]s and the panels were vacuum-bagged and fully cured under pressure in an autoclave to the manufacturer's specifications. The agglomerated cork (ECOPAN) was supplied by Etruria Cork Srl with a nominal density of 145 kg/m^3 and a thickness of 30 mm. This is a product used in the building industry as thermal and acoustic insulating material, therefore not specifically optimized for applications in composites. For comparison purposes, a closed-cell rigid foam based on polymethacrylimide (PMI) highly suited for autoclave prepreg processing and all typical resin infusion processes was used, namely Rohacell® 110WF supplied by Evonik Industries AG. This foam core has been provided with a density of 110 kg/m^3 and a thickness of 30 mm. The flax fibre laminates with a thickness of 1.4 mm and the two different cores were cut to required dimensions (10 × 10 cm) and Redux 609 by Hexcel, an epoxy film adhesive containing a cotton scrim, was used to bond the face sheets to the core. To ensure the bond between the face sheets and core was uniform and that the epoxy was fully cured, sandwich structures were vacuum-bagged and fully cured without additional pressure in an autoclave to the manufacturer's specifications.

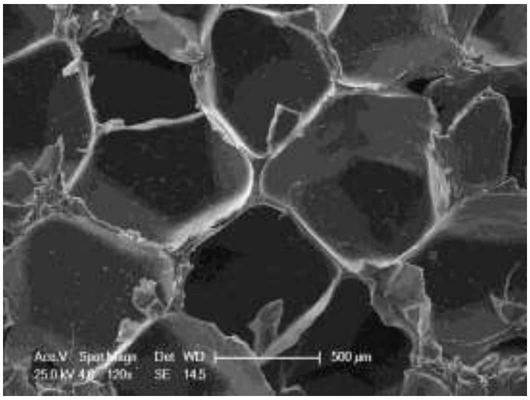
In order to characterize the static compressive behaviour of agglomerated cork and Rohacell, at least five specimens (30 × 30 × 30 mm) for each core material were tested in a Zwick/Roell Z010 testing machine equipped with a 10 kN load cell with a test velocity of 5 mm/min. Both core materials and the whole sandwich structures were subjected to low velocity impact tests using an instrumented drop-weight impact testing machine (CEAST/Instron 9340). The hemispherical impactor had a diameter of 20 mm and the dropped carriage had a total mass of 8 kg. The specimens were pneumatically clamped between two steel plates leaving a circular unsupported area with a diameter of 40 mm. At first low velocity impact tests were performed up to perforation for cores and sandwich structures and then tests were carried out at different percentages of the respective perforation energy, namely 25%, 50% and 75%. At least three specimens were impacted for each combination of material and energy level. The morphology and structure of both cork agglomerate and Rohacell foam were examined by scanning electron microscopy (SEM) (Philips XL 40). The specimens were sputter coated with gold prior to investigation.

3. Results and discussion

Figure 1 shows the morphology of cork and Rohacell. Both materials have a similar microstructure in that they are cellular but some different features can be highlighted. While Rohacell foam has cell sizes ranging from 610–836 µm, cork exhibits a significantly smaller cell size of approximately 25-43 µm; in addition cork shows a smaller cell wall thickness of about 1.26 µm compared to 22.31 µm for 110 WF.



(a)



(b)

Fig. 1. SEM micrographs of (a) agglomerated cork and (b) Rohacell

To assess their mechanical behaviour, both cork and Rohacell foam were subjected to compression tests. Figure 2 reports the typical stress-strain curves while the compression properties are summarized in Table 1.

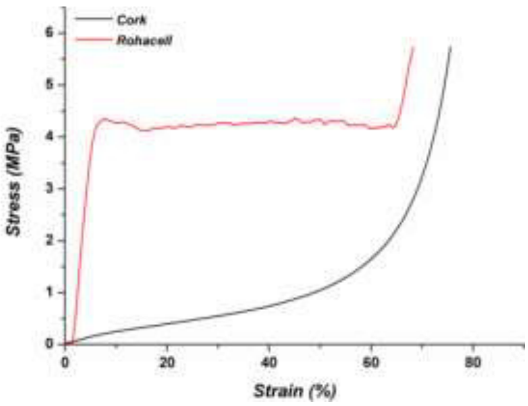


Fig. 2. Typical compression stress–strain curves for cork and Rohacell

Table 1. Mean and standard deviation for the compression properties of cork and Rohacell: E = Young's modulus, stresses required for collapse and 30 % strain ($\sigma_{plateau}$ and σ_{30}, respectively).

Specimen	E (*MPa*)	$\sigma_{plateau}$ (*MPa*)	σ_{30} (*MPa*)
Agglomerated cork	2.90±0.33	0.20±0.02	0.55±0.09
Rohacell	117.65±4.04	4.29±0.06	4.27±0.12

Young's modulus (E) was calculated from the average slope of the stress–strain curve in the elastic stage, while the collapse stress ($\sigma_{plateau}$) was evaluated as the intersection of the lines fitting the plateau and the elastic stages. σ_{30} represents the stress required for a strain equal to 30 %. Despite the heterogeneous and anisotropic nature of the cork, the experimental results revealed a homogeneous and isotropic compressive behaviour for agglomerated cork. Natural cork shows a difference in the compressive behaviour in the different directions, with the strength in the radial direction that is higher than that in axial and tangential directions, although this difference is not usually very marked [5]. In the present case, despite a relatively large size of the cork granules, the different orientation that these granules have inside the agglomerate bulk during transformation process are likely to be responsible for this homogenization process.

In figure 2, the usual three compression stages of cellular materials, as described in literature [3,4,17,18], can be easily identified. These three stages correspond to the following phenomena for the cells: the elastic region of compression curve is due to the bending of the cell walls; after this region, the plateau (with a slight positive slope with increasing strain) corresponds to the buckling of cell walls for cork and brittle crushing for Rohacell that starts in a localized region of weaker cells and further extends throughout the material. As the strain increases, the response enters the densification stage, which exhibits a sharp increase in stress, where the collapse of cells and compaction of the successive cell walls occurs. From figure 2 and table 1 it can be inferred that Rohacell foam outperformed the agglomerated cork in terms of strength and stiffness, and this would definitely play a role also in the response to impact loading.

The behaviour of neat cork and Rohacell foam when subjected to low velocity impact tests is compared in figures 3 and 4, in terms of force-displacement curves and related damage modes.

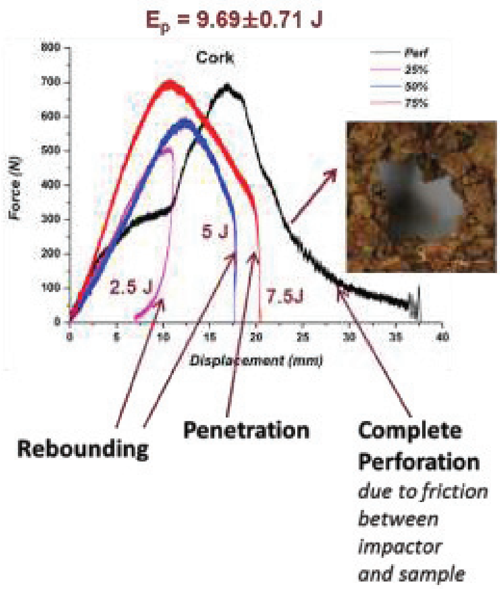


Fig 3. Typical force versus displacement curves of agglomerated cork impacted at different energy levels

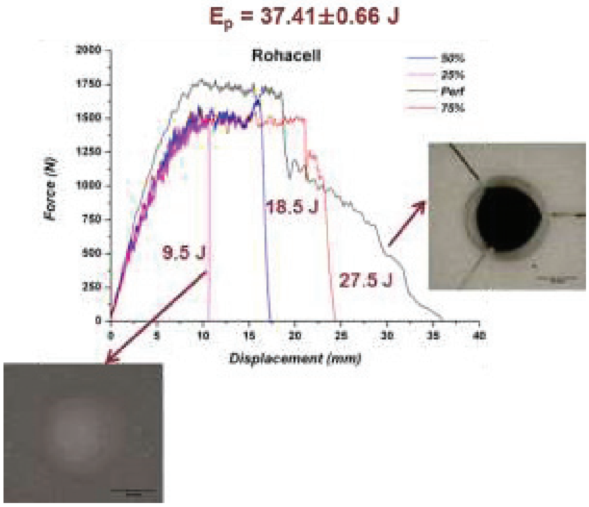
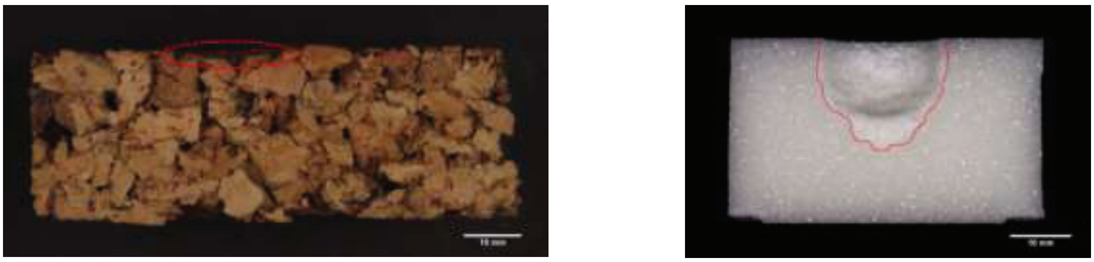


Fig. 4. Typical force versus displacement curves of Rohacell foam impacted at different energy levels

The agglomerated cork exhibited a clear rebounding phase at 25 % of the perforation energy while at 50 % some rebounding was detected even if the damage degree, defined as the ratio between absorbed energy and impact energy, was about 0.96, thus very close to unity when penetration takes place. The energy absorbed by the specimens was calculated from the force-displacement plots by numerically integrating the recorded impact force over the calculated plate displacement. No rebounding was instead observed in Rohacell specimens (figure 4) which were characterized by penetration even at very low impact energies. Rohacell specimens outperformed cork ones in terms of peak force, which is related to the plate stiffness [19], and perforation energy (E_p). Both properties are directly linked to the better mechanical properties of Rohacell foam. By comparing the cross-sections (figure 5) of impacted specimens, the different energy absorption mechanisms can be highlighted. Cork specimens exhibited a slight indentation on the impacted surface (red dashed line in figure 5a) coupled with cell wall collapse due to buckling whilst a deep indentation and an extended crushed zone (red dashed line in figure 5b) were detected for Rohacell foam.



(a) (b)

Fig. 5. Cross-sections of (a) cork and (b) Rohacell foam impacted at 50% of their respective perforation energy

These different damage modes are also responsible for the different behaviours found for the whole sandwich structures based on the two different cores and shown in figures 6 and 7.

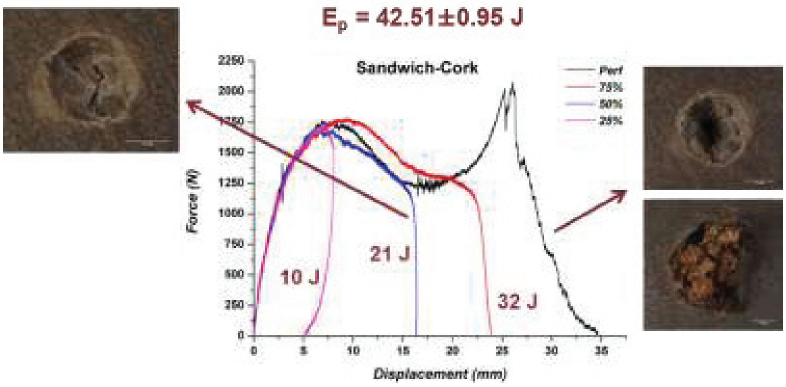


Fig. 6. Typical force versus displacement curves of sandwich structures based on agglomerated cork impacted at different energy levels

Also for sandwich structures the different core material played a significant role, with cork that allowed a rebounding stage at least up to 25 % of the perforation energy that was not observed for synthetic foam-based sandwich.

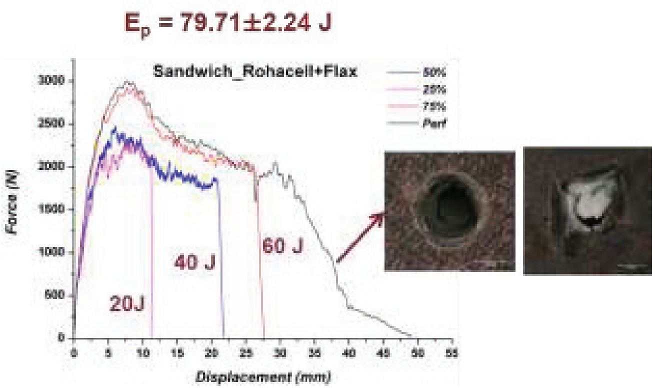
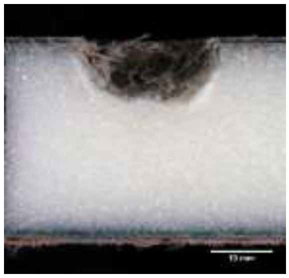


Fig. 7. Typical force versus displacement curves of sandwich structures based on Rohacell foam impacted at different energy levels

Face sheets were perforated through fracture of the flax fibres, resulting in the penetration of the impactor into specimens but force-displacement curves related to perforation were distinctly different. A curve with a mountain-like shape with two peaks for sandwich with cork was recorded (figure 6), implying the contact of impactor with top and bottom flax/epoxy face sheets, respectively, a feature that is completely missing for sandwich structures with Rohacell foam (figure 7). It is also worth noting that the second peak value for cork core sandwich samples is higher than first peak value. Probably one of the reason is the deformation characteristic of the cork core under compressive loading, which is in the form of collapsing of cells instead of breaking of cells (foam cracking). At higher strains, the cork cells have better energy absorption due to the collapse of individual cells and densification of the cork agglomerate structure which is able to resist further penetration of the impactor. As regards the synthetic foam (figure 8b), no core shear and cracking for impact energies up to 75% of perforation energy were found and no bottom face sheet damage for impact energies up to 75% of perforation energy for both sandwiches occurred (figure

8). It is also noted the lower damage degree for neat cork and resulting sandwich compared to Rohacell, coupled with a lower through-the-thickness damage extension.

(a)



(b)

Fig. 8. Cross-sections of sandwich structures based on (a) cork and (b) Rohacell foam impacted at 25% of their respective perforation energy

4. Conclusions

This study showed that green sandwich structures made of flax/epoxy skins and agglomerated cork as core can be successfully manufactured. Using cork agglomerate as a core material provides a natural, renewable alternative to traditional synthetic materials and its distinct mechanical behaviour, in particular the collapse of cell walls, allows for the absorption of high amount of energy without a considerable extension of damage inside the core material typical of other high performance core material such as Rohacell. In addition, through an effective tailoring of cork density and grain size it would be possible to reach peak loads and perforation energies comparable to those offered by high performance and much more expensive core materials.

References

[1] K.L. Pickering, M.G. Aruan Efendy, T.M. Le, A review of recent developments in natural fibre composites and their mechanical performance, Compos. Part A-Appl. S. 83 (2016) 98-112.

[2] S.K. Ramamoorthy, M. Skrifvars, A. Persson, A Review of Natural Fibers Used in Biocomposites: Plant, Animal and Regenerated Cellulose Fibers, Polym. Rev. 55 (2015) 107-162.

[3] H. Pereira, Cork: Biology, Production and Uses, first ed., Elsevier Science, 2007.

[4] J. Sargianis, H. Kim, J. Suhr, Natural Cork Agglomerate Employed as an Environmentally Friendly Solution for Quiet Sandwich Composites, Sci. Reports, 2 (2012) article number 403.

[5] V. Oliveira, M.E. Rosa, H. Pereira, Variability of the compression properties of cork, Wood Sci. Technol. 48 (2014) 937–948.

[6] C.P. Gameiro, J. Cirne, G. Gary, Experimental study of the quasi-static and dynamic behaviour of cork under compressive loading, J. Mater. Sci. 42 (2007) 4316–4324.

[7] R.A.S. Moreira, F.J.Q. de Melo, J.F.D. Rodrigues, Static and dynamic characterization of composition cork for sandwich beam cores, J. Mater. Sci. 45 (2010) 3350–3366.

[8] L. Reis, A. Silva, Mechanical behaviour of sandwich structures using natural cork agglomerates as core materials, J. Sandw. Struct. Mat. 11 (2009) 487–500.

[9] S. Petit,C. Bouvet,A. Bergerot, J.-J.Barrau, Impact and compression after impact experimental study of composite laminate with a cork thermal shield, Compos. Sci.Technol.67 (2007) 3286–3299.

[10] O. Castro, J.M. Silva, T. Devezas, A. Silva, L. Gil, Cork agglomerates as an ideal core material in lightweight structures, Mater. Des. 31 (2010) 425–432.

[11] F.A.O. Fernandes, R.J.S. Pascoal, R.J. Alves de Sousa, Modelling impact response of agglomerated cork, Mater. Des. 58 (2014) 499–507.

[12] S. Sanchez-Saez, E. Barbero, S.K. Garcia-Castillo, I. Ivañez, J. Cirne, Experimental response of agglomerated cork under multi-impact loads, Mater. Lett.160 (2015) 327–330.

[13] S. Sanchez-Saez, E. Barbero, J. Cirne, Experimental study of agglomerated-cork-cored structures subjected to ballistic impacts, Mater. Lett. 65 (2011) 2152–2154.

[14] S. Sanchez-Saez, S.K. García-Castillo, E. Barbero, J. Cirne, Dynamic crushing behaviour of agglomerated cork, Mater. Des. 65 (2015) 743–748.

[15] J. Sousa-Martins, D. Kakogiannis, F. Coghe, B. Reymen, F. Teixeira-Dias, Behaviour of sandwich structures with cork compound cores subjected to blast waves, Eng. Struct. 46 (2013) 140–146.
[16] A. Mancuso, G. Pitarresi, D. Tumino, Mechanical behvaiour of a green sandwich made of flax reinforced polymer facings and cork core, Procedia Eng. 109 (2015) 144-153.
[17] L.J. Gibson, M.F. Ashby, Cellular solids, second ed., Cambridge University Press, Cambridge, 1997.
[18] S.P. Silva, M.A. Sabino, E.M. Fernandes, Cork: properties, capabilities and applications, Int. Mater. Rev. 50 (2005) 345–365.
[19] M.O.W. Richardson, M.J. Wisheart, Review of low-velocity impact properties of composite materials. Compos. Part A-Appl. S. 27 (1996) 1123–1131.