Manufacturing and mechanical characterization of Basalt Fibre Reinforced Bio-polymer composites

R. Hoto[(2)], J.P. Torres[(3)], J.A. García-Manrique[(1)]

[(1)] Instituto de Diseño y Fabricación, Universidad Politécnica de Valencia, Spain. reho@doctor.upv.es
[(2)] Instituto de Ciencia y Tecnología de Materiales, Universidad Nac. de Mar del Plata, Argentina. jptorres@fi.mdp.edu.ar
[(3)] Instituto de Diseño y Fabricación, Universidad Politécnica de Valencia, Spain. jugarcia@mcm.upv.es

ABSTRACT

Nowadays, there is a growing interest for the use and development of materials synthesized from renewable sources in the polymer composites manufacturing industry; this applies for both matrix and reinforcement components. In the present investigation, a basalt fibre reinforced (BFR) bio-based epoxy system together with a cork core is proposed for its use in composite sandwich structures. Mechanical characterization of tensile and flexural properties was carried out. In addition, permeability measurements of the fiber reinforcement were performed. A case study, namely the fabrication of a longboard using the hand lay-up technique was carried out. A detailed description of the manufacturing process is presented along with finite element simulations of the mechanical response of the final piece.

Keywords: biopolymer composites, composite sandwich, cork, hand lay-up, FEM analysis

1. Introduction

Longboarding is a relatively modern sport born in the 1950s which was first developed by skateboarders who wanted to go faster and recreate the feeling of surfing on a hard surface. The necessary equipment consist of board with two trucks mounted wheels fixed to the board. In order to keep the weight as low as possible, boards are usually made of maple o bamboo sheets bonded together. The main disadvantage of using maple or bamboo is that its harvesting in an unsustainable ways can lead to many socials problems such as human health issues, as well as loss of recreational areas and other benefits that forest produces.

Nowadays, there is a growing need for the production and development of materials synthesized from renewable sources and to decrease the world's dependence on petroleum. In the fibre reinforced polymer composites (FRPCs) manufacturing industry, these tendencies have recently led to the investigation of possible substitutes, both for matrix and reinforcement components. Recently, bio-based matrix materials have received considerable attention mainly for being non petroleum-dependent [1]. These systems can be obtained from sustainable sources such as vegetable oil, cellulose and soy protein, among others. In the case of bio-based thermosetting resins, much research is still pending as mechanical properties comparable with those of petroleum-based counterparts are very difficult to achieve [2].

With respect to fiber reinforcements, basalt fibers (BFs) have been recently studied as sustainable alternative for fiber reinforcement as [3] the earth has practically unlimited basalt reserves and they can be recycled. BFs are produced from basalt rock, the most common rock found in the earth crust. Also, basalt is biologically inert and its weathering increases the mineral content of soil. The fibres are manufactured by melting at 1300-1700 °C and subsequent spinning. This manufacturing process requires no precursor or additives decreasing its environmental impact and production costs [4]. Regarding mechanical performance, it has been reported that BF has higher modulus and strength than GF [5]. In addition, basalt has much higher chemical resistance than glass: it can be used for the transportation and storage of corrosive liquids and gases. It also has much better electrical insulating properties and thermal-stability than glass [3]. Other advantages are high UV radiation and seawater resistance. Finally, reduction of risk of environmental pollution like high-toxic metals and oxides can be achieved by replacing glass fiber with basalt fiber. All of these features make BFs a suitable substitute for GFs. Moreover, when comparing BFs against CFs, despite having lower strength and stiffness, BFs are more attractive from an environmental protection perspective since they offer sustainability and independence from petroleum at significantly lower costs. It is important to remark that basalt fiber interface interaction with polymeric resins is not completely understood [4] and a subject of further investigation in order to gain a precise knowledge of its effect on mechanical properties.

FRPCs can be combined with a low-density core material to produce composite sandwich structures. These structures are intended to be used in lightweight applications requiring high bending stiffness and strength [6]. A fiber composite sandwich material consists of fiber composite top and bottom skins, which carry most of the in-plane and bending loads, and a core that bears the transverse shear and normal loads while providing a lightweight structure. These materials have been mainly used in the marine and aircraft industries, but nowadays their use in civil applications such as sports equipment is under constant development. Core materials typically used in sandwich structures are honeycombs, foams and balsa. A sustainable alternative for use as core material is cork, a natural product obtained from the outer bark of the cork oak. Cork is a bark that is harvested every nine years off cork oaks trees without harm. It has been used for thousands of years as a valuable renewable resource. Cork is an outstanding insulator that dampens road vibration. It also has excellent energy-absorbing capacity.

The overall objective of this work is to investigate the applicability of a novel BFR bio-based epoxy system combined with cork as core material for the fabrication of fibre composite sandwich sports equipment. For this, mechanical properties of both skin and core materials were assessed through flexural and tensile tests. A case study was performed for the manufacturing of a longboard. Permeability measurements were performed and mould-filling simulations were carried on PAM-RTM and contrasted to actual observations.

2. Experimental

2.1 Mechanical characterization

In order to determine the mechanical properties of the basalt fibre bio-epoxy composites, tensile and flexural coupons were obtained by waterjet cutting of VARTM manufactured flat panels. Cork compression samples were obtained from cork panels using a puncher. Sandwich samples were cut from remaining material in the longboard fabrication stage. All mechanical tests were performed on an INSTRON 3365 testing machine (Fig.1). Table 1 shows specimen dimensions employed in all cases.

Figure 1. *a) set-up for compression testing of cork. b) Specimen configuration for flexural testing of the composite sandwich.*

Table 1: Configuration for mechanical tests

Test type	thickness (mm)	width (mm)	length (mm)
Compression (cork)	5.0	20 (diameter)	-
Tensile (BFPC)	2.0	25	180
Flexural (BFPC)	2.0	22	60 (support span)
Flexural (sandwich)	7.0	22	60 (support span)

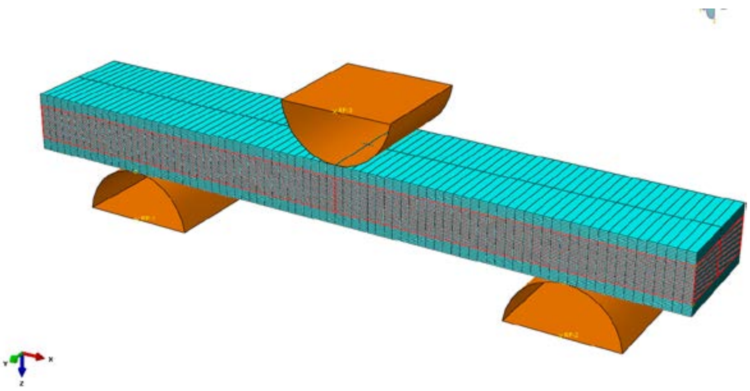

Figure 2. *Finite element mesh used for the simulation of the 3 point-bending flexural test.*

2.2 Finite element simulations

In order to assess the stress states developed in the sandwich material under flexural loads, finite element simulations of the flexural test were carried out in ABAQUS/Implicit 6.10. This study will later serve as a validation stage in the design process for the optimization of part geometry and sandwich configuration for an actual part in the case study section. The flexural test was modeled using SC8R8-node quadrilateral continuum shell elements for the basalt fiber skin and C3D8R 8-node linear brick element for the cork core. The supports and loading tip were modeled as analytical solids. Contact interaction properties were simplified assuming frictionless behavior and "hard" contact normal behavior. Fig. 2 shows the part geometry and mesh distribution employed. The cork material was modeled as an isotropic hyperelastic material using the hyperfoam option in ABAQUS. The basalt-reinforced skin was modeled as a linear orthotropic solid. Material parameters such as poisson ratio and shear modulus, that were not determined experimentally, were obtained from the literature [5].

3. Results & Discussion

3.2 Mechanical characterization

Mechanical properties for each material are presented in table 2. For the BFPC, linear elastic response with brittle rupture was observed as expected (Fig. 3a). Flexural testing on BFPC showed a linear response up to a point were stress starts to present small and continuous drops (Fig. 3b). It was observed that these drops corresponded to material failure occurring in the upper face of the test coupon, which is under a compressive stress state (Fig. 4).

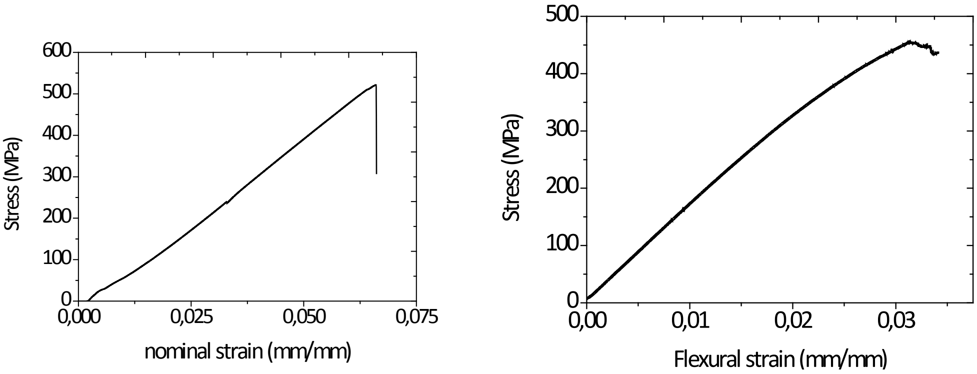

Figure 3. *Stress-strain curves for BFPC. a) tensile test; b) flexural test*

Figure 4. *Successive stages of BFPC compressive failure in flexural tests.*

Flexural testing of the composite sandwich showed a non-linear stress-strain evolution up to a point where there is a significant stress drop followed by an approximately constant stress region. This point corresponds to material failure associated with shear failure of the cork core material as can be seen in Fig. 6. Fig. 7a shows the finite element results for the simulation of the test along with a representation of the corresponding normal stress profile along the symmetry plane of the sample (plane *yz*, where z is the loading axis). Shear stresses in in the cork core are approximately homogeneous in the thickness while is assumed negligible in the skin material since they are modeled as shells. Fig.7b shows the evolution of shear stresses in the cork material as a function of distance from the axis of symmetry. Its value is 0 along the symmetry plane and increases to a maximum value located at approximately the middle point between the loading tip and the support. This fact is also confirmed in the observations of tested samples (Fig.6). Both Figs. 7a and 7b are very useful for understanding how stress and deformation distribution occurs in composite sandwich under flexural loads. From For the purpose of mechanical design, a maximum allowable shear stress (τ_{max}) assumption was made. This simplification arises from the fact that the expected application of the sandwich part will carry predominantly flexural loads. The critical value for the shear stress in the cork core was obtained from the finite element simulation shear stress profile.

Table 2. Mechanical properties obtained for sandwich components

Test type	Young modulus (MPa)	Strength (MPa)
Compression (cork)	4.5	-
Tensile (BFPC)	54,776	513
Flexural (BFPC)	56,455	462

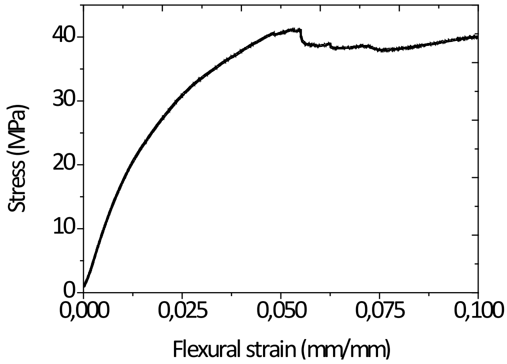

Figure 5. *Stress-strain results for the composite sandwich flexural test.*

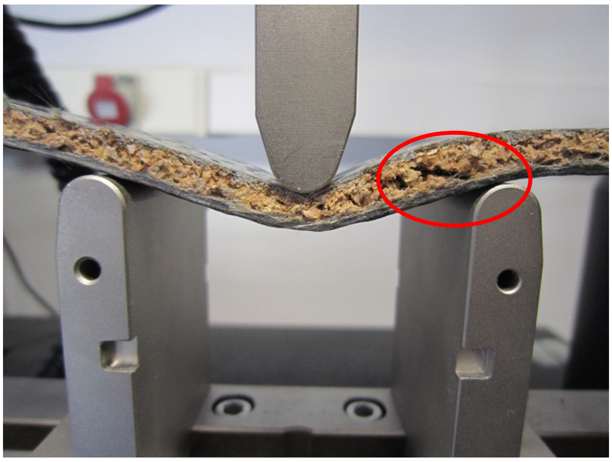

Figure 6.: *Critical failure of the sandwich sample by shear cavitation in the cork core.*

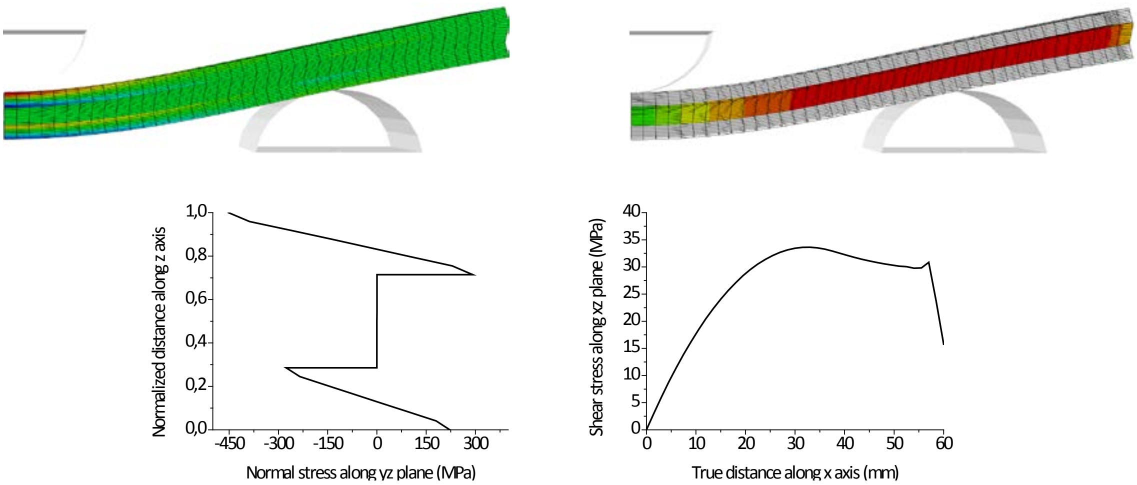

Figure 7. *a) Normal stress profile along the symmetry plane. b) shear stress evolution along the x axis in the cork core.*

4. Case Study: Manufacturing of a longboard

The proposed material system was evaluated for its use in urban longboards. The longboard was manufactured using the hand lay-up technique. First, 2 layers of basalt woven fabric were placed in open mold. Then, the bioepoxy resin was manually poured and applied over the basalt plies. Following this, a cork panel was placed above the impregnated fibers. Another 2 layer of basalt fabric were impregnated above the cork panel. Final part was consolidated placing the mold inside a bag and applying a vacuum. A bleeder material layer was placed prior to the vacuum in order to remove the excess of resin (Fig. 8). Fig. 8 also shows the final part obtained after curing for 24 hours at ambient temperature before demolding and then cured in an oven at 50ºC. The final part was obtained after milling the shape with a CNC machine.

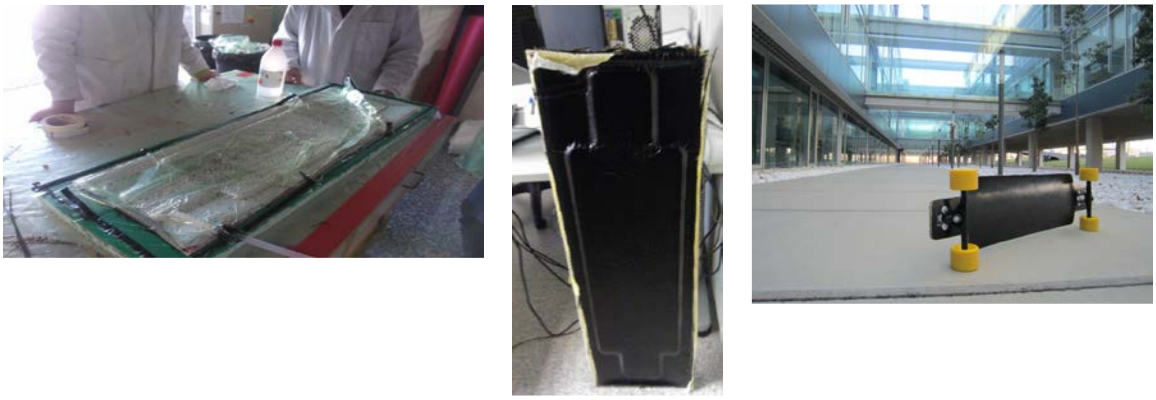

Figure 8: *Manufacturing Process and final part*

The stress analysis for the longboard under loading conditions was performed by running finite element simulations on ABAQUS/Explicit 6.10. The failure criteria presented in the previous section was used to evaluate the mechanical stability of the longboard. An extreme loading situation was modeled considering the fall of a 90 kg weight person from a 1 meter height over the board. This was simplified by applying two loads, over an area approximately equal to the size of a shoe, in the two points midway between the center and the end of the part. The resulting stress distribution is shown in Fig. 12. The stress analysis allows for the determination of the skin thickness by providing a lower bound below which deflections are so large that the cork core fails by shear cavitation. For the present design, a 1 mm. skin thickness resulted permissible.

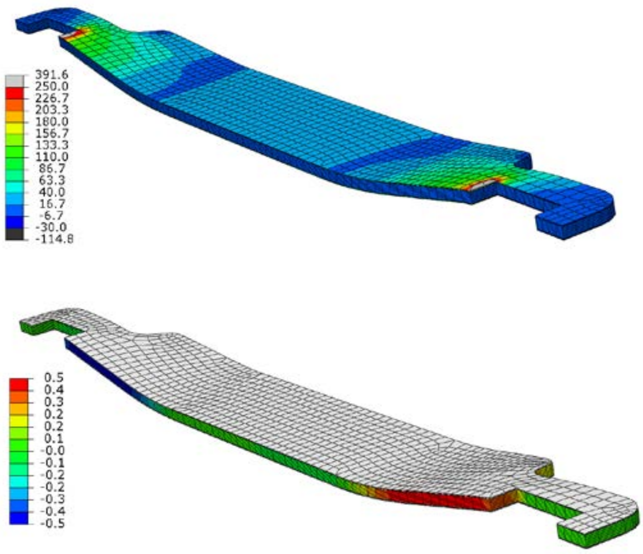

Figure 9: *Simulation results for the longboard under normal service loads. a) principal stress value b) shear stress distribution.*

4. Conclusions

An eco-friendly material system for sandwich structures, namely basalt fiber reinforced bioepoxy composite skin and cork core sandwich, made from renewable resources, was proposed. Mechanical performance under tensile and flexural loads of the sandwich and its separate constituents was assessed on an INSTRON machine. It was found that critical material failure is associated with cork shear rupture and a maximum allowable shear stress was determined for the material for its later use on design of sandwich parts.

As a case study for the manufacturing and performance of the material under service conditions, a longboard part was manufactured using the hand lay-up technique. The stress analysis and load bearing capacity of the board was studied by means of finite element simulations and the presented design proved to be acceptable for service.

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6. Referencies

[1] X.Q. Liu, W. Huang. Preparation of a bio-based epoxy with comparable properties to those of petroleum-based counterparts. xXPRESS Polymer Letters, Vol. 6, No. 4 (2012) 293-298.

[2] H Miyagawa, A. Mohanty, R. Burgueño, L. Drzal, M. Misra. Novel Biobased Resins from Blends of Functionalized Soybean Oil and Unsaturated Polyester Resin. Journal of Polymer Science: Part B, (45) (2007) 698-704.

[3] C. Colombo, L. Vergani, M. Burman. Static and fatigue characterisation of new basalt fibre reinforced composites. Composite Structures, 94 (2012) 1165-1174.

[4] V. Lopresto, C. Leone, I. De Iorio. Mechanical characterisation of basalt fibre reinforced plastic. Composites: Part B, 42 (2011) 717-723.

[5] Q. Liu. Basalt Fiber Reinforced Polymer Composites – Processing and Properties. Ph.D Thesis. University of Connecticut, 2006.

[6] A.C. Manalo. Behaviour of fibre composite sandwich structures under short and asymmetrical beam shear tests. Composite Structures, 99 (2013) 339-349.