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MECHANICAL BEHAVIOR OF BASALT AND ALUMINUM SANDWICH BEAMS UNDER 3PB AND 4PB LOADING CONDITIONS

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Summary: The main objective of this study was to characterize the actual deformation and strain fields of sandwich beams when subjected to bending tests, i.e. 3PB and 4PB loading conditions. Numerical simulations were performed by finite elements (FEM) to predict the behavior of sandwich beams at the same loading conditions of short and long beams. Also two types of sandwich beams were manufactured with vacuum bagging technique: basalt with polyurethane core and aluminum with polyurethane core, by means of different core thickness and span lengths.
The results obtained by numerical simulation using finite elements 3D were compared and validated with experimental tests of sandwich beams and are in accordance with the strain/stress obtained using digital image correlation (VIC3D).

1 INTRODUCTION

Composite structures have in recent years found widespread acceptance in advanced structural applications ranging from aerospace to civil engineering mainly because of their high specific stiffness, strength and lightweight characteristics. During the life of a composite structure, it may be subjected to various loading conditions, including mixed-mode loadings [1],[2], impacts and large flexural loadings namely in sandwich structures as in wind turbines and wings in the aerospace engineering. Common failure modes of a sandwich structure include core compression failure, debonding between facing and core, deflection of interfacial crack into the core and buckling instability. When subjected to bending, the faces carry the main part of the external bending moment as in-plane stresses while the core carries the transverse forces as shear stress and stabilizes the faces against bucking or wrinkling [3].

Standard test methods for evaluation of core shear properties exist, as the single-block shear test standard [4] and the 3PB (three-point bending) and 4PB (four-point bending) standards [5]. Other methods include the double-lap shear test [6] the panel shear test [6],[7] and the shear test presented by Arcan et al [8]. However, by the very nature of their structure, the flexural behavior of composite sandwich structures is very complex. Consequently standard methods for determining strains in skins and core and deflections of beams, such as strain gauges and displacement transducers, respectively, are not sufficient for evaluating the stress-strain behavior of these components. Teixeira de Freitas et al. [9] showed these difficulties in a study of renovation of orthotropic steel bridge decks using sandwich structures made by two steel faces and a polyurethane core. Also Reis et al. [10],[11] studied the mechanical behavior of sandwich beam using cork as core and showed that the failure occurs mainly in the core.

A method for determining displacements and strain field across and through a sandwich panel is necessary and very important. Digital Speckle Photography (DSP) is an optical, non-contact, full field technique for determining displacement and strain in two or three dimensions. Chang et al. [12] used DSP to measure micro and macro deformations in a sandwich foam core and showed that in the macro-scale the deformation pattern is quite similar to that in a homogeneous and isotropic material, however at the micro-scale, the deformation pattern is very complicated. Battley and Burman [13] used DSP to characterize ductile core materials and showed that the stress and strain fields in both single-block shear and sandwich beam tests are very different from those assumed by the testing standards. The test methods result in complex post yield states of stress in the core materials, meaning the core shear strength and ultimate shear strain should not be calculated by classical methods in the post yield region. However Fergusson et al. [14] showed that the DSP provides meaningful strain measurement for composite sandwich structures and further work is needed. Digital image correlation (DIC) system using VIC system of Correlated Solutions [15] was used in this work to measure the actual deformation and strain fields of sandwich structures subjected to bending tests. The VIC2D results were compared and validated with the finite elements (FEM).

2 MATERIALS AND SPECIMENS

A sandwich is a composite material consisting of two outer faces and a core with different characteristics. The possibility of combining a good resistance and flexural stiffness with low total weight it's the main advantage that makes it particularly suitable for different practical uses. Typically, these structures are formed by two relatively thin parallel panels of high-strength material - the faces - separated by a layer of low-density material, lighter and thicker - the core. There is a wide range of materials that can be applied in sandwich. The materials of the faces must have a high resistance, flexural and tensile stiffness. In turn, the core material must have a low density to ensure the low weight of the structure, but with good shear and compression resistance.

Two basic types of sandwich structures were considered in this work: i) sandwich with polyurethane core and aluminum faces; ii) sandwich with polyurethane core and basalt fiber faces.

The main properties of the materials used in this work are presented in Table 1.

	$\rho\ (kg/m^3)$	υ	$E\ (GPa)$	$G\ (GPa)$
Polyurethane	40	0.33	0.0106	$4 \cdot 10^{-3}$
SikaForce-7710L100	1500	0.33	0.013	
Aluminum 2024	2700	0.33	73	27.4
Composite Basalt fiber	1454	0.31	16	1.8

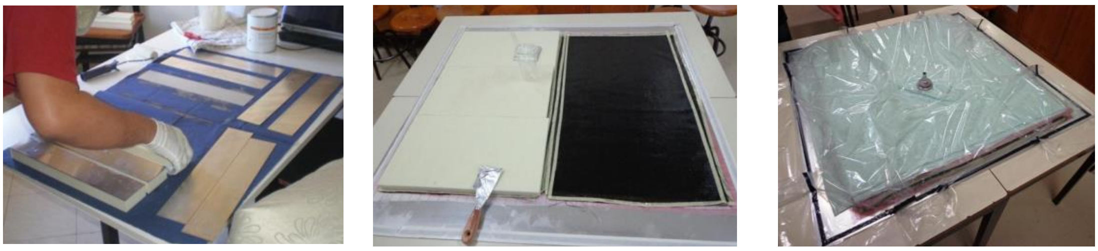
Table 1: Material Properties.

The polyurethane plates with 2m by 1m were acquired from MasterBlock® and two different thicknesses were used: 20mm and 30mm, enabling a wider range of tests and results to be analyzed.

All the specimens were cut with 390mm long and 70mm width [5]. Long and short beams were analyzed and were obtained by the adjustment of span length.

The aluminum plates with 1mm thick were glued with SikaForce-7710L100 to the previously cut polyurethane plates and pressed during 24 hours (Figure 1a).

The composite sandwiches with basalt fiber faces and polyurethane core were hand lay-up (HLU) with vacuum bagging. Thus, four layers per side with lay-up [(0/90)/(+45/-45)] of basalt fiber fabric BasltexTM BAS 220.1270.T were cut into rectangular sections (430mm by 780mm) and added to polyurethane core with epoxy resin Sicomin SR1500 and SD2505 hardener with vacuum bagging with 850mbar during 24h (Figure 1b and Figure 1c). After that, specimens with 390mm by 70mm were cut with a circular saw. Table 2 presents the resin and fiber mechanical properties.



a) b) c)

Figure 1: Detail of the manufacture of sandwich structures: a) aluminum specimens; b) basalt specimens; c) vacuum bagging.

	$\rho\ (kg/m^3)$	υ	Weight (g/m^2)	Thickness (mm)	υ (%)	$E\ (GPa)$
Resin						
SR1500 SD2505	1.0	0.26	-	-	51	3.2
Basalt (twill) 220.1270.T	2.8	0.35	220	0.13	49	78

Table 2: Properties of resin and fiber.

For the four types of specimens tested - with aluminum face or basalt fiber face and thickness core of 20 or 30mm - was created an encoding based on the assignment of characters “SA” (Sandwich with Aluminum face) or “SB” (Sandwich with Basalt fiber face), followed by the numbers “20” or “30” (for the core thick of 20 or 30mm) as appropriate.

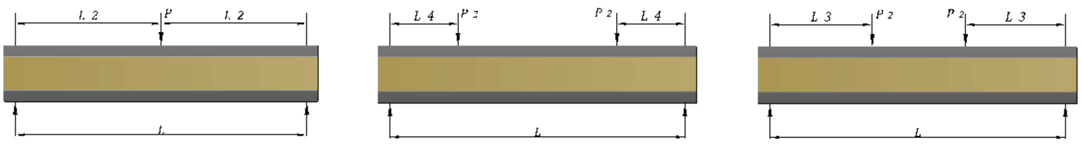
3 ANALYTICAL

The deformation of sandwich beams subjected to 3PB or 4PB can be analytically estimated using the equations from ASTM C393-00 [5]. These equations allow the estimation of the displacement (Δ) due to the applied load (P), i.e, equation (1) and (2) were used respectively for the 3PB and 4PB tests displacements.

$$\Delta = P\ \frac{L}{b}\left[\frac{L^2}{4\,E\,(d^3 - c^3)} + \frac{c}{G(d+c)^2}\right] \tag{1}$$

$$\Delta = P\ \frac{L}{2b}\left[\frac{11L^2}{32E(d^3 - c^3)} + \frac{c}{G(d+c)^2}\right] \tag{2}$$

where L is the span length of the particular test, b is the sandwich width, c is the core thickness, d is the sandwich thickness (core thickness plus 1mm per face) and E is the Young's Modulus of the face material and G is the core shear modulus. Figure 2 shows the 3PB with the mid-span loading and 4PB schemes with the quarter point and the third point loading in order to simulate short and long beam respectively.



a) b) c)

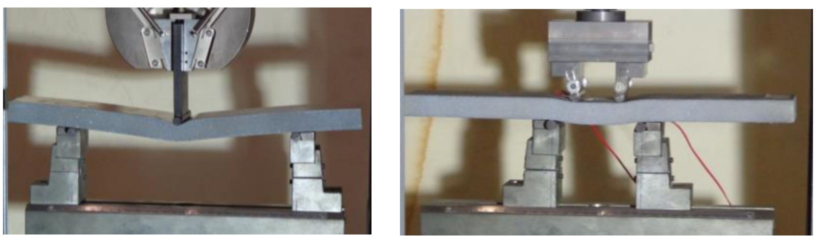
Figure 2: Scheme of applied loads: a) 3PB (mid-span loading); b) 4PB (quarter point loading); c) 4PB (third point loading).

4 EXPERIMENTAL TESTING OF COMPOSITES

Experimental tests were carried out including the situations of bending in 3 and 4 points, with the application of a mid-span loading in 3PB tests and the application of a quarter and a third span loading in 4PB tests, for short and long beams conditions respectively [5],[16]. For specimens with 20mm core thickness 90 and 250mm span lengths were used. In the case of specimens with 30mm core thickness 136 and 340mm span lengths were adopted.

Similarly to the specimens encoding, the 16 tests were also coded based on: the specimen code, the characters indicating the number of test points ("3PB" or "4PB") and span length ("90mm", "136mm", "250mm" and "340mm").

The bending tests were performed in an Instron 3369 testing machine, with a 10kN load cell and a displacement control of 2mm/min for all the sandwich specimens (Figure 3).



a) b)

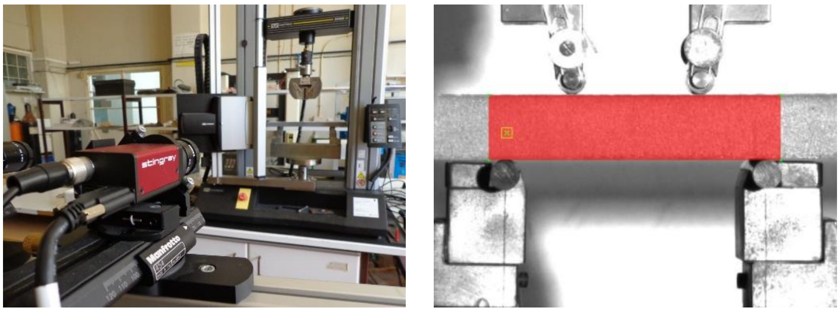
Figure 3: Bending tests specimens: a) 3PB aluminum; b) 4PB basalt.

4 DIGITAL IMAGE CORRELATION

Digital Image Correlation (DIC) is defined as a method of measuring the deformation of a surface by comparing images, thus allowing obtaining data without any interaction with the material tested. In this work it was used the VIC system of Correlated Solutions [15] in order to validate the experimental and the numerical results.

The system basically consists by one or two cameras (for analysis in two or three dimensions respectively) that capture images of an experimental test (a bending test) and by software that makes the correlation. Regarding the software component, it is divided into two parts: the VIC Snap that constitutes the image captures software and the VIC 2D (or 3D if two cameras are used simultaneously), which allows the processing and analysis of those same images. The VIC 2D software works based on the mapping and monitoring of the image pixels. This system requires the previous application of a random speckle pattern on the surface to analyze and it also requires the definition of some parameters. The longitudinal section of the specimen between the supports was defined as an area of interest (AOI) and the values of 21 and 5 were assigned for the subset and for the step, respectively (which defining the partitions to be analyzed).

In the end of the analysis, the program provides information about the displacements and strains in each direction, through a color gradient representing ranges of displacement or, or other selected variables, as well as a statistical treatment of the data in the interest zone previously selected, namely the maximum value observed. Figure 4a) presents the VIC system used and the AOI in Figure 4b).



a) b)

Figure 4: Digital image Correlation: a) VIC system; b) AOI.

5 FEA MODEL OF SANDWICH PANEL

Three-dimensional finite element model (FEM) of 3PB and 4PB tests were modeled using a commercial finite element ANSYS® v.13 software with Shell 181 element type in order to validate the experimental and DIC results. Figure 5 shows a typical FEM of a 3PB loading analysis.

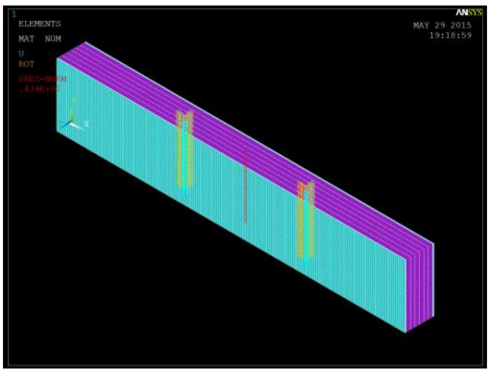


Figure 5: FEM with 3PB loading.

For each numerical analysis it was created a set of key points, based on the geometric configuration in two dimensions (length and width) of the samples, also the key points of the location of the loads and supports (boundary conditions) for both situations on 3PB and 4PB tests were created.

The third dimension of the specimen model was introduced by defining the layers: For the polyurethane core, it was considered 4 or 6 layers of 5mm thick each, respectively in the case of 20mm or 30mm core thickness; For the faces of aluminum, it was considered two layers, 1mm (for aluminum) and 0.3mm (for the adhesive); For the faces of basalt fiber composite, 4 layers [0/90, ±45] of 0.25mm thick were considered.

Each layer was assigned with the corresponding type of material.

6 EXPERIMENTAL RESULTS

Load-displacement plots of all specimens were obtained and the specimen reaches the state in which the deformation is not recoverable after the load application, getting a permanent deformation and residual stresses, which may lead to the structure's fracture. The main difference between the results obtained in 3PB and 4PB is the higher maximum load supported in 4PB tests. Also it was observed an increase of the elastic zone in 4PB indicating a higher resistance to displacement and a smoother transition between elastic and plastic areas as shown in Figure 6a).

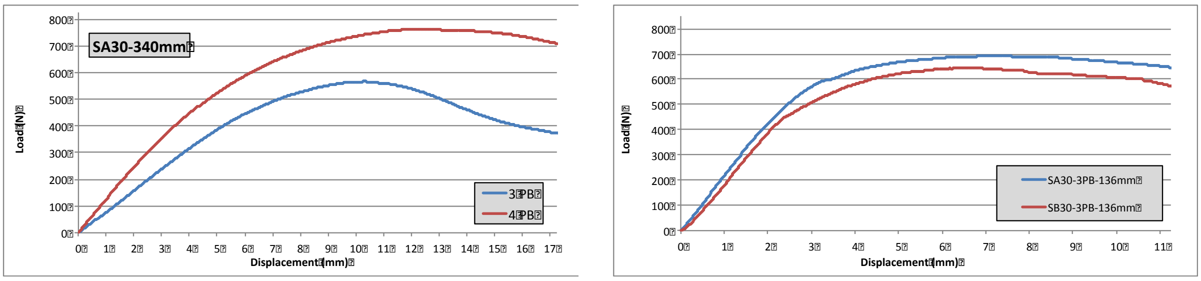


Figure 6: Typical load-displacement plots comparing: a) 3PB and 4PB; b) face material.

Regarding the face materials, it can be concluded that the aluminum sandwich (SA) specimen’s has a higher flexural stiffness than the basalt sandwich (SB), (as consequence of the higher Young’s modulus of aluminum comparing to the basalt fiber’s composite), as well as a higher maximum load and an evident abrupt transition between plastic and elastic zones as shown in Figure 6b). However, these differences are not very marked and in many practical applications, the lowest mechanical performance of basalt fiber can be overcome by the advantage of its substantially lower weight.

Regarding the span length’s, it has been verified that for a lower span length a higher slope line in elastic zone appears for both aluminum and basalt faces, reflecting a superior strength with the same displacement. Additionally, the use of smaller span lengths causes an increase of the maximum load and an abrupt transition between elastic and plastic zones (Figure 7). It was also observed that increasing the core thickness significantly increases the required load to produce the same deflection. So, the flexural stiffness of the specimen and the maximum permissible load increases.

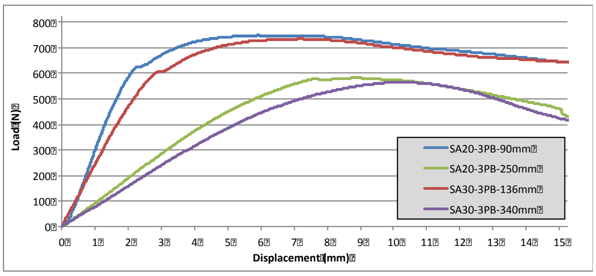


Figure 7: Typical load-displacement plots of 3PB comparing span length: short beam (90mm, 136mm); long beam (250mm, 340mm).

It was mainly observed local indentation due to the compression of the applied load in most samples either aluminum or basalt fiber (Figure 8) in both cases of 3PB and 4PB, however, some of them failed by the core cutting as observed in Figure 9.

a) b)

Figure 8: Failure Modes: local indentation: a) SA20-3PB-250mm; b) SA30-4PB-340mm.

a) b)

Figure 9: Failure Modes: core cutting: a) SB20-3PB-90mm; b) SA30-4PB-340mm.

It was also observed in all aluminum specimens that suffered some kind of failure mode, indentation or core cutting, an adhesive failure in face-core interface due to residual stress of plastic deformation. In the case of indentation, the typical situation occurred hours after test finished (Figure 10).

Figure 10: Failure Mode: indentation with off-site (post-test) (SA20-3PB-250mm).

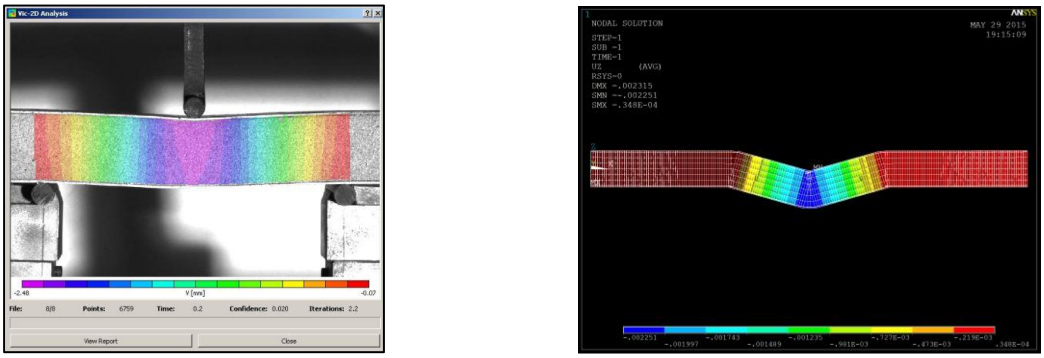
7 RESULTS AND DISCUSSION

Displacement and strain results were obtained from the 3PB and 4PB tests with the various conditions: two face materials: aluminum (SA); basalt (SB); two thickness core (20mm; 30mm) and four span lengths (90mm; 136mm; 250mm; 240mm).

7.1. Displacement Results

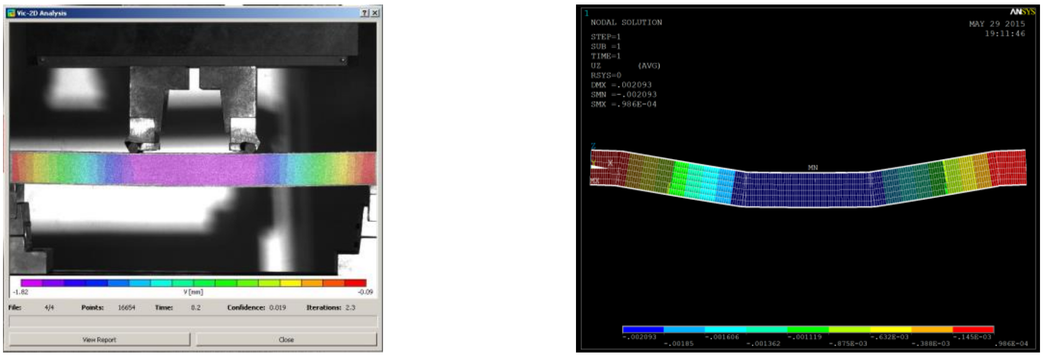
Experimental, Analytical, FEM and VIC *v* displacement results were carried out using the experimental loads from three different displacement control: 1mm; 2mm and 3mm.

Examples of 3PB and 4PB meshed finite element models are present in Figure 11b) and Figure 12b) respectively. Qualitatively DIC images are well compared with the FEM (Figure 11a) and Figure 12a)).



a) b)

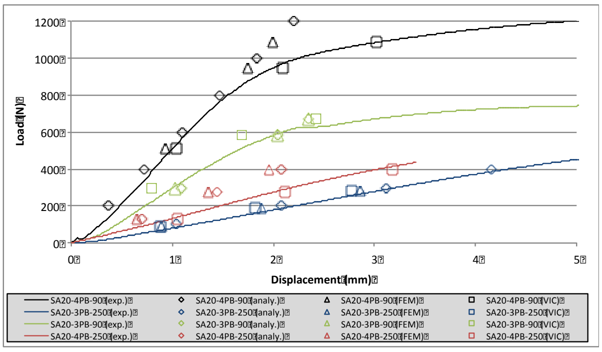
Figure 11: *v* displacement contour obtained under 3PB with 3mm of displacement control: a) VIC2D b) FEM.



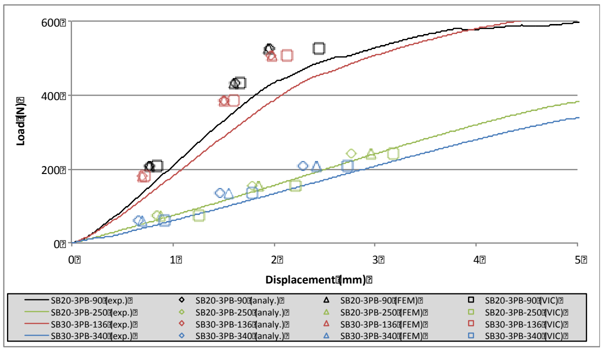
a) b)

Figure 12: *v* displacement contour obtained under 4PB with 3mm of displacement control: a) VIC2D b) FEM.

Figure 13 presents the displacement results obtained throw the experimental, analytical, FEM and VIC analysis for aluminum and basalt sandwich. It can be pointed out that the data from the FEM simulation is quite close to the corresponding obtained through analytical, experimental and VIC in case of specimens of aluminum faces, but with deviations in the faces of basalt fiber.



a)



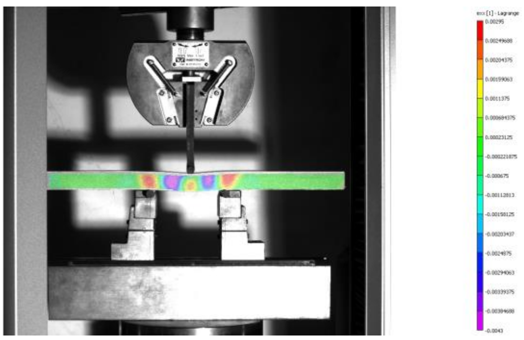
b)

Figure 13: Experimental, analytical, FEM and VIC *v* displacement comparison of: a) aluminum sandwich; b) basalt sandwich.

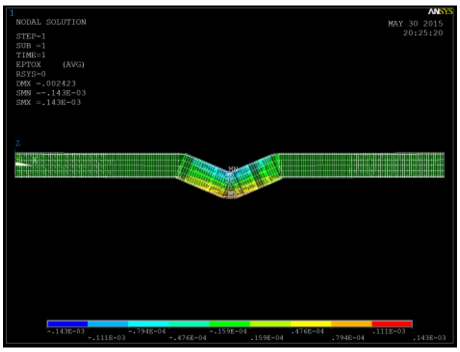
7.2. Strain Results

Also strain results (ε_{xx}) from 3PB and 4PB of all tested materials were obtained via Experimental, and VIC methods. The experimental strains were obtained using strain gauges located in the mid-span below the specimen.

Examples of 3PB and 4PB meshed finite element models are present in Figure 14b) and Figure 15b) respectively. Qualitatively DIC images of strains are well compared with the FEM (Figure 14a) and Figure 15a)).

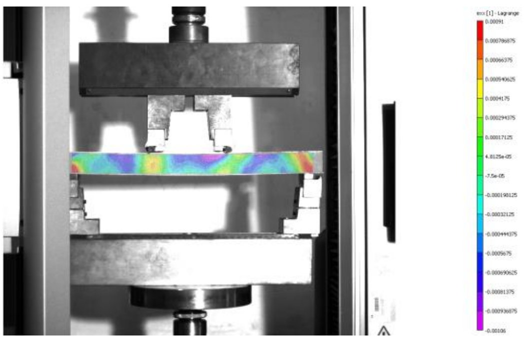


a)

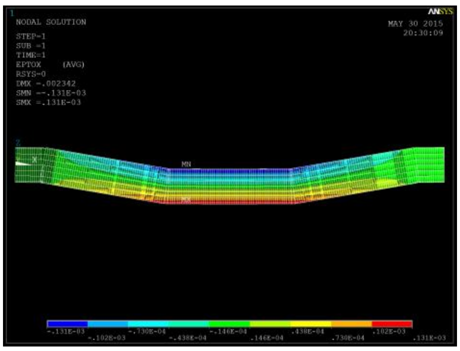


b)

Figure 14: ε_{xx} strain contour (3PB - short beam): a) VIC2D b) FEM.



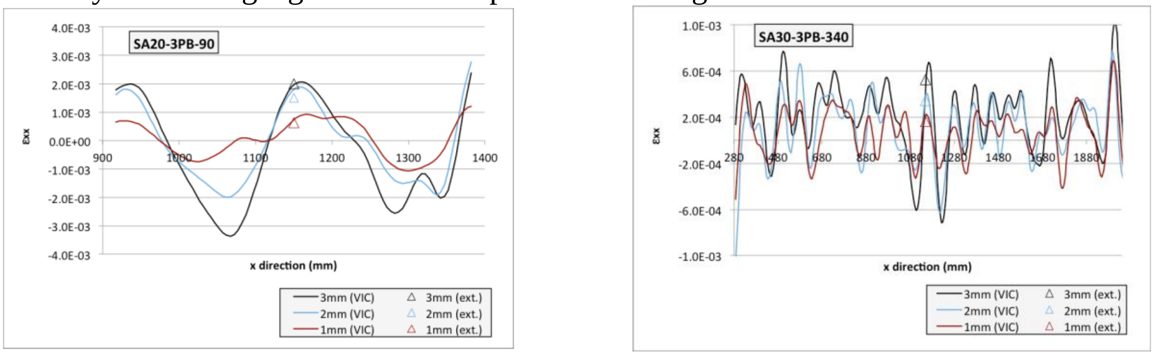
a)



b)

Figure 15: ε_{xx} strain contour (4PB - long beam): a) VIC2D b) FEM.

Strain comparisons along the span length for the 3PB specimens with short and long beams are present in Figure 16a) and Figure 16b) respectively. It can be denoted the strains obtained by the strain gauges at the mid-span and are in agreement with VIC strains.



a) b)

Figure 16: Experimental and VIC ε_{xx} strain comparison of 3PB: a) short beam; b) long beam.

8 CONCLUSIONS

3PB and 4PB tests of sandwich panel have been performed with different combinations of skin material and thickness of the core. Also different combinations of length were considered. The study involved experimental investigation, numerical simulation and Digital Image Correlation in order to obtain the deformation and strain fields of core materials when subjected to bending tests.

Comparing 4PB and 3PB tests with the same sandwich structure withstand significant higher loads and have lower beams for softening the transition between elastic and plastic zones. The span length reduction between supports causes a significant bending decrease for the application of the same load (in similar to the flexural stiffness increase), as well as an increase of the maximum load supported by the structure and a more abrupt transition between the elastic and plastic areas. The thickness increase of the sandwich core increases the maximum load carried by the structure and improves flexural rigidity as expected. The Short Beams comparatively to the Long Beams have a better behavior in terms of stiffness and higher values of maximum load, with a more abrupt transition between zones of operation in elastic and plastic areas. The use of faces with basalt fiber composite, compared to the aluminum faces, have lower mechanical properties; however, this enables a significant reduction in total weight of the structure and a large elastic recovery, showing almost no deformation after removing the applied loads in the tests.

The experimental method through a bending test machine is the most effective method in obtaining reliable data concerning the deflections characteristics and maximum load supported by the material, because it allows testing the material samples across the entire range of load and displacement values covering the elastic and plastic areas, with destructive or non-destructive tests. The digital image correlation system provides additional data to bending test machine and operates in conjunction with this, getting data from an entire area of interest which can be defined as the longitudinal section of the structure, enabling thus without any contact – and interference – on the specimen in tests, recorded data on the deflection on both faces and core along the length of the specimen. The analytical method allows obtaining data, which estimates the mechanical behavior of the structure, allowing doing it quickly and without any recourse to machinery or testing systems or specimens to be tested. The numerical method based on finite element method has the advantages referred to the analytical method - namely to not require specimens to obtain data structures.

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