Experimental test methodologies for the evaluation of the bending stiffness in asymmetric sandwich composites

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Abstract

Composite materials, including sandwich composites, are progressively seen as indispensable solutions, due to their high mechanical properties combined with low specific weight. Being a relatively new type of material, with great prospects for dissemination, the mechanical behavior of these structures still needs to be further studied. The use of a cork agglomerate in a sandwich core, strengthening a brittle material, gives it a very peculiar mechanical behavior, due to its asymmetry and non-conventional structure, that does not fit in the current flexure testing standards. This way, in this article, the author compares five different test methodologies and concludes about the valid characterization methods for this type of structures. From the results, the best method to characterize the composite sandwich, regarding the asymmetry of the sandwich and the non-common properties of the faces, was through a geometrical ratio of distinct flexure tests with different span lengths.

Keywords: sandwich composites; cork agglomerates; flexure tests; characterization method

1. Introduction

In the recent years, there has been a growth in demand and development of structural elements that combine high stiffness and mechanical resistance, with characteristics such as low specific weight and easy processing. In this context, the interest for composite materials, in particular for sandwich structures, has been increasing, offering new solutions for numerous industries and applications.

Cork agglomerate is a material known for its high mechanical shear strength, high compressibility, good capacity for thermal and acoustic insulation and vibration suppression [1] and a Poisson's ratio close to zero [2], which makes this natural material a strong candidate for core composite applications. For example, a proper application for this type of sandwich is the functional reinforcement of materials with others features and characteristics, like brittle materials, which significantly improves their mechanical behavior.

In this way, this work's purpose is to investigate and characterize a specific reinforcement system adapted to the stone material with low thickness, taking advantage of its high compressive strength and transmitting shear stresses and tensile forces to the reinforcement layers. Thus, it was idealized a composite sandwich composed of two skins with low thickness and high rigidity made with polymeric fibers, and a core made with a low specific weight cork agglomerate, enhancing also the thermal and acoustic insulation capability of stone materials. With the appropriate reinforcement sandwich, this kind of brittle materials can acquire a uniformity of their characteristics, also enhancing its applications, especially where weight is a concern, like in aerospace and naval industry.

The use of composite structures, as reinforcement of a stone layer on top and only in one face, gives it complexities at mechanical behavior level. The sandwich faces Young's modulus, whose analytical determination is not trivial, due to the stone extra layer and due to the asymmetry of the sandwich, means that it does not fit in the usual beams theories or in the current flexure testing standards, like ASTM-D7250 or ASTM-C393 [3, 4], and it is necessary to build a specific and valid method to characterize the bending stiffness of unconventional composites sandwich.

Thus, five different characterization methods, using only 4-point loading test (dividing rollers wedging stresses on two points, so it does not crush the brittle material with the applied loads), were selected based on the literature. Then the results from the sandwich composite in study were compared, coming to a final conclusion for this article.

2. Composite manufacturing

2.1 Sandwich constituents

The sandwich composite was made by hand lay-up method, with 65% mass fraction of resin/fiber, in temperature and humidity controlled conditions. The constituent materials for each layer of the sandwich material are the following ones, that are illustrated in Figure 1:

Stone: Gascone blue with 5 mm thick;
Core: Cork agglomerate provided by *Amorim Cork Composites* (ACC), with 10mm thick, density of 200kg/m^3 and shear modulus of 5.9Mpa [5];
Top Fiber: Biaxial fiberglass with 600 g/m^2;
Bottom Fiber: Interlaced fiberglass with 300 g/m^2;
Resin: Epoxy and respective hardener with recomended proportion from suppliers.

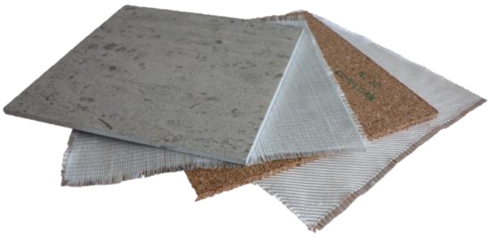
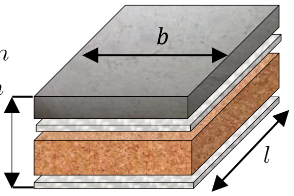


Figure 1: Sandwich composite constituents

2.2 Specimens dimensions

The specimen's dimensions were defined according to the restrictions of the bending test machine, including the permitted spans, and the rules defined in ASTM-C393. According to this standard [3], specimens must have a rectangular cross-section and respect the conditions showed in the Figure 2:

$$d \approx 15mm$$
$$\frac{S}{d} > 20 \Leftrightarrow S = 300mm$$
$$l = S + 50mm = 350mm$$
$$\frac{l}{2} > b > 2d \Leftrightarrow$$
$$150mm > b > 30mm$$



b - width
d - thickness
S - support span lenght
l - lenght

Figure 2: Specimen's dimensions and conditions

The specimen's length is limited by the distance between the testing machine columns. Taking into account that it is only a non-inhibitive recommendation, from the given standards, all the conditions above were adopted, except for the specimen's length, which it has to be slightly lower. So l=300mm, S=250mm and S/d=16,7. Finally it was possible to prepare 5 specimens with 50mm wide, and approximately 15 mm thick.

3. Characterization method's description

3.1 Method 1: Stress vs mid-span deflection graph slope

This method, being one of the most primitive ones, only allows for the determination of a comparative test stiffness, through the slope of the stress vs mid-span deflection curve of the specimen under bending loads, using the digital image correlation program named VIC. However, this method is very dependent on the type of assay used, varying the stiffness values in function of the loading type adopted, not representing an actual intrinsic characteristic of the structure.

3.2 Method 2: Shear deflection term despise for a long beam test

The mid-span deflection of a specimen subjected to a 4-point loading test with third point distance (L=S/3), is illustrated in Figure 3 and is due to the two terms given on the following equation:

$$\Delta = \Delta_{flex} + \Delta_{shear} = \frac{P(2S^3 - 3SL^2 + L^3)}{96D} + \frac{P(S-L)}{4U} \qquad (1)$$

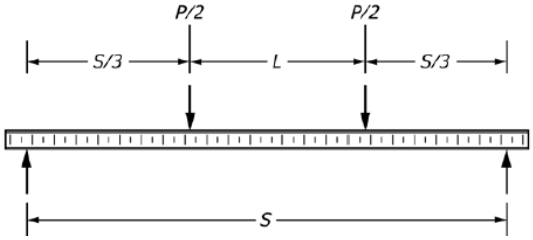


Figure 3: Third point distance loading configuration

Initially, with the illustrated type of test, all specimens were failing by face wrinkling and not by core crush. Assuming that the deflection due to shear is almost zero in a long beam test, in which the bending deflection is more significant, it seemed a good alternative to determine the specimen's bending stiffness with only one long beam test, despising the transverse shear rigidity term in equation (1).

Therefore, this method also allows for a quick understanding of the specimen's bending behavior throughout the test and through the analysis of the bending stiffness D as a function of the applied force P (Figure 4).

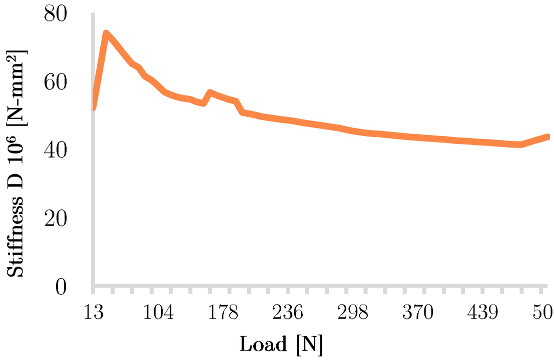


Figure 4: Bending stiffness in function of applied load

Due to the penetration of the roller into the cork, an increase in stiffness at the beginning of the test is visible and thereafter a decline caused by possible micro-cracks in the specimen occurs.

3.3 Method 3: Equivalent shear modulus assumption by tabulated core stiffness

According to [5, 6], the contribution of the transverse shear rigidity in mid-span deflection, can be obtained by an equivalent rigidity calculated through the multiplication of the cross section area with the core shear modulus G from the tables.

$$\Delta = \frac{P(2S^3 - 3SL^2 + L^3)}{96D} + \frac{P(S-L)}{4\ AG\ _{eq}} \tag{2}$$

$$(AG)_{eq} = \frac{bd^2}{c}G = bcG \tag{3}$$

This method allows for the correction of some possible associated errors from the previous method, allowing for the calculation of the bending stiffness with only one long beam test too. For the sandwich composite specimens in this study, the equivalent transverse shear rigidity is constant, where G is a standard value from *ACC* tablesa, visible in Table 1. This value was calculated with ASTM-C392, and in a sandwich, it is equal to 41MPa. Whereby, the value obtained for the transverse shear rigidity for the tested sandwich composite with this method is 52480N.

Table 1: Shear modulus of different cork agglomerates [5]

Mechanical Properties of the Core Material in a Sandwich				
Property	Method	Unit	NL10	NL20
Shear Modulus	ASTM C392	MPa	44	41

3.4 Method 4: Bending stiffness calculation from the ASTM-standard D7250 equations

This method allows for the determination of the bending stiffness, basing on two distinct tests from standard ASTM-D7250 [4], being one for long beams (i) requesting faces to bending and another for short beams (ii) requesting core to shear. These solicitations are seen in figure 5.

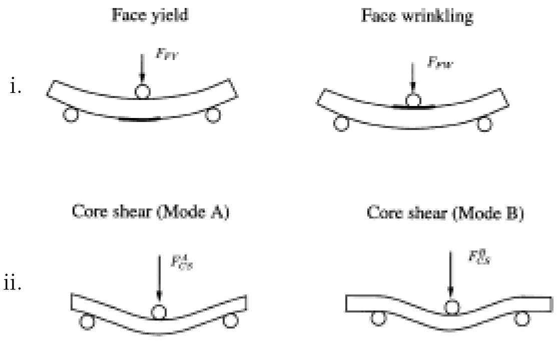


Figure 5: Solicitations of a sandwich panel on a 3-point test [6]

For the long beam test, it was chosen the standard loading type of Figure 6, with a support span much longer than the loading span ($L_1 = 2S_1/11$), while for the other short beam test, it was chosen the 4-point test with third distance ($L_2 = S_2/3$) of Figure 3, corresponding to the equations from the topic 10.2.6 of D7250 [4]:

$$D = \frac{P_1 S_1^3 (2538 - 2783 S_2^2/S_1^2)}{5805\Delta_1(22 - 27P_1S_1\Delta_2/P_2S_2\Delta_1)} \tag{4}$$

$$U = \frac{9P_1S_1(2538S_1^2/S_2^2 - 2783)}{4\Delta_1(34263(P_1S_1^3\Delta_2/P_2S_2^3\Delta_1)\ - 30613} \tag{5}$$

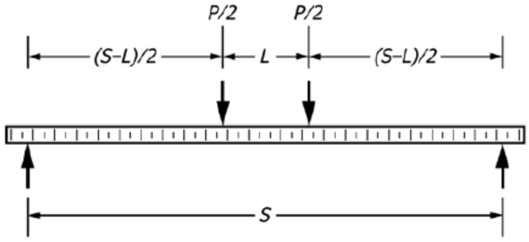


Figure 6: Standard ASTM-D7249 loading configuration

The main difficulty of this method is to identify the appropriate support span size for each loading type, in order to make sure that the specimen is being requested in distinct ways as intended, otherwise the obtained results will not be as expected. Furthermore, like it was said before, this method assumes the use of symmetrical composite sandwiches with identical faces, which excludes this sandwich as first instance.

This problem can be outwitted by the next method, which uses a larger number of distinct tests and allows for the analysis and monetarization of those solicitations and behaviors, according to the different loading setups.

3.5 Method 5: Linear regression from stiffness as a function of the support span

According to [7–9], the bending stiffness of a non-conventional composite sandwich and non-normalized structures, could be obtained through several tests by: using a geometrical ratio, and testing the specimen with the same loading type but increasing the supporting span (S=100mm, S=150mm, S=200mm, S=250mm), being each test stopped before achieving the onset of any permanent deformation or damage in the sandwich skin facings and core. Deducing the mid-span deflection equation (1) and replacing L=S/3 (4P test with third point distance), the mid-span deflection as a function of the applied load, bending and shear stiffness can be obtained, which then can be transformed into the following equation, similar to an equation of type y=mx+q:

$$\left(\frac{\Delta}{S}\frac{1}{P}\right) = \frac{1{,}7}{96D}S^2 + \frac{1}{6U} \tag{6}$$

Plotting the previous equation as a function of S^2, it is possible to determine a linear regression from the obtained results for each typology, yielding the mean results for D from the graph slope and for U from the interception of the regression line:

$$D = \frac{1.7}{96\ m}; \qquad U = \frac{1}{6\ q} \tag{7}$$

4. Experimental procedure

First, all the necessary tests, using the visual correlation program *VIC* (Figure 7) to monitor mid-span deflection, were executed, in order to compare the different methodologies. For the methods 1), 2) and 3) the initial loading type has been chosen (L=S/3, with S=250mm visible in Figure 9). For the method 4) two loading types were used, one standard (L=2S/11 with S=250mm visible in Figure 8) for the long beam test and one third point distance with S=150mm for short beam test (Figure 11). For the last method, as it was already mentioned, were used four loading types: L=S/3, with S=100, 150, 200, 250 (Figure 9-12).

Figure 7: Test assembly (VIC system and Instron 3369)

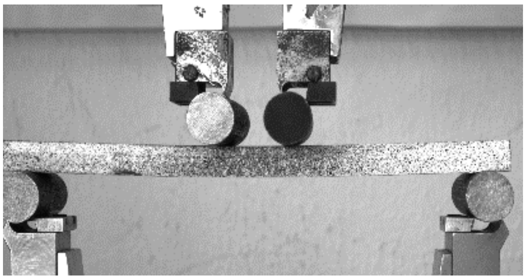


Figure 8: Loading Setup nº1 (L=2S/11, S=250mm)

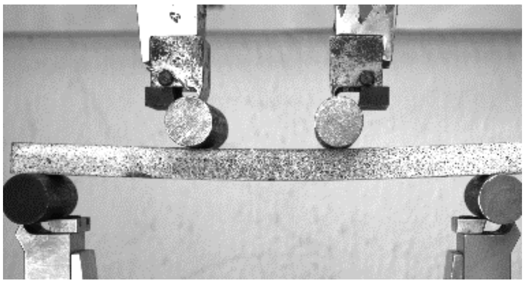


Figure 9: Loading Setup nº2 (L=S/3, S=250mm)

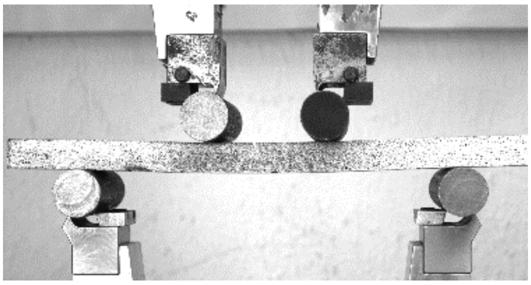


Figure 10: Loading Setup nº3 (L=S/3, S=200mm)

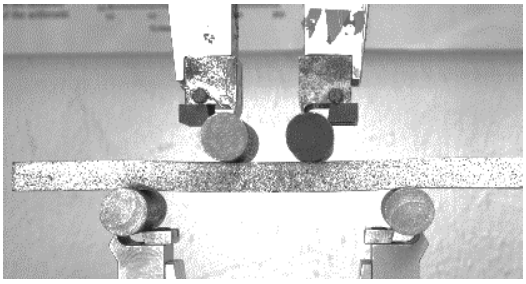


Figure 11: Loading Setup nº4 (L=S/3, S=150mm)

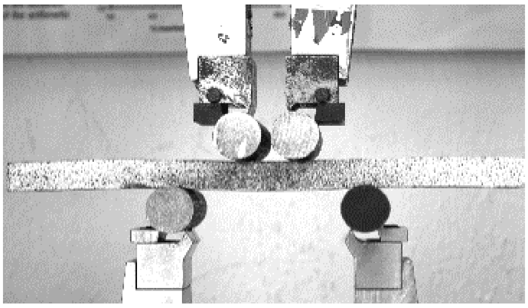


Figure 12: Loading Setup nº5 (L=S/3, S=100mm)

For the determination of the failure load of one specimen, it was essayed till the breaking point with S=250mm and L=S/3, yielding 1988N. As safety load for this loading type, a value of ¼ of the failure load was settled and the equivalent stresses and associated loads for the other kinds of tests were calculated through the following equation, assuming constant stress:

$$\sigma_{Flex} = \frac{3P\ (S - L)}{2bd^2} \Rightarrow \sigma_{flex} = const. \tag{8}$$

As expected, the equivalent load for shorter spans is much larger than the safety load for the initial test. Keeping the same specimen's size with shorter support spans, the larger length of specimen out of rollers, coupled with the bigger equivalent force, origins a critic problem: the reverse bending of the stone, which leads to a precocious failure for loads within the safety limit, as it was verified for the first tested specimen, the "STK001".

To correct this problem for the following specimens ("STK002" and "STK003"), the same safety load of 500N was used for all tests, therefore avoiding possible cracks and stiffness losses between them.

5. Results

On the tests performed with the first specimen "STK001", cracks were opened out of the rollers due to reverse bending, in the second assay made, with a support span of 150mm near 750N, being the safety load equal to 828N. This cause stiffness loss, which interferes with the further remaining results. As such, the results from this specimen (Table 2) weren't taken into account.

Table 2: Bending stiffness results from "STK001"

Method	Bending stiffness D	
1)	3.56	N/mm
2)	47.36	(10^6) N.mm^2
3)	52.41	(10^6) N.mm^2
4)	118.14	(10^6) N.mm^2
5)	334.83	(10^6) N.mm^2

On the following tests with the specimens "STK002" and "STK003", from Table 3 and Table 4 respectively, an agreement between both results was observed, which supports the hypothesis of using a constant safety load for all tests, like it is visible in the next tables. Possible variations of results between samples may be justified by the lamination method and specimen's preparation process not be automated, which might lead to small variations in mechanical properties between samples. The discussion of results will begin by method 5), being the one that in first instance is the most suitable for this non-standard sandwich and implies the most correct results, comparing them directly with the results obtained by other methods.

Table 3: Bending stiffness results from "STK002"

Method	Bending stiffness D	
1)	3.78	N/mm
2)	48.31	(10^6) N.mm^2
3)	53.63	(10^6) N.mm^2
4)	42.68	(10^6) N.mm^2
5)	80.71	(10^6) N.mm^2

Table 4: Bending stiffness results from "STK003"

Method	Bending stiffness D	
1)	3.69	N/mm
2)	44.54	(10^6) N.mm^2
3)	48.83	(10^6) N.mm^2
4)	54.16	(10^6) N.mm^2
5)	78.70	(10^6) N.mm^2

It is observable that method 5) presents the highest stiffness values with a relative error for this method of 2.5%, revealing a good uniformity and agreement between results.

As reference, the plot for specimen "STK003" obtained with this method is shown in Figure 13, where the linear regression was also taken:

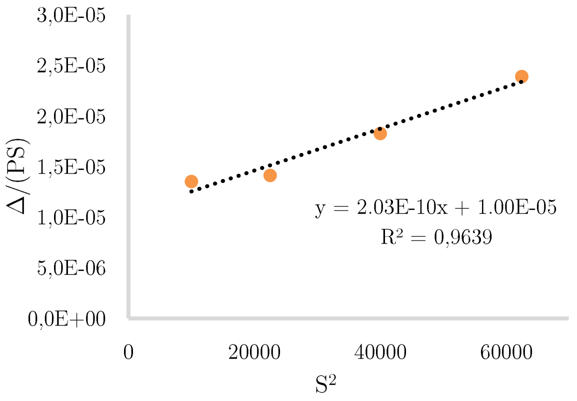


Figure 13: Plot of method 5) for specimen "STK003"

It is apparent that a good correlation was obtained with this plot, being $R^2 > 0{,}9$ the acceptance criterion used. The only test that diverge from the others is the first one for S=100, where a slightly higher deflection was obtained, in relation to what the result was supposed to be. This phenomenon, common to the three specimens, could be justified by the closer distance between rollers in this assay, making it similar to a 3-point bending test and applying a lower bending moment to the specimen (Figure 14). Furthermore, due to the smaller moment applied in this span, is there less deflection due to bending, making the crushing of cork more pronounced and interfering with the results. This way, it isn't possible to use this method with smaller support spans, being a test constraint.

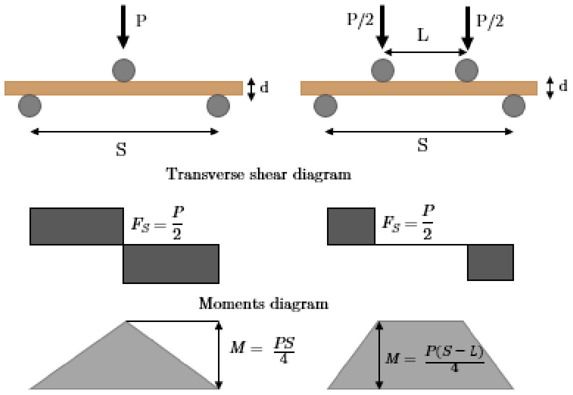


Figure 14: Transverse shear and moment diagrams for 2 tests

The method 4) presents a considerable discrepancy between the two specimens, with a relative error of almost 20%, possibly indicating that the chosen loading types for the different requesting (long and short beam) are not the most correct. Choosing a test with a smaller span (S=100mm instead of S=150mm), in order to request the core to even more shear, it is possible to notice an improvement of results in proximity of both specimens (relative error of 6.4%), as well as an approximation to the results of stiffness obtained with method 5). These results can be observed in Tables 5 and 6.

Table 5: Comparative method results for "STK002"

Method	Bending stiffness D	
4) S=150mm	42.68	N.mm^2
4) S=100mm	66.14	N.mm^2
5)	80.71	N.mm^2

Table 6: Comparative method results for "STK003"

Method	Bending stiffness D	
4) S=150mm	54.16	N.mm^2
4) S=100mm	70.69	N.mm^2
5)	78.70	N.mm^2

Method 4) was used by the *American Society of Composites* [11] to determine the bending stiffness of three types of three specimens (one made with low specific weight cork core and the other two made with Rohacell® core), through two 4 point bending tests, where the results from the Table 7 were obtained.

Table 7: Obtained results in [11] for 3 specimens with ASTM D7250 (method 4))

Core material	**Density ρ (Kg/m^3)**	**Bending stiffness D (10^6 N.mm^2)**	**Core shear modulus G (MPa)**
Cork agglomerate	120	24.60	2.4
Rohacell® 110 IG	110	24.90	50
Rohacell® 110 WF	110	27.90	70

The bending stiffness values shown have the same order as the results obtained for the specimens tested in this paper (10^6 N-mm^2), despite being slightly lower. This fact was however expectable due to the different characteristics of fiber facings and core materials.

Therefore, the choice of the ideal loading types on method 4) is a very important factor, that might even be critical, because the sandwich isn't conventional and the standard doesn't specify which are the correct dimensions to use on each loading type. Thus, it is possible to conclude that method 5) is a more uniform one and it helps to despite those variations, allowing for the obtainment of more accurate and realistic values.

Relatively to methods 2) and 3), they are very rough approximations, by despising or approximating shear terms. As such, very different results from other methods prove that the previous shear terms cannot be despised in this sandwich and these methods can be excluded for this specimen's typologies characterization.

The results obtained with the first method are consistent between them (presenting a maximum relative error of 6%), despite its significance being overly dependent on the type of assay and not an intrinsic characteristic of the material. For the implementation of this method, the load values obtained from the Instron machine have to be synchronized with the mid span values obtained from the VIC system, thus avoiding the use of values from the system displacement, which are not entirely correct. From Instron results three signals (displacement of cross bar, force measured at the load cell and the time duration of the test) and VIC system provides other two, by processing the obtained images (mid-span deflection in the specimen and duration time since first photo). The previous synchronization, prepared by a developed programming routine, allows to obtain the plot presented in Figure 15 and the appropriate slope of the linear regression:

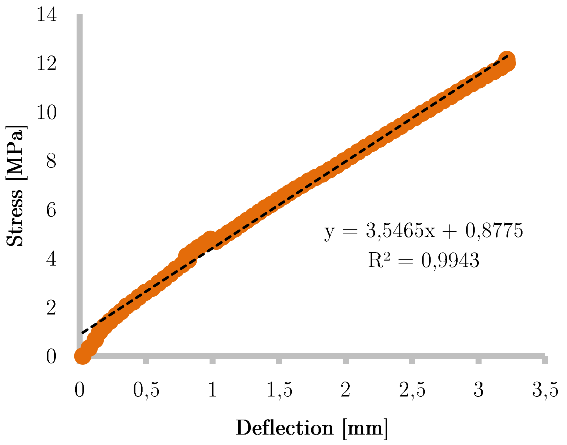


Figure 15: Stress vs mid-span deflection of "STK001"

Now, relatively to the shear rigidity, the results are in Table 8 and Table 9. There is a greater discrepancy of results in method 4) for the initial chosen span with a relative error of 66%, which are then greatly improved with the shorter span S=100, presenting only a relative error of 6% and making it closer with method 5. The relative difference between methods decreased from 246% to just 13%.

It can be verified once again, that method 4) results variate according to the different loading types chosen.

Table 8: Shear rigidity results of "STK002"

Method	Shear rigidity U	
2)	0	N
3)	52480	N $(AG)_{eq}$
4) S=150	72210.94	N
4) S=100	18089.80	N
5)	20833.33	N

Table 9: Shear rigidity results of "STK003"

Method	Shear rigidity U	
2)	0	N
3)	52480	N $(AG)_{eq}$
4) S=150	26037.25	N
4) S=100	15002.15	N
5)	16666.67	N

6. Conclusions

Taking into account the obtained results with the different referred methodologies, as well as the assumptions and approximations made, one may conclude that the best method for the determination and characterization of the stiffness of each specimen is method 5), because it allows for the standardization of the results and for the elimination of variations of the method 4), depending on the chosen loading type.

Method 5), using four tests variations, also owns a greater accuracy on experimental results. Allied to this, it also corresponds to the method that uses less simplifications from the theoretical point of view, simplifications that this sandwich doesn't follow. Thus, method 5) may be used for the determination and characterization of the bending stiffness of asymmetrical and unconventional sandwiches structures.

7. List of symbols

ACC	Amorim Cork Composites
ASTM	American Society for testing and materials
VIC	Visual Image Correlation
A	Cross-Section Area
b	Specimens width
c	Core sandwich thickness
D	Bending stiffness
d	Sandwich thickness
F_S	Transverse shear force
G	Core shear modulus
L	Loading span lenght
l	Specimens lenght
M	Applied moment
m	Slope of linear regression
P	Applied load
q	Interception of linear regression
S	Support span lenght
U	transverse shear rigidity
Δ	Mid-span deflecyion
σ_{flex}	Bending stiffness

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