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Experimental and analytical investigation of the bending behaviour of 3D-printed bio-based sandwich structures composites with auxetic core under cyclic fatigue tests

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Abstract

In the present paper, fatigue behaviour of sandwich composites with auxetic core under various stress ratios and for four different core densities is studied. Experimental and analytical analyses are performed on sandwiches subjected to cyclic bending tests in order to determine the influence of stress ratios on their fatigue properties. Experimental and analytical prediction result show good agreement. The analytical method predicts fatigue life as well as damage parameters of the structures and its reliability is verified by experiments. The acoustic emissions method is also used to monitor damage initiation and propagation up to failure. It is found that sandwiches with low core density present the maximum fatigue life.

Keywords

A. Sandwich structures; B. Fatigue; D. Acoustic emission; E. 3D-Printing

1. Introduction

Recently, advances in new biomaterials with high mechanical properties, have been getting a lot of attention. Evolution in the synthesis of new bio-composites for applications requiring light weight and excellent strength-to-weight ratios does not go unnoticed. Topological design is used to further adjust the properties of composites and make them more suitable for a specific application. Until recently, adjusting properties was hindered by the limited techniques of manufacturing. Recent developments in additive manufacturing (3D

printing) techniques [1,2], have made it possible to produce materials with complex shapes. This explains the rapid evolution in the development of metamaterials in the last few years. Different research reported recent developments in additive manufacturing (AM) of fiber reinforced polymer composite [3,4]. It has been shown that the AM process can produce composites with good mechanical properties when compared to conventionally fabricate composites. Also, AM are considered as a sustainable alternative to traditional textile forming technique for the production of multi-directional performs for composites [5]. Combining a base material with the design of the unit cells [6] gives the metamaterial specific mechanical properties, in the areas of energy absorption [7], density [8] and negative Poisson's ratio [9]. Re-entrant foams and some metallic crystals have a negative Poisson's ratio [10] and are called auxetic structures. Thanks to this unusual behaviour, the field of auxetic materials and structures has become the center of interest of many researchers. Auxetic materials and structures show high shear resistance [11] and indentation resistance [12]. This behaviour makes auxetic structures potential candidates for different applications such as fatigue resistance [13] and vibration dampers [14,15].

Auxetic structures are included in composites materials specifically in sandwich composites. They are used as core materials including others such as wood [16] and foams [17]. It must be noted that the core topology is the most important parameter that affects the response of the sandwich composites. This type of composite is widely used in aerospace, automobile and marine applications due to their high flexural stiffness and high energy absorption capabilities [18]. Also, environmental impact has driven the use of bio-based materials. They present different advantage such as biodegradability, recyclability, low cost and they have proven their ability to face different engineering challenges. Plant fiber reinforced polymers are widely studied. Many researches have proven that natural fibers possess high mechanical properties. Flax fiber is one of the most common natural fibers used in the literature. Daoud et al. [19,20] established the high dynamic properties of flax fibers due to the high degree of internal friction between hemicellulose and cellulose. They represent an eco-friendly alternative to glass fibers in terms of mechanical strength and stiffness [21].

During the use of composite materials in any application, low cycle fatigue problems result from vibration. Statistically, about 80% of fracture accidents in planes caused by fatigue failure. Therefore, it seems very important to study the fatigue response and failure mechanism of these materials. In this area, many researches have been done on the dynamic mechanical properties [22,23] of honeycomb sandwich structure. Finite element analysis is used to determine the mechanical parameters [24] and the fatigue life of honeycomb sandwich structures with flaws [25]. Crupi et al. [26] study the static and dynamic behaviour of honeycomb sandwich panels, and fatigue life was calculated using different failure modes. Abbadi et al. [27] study the bending fatigue behaviour of composite honeycomb materials on the L and W directions. Bezazi et al. [28] studied the fatigue behaviour of conventional and auxetic foams under compressive loading. The response of each structure depends on the applied load level. It has been shown that auxetic structure decrease the rigidity, but in return it increases the energy dissipation. Further, the acoustic emissions (AE) method is used to identify the exact damage initiation and propagation in sandwich structures under quasi-static indentation tests with different indenter geometry [29-31].

In order to guarantee the reliability of the structural design of sandwich composites and the safety of the structure during use, it is necessary to determine the resistance of the material to fatigue. For that reason, the aim of this paper is to study the fatigue behaviour and to determine the fatigue life of a 100% bio-based sandwich with a re-entrant honeycomb core. In this context, sandwich composites with auxetic cores are designed using CAD software (Solidworks) and then manufactured using a 3D printing technique (3D printer MakerBot). Four different densities of auxetic structure are considered. This work highlights the influence of the density of the core on the fatigue life of sandwich composites. The impact of the different sandwich configurations in damage initiation and propagation and the failure mechanisms due to bending fatigue tests are studied. Afterward, analytical analysis is carried out to predict the fatigue life as well as damage parameter and describe the bending behaviour of sandwich composites under cyclic fatigue. Analytical obtained results are compared and validated with experimental data. In addition, damage initiation and propagation are examined using a highly-sensitive AE testing method. Results are discussed in terms of damage parameters combined with the appearance of acoustic emission monitoring data points.

2. Experimental analysis

2.1. Materials and manufacturing

The sandwich structures were all constructed using the same bio-based material. It is a tape of polylactic acid (PLA) reinforced with flax fiber filaments (PFF). The material is dedicated to additive manufacturing techniques. It is provided by NANOVA company. The filament diameter is 1.75 mm. The 3D printer used in this study is the MakerBot Replicator2 Desktop. The specimens were designed using CAD software, then translated for manufacturing into instructions compatible with the 3D printer. The extrusion temperature is set to be equal to 210 °C with a movement speed of 100 mm/s and the building environment (heating platform) temperature is equal to 55 °C. These parameters are the results of a parametric study. The temperature and the movement speed were studied and only values that lead to the stability of specimens were chosen. Due to the layer by layer 3D printing technique, printing orientation is considered. Three different orientations were tested. The sandwiches were printed in X, Y and Z directions as shown in Fig. 1 (a). It was found that X-printing orientation is the direction that improves the mechanical properties of the specimens. Therefore, all specimens are printed using the same orientation (X-orientation).

An auxetic structure is used as the core material of the sandwich composite, as shown in Fig. 1. l is the original length of the inclined cell walls and h is the length of the vertical ones. θ is the initial angle between the inclined walls and the X axis. t is the cell wall thickness. $H=2(h+l\sin\theta)$ and $L=2l\cos\theta$ are the specimen length on the X and Y axes, respectively. The thickness of the auxetic structure is 5 mm. The thickness of the sandwich is equal to 7 mm (1 mm for each skin and 5 mm for the core). The length of the specimens is 120 mm. The width of the specimens is equal to 25 mm. It is discretized to one, two, three- and four-unit cells. Each number of cells along the width gives a specific density to the core. The relative density [1,32] of the auxetic core is calculated by:

$$\frac{\rho}{\rho_s} = \frac{t/l(h/l + 2)}{2 \cos \theta (h/l + \sin \theta)} \quad (1)$$

The parameters of the unit cell used in the core and the relative densities of each configuration are given in Table 1. The material properties are measured using uniaxial tensile testing performed on 3D printed dogbone following the ASTM D638 standard. Table 2 presents the material properties.

2.2. Experimental process

Three-point bending tests are performed on a standard hydraulic machine INSTRON 8801 of 1 kN capacity, as shown in Fig. 2. Experimental tests were carried out according to the ASTM D790-86 standard. They were carried out using a sinusoidal waveform at a frequency of 5 Hz. The specimens were tested with a span length of 110 mm. A loading ratio R , defined as follows, was set to 0.2:

$$R = \frac{d_{min}}{d_{max}} \quad (2)$$

where d_{min} and d_{max} are the minimum and the maximum displacements applied during the cycle, respectively. The average displacement d_{mean} and the amplitude of displacement d_{amp} were then varied in order to diversify the loading level r defined by:

$$r = \frac{d_{max}}{d_{rup}} \quad (3)$$

where d_{rup} is the failure displacement under quasi-static three-point bending tests. At least two specimens per loading configuration were tested in order to take into account the variability of experimental results. The value of the failure displacement d_{rup} for each sandwich composite configuration is given in Table 3.

3. Results

3.1. Fatigue loading

The fatigue bending behaviour of the sandwich structures with different densities of auxetic core are investigated. Fatigue tests are performed to quantify the life of those structures for different loading levels. Results are obtained for the evolution in stiffness loss (F/F_0) according to the number of cycles. This method is one of the most commonly used approaches to follow damage propagation in a structure. Fig. 3 presents the changes in the mechanical properties of the beams with the number of cycles for different loading levels using a semi-logarithmic scale. For each structure, the loss of stiffness to failure of the beam can be discretized in three phases. In the first few cycles, a rapid reduction of the stiffness loss appears. It corresponds to a rapid initial loss of the mechanical properties of the sandwich structure. It can be explained by damage initiation in the beams. It corresponds to the multiplication of cracking in the polylactic acid (PLA). In the second phase, the reduction of the stiffness loss becomes very slow. It corresponds to the quasi-totality of the life of the beams. This phase corresponds to damage propagation in the sandwich

structure. The third phase is manifested by a sudden decrease in the loss of stiffness. It corresponds to the total failure of the specimens. For each core density, it is clearly shown that the fatigue life increases with the decreasing in the loading levels. In fact, for high loading levels, the sandwich beams present a higher degradation rate and fail earlier than those with the lowest ones.

Fig. 4 presents a comparative study between sandwich structures with different relative core densities: 8.3%, 16.7%, 25.1% and 33.5% for an applied load level of 65%. Analysis of these results shows the high fatigue resistance of sandwiches with smaller relative core densities. Sandwiches with high relative core density have the smallest number of cycles at failure. An increase in density leads to an increase in the quantity of material in the core of the sandwich and therefore an increase of the porosity in the core. During the fatigue test, this structure will undergo a significant stress concentration. Thus, the cyclic solicitation will increase rapidly the onset of damage in this structure, hence the rapid breakage. A decrease in the core density improves the flexibility of the material and thus decreases its brittle breakage.

3.2. End of life; Wöhler curves

Fatigue life is an important parameter to characterise the fatigue behaviour of a material. Fig. 5 shows the Wöhler curves of sandwich composites with different relative core densities. It relates the maximum applied stress σ_{max} to cycles to failure N_r . The result shows some dispersion of fatigue failure which is normally observed in fatigue tests. It is due to the variability caused by using 3D printing as an experimental setup. However, this scattering is not as pronounced as in the case of other biobased sandwiches manufactured using other methods [33]. That's why only two specimens were tested for each loading level. The result of the bending fatigue test showed that the applied loading level r varies approximately linearly with $\ln(N_r)$, as shown in Fig. 5. The maximum stress is calculated using the quasi-static results. Indeed, the maximum applied stress in the sandwich beam is given by [34]:

$$\sigma_{max} = \frac{F_{max}d}{4bt_f(t_f + t_c)} \quad (4)$$

where t_f is the skin thickness, t_c the core thickness, b the width of the beam and d is the span length which is equal to 110 mm. The result shows dispersion in the fatigue life. However, failure of the specimens is obtained for low numbers of cycles when the maximum applied stress is close to that of the static fracture. It

is clearly seen that the density of the core has a significant effect on the fatigue life of the sandwich. The evolution of the maximum stress as a function of cycles to failure is expressed by:

$$\sigma = A - B \ln N_r \quad (5)$$

Sandwich beams with high core densities present the highest value for B parameter in Eq. (5) which indicates the highest degradation rate of this material. In fact, an increase of about 25% in the core density leads to an increase of about 30% in the degradation rate. This result can be explained by the nature of the core used as well as the shape of the unit cells. Indeed, by increasing the density of the core, the number of printed cells increases, and thus the specimen becomes stiffer. Also, several cells will be subjected to the cyclic fatigue bending test. This increases the onset and the propagation of damage in the material and thus the rapid failure. Mathematically, parameter A in Eq. (5) corresponds to the maximum applied stress for low numbers of cycles. However, this linear relation does not verify the experimental observation that no specimen is fractured for very low values of the applied displacement levels. This is due to the loading ratio R and the value of the failure displacement d_{rup} fixed from the beginning.

4. Analytical validation

4.1. Derivation of analytical model

Fatigue tests are performed using displacement control with an average displacement d_{mean} and an amplitude of displacement d_{amp} . During the fatigue tests, the decrease in stiffness as a function of the number of cycles is recorded. It is performed in three stages. The first stage is characterized by a rapid reduction in stiffness. The second stage is characterized by a progressive load reduction. The final stage is characterized by a rapid stiffness reduction due to specimen failure. It has been shown [35] that for sandwich composites, the stiffness reduction can be expressed as:

$$\frac{F_{max}}{F_{max}^0} = A_0 - A \ln(N) \quad (6)$$

where A_0 and A depends on the initial conditions, the material properties and the applied displacement levels. In the first cycle, the maximum load F_{max} is equal to the applied load F_{max}^0 . Therefore, the theoretical equation becomes:

$$\frac{F_{max}}{F_{max}^0} = 1 - A \ln(N) \quad (7)$$

Examining the evolution of parameter A , it is possible to consider that its evolution as a function of the loading level r is followed by a power function:

$$A = a_0 r^a \quad (8)$$

where a_0 and a are the parameters determined experimentally. Therefore, the expression of stiffness reduction becomes:

$$\frac{F_{max}}{F_{max}^0} = 1 - a_0 r^a \ln(N) \quad (9)$$

Fatigue life is an important feature that must be evaluated during fatigue tests. Fatigue life is correlated to the number of cycles at failure. Sometimes, it is impossible to obtain failure during fatigue tests of composite materials. Thus, a fatigue life criterion must be defined. The critical number N_α which corresponds to a stiffness reduction by α % can be calculated using Eq. (9):

$$N_\alpha = \exp\left(\frac{\alpha}{100(a_0 r^a)}\right) \quad (10)$$

Fatigue life can be related to the damage state of the composite structure. The damage parameter D represents the damage state in the composite material during fatigue tests. It is equal to zero at the first cycle and equal to 1 when the failure criteria are reached. In the case of fatigue tests in displacement control [35], the damage parameter D can be calculated as:

$$D = \frac{F_{max}^0 - F_{max}}{F_{max}^0 - F_{max}^\alpha} \quad (11)$$

Where F_{max}^α is the maximum load at the critical cycle number N_α . Replacing Eq. (9) and (10) in Eq. (11) leads to the following equation:

$$D = \frac{100}{\alpha} [a_0 r^a \ln N] \quad (12)$$

These equations are valid for the first two stages of stiffness degradation.

4.2. Fatigue life prediction

Fatigue tests are performed to study the effect of cycling loading level on the behaviour of sandwich composites with an auxetic core. The analytical model is applied to the first two stages of the stiffness loss versus the number of cycles curves. The final stage of rupture is not taken into account in the model. Using these experimental results, the parameters of the Eq. (9) are determined. Fig. 6 presents the coefficient A in

Eq. (8) according to the applied displacement level r . The adjustment between the results and Eq. (8) leads to the evaluation of the coefficients a_0 and a in Eq. (12). These parameters are given in the Table 4 for sandwich composite with different core densities.

The experimental results are compared with the analytical model based on the maximum stress degradation. The results are plotted as maximum fatigue stress degradation versus cycles to failure, given the Wöhler curves. Determining all the parameters in equation Eq. (10) allows us to predict fatigue life. We choose to characterize the fatigue life by the critical number of cycles N_{10} . The stress reduction in this case is equal to 10%. The experimental and the analytical results are shown in Fig. 7 for sandwich composites with different core densities. Close correlation is observed between the results. The analytical model describes closely the evolution of experimental results for each sandwich structure, despite the complex behaviour of composites. This proves the interest of the additive manufacturing technique and of the prediction method used. We observe that this analytical model [35] predicts fatigue life only when loading levels are already known.

5. Discussion

5.1. Damage prediction

The response of the sandwich composites under cyclic bending tests depends on the onset and propagation of damage in the material. Damage parameter D (defined in section 4.1 by equation Eq. (11)) combines all damage mechanisms which depend on the constitutive material, core structure, type of loading and the applied loading level r . Fig. 8 presents the experimental results compared with the analytical model given by Eq. (12) for each sandwich structure. The evolution of the damage parameter as a function of the number of cycles is shown for a loading level r equal to 95%. Close agreement between the analytical model and experimental results is observed. It is clearly seen that the evolution in damage depends on the density of the auxetic core. The growth of damage in sandwiches with high core densities is faster in the initial number of cycles. When damage parameter D is equal to 80%, the number of cycles is equal to 200, 100, 40 and 20 cycles for the sandwich with core density equal to 8.3%, 16.7%, 25.1% and 33.5%. It must be remarked that the first cycles are very important because they are responsible for the initiation and progression of damage in the material. It is clearly seen from the results that damage is accumulated at the first cycles. Then, it spreads progressively for a high number of cycles. These results can be explained by the initial damage

applied to the material. Indeed, the sandwich structures are initially subject to charge by the application of a loading level r , which varies between 40% to 95%. Therefore, the material suffers initial damage before cyclic loading, and when it is subjected to cyclic bending loading, there is quick propagation of damages in the first cycles and subsequently low progression is observed.

5.2. Damage initiation and propagation from acoustic wave signals

In order to better explain the evolution of damage, an acoustic emissions (AE) approach is used. This approach is used to predict the exact failure behaviour of the sandwich composite under cyclic fatigue tests. The response of the material depends on the progression of damage mechanisms. The evolution of the damage parameter with the number of cycles and the AE data as a function of time is shown in Fig. 9 for a loading level r equal to 70%. Both fatigue tests and AE data are performed at the same time and results are compared. Even invisible damages are detected with the highly sensitive sensors used. Thus, damage initiation and propagation can be clearly observed. The acoustic emission initial detection depends on the relative core densities of the sandwich structure. However, for all specimens, the AE detection starts when the damage parameter D is between 20% and 40%. The different sandwich configurations undergo the same curve shape for damage as a function of number of cycles as well as the appearance of AE hits during the fatigue test. The difference is observed at life time for each configuration. The signals acquired during fatigue tests have amplitudes which vary between 40 dB and 80 dB. As was explained previously, the material is damaged from the first cycles because of the applied loading level. This explains the quick appearance of acoustic data. Damage initiation is characterized by low acoustic amplitude (between 40 and 50 dB) which correspond to crack initiation in the bottom skin. This is linked to the rapid increase in damage parameters at the beginning of cyclic loading. Afterward, damage propagation in the core structure combined with skin-core debonding is characterized by AE amplitudes varying between 50 and 80 dB. This is linked to the progressive increase in damage parameters. It should be noted that the damage in the core is also observed at the beginning of loading. Also, there is minor core damage characterized by the appearance of some AE data at the beginning.

In order to better explain the failure mechanisms, the failure profile of the sandwich is given in Fig. 10. At the beginning of the fatigue test, there is a cracking of the bottom skin. Due to the cyclic loading, the crack

propagates to the core. The fail of the bottom skin is due to the breaking of the layers deposited by the 3D printing during the manufacturing of the specimens. Thus, a progressive decohesion of the skin/core interface is established. Finally, increasing the number of fatigue cycles leads to the total fail of the specimens. These fracture morphologies are also seen using compressive loading for 3D printed bio-inspired structure [36]. It has been shown that the defects (cracks, pores) occurred on the bottom side are the source of the failure of the material. It is to highlight that the response of auxetic structure depends on the nature of the loading and its direction, the parent material and eventually on the shape of the auxetic structure [37]. Adding skins to these auxetic structures (create a sandwich composite) will influence automatically the response of the material.

6. Conclusion

Sandwich composites with re-entrant honeycomb cores are manufactured using additive manufacturing technology (3D printing). The bending fatigue behaviour of the sandwiches is determined using experimental tests and analytical models. The skins and core are made using the same bio-based material. It is a tape of PLA reinforced with flax fibers (<20%). Several dynamic tests are performed on sandwiches with four different core densities.

The S-N fatigue life curve of the sandwich composites is obtained by bending fatigue tests. Based on the experimental results, the parameters of the analytical model are carried out. Close agreement with experiments suggests that fatigue behaviour of sandwich composites is being correctly predicted by the analytical model. The results show the important effect of core density on fatigue performances of sandwich composites. Sandwich with low core density have the maximum fatigue life. It should also be noted that the maximum load supported by the sandwich with low core density is lower. That's why a compromise between the maximum load and the fatigue life must be taken into account when selecting the core density. It also shows the strong influence of the loading level r , and highlights the impact of the stiffness degradation on fatigue strength. The analytical model predicts the fatigue life and the evolution of damage in the sandwich and therefore considerably reduces the number of experiments needed. Furthermore, a damage monitoring approach using an acoustic emissions technique to monitor damage initiation and prediction in the sandwich is applied. This technique indicates visible and invisible damage in the specimen up to failure.

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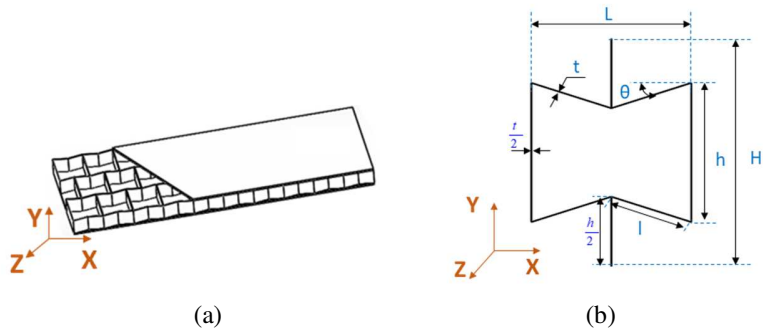


Fig. 1. a) Sandwich composite with re-entrant honeycomb core; b) Design of the unit-cell of the 3D re-entrant honeycomb structure.

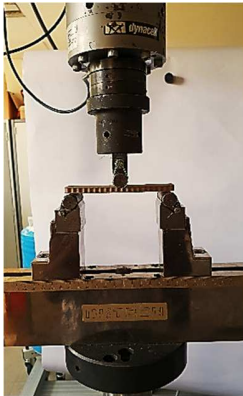


Fig. 2. Three-point bending test set up.

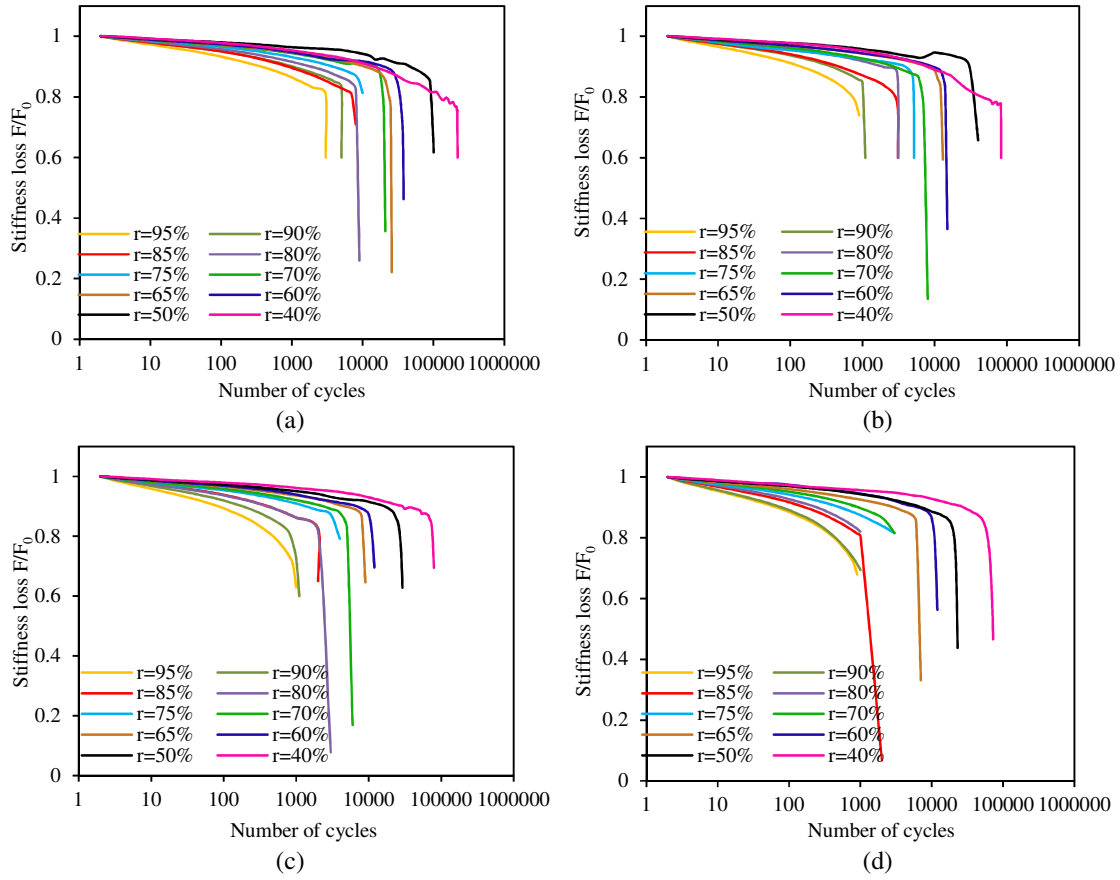


Fig. 3. Stiffness loss versus the number of cycles for various loading levels of the sandwich with different relative core densities: a) 8.3%; b) 16.7%; c) 25.1% and d) 33.5%.

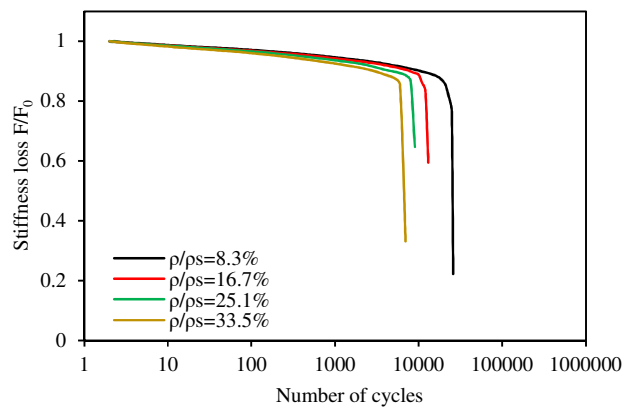


Fig. 4. Stiffness loss versus the number of cycles for a loading level $r = 65\%$ of the sandwich composite with different relative core densities.

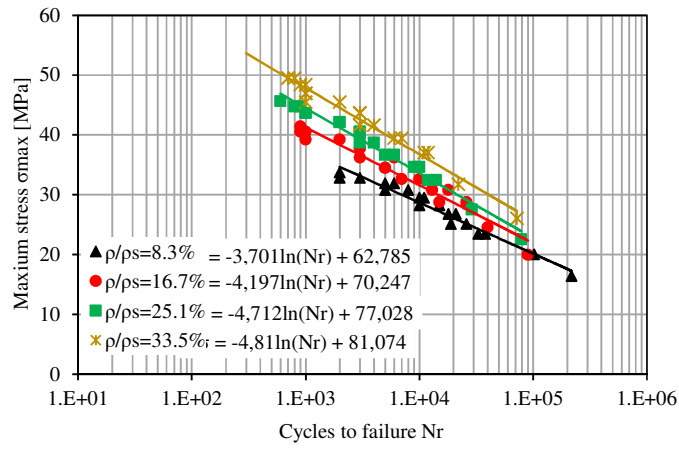


Fig. 5. Wöhler S-N diagram comparing the fatigue performance of the sandwich composite with different relative core densities.

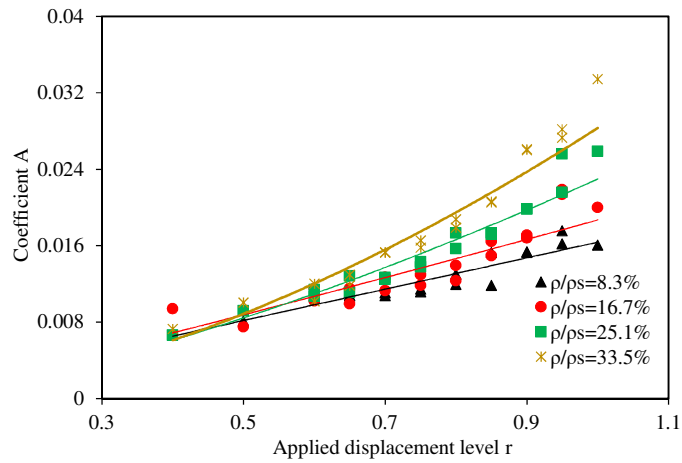


Fig. 6. Coefficients of the interpolation functions in the sandwich composites with different relative core densities.

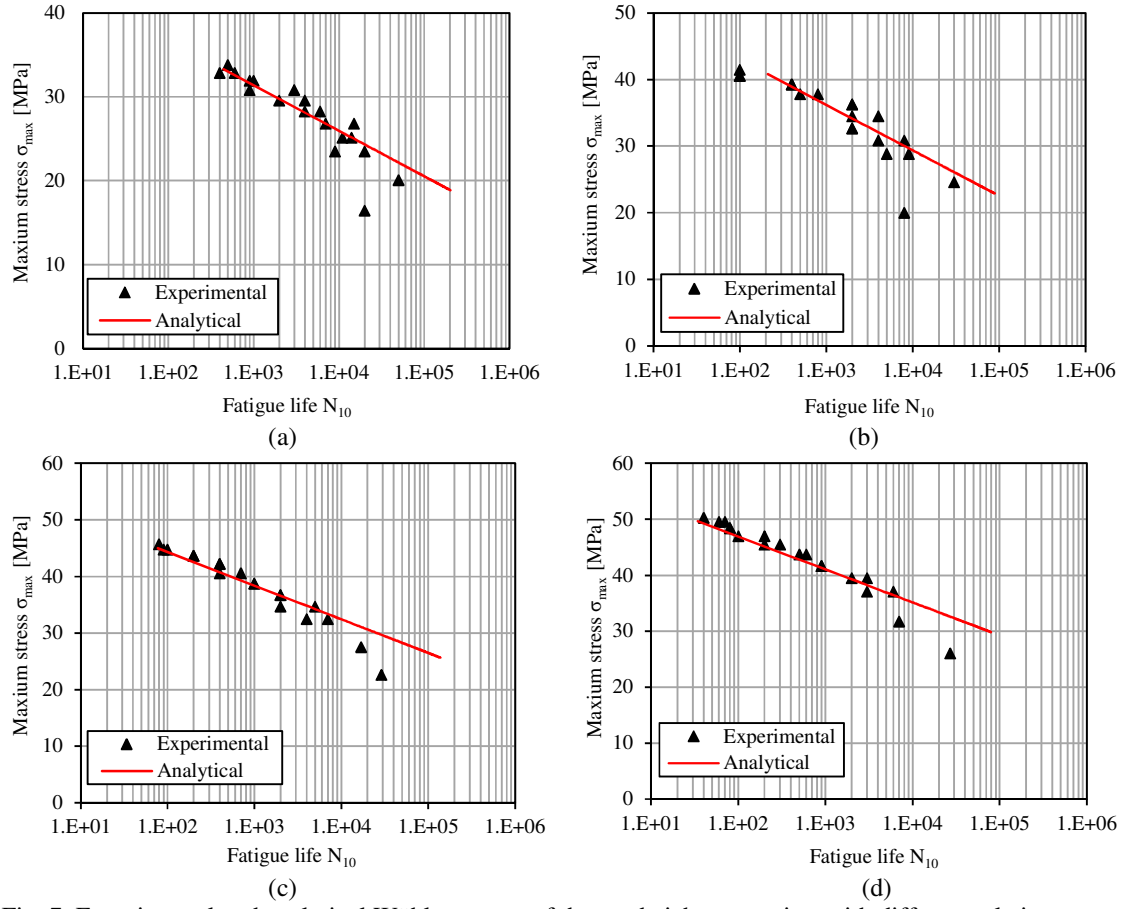


Fig. 7. Experimental and analytical Wöhler curves of the sandwich composites with different relative core densities: a) 8.3%; b) 16.7%; c) 25.1% and d) 33.5%.

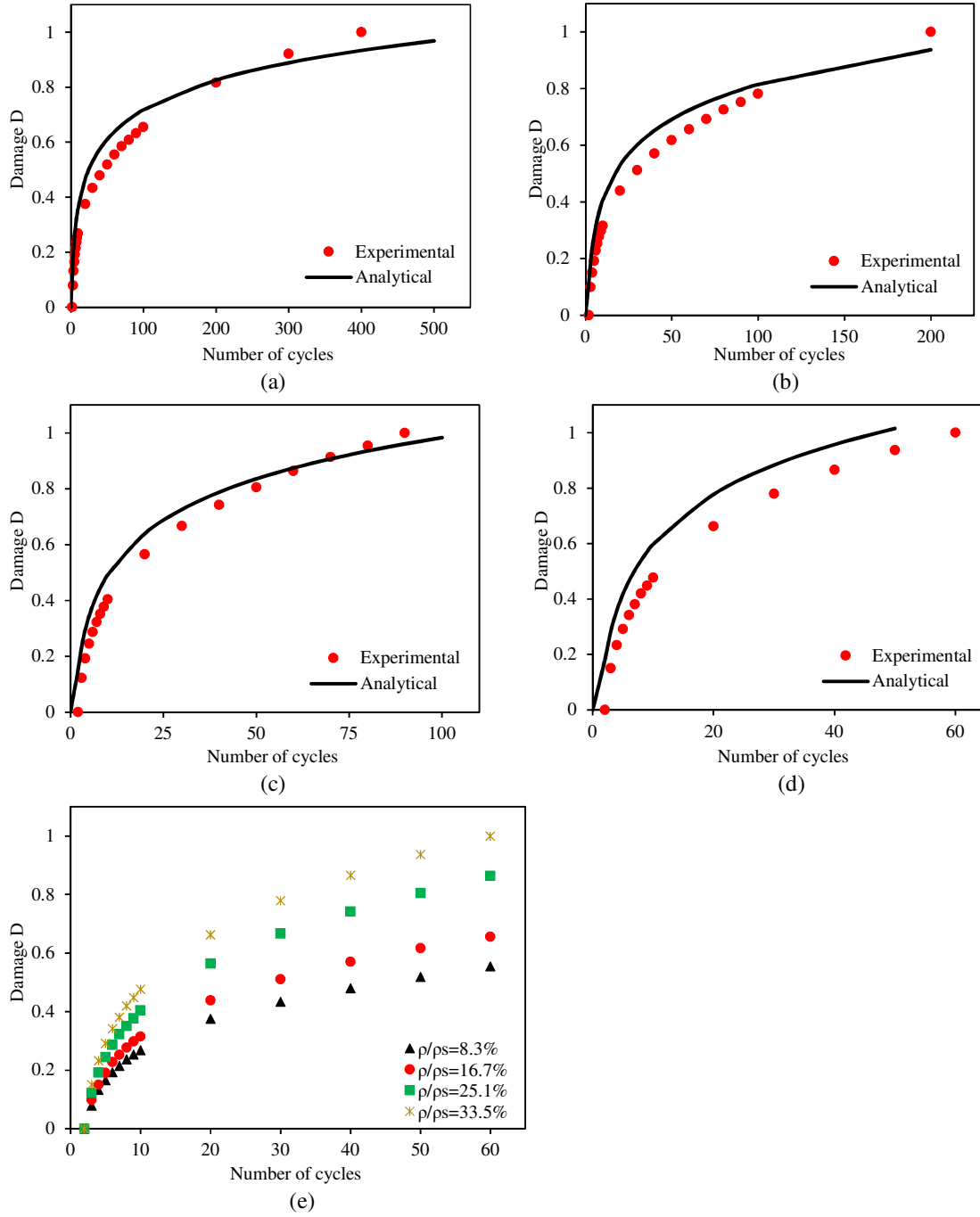


Fig. 8. The damage parameter according to number of cycles for a loading level $r = 95\%$ of the sandwich composites with different relative core densities: a) 8.3%; b) 16.7%; c) 25.1%; d) 33.5% and e) all densities.

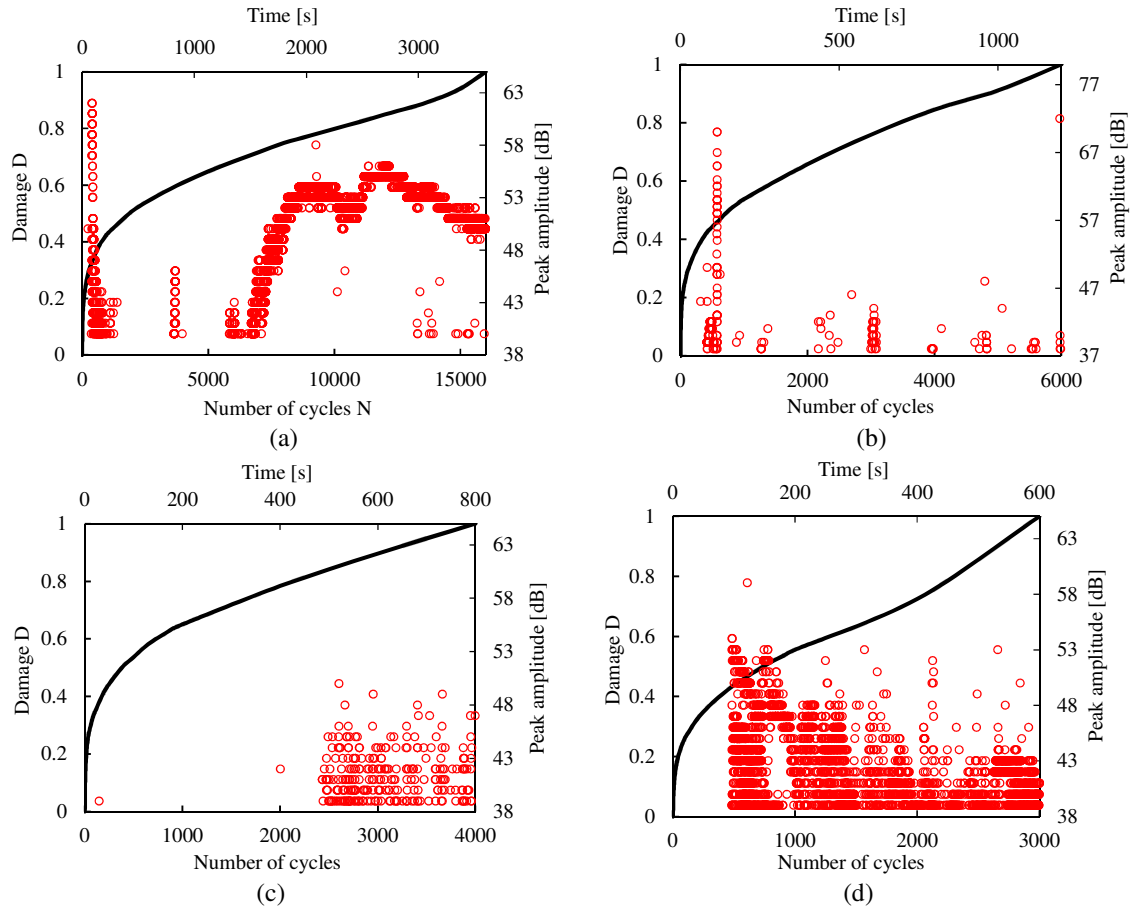


Fig. 9. Experimental damage according to number of cycles and acoustic emission data points of the sandwich composites with different relative core densities: a) 8.3%; b) 16.7%; c) 25.1% and d) 33.5%.

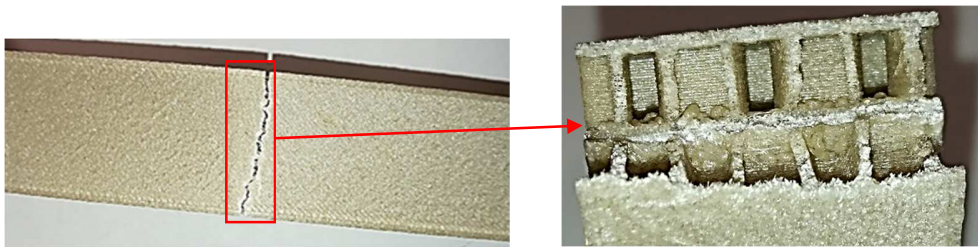


Fig. 10. The failure profiles of the sandwich composite.

Table 1. Design parameters of auxetic core.

Cells in width	l (mm)	h (mm)	θ (degree)	t (mm)	b (mm)	ρ/ρ_s (%)
1 cell	13.3	17.04	-20	0.6	5	8.3
2 cells	6.65	8.52	-20	0.6	5	16.7
3 cells	4.43	5.68	-20	0.6	5	25.1
4 cells	3.32	4.26	-20	0.6	5	33.5

Table 2. Engineering constants of polylactic acid (PLA) reinforced with flax fibers.

Material	E (MPa)	ν	ρ (kg.m ⁻³)	Fiber volume fraction (%)
PFF	2000	0.3	1000	< 20

Table 3. Failure displacement for the different sandwich configuration.

Cells in width	1 cell	2 cells	3 cells	4 cells
Failure displacement d_{rup} (mm)	6.5 ± 0.15	7 ± 0.2	7.5 ± 0.3	8 ± 0.2
Max force (N)	184.3 ± 10	227.5 ± 14	249.8 ± 2	276.6 ± 8

Table 4. Analytical parameters.

Cells in width	a_0	a
1 cell	0.0164	1.0022
2 cells	0.0187	1.0911
3 cells	0.023	1.4446
4 cells	0.0283	1.6744