中國機械工程學刊第四十三卷第五期第 473~483 頁(民國一百一十一年)
Journal of the Chinese Society of Mechanical Engineers, Vol.43, No.5, pp.473~483 (2022)

# Investigation of the Static and Dynamic Behavior of a 3D-Printed PFF Sandwich Composite with Conventional Honeycomb and Auxetic Core

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**Keywords**：auxetic, bending, dynamic, conventional honeycomb.

## ABSTRACT

The environmental problems demanded to use bio-material in several industrial applications. In this case, the use of biological material in composite structure have been increased in this century. The main idea of this research is to use a bio-based material in sandwich composite structure dedicated to transport industrial applications. Also, auxetic structures have presented a good mechanical property such as higher stiffness, strength, and energy absorption. This study presents an experimental analysis of the static and dynamic properties of a bio-sandwich composite with conventional honeycomb and auxetic core. An additive manufacturing technique is used to produce the sandwich composites. Static tensile, static and fatigue three-point bending and vibration tests were used to characterize the tested sandwiches. The effect of the bio-based material, the number of cells in the core as well as the core topology are investigated. The Young modulus and ultimate strength and strain under tensile tests are determined for the two tested material which are the polylactic acid and the polylactic acid reinforced with flax fibers. Also, the static bending stiffness is calculated for each sandwich configurations.

The loss factor is calculated under vibration tests. The determined properties in this study, give a large idea on the comportment of bio-sandwich with conventional honeycomb and auxetic core under a diverse test. It was found that sandwich made with polylactic acid and high number of cells presents the highest stiffness. However, sandwich made with polylactic acid reinforced with flax fibers and auxetic core improves the dissipated energy and damping properties.

*Paper Received January, 2022. Revised May, 2022. Accepted July, 2022. Author for Correspondence: Khawla Essassi.*

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## INTRODUCTION

The advances in manufacturing technique helped metamaterials to integrate in a variety of applications. It is noticed that 3D printing, also known as additive manufacturing technique, presents a high advantage to fabricate complex geometries than traditional manufacturing process (Goh et al., 2017). Sandwich composite with complex core structure have started to emerge into aerospace and aeronautic industries. The base material and the microstructural geometry are the basic factors responsible for these high performances (Yu et al., 2018). Conventional honeycomb and auxetic structures are an example of metamaterials. Auxetic structures exhibits a negative Poisson’s ratio. They present a variety of advantages such as energy absorption (Essassi et al., 2021(1)), shear properties (Lira and Scarpa, 2010), bending behavior (Li and Wang, 2017), indentation resistance (Xiao et al., 2019) and damping capacities (Strek et al., 2015; Boldrin et al., 2016). Because of their complex geometry, many research were developed on additive manufacturing technique (or 3D printing) in order to facilitate its fabrication (Bitzer, 1997). 3D printing gives a robust fabrication process to control the porosity in the material (polymers, composites or metals). It presents a good method to manufacture honeycomb and auxetic structures. Therefore, 3D printing machine are used in many industrials' fields (Wang et al., 2017; Zhang et al., 2018; Tian et al., 2007; Nikman and Akbarzadeh, 2018; Sugiyama et al., 2018).

Unfortunately, the use of these structures can pose environmental and ecological problems. Nowadays, environmental issues impose the use of biological and biodegradable material instead of synthetic ones. They have shown many advantages such as biodegradability, available resources and recyclability (Baghaei et al., 2013). Natural fibers reduce the environmental impact. They are utilized as reinforcement in composite materials (Faruk et al., 2012; Trujillo et al., 2014). Flax fibers are the most studied fibers in the past decades (Daoud et al., 2018). They have proven their ability to enhance mechanical and damping properties (Assarar et al., 2018). They are considered as a good alternative to glass fibers (Baley and Bourmaud, 2014). The mechanical and dynamic properties of these structures depend essentially on the based material and the core topology (Monti et al., 2017).

Architectural structure made with biological material can be used in sandwich structures. Sandwich structures are subjected to support bending loading. The bending behavior of sandwich composite has been widely studied (Ramnath et al., 2019). The bending comportment of sandwich composite with different core topologies is studied (Li and Wang, 2017; Sharaf et al., 2010). They have tested truss, conventional and auxetic core. Results show that truss core enhance the bending stiffness and strength compared to conventional honeycomb because of their buckling resistance. However, auxetic core dissipate more energy than author core topology. In addition, fatigue loading is a challenge to overcome when using composite materials in any applications. Therefore, the fatigue comportment must be studied during the design process. The fatigue comportment of an auxetic structure is studied (Essassi et al., 2020, 2021(2)). Results show that the fatigue behavior depends on the cell size, number of cells and cyclic stress range. It has been shown that the sandwich with honeycomb core material failed under bending fatigue test due to the crumpling of cell walls (buckling phenomena) (Crupi et al., 2012). The mechanical parameters (Wu et al., 2019) and the fatigue life (Ben ammar et al., 2014; Abbadi et al., 2010) of sandwich with honeycomb core are determined. The compression fatigue comportment of conventional and auxetic foams is investigated (Bezazi and Scarpa, 2007). It is found that sandwich with auxetic core enhance the energy dissipation and decrease the rigidity.

Furthermore, the vibration properties are a significant factor in the characterization of structural materials. The damping property of architectural structure is widely studied (Bianchi and Scarpa, 2013; Ma et al., 2013). The loss factor of sandwich composite with pyramidal truss core is investigated (Yang et al., 2013). Author discovered that the loss factor of the studied sandwich composite increases with the insertion of viscoelastic layers without any change in its natural frequencies. In addition, the dynamic properties of conventional honeycomb and auxetic structures are determined and optimized to reduce the dynamic response (Lira et al., 2011; Murray and Gandhi, 2013). They have studied a gradient topology which use positive and negative angle orientations together. Results show that the optimized configurations lead to a decrease in the mass and in the first three natural frequencies of the structure. Moreover, the vibration behavior of an auxetic structure is evaluated numerically and experimentally (Strek et al., 2015; Boldrin et al., 2016). Results show that the damping properties are sensitive to the angle of the unit cell. The effective young's modulus increases when the Poisson's ratio tends to -1.

The main idea of this research is to use a bio-based material in sandwich composite structure dedicated to transport industrial applications. The information taken from the literature prove that the use of acid-polylactic with flax fibers in sandwich composites, combined with auxetic structures, can constitute a material with good compromise between static and damping properties. The idea of this paper was to take advantages from the specific performances of sandwich composites, the high dissipative properties of auxetic materials and the high damping characteristics of flax fibers. The objective of this study is to find a sandwich structure which makes a good compromise between the static properties such as the strength and stiffness as well as the dynamic properties such as fatigue energy absorption and damping ratio. The purpose of the present work is to determine the static, the fatigue and the vibration behavior of a bio-sandwich composite. The effects of the bio-based material polylactic acid (PLA) and polylactic acid reinforced with flax fibers (PFF), number of the cells (2 and 4 cells in width) and core topologies (conventional honeycomb and auxetic core) are highlighted. The sandwich composites are designed adopting a CAD software (SolidWorks) and manufactured using 3D printing technique. Uniaxial tensile tests are conducted to determine the material properties. Static three-point bending tests are then performed to determine the mechanical properties of the sandwich structures. The experimental bending fatigue tests are also accomplished. The stiffness loss, energy dissipation and loss factor of the tested configurations are discussed. Finally, the damping properties under experimental clamped-free vibration tests are determined.

# EXPERIMENTAL ANALYSIS

## Materials and Structures Manufacturing

There is two different bio-based material used to manufacture the sandwich structures: the polylactic acid (PLA) and the polylactic acid reinforced with flax fibers (PFF). The materials are in the form of a filament spool, dedicated to additive manufacturing technique. The 3D printing machine used in this work is the MakerBot Replicator2 Desktop. The extrusion and the building platform temperature are equal to 210°C and 55°C, respectively, with a travel speed of 100 mm.s-1. The filament diameter is of 1.75 mm. For the PFF material, the fiber volume fraction is less than 20 %. Figure 1 depicts the geometry of the conventional honeycomb and auxetic structures utilized as core material in the sandwich specimens. The sandwiches were designed according to a CAD software, then, the specimens design was implemented in the machine to be manufactured.

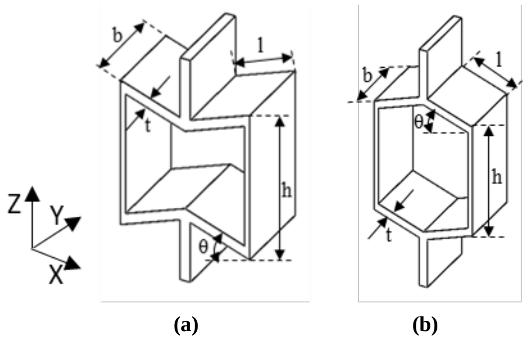


Fig. 1. Geometry of the core structures: (a) auxetic, (b) conventional.

The sandwich thickness is equal to 7 mm (1 mm for each skin and 5 mm for the core). θ is the angle between the inclined walls of the unit cell and the X direction and it is equal to -20° for auxetic structure and 20° for conventional honeycomb structure. t is the thickness of the unit cell wall and it is equal to 0.6 mm. For all tests, the width of the specimens is fixed to be 25 mm. The width is divided to obtain two different integer number of cells: 2 and 4 cells. The unit cell will be imposed in a square. Thus, the other parameters (cell wall length h and l) are generated according to the number of cells in the width. Table 1 presents the design parameters of the tested structures.

Table 1. Design parameters of the tested structures.

| Cells number | Core configuration | l [mm] | h [mm] | θ [°] | t [mm] | b [mm] |
|---|---|---|---|---|---|---|
| 2 cells | auxetic | 6.6 | 8.5 | -20 | 0.6 | 5 |
| | conventional | 6.6 | 3.6 | 20 | 0.6 | 5 |
| 4 cells | auxetic | 3.3 | 4.2 | -20 | 0.6 | 5 |
| | conventional | 3.3 | 2 | 20 | 0.6 | 5 |

Figure 2 presents the different tested configurations.

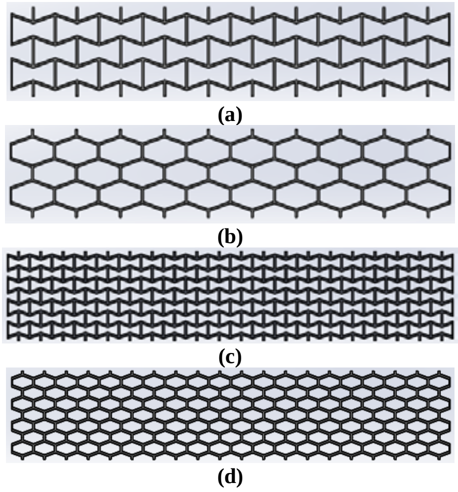


Fig. 2. Auxetic core with (a) 2 cells in width and (c) 4 cells in width; conventional honeycomb core with (b) 2 cells in width and (d) 4 cells in width.

## Tensile test

The material properties are determined through tensile tests performed on 3D printed dog-bone made with PLA and PFF material according to the (ASTM D638) standard test method. Figure 3 depicts the tensile test set-up. A standard hydraulic machine INSTRON 8801 with a load cell of 10 kN and rate of 1 mm/min is used in order to elaborate this test. A displacement extensometer is utilized to measure the displacement of the beams during testing. Five samples are tested for each configuration during mechanical tests in order to take into account the variability of the experimental results.

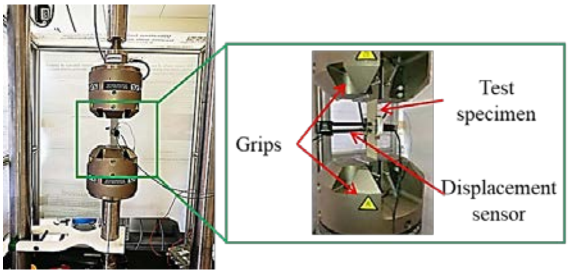


Fig. 3. Tensile test set-up.

## Three-point bending test

Three-point bending test are performed using the same standard hydraulic machine INSTRON 8801 with ±10 kN capacity. Bending tests were executed according to (ASTM C393) standard test methods, as shown in Fig. 4. During the quasi-static test, the sandwich specimens were loaded at a displacement rate of 5 $mm.min^{-1}$. A displacement sensor (LVDT) is used to measure the deflection of the beams. For each sandwich configuration, the length, width and thickness are fixed to be 120, 25 and 7 mm, respectively. The test consists of applying a load P to the sandwich specimen supported by two pins (diameter 15 mm) with a span length of 110 mm in order to analyze the sandwiches properties at failure. The load is applied in a single line using a 15 mm diameter pin too. Also, an anti-rotation device is used in order to prevent the rotation of the lower supports around the axis of the hydraulic cylinder. During the bending fatigue test, the machine is equipped with load cells of 1 kN. A sinusoidal type of waveform is used with a frequency of 5 Hz. Tests were implemented using displacement control technique. An average displacement $d_{mean}$ of 4 mm is chosen with an amplitude damp of 1 mm. To take into account the variability of results due to experimental conditions, three specimens for each configuration are tested.

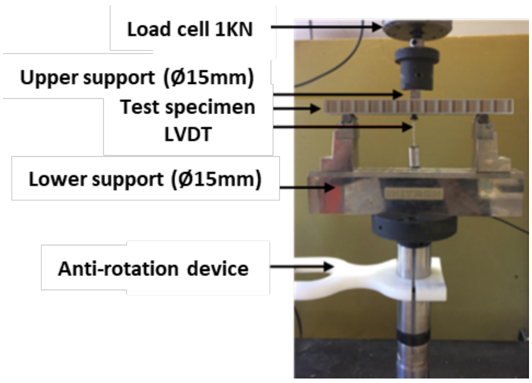


Fig. 4. Three-point bending test set-up.

### Vibration analysis

Composite materials are used in transport fields in order to have a light structure with a minimum loss of mechanical properties. However, these materials can cause vibration problems (more resonant structure). Therefore, knowledge of vibration characteristics, especially damping, is essential for the development of composite structures for high performance applications. The damping which translates the dissipation of the energy in the material is an important factor for the establishment of the dynamic behavior.

The vibration comportment of the sandwich structures is obtained according to a free vibration test in a clamped-free configuration, as shown in Fig. 5. During the vibration test, sandwich beams are supported horizontally. To avoid damaging the conventional honeycomb or the auxetic core while clamping, the length of the clamped end was set to 40 mm printed with the sandwich beams. Three different free lengths were tested, 170, 200 and 230 mm, in order to vary the peak frequency values. The sandwich beams width is set to 25 mm. The flexural vibration excitations are produced near the clamped end with an impact hammer (PCB084A14). The response of the sandwich beams is detected near the free end with a laser vibrometer (OFV 303 Sensor Head). The excitation and the response signals were processed with an acquisition card system and analyzed using the NVGate software. In order to determine the dynamic properties of the sandwich beams, different technique can be adopted, such as, the dynamic mechanical analysis method (Xu et al., 2019) and the experimental Frequency Response Functions (FRF) (Essassi et al., 2019; 2021(3)). In the present study, the frequency response analysis (FRF) method is used to obtain the natural flexural frequencies. This method is widely used because of its efficiency to evaluate the natural flexural frequencies. The half power bandwidth (HPB) method is utilized to calculate the damping factor (El mahi et al., 2008; Monti et al., 2017). The damping factor is calculated using equation (1): it is defined as the ratio of the difference between the bandwidth frequencies (Δfi), at which the amplitude resonance decreases by 3 dB, divided by the resonance frequency (fi). The loss factor is used to compare the damping capacities of different material. The material with the highest loss factor is the one that absorbs more energy. In this case, it is the most preferable to use in applications that require less vibration especially in the field of transport.

$$\eta_i = \frac{\Delta f_i}{f_i} = \frac{f_2 - f_1}{f_i} \quad (1)$$

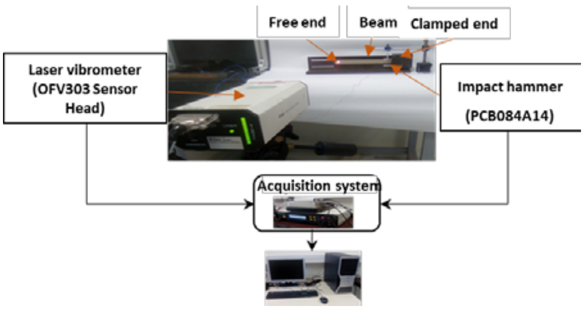


Fig. 5. Experimental equipment for clamped-free vibration tests.

## RESULTS AND DISCUSSION

### Materials properties

In order to investigate the static and dynamic behavior of the different sandwich structures, it is required to characterize the bio-based materials: PLA and PFF. It is to highlight that the specimens are manufactured considering the same layer orientation in the 3D printing machine. Figure 6 depicts the average mechanical properties (Young's modulus, ultimate strength, ultimate strain and plastic strain at failure) of PLA and PFF materials. It can be seen that PLA material is stiffer and harder than PFF material.

However, PFF is more ductile than PLA material. This observation is explained by the presence of flax fibers in the PFF material. In fact, the reinforcement used has viscoelastic properties (Daoud et al., 2017). Fibers are constituted from different natural polymers with viscoelastic behaviors which increase the flexibility of the PFF material compared to PLA. This justifies the high stiffness and hardness of PLA and the high ductility of PFF material.

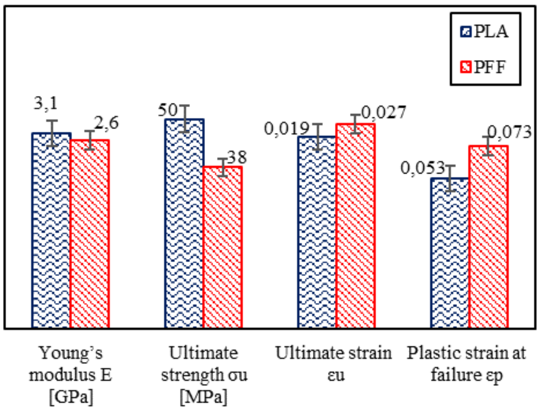


Fig. 6. Mechanical properties of PLA and PFF materials.

## Static bending performance of sandwich composites

*Material effect*

Figure 7 presents the mechanical properties of 3D printed sandwich beams with auxetic structure, 2 cells in width and two different materials (PLA and PFF) under 3-point bending tests. The failure deflection is the same for the two materials. However, the maximum load and the bending stiffness of the sandwich made with PLA is higher than that made with PFF. The bending stiffness of the sandwich made with PLA is higher with 25 %. Moreover, the failure load of the sandwich made with PLA is higher with 27 % than that made with PFF. In fact, the viscoelastic comportment of the flax fibers utilized as reinforcement in the PFF material is the essential factor that explains this result. The presence of flax fiber makes the structure more flexible which reduces its stiffness as well as the maximum load necessary to crush the sandwich composite.

*Configuration effect*

Figure 8 depicts the mechanical properties of 3D printed sandwich beams with conventional and auxetic core made with PFF material and 2 cells in width. One can observe a difference between the response of the sandwich with conventional honeycomb core and the sandwich with auxetic core. The maximum load is quite different, with the specimen with conventional honeycomb core against the indenter exhibiting peak load values of 220 N, while the sample with auxetic core sustains peak load of 204 N. However, the failure deflection of the sandwich with conventional honeycomb core is larger than that with auxetic core with about 41 %. In order to explain this result, it is interesting to report the damage behavior around the indenter area of each configuration until static bending test. The area of the sandwich with auxetic core facing up the indenter present a strong localization of the damage. However, the sandwich with conventional honeycomb core presents more wall buckling under bending test. This damage behavior explains the higher value of the maximum load and the failure deflection of the sandwich with conventional honeycomb. Wall buckling is also observed for the sandwich with conventional honeycomb and auxetic core under compression loading (Ramnath et al., 2019).

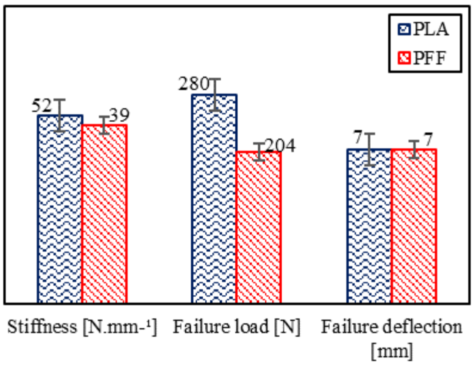


Fig. 7. Bending characteristic of sandwich beams with two different materials.

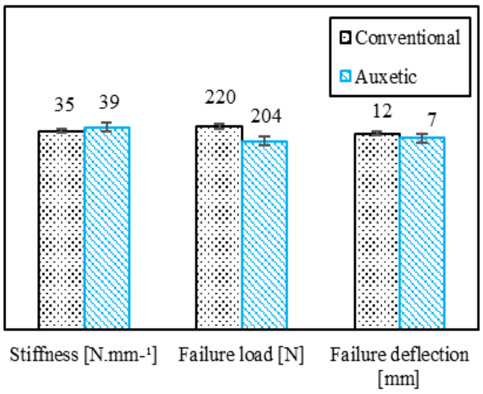


Fig. 8. Bending characteristic of sandwich beams with conventional and auxetic structure.

*Number of cells effect*

Figure 9 presents the static-bending characteristics of the sandwich specimens made with PFF material and auxetic core structure. Results show a difference between the response of the sandwich with 2 and 4 cells in width. There is a small difference on the bending stiffness between the two sandwich configurations. However, a significant difference can be seen in the maximum load and the failure deflection between the two types of sandwiches. The maximum load of the sandwich with 4 cells in width are larger than those of the sandwich with 2 cells in width with 26 %. In fact, with the increase of the number of cells of the sandwich core, the structure become stiffer.

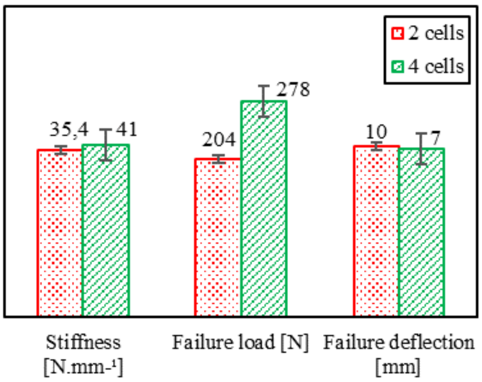


Fig. 9. Bending characteristic of sandwich beams with different number of cells in width.

## Fatigue bending performance of sandwich composites

Experimental fatigue bending tests were realized on the bio-sandwich composites made with PFF material. The effect of the configuration and the number of cells on the fatigue loading, dissipated energy and loss factor were discussed.

*Fatigue loading*

The evolution of the stiffness loss $F/F_0$ under fatigue loading conditions as a function of the number of cycles are determined and presented in Fig. 10. This method consists to discover the damage propagation during cycling loading. Figure 10 depicts the changes in the mechanical comportment of the sandwich structures according to the number of cycles for a variety of sandwich configurations. Results show that there are three phases of stiffness loss up to failure. Firstly, the stiffness loss decreases rapidly which trigger the begin of the initial degradation of the sandwich structure. This phase corresponds to the cracking multiplication in the material. The next phase corresponding to the majority of the material life is defined with a very slow reduction in the stiffness loss. This phase presents the damage propagation in the material. Finally, the stiffness loss decreases suddenly which corresponds to the total failure of the specimen. Figure 10 presents the high fatigue resistance of sandwiches with auxetic core structure compared to that with conventional core structure. Moreover, the sandwich with larger number of cells presents a higher degradation rate than that with smaller number of cells. A decrease in the number of cells leads to a decrease in the density of material in the composite and improves its flexibility.

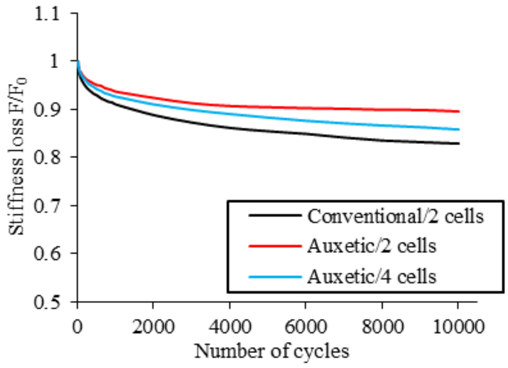


Fig. 10. Stiffness loss vs. the number of cycles of sandwiches with conventional/2 cells, auxetic/2 cells and auxetic/4 cells structures.

*Energy analysis*

The cyclic loading tests are utilized to compare the dissipated energy capacity of the tested sandwich. Conventional and auxetic core are considered. Also, sandwiches with two and four cells in width are tested. In order to determine the energy dissipation of these structures, it is essential to determine firstly the hysteresis curves. It corresponds to the experimental load/displacement curves for loading and unloading cycles. Figure 11 presents the dissipated energy $E_d$ and the potential energy stored $E_p$ of a hysteresis cycle (Essassi et al., 2021(2)). The determination of these energies is essential to characterize the ability of the material to dissipate energy during fatigue test. The material that dissipates more energy is that with the highest $E_d$.

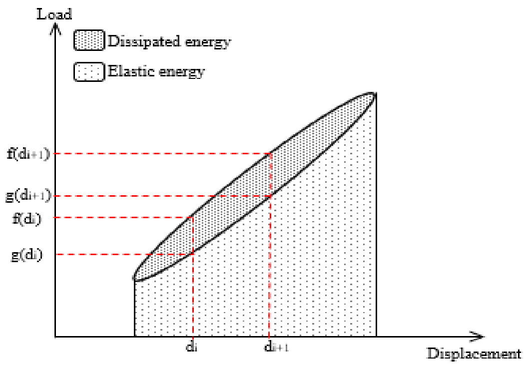


Fig. 11. Illustration of a hysteresis cycle (Essassi et al., 2021(2)).

The dissipated energy Ed and the potential energy stored Ep are the area enclosed and the area under the loading part of the hysteresis loops, respectively. These energies are calculated using a trapezoidal summation of the area (Monti et al., 2019), according to the equations (2) and (3):

$$E_p = \frac{1}{2}\sum_{i=1}^{n}(d_{i+1} - d_i)\left[f(d_{i+1}) + f(d_i)\right] \quad (2)$$

$$E_d = \frac{1}{2}\sum_{i=1}^{n}(d_{i+1} - d_i)\left\{\left[f(d_{i+1}) + f(d_i)\right] - \left[g(d_{i+1}) + g(d_i)\right]\right\} \quad (3)$$

Figure 12 depicts the dissipated energy as a function of the number of cycles for the tested sandwich composite. Results give us an idea on the lifetime of the sandwich material. It is clearly seen that sandwich with auxetic structure possess a high ability to dissipate energy compared to that with conventional honeycomb. Moreover, sandwich with high number of cells dissipates more energy than sandwich with low number of cells. For all tested sandwiches, the dissipated energy decreases from the first part of life-time to the end of life. This can be explained with the rise of damage in the material during cyclic loading tests. Moreover, the difference in the air volume in the core structure between the tested configurations plays the major role in the dissipated energy. The large quantity of the energy is dissipated during the collapsing of the cell walls. Therefore, sandwich with high number of cells dissipate more energy. Also, auxetic structure exhibits a synclastic deformation (Ramnath et al., 2019) which waste a large quantity of energy compared to conventional one.

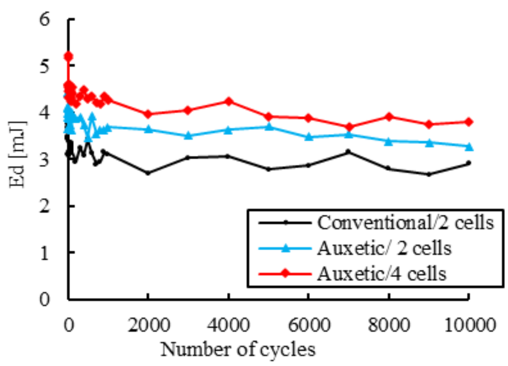


Fig. 12. Energy dissipation vs. number of cycles of sandwiches with conventional/2 cells, auxetic/2 cells and auxetic/4 cells structures.

**Vibration behavior of sandwich composites**

*Material effect*

The vibration tests are performed on sandwich composites with auxetic core and 2 cells in width. Two different bio-based material are used, PLA and PFF, in order to determine the flax fiber reinforcement effect on the vibration behavior of the sandwich specimens. Three different free lengths: 170, 200 and 230 mm are tested in order to obtain variation in the peak frequency values. The thickness of the sandwich beams is 7 mm and the width is 25 mm. At least, three specimens are tested for each bio-based material. Figure 13 presents the variation of the loss factor as a function of the frequencies for the sandwich with PLA and PFF material. The results show that the damping factor increases when the frequency increases. On a frequency range from 0 Hz to 4000 Hz, the loss factor increases about 40 % for the sandwich composite with PLA and PFF material. The difference between the two types of materials used in this study is the flax fiber reinforcement presented in the PFF material. The effect of the flax fiber reinforcement on the damping properties is clearly observed. The presence of flax fiber reinforcement in the sandwich composite significantly improves its dynamic properties. In fact, flax fibers have excellent vibration behavior due to their high loss factor compared to synthetic fiber reinforcement (El mahi et al., 2008; Duc et al., 2014). The high values on the loss factor for flax fibers refers to their morphology through the internal friction between cellulose and hemicellulose. It contains several viscoelastic components. It is composed of natural polymers, such as cellulose (70 %), hemicellulose (15 %), lignin (2.5 %) and pectines (1 %), with viscoelastic behaviors (Daoud et al., 2017). Moreover, the defect presented in the composite reinforced with flax fiber as well as the inter-fiber friction can contribute to energy dissipation in the material. The dissipated mechanisms listed previously explain the high damping results of the sandwich made with PFF compared to that with PLA material.

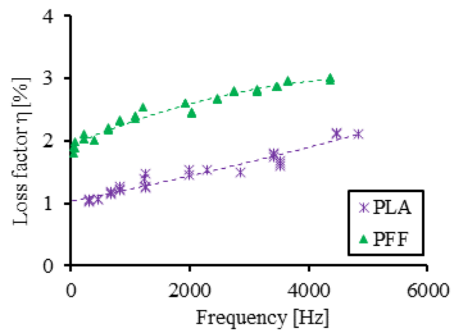


Fig. 13. Evolution of the loss factor of sandwich beams with two different materials.

*Configuration effect*

The damping properties of the sandwich composite made with PFF material is already conducted (Essassi et al., 2019). In this section, the damping properties of the sandwich with PLA material is studied. Conventional honeycomb and auxetic core are tested. Damping properties were measured by the Half Power Bandwidth (HPB) method used by El Mahi et al. (2008) and Essassi et al. (2019; 2021(3)). The variations of the loss factor as a function of the frequency for the two sandwich configurations are examined and shown in Fig. 14. It is observed that, for each configuration, the damping factor increases with the frequency. This increase is much higher for the sandwich with auxetic core. For the sandwich with conventional honeycomb core, the values of the loss factor are between 1% (for the low frequencies) and 1.7 % (for the frequency equal to 5000 Hz). However, for the sandwich with auxetic core, the value of the loss factor is 2.2 % for the frequency equal to 5000 Hz. In addition, it can be observed that at low frequency (from 0 Hz to 1000 Hz) there is close agreement between the two core configuration results for damping values. Above this point, the curves gradually diverge. It increases slowly for the sandwich with conventional honeycomb core. In fact, auxetic structures are better potential candidates for energy absorption compared with conventional honeycomb (Li and Wang, 2017). Due to the deformation mechanisms during vibration test, the specific energy dissipation of the auxetic sandwich composites is as large as conventional honeycomb which have proven to exhibit smaller specific energy dissipation.

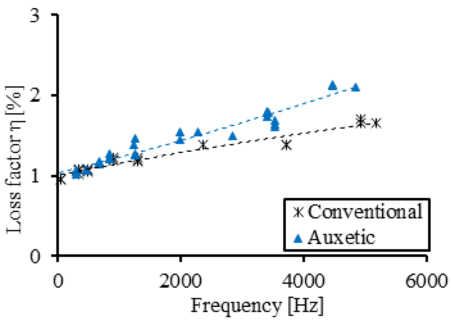


Fig. 14. Evolution of the loss factor of sandwich beams with conventional and auxetic structure.

*Number of cells effect*

The vibration tests are performed on sandwich composites made with PFF material and auxetic core. The effect of the number of cells in width is examined. Figure 15 presents the evolution of the loss factor as a function of frequencies. The sandwiches loss factor increases when the frequency increase for the two tested specimens. Results show that there is a slight increase in the loss factor for the sandwich with 2 cells in width compared to that with 4 cells in width. Several explanations can be proposed to understand the damping behavior of the proposed sandwich beams. During vibration test, a part of energy is dissipated through the bio-based material. In addition, the geometry of the unit cells and its porosity as well as its periodicity can contribute to the energy dissipation. The decrease in the number of cells of the core leads to an increase in the empty space in the sandwich beams and thus increases its flexibility.

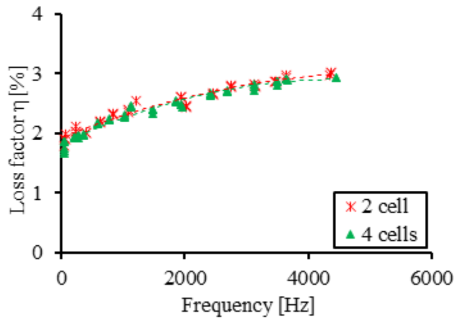


Fig. 15. Evolution of the loss factor of sandwich beams with different number of cells in width.

## CONCLUSIONS

Bio-sandwich composites manufactured using 3D printing machine are studied. The sandwiches are manufactured using two different biological material which are the PLA and the PLA reinforced with flax fibers (<20%). Two different core topologies are tested: the conventional honeycomb and auxetic structures. In addition, the effect of the number of cells in the core is highlighted (2 and 4 cells in width). Uniaxial tensile test is performed to determine the based material behavior. Results show that PLA presents the highest stiffness and hardness and PFF presents the highest ductility. The static three-point bending tests are also performed on the sandwich composites. It is found that sandwich with auxetic core, high number of cells made with PLA material presents the high bending stiffness compared to other configurations. Moreover, the cyclic bending tests are conducted. Results show that sandwich with auxetic core and two cells in width presents the highest dissipated energy. The vibration behavior is also treated. It is found that sandwich with auxetic core made with PFF material presents the highest damping properties. Based on these experimental results, it appears possible to develop numerical model to optimize the honeycomb parameters in order to enhance the static and dynamic properties to mass ratio of the sandwich. This work highlights the effect of different parameters in the static and dynamic properties of the sandwich composite. According to the founded results, each parameters enhance a specific property. Using flax fibers as reinforcement include a decrease in the static stiffness but in the other hand, it enhances the damping properties. Also, the auxetic structure enhance the static, fatigue and damping properties compared to conventional honeycomb structure. And finally, the increase of the number of cells increases the mechanical properties of the sandwich composite. In this case, the choose of each parameter is related to the industrial application. For example, for the transport domain, the parameter that enhance the damping properties is better to be used.

## REFERENCES

Abbadi, A., Azari, Z., Belouettar, S., Gilgert, J., Freres, P., "Modelling the fatigue behaviour of composites honeycomb materials (aluminium/aramide fibre core) using four-point bending tests," International Journal of Fatigue, Vol. 32, No. 11, pp.1739-1747 (2010).

Assarar, M., Zouari, W., Ayad, R., Kebir, H., Berthelot, J.M., "Improving the damping properties of carbon fibre reinforced composites by interleaving flax and viscoelastic layers," Composites Part B: Engineering, Vol. 152, pp.248-255 (2018).

ASTM C393/C393M –16. Standard test method for core shear properties of sandwich constructions by beam flexure.

ASTM D638 - Standard Test Method for Tensile Properties of Plastics.

Baghaei, B., Skrifvars, M., Berglin, L., "Manufacture and characterisation of thermoplastic composites made from PLA/hemp co-wrapped hybrid yarn prepregs," Composites Part A: Applied Science and Manufacturing, Vol. 50, pp.93-101 (2013).

Baley, C. and Bourmaud, A., "Average tensile properties of French elementary flax fibers," Materials letters, Vol. 122, pp.159-161 (2014).

Ben Ammar, I., Karra, C., El Mahi, A., El Guerjouma, R., Haddar, M., "Mechanical behavior and acoustic emission technique for detecting damage in sandwich structures," Applied Acoustics, Vol. 86, pp.106-117 (2014).

Bezazi, A. and Scarpa, F., "Mechanical behaviour of conventional and negative Poisson's ratio thermoplastic polyurethane foams under compressive cyclic loading," International Journal of fatigue, Vol. 29, No. 5, pp.922-930 (2007).

Bianchi, M. and Scarpa, F., "Vibration transmissibility and damping behaviour for auxetic and conventional foams under linear and nonlinear regimes," Smart materials and structures, Vol. 22, No. 8, pp.084010 (2013).

Bitzer, T.N., "Honeycomb technology: materials, design, manufacturing, applications and testing," Springer Science & Business Media (1997).

Boldrin, L., Hummel, S., Scarpa, F., Di Maio, D., Lira, C., Ruzzene, M., Patsias, S., "Dynamic behaviour of auxetic gradient composite hexagonal honeycombs," Composite Structures, Vol. 149, pp.114-124 (2016).

Crupi, V., Epasto, G., Guglielmino, E., "Collapse modes in aluminium honeycomb sandwich panels under bending and impact loading," International Journal of Impact Engineering, Vol. 43, pp.6-15 (2012).

Daoud, H., El Mahi, A., Rebiere, J.L., Taktak, M., Haddar, M., "Characterization of the vibrational behaviour of flax fibre reinforced composites with an interleaved natural viscoelastic layer," Applied acoustics, Vol. 128, pp.23-31 (2017).

Daoud, H., El Mahi, A., Rebiere, J.L., Mechri, C., Taktak, M., Haddar, M., "Experimental analysis of the linear and nonlinear vibration behavior of flax fibre reinforced composites with an interleaved natural viscoelastic layer," Composites Part B: Engineering, Vol. 151, pp.201-214 (2018).

Duc, F., Bourban, P.E., Plummer, C.J.G., Månson, J.A., "Damping of thermoset and thermoplastic flax fibre composites," Composites Part A: Applied Science and Manufacturing, Vol. 64, pp.115-123 (2014).

El Mahi, A., Assarar, M., Sefrani, Y., Berthelot, J.M., "Damping analysis of orthotropic composite materials and laminates," Composites Part B: Engineering, Vol. 39, No. 7-8, pp.1069-1076 (2008).

Essassi, K., Rebiere, J.L., El Mahi, A., Ben Souf, M.A., Bouguecha, A., Haddar, M., "Dynamic characterization of a bio-based sandwich with auxetic core: Experimental and numerical study," International Journal of Applied Mechanics, Vol. 11, No, 02, pp.1950016 (2019).

Essassi, K., Rebiere, J.L., El Mahi, A., Ben Souf, M.A., Bouguecha, A., Haddar, M., "Experimental and analytical investigation of the bending behaviour of 3D-printed bio-based sandwich structures composites with auxetic core under cyclic fatigue tests," Composites Part A: Applied Science and Manufacturing, Vol. 131, pp.105775 (2020).

Essassi, K., Rebiere, J.L., El Mahi, A., Ben Souf, M.A., Bouguecha, A., Haddar, M., "Health monitoring of sandwich composites with auxetic core subjected to indentation tests using acoustic emission," Structural Health Monitoring, pp.14759217211053991 (2021).

Essassi, K., Rebiere, J.L., El Mahi, A., Ben Souf, M.A., Bouguecha, A., Haddar, M., "Damping Analysis and Failure Mechanism of 3D Printed Bio-Based Sandwich with Auxetic Core under Bending Fatigue Loading," Journal of Renewable Materials, Vol. 9, No. 3, pp.569-584 (2021).

Essassi, K., Rebiere, J.L., El Mahi, A., Ben Souf, M.A., Bouguecha, A., Haddar, M., "Experimental and numerical analysis of the dynamic behavior of a bio-based sandwich with an auxetic core," Journal of Sandwich Structures & Materials, Vol. 23, No. 3, pp.1058-1077 (2021).

Faruk, O., Bledzki, A.K., Fink, H.P., Sain, M., "Biocomposites reinforced with natural fibers: 2000–2010," Progress in polymer science, Vol. 37, No. 11, pp.1552-1596 (2012).

Goh, G.D., Agarwala, S., Goh, G.L., Dikshit, V., Sing, S.L., Yeong, W.Y., "Additive manufacturing in unmanned aerial vehicles (UAVs): Challenges and potential," Aerospace Science and Technology, Vol. 63, pp.140-151 (2017).

Li, T. and Wang, L., "Bending behavior of sandwich composite structures with tunable 3D-printed core materials," Composite Structures, Vol. 175, pp.46-57 (2017).

Lira, C. and Scarpa, F., "Transverse shear stiffness of thickness gradient honeycombs," Composites Science and Technology, Vol. 70, No. 6, pp.930-936 (2010).

Lira, C., Scarpa, F., Rajasekaran, R., "A gradient cellular core for aeroengine fan blades based on auxetic configurations," Journal of Intelligent Material Systems and Structures, Vol. 22, No. 9, pp.907-917 (2011).

Ma, Y., Scarpa, F., Zhang, D., Zhu, B., Chen, L., Hong, J., "A nonlinear auxetic structural vibration damper with metal rubber particles," Smart Materials and Structures, Vol. 22, No. 8, pp.084012 (2013).

Monti, A., El Mahi, A., Jendli, Z., Guillaumat, L., "Experimental and finite elements analysis of the vibration behaviour of a bio-based composite sandwich beam," Composites Part B: Engineering, Vol. 110, pp.466-475 (2017).

Monti, A., El Mahi, A., Jendli, Z., Guillaumat, L., "Quasi-static and fatigue properties of a balsa cored sandwich structure with thermoplastic skins reinforced by flax fibres," Journal of Sandwich Structures & Materials, Vol. 21, No. 7, pp.2358-2381 (2019).

Murray, G.J. and Gandhi, F., "Auxetic honeycombs with lossy polymeric infills for high damping structural materials," Journal of intelligent material systems and structures, Vol. 24, No. 9, pp.1090-1104 (2013).

Niknam, H., Akbarzadeh, A.H., "In-plane and out-of-plane buckling of architected cellular plates: Numerical and experimental study," Composite Structures, Vol. 206, pp.739-749 (2018).

Ramnath, B.V., Alagarraja, K., Elanchezhian, C., "Review on sandwich composite and their applications," Materials Today: Proceedings, Vol. 16, pp.859-864 (2019).

Sharaf, T., Shawkat, W., Fam, A., "Structural performance of sandwich wall panels with different foam core densities in one-way bending," Journal of composite materials, Vol. 44, No. 19, pp.2249-2263 (2010).

Strek, T., Jopek, H., Nienartowicz, M., "Dynamic response of sandwich panels with auxetic cores," Physica status solidi (b), Vol. 252, No. 7, pp.1540-1550 (2015).

Sugiyama, K., Matsuzaki, R., Ueda, M., Todoroki, A., Hirano, Y., "3D printing of composite sandwich structures using continuous carbon fiber and fiber tension," Composites Part A: Applied Science and Manufacturing, Vol. 113, pp.114-121 (2018).

Tian, J., Lu, T.J., Hodson, H.P., Queheillalt, D.T., Wadley, H.N.G., "Cross flow heat exchange of textile cellular metal core sandwich panels," International journal of heat and mass transfer, Vol. 50, No. 13-14, pp.2521-2536 (2007).

Trujillo, E., Moesen, M., Osorio, L., Van Vuure, A.W., Ivens, J., Verpoest, I., "Bamboo fibres for reinforcement in composite materials: Strength Weibull analysis," Composites Part A: Applied Science and Manufacturing, Vol. 61, pp.115-125 (2014).

Wu, X., Yu, H., Guo, L., Zhang, L., Sun, X., Chai, Z., "Experimental and numerical investigation of static and fatigue behaviors of composites honeycomb sandwich structure," Composite Structures, Vol. 213, pp.165-172 (2019).

Wang, K., Ho, C.C., Zhang, C., Wang, B., "A review on the 3D printing of functional structures for medical phantoms and regenerated tissue and organ applications," Engineering, Vol. 3, No. 5, pp.653-662 (2017).

Xiao, D., Chen, X., Li, Y., Wu, W., Fang, D., "The structure response of sandwich beams with metallic auxetic honeycomb cores under localized impulsive loading-experiments and finite element analysis," Materials & Design, Vol. 176, pp.107840 (2019).

Xu, X., Koomson, C., Doddamani, M., Behera, R.K., Gupta, N., "Extracting elastic modulus at different strain rates and temperatures from dynamic mechanical analysis data: A study on nanocomposites," Composites Part B: Engineering, Vol. 159, pp.346-354. (2019).

Yang, J., Xiong, J., Ma, L., Wang, B., Zhang, G., Wu, L., "Vibration and damping characteristics of hybrid carbon fiber composite pyramidal truss sandwich panels with viscoelastic layers," Composite Structures, Vol. 106, pp.570-580 (2013).

Yu, X., Zhou, J., Liang, H., Jiang, Z., Wu, L., "Mechanical metamaterials associated with stiffness, rigidity and compressibility: A brief review," Progress in Materials Science, Vol. 94, pp.114-173 (2018).

Zhang, X., Zhou, H., Shi, W., Zeng, F., Zeng, H., Chen, G., "Vibration tests of 3D printed satellite structure made of lattice sandwich panels," AIAA Journal, Vol. 56, No. 10, pp.4213-4217 (2018).