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Mechanical characterization of an epoxy panel reinforced by date palm petiole particle

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Abstract. The past years were marked by an increase in the use of wood waste in civil and mechanical constructions. Date palm waste remains also one of the most solicited renewable and recyclable natural resources in the composition of composite materials. In Algeria, a great amount of this type of plant wastes accumulates every year. In order to make use of this waste, a new wood-epoxy composite material based on date palm petiole particleboard is developed. It makes use of date palm petiole particleboard as reinforcement and epoxy resin as matrix. The size of the particles reinforcement are between 1~3 mm and proportion of reinforcement used is 37%. In this work, experimental and numerical studies are conducted in order to characterize the wood fibre-epoxy plates. Firstly, experimental modal analysis test was carried out to determine Young's modulus of the elaborated material. Then, in order to validate the results, compression test was conducted. Furthermore, additional information about the shear modulus of this material is obtained by performing an experimental modal analysis to extract the first torsional mode. Moreover, a finite element model is developed using ANSYS software to simulate the vibration behaviour of the plates. The results show a good agreement with the experimental modal analysis, which confirms the values of Young's modulus and shear modulus.

Keywords: palm; wood-epoxy composite; experimental analysis; finite element analysis

1. Introduction

Recently, the characterization of composite materials has more attracted many researchers for static and dynamic analysis. Lakshmipathi and Vasudevan (2019) presented a dynamic characterization of a CNT reinforced hybrid uniform and non-uniform composite plates. The mechanical characterization of a self-compacting polymer concrete called isobeton was presented by Boudjellal *et al.* (2016). Copper/silicon nitride (Cu/Si3N4) composites were fabricated by powder technology process (Ahmed *et al.* 2016), where copper was used as a metal matrix and very fine Si3N4 particles (less than 1 micron) as reinforcement material.

Recycling of wastes wood is becoming one of the most important challenges of future building (Sarbu *et al*. 2009, Asdrubali *et al.* 2015). According to Asdrubali *et al*. (2015), buildings consume about 40% of global energy. Nowadays, due to the immense consumption of electrical and thermal energies for the production of building products, many environmental problems appear.

Therefore, several countries have made many efforts to solve this problem by inventing buildings materials with renewable and recyclable aspects (Zhang *et al*. 2005). Actually, in the last decades, the research is focused on the incorporation of plant resources constituent in composite materials (Cheung *et al.* 2009). Indeed, the use of plant resources in the conception of materials is not a new idea as our ancestors used a straw to reinforce the mud-bricks (Herakovich 2012). Therefore, the plant resources draw considerable attention, mainly due to their low cost, low weight, and high thermal and mechanical properties (Mitra *et al.* 1998, Cabeza *et al.* 2013). After the annual date fruit harvesting, a considerable amount of date palm wastes accumulates every year in Algeria. Its use as a raw material in the industry may offer the high advantage of recycling an abundant waste with a high added value (Benzidane *et al*. 2018). Wood-plastic composites (WPC) are defined as composite materials containing wood in various forms and thermoplastic materials. These materials are a relatively

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new family of composite materials, in which a natural fibre and /or filler (such as wood flour/fibre, kenaf fibre, hemp, sisal, etc.) is mixed with a thermoplastic such as polyethylene (PE), polypropylene (PP) (Tabarsa *et al.* 2011). A comprehensive survey of the literature indicates that very much information is available on the behaviour of WPC in various fields (mechanics, thermal) and can be found in Wambua *et al*. (2003). In this reference, the characterization of mechanical properties of polypropylene composite incorporated with various natural fibres was reported. The authors showed that generally, the specific properties of natural fibre composites are comparable with those of glass. An experimental study was proposed by Chikhi *et al*. (2013) to show the effect of palm fibres on mechanical properties, thermal conductivity and water absorption of gypsum-based materials. The material exhibited good thermal performance, allowing it to be a good candidate for thermal insulation.

An experimental investigation was carried out by Al-Sulaiman (2003) by making panels of WPC. The authors demonstrated that the studied materials presented a very low thermal conductivity. Dehghani *et al*. (2013) have investigated the mechanical, thermal and morphological properties of date palm leaf fibre reinforced with recycled poly-ethylene-terephthalate. The authors concluded that the incorporation of date palm leaf fibres constituent in composite materials improved the mechanical properties. Masri *et al.* (2018) have characterized mechanical, thermal and morphological properties of new composites based on date palm leaflets and expanded polystyrene wastes. Their results confirmed that date palm waste was very suitable for the formulation of effective and safe insulating materials when compared to the other natural materials. Some physical properties of the coconut palm stem were presented by Killmann (1983). Mechanical characterization and quantification of tensile, fracture, and visco-elastic characteristics of wood filler reinforced epoxy composite were reported by Kumar *et al*. (2018).

The challenge of replacing conventional plastics with biodegradable composite materials has attracted much attention in product design, particularly in the tensile-related areas of application by Anyakora *et al*. (2017). In this study, fibres extracted from oil palm empty fruit bunch (EFB) were treated and utilized in reinforcing polyester matrix by hand lay-up technique. The effect of fibre loading and combined influence of alkali and silane treatments on porosity and water absorption parameters and its correlation with the tensile behaviour of composites were analysed. Huda *et al*. (2017) discussed the aggregate properties of oil palm shell (OPS) and palm oil clinker (POC) were plotted in conjunction with mechanical and structural behaviour of OPS concrete (OPSC) and POC concrete (POCC).

Based on the above literature, the authors concluded that the recycled palm leaf fibre/flour composite appears to be a very good alternative to obtain an environmentally friendly product. The idea of recycling the date palm wastes from nature to create composite materials can be an alternative solution from the environmental and economical point of view. To overcome the lack of knowledge on the mechanical performances of natural fibre composite plates, we studied the mechanical behaviour of polymers reinforced with palm particleboard. The main objective of the experimental and numerical studies in this paper is to characterize the composite material using both static and dynamic analyses. Dynamic tests were carried out to predict Young's modulus of fabricated WPC plates. Compression tests were also conducted on specimens to validate the obtained parameter. Experimental modal analysis was performed to extract the modal parameters, i.e., natural frequencies and associated modes shapes. The first torsional mode allows us to determine the shear modulus, which is used to identify Poisson's ratio. Thereafter, the predicted parameters were used for numerical simulations. Using ANSYS software, a finite element model was developed to simulate the modal parameters of the WPC plate. This study shows a good agreement between numerical and experimental modal analysis in terms of frequencies and modes shapes.

2. Preparation of test specimens

Date palm petiole particles used in this study are the residues of petiole date palm trees, as shown in Fig. 1. This waste is collected from Ghardaya oasis in Algeria.

The petiole section used in this work were cleaned with water to remove dust and impurities and naturally dried during one week in order to reduce water content. Dried petioles were grinded to obtain a particles of 1 to 3 mm, used as a reinforcement in the preparation of the material. Fig. 2 shows the petiole section after grinding.

The type of resin used to fabricate the composite plates is Medapoxy STR (Mat1) (Hamamousse *et al.* (2019)) obtained from granite company (granite, Oued Smar, Algeria). The resin was prepared by mixing Medapoxy resin with an adequate hardener in a 2:1 ratio polymerization at ambient temperature for approximately 15 days. The Young modulus of the mixture (Medapoxy resin and adequate hardener) is 2.13 GPa. The elaboration of new composite material is obtained by mixing the resin and the reinforcement with 0% water content. Then the mixture is poured into two moulds. A pressure of 5 Kn/m^2 with a holding time of 48h are considered in the development of the material. The obtained plates are dried at air under ambient conditions for at least 17 days.

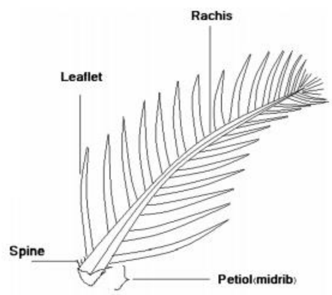


Fig. 1 Structural parts of date palm (Mirmehdi *et al.* 2014)

Fig. 2 Date palm petiole Particles

(a)

(b)

Fig. 3 Palm fibre composite plates: (a) specimen 1 for modal analysis test and (b) specimen 2 for compression test

Table 1 Dimensions of palm fiber composite plates according to test standards: UNI EN 1015-11:2019

	Length (mm)	Width (mm)	Thickness (mm)
Specimen 1	295	75	17
Specimen 2	85	41	23

Two specimens are considered in this present study. The first specimen was used for modal analysis and the other was used for compression tests. For the modal analysis, we study one specimen in different tests. Each test is based on the average of different strike positions to make sure that the response is well recorded by the accelerometer as the first step. The second step is the static compression test using four reading strain. The main objective of this study is to characterize of the new composite using modal analysis and static tests.

The dimensions of specimens are given in Table 1. Two specimens were tested; one for modal analysis and one for static compression test.

Table 2 Material details

	Percentage (%)	Weight (g)
particles	37	300
polymer	63	514.2

The quantity and the weight of the palm particles and the polymer are presented in Table 2.

3. Experimental analysis of Palm fibre composite (P-FRP)

3.1. Modal analysis

3.1.1 Natural frequencies

This part is dedicated to studying the influence of the position of the accelerometer and the hammer strike on the frequencies. The test is simulated using free-free boundary conditions by hanging the structure using two flexible strings. Fig. 4 shows the experimental setup and Fig. 5 illustrates the arrangement of measurement points.

3.1.1.1 Fixed accelerometer position

In this test, we fixed the accelerometer in a single position, then we excite the structure by the hammer at different points. The letter '*b*' in Fig. 5 refers to the position of the accelerometer, whereas M1, M2, and M3 are the striking points with an instrumented hammer.

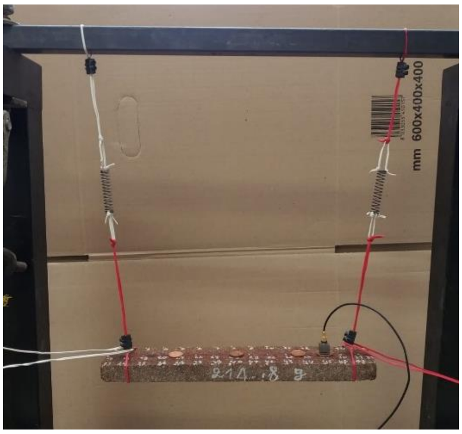


Fig. 4 Modal analysis test configuration of palm fibre composite (P-FRP)

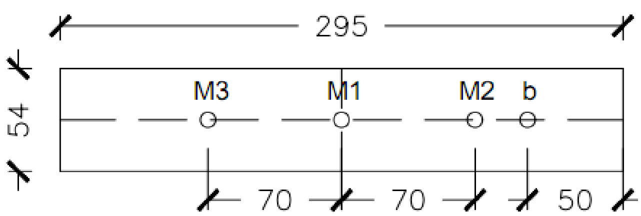


Fig. 5 Arrangement of measurement points

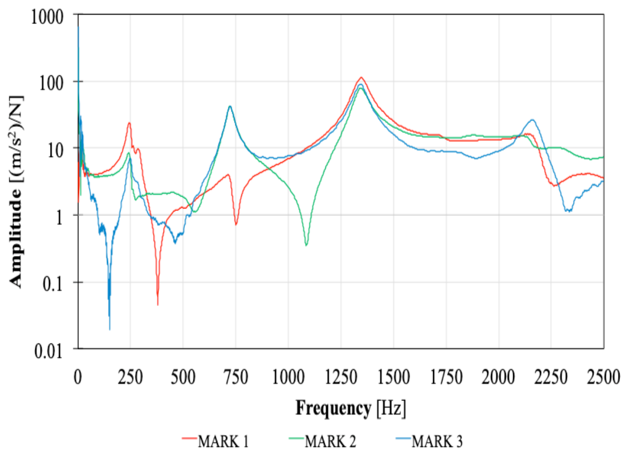


Fig. 6 FRFs for a fixed accelerometer position

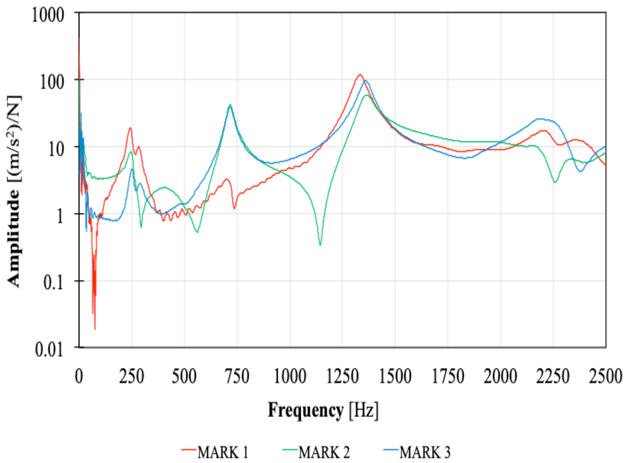


Fig. 7 FRFs for a fixed impact hammer position

Fig. 6 illustrates the Frequency Response Function (FRF) results obtained for the fixed accelerometer and three different striking positions. The results show that the change in striking position does not have a major influence on the natural frequencies.

3.1.1.2 Fixed hammer strike position

In this case, at each measurement, we change the position of the accelerometer by keeping the same position of excitation using a hammer. Therefore, in this test, the letter '*b*' in Fig. 5 refers to the instrumented hammer position, whereas M1, M2, and M3 are the positions of accelerometers. The effect of changing the position of the accelerometer is shown in Fig. 7. From Fig. 7, it is clearly seen that the results are almost the same, i.e., no major influence on the natural frequencies. Therefore, we considered that the produced material is elastic, homogeneous and isotropic.

Using Bernoulli's hypotheses and in the context of small deformations, the analytical solutions for the natural frequencies ω_n are

$$\omega_n = \left(\frac{\beta_n l}{l}\right)^2 \sqrt{\frac{EI}{\rho A}} \tag{1}$$

Where $\beta_n l$ is the eigenvalue for a free end beam at the n mode; l is the length of beam; E is Young's modulus; I is the second moment of area of the cross-section; ρA is the mass per unit length of the beam. This equation makes use of only the fundamental frequency and allows us to identify the elasticity modulus, $E_{Dynamic}$, as

$$E_{Dynamic} = 1.15\times 10^9\,\text{Pa} \tag{2}$$

3.1.2 Mode shapes and shear modulus

To determine the mode shapes, the modal parameters of the studied structures are identified by the hammer impact method, and the experimental equipment is shown in Fig. 8. The studied specimens face is marked by 16×3 parallel grid points and suspended on the steel bracket using two flexible strings to simulate the free-free boundary conditions. An impulse PCB086C03 hammer with a force transducer whose sensitivity is 2.5 mv, was used to excite the specimen, and the force history of the hammer impact is recorded by the force transducer connected with the hammer. Afterward, the response of the structure is detected using a PCB356A15 accelerometer. Then, the frequency response functions (FRFs) are obtained as shown in Fig. 9. The associated mode shapes are presented in the results section and compared to the numerical ones.

To measure the vertical bending vibration, the same composite beam is marked by 16 grid points in the longitudinal direction in rigid section and the accelerometer is fixed above point number 16 as shown in Fig. 10. The obtained FRFs are shown in Fig. 11.

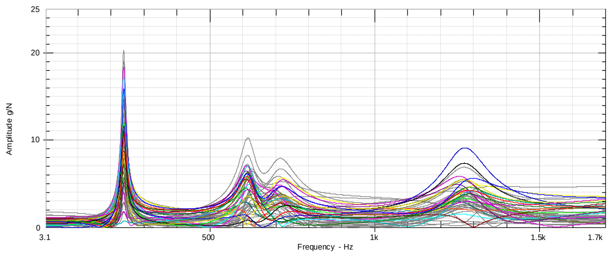
To determine the shear modulus, the first mode of torsion is used. The natural frequency of the torsion modes of the free beam can be calculated as follows (Rao 2007)

$$f_{Torsion} = \frac{n}{2l}\sqrt{\frac{GJ}{I}} \tag{3}$$

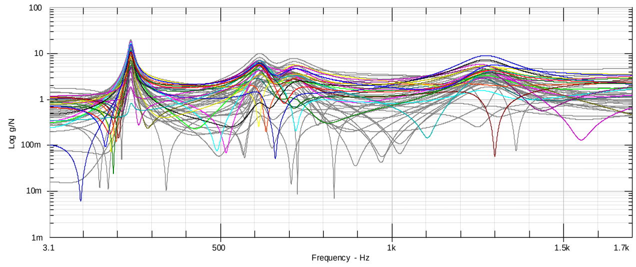
Where n is torsion mode number and J is the polar moment of inertia of the cross-section

$$J = [\frac{1}{3} - 0.2\frac{b}{a}(1 - \frac{b^4}{12\times a^4})]ab^3 \tag{4}$$

Fig. 8 Experimental set-up to determine mode shapes



(a)



(b)

Fig. 9 FRFs at 48 different grid points: (a) amplitude scale and (b) logarithmic scale

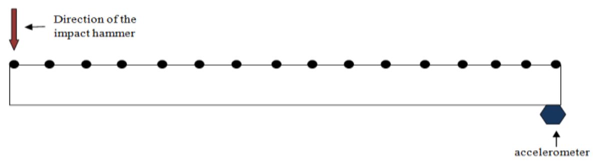


Fig. 10 Arrangement of accelerometer and excitation points for measuring vertical vibration

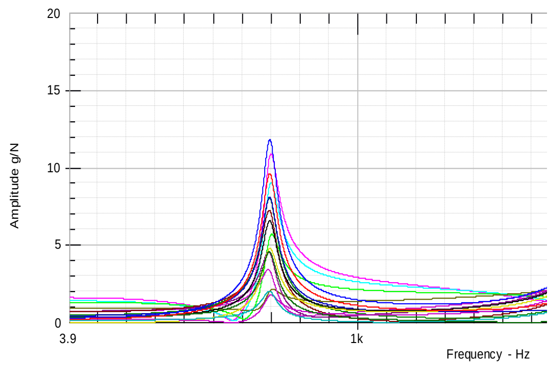


Fig. 11 FRFs for 16 different grid points

And I is a mass polar moment of inertia of the shaft per unit length

$$I = \frac{1}{12} m(h^2 + w^2) ab^3 \tag{5}$$

When we determine the shear modulus (G), we can extract Poisson's ratio as

$$\nu = \frac{E}{2G} - 1 \tag{6}$$

Table 3 Shear modulus and Poisson's ratio obtained by experimental modal analysis

Shear modulus [N/m^2]	Poisson's ratio
3.9×10^8	0.35

The estimated shear modulus and Poisson's ratio are listed in Table 3.

4. Static compression test

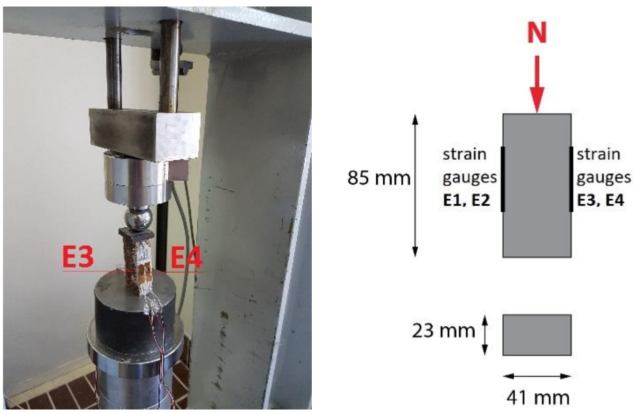
The basic objective of the static test is to identifying Young's modulus of the composite beam. Static test was carried out through a compression increasing testing fixture device schematically shown in Fig. 12(a). The specimen is 85 mm in length and has a rectangular cross-section of 23 mm × 41 mm as shown in Fig. 12(b). The instruments used in the static test were: a manual system to transmit the vertical load N in one point and four strain gauges, labelled as E1, E2, E3 and E4, to measure the evolution of deformations during the compression tests at two opposite faces of the specimen. The sample was subjected to monotonically increasing compression load until failure at a load value of 5 kN. The results are shown in Fig. 13.

Using the experimental diagrams of compression load versus strain, in Fig. 9, and considering a value of compression force N equals to the 40% of the failure load, we can determine Young's modulus as follows

$$E_{Static} = \frac{N}{\varepsilon_{av} A} \tag{7}$$

Where N is the compression force, ε_{av} is the average strain recorded by strain gauges and A is the cross-section area of beam.

It is possible to observe that Young's modulus obtained by experimental modal analysis and static test are very similar.



(a) (b)

Fig. 12 (a) Compression test system set-up and (b) dimensions of the specimen

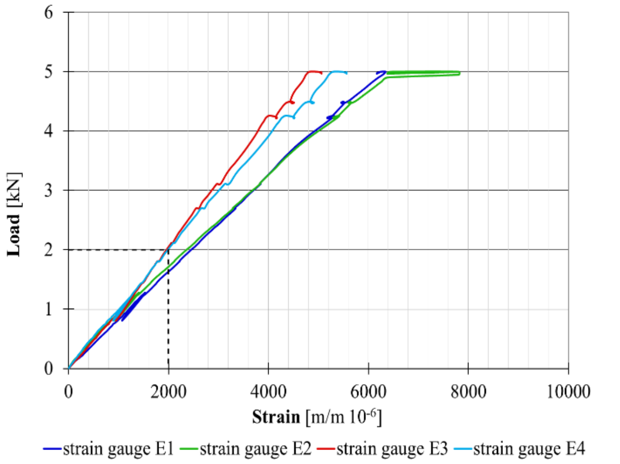


Fig. 13 Experimental diagrams for compression load vs strains

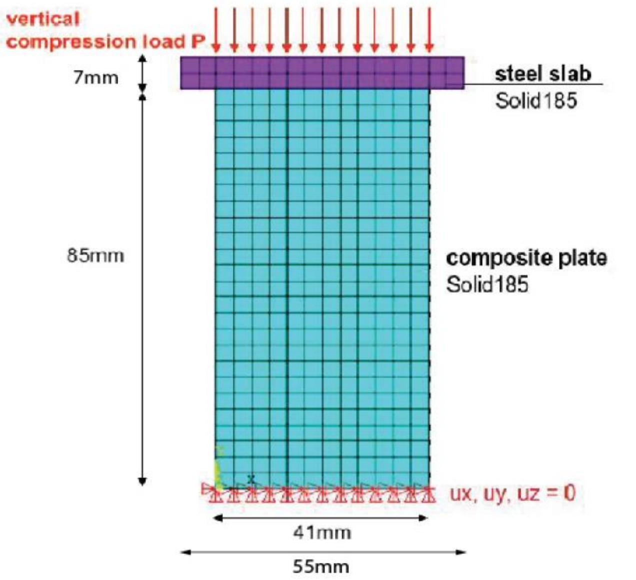


Fig. 14 Finite element model of the composite specimen for static analysis

The results show a good agreement between the two experiments. The ratio between the dynamic Young's modulus (Eq. (2)) and the static Young's modulus (Eq. (7)) is approximately 1.085. This implies that the dynamic Young's modulus is 8.5% higher than the static Young's modulus, which is commonly expected behaviour of materials.

Numerical analysis using finite element method has been developed to analyse the mechanical behaviour of wood fibre-epoxy model (Fig. 14) under compression test and to confirm the experimental results. The behaviour of the composite element was analysed by a linear procedure implemented in the finite element code ANSYS using brick solid finite elements. Eight-node isoparametric finite elements having three degrees of freedom at each node

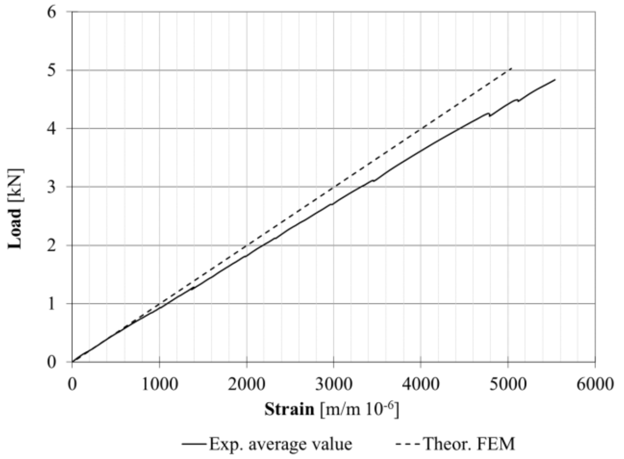


Fig. 15 Comparison between experimental and numerical results for compression test on composite model

(Solid185) were employed. An elastic, isotropic and homogeneous behaviour has been considered by assuming an elastic stiffness value equal to Young's modulus and a Poisson's ratio as obtained by the experimental tests.

Linear analysis was performed, by considering a progressive increase of the compression vertical load, which was applied to the steel slab, in order to guarantee a good distribution of the vertical pressure.

The accuracy of the numerical results is assessed through a comparison with experimental average results (Fig. 15). From the analysis of the comparison diagrams, it can be seen that the ultimate load and strain predicted by the numerical model agrees well with that from the experiments. In particular the failure load predicted by the FE analysis is 5.031 kN, which is in good agreement with the experimental value of 4.899 kN. This confirms the correctness and adequacy of the developed model.

5. Numerical simulations for modal analysis

In the numerical simulations, we adopt the predicted experimental parameters (Young modulus, Shear modulus and Poisson's ratio) to simulate the vibration behaviour of the composite plate fabricated from palm particleboard and Medapoxy resin.

The numerical study was performed using the commercial software ANSYS. A finite element model is presented in Fig. 16 and the predicted experimental parameters are introduced in the material model. The material is modelled as a homogeneous, isotropic and elastic. The FE mesh consists of 360 elements.

To validate the accuracy of the numerical model, the obtained results are compared with the experimental results. Natural frequencies and associated mode shapes are analysed and compared with the experimental ones in Fig. 17. According to the results in Fig. 17, the mode shapes extracted by experimental and numerical analysis are very much alike from visual inspection point of view. Only a few discrepancies

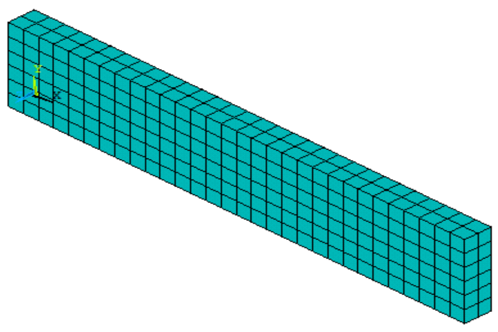
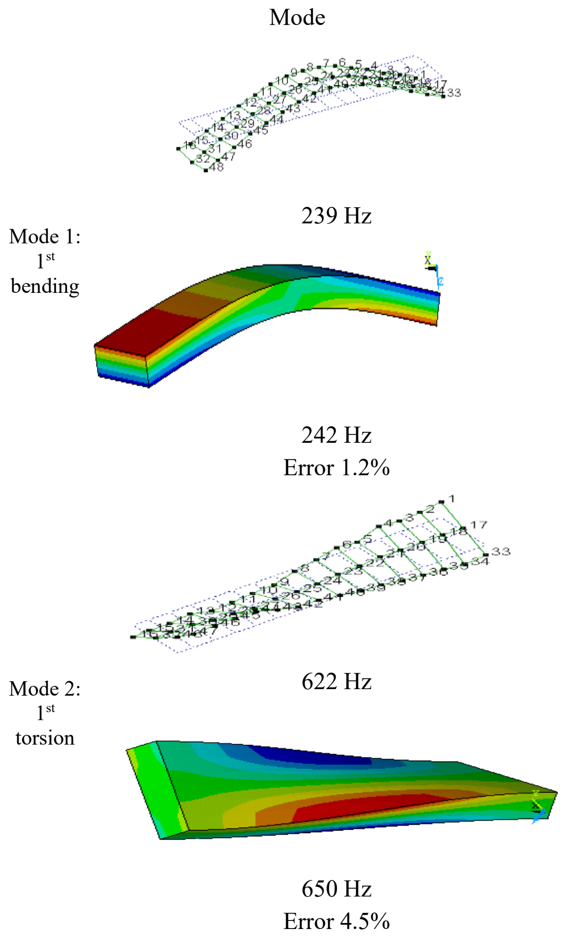


Fig. 16 Finite element model for modal analysis

could be observed in the frequencies. This can be explained by the numerical errors due to the discretisation in the finite element simulations. This comparison confirms the accuracy of the mechanical parameters identified in previous sections.

The good agreement of frequencies and also corresponding mode shapes between numerical and experimental results show that:

- Non-destructive experimental method based on a precise contact free–free measurement system is very effective.
- The quality of the obtained experimental results may be improved in future by using more advanced equipment.



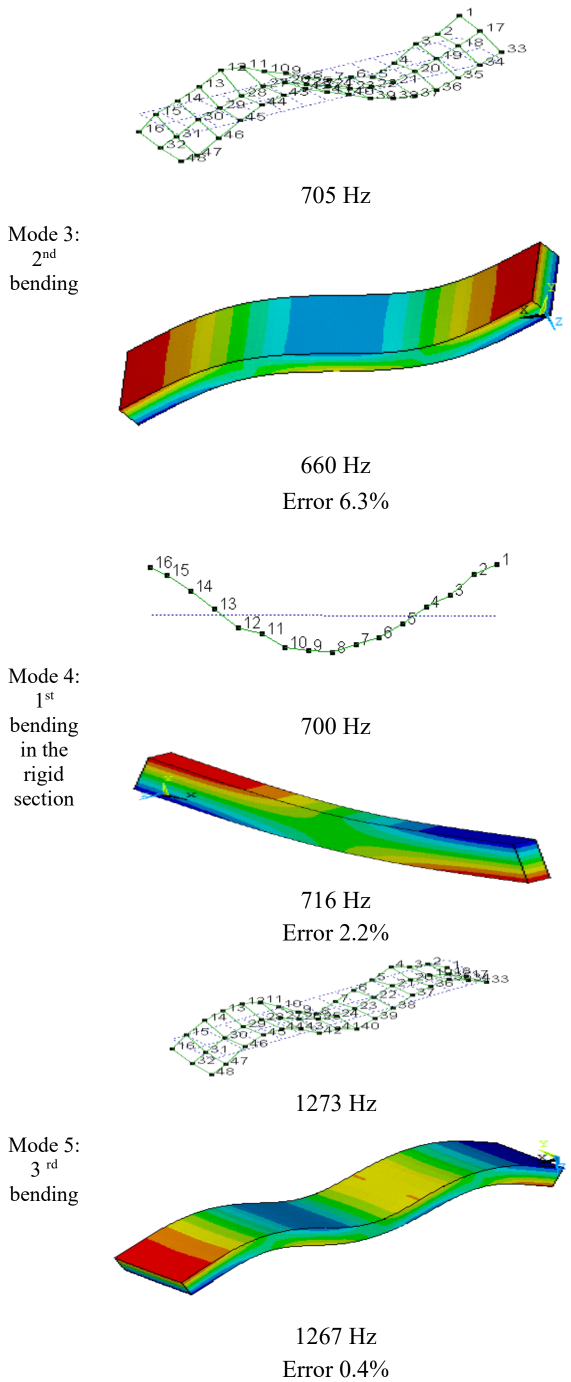


Fig. 17 Numerical and experimental results.

6. Conclusions

In order to make use of the waste plant in building, we are particularly interested in date palm petiole wood as a local and renewable material. This is because of its large quantities wastes accumulate every year in Algeria. Therefore, we have investigated the mechanical behaviour of new composite material with particles, which was used as the reinforcement and Medapoxy resin as the matrix. Modal analysis test was performed to extract Young's modulus of the material. Afterward, a compression test has confirmed the predicted parameters. The following conclusions are highlighted:

1. Experimental modal analysis is very important for the characterization of any material because it allows us to measure both bending and torsion modes.
2. By using the first torsion mode of the plate, we have determined the shear modulus of the investigated material. Numerical modal analysis of plate was carried out using the obtained experimental constants. The results show a good agreement.

This investigation shows the perfect mechanical characteristics of the new studied material. This demonstrates the efficiency of date palm wood to be a useful environmentally friendly product if it is used as reinforcement in polymer composite material. Furthermore, its cost is very low compared with other types of fibres. Further research and development will be conducted to improve the quality of the product of its applications.

References

Ahmed, M.A., Daoush, W.M. and El-Nikhaily, A.E. (2016), "Fabrication and characterization of Copper/Silicon Nitride composites", *Adv. Mater. Res.*, **5**(3), 131-140. https://doi.org/10.12989/amr.2016.5.3.131.

Al-Sulaiman, F.A. (2003), "Date palm fibre reinforced composite as a new insulating material", *Int. J. Energy Res.*, **27**(14), 1293-1297. https://doi.org/10.1002/er.957.

Anitescu, C., *et al.* (2019), "Artificial neural network methods for the solution of second order boundary value problems", *Comput. Mater. Continua*, **59**, 345-359. https://doi:10.32604/cmc.2019.06641.

Anyakora, A.N., *et al.* (2017), "Effect of fibre loading and treatment on porosity and water absorption correlated with tensile behaviour of oil palm empty fruit bunch fibre reinforced composites", *Adv. Mater. Res.*, **6(4)**, 329-341. https://doi.org/10.12989/amr.2017.6.4.329.

Asdrubali, F., D'Alessandro, F. and Schiavoni, S. (2015), "A review of unconventional sustainable building insulation materials", *Sustainable Mater. Technol.*, **4**, 1-17. https://doi.org/10.1016/j.susmat.2015.05.002.

Benzidane, R., *et al.* (2018), "Morphology, static and fatigue behavior of a natural UD composite: the date palm petiole 'wood'", *Compos. Struct.*, **203**, 110-123. https://doi.org/10.1016/j.compstruct.2018.06.122.

Boudjellal, K., Bouabaz, M. and Belachia, M. (2016), "Mechanical characterization of a self-compacting polymer concrete called isobeton", *Struct. Eng. Mech.*, **57**(2), 357-367. https://doi.org/10.12989/sem.2016.57.2.357.

Cabeza, L.F., *et al*. (2013), "Low carbon and low embodied energy materials in buildings: A review", *Renew. Sust. Energ. Rev.*, **23**, 536-542. https://doi.org/10.1016/j.rser.2013.03.017.

Cheung, H.Y., *et al.* (2009), "Natural fibre-reinforced composites for bioengineering and environmental engineering applications", *Compos. Part B: Eng.*, **40**(7), 655-663. https://doi.org/10.1016/j.compositesb.2009.04.014.

Chikhi, M., *et al.* (2013), "Experimental investigation of new biocomposite with low cost for thermal insulation", *Energy Build.*, **66**, 267-273. https://doi.org/10.1016/j.enbuild.2013.07.019.

Dehghani, A., *et al.* (2013), "Mechanical and thermal properties of date palm leaf fiber reinforced recycled poly (ethylene terephthalate) composites", *Mater. Design*, **52**, 841-848. https://doi.org/10.1016/j.matdes.2013.06.022.

Hamamousse, K., *et al.* (2019), "Experimental and numerical studies on the low-velocity impact response of orthogrid epoxy panels reinforced with short plant fibers", *Compos. Struct.*, **211**, 469-480. https://doi.org/10.1016/j.compstruct.2019.01.005 .

Herakovich, C.T. (2012), "Mechanics of composites: a historical review", *Mech. Res. Commun.*, **41**, 1-20. https://doi.org/10.1016/j.mechrescom.2012.01.006.

Huda, M.N., *et al.* (2017), "Palm oil industry's bi-products as coarse aggregate in structural lightweight concrete", *Comput. Concrete*, **19**(5), 515-526. https://doi.org/10.12989/cac.2017.19.5.515.

Killmann, W. (1983), "Some physical properties of the coconut palm stem", *Wood Sci. Technol.*, **17**, 167-185. https://doi.org/10.1007/bf00372314.

Kumar, R., Kumar, K. and Bhowmik, S. (2018), "Mechanical characterization and quantification of tensile, fracture and viscoelastic characteristics of wood filler reinforced epoxy composite", *Wood Sci. Technol.*, **52**, 677-699. https://doi.org/10.1007/s00226-018-0995-0.

Lakshmipathi, J. and Vasudevan, R. (2019), "Dynamic characterization of a CNT reinforced hybrid uniform and non-uniform composite plates", *Steel Compos. Struct.*, **30**(1), 31-46. https://doi.org/10.12989/scs.2019.30.1.031.

Masri, T., *et al*. (2018), "Characterization of new composite material based on date palm leaflets and expanded polystyrene wastes", *Constr. Build. Mater.*, **164**, 410-418. https://doi.org/10.1016/j.conbuildmat.2017.12.197.

Mirmehdi, S.M., Zeinaly, F. and Dabbagh, F. (2014), "Date palm wood flour as filler of linear low-density polyethylene", *Compos. Part B: Eng.*, **56**, 137-141. https://doi.org/10.1016/j.compositesb.2013.08.008.

Mitra, B., Basak, R. and Sarkar, M. (1998), "Studies on jute-reinforced composites, its limitations, and some solutions through chemical modifications of fibers", *J. Appl. Polymer Sci.*, **67**(6), 1093-1100. https://doi.org/10.1002/(sici)1097-4628.

Rao, Singiresu S. Vibration of continuous systems. Vol. 464. New York: Wiley, 2007.

Sarbu, A., *et al*. (2009), "Polystyrene wastes recycling by lightweight concrete production", *Revista de chimie*, **60**, 1350-1356.

Tabarsa, T., Khanjanzadeh, H. and Pirayesh, H. (2011), "Manufacturing of wood-plastic composite from completely recycled materials", *Key Eng. Mater. T. Tech. Publ.*, 62-66. https://doi.org/10.4028/www.scientific.net/KEM.471-472.62.

Wambua, P., Ivens, J. and Verpoest, I. (2003), "Natural fibres: can they replace glass in fibre reinforced plastics?", *Compos. Sci. Technol.*, **63**(9), 1259-1264. https://doi.org/10.1016/s0266-3538(03)00096-4

Zhang, M.Q., Rong, M.Z. and Lu, X. (2005), "Fully biodegradable natural fiber composites from renewable resources: all-plant fiber composites", *Compos. Sci. Technol.*, **65**(15-16), 2514-2525. https://doi.org/10.1016/j.compscitech.2005.06.018.

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