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Vibration of damaged bio-composite beams reinforced with random short Alfa fibers: Experimental and analytical investigations

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Abstract. This paper describes an investigation of the vibration of a cracked bio-composite beam reinforced with random short Alfa fibers using both analytical and experimental methods. The main novelty is the incorporation of local natural short fibers in the dynamic study of bio-based beams in the presence of a transverse crack. In addition, damping coefficient was predicted versus the crack length, crack position and fibers content. In the experimental model, tensile tests were made to predict Young's modulus and ultimate strength of specimens. After that, vibration tests were made to predict natural frequencies and damping coefficients versus crack depths, crack positions and fibers content. In the absence of similar experimental works on Alfa fibers, a simplified analytical model of flexural vibration has been developed to compare the results of experimental measurements. For different boundaries conditions, the linear fracture mechanics combined with Castigliano's theorem were used to estimate the local flexibility matrix at the cracked zone. For the natural frequencies, close agreement was found between the experimentally measured values and those given by the analytical model. From obtained results, we showed the increase in fiber content tends to reduce the strength and the natural frequencies of Alfa reinforced composite beams. Finally, we concluded that depth and position of the crack had a significant effect on the natural frequencies and damping coefficients of the bio-composite beam.

Keywords: Alfa fibers; cracked composite beam; flexural vibration; natural frequencies

1. Introduction

Bio-sourced composite materials have become a potential substitute to composite materials with synthetic fibers (Faruck *et al*. 2012, Pickering *et al*. 2016). Their low cost, moderate-specific ratio of stiffness, renewable resources, and environmentally friendly impact have motivated scientists and engineers to study them. In addition, bio-composite materials reinforced with natural fibers have attracted attention in the aircraft industry because of their notable acoustic absorption

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properties Balakrishnan *et al*. (2016), Khan *et al*. (2018). Other applications have also used these promising future materials, such as automotive, marine, aerospace, sporting consumer goods, and electronics industries. Interesting research also reflects the importance of growing bio-sourced materials reinforced with palm. (Benzidane *et al*. 2018, hemp (Dalmay *et al*. 2010), Alfa (Khaldi *et al*. 2016) and sisal (Li *et al*. 2000)).

Throughout literature, composite materials reinforced with Alfa fibers are of significant importance. The advantage of the incorporation of Alfa fibers in polymer matrix is the possibility of their being used as reinforcement to enhance the mechanical proprieties of entire composite materials. The hydrothermal and mechanical could be improved by using thermal and chemical treatments effectively. The main limitation of the use Alfa fiber in structures caused by the huge variation in their physical properties El-Abbassi *et al*. (2020). Arrakhiz *et al*. (2012, 2013) investigated the effect of Alfa fibers on the mechanical properties of composite materials such as tensile, flexural and torsion properties under different chemical treatments. In addition, Ben Brahim and Ben Cheikh (2007) studied the influence of extraction processes, fibers content, and orientation on the mechanical behavior of Alfa/Polyester composite specimens. To improve their mechanical properties, the combined use of Alfa fibers with a polymer resin has been reported by several authors in thermo-mechanical and chemical treatments (Bessadok *et al*. 2009, Hanana *et al*. 2015, El-Abbassi *et al*. 2015).

To illustrate the crystallization capacity and chemical composition (Paiva *et al*. 2007, Trachea *et al*. 2014). The prepared bio-composites were also investigated by chemical and morphological analysis, such as frustrated total internal reflection and differential scanning calorimetry. Few works have focused on the mechanical characterization of bio-composites using dynamic analysis technique. which considered as an indispensable tool for predicting the mechanical characteristics and dynamical properties of natural fiber-reinforced composite materials. Among this research, Saba *et al*. (2016) reviewed the dynamic mechanical properties of natural fiber reinforced polymer composites. Zaman *et al*. (2010) analyzed the effect of natural fibers fraction on the composite mechanical properties and its dynamic characteristics. Pothana *et al*. (2003) investigated the dynamic mechanical properties of short banana fiber reinforced polyester composites. After that Kumar *et al*. (2014) proposed a study on the free vibration of a composite beam reinforced with short randomly oriented sisal and banana polyester. they found that fiber length and weight fraction affect significantly the mechanical and damping properties of composites. Ben Abderrahmane and Ben Cheikch (2008) used a dynamic mechanical analyzer to study the mechanical thermal proprieties of chemically modified Alfa combined with unsaturated polyester resin. Recently, a new nonlinear dynamic models have proposed by Li *et al*. (2018,2019,2020) to assess effectively mechanical behavior of fiber reinforced composite thin plate where the first model using amplitude dependent properties and the second using the temperature dependence in thermal environment. Recently, a damping model of fiber reinforced composite is included with the consideration of amplitude-dependent property, using the Jones–Nelson nonlinear theory in conjunction with the classical laminated theory.

Damage detection is a research interest subject in structural health monitoring (SHM), which uses the change in the dynamic characteristics of cracked structures as a potential damage indicator. The presence of cracks in structures changes the natural frequencies, shape modes, and consequently, its dynamic response. Due to this, experimental and analytical models have proposed by several researchers as vibration-basted identification techniques. Among, Petrone *et al*. (2017) studied the change in the structural intensity of damage plate based on the vibration techniques. Petrolo *et al*. (2015) proposed advanced finite element models based on Carrera

Unified Formulation (CUF) to study the free vibration of damaged beams. Gillich *et al.* (2019) developed a new damage detection which permits assessing damages in beams used a change in the temperature due to axial forces. Khatir *et al.* (2018) presented an inverse algorithm based on Proper Orthogonal Decomposition (POD) and Radial Basis Functions (RBF) for single and multiple cracks identification in plate structures. After that, the same authors (Khatir *et al.* (2019a)) combined the Extended Finite Element (XFEM) and the eXtended Iso Geometric Analysis (XIGA) with two optimization techniques to predict accurately the damage in structure. To quantify the damage evolution in laminated composite plates, they (Khatir *et al.* 2019b) proposed an Artificial Neural Network (ANN) combined with Particle Swarm Optimization (PSO).

The dynamic behaviour of cracked composite beams with synthetic fibers has attracted many researchers. According to literature, Krawczuk *et al.* (1997) predicted the natural frequencies of a cracked cantilever composite beam, they proposed an algorithm to find the flexibility coefficients matrix of a composite beam with a single transverse fatigue crack. They noted that the decrease of the natural frequencies depends not only on the crack location and its depth but also on the material properties. Wang *et al.* (2005) proposed a new mathematical model for computing the natural frequencies and their corresponding mode shapes of a fiber-reinforced composite beam under coupled flexural–torsion loading. Kisa (2004) studied the effect of a crack on the natural frequencies of a cantilever composite beam, using finite element associated with component mode synthesis method. The Generalized Differential Quadrature (GDQM) method has been used by Daneshmehr *et al.* (2013) to study the free vibration of a cracked composite beam, based on the first order shear deformation theory (FSDT). Recently, Kim *et al.* (2019) proposed a new modeling method based on the Jacobi-Ritz method and the first-order shear deformation theory for vibration analysis of cracked laminated composite beam with arbitrary boundary condition. All experimental and numerical investigations cited above confirm that the presence of cracks in the composite beam introduces a local flexibility around the crack tip and changes its dynamical characteristics.

In fact, studies dealt with free vibration analysis of bio-composite beams are very rare. From previous studies, Abral *et al.* (2014) studied the effect of vibration duration of high ultra-sound applied for bio-composite materials while gelatinized on its properties. The free vibration behavior of hybrid polymer composite beam reinforced randomly with short sisal and banana natural fibers has been investigated by Rajesh *et al.* (2016). Monti *et al.* (2017) reported experimental and numerical results of the flexural vibration behavior of a bio-based sandwich panel reinforced by flax fibers and balsa wood core. The vibration and damping performances of flax fiber reinforced composites with an inter-leaved natural visco-elastic layer was investigated by Daoud *et al.* (2017). Experimental investigation of mechanical and dynamical characteristics of pineapple leaf fiber reinforced composites was studied by Senthilkumar *et al.* (2019). The vibration characteristics such as natural frequency, damping factor, and logarithmic decrement are found by Fast Fourier Transform (FFT) analyzer. The dynamical behavior of bio-based natural fibers is studied solely for an intact beam.

Due to limited work on the vibration behavior of cracked bio-composite beams, the effect of a transverse crack on the free vibration of bio-composite beams reinforced with short Alfa fibers is proposed in this study, which theoretically and experimentally evaluates the natural frequencies for the different fibers' content, crack depth, and position**.** An analytical method has been developed using Euler-Bernoulli model beam. Furthermore, the proposed beam is thin and having a lower geometric ratio h/L (thickness/length). According to the study proposed by Majkut (2009), the Timoshenko model is recommended, if $(h/L)\geq 10\%$. Otherwise, the Euler-Bernoulli model can be used because the shear effect tends to disappear. In addition, Zhang *et al.* (2020) found that there is no difference at lower frequencies given by both models (Euler-Bernoulli and Timoshenko). A slight difference appears only at higher natural frequencies. In comparison with synthetic fiber reinforced composite beams (glass or carbon fibers), natural fiber-based composites have rather weak mechanical characteristics (i.e., they are less stiff). This low stiffness produced lower natural frequencies. However, there is damping factor which increased in bio-composite materials Merzoug *et al.* (2020). Therefore, the effect of shear does not have a large magnitude at natural frequencies.

Using the general solution for clamped, free, or hinged beams, the natural frequencies are determined. For the experimental procedure, extraction and thermal treatment have achieved better technical fibers. Next, tensile tests are performed to predict the mechanical properties of the treated Alfa fibers, using a universal test machine with a 5kN load cell. A vibration analyzer is used to evaluate the natural frequencies of a cracked beam. To find the natural frequencies, the beam is excited with a hammer at different positions. The data acquisitions are recorded and stored using a SO analyzer. Experimental and theoretical results are compared, and the findings are revealed.

2. Theoretical model

2.1 Estimation of effective elastic modululs

The composite material is made from a mixture of isotropic matrix (epoxy resin), and randomly distributed short fibers. The theoretical model of Halpin *et al.* (1969) is used in this study to determine the elastic properties of bio-composite materials.

$$E = E_m\left[\frac{3}{8}\left(\frac{1+\xi\eta_L V_f}{1-\xi\eta_L V_f}\right)+\frac{5}{8}\left(\frac{1+2\eta_T V_f}{1-\eta_T V_f}\right)\right] \tag{1}$$

where

$$\eta_L = \frac{E_f / E_m - 1}{E_f / E_m + 2l_f / d_f} \tag{2}$$

$$\eta_T = \frac{E_f / E_m - 1}{E_f / E_m + 2} \tag{3}$$

$$\xi = 2l_f / d_f \tag{4}$$

E_f , E_m are the elastic modulus of the fiber and the matrix, respectively, V_f is the volume fraction of the fibers, l_f and d_f are length and diameter of a fiber, respectively. in the present paper (fibers are 0.1 mm to 0.5mm in diameter and 0.86 mm to 4.5 mm in length).

2.2 Vibration of a cracked bio-composite beam

A cantilever composite beam reinforced with distributed short Alfa fibers, having an uniform cross-sectional, and a crack which is supposed to be open with various uniform depths a (b/3, b/2

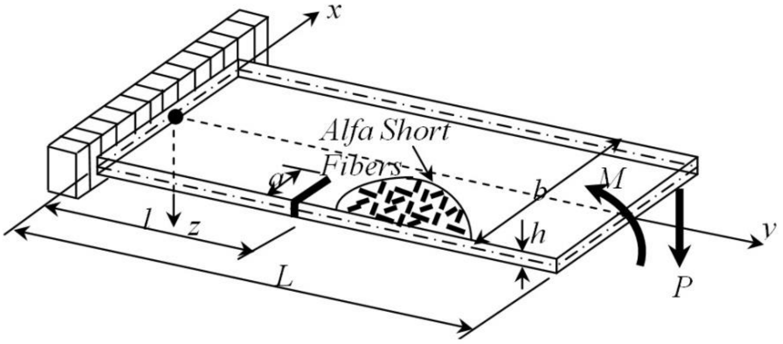


Fig. 1 Bio-based composite cantilever beam with an open edge crack

and 2b/3) located at various lengths (L/3, L/2 and 2L/3) Fig. 1. The geometrical characteristics of the composite beam are the length (L), height (h) and width (b). The beam is subjected to bending load; where P is a shear force and M is a bending moment.

According to Castigliano's theorem and Paris' equation the local flexibility matrix [C] of an open edge cracked beam is given by Wang *et al.* (2005):

$$C_{ij} = \frac{\partial U_i}{\partial P_j} = \frac{\partial^2}{\partial P \, \partial M} \int_{-h/2}^{h/2} \int_0^a J(\alpha) \, d\alpha \, dz \tag{5}$$

By considering shear force P and bending moment M, the strain energy release J is reduced to (Nikpour and Dimarogonas 1988):

$$J = D_1 K_I^{\,2} + D_3 K_{III}^{\,2} \tag{6}$$

where

$$K_I = \frac{12M}{bh^3} \sqrt{\pi a} \; F_I \left(\frac{a}{b} \right) ; \; K_{III} = \frac{P}{bh} \sqrt{\pi a} \; F_{III} \left(\frac{a}{b} \right) \tag{7}$$

$$F_I \left(\frac{a}{b} \right) = \sqrt{\frac{\tan s}{s}} \frac{\left[0.752 + 2.02 \left(\frac{a}{b} \right) + 0.37 \left(1 - \sin s \right)^3 \right]}{\cos s} \quad ; \quad F_{III} \left(\frac{a}{b} \right) = \sqrt{\frac{\tan s}{s}} \tag{8}$$

where $s = \pi a / 2b$

K_I and K_{III} denote the stress intensity factors of mode I and III.

The final local flexibility is obtained by the substitution of Eq. (6) in Eq. (5)

$$C_{ij} = \frac{\partial^2}{\partial P \, \partial M} \int_{\frac{-h}{2}}^{\frac{h}{2}} \int_0^a \left[D_1 K_I^{\,2} + + D_{12} K_I^{\,2} + D_3 K_{III}^{\,2} \right] d\alpha dz \tag{9}$$

D_1, D_{12} and D_3 are the constants given by Nikpour, K., Dimarogonas, A. (1988) and Wang *et al.* (2005).

Only shear force (P) and bending moment (M) components are considered in the local flexibility matrix yield:

$$\begin{aligned} C_{11} &= \frac{2\pi D_3}{b^2 h}\int_0^a \alpha\left[F_{III}\left(\frac{\alpha}{b}\right)\right]^2 d\alpha = \frac{2\pi D_3}{h}A_{III} \\ C_{22} &= \frac{24\pi D_1}{b^2 h^3}\int_0^a \alpha\left[F_{I}\left(\frac{\alpha}{b}\right)\right]^2 d\alpha = \frac{24\pi D_1 Y_I^2}{h^2}A_{I} \end{aligned} \tag{10}$$

To study the free vibration, the differential equation governing the flexural behavior is given as follows

$$EI\frac{\partial^4 w}{\partial y^4} - m\frac{\partial^2 w}{\partial t^2} = 0 \tag{11}$$

where; *EI*, m and w denote the flexural rigidity, the mass and the transverse displacement of beam, respectively.

Using the variable-separation method $w(y,t)=W(y)e^{iwt}$, Eq. (11) will be :

$$EI\,W^{iv} - m\omega^2 W = 0 \tag{12}$$

The general solution in the normalized form is given by Banerjee (2001).

$$W(\xi) = A_1\cosh\lambda\xi + A_2\sinh\lambda\xi + A_3\cos\lambda\xi + A_4\sin\lambda\xi \tag{13}$$

where $\lambda = \left(m\omega^2 L^4/EI\right)^{1/4}$ and ξ=x/L.

By successive derivation of Eq. (13), the rotation θ (ξ), the bending moment M (ξ) and the shear force $S(\xi)$ take the forms. The cracked beam is divided in two sub-beams at a cracked zone.

$$0 \le \xi \le \xi_c \quad W_1(\xi) = A_1\cosh\lambda\xi + A_2\sinh\lambda\xi + A_3\cos\lambda\xi + A_4\sin\lambda\xi \tag{14}$$

$$\xi_c \le \xi \le 1 \quad W_2(\xi) = A_5\cosh\lambda\xi + A_6\sinh\lambda\xi + A_7\cos\lambda\xi + A_8\sin\lambda\xi \tag{15}$$

For the two sub-beams, we have eight unknowns. Consequently, eight conditions are required to resolve the problem. Additional continuity conditions at a cracked zone are

$$M_1(\xi_c) = M_2(\xi_c) \tag{16}$$

$$S_1(\xi_c) = S_2(\xi_c) \tag{17}$$

$$W_2(\xi_c) = W_1(\xi_c) + c_{11}S_1(\xi_c) \tag{18}$$

$$\theta_2(\xi_c) = \theta_1(\xi_c) + c_{22}M_1(\xi_c) \tag{19}$$

Using the boundary conditions for the cantilever beam, we obtained the characteristic equation:

$$\left[B\right]\left\{A\right\}=\left\{0\right\} \tag{20}$$

$\{A\}=\{A1, A2, A3, A4, A5, A6, A7, A8\}^T$ is a vector composed of eight unknowns and $[B]$ represents 8*8 characteristic matrix given as a function of natural frequency. By considering the *Det[B]=0*, the natural frequencies were obtained. For more details related to the mathematical development, see Banerjee (2001) and Wang *et al*. (2005).

3. Materials and experimental testing

3.1 Materials and processing

To improve the mechanical properties of Alfa natural fibers. Mechanical and thermo-mechanical treatments were conducted and effects on tensile strength were investigated. To reach this objective, Alfa fibers were treated using the following steps: first, all impurities (such as dead leaves, straw, and dust) were removed from the raw materials. Second, both mechanical and thermo-mechanical treatments were conducted to separate properly the elementary fibers and also enhance their mechanical properties. Technical fibers were extracted using a metal brush, chopped to a length of 30mm, and soaked in heated water at a maximum temperature of 160°C for 1 hr, 2hrs, and 3 hrs.

Three measurements of diameter were taken for each single fiber at different regions (upper, lower, and middle), using an optical microscope (OM) equipped with a digital camera and controlled by the Motic Images software. The density was obtained by weighing 10 specimens.

Fig. 2 shows the dispersion of the diameter, this is due mainly to the variation from upper to lower extremity of Alfa fiber diameter. It is worth mentioning that the thermo-mechanical treatment decreases the diameters of fibers Placet (2009). It is also noted that the thermomechanical treatments affect the fiber diameter because at elevated temperatures, there is thermal expansion. The fibers become more porous, but with a quantity of pectin the impurities will be easily eliminated. Consequently, the diameter of fibers is reduced.

3.2 Fibers tensile test analysis

It is evident from the literature that the benefit of using vegetable fibers varies from fiber to fiber. This will depend on the fiber's structure, chemical and physical composition, and mechanical characteristics. Other factors include the proportion of cellulose and the degree of surface polymerization. There are common properties these fibers share that are also beneficial. Advantages include having low density and low abrasive behavior and positive renewable mechanical, acoustic, and thermal properties. In particular, there are ecological advantages when using vegetable fibers due to their hydrophilicity and biodegradability. Table 1 shows that, compared to sisal and jute, Alfa fibers' characteristics and performance are similar. The cost of a fiber is based on its regional availability. Since there is an abundance of Alfa in Algeria , it is available at a low cost; as a result, along with its low density, it is frequently used in industry.

The mechanical properties (stress, strain failure, and Young's modulus) of the fibers at a gauge length of 30 mm were measured according to the ASTM D 3822-01 standard, using a universal

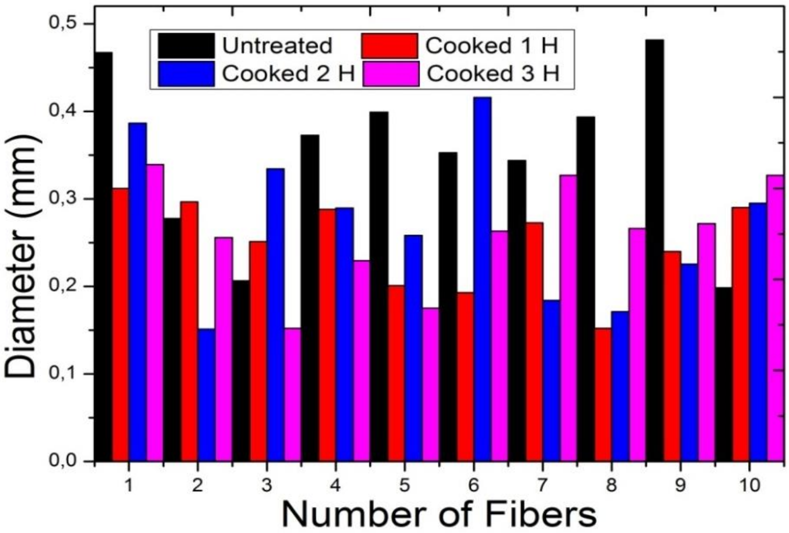


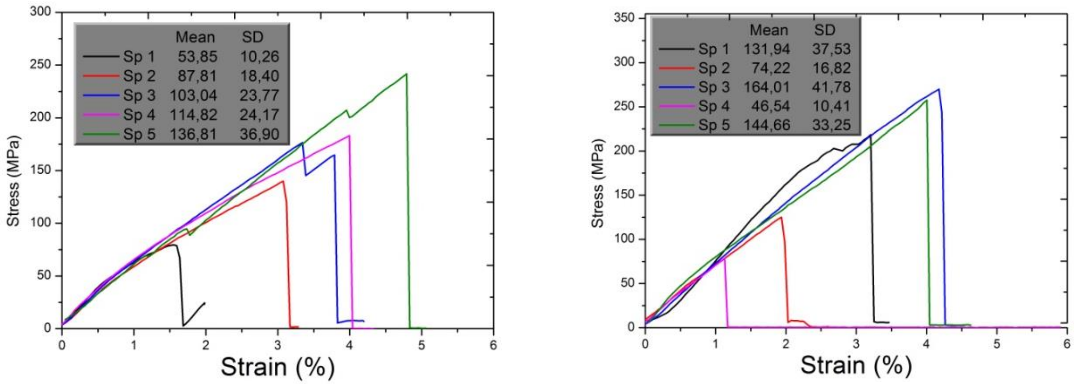
Fig. 2 Diameter variation versus number of fibers

Table 1 Tensile properties of natural fibers (Akil *et al.* 2014, Arrakhiz *et al.* 2012 and El-Abbassi *et al.* 2020)

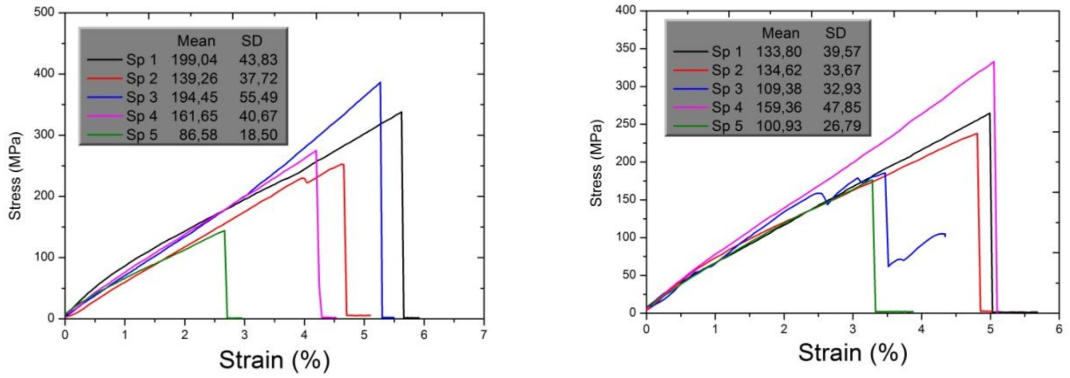
Type of fiber	Cellulose (wt%)	Density (g/cm^3)	Tensile strength (MPa)	Young's Modulus (GPa)	Tensile stain (%)
Alfa	45	1.2	150-450	5-23	1.5-4.5
Flax	71	1.5	345-1500	23.9-27.6	1.6-3.2
Sisal	66-78	1.45	468-700	9.4-22	2.0-3.7
Coir	32-43	1.15-1.46	120-304	4-6	15-40
Ramie	68.6–76.2	1.55	400-938	44-128	1.2-8
Jute	61–71.5	1.3-1.49	393-780	13-30	1.9
Hemp	70–74	1.47-1.49	690	60-70	1.6-4
Oil palm	65	0.7–1.55	70.9-248	14-67	14-25

machine with a 5 KN load cell. During the tests, the clamps were adjusted manually by mechanical springs equipped with a self-concentric alignment. The tensile tests were performed at a constant speed of 1 mm/min. All tests were conducted at a room temperature of 21°C and 65% relative humidity.

Fig. 3 shows the stress-strain curves of the tested fibers at 25 mm a gauge length. The tensile samples were extracted during the mechanical and thermomechanical processes. All curves exhibited a brittle behavior under quasi-static testing. and a maximum value corresponding this failure, was noted for all curves. In mechanical and thermomechanical processes, a notable dispersion was observed caused by a large number of random factors. This is due to the fact that with natural fibers there is often a significant variation in their diameter and irregularity along their length. Furthermore, the cross-section is not perfectly cylindrical Benzidane *et al.* (2018). All of these factors bring about this important dispersion in the mechanical behavior of natural fibers (Amroune *et al.* (2015), Paiva *et al.* (2007)). Such dispersion; However, is not observed with synthetic fibers. Table 2 shows the mean average mechanical properties of cooked and uncooked



(a) Untreated fibers (b) Cooked for 01 hour



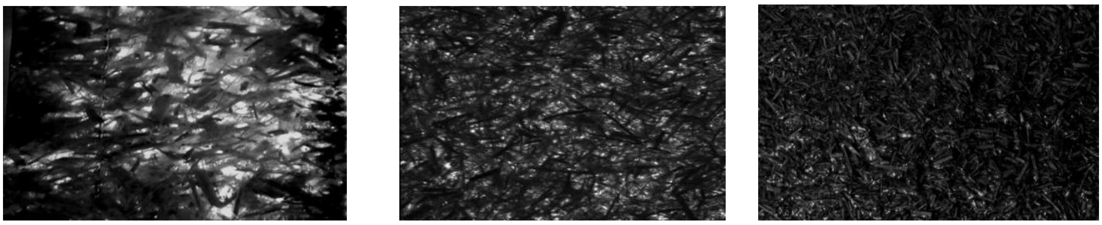
(c) Cooked for 02 hours (d) Cooked for 03 hours

Fig. 3 Stress-strain curves of treated and untreated Alfa fibers

Table 2 Average mechanical properties of untreated and cooked technical fibers

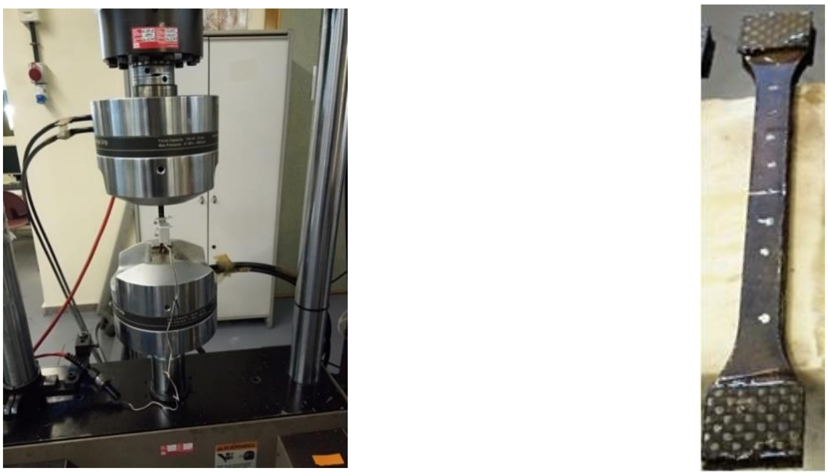
	Tensile modulus GPa	Ultimate strength MPa	Ultimate strain (%)	Mean (MPa)	SD (MPa)
Untreated	7.49	163.42	3.48	99.27	22.71
Cooked 1 Hour	8.27	189.82	2.94	112.27	36.16
Cooked 2 Hours	9.28	277.96	4.58	156.19	39.24
Cooked 3 Hours	8.61	239.32	4.33	127.61	31.16

Alfa fibers and the standard deviation of these data. A significant change in tensile strength is noted with cooking times. Untreated Alfa fibers have lower average tensile modulus compared to the treated Alfa fibers 7.49 GPa vs. 9.28 GPa at cooking time up to 02 Hours and the average ultimate strength increases from 163.42 MPa to 189.82 MPa; However, for specimens cooked up to 3 Hours, there is small decrease in the Young's modulus (8.61MPa). Strain failure is slightly affected by heating time. The Alfa fibers performed best when cooked at 160°C for two hours. When the cooking time was increased, the mechanical properties of the fibers showed a slight degradation. This can be explained by the hot water particles being able to infiltrate the fibers more quickly (water absorption was accelerated). At elevated temperatures, the fibers become



(a) 30% of fibers (b) 45% of fibers (c) 60% of fibers

Fig. 4 Electronic camera view of distributed fibers in matrix versus different weight fractions (30, 45 and 60%)



(a) Servo-hydraulic machine (b) Bio composite Specimen

Fig. 5 Specimens and tensile test

more porous and, therefore, the impurities from the pectin present are easily eliminated. But, if the cooking time is increased further, the hemicelluloses and celluloses can be damaged. Therefore, it is essential to control the cooking time to ensure the best performance of the fibers.

3.3 Specimens preparation and tensile tests

To predict mechanical properties of the prepared reinforced bio-composite beam, three fiber contents (30%, 45%, and 60%) were impregnated in Medapoxy STR resin. Fig. 4 shows the distributed fibers, using an electronic camera. The unit fibers/resin was judiciously mixed and poured in a normalized mold to fabricate the specimens. Using the MTS 810 servo-hydraulics testing machine with 100 KN load cell, tensile tests were performed following ASTM D3822-01 norm Fig. 5(a). In order to ensure a good adherence, and avoid the slip phenomenon between specimens and machine jaws, plastic sheets were bonded on the both faces of specimens Fig. 5(b).

The stress-strain curves of bio-composite beams, constituting 30% Alfa fibers and 70% STR epoxy resin,are shown in Fig. 6. They indicate stress-strain curves typical of the monotonic tensile test. The general behavior of the composite is viscoelastoplastic, which could be attributed to the behavior of the non-linear matrix and fiber. A small dispersion was observed for the three tested

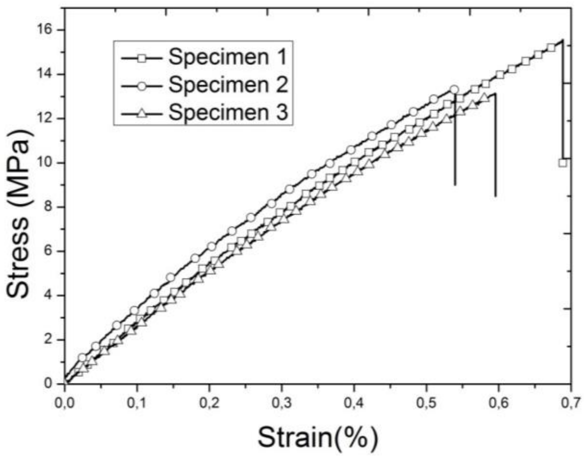


Fig. 6 Stress-stain curves of bio-composite beam with 30% of Alfa fibers and 70% of Epoxy resin.

Table 3 Mechanical properties of bio-composite beam with three Alfa fibers contents

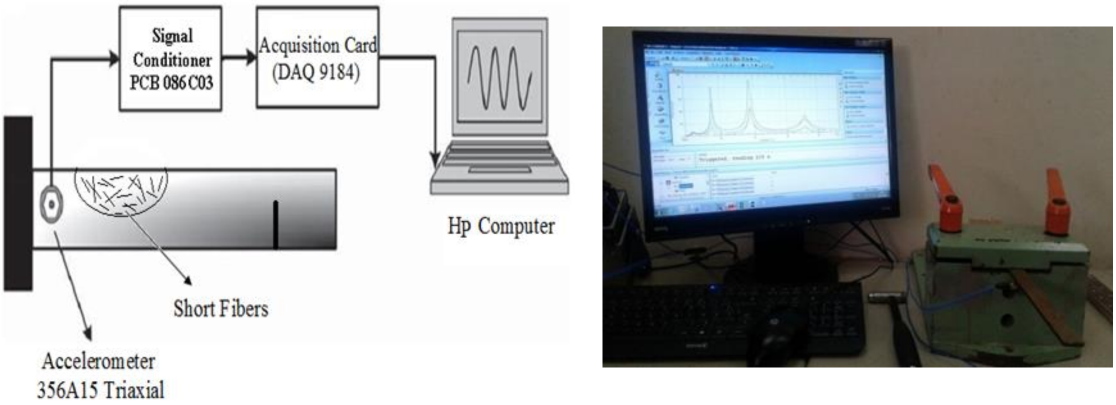
	Tensile modulus GPa	Ultimate strength MPa	Ultimate strain
30 % Alfa+70% Resin	2.682	13.938	0.605
45 % Alfa+55% Resin	1.401	12.022	0.525
60 % Alfa+40% Resin	0.991	9.239	0.432

specimens (Benzidane *et al.* (2018), Hamamousse *et al.* (2019)). This dispersion is caused by variations in the fibers' length, diameter, and orientation. Furthermore, the distribution of fibers in the matrix is not homogeneous, as shown in Fig. 4. We noted that the fiber content clearly affected bio-composite specimens. The mechanical properties of bio-composite beam with three Alfa fiber contents are given in Table 3.

3.4 Experimental procedure of natural frequencies

To determine the experimental natural frequencies of bio-composite beam, the following scenario was established: Firstly, specimens with dimensions (200 x 20 x 5 mm^3) were cut from the prepared plate (dimensions: 200 x 200 x 5 mm^3) versus three volume fractions (30%,45%, and 60%). Secondly, an intermediate crack was created Fig. 7(a) with three depth ratios a/b (0.25,0.5 and 0.75) and three length ratios l/L (0.25, 0.5 and 0.75).

For experimental tests, an appropriate dispositive was realized Fig. 7(b). which is composed of FFT analyzer equipped with an acquisition card (DAQ 9184), a piezoelectric accelerometer (Model 356A15 Triaxial) with a sensitivity of 98.8 mV/g, HP computer and impulse force hammer (Model 086C03) with the sensitivity of 2.325 mV/N. (Fig. 7(b)). Moreover, an analyzer is associated with resident software and signal processing (SO Analyzer m+p International). The acquisition card is equipped with a processor allowing the simultaneous acquisition of signals of 5000 Hz during 0.4s. To ensure the suitability of specimen fixation, all tested specimens were properly clamped at one end using a steel-frame. The bio-composite beams are excited



(a) Schematic layout (b) Vibration set-up of a cracked beam

Fig. 7 Experimental dispositive installation to measure the natural frequencies

perpendicularly with an impact hammer. The average value is considered by taken three measurements of flexural natural frequencies for each individual specimen.

4. Results and discussions

In this section, we have analyzed the effect of the accelerometer position on the magnitude of the natural frequencies measured experimentally. Indeed, this accelerometer mass is relatively large (12 g) compared to that of the samples (16-18 g). Thus, the first three natural frequencies have been plotted in Fig. 8 at three accelerometer positions (fixed, middle, and free end). Compared to the fixed end, the natural frequencies are reduced when the accelerometer is positioned at the middle and free end. This reduction caused by the accelerometer mass becomes more important with higher mode shapes. For the third mode, the frequency that is 538 Hz for an accelerometer at the fixed end will only be 448 Hz at the middle. We can suggest mounting the accelerometer at the fixed end because its mass has less influence on the natural frequencies. This choice is justified because this added mass creates a secondary bending moment, which appears when the accelerometer comes close to the free end. The same observation was made by Karaagac *et al.* (2009), where he recommended bringing the accelerometer mass closer to the fixed end to minimize its effect.

Fig. 9 shows the effect of a crack (0.5 L and 0.4 b) on natural frequencies of the cracked composite beam. It is noted that the presence of cracks reduces the natural frequencies. As consequence, the rigidity of bio-composite beam is locally influenced at a cracked zone.

For analytical results, a MATLAB programme is used to compute the flexural natural frequencies of the cracked bio-composite beams with different fibre contents. Geometrical dimensions and the measured mechanical properties were used. To prove the validity and efficiency of the experimental analysis, the first three natural frequencies were computed as a function of fibre contents and the relative crack position. From Table 4, it can be noted that analytical and experimental results are in agreement. The maximum relative error is less than 15%. Higher differences are observed for the third natural frequency. The natural frequencies are almost

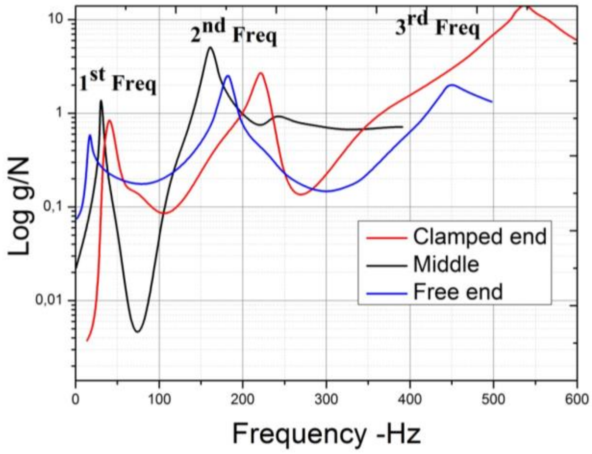


Fig. 8 Stress-stain curves of bio-composite beam with 30% of Alfa fibers and 70% of Epoxy resin

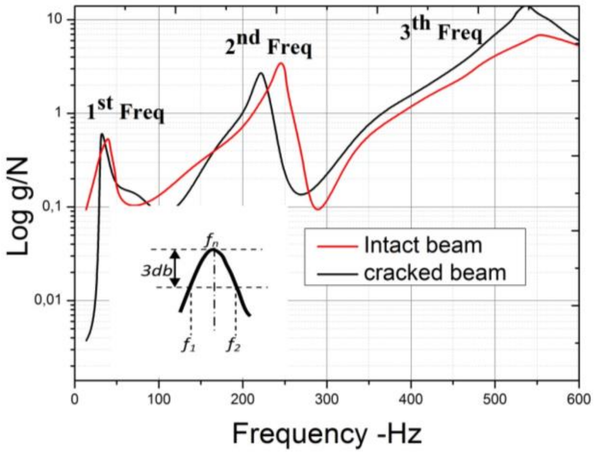


Fig. 9 First three measured natural frequencies of intact and cracked beam

reduced when the crack is located closer to a clamped edge due to maximum bending moment which is more at the fixed end Sahu *et al.* (2019), This decreases are more pronounced for the second and third natural frequencies. It is explained by the stiffness loss. For example, fibers content of 30%, the third natural frequency is 450.94 Hz for the relative crack at 0.25L becomes 487.05 Hz for the relative crack at 0.75L. In addition, slightly higher frequencies compared the bio-composite with 30% of Alfa fibers content to 45% and 60 % fibers content. This observation is confirmed by other papers (Rao *et al.* 2007, Zaman *et al.* 2010, Palanikumar *et al.* 2019).

4.1 Effect of crack depth and position

The first three natural frequencies of cracked bio-composite beam versus crack depths and fiber contents are reported in Table 5. As compared to un-cracked beam, the presence of a crack causes a slight variation in the natural frequencies. This variation becomes more sensitive to an increase

Table 4 Experimental and analytical natural frequencies versus fibers content and crack positions

Natural frequencies (*Hz*) Fibers content (30%)									
Crack position *(l/L)*	0.25			0.5			0.75		
	Exp.	Ana.	Dif (%)	Exp.	Ana.	Dif (%)	Exp.	Ana.	Dif (%)
1st Freq.	39.56	35.65	9.88	39.56	39.75	0.48	40.625	41.49	2.12
2nd Freq.	224.9	259.59	15.42	251.9	254.25	0.93	256.25	242.79	5.25
3rd Freq.	591.3	660.92	11.77	682.9	683.59	0.10	581.25	615.55	5.90
Natural frequencies (*Hz*) Fibers content (45%)									
Crack position *(l/L)*	0.25			0.5			0.75		
	Exp.	Ana.	Dif (%)	Exp.	Ana.	Dif (%)	Exp.	Ana.	Dif (%)
1st Freq.	30	28.92	3.6	38	32.25	15.13	33.33	33.67	0.01
2nd Freq.	201.33	179.35	10.91	218	210.62	3.38	211.33	196.98	0.06
3rd Freq.	534	536.24	0.41	558	593.07	6.28	558.66	599.42	0.07
Natural frequencies (*Hz*) Fibers content (60%)									
Crack position *(l/L)*	0.25			0.5			0.75		
	Exp.	Ana.	Dif (%)	Exp.	Ana.	Dif (%)	Exp.	Ana.	Dif (%)
1st Freq.	24.688	25.40	2.88	30	29.27	2.43	29.56	29.72	0.54
2nd Freq.	210	184.96	11.92	198	175.43	11.39	172.99	181.16	4.72
3rd Freq.	450.94	470.92	4.43	520	514.03	1.14	438.59	487.05	11.04

in the crack depth. Moreover, the natural frequencies are significantly reduced with an increase in the fibers content. From experimental results, the first natural frequency varies from 39.6 Hz with 30% fibers content until 32.5 Hz with 60% fibers content. Similarly, for a given fibers content, the increase in the crack depth generates a small reduction in the natural frequency. However, this reduction becomes more evident, especially for the third frequency. In the case of composite beam with 30% of fibers, the first natural frequency which is 38.75 Hz with crack depth (0.25%) will be only 37.81Hz, when the crack depth reaches (0.75%). Contrary, the third natural frequency which is 650 Hz with crack depth (0.25%) is reduced until 454.0 Hz, when the crack depth reaches 0.75%.

But, for some cases the difference between the experimental measurements and the analytical model is quite remarkable. This difference can be caused by a significant dispersion in results of the bio-composites characterization. Since the average mechanical properties obtained from experimental tests are used as data to feed the analytical model, it is obvious that these values do not correspond to each samples tested for vibration. Furthermore, it is clear that the distribution of fiber in the matrix Fig. 4 is not homogeneous. Therefore, the fibers content used in the analytical model does not reflect reality, because we considered an homogeneous distribution. Otherwise, the damping effect obtained experimentally is not considered in the analytical model.

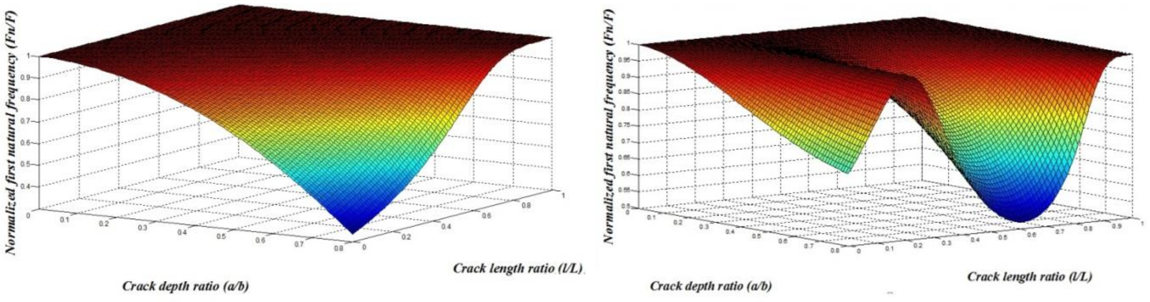
Table 5 Experimental and analytical natural frequencies versus fibers content and crack depth

Natural frequencies (*Hz*) Fibers content (30%)												
Crack depth (*a/b)*	Uncracked beam (0)			0.25			0.5			0.75		
	Exp.	Anal.	Diff (%)	Exp.	Ana.	Diff (%)	Exp.	Ana.	Dif (%)	Exp.	Anal.	Diff (%)
1stFreq	39.6	39.4	0.50	38.7	39.1	1.02	37.8	37.	2.11	37.8	31.4	16.9
2ndFreq	249.0	247.0	0.80	247.5	237.7	4.12	227.0	209.1	7.88	226.2	215.1	15.8
3rd Freq	650	691.6	6.4	558.	691.6	19.3	539.5	691.5	28.1	454.0	691.2	52.2
Natural frequencies (*Hz*) Fibers content (45%)												
	Uncracked beam (0)			0.25			0.5			0.75		
Crack depth *(a/b)*	Exp.	Ana.	Diff (%)	Exp.	Ana.	Diff (%)	Exp.	Ana.	Diff (%)	Exp.	Ana.	Diff (%)
1stFreq	36.7	33.5	8.71	33	33.1	8.71	33.3	32.2	3.30	31.25	26.9	13.92
2ndFreq	212.1	206.9	2.45	206.7	203.8	1.40	207.3	179.3	13.5	194.5	132.2	32.03
3rd Freq	558.4	593.2	6.23	531.9	579.3	8.91	526.4	593.1	12.6	475.	592.8	24.8
Natural frequencies (*Hz*) Fibers content (60%)												
Crack depth *(a/b)*	Uncracked beam(0)			0.25			0.5			0.75		
	Exp.	Ana.	Diff (%)	Exp.	Ana.	Diff (%)	Exp.	Ana.	Diff (%)	Exp.	Ana.	Diff (%)
1stFreq	32.5	29.7	8.61	29.7	29.6	0.33	30.1	29.3	2.65	29.7	28.7	3.36
2ndFreq	189.7	189.1	0.31	183.4	182.6	0.43	198.0	175.4	11.4	170.0	161.8	4.82
3rd Freq	475.3	520.7	9.55	457.5	515.9	12.7	520.1	514.0	1.17	454.1	510.	12.3

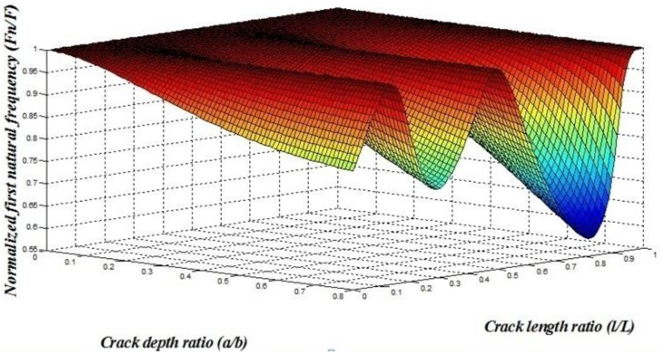
The large discrepancies could also explained by the instability occurred in experimental measurement for a large crack length (0.75%). However, this phenomena has not been considered in the Analytical method.

4.2 Normalized natural frequencies

The variation of the three normalized natural frequencies of cantilever cracked bio-composite beam as a function of crack depth (a/b) and crack position (l/L) are plotted in Fig. 10, where the fiber content herein is assumed to be 30%. It is clearly seen that the natural frequencies have higher values for a small crack, which is located at the maximum position from clamped edge. Much interesting results are observed for maximum crack depth ratio, when the crack is located near to a fixed end, the natural frequencies are intensively reduced. For the first frequency, this reduction is more important for small crack length. However, for the second and the third frequencies, the lowest values appearing at the distances of (0.63L), and (0.21L, 0.81L),



(a) 1st frequency (b) 2nd frequency



(c) 3rd frequency

Fig .10 Effect of crack depth and position on the normalized natural frequencies for 30% of fibers

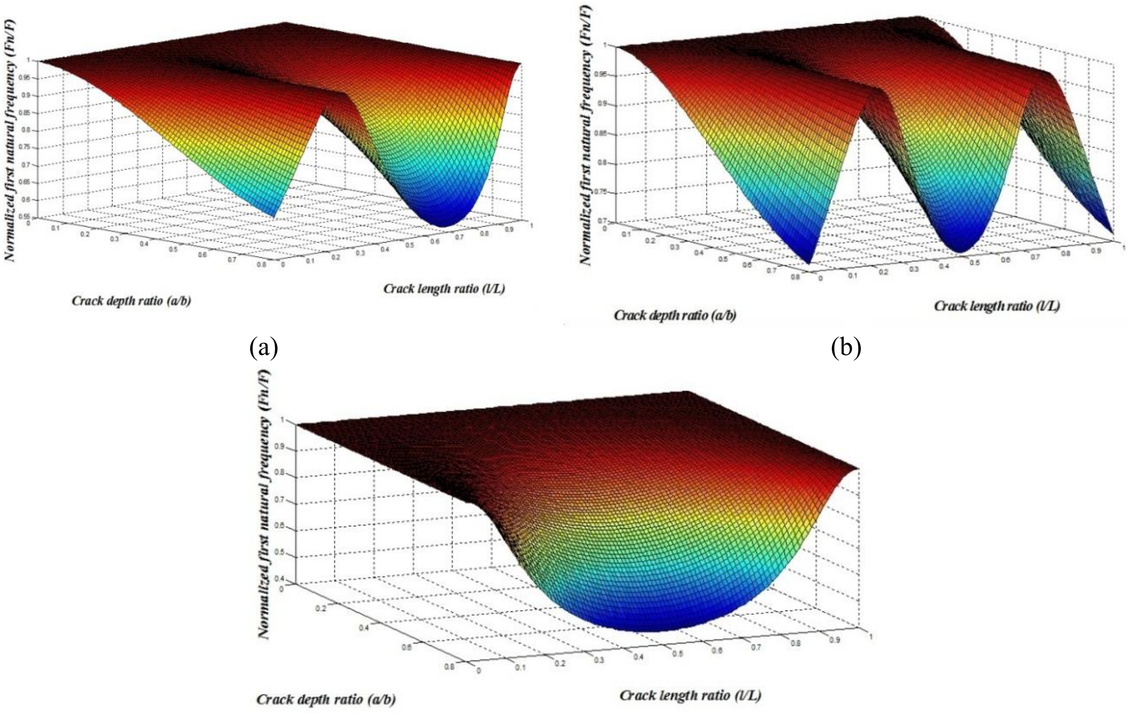
Table 6 Effect of boundary conditions on the natural frequencies for 30% of fibers content having crack length (0.4 L) and depth (0.5b)

Natural frequencies (Hz)	Clamped - Free (C-F)	Clamped-Clamped (C-C)	Clamped-Hinged (C-H)	Hinged-Hinged (H-H)
1st Frequency	38.34	243.05	173.05	105.42
2nd Frequency	233.18	685.05	534.38	433.25
3rd Frequency	687.39	1390.20	1230.20	995.36

respectively. Due to fact, that the crack is situated closer to the mode shape nodes of a beam (Ghoneam (1995), Wang *et al*. (2005)).

4.3 Effect of the boundary conditions

In Table 6, the first natural frequencies of the cracked composite beam are given versus various boundary conditions, with fiber content (30%), crack length (0.4 L) and depth (0.5b). This Table shows the comparison of the first natural frequencies for Clamped- Clamped (C-C), Clamped-Hinged (C-H) and Hinged-Hinged (H-H). It can be seen, that higher values of the natural frequencies are offered by the C-C, followed by C-H and H-H conditions. Moreover, lower values of the natural frequencies are given by C-F condition. It should be noted that, comparatively to C-C condition, the reduction percentage of the first natural frequency is almost 84.22% for C-F, 56%



(a) (b)

(c)

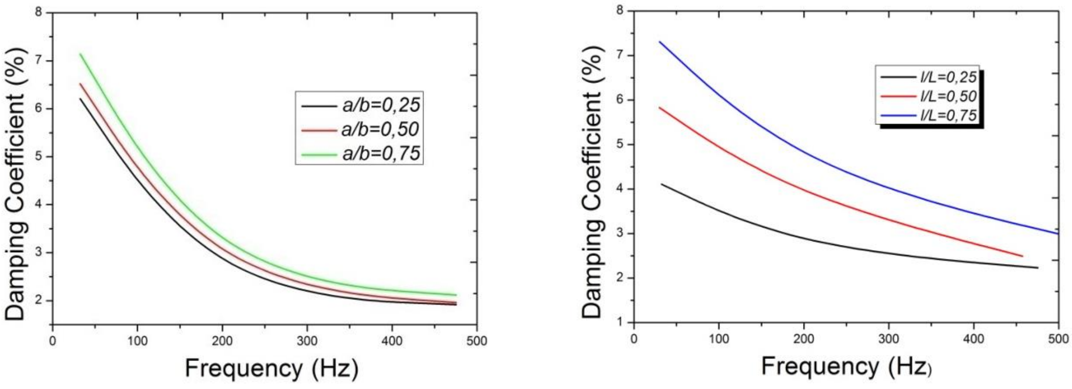
Fig.11 The first normalized natural frequency variation versus a crack depth and position for different boundary conditions.(a) Clamped-Hinged, (b) Clamped-Clamped and (c) Hinged-Hinged

for H-H and 31% for C-H. For the higher natural frequencies, C-C condition gives already maximum natural frequencies, but the reduction percentage is less sensitive especially for the third frequency. For this frequency, the reduction percentage becomes 50.58% for C-F, 27% for H-H and 14% for C-H conditions.

Fig. 11 displays the first normalized natural frequency versus crack depth and position for various boundary conditions. It is clear that, for C-C condition Fig. 11(b), an important perturbation of the first normalized natural frequency is observed particularly at a maximum crack depth, but is less significant for the C-F condition Fig. 11(a).

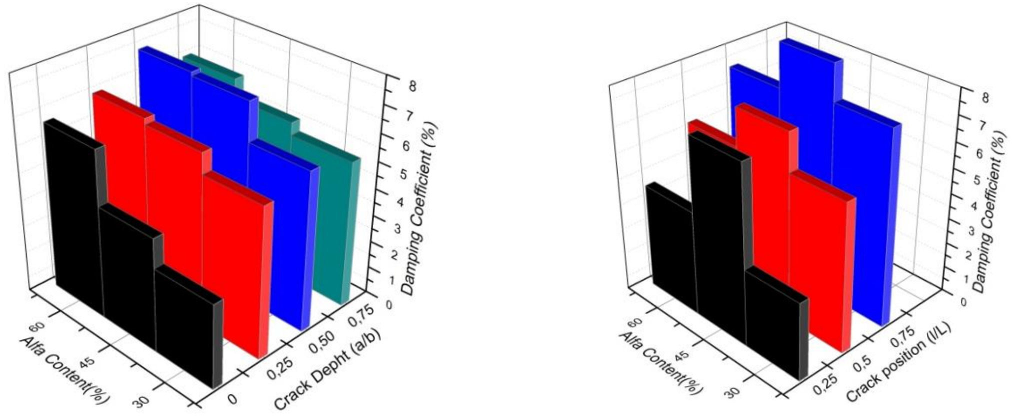
4.4 Damping coefficient

Bio-composite materials are usually of a complex behavior, hence the dynamic analysis could be complicated. Otherwise. As compared to metals, the damping is almost higher, and is a difficult to predict it, due to the such factors include manufacturing techniques and fiber-matrix bonding. Further, the damping associated with each mode is determined through FFT analyzer data by frequency bandwidth measurement. Diagrams or fitted curve algorithms estimates mass, stiffness and damping from response curves Duc *et al.* (2014). The amplitude response, as shown in Fig. 9, can be used to obtain the damping coefficients. The frequencies f_1 and f_2 are respectively, γ f_n below and γ f_n above f_n, corresponding a maximum amplitude value. Thus, the damping coefficient



(a) (b)

Fig. 12 Damping coefficient versus the frequency for 60% of Alfa Fibers. (a) Variation of crack depth and (b)Variation of crack position



(a) (b)

Fig. 13 Variation of the damping coefficient versus Alfa content (a) Versus the crack depth at (*l/L*)=0.5 and (b) Versus the crack position at (*a/b*)=0.5

γ is calculated approximately Ben Ameur *et al.* (2018), and given as:

$$\gamma = \frac{(f_2 - f_1)}{2 f_n} \tag{21}$$

frequencies f_1 and f_2 are known as the half-power points.

Fig. 12 shows the variation of the damping coefficients as a function of the natural frequencies. The results are obtained for 60% of Alfa fiber, concerning different crack positions Fig. 12(a) and crack depths Fig. 12(b) of tested specimens. They showed that the damping coefficient of bio-composite beams is increased by increasing in the crack position and crack depth. On the other hand, it decreases according to the increase in frequency or mode shape. From literature, the damping coefficients of alfa fiber composite beam are significantly higher than those attributed by carbon fiber and metal structures Ben Ameur *et al.* (2018).

Fig. 13 shows the 3D bars of the damping coefficients versus Alfa content for given crack depth and position. At fixed crack position (*l*/*L*)=0.5, the increase of crack depth showed that the maximum damping coefficients are given for 60% of Ala fibers Fig. 13(a). Contrary, they are maximum for 45% of Alfa fibers with the variation of crack position Fig. 13(b). It is concluded that the increase in the Alfa fibers content allows an increase in the damping coefficient.

5. Conclusions

This paper was devoted to investigating the effects of an intermediate crack on the natural frequencies of bio-composite beams reinforced with short Alfa fibers. Using both analytical and experimental analysis, the first three natural frequencies were given according to the fiber content, boundary conditions, and a crack depth and position. A thermo-mechanical extraction was performed to improve the mechanical properties of the Alfa fibers. Optimal mechanical behavior is attributed to fibers socked in heated water at 160°C for 2 hours. Bio-based composite beams were manufactured and characterized using tensile tests for three Alfa fiber contents (30%, 45%, and 60%). The increase in the fiber content reduces relatively the tensile modulus and ultimate strength, but these results remain relatively efficient because the mechanical properties, manufacturing costs, and ecological impacts of bio-composite beams are always favorable. Experimental tests were performed to predict the natural frequencies of a cantilever-cracked bio-composite beam. For this purpose, an analytical model was also developed for this study. Moreover a MATLAB program was established to compute the natural frequencies for various boundary conditions. The comparison of both analytical and experimental results showed good accordance. A parametric study was carried out to show the effects of boundary condition, fiber content, and crack length and depth on natural frequencies. The results obtained showed that the natural frequencies became more important for lower crack depth and maximum crack length ratios. Comparison of the three first natural frequencies for Clamped-Free (C-F), Clamped-Clamped (C-C), Clamped-Hinged (C-H) and Hinged-Hinged (H-H) showed that higher natural frequency values are offered by C-C, followed by the C-H and H-H conditions. In addition, the bio-composite with 30% Alfa fiber content indicated higher frequency values compared with the 45% and 60% fiber contents. Experimental results obtained for the damping coefficient present a significant increase with increasing in the crack position and crack depth. On the other hand, it decreases according to the increase in natural frequencies. We noted that the increase in the Alfa fibers content allows an increase in the damping coefficient. Finally, we conclude that bio-composite beams reinforced with Alfa fibers are good candidates for dynamic behavior. In order to reduce structural vibrations, further research and development will lead to improving the quality of the Alfa fibers through the extraction methods and manufacturing processes of bio-composite materials.

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