Free vibration, Mechanical and damping properties of woven jute FRP composites with the effect of stacking arrangements

S. Senthilrajan [a], N. Venkateshwaran [b,*], Rajini Nagarajan [c,*], Sikiru Oluwarotimi Ismail [d], P.Sivaranjana [e], Suchart Siengchin [f]

[a] Department of Mechanical Engineering, A.V.C.College of Engineering, Mayiladuthurai-609301, Tamilnadu, India.

[b] Department of Mechanical Engineering, Rajalakshmi Engineering College, Chennai-602105, Tamilnadu, India.

[c] Department of Mechanical engineering, Kalasalingam Academy of Research and Education, Virdhunagar-626126, Tamilnadu, India.

[d] Department of Engineering, Centre for Engineering Research, School of Engineering and Computer Science, University of Hertfordshire, Hatfield, AL10 9AB, England, UK.

[e] Department of Chemistry, Kalasalingam Academy of Research and Education, Virdhunagar-626126, Tamilnadu, India.

[f] Department of Mechanical and Process Engineering, The Sirindhorn International Thai-German Graduate School of Engineering (TGGS), King Mongkut's University of Technology North Bangkok, 1518 Wongsawang Road, Bangsue, Bangkok 10800, Thailand.

*Corresponding authors:

N. Rajini, E-mail: rajiniklu@gmail.com; Telephone: +91 99421 39392; Fax: +91 4563 289042.

Abstract

Currently, the demand for vibration damping, lightweight and environmentally friendly material is increasing in automotive and aerospace sectors. Due to this quest, the use of eco-friendly fibrous material has gained importance for its use as a reinforcement in polymeric matrix composite. Therefore, in this present investigation, woven jute fiber mats or layers were added to pure polyester resin to form various composite samples, using compression molding technique. Five different samples were fabricated: neat polyester resin plate and 2-5 woven jute/polyester composites, denoted as NPRP, 2WJPC, 3WJPC, 4WJPC and 5WJPC samples, respectively. The natural frequencies and viscoelastic behaviours of the various samples were examined by free vibration test. From the free vibration test, both natural frequencies and damping factors were obtained. From the results obtained, it was evident that 4WJPC sample exhibited the maximum natural frequencies of 32.96, 231.9 and 659.2 Hz under modes I, II and III, respectively. Also, the natural frequency of 4WJPC sample was 40% higher than that of NPRP. Therefore, it was evident that the addition of woven jute fiber mat has a significant and good influence on the composite natural frequency. Comparison between experimental and theoretical analysis was carried out and found closely related with each other. Applicably, woven jute fiber mat reinforced polyester composite can be used as a vibration absorbing material (damper), low cost and efficient engineering structure.

Keywords: Natural frequency, Damping factor, Woven jute fiber mat, Vibration damping

1. Introduction

Fiber reinforced polymer (FRP) composite materials find their relevance in various automotive structural application over past two decades, due to their higher strength-to-weight ratio, design capability, durability, higher corrosion and wear resistances. Due to the adverse environmental impact of the polymers reinforced with mainly glass and carbon fibers, several studies are being carried out across the world to replace them with natural fiber reinforced composites[1–5]. Reinforcing elements of the natural fiber composites include, but are not limited to the following natural fibers: jute, sisal, flax, banana, risk husk, cotton, bamboo and hemp. They possess inherent properties, such as biodegradability, equivalent specific strength and stiffness, low cost, renewability and non-corrosive nature. Researchers focus on these natural fibers as reinforcements for various applications [6–8]. Recently, the natural fiber reinforced composites-based applications are increasing in automotive sector, aircraft and construction industries, due to their excellent properties of low density, corrosion resistance, less environmental impact, ease of processing method and less cost, when compared with glass, kevlar and carbon (synthetic) fibers [9–11]. Biodegradable polymer composites were estimated to grow at 16% per annum [12].

Several studies have been conducted on numerous natural fiber reinforced composites. To start with, Amico et al. [13] examined the mechanical properties of sisal, glass and hybrid of sisal and glass woven mat composite. From their results, it was concluded that the stacking sequence and hybridization influenced the mechanical properties of the composites. Sapuan et al. [14] investigated into the mechanical properties of woven banana/epoxy composite. They also studied the statistical analysis, using the ANOVA results. Jacob et al. [15] studied the woven sisal and natural rubber composite. They carried out surface modification, using mercerization, salinization and thermal treatments for sisal woven, and concluded that the water absorption was observed to be lowered, due to the fiber surface treatments. Pothan et al. [16] carried out investigation into sisal fabric/polyester resin composite. They fabricated the composite by resin transfer molding technique. They used different weave structures, such as plain, twill and mat. From their experimental results, they analyzed the mechanical properties of the composites. The result analysis revealed that the woven sisal fibers possessed 32% in volume showed better mechanical properties than the rest of the composites. Venkateshwaran et al. [17] reported the mechanical and water absorption behaviors of woven jute/banana hybrid composites. They concluded that the hybridization influenced the mechanical properties. However, it showed less effect on water absorption behavior. Ahmed et al. [18] considered the influence of hybridization of glass fiber and jute fabric on low-velocity impact behavior and damage tolerance capability of the composites. Drop weight hammer was used for the investigation of impact behaviour. C-scan method was used to study the delamination and damage extent area of the composites. From the results obtained, it was concluded that jute fabric composite exhibited a better absorption capability than jute/glass hybrid composite. Also, damage tolerance capacity was lower than that of jute/glass hybrid composites. Rajesh et al. [19] compared the mechanical behaviors of the braided and conventional woven composites. The results obtained were compared with randomly oriented natural fiber composite, which depicted that the braided yarn composites produced better mechanical properties than other types of the composites.

In addition, Rajini et al. [20] reported the mechanical and free vibration properties of montmorillonite clay dispersed woven coconut sheath composites. From their investigation, it was observed that the stacking sequence and alkali treatment contributed to the better mechanical and free vibration behaviours achieved. Ettai et al. [21] studied the vibration damping characteristics of short hemp fiber thermoplastic composites. The results showed that the 30 wt% of noil hemp fiber with 2.5 wt% anhydride-grafted polyethylene octane exhibited the highest damping ratio. Similarly, Chandradass et al. [22] experimented the effect of nanoclay addition on vibration properties of glass fiber reinforced vinyl ester composite. From the results obtained, it was observed that the addition of organically modified clay increased the natural frequency of the composite. Ganesa et al. [23] carried out the free vibration behavior of glass fiber/vinyl ester treated and untreated composites. It was evident from their results that NaOH treated glass fiber reinforced composite had better values than HCL treated and untreated glass fiber composites. The damping ratio of the alkali treated composite was higher than untreated glass fiber composite. Ahmed et al. [24] focused on the vibration and damping behaviors of composite structure by varying the ply angle of the fiber. They concluded that the outer laminate angle orientation had a significant effect on the inner laminate. Rajesh et al. [25] studied on mechanical, vibration and dynamic mechanical behaviors of the nanoclay added banana/jute hybrid intra-ply woven composite. In this investigation, addition of nanoclay improved the mechanical properties of the composites and also increased the storage modulus and glass transition temperature. From the free vibration results obtained, addition of nanoclay up to 2 wt% increased the natural frequency of the composite. Rajesh et al. [26] analyzed the woven fiber/polyester resin composite. They prepared different woven fabrics, such as plain, twill, basket, randomly orientated sisal fiber and unsaturated polyester resin composites. They used rice husk as a filler to enhance the properties. From the results obtained, it was concluded that the basket woven composite showed better stiffness and strength, while the natural filler increased the vibration behavior.

Moving forward, Rajesh et al. [23] studied the free vibrational characteristics of banana/sisal/polyester composite. They used random oriented fiber. From the results obtained, it was concluded that the surface treatment increased the mechanical and vibration behaviors of the composites. Vaziri et al. [27] conducted vibration analysis of cantilever beam using fast Fourier transform analyzer and the results showed that the fiber length and volumetric fraction influenced the vibration and mechanical properties of the composites. Rajeshkumar et al. [28] investigated into the vibration characteristics of phoenix species fiber/polyester resin reinforced composite beams. The results depicted that the highest natural frequency was obtained with 30 mm fiber length composite beam. Bennet et al. [29] carried out vibration analysis of a *Sansevieria cylindrica*/coconut sheath/polyester composite. The results showed a better natural frequency of the alkali-treated and silane-treated composites than the untreated. Lei et al. [30] studied the effect of woven structures on the vibration characteristic of glass fabric/epoxy composite plates. The results showed that the fiber volume content and yarn architectures had significant effects on the storage modulus, damping properties and frequencies of the composites. In addition, they recommended interlocked woven structure, because of its better properties when compared with the plain-woven. Rajesh et al. [25] researched on the viscoelastic properties and vibration characteristics of woven banana/jute hybrid composites. In like manner, Pothan et al. [31] investigated into the woven banana, glass fiber and polyester composites. Their results showed that two-layer composite enhanced or produced better tensile properties. Rajesh et al. [32] reported that the free vibration behavior and dynamic mechanical analysis of natural fiber composites and compared them with conventional and knitted composites. They concluded that the intra-ply laminate provided better results in terms of storage modulus and loss factor. Also, an addition of fabric yarn enhanced modal analysis more than other samples.

Based on the aforementioned extensive reported results from literature, the present work was done to fill the revealed research gap on influence of stacking arrangements vibration damping of 2-5 woven jute fiber mats/layers reinforced polyester composites, fabricated by compression molding technique. This is rarely and scarcely reported. Hence, this study addressed this gap both experimentally and analytically to benefit composite researchers, designers, manufacturers and users, as quest for optimization of properties and better application of natural fiber-based composites increase.

2. Experimental details

2.1. Materials used

Woven jute fiber mat of 300 x 300 mm and isophthalic polyester resin were used as reinforcement and matrix in the present study, respectively. The reinforcement and matrix were purchased from a local dealer at Chennai, Tamilnadu, India. The composite laminates were fabricated under four different categories by increasing the number of woven mats from 2 to 5, using compression molding technique at a room temperature. After curing, the mold was taken from compression molding machine. The composite was removed from the mold and later cut into samples for flexural, short beam shear strength and free vibration tests, according to their respective ASTM standards. Various types of sample systems used and their notations are presented in Table 1. The samples are also schematically shown in Fig. 1, as fabricated.

Table 1

Different types of sample systems and their notations.

S/No.	Description of sample systems	Sample
1	Neat polyester resin plate	NPRP
2	2 Jute woven layer/polyester composite	2WJPC
3	3 Jute woven layer/polyester composite	3WJPC
4	4 Jute woven layer/polyester composite	4WJPC
5	5 Jute woven layer/polyester composite	5WJPC

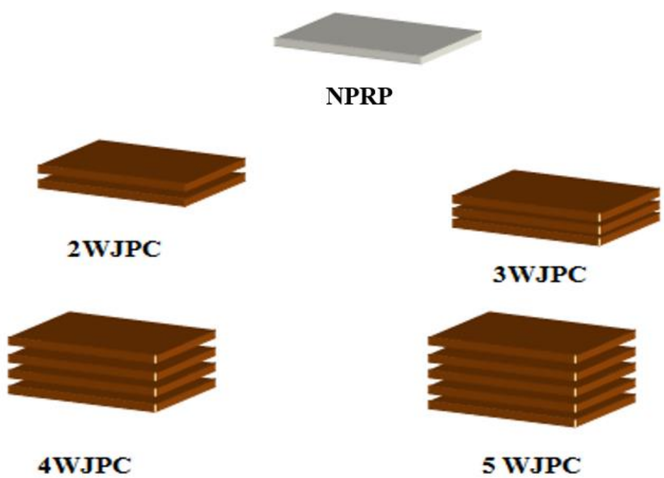

Fig. 1. Schematic illustration of the various sample systems used.

2.2. Flexural test

To evaluate the flexural strengths and moduli of the various five samples, three-point bending test was conducted by using Zwick/Roell universal testing machine. The flexural test set-up followed the ASTMD-790 standard with a test speed of 2 mm/min. For each type of sample, five similar samples were tested and the average values were reported. The obtained values of moduli were used to evaluate the natural frequency theoretically, as later expressed in Eq. (3).

2.3. Inter-laminar shear strength

Inter-laminar shear strength (ILSS) was performed according to ASTM D2344 standard. The short beam shear test was carried out with the sample length that was 6 times the thickness and the span length was 4 times the sample thickness. The width of the sample was 2 times the sample thickness. Five similar samples were tested for each sample type and then short beam shear strength was calculate by using Eq. (1).

$$F_{sbs} = \frac{0.75 \ x \ P_{max}}{b \ x \ t} \quad (1)$$

Where F_{sbs}= Short beam strength (MPa),

P_{max} = Maximum load observed during the test (N),

b = Sample width (mm), and

t = Sample thickness (mm).

2.4. Free vibration test

The free vibration test was conducted in the cantilever mode with a sample size of 250 x 25 x 3 mm^3. An 8778A500sp accelerometer was fixed at one point on the cantilever and impulse was given at predetermined points with Model 1H-01 impulse hammer. NI-9233 data acquisition software was used to store the output data of the accelerometer and impact hammer. The DEWSoft 7.1.1 software was used for time signal conversion, using a fast Fourier transform. With the help of the curve fitting techniques, modal identification function was generated, which showed the peaks of the natural frequencies. The natural frequency and damping ratio were estimated from the amplitude *versus* frequency and acceleration *versus* time plots, respectively. The damping ratio (ζ) was determined using the logarithmic decrement formula, as expressed in Eq. (2).

$$\xi = \frac{1}{2\pi j} \ln \frac{X_i}{X_{i+j}} \quad (2)$$

Where X_i represents the peak acceleration of the i^{th} peak and X_{i+j} denotes the peak acceleration of the peak j cycles after i^{th} peak. The experimental set-up for the free vibration test is shown in Fig. 2.

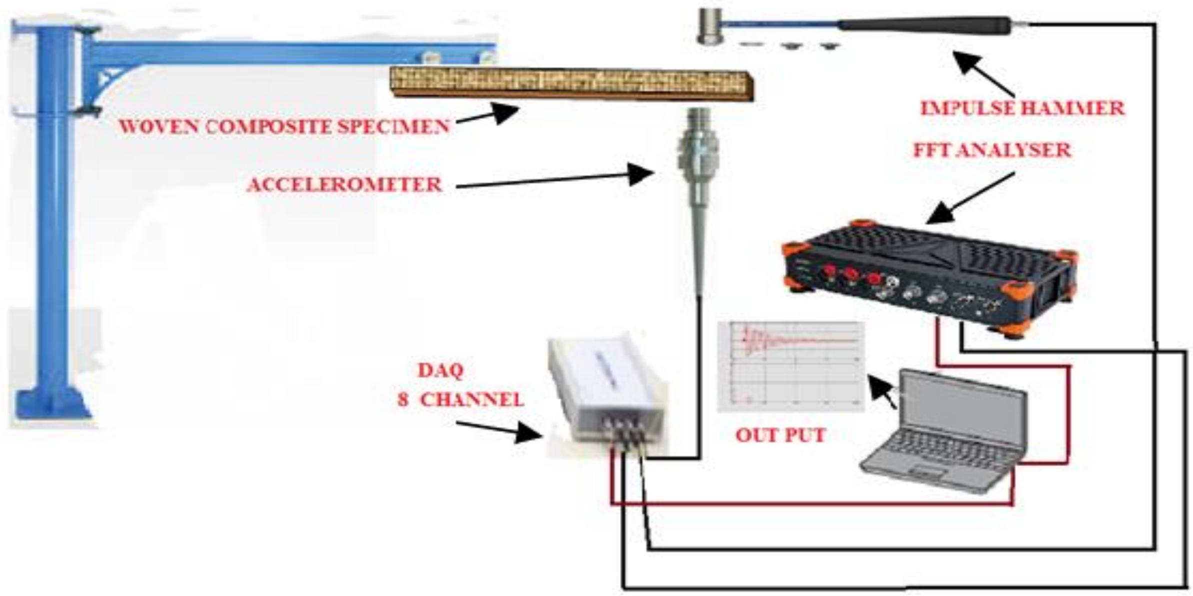

Fig. 2. Schematic illustration of the free vibration test set-up.

2.5. Theoretical modal analysis

The theoretical natural frequency of cantilever beam was obtained from the Euler-Bernoulli model, as given in Eq. (3) [22]

$$\omega_1 = (\beta L)^2 \sqrt{\frac{EI}{\rho A L^4}} \quad \text{(rad/sec)} \tag{3}$$

Where E = Modulus of the beam (MPa),

I = Moment of Inertia (mm^4),

ρ= Density of composites (kg/mm^3),

A = Cross-sectional area of the cantilever beam (mm^2),

L= Length of the beam (mm), and

β = Determined from the boundary conditions ($\beta = 1.875^2$ and 4.694^2).

3. Results and discussion

3.1. Flexural modulus

The influence of stacking 2-5 woven jute fiber mats/layers on the flexural modulus of various composite samples as well as neat polyester matrix were obtained according to the ASTMD-790 standard. Fig. 3 shows the average moduli for the various stacking sequences of the composite samples and NPRP. It was observed that the 4WJPC sample has the maximum modulus of 12.853 GPa, which was 78% higher than that of the NPRP.

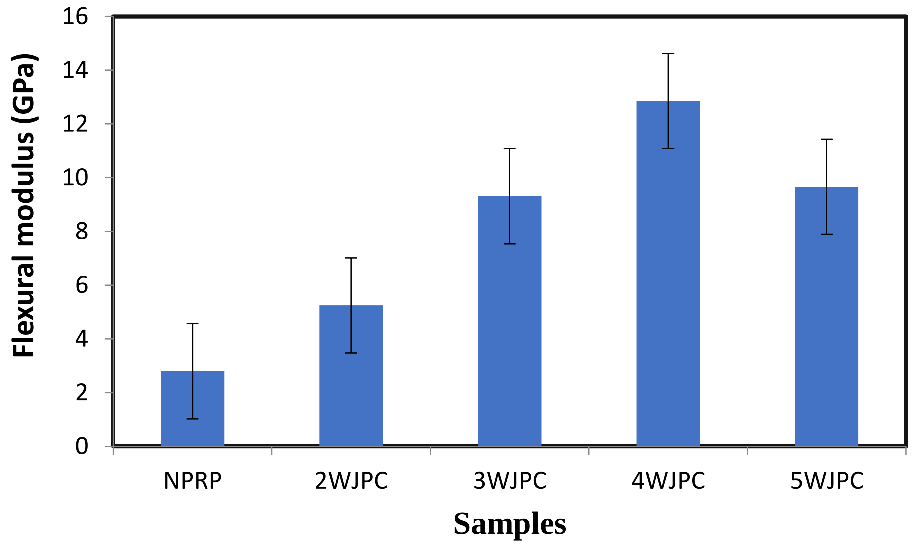

Fig. 3. Flexural moduli of the various samples.

3.2. Inter-laminar shear strength

The ILSS plays a dominant role in estimating the adhesion between the reinforcement and matrix of a composite material. The short beam shear strength was calculated, using Eq. (1) for the various samples used. Fig. 4 depicts the ILSS values of the various samples. It was observed that an increase in the number of woven jutes fiber layers caused an increase in the ILSS of the composite samples till a threshold value was achieved with addition of 4 layers, thereafter the ILSS decreased. In addition, it was observed that the 4WJPC sample has the maximum ILSS of 6.035 MPa and this value was calculated to be 40.62% higher than that of the matrix. The improvement in the ILSS was attributed mainly to the better interfacial strength/adhesion between the jute fiber mat and polyester matrix. However, the addition of 5 layers/mats to the matrix decreased the ILSS property of the 5WJPC sample, due to the poor interfacial adhesion between the fiber and matrix. This implied that the addition of woven jute fiber mat has a significant influence on the ILSS of the composite samples. For mat type of reinforcement, ILSS plays a major role in determining the properties of the composite, especially against delamination.

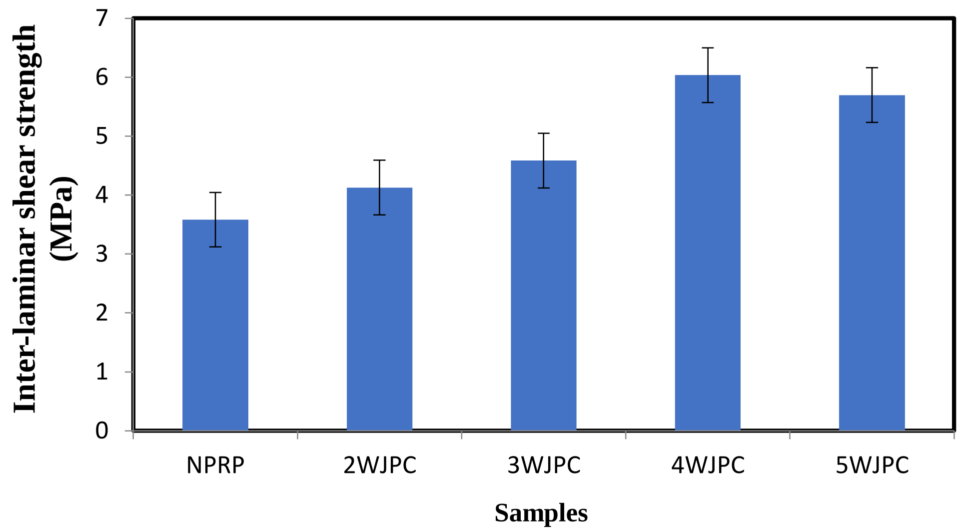

Fig. 4. Short beam shear strengths of the various samples.

3.3. Free vibration test

Free vibration test (FVT) was carried out on the various samples used under cantilever mode. A sample plot of frequency *versus* time and amplitude *versus* time for the NPRP and 4WJPC sample are shown in Figs 5(a) and (b), respectively. The peak from the frequency *versus* time plot provided the natural frequencies at modes I, II and III. Table 2 presents the natural frequencies of the various samples under modes I, II and III. In mode I. From the results obtained, the natural frequency of the NPRP was 13.43 Hz. Furthermore, from Table 2, it was evident that the natural frequency increased with the addition of woven jute fiber mats. The maximum value of natural frequency of 32.96 Hz was obtained for the 4WJPC sample material. Similarly, the mode II frequency of resin was 119.6 Hz. Whereas, frequency of 231.9 Hz was recorded for 4WJPC sample. The experimental results thus obtained from free vibration tests were compared with the theoretical values that were obtained by using Eq. (3). Table 2 shows the comparison of the experimental and theoretical values of the natural frequencies at modes I, II and III, damping factors along with the moduli and short beam shear strengths of all the various samples (Table 3).

From the results presented in Table 3, it was further observed that the increase in the natural frequency and damping factor of the composite material depended on the modulus of the composite, ILSS, fiber-matrix interfacial bonding and the laminate arrangement [23].

Furthermore, the natural frequency of the woven fiber mat reinforced composite could depend on the fiber yarn orientation, gap and crimp [32]. In addition, it showed that the 5WJPC sample recorded a lower frequency, due to further addition of a layer. Hence, it suggested that a decrease in the fiber aspect ratio caused a resultant reduction in the modulus and thereby the frequency of the composite samples.

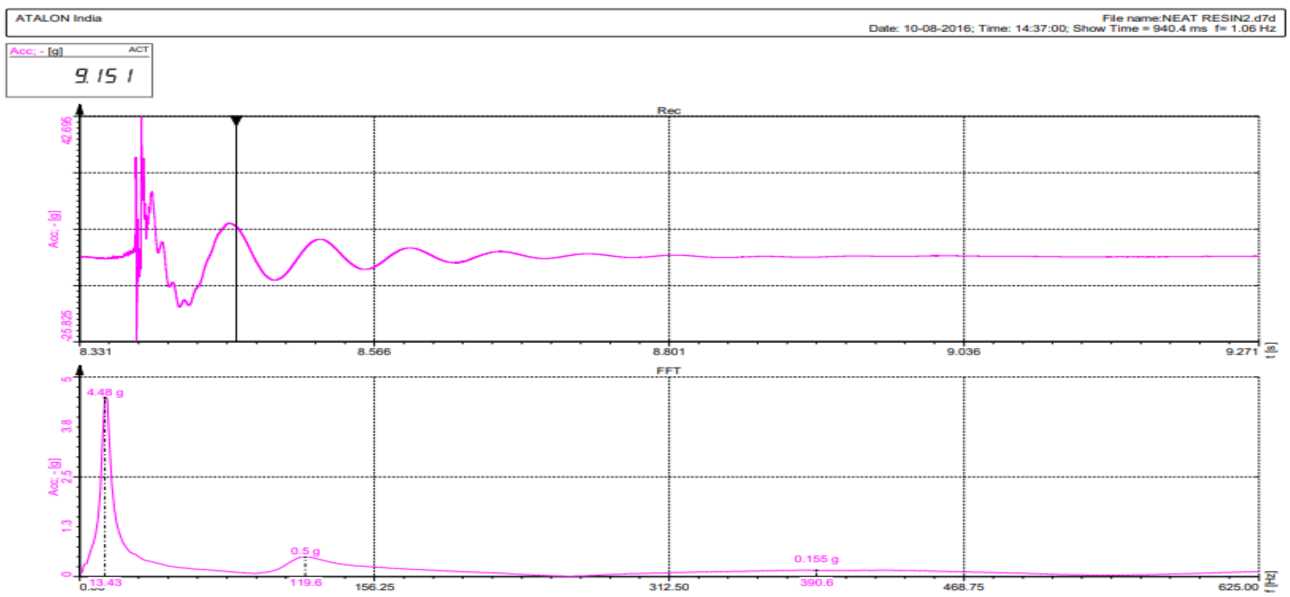

Fig. 5(a) NPRP: (i) frequency *versus* time and (ii) acceleration *versus* time.

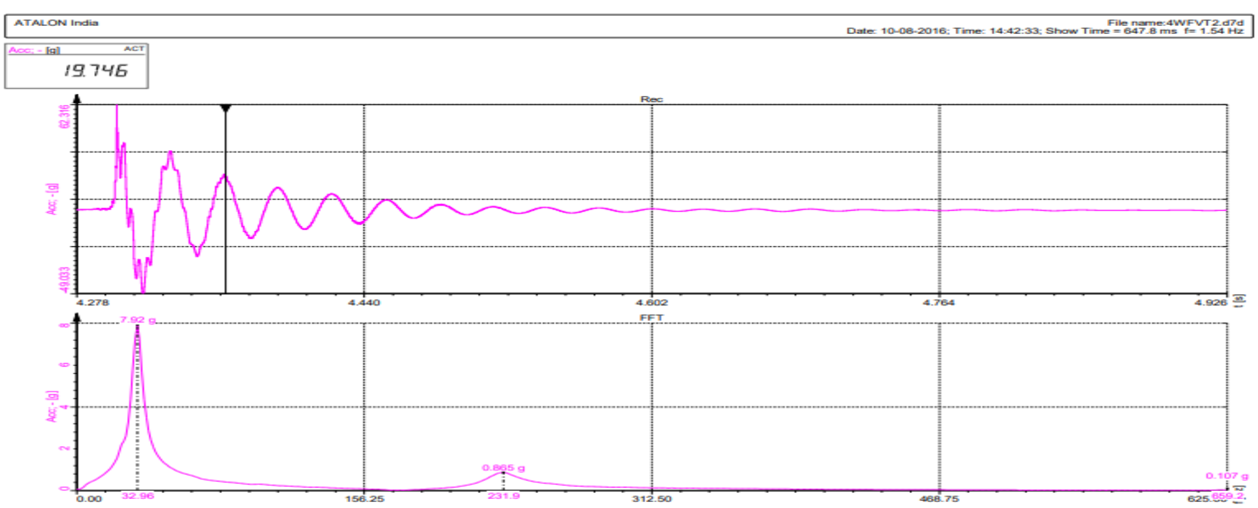

Fig. 5(b) 4WJPC: (i) frequency *versus* time and (ii) acceleration *versus* time.

Table 2

Experimental and theoretical natural frequencies and damping factors of the various samples for all modes.

Sample	Natural frequencies (Hz)						Damping factor (ξ)		
	Experimental			Theoretical					
	Mode								
	I	II	III	I	II	III	I	II	III
NPRP	13.43	119.6	390.6	20.75	121.50	221.30	0.07041	0.05122	0.04324
2WJPC	19.53	128.2	262.5	9.86	133.10	173.02	0.04187	0.03642	0.04215
3WJPC	21.97	158.7	277.1	19.90	142.75	349.25	0.04829	0.03923	0.04213
4WJPC	32.96	231.9	659.2	28.15	176.46	494.20	0.04865	0.05683	0.04682
5WJPC	20.75	159.9	473.6	37.60	235.68	659.20	0.03334	0.027328	0.0315

Table 3

Mechanical properties of the various samples.

Sample	Mechanical properties	
	Flexural modulus (GPa)	Short beam shear strength (MPa)
NPRP	2.796	3.583
2WJPC	5.247	4.586
3WJPC	9.312	5.996
4WJPC	12.835	6.035
5WJPC	9.659	4.127

The damping ratios (ξ) of the various samples were obtained, using Eq. (2). The average damping ratios of all the various samples are presented in Fig. 6, considering modes I, II and III. It was observed that the 2WJPC sample recorded the lowest damping factor. This result showed that the addition of woven jute fiber mat decreased the damping factor of the composite, due to the absorption of energy, which was dissipated during the vibration. The 4WJPC sample recorded the highest damping factor among the composite samples, due to a better interfacial interaction between fiber and matrix. Also, this was previously evident from the ILSS results obtained. The 5WJPC samples recorded less damping factors in all the three bending modes considered, due to interaction between the fiber and low matrix as well as a resistance of free molecular mobilization [32]. Summarily, the addition of woven jute fiber mat to polyester resin increased the damping property of the composites.

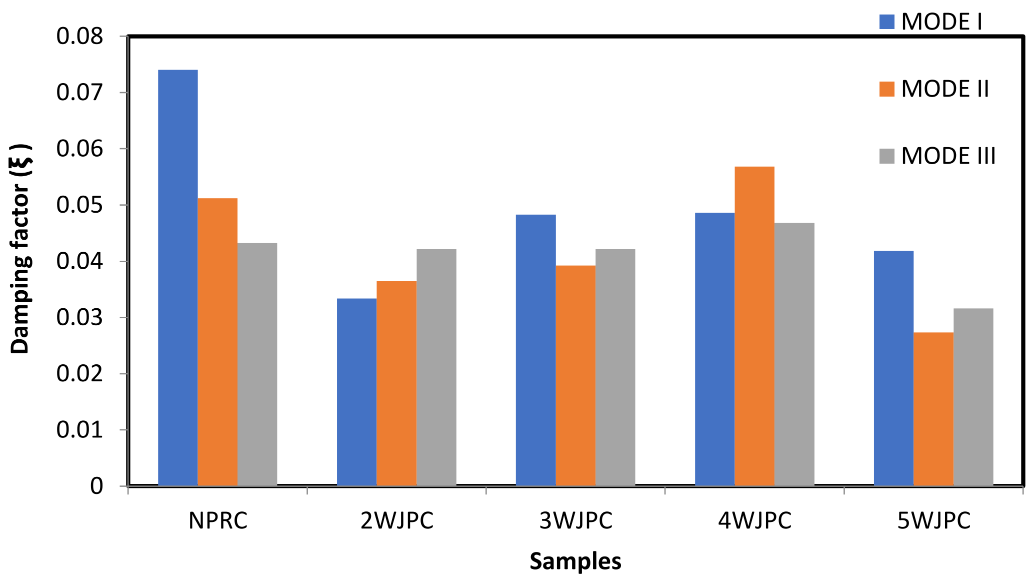

Fig. 6. Damping factors of the various samples.

3.4. Analysis of variance

The results obtained from ANOVA of natural frequency of modes I, II and III are shown in Table 4.

Table 4 ANOVA test for natural frequency of woven jute fiber composites for modes I, II and III.

Properties	Model term	Sum of square	Degree of freedom	Mean square	F-value	Prob. level	Reject equal means (**α**=0.05)	Power (**α**=0.05)
Natural	Between	392974.7	2	196487.3	20.6971	0.0001	Yes	0.99947

frequenc						3		
y	Within	113921.8	12	9493.484	-			
	Adjusted Total	506896.5	14					
	Total		15					

ANOVA simply described source of variation in frequency as per between and within groups. The p-value used was less 0.05. Also, from Table 4, it can be concluded that the F-critical was lesser than F-value. Therefore, there was null hypothesis, which can be rejected, while accepting alternative hypothesis, which implied that there was significant effect of layer sequence on the natural frequency of the composite. ANOVA does not reveal the differences between the means of layer arrangement. For this purpose, Tukey-Kramer's method was employed. This method provides 95% accuracy level**.** From Table 5, it was observed that the method provided joint simultaneous confidence intervals for all pairwise differences between the means. Also, its reports also provided the multiple comparison of p-values. This was the significance level at which this difference became significant, using the Tukey-Kramer multiple comparison procedure.

Table 5 Tukey-Karmer's method for natural frequency.

Tukey-Kramer's all pairs simultaneous confidence intervals of mean difference and p-value						
Response of modes I, II and III						
Term A						
Alpha = 0.050, Error term = S(A), DF =12, MSE = 9493484, Critical value = 37727						
Comparison groups	**Count**	**Mean**	**Lower 95.0% Simult. C.I**	**Mean difference**	**Upper 95.0% Simult. C.I**	**P-value**
Mode I	5	21.728				
Mode II	5	159.66	-302.322	-137.932	26.45803	0.10466
Mode III	5	412.60	-555.262	-390.872	-226.482	0.00010
Mode II	5	159.66				
Mode I	5	21.728	-26.45803	137.932	302.3220	0.10466

Mode III	5	412.60	-477.330	-252.940	-88.54997	0.00386
Mode III	5	412.60				
Mode I	5	21.728	226.4820	390.872	555.2620	0.000010
Mode II	5	159.66	88.54997	252.940	417.3300	0.003860

4. Conclusions

The effects of reinforcing polyester resin with 2-5 jute woven mats on vibration damping and viscoelastic behaviors of the resultant composite samples have been extensively analysed, using both experimental and analytical methods. From the results obtained, the following concluding remarks can be deduced.

- The 4WJPC sample has the maximum natural frequencies of 32.96, 231.90 and 659.20 under modes I, II and III, respectively. With addition of woven jute fiber mat, the natural frequency of the composite increased, 40% higher than that of NPRP. However, 5WJPC sample produced the lowest damping factor at all modes, when compared with other samples. This was attributed to absence of better fiber-matrix interfacial adhesion.
- From the ANOVA results obtained from the natural frequencies of modes I, II and III, the p-value was less 0.05 and F-critical was lesser than F-value. Therefore, there was null hypothesis. It can be rejected, while alternative hypothesis was accepted. This implied that there was significant effect of layer sequence on the natural frequency of the composite. Therefore, Tukey-Kramer's method was suggested for alternative hypothesis, which provided an accuracy level of 95% and multiple comparison of p-values.
- Lastly, from experimental and theoretical comparison, both 2WJPC and 4WJPC experimental results agreed with Guth model, at lower frequencies than others. This can be attributed to the absence of constraints in the effect of fiber-matrix adhesion and heterogeneous composite structure.

Acknowledgment

We hereby acknowledge and sincerely appreciate unalloyed supports from the managements of the following institutions: A.V.C. College of Engineering, Mayiladuthurai, Rajalakshmi Engineering College, Chennai as well as the Kalasalingam Academy of Research and Education Tamil Nadu, India.

Data availability

The raw/processed data required to reproduce these findings cannot be shared at this time as the data also forms part of an ongoing study.

References

1. Zhang C, Garrison TF, Madbouly SA, Kessler MR (2017) Recent advances in vegetable oil-based polymers and their composites. Prog Polym Sci 71:91–143. https://doi.org/10.1016/j.progpolymsci.2016.12.009

2. Thakur VK, Thakur MK, Gupta RK (2014) raw natural fiber–based polymer composites. Int J Polym Anal Charact 19:256–271

3. Drzal LT, Mohanty AK, Misra M (2001) Bio-composite materials as alternatives to petroleum-based composites for automotive applications. Magnesium 40:1–3

4. Krishnasamy S, Thiagamani SMK, Muthu Kumar C, et al (2019) Recent advances in thermal properties of hybrid cellulosic fiber reinforced polymer composites. Int J Biol Macromol 141:1–13. https://doi.org/10.1016/j.ijbiomac.2019.08.231

5. Senthilkumar K, Siva I, Rajini N, Jeyaraj P (2015) Effect of fibre length and weight percentage on mechanical properties of short sisal/polyester composite. Int J Comput Aided Eng Technol 7:60–71

6. Faruk O, Bledzki AK, Fink H, Sain M (2014) Progress report on natural fiber reinforced composites. Macromol Mater Eng 299:9–26

7. Senthilkumar K, Saba N, Rajini N, et al (2018) Mechanical properties evaluation of sisal fibre reinforced polymer composites: A review. Constr. Build. Mater. 174

8. Thiagamani SMK, Krishnasamy S, Muthukumar C, et al (2019) Investigation into mechanical, absorption and swelling behaviour of hemp/sisal fibre reinforced bioepoxy hybrid composites: Effects of stacking sequences. Int J Biol Macromol 140:637–646. https://doi.org/10.1016/j.ijbiomac.2019.08.166

9. Sanjay MR, Arpitha GR, Naik LL, et al (2016) Applications of natural fibers and its composites: An overview. Nat Resour 7:108–114

10. Krishnasamy S, Muthukumar C, Nagarajan R, et al (2019) Effect of fibre loading and

Ca(OH) 2 treatment on thermal, mechanical, and physical properties of pineapple leaf fibre/polyester reinforced composites . Mater Res Express 6:085545. https://doi.org/10.1088/2053-1591/ab2702

11. Thiagamani SMK, Krishnasamy S, Siengchin S (2019) Challenges of Biodegradable Polymers: An Environmental Perspective. Appl Sci Eng Prog x:1. https://doi.org/10.14416/j.asep.2019.03.002

12. Mohanty AK, Misra M, Hinrichsen G (2000) Biofibres, biodegradable polymers and biocomposites: An overview. Macromol. Mater. Eng.

13. Amico SC, Angrizani CC, Drummond ML (2008) Influence of the Stacking Sequence on the Mechanical Properties of Glass/Sisal Hybrid Composites. J Reinf Plast Compos 29:179–189. https://doi.org/10.1177/0731684408096430

14. Sapuan SM, Leenie a., Harimi M, Beng YK (2006) Mechanical properties of woven banana fibre reinforced epoxy composites. Mater Des 27:689–693. https://doi.org/10.1016/j.matdes.2004.12.016

15. Jacob M, Varughese KT, Thomas S (2006) A study on the moisture sorption characteristics in woven sisal fabric reinforced natural rubber biocomposites. J Appl Polym Sci 102:416–423

16. Pothan L a., Mai YW, Thomas S, Li RKY (2008) Tensile and Flexural Behavior of Sisal Fabric/Polyester Textile Composites Prepared by Resin Transfer Molding Technique. J Reinf Plast Compos 27:1847–1866. https://doi.org/10.1177/0731684408090342

17. Venkateshwaran N, ElayaPerumal A (2012) Mechanical and water absorption properties of woven jute/banana hybrid composites. Fibers Polym 13:907–914

18. Ahmed KS, Vijayarangan S, Rajput C (2006) Mechanical behavior of isothalic polyester-based untreated woven jute and glass fabric hybrid composites. J Reinf Plast Compos 25:1549–1569. https://doi.org/10.1177/0731684406066747

19. Rajesh M, Pitchaimani J (2017) Mechanical properties of natural fiber braided yarn woven composite: comparison with conventional yarn woven composite. J Bionic Eng 14:141–150

20. Rajini N, Jappes JW, Rajakarunakaran S, Jeyaraj P (2012) Dynamic mechanical analysis and free vibration behavior in chemical modifications of coconut sheath/nano-clay reinforced hybrid polyester composite. J Compos Mater. https://doi.org/10.1177/0021998312462618

21. Etaati A, Mehdizadeh SA, Wang H, Pather S (2014) Vibration damping characteristics of short hemp fibre thermoplastic composites. J Reinf Plast Compos 33:330–341

22. Chandradass J, Kumar MR, Velmurugan R (2007) Effect of nanoclay addition on vibration properties of glass fibre reinforced vinyl ester composites. Mater Lett 61:4385–4388

23. Rajesh M, Pitchaimani J, Rajini N (2016) Free Vibration Characteristics of Banana/Sisal Natural Fibers Reinforced Hybrid Polymer Composite Beam. Procedia Eng 144:1055–1059. https://doi.org/10.1016/j.proeng.2016.05.056

24. Maher A, Ramadan F, Ferra M (1999) Modeling of vibration damping in composite structures. Compos Struct 46:163–170

25. Rajesh M, Jeyaraj P, Rajini N (2016) Mechanical, dynamic mechanical and vibration behavior of nanoclay dispersed natural fiber hybrid intra-ply woven fabric composite. In: Nanoclay reinforced polymer composites. Springer, pp 281–296

26. Rajesh M, Singh SP, Pitchaimani J (2018) Mechanical behavior of woven natural fiber fabric composites: Effect of weaving architecture, intra-ply hybridization and stacking sequence of fabrics. J Ind Text 47:938–959

27. Vaziri M, Vaziri A, Kadam SS (2013) Vibration analysis of a cantilever beam using FFT analyzer. Int J Adv Eng Technol 4:112–115

28. Rajeshkumar G, Hariharan V (2014) Free vibration characteristics of phoenix Sp fiber reinforced polymer matrix composite beams. Procedia Eng 97:687–693. https://doi.org/10.1016/j.proeng.2014.12.298

29. Bennet C, Rajini N, Jappes JTW, et al (2015) Effect of the stacking sequence on vibrational behavior of Sansevieria cylindrica/coconut sheath polyester hybrid composites. J Reinf Plast Compos 34:293–306

30. Lei X, Rui W, Yong L, Jin L (2011) The Effect of Woven Structures on the Vibration Characteristics of Glass Fabric/Epoxy Composite Plates. Def Sci J 61:

31. Pothan L a. (2005) The Static and Dynamic Mechanical Properties of Banana and Glass Fiber Woven Fabric-Reinforced Polyester Composite. J Compos Mater 39:1007–1025. https://doi.org/10.1177/0021998305048737

32. Rajesh M, Pitchaimani J (2018) Dynamic mechanical and free vibration behavior of natural fiber braided fabric composite: comparison with conventional and knitted fabric composites. Polym Compos 39:2479–2489