Dynamic Behaviour of Woven Bio Fiber Composite

Murugan Rajesh,[a] Mohamed Thariq Hameed Sultan,[b,e] * Marimuthu Uthayakumar,[c] Kandasamy Jayakrishna,[d,]* and Ain Umaira Md Shah [b]

The effect of weaving pattern and natural filler addition on the dynamic properties of composite structure was investigated. The reinforcement effect of plain, basket, and twill weave were compared with randomly oriented natural fiber in short form. An experimental modal analysis was used to determine the fundamental natural frequency and modal damping factor of composite structure. The results for a woven reinforced composite were compared with those of a randomly oriented short fiber composite. Reinforcement with woven form enhanced the fundamental natural frequency, while randomly oriented short fiber enhanced the damping factor of composite material. In addition, mechanical properties, such as tensile and flexural behavior, were examined to understand the effect of reinforcement on the composite material. The sisal bio fiber with woven form enhanced the properties of the composite material.

Keywords: Bio fiber; Weaving pattern; Natural frequency; Damping factor

*Contact information: a: Department of Design and Automation, School of Mechanical Engineering, VIT University, Vellore Campus, Tamilnadu, India 632014; b: Aerospace Manufacturing Research Centre (AMRC), Universiti Putra Malaysia 43400 UPM Serdang, Selangor Malaysia; c: Dean, International Relations, Kalasalingam University, Krishnankoil Virudhunagar Dist, Tamil Nadu, India 626 126; d: Department of Manufacturing Engineering, School of Mechanical Engineering, VIT University, Vellore Campus, Tamilnadu, India 632014; e: Laboratory of Biocomposite Technology, Institute of Tropical Forestry and Forest Products (INTROP), Universiti Putra Malaysia, 43400 UPM Serdang, Selangor Darul Ehsan, Malaysia; *Corresponding authors: mail2jaikrish@gmail.com; thariq@upm.edu.my*

INTRODUCTION

Natural fiber-reinforced composites can be used as good alternatives for composites that are reinforced by metal or synthetic fibers, in applications where the load range varies from low to medium. Compared with synthetic fibers such as glass, Kevlar, and carbon fiber, the main advantages of natural fiber are low density, less cost, and low pollutants. The usage of natural fiber-reinforced composites for low and medium load applications is supported by earlier work (Joshi *et al.* 2004; Rajesh *et al.* 2016b). The material used in the structural application should have higher energy dissipating capabilities along with high strength and stiffness. Structures made of conventional material have high stiffness with poor energy dissipating properties. In a composite, enhancing both the stiffness and energy dissipating properties of structure is important (Rajesh and Pitchaimani 2017a). Most research on the development of new natural fiber composites has focused on their mechanical properties, such as tensile, flexural, and impact (Dhawan *et al.* 2013; Vimalanathan *et al*. 2016). An exhaustive amount of research has been carried out on mechanical properties of natural fiber composite for low and medium load applications. Jute, sisal, flax, hemp, coir, and bamboo natural fibers are commonly used as reinforcement (Lee and Wang 2006; Bodros *et al.* 2007). Monteiro *et al.* (2008) analysed effects of weight percentage of short coir natural fiber-reinforced composite on mechanical properties and found that a 50 wt.% coir content enhances the properties of the composite material due to better load carrying capacity. Venkateshwaran *et al*. (2011) analysed the influence of hybridization on mechanical properties of banana-sisal randomly oriented short fiber composite and found that sisal fiber reinforcement in a composite enhances the tensile, flexural, and impact strength of composite compared to banana-sisal hybridization. Boopalan *et al.* (2013) made a similar observation for banana-jute fiber composite. Thus, a composite with a high strength fiber enhances the strength of the composite material. Researchers have used textile concepts to improve the strength of composite materials.

Recently, biofibers have been reinforced in woven form, which enhances the composite strength. Sapuan and Maleque (2005) investigated the mechanical properties of woven banana biofiber-reinforced composites, and they also fabricated a household telephone stand. Sastra *et al.* (2006) analysed the reinforcement effect on the tensile properties of composites using three types of reinforcement: long random, short random, and woven roving form. The woven reinforcement resulted in higher mechanical properties. Although woven form biofiber enhances the mechanical properties of composites, it is important to analyse the dynamic behaviour of composite structure. Berthelot (2006) conducted a modal analysis of differently oriented glass and Kevlar composites, finding that 60 degree oriented glass and Kevlar composites enhance the damping properties. Senthil Kumar *et al.* (2016) analysed free vibration characteristics of woven coconut composites and found that the addition of banana fiber to the woven coconut composite enhances the damping behaviour of composites. To further improve the stiffness properties of composites, natural fillers such as rice husk, wheat husk, and coconut coir have been used as secondary reinforcement (Dhawan *et al*. 2013; Rajesh and Pitchaimani 2017b). Haq *et al.* (2008) analysed the effect of nanoclay in polyester/soybean oil/hemp composite on stiffness, ultimate tensile stress, and toughness. The composite with nanoclay had enhanced properties. Kokta *et al.* (1989) studied the enhanced mechanical properties with polypropylene composite containing added wood powder.

The poor properties associated with natural fiber can be improved by reinforcing natural fiber in woven form. The addition of filler material in the matrix with natural fiber woven reinforcement will improve the strength, stiffness, *etc*., of composite materials.

The present work aims to enhance the structural properties of poor strength natural fiber composite laminate. Most studies have analysed the properties of natural fiber in short and random orientation form, but the influence of different weaving patterns and natural filler addition is yet to be explored. The present work focuses on the fundamental natural frequency and damping factor of different styles of sisal bio fiber reinforced composite. Plain, basket, and twill weaving styles were used, and rice husk natural filler was used as secondary reinforced material to improve the properties. These composites were compared with randomly oriented short fiber composites.

EXPERIMENTAL

Materials Used

Sisal fiber was used as the primary reinforced material, and rice husk was the secondary reinforced material. Initially, individual sisal fiber was converted into continuous yarn to prepare a different weaving pattern. Similar to previous work carried out by Rajesh and Pitchaimani (2016), plain, basket, and twill weaving patterns were employed. Unsaturated polyester resin was used as matrix material, and methyl ethyl ketone peroxide (MEKP) ($C_8H_{18}O_6$) and cobalt naphthenate ($CoC_{22}H_{14}O_4$) were used as the catalyst and accelerator, respectively. The matrix mixture was prepared using unsaturated polyester resin, MEKP, and cobalt naphthenate with weight ratio of 100:1:1. The diagram of different woven composites used in the study is presented in Fig. 1.

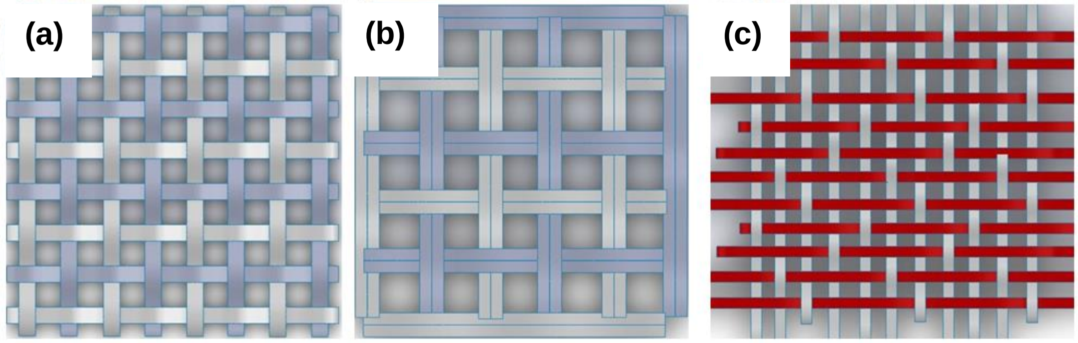

Fig. 1. Different woven fabric used in the study. (a) Plain; (b) basket; (c) twill

Fabrication of Composites

The hand lay-up technique was employed to fabricate different woven fiber reinforced composite laminate. A mould cavity with a size of 300 mm × 300 mm × 3 mm made of stainless steel was used to fabricate the composite laminate. A known amount of matrix mixture was poured into the mould cavity, and then a woven fabric was set into place. The remaining amount of matrix material was then poured, and the natural fiber sisal fabric was placed one at a time. A stiff parallel plate was placed over the mould cavity, followed by a 60 kg weight to achieve the uniform composite laminate. After 24 h of curing, composite laminates were sized for the mechanical and free vibration tests. A previous analysis showed that a four layered model enhances the composite strength (Rajesh *et al.* 2016c). Hence, in this study, four layered bi-directional (90 degree) composites were used to analyse the dynamic properties of sisal fiber reinforced composite structure. Thickness of different fabrics used in the study varies between 1 mm to 1.5 mm and weight of woven fabric such as plain, basket and twill is around 23, 27, and 24 grams respectively.

Rice husk natural filler was used as a secondary reinforcement to enhance the dynamic properties of composites. The secondary reinforced material, rice husk, was mixed with unsaturated polyester resin and stirred at 900 rpm for 4 h, using a high speed mechanical shear mixer to achieve uniform mixing (Rajesh *et al.* 2016a). Different composites used in the study included plain woven composite (PC), basket woven composite (BC), twill woven composite (TC), randomly oriented short fiber composite (SR), and natural filler added composite (BNC). Figure 1 shows the different woven sisal fiber fabrics used in the study.

ASTM standards D-638 (2003) and D-790 (2003) were employed to analyse the tensile and flexural strength of woven fabric and natural filler reinforced composites. Five samples of each type of composites were tested in both testing, to obtain a reliable average value of respective results. A loading speed of 2 mm/min was used to find the tensile strength of laminated the composites. A three point bending test was carried out to find the bending strength of the composite laminate. The fundamental natural frequency and corresponding modal damping factor of different composites used in this study were obtained using modal analysis.

Free vibration analysis

Experimental modal analysis was conducted to find out the fundamental natural frequency and damping factor of various composites used in this study. The values were calculated using modally tuned impulse hammer technique under fixed-free boundary condition. Five composite beams with dimensions of 170 mm × 17 mm × 3 mm each were used to analyse the natural frequency and associated damping factor of composite laminates (Rajesh and Pitchaimani 2016b). In this experiment, a modally tuned impulse hammer (Kistler 9722A2000, Amherst, NY, USA) was used for excitation of the composite beam, while a light-weight accelerometer (Kistler 8778A500) was used to acquire a corresponding displacement signal. An acquired displacing signal was sent to DEWE - data acquisition system (DEWETRON, DS7.1, Grambach, Austria) for converting time domain signal to frequency response signal through a fast Fourier transfer algorithm (FFT). A corresponding peak of frequency response signal provided the fundamental natural frequency to the composite beam. A schematic diagram of samples used for free vibration analysis in the study is shown in Fig. 2. Figure 3 shows the experimental setup used to find the fundamental natural frequency and the associated modal damping factor of composite material.

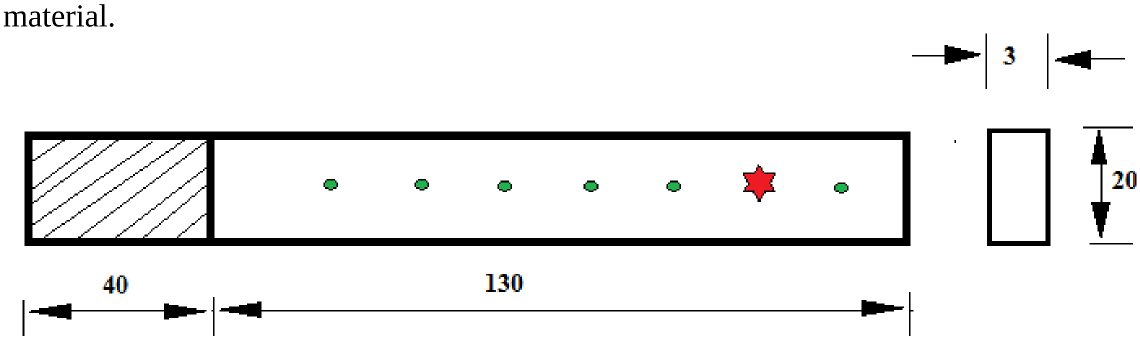

Fig. 2. Schematic diagram of test specimen used in the study. All dimensions are in mm.

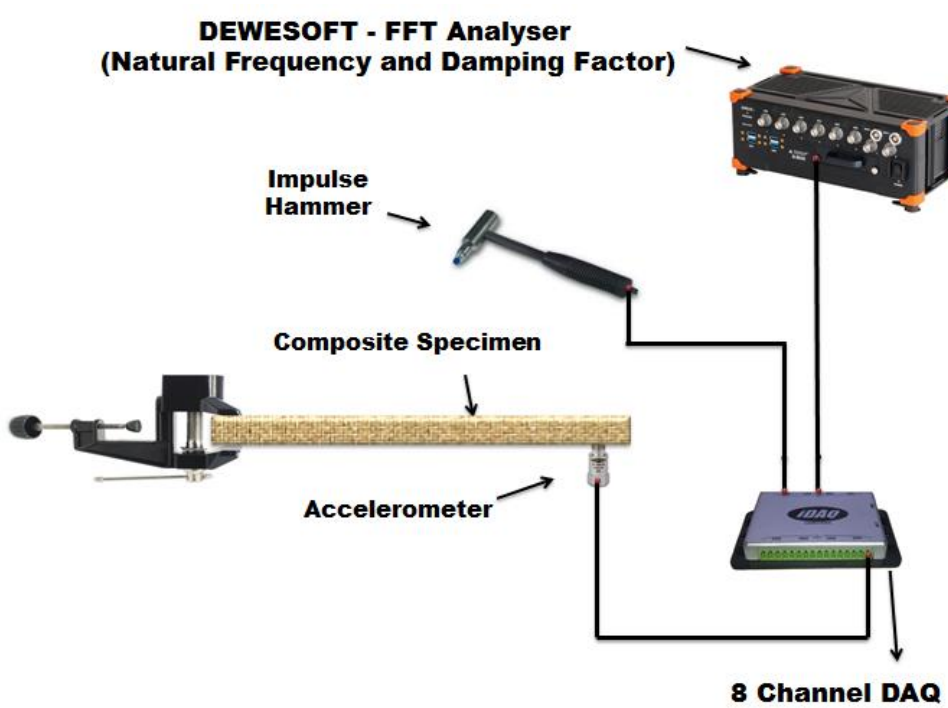

Fig. 3. Experimental setup of free vibration analysis

Material Characterization

Scanning electron microscopy (SEM) with a Hitachi model S3400 microscope (Krefeld, Germany) was used to analyze the surface morphology and interfacial bonding between fiber and matrix.

RESULTS AND DISCUSSION

Free Vibration Analysis

The fundamental natural frequency and corresponding damping factor of different composites under the fixed-free boundary conditions are presented in Table 1. The properties of the composite beam were enhanced in composites with basket reinforcement, in comparison to other types of reinforcement. The basket weave reinforcement enhanced the stiffness. The twill weave enhanced the damping factor of composite beam, and plain weave fell between basket weave and twill weave. An explanation for the higher natural frequency associated with the basket weaving pattern is tightness and lower crimp of fiber yarn in the warp and weft directions, combined with the lower stress concentration between two successive yarns. This provides high resistance against free molecule movement. The basket style reinforcement increased the first fundamental natural frequency of the composite beam by 15% and 20% compared with plain and twill weave, respectively (Table 1). Similarly, the second and third fundamental natural frequency of the basket woven reinforced composite beam increased from 12% to 22% compared with plain weave and twill weave reinforcement. From the observation it is apparent that the fundamental natural frequency and damping factor of natural fiber composite materials depended on aspect ratio, fiber orientation angle, laminate stacking sequence, and adhesion between fiber and matrix. However, other than the factors mentioned, fiber yarn orientation, gap, tightness, and crimp in the warp and weft direction were found to influence the natural frequency of composite laminate. In the case of basket, two fiber yarns are moving together in the warp and weft direction whereas single fiber yarn is moving in plain weave. It also, influences the strength behaviour of respective composite. Also crimp in the plain weave was higher compared to basket this reduces the natural frequency of plain weave composite. Furthermore, the same weight percentage of the basket weave reinforcement was compared with randomly oriented short fiber composites.

Table 1. Free Vibration Characteristics of Different Woven Composites

Type of Composite	Natural Frequencies (Hz)			Damping Factor		
	1st Mode	2nd Mode	3rd Mode	1st Mode	2nd Mode	3rd Mode
PC	51.7	330.6	879.0	0.0514	0.0348	0.0430
BC	59.4	390.2	990.1	0.0405	0.0333	0.0314
TC	49.7	319.0	820.0	0.0556	0.0398	0.0470
SR	29.3	185.5	498.0	0.0956	0.0515	0.0491
BNC	62.0	401.9	1062.8	0.0345	0.0293	0.0234

PC, plain woven composite; BC, basket woven composite; TC, twill woven composite; SR, randomly oriented short fiber composite; and BNC, natural filler added composite

Randomly oriented composites did not influence the fundamental natural frequency of the composite beam, due to the poor resistance provided against free molecule movement and high stress concentration produced by short natural fiber in the matrix. It also affected the stiffness of the composite laminate. The SR composite enhanced the damping factor of the composite beam due to the strong interaction between the fiber and the matrix. Compared with the SR composite, the woven composite provides high resistance against molecule movement, which reduces the interaction between the fiber and the matrix. Table 1 shows observed that the BR composite has less damping factor for first three bending modes (0.0405, 0.0333, and 0.0314) compared with the TC (0.0556, 0.0398, and 0.0470) and PC (0.0514, 0.0348, and 0.0430) composites. Thus, sisal biofiber with woven reinforcement enhances the stiffness of a composite beam because of the high Young's modulus of woven fabric. This stiffness allows the composite to carry a higher load and provides more resistance against failure. Main reason behind lower natural frequency associated with PC composite is the higher gap observed in plain weave. Due to this gap, more stress and crimp is produced which reduces the strength and results in poor load carry capacity. In the case of basket weave, fiber yarn movement is almost flat in the fabric, whereas in plain weave it is moving up and down. Stress concentration and load carry capability are the main factors in determining the strength behaviour.

Table 2. ANOVA Test for Natural Frequency of Different Woven Composite

Properties	Source of Variation	Sum of square	Degree of freedom	Mean square	F- value	P-value
Natural frequency	Within rows	184339.18	3	61446.39	5.293608	0.1022419
	Within in columns	537840.06	1	537840.0	46.33493	0.0064842

From the analysis of variance (Table 2), natural frequency was analyzed in both column (different type of composite) and row wise (different types of modes). From the table it can be concluded that the model was statistically significant and also there was significant difference between input and output responses.

Table 3. Mechanical Properties of Different Woven Fabric Composites

Type of Composite	Fiber Weight percentage (%)	Tensile Properties		Flexural Properties	
		Tensile Strength (MPa)	Tensile Modulus (GPa)	Flexural Strength (MPa)	Flexural Modulus (GPa)
PC	40	34.13±0.79	1.46±0.28	60.77±0.90	1.51±0.11
BC	47	43.60±0.72	1.67±0.25	69.54±0.91	2.50±0.13
TC	40	31.42±0.68	1.20±0.13	56.37±0.27	1.39±0.11
SR	47	27.12±0.47	1.15±0.10	48.61±0.29	1.31±0.17
BNC	5% filler	46.32±0.87	1.72±0.24	72.15±0.57	2.71±0.07

PC, plain woven composite; BC, basket woven composite; TC, twill woven composite; SR, randomly oriented short fiber composite; and BNC, natural filler added composite

The variation in stiffness properties of the woven reinforcement were confirmed with the variation in their strength behavior. Tensile and flexural tests were conducted on different fiber-reinforced composites to understand the influence of fiber yarn orientation on the warp and weft direction of strength of the respective composites. Table 3 reveals that the BC composite had enhanced the tensile and flexural strength compared with the TC and PC composites. The main reason for this effect is the basket woven reinforcement, which enhances the Young's modulus, resulting in increased resistance to loading. Another important reason is the uniform stress distribution and less stress concentration between two successive fiber yarns, which influences many of their properties. In a plain weave, the gap between two successive fiber yarns in the warp and weft directions is greater than in a basket weave. This generates more stress concentration under loading and may lead to early failure. The twill weave produces non-uniform stress distribution due to the fiber yarn arrangement in the warp and weft directions.

In the twill weave fiber, yarns were oriented in the warp direction diagonally, which transfers stress non-uniformly under loading. Compared with the twill weave, plain weave enhanced the tensile and flexural strength of composite laminates. This enhanced strength was attributed to the high crimp in the plain weave. Therefore, the arrangement of the fiber yarn influenced much of their strength and stiffness behavior. It is evident that the PC composite had higher natural frequency than TC (Table 1). Furthermore, the strength of woven composites with the basket weave style was compared with SR. Composites with randomly oriented short fiber composites produced more stress in the matrix under loading, which leads to cracks that form and propagate randomly.

The natural filler was added as a secondary reinforced material in the polymer matrix to improve the properties of the BC composite. The addition of 5 wt.% natural filler in the polymer matrix enhanced the tensile and flexural strength of the composite. When the filler was reinforced with the secondary reinforcement in the matrix, the load carrying ability of the composite material was increased. This increase occurs when the filler material in the matrix fills the gap between the two successive fiber yarns in the warp and weft directions. Hence, it reduces the stress concentration. The addition of the natural filler in the matrix encircles the fiber yarn, thus it providing more stiffness and resistance against loading. A similar conclusion was drawn from the data in Table 1. The fundamental natural frequency of the composite material reveals the addition of the natural filler in the matrix, which enhances the stiffness of composites. The addition of the natural filler forms a rough surface over the fiber yarn, which enhances the adhesion between the fiber and the matrix by increasing the surface contact. Hence, the addition of filler increases the mechanical interlocking capability of the fiber and the matrix. The enhancement in adhesion results in resistance against crack propagation and its rapid growth.

The results also revealed that the addition of natural filler increases the first three fundamental natural frequencies in the range of 2% to 8%. This result is also confirmed by the increase in tensile and flexural modulus of composite material.

Tensile Fracture Morphology

The fiber-matrix adhesion and matrix damage of tensile fracture specimens were analyzed by SEM (Fig. 4). Figure 4a shows a bundle of fiber yarn pull-out under tensile loading. This result reveals that early failure of the composites is due to poor stress transferring behavior and high stress concentration between two successive fiber yarn in the warp and weft directions. Figures 4b and 4c reveal the fiber-matrix adhesion of the basket weave. No crack formation or matrix damages were apparent under tensile loading. There was no observation of fiber and fiber yarn pull-out under loading. These results reveals that basket weave transferred stress uniformly and carried more load. Figure 4d reveals rough surface formation over fiber due to the inclusion of natural fillers in the fiber matrix. This increases the adhesion between the fiber and the matrix, due to increasing capability of mechanical inter lock.

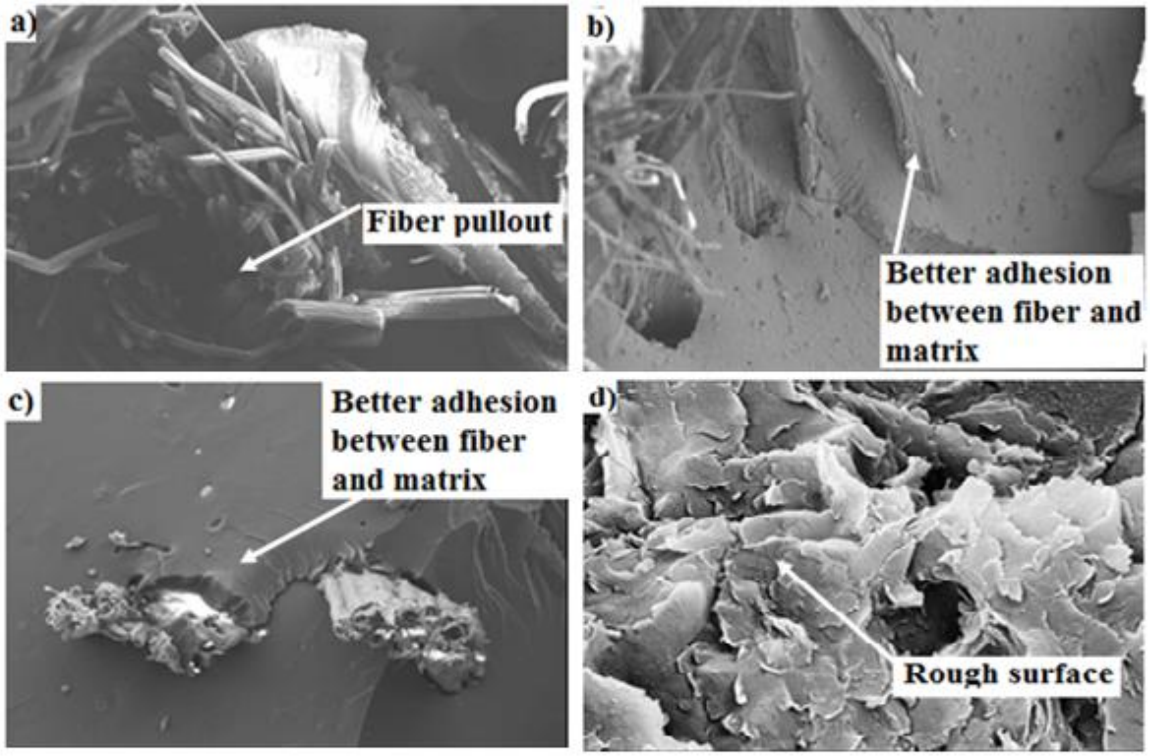

Fig. 4. SEM morphology of tensile fractured specimen at magnification 120x. (a) Plain weave; (b and c) basket weave; (d) BCR composite

CONCLUSIONS

1. Basket woven reinforcement enhances the stiffness and strength of composite laminate, compared with other weaving style.
2. Woven reinforcement enhances the stiffness and strength of composite materials, compared with the same weight percentage of fiber with random orientation. This is a result of the higher Young's modulus of woven fabric, which enhances the load carry capacity and provides the resistance against loading while randomly oriented composites increase the stress concentration in the matrix.
3. The natural filler addition increases the fundamental natural frequency of the composite material, due to the enhancement of adhesion between the fiber and the matrix.
4. The damping factor results illustrate that it can be enhanced *via* the twill woven style, due to the higher interaction of fiber and matrix and the addition of filler that enhances the natural frequency of composites.
5. Analysis of variance was conducted for this model and found to be statistically significant, and there is a significant difference between input and output responses.

ACKNOWLEDGEMENTS

The authors wish to thank the Department of Design and Automation, School of Mechanical Engineering, VIT University, Vellore Campus, Tamil Nadu India, Kalasalingam University, Tamil Nadu India, for providing their support. Thanks are also due to the Universiti Putra Malaysia for the close collaboration provided through the Grant Putra GP-IPB grant No. 9490600 for this research work. Special thanks to Aerospace Manufacturing Research Centre (AMRC) Universiti Putra Malaysia and also to Laboratory of Biocomposite Technology, Institute of Tropical Forestry and Forest Products (INTROP), University Putra Malaysia.

REFERENCES CITED

Berthelot, J. M. (2006). "Damping analysis of laminated beams and plates using the Ritz method," *Composite Structures* 74(2), 186-201. DOI: 10.1016/j.compstruct.2005.04.031

Bodros, E., Pillin, I., Montrelay, N., and Baley, C. (2007). "Could biopolymers reinforced by randomly scattered flax fibre be used in structural applications?," *Composites Science and Technology* 67(3–4), 462-470. DOI: 10.1016/j.compscitech.2006.08.024

Boopalan, M., Niranjanaa, M., and Umapathy, M. J. (2013). "Study on the mechanical properties and thermal properties of jute and banana fiber reinforced epoxy hybrid composites," *Composites Part B: Engineering* 51, 54-57. DOI: 10.1016/j.compositesb.2013.02.033

Dhawan, V., Singh, S., and Singh, I. (2013). "Effect of natural fillers on mechanical properties of GFRP composites," *Journal of Composites* 2013, 1-8. DOI: 10.1155/2013/792620

Haq, M., Burgueño, R., Mohanty, A. K., and Misra, M. (2008). "Hybrid bio-based composites from blends of unsaturated polyester and soybean oil reinforced with nanoclay and natural fibers," *Composites Science and Technology* 68(15–16), 3344-3351. DOI: 10.1016/j.compscitech.2008.09.007

Joshi, S., Drzal, L., Mohanty, A., and Arora, S. (2004). "Are natural fiber composites environmentally superior to glass fiber reinforced composites?," *Composites Part A: Applied Science and Manufacturing* 35(3), 371-376. DOI: 10.1016/j.compositesa.2003.09.016

Kokta, B. V., Raj, R. G., and Daneault, C. (1989). "Use of wood flour as filler in polypropylene: Studies on mechanical properties," *Polymer-Plastics Technology and Engineering* 28(3), 247-259. DOI: 10.1080/03602558908048598

Lee, S. H., and Wang, S. (2006). "Biodegradable polymers/bamboo fiber biocomposite with bio-based coupling agent," *Composites Part A: Applied Science and Manufacturing* 37(1), 80-91. DOI: 10.1016/j.compositesa.2005.04.015

Monteiro, S. N., Terrones, L. a H., and D'Almeida, J. R. M. (2008). "Mechanical performance of coir fiber/polyester composites," *Polymer Testing* 27(5), 591-595. DOI: 10.1016/j.polymertesting.2008.03.003

Rajesh, M., Jeyaraj, P., and Rajini, N. (2016a). "Mechanical, dynamic mechanical and vibration behavior of nanoclay dispersed natural fiber hybrid intra-ply woven fabric composite," in: *Nanoclay Reinforced Polymer Composites: Natural Fibre/Nanoclay Hybrid Composites*, M. Jawaid, A. el K. Qaiss, and R. Bouhfid, eds., Springer

Singapore, Singapore, pp. 281-296. DOI: 10.1007/978-981-10-0950-1_12

Rajesh, M., and Pitchaimani, J. (2016a). "Dynamic mechanical analysis and free vibration behavior of intra-ply woven natural fiber hybrid polymer composite," *Journal of Reinforced Plastics and Composites* 35(3), 228-242. DOI: 10.1177/0731684415611973

Rajesh, M., and Pitchaimani, J. (2016b). "Dynamic mechanical and free vibration behaviour of natural fiber braided fabric composite: Comparison with conventional and knitted fabric composites," *Polymer Composites*. DOI: 10.1002/pc.24234

Rajesh, M., and Pitchaimani, J. (2017). "Mechanical properties of natural fiber braided yarn woven composite: Comparison with conventional yarn woven composite," *Journal of Bionic Engineering* 14(1), 141-150. DOI:10.1016/S1672-6529(16)60385-2

Rajesh, M., Pitchaimani, J., and Rajini, N. (2016b). "Free vibration characteristics of banana/sisal natural fibers reinforced hybrid polymer composite beam," *Procedia Engineering*, 144, 1055-1059. DOI: 10.1016/j.proeng.2016.05.056

Rajesh, M., Singh, S. P., and Pitchaimani, J. (2016c). "Mechanical behavior of woven natural fiber fabric composites: Effect of weaving architecture, intra-ply hybridization and stacking sequence of fabrics," *Journal of Industrial Textiles*. DOI: 10.1177/1528083716679157

Sapuan, S. M., and Maleque, M. a. (2005). "Design and fabrication of natural woven fabric reinforced epoxy composite for household telephone stand," *Materials and Design* 26(1), 65-71. DOI: 10.1016/j.matdes.2004.03.015

Sastra, H. Y., Siregar, J. P., Sapuan, S. M., and Hamdan, M. M. (2006). "Tensile properties of *Arenga pinnata* fiber-reinforced epoxy composites," *Polymer-Plastics Technology and Engineering* 45(April 2015), 149-155. DOI: 10.1080/03602550500374038

Senthil Kumar, K., Siva, I., Rajini, N., Winowlin Jappes, J. T., and Amico, S. C. (2016). "Layering pattern effects on vibrational behavior of coconut sheath/banana fiber hybrid composites," *Materials and Design* 90, 795-803. DOI: 10.1016/j.matdes.2015.11.051

Srinivasa, C. V., Suresh, Y. J., and Kumar, W. P. (2014). "Experimental and finite element studies on free vibration of skew plates," *International Journal of Advanced Structural Engineering*. 2014. 6. 48.

Venkateshwaran, N., ElayaPerumal, A., Alavudeen, A., and Thiruchitrambalam, M. (2011). "Mechanical and water absorption behaviour of banana/sisal reinforced hybrid composites," *Materials and Design* 32(7), 4017-4021. DOI: 10.1016/j.matdes.2011.03.002

Vimalanathan, P., Venkateshwaran, N., and Santhanam, V. (2016). "Mechanical, dynamic mechanical, and thermal analysis of *Shorea robusta*-dispersed polyester composite," *International Journal of Polymer Analysis and Characterization* 21(4), 314-326. DOI: 10.1080/1023666X.2016.1155818

Article submitted: August 8, 2017; Peer review completed: October 1, 2017; Revised version received and accepted: January 24, 2018; Published: January 30, 2018.
DOI: 10.15376/biores.13.1.1951-1960