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Vibration analysis of carbon and Kevlar fiber reinforced composites containing SiC particles

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Abstract

This study investigates the vibration-damping properties of Kevlar and carbon fiber reinforced composites with addition of SiC particles within epoxy resin. Experimental modal analysis was performed to extract natural frequency and damping property with aim of the enhancing dynamic performance of the composite system containing SiC particles. A numerical model using ABAQUS software was developed in attempt to predict higher mode frequencies with mode shapes. Results showed that addition of SiC particles with the carbon/epoxy and Kevlar/epoxy composites resulted in a significant effect by means of vibration and damping properties due to interface strength between SiC particles and polymer matrix those influencing elastic properties.

Keywords: Carbon fiber composite, Kevlar fiber composite, silicon carbide (SiC) particles, damping and vibration.

1. INTRODUCTION

Composite materials are extensively used in the aerospace, automobile and other engineering applications, as it exhibits outstanding performance to insight a stronger, stiffer and lightweight material. In the last decades, many researcher have shown their concern on enhancement of mechanical properties in composite materials incorporating micro or nano scale particles [1-4]. Herein, matrix modification is most appreciated method for increasing of mechanical performance, and several researchers have indicated that incorporation of particulate filler in the epoxy resin results in significant increase in tensile strength, modulus and impact strength as a result of synergistic effects [5-6]. Among the fillers, SiC reinforced composites provide an effective way to increase mechanical properties of composite materials because of high specific strength and rigidity, ductility, high mechanical performance at elevated temperatures, high conductivity of thermal and electric, and excellent wear resistance [7];[8];[9];[10];[11], and [12]. Besides mechanical properties, knowledge on vibration properties of fiber-reinforced composites plays an important role for sustaining structural performance of the components since they are often exposed to the external cyclic and impact loadings leading to a significant effect on the stability of the system. To overcome this difficulty, incorporation of particle within the common matrix is an effective way to increase mechanical and dynamic stability of the composite structures, and several researchers [13-15] showed that incorporating of particles with a certain weight content would significantly increase in the mechanical properties because of good bonding strength between particle and matrix, leading to increasing of mechanical, impact and vibration properties.

SiC particles are mostly preferred as the reinforcement material [16, 17] since they exhibit high wear resistance, superior mechanical properties at temperatures, and low cost. In addition, SiC particles does not react with the matrix resin at high temperatures, and form

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undesired phases [18]. With advent of technical developments, they are improved including suitability between reinforcement and matrix, and primary and secondary processing techniques are capable of adequately controlling particle distributions, methodology of engineering design, and characterization and controlling of interfacial properties [19].

It is commonly known that mechanical properties of the composites are significantly affected by size and amount of the particles used as filler. The agglomeration or aggregation of particles with large sized clustered of SiC particles cannot efficiently transfer the load between particle and matrix, leading to decreasing of mechanical and interlaminar fracture properties [20-24].

Present study aims to investigate the vibration and damping characterization of polymer composites reinforced with carbon and Kevlar fibers. Microstructures of the prepared samples were investigated by SEM. The variation of natural frequencies was experimentally compared according to SiC content and fiber types. For reliability of the experimental results, numerical analysis have been performed to predict natural frequency and modal shapes for extended frequency range.

2. PREPARING TEST SAMPLES

The fiber used as reinforcing materials were woven carbon with plain weave and woven Kevlar with twill weave, and their areal densities are 200 g/m2 and 173 g/m2, respectively. Chemical materials used for lamination (MGS L285-epoxy resin MGS 285-hardener) were supplied Dost Kimya Company, and SiC particles were purchased from Eti Mine Works General Management. The mixing ratio of the epoxy and hardener is 100:40 in the weight. SiC particles were used as additive filler for production of SiC filled composites. Particles have the 35 µm size of the average diameter with bulk density of 1.49 g/cm^3. Four different weight ratios of 5, 10, 15 and 20 wt% were considered for vibration analyses. Table 1 shows the measured physical properties of the samples, and mechanical properties of fibers, matrix and SiC particle were presented in Table 2. Figure 1 shows the SEM images of the cross sectional area for the samples of unfilled and CFRE-SiC15 and KFRE-SiC15 composites.

Table 1. Physical properties of SiC filled composites.

Specimens	SiC content (wt%)	Measured density (gr/cm^3)	Thickness (mm)
CFRE	0	1.476	3.71
CFRE-SiC$_5$	5	1.401	4.15
CFRE-SiC$_{10}$	10	1.409	4.29
CFRE-SiC$_{15}$	15	1.428	4.37
CFRE-SiC$_{20}$	20	1.445	4.51
KFRE	0	1.231	4.63
KFRE -SiC$_5$	5	1.224	5.22
KFRE -SiC$_{10}$	10	1.238	5.25
KFRE -SiC$_{15}$	15	1.234	5.36
KFRE -SiC$_{20}$	20	1.239	5.38

Table 2. Mechanical properties of materials used in experiments [21].

Material	Areal density (g/m^2)	Density (g/cm^3)	Tensile strength (MPa)	Elastic Modulus (GPa)
Carbon	200	1.75-1.96	2500-4000	275-630
Kevlar	200	1.44	2800-3000	82-124
Epoxy	-	1.25	69	3.5
SiC	-	1.49	206.89	482.758

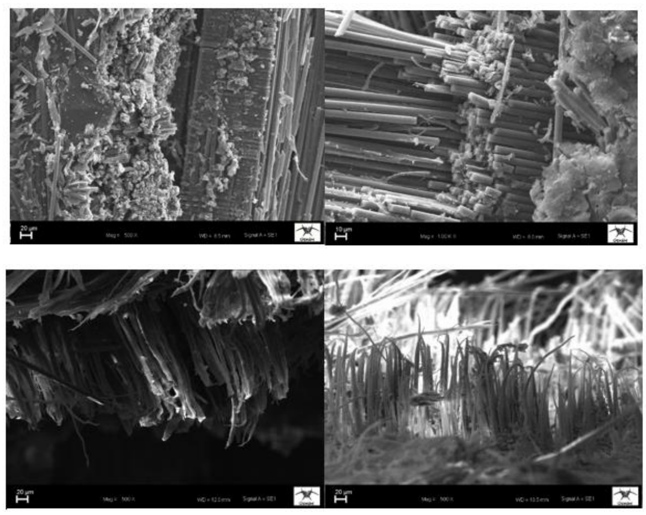


Figure 1. SEM figures (a) CFRE, (b) CFRE-SiC15, (c) KFRE, (d) KFRE-SiC15 composites

3. VIBRATION TESTS

An accelerometer (PCB 352C03 ceramic shear ICP ®) for output signal, an impact hummer (PCB 086C03) for excitation of sample, and a signal acquisition data card (NI 9234) with LABVIEW software were used. Manufactured test samples were excited by impact hammer to release dynamic characteristics in terms of acceleration and frequency response. Free decaying curves of the samples were evaluated by the excitation of the samples using impact hammer. During the vibration tests, frequency response properties of the samples were recorded as a function of amplitude and frequency (Hz) by using Fast Fourier Transforms (FFTs), which allows to determine natural frequencies and damping factors. Frequency responses were measured within the constant frequency range from 0 to 500 Hz. Figure 2 describes the experimental set-up to measure vibration properties of test samples, also illustrating location of accelerometer, and test samples for vibration tests.

During the measuring natural frequencies in vibration tests, position of accelerometer played an important role natural frequency and its maximum amplitude, and this was attributed to the weight of the accelerometer (5.8 g) which was significant according to beam weight. In order to abstain weght effect due to accelerometer, accelerometer was mounted near the fixed edge away from clamped edge by 25 mm.

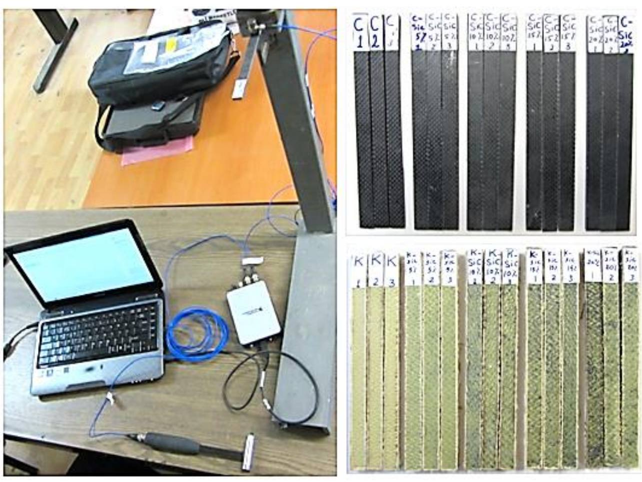


Figure 2. Vibration test setup and test samples

4. NUMERICAL STUDIES

It is attempted in numerical studies that procedures of Abaqus frequency analysis were used to calculate the natural frequencies and the corresponding mode shapes of the shell plate system. While solving the natural frequencies of the system, following eigenvalue equation (Equation 1) was performed to extract natural frequencies [25]

$$(-\omega^2 M^{MN} + K^{MN})\phi^N = 0 \quad (1)$$

Where, M^{MN} is the mass matrix (which is symmetric and positive definite), K^{MN} is the stiffness matrix (which includes initial stiffness effects if the base state included the effects of nonlinear geometry), and ϕ^N is the eigenvector (the mode of vibration); and M and N are degrees of freedom.

In Abaqus/Standard, Linear perturbation analysis was used for extraction of natural frequencies. Method of Lanczos was used for extraction of eigenvalues. Number of nodes and elements used in the numerical analyses were 1410 and 1316, respectively. Element type of S4R was used for modelling of conical shell structure. Five first modes were extracted for different modes and boundary conditions. Figure 3 illustrates the numerical model constructed in Abaqus software.

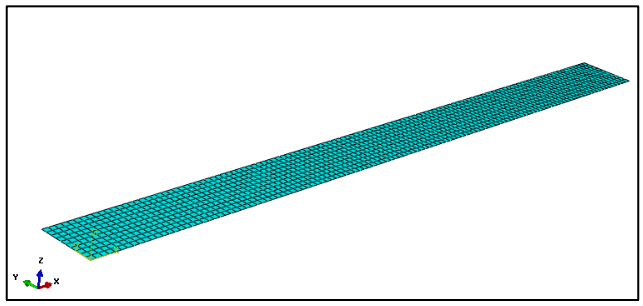


Figure 3. 3-D numerical modelling of composite shell for vibration analysis

5. RESULTS AND DISCUSSIONS

5.1. Vibration tests

Dynamic behavior of the structure were characterized by the damping and natural frequencies.

In the vibration theory, equation of time response can be written as equation (2) for a single degree freedom:

$$f(t) = Ae^{-\zeta\omega_n t} \quad (2)$$

A is a constant and t is time. Relationship between natural frequency and damping ratio can be written as equation (3). Where ζ and ω_n are damping ratio and natural frequency, respectively.

$$\omega_d = \omega_n\sqrt{1-\zeta^2} \quad (3)$$

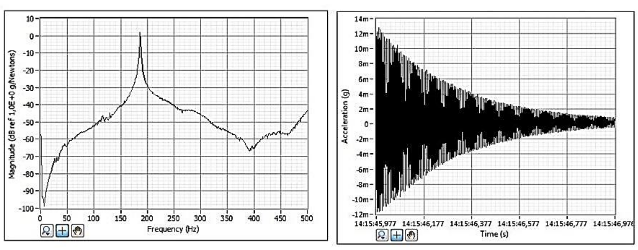
Time response of the damped system has been measured from Fourier transform (FFT). From experimental modal analysis, FFT has been performed using a software (NI Signal Express) to indicate frequency response of the system. Equation of envelope curves and frequency responses can be determined using time and frequency responses those obtained with experimental data. Frequency and time responses were illustrated in Figure 4. In addition, from experimental results, FEM models of the full samples (KFRE and CFRE) were developed by using ABAQUS software in order to show mode shapes and natural frequencies for higher modes. Table 3 and Table 4 present both experimental and numerical results implying that experimental and numerical results were in good agreement for fundamental frequency. It is clear that inclusion of SiC particles by 10 wt% into the epoxy resin contributed an 11.2 % improvement in natural frequency for CFRE samples, while maximum 9.4 % improvement in natural frequency has been occurred when incorporation of SiC particles into the epoxy resin of KFRE samples at filler content of 15 wt%.

Table 3. Numerical and experimental results for natural frequencies of CFRE-SiC composites

	CFRE		$CFRE\text{-}SiC_5$		$CFRE\text{-}SiC_{10}$		$CFRE\text{-}SiC_{15}$		$CFRE\text{-}SiC_{20}$	
Mode	FEM	Exp.	FEM	Exp.	FEM	Exp.	FEM	Exp.	FEM	Exp.
1	184.7	186.3	195.6	195.5	205.1	202.7	206.2	195.5	207.6	194.5
2	463.2		489.6		504.6		507.0		510.3	
3	1131.5		1200.0		1255.4		1261.3		1269.2	
4	1471.4		1606.4		1620.8		1610.6		1596.4	
5	2558.1		2721.5		2785.9		2792.3		2800.6	

Table 4. Numerical and experimental results for natural frequencies of KFRE-SiC composites

	KFRE		$KFRE\text{-}SiC_5$		$KFRE\text{-}SiC_{10}$		$KFRE\text{-}SiC_{15}$		$KFRE\text{-}SiC_{20}$	
Mode	FEM	Exp.	FEM	Exp.	FEM	Exp.	FEM	Exp.	FEM	Exp.
1	179.5	180.224	179.3	181.2	185.9	185.3	193.6	197.6	173.2	175.1
2	401.2		390.0		404.1		420.5		377.0	
3	1106.4		1105.5		1144.9		1190.6		1068.8	
4	1840.8		1871.7		1873.0		1874.6		1870.5	
5	2328.1		2271.5		2342.8		2424.5		2204.3	



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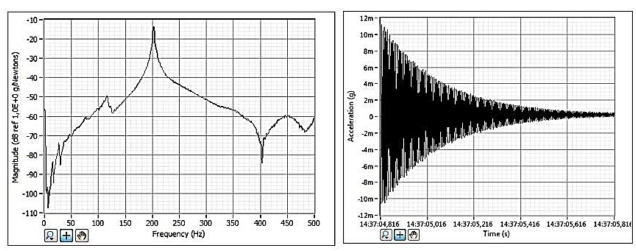

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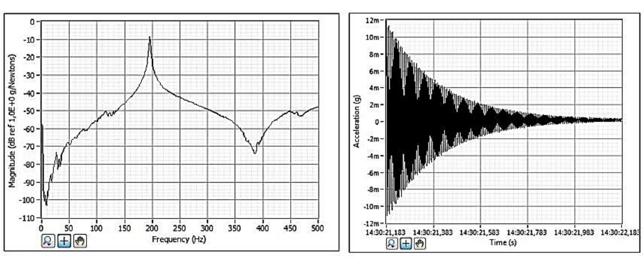

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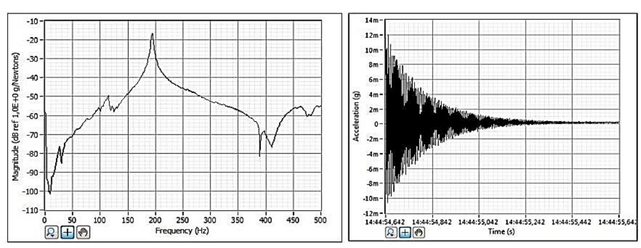

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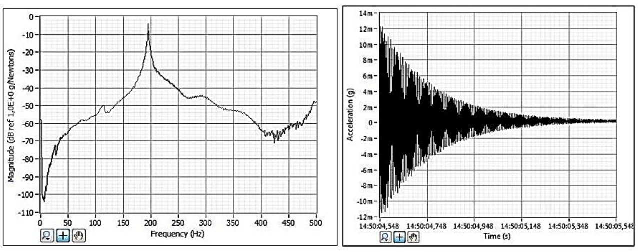


(e)

Figure 4. Vibration response of the CFRE samples with and without filler. (a) CFRE, (b) CFRE-SiC_5, (c) CFRE-SiC_{10}, (d) CFRE-SiC_{15}, (e) CFRE-SiC_{20}

Results from Figure 4 showed that incorporation of SiC particles in epoxy resin of CFRE samples lead to increasing of fundamental frequency up to the SiC content of 10 wt%, and further increasing particle content in the epoxy resin resulted in a reverse effect on fundamental frequency with decreasing trend. This was attributed the presence of agglomeration or aggregation leading to decrease mechanical and dynamic properties [26]. Interfacial properties significantly depend on enhanced stiffness and damping in the polymeric nanocomposites.

It is well known that well distribution of particles in the epoxy resin, and good adhesion between particle and matrix result in a significant enhancement in terms of stiffness leading to better load transfer between matrix and fibers. Another important parameter to enhance mechanical or dynamic properties is the filler content. It can be obtained a significant enhancement for mechanical properties at low content of SiC particles which were well distributed in the epoxy resin. This implies better interfacial strength between particle and fiber/epoxy system showing improvement of load transfer between particle and epoxy resin [27]

It is clear in Figure 4 that further increasing SiC content in epoxy resin after the SiC content of 10 wt%, local agglomeration effect has been occurred. These local agglomerations around the clustering SiC particles contribute the decreasing in stiffness and also dynamic properties in terms of natural frequency. As it is illustrated in Figure 4 denoting the acceleration curves of samples according to time, for comparison of damping characteristics according to SiC content in the epoxy resin, it can clearly be inferred that amplitude of CFRE samples faster decays at particle content of 15 wt% than control samples (unfilled), resulting in high damping capacity. As the loading of the SiC particles into the epoxy resin of KFRE samples results in increasing of stiffness, while also increasing of damping property as a results of high dissipation of vibration energy. This can be attributed the fact of enhancement of interfacial slippage effect between particle and epoxy, and perfect interfacial bonding strength between particle and matrix [28].

Figure 5 shows the mode shapes of the CFRE samples (unfilled) those obtained with numerical simulations. Modal simulations showed that first and three modes were in bending mode, second and fifth modes were in lateral mode, and fourth mode was in twisting mode. It can be concluded also natural frequency increases while increasing mode number.

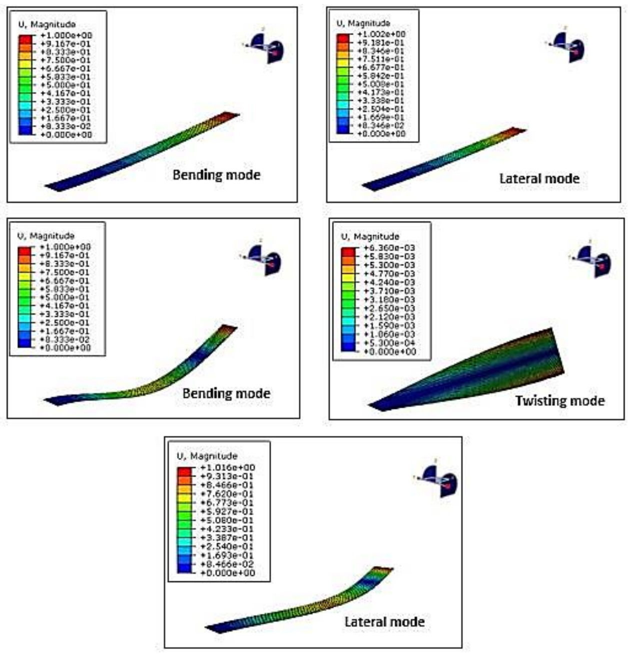
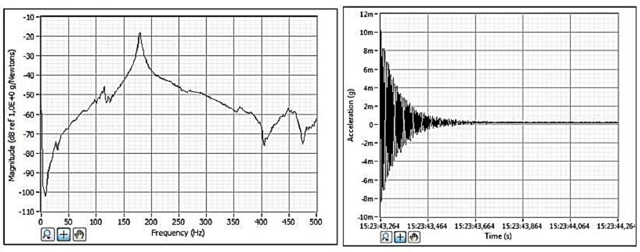


Figure 5. Mode shapes of the CFRE composite samples

The results of natural frequency values for KFRE reinforced with SiC particles were represented in Figure 6, and modal shapes for KFRE were shown in Figure 7. Similar results were observed for KFRE-SiC particle interaction compared with CFRE-SiC interaction. It is concluded that natural frequency of the KFRE samples increases up to the certain amount of SiC content of 15 wt%, then followed suddenly drop in natural frequency while increasing in SiC content in the epoxy resin. Modal simulations for KFRE samples showed that first and three modes were in bending mode, second and fifth modes were in lateral mode, and fourth mode was in twisting mode, indicating enhancement of natural frequency while increasing mode number.

As it is illustrated in Figure 6 denoting the acceleration curves of samples according to time, for comparison of damping characteristics according to SiC content in the epoxy resin, it can clearly be inferred that amplitude of KFRE samples (unfilled) faster decays than other samples (SiC filled samples), resulting in high damping capacity. As the loading of the SiC particles into the epoxy resin of KFRE samples results in increasing of stiffness, while reducing of damping property as a results of poor dissipation of vibration energy. This can be attributed the fact of reduction of slippage effect between particle and epoxy [29], and high damping capacity of the Kevlar fiber exhibiting high toughness [30].



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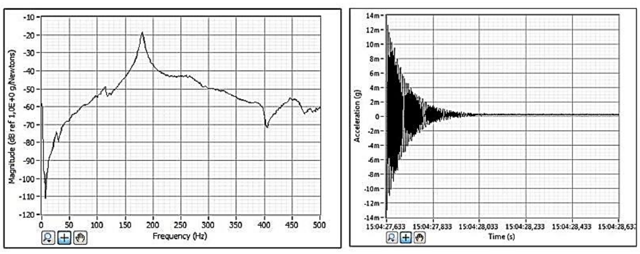

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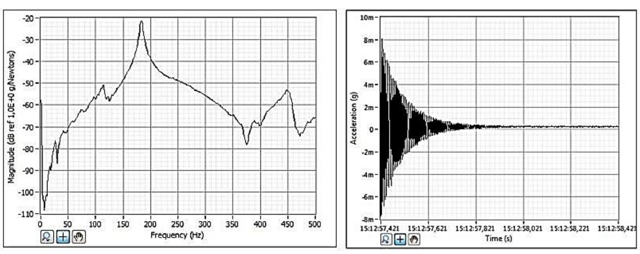

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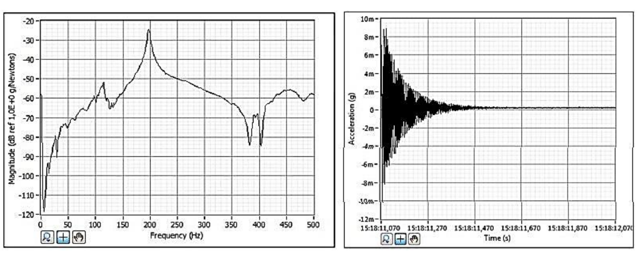

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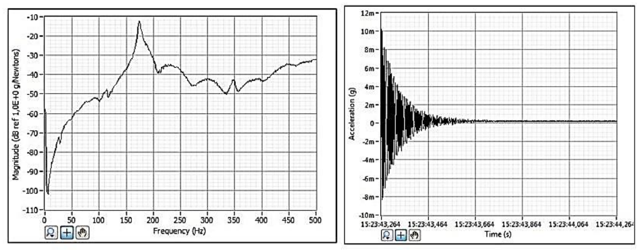


(e)

Figure 6. Vibration response of the KFRE samples with and without filler. (a) KFRE, (b) KFRE-SiC_5, (c) KFRE-SiC_{10}, (d) KFRE-SiC_{15}, (e) KFRE-SiC_{20}

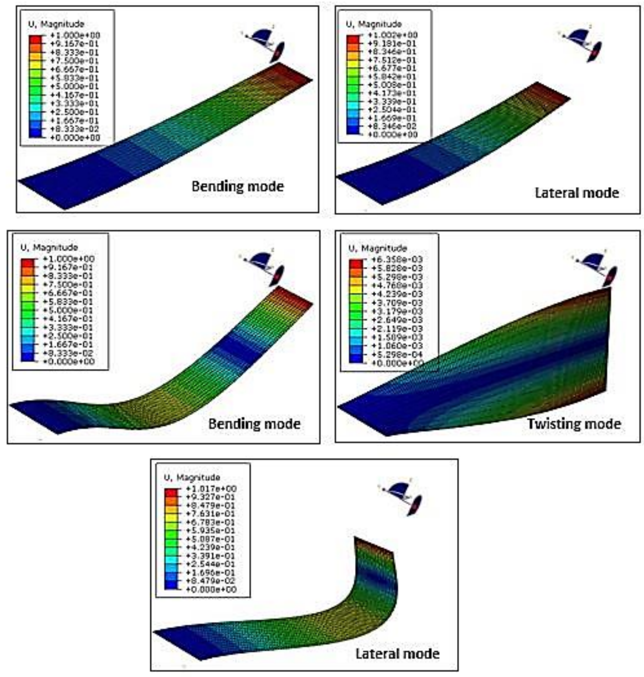


Figure 7. Mode shapes of the KFRE composite samples

5.2. Damping properties

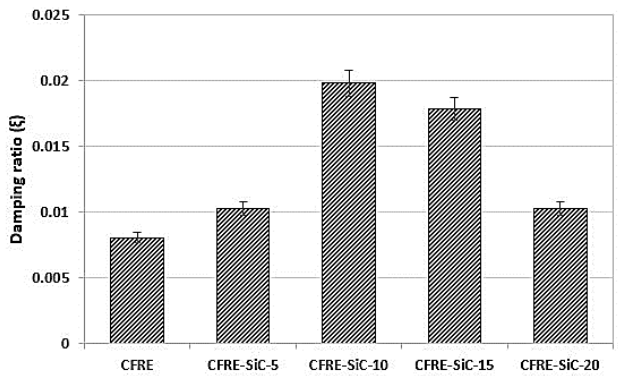
Log decrement method is a popular method to measure damping properties for an under-damped system, and can be evaluated by using equation 4.

$$\delta = \frac{1}{n} \ln \frac{A_0}{A} \qquad (4)$$

Where δ is the log decrement, A_0 is the maximum amplitude of first cycle and A is the maximum amplitude of nth cycle. Damping ratio (ξ) can be calculated from equation 5 by substitution of equation 4 into equation 5.

$$\xi = \frac{1}{\sqrt{1+\left(\frac{2\pi}{\delta}\right)^2}} \qquad (5)$$

In this way, it is can be explained that interfacial bonding between SiC particles-fiber-epoxy interfaces plays an important role for dissipation of energy in the composites. Figure 8 presents the comparison of the damping ratio values indicating that maximum enhancement in damping ratio was recorded at SiC loading of 10 wt% for CFRE-SiC interaction, while KFRE with SiC content of 5 wt% showed the highest value damping ratio revealing lower dissipation of energy per cycle of damping than other samples. A decreasing trend in terms of damping ratio was followed as increasing in SiC content in the epoxy resin after the SiC content of 10 wt% and 5 wt% for CFRE and KFRE composites, respectively. This was attributed the decreasing of interfacial bonding between SiC particle-fiber-epoxy interfaces because of particle agglomeration effect.



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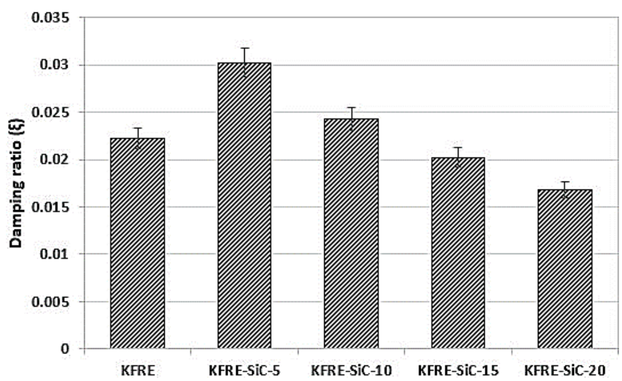

(b)

Figure 8. Damping ratios of the samples. (a) CFRE-SiC interaction, (b) KFRE-SiC interaction

It is attractive to possibility of the introducing SiC in KFRE and CFRE composites in order to control damping properties. An interface with poorly bonded structure may contribute to increasing of damping property as a result of sliding friction or slippage effect. A marginal enhancement in damping ratio was recorded as increasing of SiC content in epoxy resin, leading 36 % and 145 % improvement for KFRE and CFRE composites. This enhancement may be attributed the better interfacial bonding strength between particle and matrix, and also increasing of slippage effect leading to exhibit more absorption of vibration energy, and high damping capacity. However, further increasing of SiC resulted in decreasing of damping ratio leading to decreasing of slippage effect with enhanced interfacial bonding strength between SiC particles and matrix. Therefore, damping capacity through slippage effect will be followed by reduction in the stiffness and strength of composites. Enhancement of damping property may be also caused by increasing of dislocation density near the SiC particle and fiber/epoxy interface, and the heterogeneity and stress concentration effects are another major parameters those effecting damping capacity of the system.

6. CONCLUSIONS

In this study, vibration properties of the Kevlar and carbon fiber reinforced composites containing SiC particles were investigated for different content of SiC particle in the epoxy resin. Results showed that incorporation of certain amount of SiC particles in the CFRE and KFRE samples resulted in a significant improvement for natural frequency and acceleration decaying curves as a result of perfect interfacial bonding strength between SiC particles and fiber/epoxy resin system. Damping property also varies as a results of interfacial slippage effect those effecting acceleration decaying curves. Enhancement of damping properties was attributed the better interfacial bonding strength between particle and matrix, and also increasing of slippage effect leading to exhibit more absorbance of vibration energy and high damping capacity. Finally, for the stability and safety of carbon or Kevlar fiber reinforced composite systems, it is possible to arrange for requirement of designed system with incorporation of SiC particles in the epoxy resin at a certain amount of the weight content. However, excessive SiC loading into the epoxy resin results in reduction of mechanical and dynamic properties as a result of aggregation or agglomeration effects, leading to decrease load transfer between particle and matrix.

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