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Comparative Study of Damping in Pristine, Steel, and Shape Memory Alloy Hybrid Glass Fiber Reinforced Plastic Composite Beams of Equivalent Stiffness

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ABSTRACT

Several efforts were made over the years to control vibration of structural components made of composite materials. This paper consists of study on effect of using shape memory alloy (SMA) to increase the damping of glass fiber reinforced plastic (GFRP) composites. A comparative study between SMA and steel was made as reinforcement material in GFRP composites to enhance damping. Dimensions of each beam were calculated such that all the beams i.e. pristine GFRP beam, GFRP beam embedded with steel wires and GFRP beam embedded with SMA wires have same flexural stiffness and first mode of frequency of vibration. Damping ratio was measured experimentally through logarithmic decay method. Through experiments damping ratio obtained for SMA hybrid composite beam was found to be higher as compared to the pristine and steel hybrid GFRP composite beams.

Keywords: Shape memory alloy; Damping ratio; Glass fiber reinforced plastic; Vibration; Flexural stiffness

1. INTRODUCTION

Today composite materials find wide application in many newer areas both in civil[1] as well as military[2] because of their superior properties like high specific strength, high specific stiffness, and resistance to corrosion. Many researchers had tried to improve the properties of composite materials by hybridising them with other materials like toughened fibers and/or matrix[3], nano materials[4], smart materials like shape memory alloy (SMA)[5]. Among them SMAs have attracted a lot of attention from researchers for improving the performance of composites[6-9] due to their properties like Pseudoelasticity and shape memory effect. Mostly SMAs are embedded in composites to improve their energy absorbing capability for reducing damage induced due to impact[10,11]. SMAs possess unique properties like pseudoelasticity wherein materials recover their original shape even after strained up to 6 per cent to 8 per cent while loading. This is possible due to stress induced transformation of SMAs from austenite phase to martensite phase. While doing so SMAs develop a hysteresis, which is one of the causes of energy dissipation. The phase transformation events like formation of defects and dislocation movements cause energy dissipation. During vibration, there is a need to dissipate energy of the system so that the system will not vibrate near its natural frequency. The energy of the system can be reduced by internal friction or any other energy dissipating mechanisms which dampened the vibrating system. Therefore damping can be attributed to the capability of the material to dissipate mechanical energy into another form of energy. By hybridising composites with pseudoelastic SMAs, it may be possible to dissipate the energy of vibrating system while conversion of austenite phase into martensite phase and vice a versa. Because of this, hybridising pseudoelastic SMAs improves damping property of the composites.

Treviso[12], *et al.* had done literature review on damping of composite materials. They had presented details of recent developments of nano-composites, hybrid composites and sandwich materials on damping properties of composites. Vibration characteristics of composite material are also affected by fiber architecture. Lie[13], *et al.* had studied the effect of weaving pattern and found out that interlocked woven structures have better vibration performance than that of the plain-weaved fabric. Change in damping by embedding SMA wires in composites was studied by Lau[14], *et al.* He found out that the beam embedded with SMA wires shows higher damping ratio as compared to unhybridised beam. Run-Xin Zhang[15] carried out both experimental and simulation studies to find out the effective way of damping control in composite structures embedded with SMA wires and woven mesh. They found that woven SMA mesh provides higher damping in composites than SMA wires. Dehkordi[16], *et al.* had done numerical simulations of forced vibration of SMA hybrid composites and numerically found that the hysteresis behaviour of SMA helps in damping of the composites beam under vibration. Gupta[16], *et al.* had studied the vibration control in FRP shaft by using NiTi shape memory alloy to achieve rotor vibration control. They had found the change in natural frequency of shaft by activation and deactivation of SMA wires using electric resistive heating.

Presently, there is no comparative study on damping behaviour of composites embedded with SMA wires as

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compared to composites embedded with other metallic materials. Also there has been no study to quantify the improvement in damping properties of SMA hybrid composites and their effect on stiffness and natural frequency of the system. In the present paper attempt is made to find out the change in damping properties of composites hybridised with SMA wires as compared to damping properties of pristine (without any hybrid material) composite beams and steel wires embedded composite beams. All the beams i.e. pristine, SMA embedded and steel embedded GFRP beams are designed such that they have nearly the same stiffness and first mode of frequency of vibration. This was done to avoid the effect of increase in stiffness and mass of beam due to embedment of SMA and steel wires.

Table 2. Material properties of SMA and Steel

Material	Properties	Value
Shape memory alloy	Young's Modulus of martensite phase (E_M)	70 GPa
	Young's Modulus of austenite phase (E_A)	28 GPa
	Austenite Finish Temperature (A_f)	14 °C
	Start of transformational stress during loading (σ_L^S)	450 MPa
	End of transformational stress during loading (σ_L^E)	530 MPa
	Start of transformational stress during unloading (σ_{UL}^S)	250 MPa
	End of transformational stress during unloading (σ_{UL}^E)	125 MPa
	Recovery strain (ϵ^L)	6.5 %
	Density (ρ)	6450 kg/m^3
Steel	Young's Modulus (E)	203 GPa
	Density (ρ)	7860 kg/m^3

2. BEAM CONFIGURATION

All the three beams were designed such that they have equal flexural stiffness and frequency of vibration. In steel and SMA embedded GFRP beams it was assumed that wires were distributed uniformly in each layer of the beams. In all three beams 50 per cent glass fiber volume fraction was considered for calculation. A schematic of the beam configuration used for the study is shown in Fig. 1.

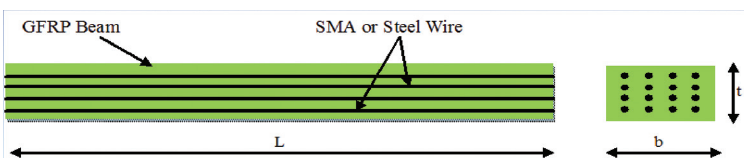


Figure 1. Schematic of beam.

The length, width and thickness of the beam are denoted as L, b and t respectively. The composite beam was designed and fabricated using glass fiber and epoxy resin. Reinforcement used in the present study was UD E-glass fabric (Chomarat Ruban 8033/1 F) of 500 gsm areal density. The matrix used for the composites was epoxy resin. Pseudoelastic SMA wires consisting of 50.8 per cent Ni (Nickel) and 49.2 per cent Ti (Titanium) supplied by the National Aerospace Laboratory, Bangaluru, India were used for hybridising with GFRP beam. Commercially available steel wires (SS 304) were used for the fabrication of steel embedded GFRP beam. The diameter of both SMA and steel wires used was 300 micron. Table 1 shows material properties of GFRP laminate considering 50 per cent fiber volume fraction. In Table 1, E is the Young's Modulus of material, G is the Shear Modulus and μ is the Poisson's ratio. Subscript '1' is longitudinal direction, '2' is transverse direction and '3' is out of plane direction. The material properties of SMA and steel wire are given in Table 2.

Table 1. Material properties of GFRP composite

$E_1 = 36.5$ GPa, $E_2 = E_3 = 9.5$ GPa
$G_{23} = 2.1$ GPa, $G_{12} = G_{13} = 7$ GPa
$\mu_{23} = 0.23$, $\mu_{13} = \mu_{12} = 0.29$

2.1 Beam Design

The vertical deflection (w) of the cantilever beam subjected to load P is given by

$$w = \frac{PL^3}{3EI}$$

The corresponding flexural stiffness (K) is given by

$$K = \frac{3EI}{L^3} = \frac{Ebt^3}{4L^3} \quad (1)$$

where E is the longitudinal Young's modulus, I is the moment of inertia, L is the length of beam, b is the width of beam, t is the thickness of beam.

Longitudinal young's modulus of pristine and hybrid composite beams was obtained from rule of mixtures which is given by :

$$E = E_f V_f + E_m V_m + E_h V_h \quad (2)$$

In Eqn. (1) values of t and L were kept the same in all the three beams. The value of flexural modulus in all the three beams was kept same by varying the width and number of wires. The length and thickness of the beams were kept the same, as small variations in their value cause considerable change in the value of flexural stiffness.

The frequency (f) of first mode of vibration for a cantilever beam is given by:

$$w = 2\pi f = (1.875)^2 \sqrt{\frac{EI}{\rho A L^4}}$$

$$f = 0.559 \times \sqrt{\frac{EI}{\rho A L^4}} \quad (3)$$

where ρ is the density of the beam material and A is the area of cross section of the beam. For pristine beam, width is assumed to be 40 mm. Substituting the values of dimensions and material properties, the value of flexural stiffness was calculated as 1443 N/m^2 and the frequency of first mode of vibration was calculated as 43.65 Hz for pristine GFRP beam.

For calculating the dimensions of SMA and steel hybrid composite beams, parametric analysis was carried out wherein the width and number of wires were varied. For the SMA hybrid composite beam, width of 37.5 mm was fixed and number of wires were varied to calculate the equivalent flexural stiffness and first mode of frequency of vibration which should be equal to corresponding values of pristine composite beam. Parametric analysis carried out by varying the number of wires is shown in Fig 2. In Fig. 2, number of wires is shown on X-axis and different values of stiffness and frequency are shown on Y-axis. By substituting different values of number of wires in Eqns. (1) and (3), different values of stiffness and frequency were obtained which are plotted in Fig. 2. For a stiffness value of 1443 N/m^2 and frequency value of 43.65 hz, a unique value of number of SMA wires i.e. 70 was obtained from the graph. From the parametric analysis, it was observed that number of SMA wires required to get the same stiffness and frequency of SMA hybrid beam as pristine beam is 70. Similarly same methodology was adopted for steel wires hybrid beam where the width of the beam was taken as 35 mm and the corresponding number of steel wires were calculated, which was equal to 50. The final dimension (mm) of all the three beams are given in Table 3.

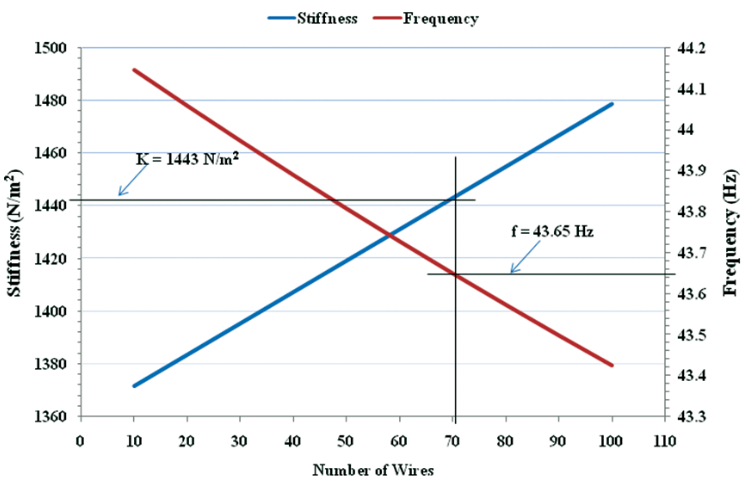


Figure 2. Graph showing beam parametric analysis.

Table 3. Dimension of GFRP beams

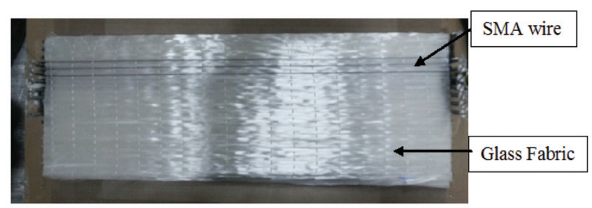
Beam dimension	Pristine (mm)	SMA embedded (mm)	Steel embedded (mm)
Length (L)	250	250	250
Width (b)	40	37.5	35
Thickness (t)	3.96	3.96	3.96
No. of Wires	0	70	50

3. FABRICATION OF TESTING SAMPLE

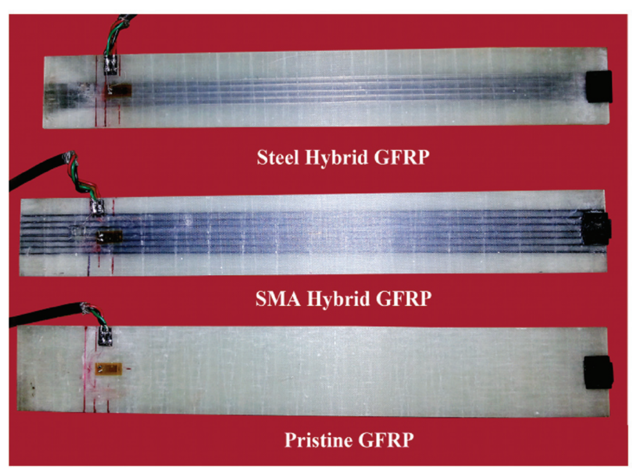
All the beams were fabricated by resin film infusion (RFI) process[18]. All three beams were fabricated together to maintain the same manufacturing conditions. Three beams fabricated were: pristine beam having only glass reinforcement with epoxy as matrix, beam hybridised with SMA wires of 300 micron diameter and the beam hybridised with steel wires of 300 μm diameter. For fabrication of beams, twelve layers of glass fabric reinforcement (0.33 mm cured ply thickness) were laid over the aluminum flat plate after applying a thin coat of proper releasing agent on the plate. The amount of epoxy resin required to achieve 50 per cent fiber volume fraction was calculated and stacked in the form of resin films with glass fabric plies. During layup of the fabric, the SMA and steel wires were also laid as shown in Fig. 3(a). Metallic screws fixed in the moulding plate were used to anchor and align the wires with respect to layup. The whole layup was then vacuum bagged using nylon bag and an adhesive tape. It was bagged properly to achieve a vacuum using a rotary pump. After achieving a vacuum level of 20 millibar, the whole layup under vacuum was placed inside an oven to cure the layup. After curing, the laminate was demoulded from flat plate and the demoulded laminate was then cut to the required dimensions of beam as shown in Table 3. Figure 3 (b) shows all the fabricated beams, cut to the given size, and used later for damping experiments.

4. EXPERIMENTAL SETUP

Figure 4 shows the testing arrangement used to find the damping ratio. Testing arrangement consists of testing GFRP beam which is fixed at one end and an accelerometer is pasted at the free end. To capture the acceleration of the vibrating beam LMS system was used. Experiments to find the damping ratios were carried out using LMS SCADAS III, model SC 316 mainframe. The mainframe consists of a system controller with SCSI interface for transferring data to computer. For vibration measurements, a Dytran accelerometer (model 3041A2) was used. The specification of accelerometer used are: nominal sensitivity of 100 mV/g and operating frequency of about 1-3000 Hz.



(a)



(b)

Figure 3. (a) Stacking of glass reinforcement along with wires, (b) Fabricated beam specimens.

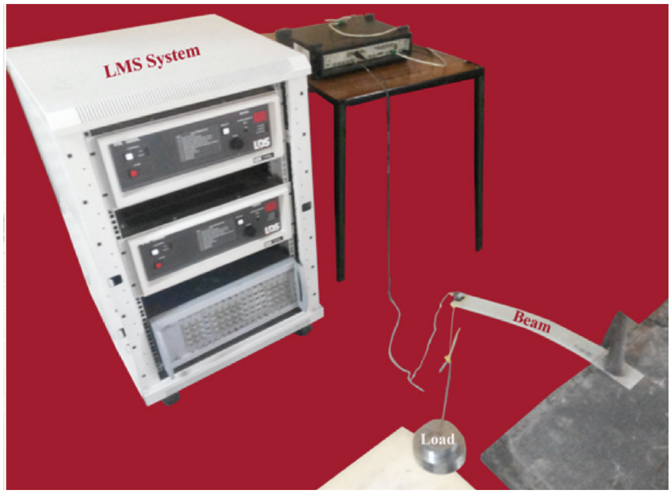


Figure 4. Instrumentation used for damping measurement.

5. RESULTS AND DISCUSSIONS

5.1 Determination of Volume Fraction of Constituents

Beams were tested for as per ASTM D3171 to find out the volume fraction of different constituents. This was done to verify the percentage of constituent materials in the fabricated beams. For evaluation of volume fraction, the trimmed parts of the laminate were kept in a furnace at 600 °C for 6 h to remove the matrix portion of the composite beam. Remaining of the constituents like glass fibers in pristine beam, glass fiber and SMA wires in SMA hybrid beam and glass fibers and steel wires in steel hybridised beam was then cooled and weighed separately. Using these, weight fractions of different constituents were calculated. Using weight fractions and densities, the volume fraction was calculated. The details of volume fraction calculated for all the three beams are shown in Table 4.

Calculated volume fractions show that all three beams have approximately 50 per cent fiber volume content as was considered for analytical calculation. Flexural stiffness of each beam was then measured experimentally by mounting beams in cantilever fashion by clamping one end of the beam. Vertical deflection of beam at free end was measured by putting dial gauge at the free end and a known weight of 3 kg at the free end. The vertical deflection obtained for each pristine, SMA hybrid and steel hybrid beams was approximately 19 mm. Equal deflection for same load of all beams confirmed that flexural stiffness of each beam was same, which was also considered same for analytical calculations.

Table 4. Volume fraction of beams

Beam	Fiber	Resin	SMA/Steel	Void fraction
Pristine	50.8	48.63	0	0.67
SMA hybrid	50.5	48.567	0.033	0.9
Steel hybrid	50.2	48.675	0.025	1.1

5.2 Calculation of Damping Ratio

Damping ratio was calculated for each beam in cantilever condition. At the free end of each beam, an accelerometer was bonded. Each of the beams was excited by removing a known weight which was hang at the free end of beam by using a thread as shown in Fig. 4. Acceleration time history was then measured for vibrating beams through a data acquisition system. Figure 5 shows the acceleration time history obtained for pristine, SMA hybrid and steel hybrid GFRP composite beams. From Figs. 5(a), 5(b), and 5(c), it is clear that the input energy for each of the three beams is the same. But the rate of decay in each of the three beams is different. It can be clearly observed from figures that rate of decay in case of SMA hybrid beam is much faster as compared to pristine and steel hybrid beam. This is mainly attributed to the large energy absorption capability of pseudoelastic SMA wire when it is strained. Due to straining austenitic phase of SMA wire transforms to martensitic phase and while doing so material absorbs energy. For phase transformation energy is dissipated and this energy dissipation helps to improve the damping of material. Also from Figs. 5(a) and 5(c), it can be noticed that rate of decay in steel hybrid beam is more than GFRP beam. However the difference is very less than SMA hybrid beam. It can be implied here that hybridisation of SMA increases damping of GFRP composite beam.

To find out the frequency of vibration of each beam, Fourier transform (FT) was done on experimentally captured acceleration signals of each beam. Through FT, frequency of vibration of first mode of pristine, SMA hybrid and steel hybrid composite beams were 43.1 Hz (Fig. 6(a)), 43.7 Hz (Fig. 6(b)) and 44.1 Hz (Fig. 6(c)), respectively were found out. In analytical calculations value of first mode of frequency of vibration was kept nearly 43.7 Hz. Experimental results show close match with analytical calculation.

To find out the value of damping ratio logarithmic decay method was used for calculation. Logarithmic decay is the natural logarithm of the ratio of any two successive amplitudes of vibration, which is given by the Eqn. (4)

$$\frac{A_n}{A_{n+1}} = e^r \quad (4)$$

where A_n and A_{n+1} are two successive amplitudes of vibration at time instants n and n+1 respectively. Logarithmic decrement can also be rewritten as

$$r = \frac{2\pi\delta}{\sqrt{(1-\delta^2)}} \quad (5)$$

where δ is damping ratio. For very small values of δ denominator equals to unity.

$$r = 2\pi\delta \quad (6)$$

Eqns. (4) and (6) are used to get

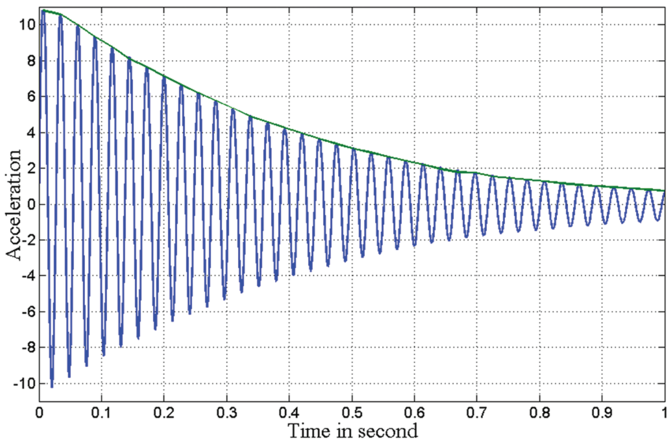
$$\frac{A_n}{A_{n+1}} = e^{2\pi\delta} \quad (7)$$

Eqn. (7) can be rewritten as

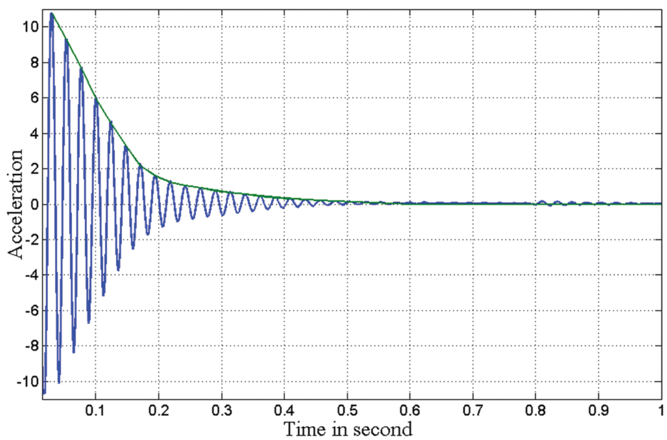
$$\log\left(\frac{A_n}{A_{n+1}}\right) = 2\pi\delta$$

or

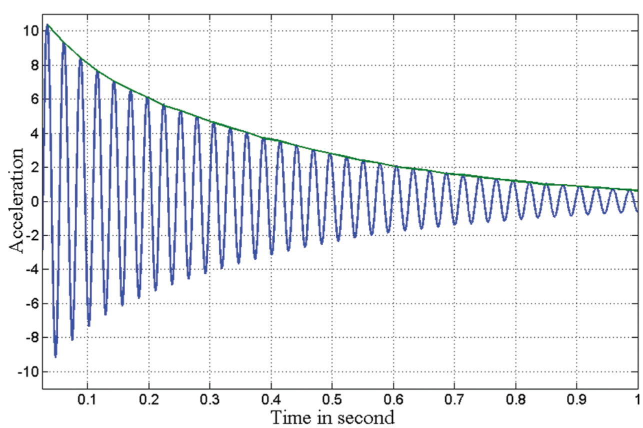
$$\delta = \frac{1}{2\pi}\log\left(\frac{A_n}{A_{n+1}}\right) \quad (8)$$



(a)

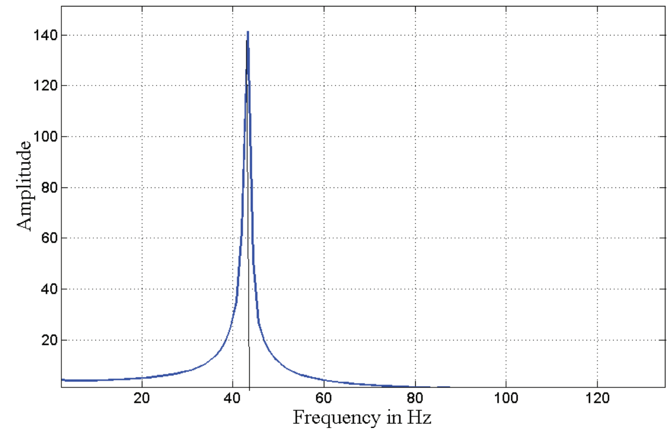


(b)

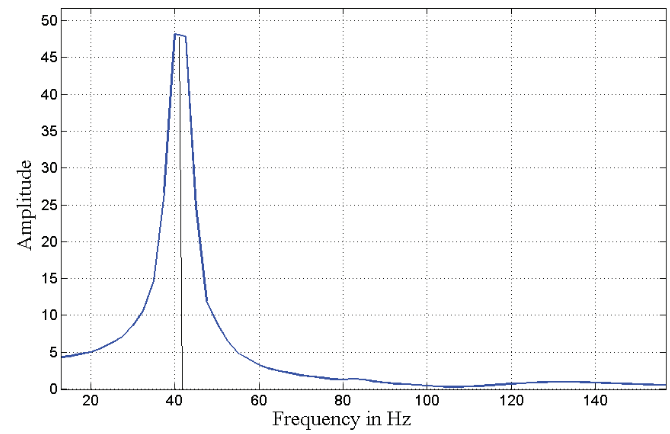


(c)

Figure 5. Acceleration time history of: (a) Pristine composite, (b) SMA hybrid, and (c) Steel hybrid.



(a)



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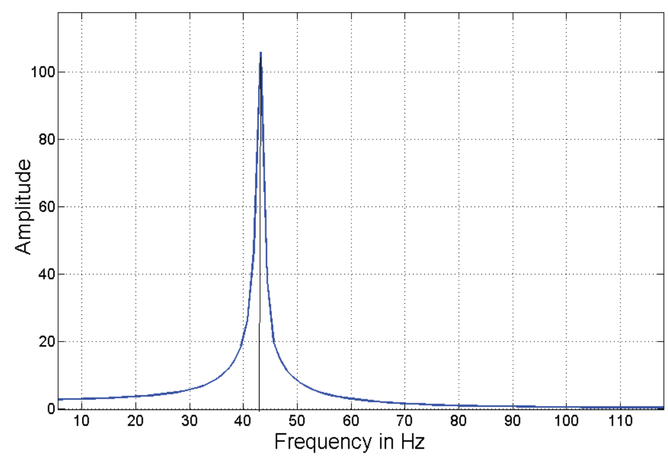

(c)

Figure 6. Frequency response of (a) Pristine composite (b) SMA Hybrid (c) Steel hybrid.

Substituting the values of A_n and A_{n+1} from experimental data in the above equation for all the three beams, damping ratio was calculated. Damping ratio calculated for each of the three beams is given in Table 5. Damping ratio for SMA hybrid GFRP beam was found to be 141 per cent more than the pristine beam whereas damping ratio of steel hybrid beam was found out 70 per cent more than that of pristine GFRP beam. Higher damping ratio of SMA hybrid composite beam is attributed

Table 5. Measured damping values of all beams

GFRP Beam	Damping ratio	Percentage increase	Frequency (Hz)
Pristine	0.0096	-	43.2
SMA hybrid	0.0232	141	43
Steel hybrid	0.0163	70	42.9

to energy loss in hysteresis of pseudoelastic SMA material. Straining of SMA wires during vibration, results in extension and contraction of wires. The extension and contraction result in loading and unloading of wires because of which austenite phase of SMA is converted into martensite phase and vice versa. These repeated conversion from one phase to another during vibration result in more dissipation of energy. This increased dissipation of energy increases the damping. On the other hand composite beam embedded with steel wires shows less increase in damping capacity due to absence of any energy dissipation mechanism as in SMA. Improvement in damping of steel embedded composite as compared to pristine composite was due to increase in the number of interfaces between the steel wires and viscoelastic epoxy matrix, which results in increase in damping ratio.

6. CONCLUSIONS

Damping characteristics of SMA hybrid composite beams were studied in the present work by evaluating damping ratio of cantilever beam and compared them with pristine GFRP beam. A comparison of improvement in damping characteristics of SMA hybrid composites was made with steel hybrid composites. Dimensional details like length, width, thickness, number of wires, etc of all the beams were work out keeping constraint of equal flexural stiffness and first mode of frequency of vibration. All the GFRP beams with and without embedded wires were fabricated by resin film infusion process. All beams machined to the final dimensions were tested to find out their flexural stiffness. The damping ratio of all beams were found out by logarithmic decay method.

It clearly demonstrates the enhancement in damping characteristics of the composite materials by embedding SMA as compared to any other metallic material like steel. Therefore it can be concluded that to reduce the vibration of composite structures, composite structure with embedded SMA wires shall be preferred to pristine composites or composites embedded with other material like steel.

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In the current study, he has guided in the GFRP material characterisation and fabrication of hybrid beams and reviewed the manuscript.