International Journal of Engineering & Technology, *7 (3.4) (2018)* 143-150

International Journal of Engineering & Technology

Website: www.sciencepubco.com/index.php/IJET

Research paper

Vibrational Analysis of Composite Beam Embedded with Nitinol Shape Memory Alloy Wires

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Abstract

In this paper, laminated composite materials were hybridized with fibers (E-glass) and shape memory alloy wires which considered a smart material. The effect of changing frequency on the (acceleration- frequency) response curve, the damping ratio of the vibration modes, the natural frequencies of the vibration mode, the effect of shape memory alloy wires number on the damping characteristics were studied. Hand lay-up technique was used to prepare the specimens, epoxy resin type was used as a matrix reinforced by fiber, E-glass. The specimens were manufactured by stacking 2 layers of fibers. Shape memory alloy, type Nitinol (nickel-titanium) having a diameter (1 and 2mm), was used to manufacture the specimens by embedding (1,2 and 3) wires into epoxy. Experimentally, the acceleration- frequency response curve was plotted for the vibration modes, this curve was used to measure the natural frequencies of the vibration modes and calculate the damping ratio of the vibration modes. ANSYS 15- APDL was used to determine the mode shape and find the natural frequencies of the vibration modes then compared with the experimental results. The results illustrated that, for all specimens increasing the natural frequency leads to decreasing the damping ratio. Increasing the number of shape memory alloy wires leads to increase the values of the damping ratio of the vibration modes and the natural frequencies of the vibration modes at room temperature.

Keywords: *-glass, NiTi, shape memory alloy wires, ANSYS, vibration analysis, the natural frequency, damping ratio, mode shape, composite material, Nitinol wires.*

1. Introduction

Damping is an important dynamic parameter for the design to control the noise and vibration. It prevents the resonance vibrations from building up to dangerous amplitudes. The stability of the system will be reduce without good damping.[1]

The damping mechanisms of the composite polymer depends on the behavior of viscoelastic polymer and the damping characteristics of reinforcement. Reinforcement of polymer with carbon fabrics, glass fabrics or shape memory alloy wire provides improvements in characteristics of the damping and other mechanical properties. Schrooten et al.,2002,[2] evaluated the thermomechanical behavior and vibration response of smart composite materials having embedded shape memory alloys (SMAs). Pre-strain shape memory alloys (NiTiCu) wires and Aramid fibers were embedded into the composite materials, epoxy resin was used as a matrix. The result showed that, SMA composite is able to adapt its thermal behavior, shape and vibrational characteristics during service. Gupta et al.,2003, [3] studied the effect of activation and deactivation of SMA wires on the natural frequency of composite shaft (made of fiber glass and epoxy resin) with embedded shape memory alloy (Nitinol) wires. The shaft was fabricated and tested. Electric resistance heating was used to activate the shape memory alloy wires, activation and deactivation of SMA wires changed the shaft stiffness value, which led to change the natural frequency of the rotor system, through critical speeds, to avoid resonance, which induce large stresses that may lead to failures.

Leal et al., 2011,[4] studied thermomechanical behavior in the range of phase transformation of SMA during heating for composites of epoxy resin containing Ni-Ti shape memory alloy (SMA), the volume fraction of Ni-Ti wires are 1.9% and 3.8%. The results shown a significant increase of storage modulus in the active composite during heating in the range of the phase transformation of Ni-Ti (SMA) wires when the volume fraction at 3.8 %, and no effect was observed when the volumetric fraction at 1.9%, because of the volume fraction was not enough to affect on the composite at the phase transformation of the SMA wires. Mwita and Mtawa,2012,[5] developed and tested intelligent Hybrid Polymeric Composite (IHPC) by embedded Ni-Ti Shape Memory Alloy (SMA) into composite to prevent crack growth ability. The composite matrix was fabricated from epoxy resin. The results showed that, embedding the Ni-Ti SMA into a hybrid polymeric composite produces a significant recovery stress leads to induce a compressive stress in the matrix. Chavan , 2014,[6] studied analytically and experimentally a smart composite beam by using embedded Nitinol (SMA) wires in the epoxy resin, the activation of shape memory alloy wires was done by using electric current, leading to convert the thermal energy to mechanical energy. The change of Nitinol wires temperature changed the mechanical properties of composite, strain rates, stiffness, amplitudes, energy dissipation and natural frequency. The result showed that, using embedded Nitinol (SMA) wires based composite gives a good energy dissipation ability and controls the vibration.R. KarimiMahabadi et al., 2016 [7]study, an analytical closed form solution for free vibrationresponse of hybrid composite plate reinforced with shape-memory alloy (SMA) fibers. Recovery stresses generatedduring martensitic phase transformation are obtained based on onedimensionalBrinson's model.

AchutanandaParhi and B. N. Singh, 2017 [8]are focused on the nonlinear free vibration analysis of spherical and cylindrical composite shell panels embedded with shape memory alloy fibers.

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Nicholas G. Garafolo and Garrett McHugh , 2018, [9]studied the effect of embedded shape memory alloy (SMA) wire as an active suppression system to mitigate such vibrations in a flexible clamped-free beam.
The main objective of this paper is to investigate the damping behavior of hybrid composite material reinforced by shape memory alloy (Nitinol wires).

2. Material Used

The materials used to prepare samples consist of epoxy resin as a matrix and reinforcement composed materials which are shape memory alloy wires (Nitinol) and two E-glass layers of fiber (0°-90°). The preparation of specimens include:
Hybrid composite include epoxy reinforced by 2 layers E-glass and shape memory alloy (1,2,3) wires with (1 and 2mm) diameter.

2.1. Fiberglass

Fiberglass is the most common reinforcement type used in polymer composites (over 95%) [1]. It is widely used in composite applications, such as marine bodies, automotive, roofs, and plastic pipes [10]. Its advantages include:
1. Relatively good strength. [10]
2. Heat resistance. Fiberglass has good strength when the temperature increases to 200° C.
3. High moisture resistance.
4. Good chemical and corrosion resistance.
5. Good electrical characteristics. Fibers type E-glass have a high electrical insulation.
6. Economy, low cost and wide available.
7. Good weather ability (not affected by sunlight) and no biodegradation. [11]
There are several types of fiberglass; the electrical glass (E-glass) and high strength glass (S-glass) are the most common, other types are used in non-structural applications, such as chemical glass (C-glass) used for corrosion resistance, appearance glass (A-glass) used to give the surface good appearance. [12] Using fiberglass is limited in high performance applications because it has low stiffness, sensitivity to abrasion and low fatigue resistance. [13] Depending on the requirements fiberglass can be reinforced the composites as discontinuous or continuous fiber, discontinuous fiber used for low-performance requirements. Table.1 shows the properties of the E-glass.

Table 1: The properties of the E-glass fiber [14]

Properties	Values
Density (kg/m3)	2580
Modulus of Elasticity (GPa)	72
Strength (MPa)	3450
Poisson's Ratio	0.22

2.2. Shape Memory Alloy (Nitinol)

Nitinol, a near perfect 50/50 combination of nickel and titanium, to reset the memory shape most, holding the wire in a predetermined (desire) shape, then heating the wire to 500°C (950°F), and quickly cooling it by sink in water. The wire can be deformed or bent into any shape. In order to spring back to its memory shape, just heating it up in a heat source as hot air. The start transformation temperature from martensite to austenite ($\boldsymbol{As}$) is 37°C (98°F) and austenite finish temperature ($\boldsymbol{Af}$) is 45°C (115°F). There are many applications for Nitinol, such as (1) Robot, (2) Biomedical, (3) Toys, (4) Actuators, (5) Thermal Switches Heat Engines, (6) Sensors, (7) Eyeglasses Frames, (8) Lifting Devices, (9) Clothing, and (10) Cell Phone Antennas. Table.2 contains the physical properties of Nitinol [15].

Table 2: The properties of the nitinol [15]

Properties	Values
Melting point (°C)	1240-1310
Density (kg/m3)	6450
Modulus of Elasticity (GPa)	28 (martensite)
	75 (austenite)
Strength (MPa)	68.95 (martensite)
	241.3 (austenite)
Poisson's Ratio	0.33
Austenite start temperature (As) °C	37
Austenite finish temperature (Af) °C	45

2.3. Epoxy Resin (Thermoset)

Although a higher cost, than other type of polymer matrix composite (PMC), epoxies are the most commonly used in the industrial applications, because they have good adhesion properties with the reinforcement, low density, low volatility gases at cure, [13] good mechanical properties, good electrical insulation and heat resistant. They are resistant to corrosion and number of acids, very low shrinkage rate at curing and easy to form. [16] For that, epoxies are used as a matrix for composite materials in aerospace applications, electrical applications, wind mill, sport equipment, etc.
Epoxy resin (type Quickmast105) was used in this study, in the form of liquid, which transferred from its liquid state to solid by adding the hardener. The hardener is in the form of liquid, with yellow color, the ratio between the hardener and the epoxy resin is 33% by weight. Table.3 lists the properties of the epoxy used in this work.

Table 3: The properties of epoxy [17]

Properties	Values
Density (kg/m3)	1100
Modulus of Elasticity (GPa)	2.1
Strength (MPa)	≥ 25
Poisson's Ratio	0.35

3. Molds Preparation

Hand lay-up technique was used to prepare the samples, which is the simplest method formed by stacking the layers within the laminates. The infrastructural requirements is minimal, the mold can be glass, wood, metallic or any other materials
In this work, a glass with thickness 4 mm was used to prepare the molds, to ensure getting a smooth surface of the sample, with dimensions (300 x 200 x 4) mm, as shown in Fig.1.

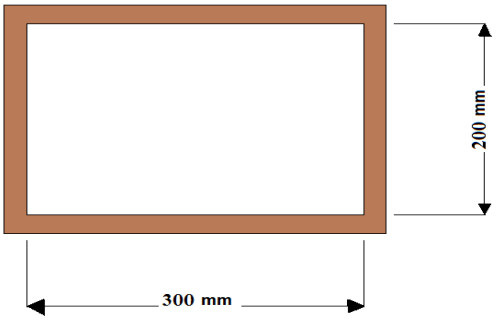


Fig. 1: the shape of the mold.

4. Specimen Preparation

To prepare specimens, the following steps were used:
1. Painting a coat of Vaseline on the inner surface of the mold to prevent sticking between the epoxy and glass.
2. Epoxy is mixed very well with the hardener by a glass rod, at room temperature.
3. Fixed the shape memory alloy wires in a mold by holing the frame and fixing its ends.

4. Pouring a layer of epoxy on the side of the mold, until flowing to all parts of the mold to avoid bubbles, then putting a layer of reinforcing material (E-glass mat 0°-90°), while the epoxy still wet, removing any air bubbles by dragging them to the edge of the mold, and then brush the reinforcing material by a stiff brush until becomes completely saturated with epoxy. Pouring another layer of epoxy and so on.
5. Leaving the samples in the mold 48 hour at room temperature to cure, and then extracting the samples from the mold.
6. using wire cutting machines to cut the samples to the required dimensions, (4 x 20 x 250) mm Fig.2.

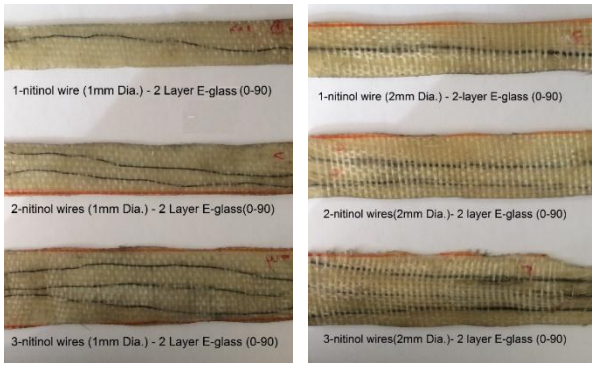


Fig. 2: Composite Specimens reinforced by NiTi wires

5. Vibration Devices

The vibration test includes studying the fundamental natural frequency for composite beam as shown in Fig.3 .

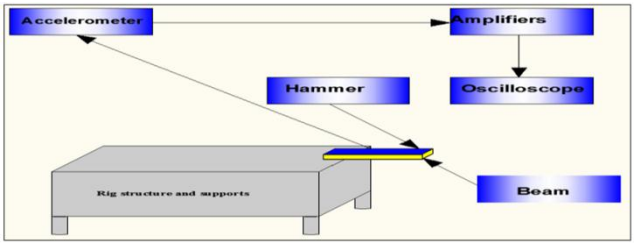


Fig. 3: Design of the Vibration Test.

ASTM recommends the use of non-contact transducers to excite the beam. Transducers powerful enough to produce a measurable response for the beams studied are not readily available. An impact hammer was used to excite the beam, as shown in Fig.4. The additional information for the hammer is as follows:

- The hammer model consists of (086C01 – Bisotronics split vibration).
- The sensitivity is (11.2 mph / N).
- The measurement range shall be ($\mp$ 444N).
- Resonance frequency approx. (≥ 15KHZ).
- Non-linearity (≤1%) .
- Stimulation voltage (20to 30VDC).
- Steady current stimulation (2 to 20 mA).
- Output bias voltage (8 to 14 VDC).
- Emptying time constant(≥ 500sec).
- The mass hammer consists of (0.1 kg) of head with a diameter of (1.57 cm), the tip of diameter is (0.63 cm), the length of it was (21.6 cm).

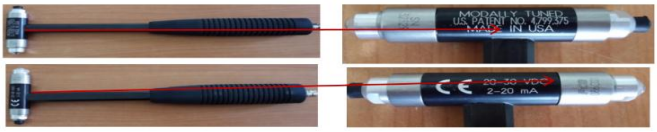


Fig. 4: Instrumented Dynamic ForceHammer

5.1 Model of Accelerometer

The model of accelerometer (352C68) is shown in Fig.5. The properties related for accelerometer are [18]:
sensitivity (10.2 mV/(m/s^2).
measurement range (491 m/s^2).
resonant frequency (≥ 35KHZ).
non-linearity (≤ 1%).

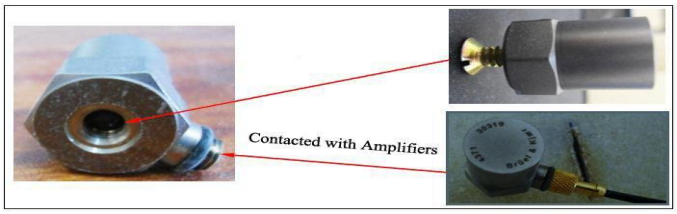


Fig 5: Accelerometer Part Machine.

5.2 Model of Amplifier

The amplifier used with the model No. (480E09) is shown in Fig.6. It amplifies the signal measured by the accelerometer to be displayed by the oscilloscope.



Fig.6: Amplifier Part.

5.3 Model of Oscilloscope

Digital storage oscilloscope model (ADS 1202CL+) and serial No.01020200300012 is shown in Fig.7. The properties related for oscilloscope are :-

- Maximum frequency (200 MHz).
- Maximum reading you take for one sample in one second (500 MSa/s).
- In addition to the above specimens, it has a convex spectral analysis FFT and has two inputs channels.

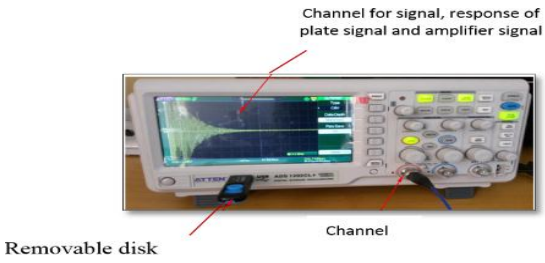


Fig.7: Oscilloscope Part

The signal obtained is displayed by oscilloscope advise then it is converted into FFT function by (sig-view) program. The purpose of this conversion is to obtain the natural frequency of the intact beam (Fixed-Free, Fixed-Fixed and Fixed- simply support) boundary condition. While the value of damping ratio is calculated by used half power band width for each mode. The signal obtained in a moving disk is saved and data is opened through the Excel

program. Through the Excel program, the response to the signal is determined by sending the response file to the (sig-view) program. Through the latter program, the signal is converted by using of spectral analysis FFT from t domain, to ω domain in order to obtain the natural frequencies of the samples are used in the vibration test, shown Fig.8.

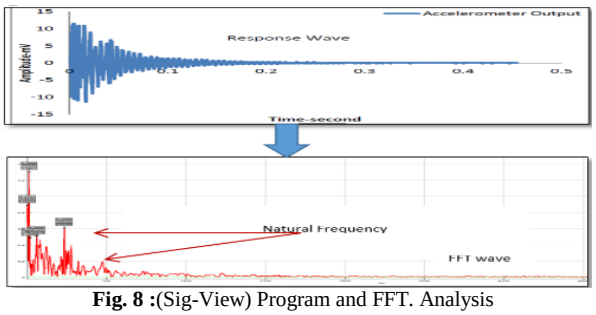


Fig. 8 :(Sig-View) Program and FFT. Analysis

The accelerometer was placed along the middle path of the beam and is travelled at three different locations (start, middle, and end) along the beam length shown Fig.9.



Fig.9 :(Fixed-Free) Boundary Condition

The samples have dimensions (4 x 20 x 250) mm, the length decreases 20 mm for fixation. The samples were fixed from one end on the shaker and free from the other end (as a cantilever beam), this mounting of the beam on the shaker is according to [19, 20, 21]. Fig.10 observed the Flowchart Stepping of Vibration Test of composite beam.

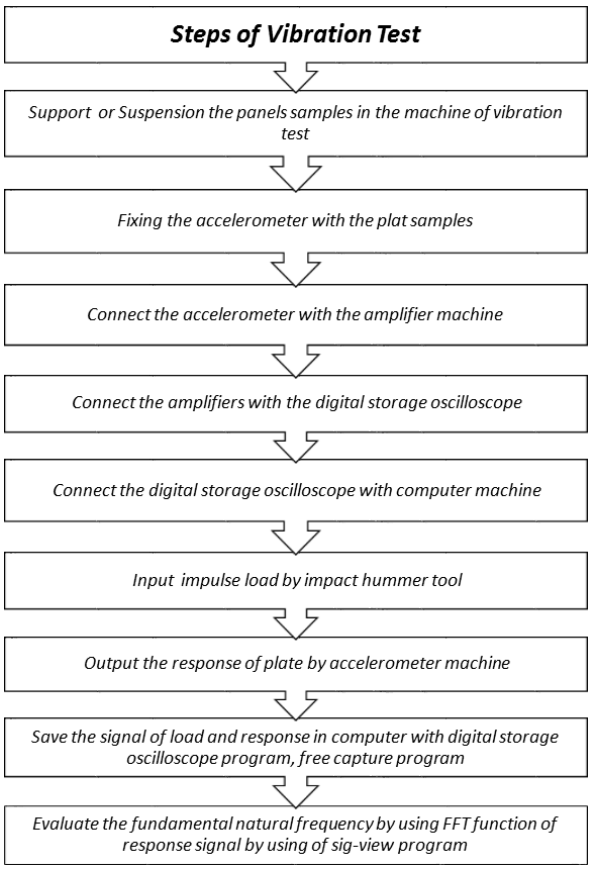


Fig.10: Flowchart Stepping of Vibration Test of composite beam

6. Natural Frequencies and Mode Shapes

The modal analysis is used to determine the vibration characteristics (natural frequencies and mode shapes) of the structure. It can be a starting point for the harmonic response analysis. The basic equation solved in a typical modal analysis is the classical eigenvalue problem. The natural frequencies and mode shapes of a structure are very important parameters in the design of a structure for dynamic loading conditions. The un-damped basic equation solved by the modal analysis is [22]:

$$\{0\} = [\mathrm{k}]\{w\} + [\mathrm{M}]\{\ddot{w}\} \quad (1)$$

Assuming harmonic motion that is:

$$\{w_i\} = \{\varphi_i\} \sin \omega_i t \qquad ; i = 1,2, \ldots . n \quad (2)$$

Where, n is the number of degree of freedom of the system.
$\{\varphi_i\}$= the mode shape vector for the ith mode of vibration, and
ω_i = the angular frequency of mode i.
Differentiating Equation (2) twice with respect to time yields:

$$\{\ddot{w}_i\} = -\omega_i^2\{\varphi_i\} \sin \omega_i t \quad (3)$$

Then, substituting equations (2) and (3) into equation (1) yields, after cancelling the term$(\sin \omega_i)$:"

$$"[K] - \omega_i^2[M]\{\varphi_i\}\{\varphi_i\}^T = \{0\} \quad (4)$$

Equation(4) has the form of the algebraic eigenvalue lem($K\phi = \lambda M\phi$). From the theory of homogenous equations, nontrivial solutions exist only if the determinant of the coefficient matrix is equal to zero. [22]. Expansion of the determinant yields a polynomial of order NR called characteristic equation. The NR roots of this polynomial (ω_i^2) are the characteristic values or the eigenvalues. Substitution of these roots (one at each time) into the homogeneous Equation(1), produces the characteristic vectors or the eigenvectors {ϕi}within arbitrary constants. Alternatively, each eigenvector may be found as any column of adjoins matrix $[H_i^a]$ of the characteristic matrix [Hi], obtained from Equation (4) as follow. [19]:

$$[H_i]\{\varphi\} = [0] \quad (5)$$

Where,

$$[K] - \omega_i^2[M] = [H_i] \quad (6)$$

In this work Subspace method is applied as numerical method that is able to solve the up equation by using FEM. [23].

$$[K] - \omega_i^2[M] = \{0\} \quad (7)$$

7. Finite Element Analysis via ANSYS -V15

ANSYS APDL, version 15, is used for the finite element analysis. It's offer design complex composites with different materials, fabrics thickness, and defines the element and fabrics orientations and ply layup efficiently. It provides all the functions necessary for building up the layers and the analysis of the composite materials by using Element soild186, as shown in the Fig.11 [24].SOLID186 Layered Structural Solid to model layered thick shells or solids. The layered section definition is given by ANSYS section (SECxxx) commands. To study the vibration characteristics of a system, Modal Analysis is an important analysis which investigates the natural frequencies and the corresponding vibration mode shapes [25-26].

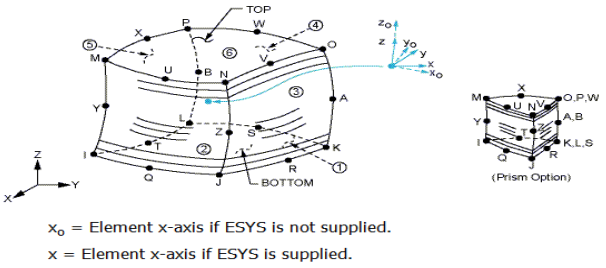
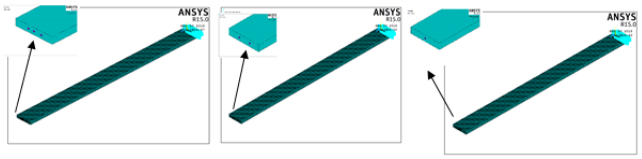


Fig. 11:SOLID186 Layered Structural Solid Element

8. Cases Study

The samples were made by epoxy resin as a matrix and 2 layers E-glass fiber embedded with one NiTi wire, two NiTi wires and three NiTi wires, once with a diameter of 1 mm and then with a diameter of 2 mm. Three cases of boundary condition that fixed-free , fixed- fixed and fixed- simply support were investigated experimentally and numerically by ANSYS software to determine the natural frequency in each case and its mode shapes and compare the results between them. Fig.12 shows the Ansys model for these cases.



Three NiTi wire Two NiTi wire One NiTi wire

Fig.12: Ansys Models

9. Results and Discussion

For any system exposed to mechanical vibrations, the natural frequency has a significant influence on the design of the system. When the system is operated at a frequency near the natural frequency, the acceleration will be at the maximum value, leading to generate high stresses which may be lead to the failure of the system. So, before any a practical application, the design of the system needs to determine the natural frequencies to avoid reaching the system near to the natural frequency. The half-power bandwidth method was used to measure the damping ratio and the natural frequency for the vibration modes, which includes all the samples. Table.4 shown the acceleration- frequency response curve for specimen with nitinol wire diameter (1mm) and Table.5 shown the acceleration- frequency response curve for specimen with nitinol wire diameter (2mm)

Table 4: Experimental Results of acceleration- frequency response curvewith nitinol wire (1mm dia.)

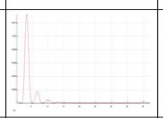
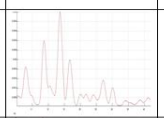
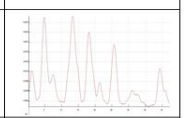
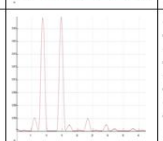
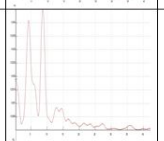
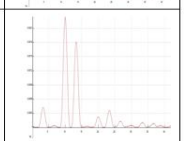
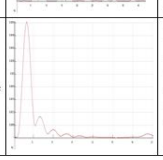
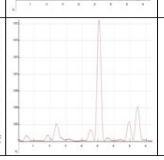
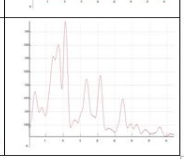
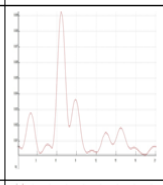
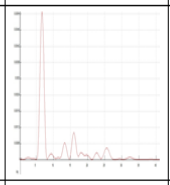
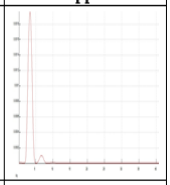
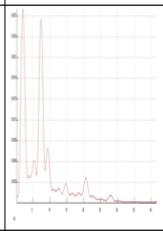
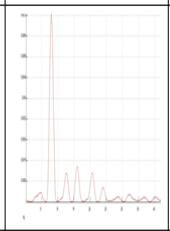
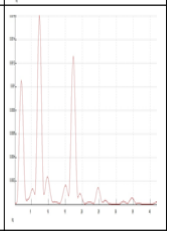
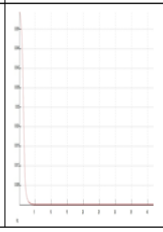
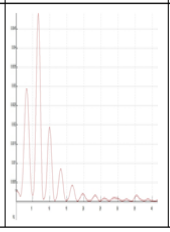
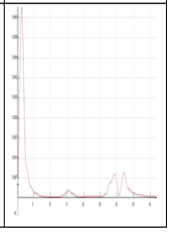
	Fixed- Free	Fixed - Fixed	Fixed – Simply Support
One wire			
Two wire			
Three wire			

Table 5: Experimental Results of acceleration- frequency response curvewith nitinol wire (2mm dia.)

	Fixed- Free	Fixed - Fixed	Fixed – Simply Support
One wire			
Two wire			
Three wire			

Tables.6 to 11 depict the natural frequencies results and its mode shapes that obtained numerically by ANSYS program for six mode shapes with one , two and three embedded Nitinol wire and three boundary conditions (fixed- free , fixed – fixed , and fixed-simply support) .

Table 6: Natural frequencies values and its mode shapes for Nitinol wire Diameter=1mm - Boundary condition Fixed-Free

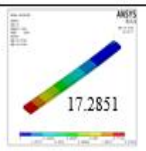
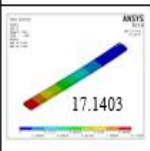
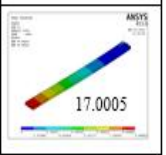
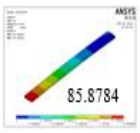
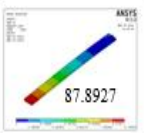
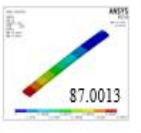
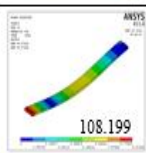
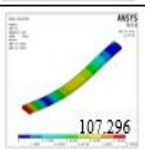
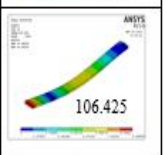
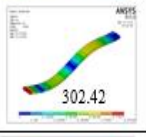
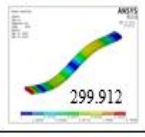
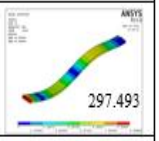
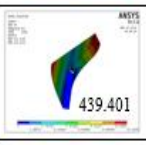
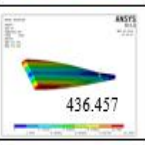
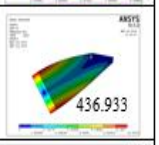
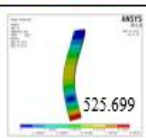
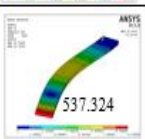
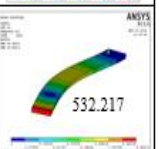
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2	 85.8784	 87.8927	 87.0013
3	 108.199	 107.296	 106.425
4	 302.42	 299.912	 297.493
5	 439.401	 436.457	 436.933
6	 525.699	 537.324	 532.217

Table 7: Natural frequencies values and its mode shapes for Nitinol wire Diameter=1mm - Boundary condition Fixed-Fixed

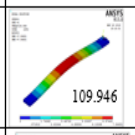
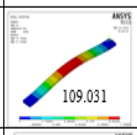
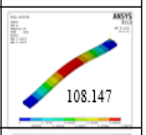
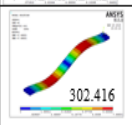
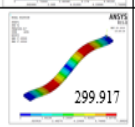
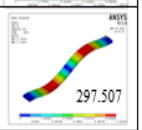
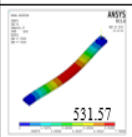
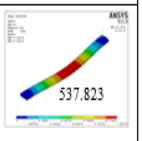
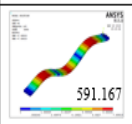
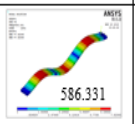
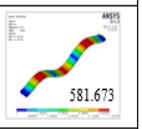
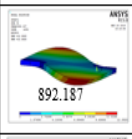
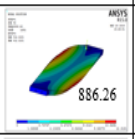
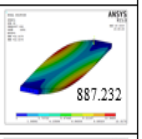
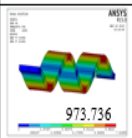
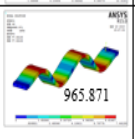
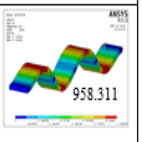
Mode NO.	One wire	Two wire	Three wire
1	 109.946	 109.031	 108.147
2	 302.416	 299.917	 297.507
3	 531.57	 542.875	 537.823
4	 591.167	 586.331	 581.673
5	 892.187	 886.26	 887.232
6	 973.736	 965.871	 958.311

Table 8: Natural frequencies values and its mode shapes for Nitinol wire Diameter=1mm - Boundary condition Fixed-simply support

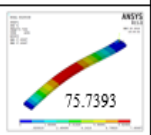
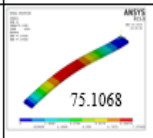
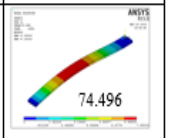
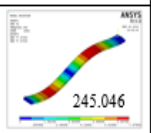
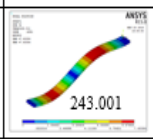
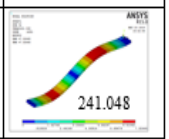
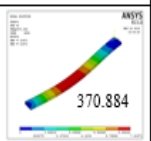
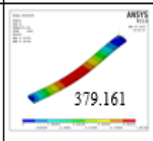
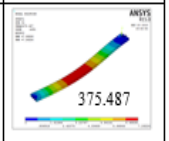
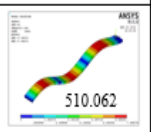
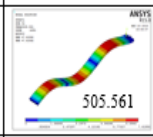
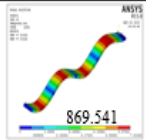
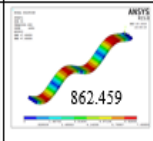
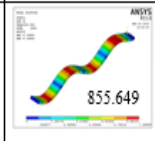
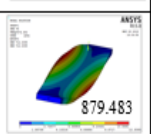
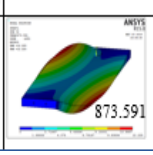
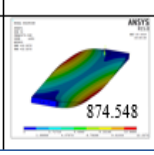
Mode NO.	One wire	Two wire	Three wire
1	 75.7393	 75.1068	 74.496
2	 245.046	 243.001	 241.048
3	 370.884	 379.161	 375.487
4	 510.062	 505.561	 501.815
5	 869.541	 862.459	 855.649
6	 879.483	 873.591	 874.548

Table 9: Natural frequencies values and its mode shapes for Nitinol wire Diameter=2mm - Boundary condition Fixed-Free

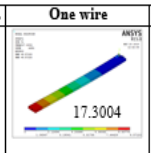
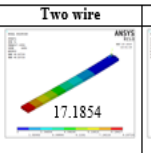
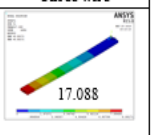
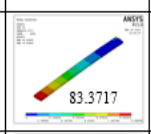
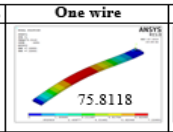
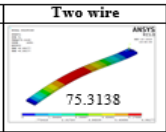
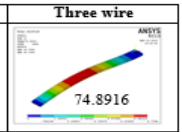
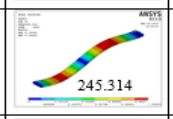
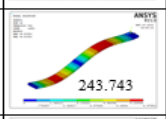
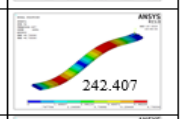
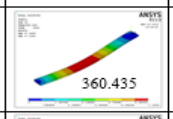
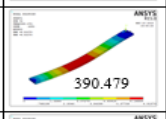
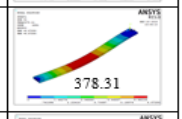
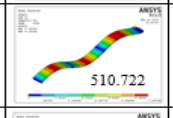
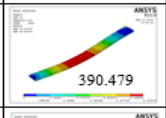
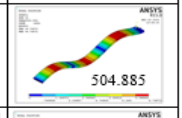
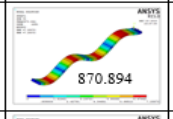
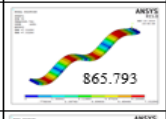
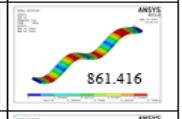
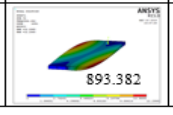
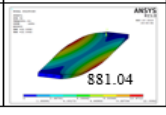
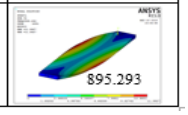
Mode NO.	One wire	Two wire	Three wire
1	 17.3004	 17.1854	 17.088
2	 83.3717	90.7118	87.6671
3	108.305	107.597	106.996
4	302.761	300.834	299.195
5	446.356	440.181	447.306
6	511.145	553.309	536.494

Table 10: Natural frequencies values and its mode shapes for Nitinol wire Diameter=2mm - Boundary condition Fixed-Fixed

Mode NO.	One wire	Two wire	Three wire
1	110.065	109.355	108.752
2	202.797	300.912	299.302
3	517.056	557.988	541.765
4	592.056	588.539	585.518
5	906.019	893.858	908.109
6	975.494	970.048	965.333

Table 11:. Natural frequencies values and its mode shapes for Nitinol wire Diameter=2mm - Boundary condition Fixed-simply support

Mode NO.	One wire	Two wire	Three wire
1	 75.8118	 75.3138	 74.8916
2	 245.314	 243.743	 242.407
3	 360.435	 390.479	 378.31
4	 510.722	 390.479	 504.885
5	 870.894	 865.793	 861.416
6	 893.382	 881.04	 895.293

The tables12 to 17 shown the results which include: the experimental and numerical results of the natural frequency of the vibration modes, and the results of the damping ratio. The half-power bandwidth method was used to measure the damping ratio and the natural frequency for the vibration modes, which includes all the samples. Tables 4 and 5 shown the acceleration- frequency response curve, that the maximum acceleration response at the peak corresponds to natural frequency, reduces to $1/\sqrt{2}$ which represents half-power points, where damping ratio can be assessment.
The comparison between the experimental and numerical results of the natural frequency showed the error percentage, which is lower at the high frequencies and increases at the low frequencies because of the noise.

Table 12: Experimental and ANSYS results of the natural frequencies for three modes, and it's the damping ratio for Nitinol wire Diameter=1mm and Fixed-Free condition.

Epoxy+ Layers+ wire no.	Modes	Natural Frequency (HZ)			Damping ratio (ξ)
		Experimental results	ANSYS results	Errors%	
Epoxy+ 2Layer+ 1wire	Mode1	18.3	17.2851	5.545902	0.0877
	Mode2	83.6	85.8784	2.725359	0.038
	Mode3	101.4	108.199	6.705128	0.0165
Epoxy+ 2Layer+ 2wire	Mode1	20.4	17.1403	15.97892	0.095
	Mode2	89.6	87.8927	1.905469	0.04
	Mode3	112.3	107.296	4.455922	0.018
Epoxy+ 2Layer+ 3wire	Mode1	19.3	17.0005	11.91451	0.096
	Mode2	88.6	87.0013	1.804402	0.042
	Mode3	112.7	106.425	5.567879	0.018

Table 13: Experimental and ANSYS results of the natural frequencies for three modes, and it's the damping ratio for Nitinol wire Diameter=1mm and Fixed-Fixed condition.

Epoxy+ Layers+ wire no.	Modes	Natural Frequency (HZ)			Damping ratio (ξ)
		Experimental results	ANSYS results	Errors%	
Epoxy+ 2Layer+ 1wire	Mode1	108.5	109.946	1.332719	0.075
	Mode2	311.3	302.416	2.853839	0.048
	Mode3	542.6	513.57	5.350166	0.0252
Epoxy+ 2Layer+ 2wire	Mode1	110.5	109.031	1.329412	0.085
	Mode2	301.2	299.917	0.425963	0.051
	Mode3	545.7	542.875	0.517684	0.026
Epoxy+ 2Layer+ 3wire	Mode1	108.9	108.147	0.69146	0.102
	Mode2	301.6	297.507	1.357095	0.071
	Mode3	544.7	537.823	1.26253	0.039

Table 14: Experimental and ANSYS results of the natural frequencies for three modes, and it's the damping ratio for Nitinol wire Diameter=1mm and Fixed-simply support condition.

Epoxy+ Layers+ wire no.	Modes	Natural Frequency (HZ)			Damping ratio (ξ)
		Experimental results	ANSYS results	Errors%	
Epoxy+ 2Layer+ 1wire	Mode1	77.8	75.7393	2.648715	0.065
	Mode2	251.1	245.046	2.410992	0.041
	Mode3	371.9	370.884	0.273192	0.0312
Epoxy+ 2Layer+ 2wire	Mode1	74.4	75.1068	0.95	0.075
	Mode2	245.3	243.001	0.93722	0.082
	Mode3	382.2	379.161	0.795133	0.053
Epoxy+ 2Layer+ 3wire	Mode1	74.1	74.496	0.534413	0.156
	Mode2	243.1	241.048	0.844097	0.083
	Mode3	377.6	375.487	0.559587	0.072

Table 15: Experimental and ANSYS results of the natural frequencies for three modes, and it's the damping ratio for Nitinol wire Diameter=2mm and Fixed-Free condition.

Epoxy+ Layers+ wire no.	Modes	Natural Frequency (HZ)			Damping ratio (ξ)
		Experimental results	ANSYS results	Errors%	
Epoxy+ 2Layer+ 1wire	Mode1	18.7	17.3004	7.484492	0.0977
	Mode2	85.6	83.3717	2.603154	0.048
	Mode3	112.3	108.305	3.557435	0.0265
Epoxy+ 2Layer+ 2wire	Mode1	17.8	17.1854	3.452809	0.105
	Mode2	93.3	90.7118	2.774062	0.05
	Mode3	109.6	107.597	1.827555	0.028
Epoxy+ 2Layer+ 3wire	Mode1	18.3	17.088	6.622951	0.106
	Mode2	89.3	87.6671	1.828555	0.052
	Mode3	107.2	106.996	0.190299	0.028

Table 16: Experimental and ANSYS results of the natural frequencies for three modes, and it's the damping ratio for Nitinol wire Diameter=2mm and Fixed-Fixed condition.

Epoxy+ Layers+ wire no.	Modes	Natural Frequency (HZ)			Damping ratio (ξ)
		Experimental results	ANSYS results	Errors%	
Epoxy+ 2Layer+ 1wire	Mode1	111.4	110.065	1.198384	0.085
	Mode2	201.3	202.797	-0.74367	0.058
	Mode3	516.3	517.056	-0.14643	0.0352
Epoxy+ 2Layer+ 2wire	Mode1	110.4	109.355	0.946558	0.095
	Mode2	302.1	300.912	0.393247	0.061
	Mode3	554.3	557.988	-0.66534	0.036
Epoxy+ 2Layer+ 3wire	Mode1	104.3	108.752	-4.26846	0.112
	Mode2	296.3	299.302	-1.01316	0.081
	Mode3	547.4	541.766	1.029229	0.049

Table 17: Experimental and ANSYS results of the natural frequencies for three modes, and it's the damping ratio for Nitinol wire Diameter=2mm and Fixed-simply support condition.

Epoxy+ Layers+ wire no.	Modes	Natural Frequency (HZ)			Damping ratio (ξ)
		Experimental results	ANSYS results	Errors%	
Epoxy+ 2Layer+ 1wire	Mode1	74.3	75.8118	2.034724	0.075
	Mode2	247.4	245.314	0.843169	0.051
	Mode3	358.1	360.435	-0.65205	0.0412
Epoxy+ 2Layer+ 2wire	Mode1	76.3	75.3138	1.292529	0.085
	Mode2	247.3	243.743	1.438334	0.092
	Mode3	396.5	390.479	1.518537	0.063
Epoxy+ 2Layer+ 3wire	Mode1	73.2	74.8916	2.310929	0.166
	Mode2	248.3	242.407	2.373339	0.093
	Mode3	382.2	378.31	1.017792	0.082

The damping ratio results were obtained experimentally for all the specimen by using the half-power bandwidth techniques. The significant sources of damping in polymeric composites are due to viscoelastic nature of the polymer and during the interface slipping between the reinforcement (E-glass fibers or shape memory alloy wire) and the epoxy. The damping characteristic affected by the fiber type, the volume fraction of the reinforcement, the layers number, and the environmental influence.

10. Conclusions

The main aims of this work is to study the damping characteristics and the natural frequencies of laminated hybrid composite embedded with shape memory alloy wires. The following conclusions are drawn:

1. For all the specimen, increasing the natural frequency leads to decreasing the damping ratio.
2. The shape memory alloy type Nitinol is preferred and is most common among the other types of shape memory alloy.
3. Using the shape memory alloy into the composite materials changes their mechanical properties and the dynamic behaviors.
4. Epoxy is the most matrix material used among the other types of polymer because it has a good compatibility with shape memory alloy at phase transformation.
5. Embedding a combination of shape memory alloy and fibers into the matrix as a Hybrid composite can improve the mechanical properties and the dynamic behaviors.
6. Study the effect of the following parameter are suggestedfor future works:

i. Embedding other forms of shape memory alloy, such as ribbons or particles into the hybrid composite materials.
ii. Using other types of shape memory alloy, such as Copper-Aluminum-Nickel or Copper-Zinc-Aluminum.
iii. Using other types of matrix materials, such as polyesters.
iv. Using other types of test for the prepared samples such as fatigue and creep.

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