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Transient analysis of shape memory alloy (SMA) reinforced composite

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Abstract

This paper discusses the damping effect of Shape Memory Alloy (SMA) reinforced composite by making martensite to austenite transformation with the help of resistance heating.The martensite phase allows high mobility of atomic structure during twining-detwining process. When they are subjected to vibration, their movement and friction in the atomic structure dissipate elastic energy thus damping the vibration energy.Thus the martensite phase is known to have high intrinsic damping capacity. An austenite phase undergoes a stress-induced phase transformation(into fully martensite or partially martensite) Thus at higher temperatures also, the Shape memory alloy can work as good damper. The energy is dissipated (reversible isothermal process) as the material is cycled in a hysteretic stress-strain loop. In this paper an experimental study was performed to calculate the damping factor in both martensite and austenite phase in a Shape memory alloy reinforced compsoite. The calcuated damping factor is used in FEA software to validate the experimentally observed response of the composite. The methodology starts with the design of composite based on the strength requirement and critical volume fraction method. This involved determining the critical volume fraction, number of SMA reinforcement wires and their diameter. The process of composite fabrication is described in the Experimentation section. Both numerical results and experimental results show the agreement to close level.

1. Introduction

Shape Memory Alloy are widely used as smart material because of their properties such Shape Memory

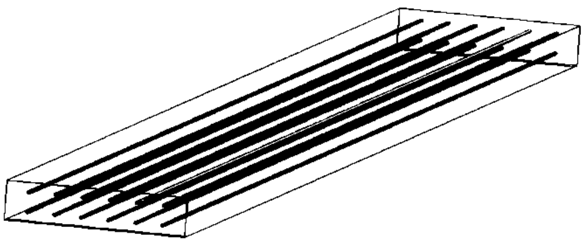

Fig 1. Composite model

Effect (SME), Pseudoelasticity,high damping capacity. The unusual properties are because of the ability of shape memory alloys to make solid to solid phase transition by changing the temperature. Additionally, the phase transition is reversible which is making shape memory alloys suitable material for cyclic environmental conditions.Shape Memory alloy has two phases. At lower temperatures, it exhibits the martensite phase. At higher temperatures, it exhibits the austenite phase. Phase transformation temperature can be changed depending upon the NiTi fraction. In the martensite phase, SMA exhibits low stiffness and excellent damping properties. SMA can be made into composites along with suitable matrix material, and they can be effectively used as a damper. In the austenite phase, SMA exhibit high stiffness and large recoverable strain. Composite materials embedded with Shape memory alloy has found advantages in replacement for conventional material because of i) their high specific stiffness and strength while weighing far less than the conventional material ii) smart sensing and actuation.The property of composite depends upon the orientation and position of reinforcement SMA fibres. The SMA fibres are placed either along the neutral axis, in transverse direction or at an angle. The position of SMA fibres can be at neutral axis plan or non-neutral axis plane.

Shape memory alloy are widely used in applications found aerospace, automotive and civil structures. They are used to tune the properties of a structure such shape adaptation, damping, natural frequency, stiffness, strain and other static and dynamic properties. SMAs are investigated to study the properties i) shape morphing ii) damping and vibration response iii) impact and iv) crack closure. The high strength and better energy absorption of Shape memory alloys make them suitable in the applications which are prone to impact and damping unpleasant vibrations.The damping properties of the SMA reinforced composite are different in martensite phase and austenite phase. By using suitable phase transition method, multiple level of damping can be achieved.

This paper comparatively discusses the damping effect achieved using SMA reinforced composite in a martensite phase and austenite phase. For this, numerical evaluation is carried out using Ansys Mechanical. Furthermore, the results are validated by in-house experimental calculation. A composite is fabricated in-house. The method of fabrication is also discussed below. Experimental methodology is also discussed in detail, including the numerical analysis approach and experimental validation method. The experimental result agree with numerical analysis. Fig 1. shows composite model which is studied in this paper.

2. Literature Survey

SMA composites have been researched for applications of impact, bending, and vibrations. Z.G. Wei reviewed the current research in the field of shape-memory materials such as shape-memory alloys, shape-memory ceramics and shape-memory polymers.The author found the current researches used the basic phenomena, phase transformations induced by the input stimulus, which result in the remarkable changes in properties of the materials[1]. ACohades et al**.** discussed the applications of shape memory alloy (SMA) reinforced polymer composite materials (FRPs). SMAs have been investigated forfour primary areas of properties:(i) damping and vibrational response; (ii) impact; (iii) crack closure; and (iv) shape morphing.The research has found that the martensite variants are very mobile, their movement andfriction between the variant interfaces dissipate a large amount ofenergy when elastic waves travel into the material. As a result, theintrinsic damping capacity of the martensite phase (inthe transformation temperature range) is high; this can beexploited to confer added passive damping to the composite material. A fully austenitic material can also undergo a stress-induced phase change called superelasticity. The transformation thus occurs in reversible isothermal conditions. The energy is dissipated (under the form of heat) when the material is cycled in the hysteretic stress-strain loop, materials in this state can also act as passive dampers[2]. S.B.Kumbhar et al. discussed the method of tuning the stiffness of SMA reinforced-magnetorheological elastomer matrix composite. The researcher proposed a method to study the dynamic response of a composite[3]..S.L. Angioni et al. discussed selection of matrix material forhybridizing composites of shape memory alloys (SMA). The SMA composite materials are subjected to the impact through superelastic deformation or recovery stress. They absorb the energy, thus reducing the effects of the impact on the composite structure[4]. J. Schrooten et al. reported results of a concerted European effort towards a fundamental understanding SMA composites for the manufacturing and design process. Thermodynamic and thermomechanical experiments were performed on SMA wires. A model was developed to simulate the thermomechanical behaviour of the wires.The requirements of the host composite materials for different applications of SMA composite are discussed for precise working[5]. Kelley A. Tsoi et al. investigated the absorption of impact energy by SMA composite, and it was found that a 1.8 % volume fraction of wire gives the best results [6]. Quighao Menget al. have researched shape memory polymer compositefor its properties such as recovery time, thermal conductivity, and magnetic and electrical properties[7]. There has been a lot of research on the SMA composite to analyze its mechanical properties and experimentation methods [9–26].

3. Methodology

3.1. Design of Composite

Wei[1]concluded that many researchers have integrated shape-memory materials within monolithic or composite host materials. These compositesenhanced the mechanical properties or actively tuned in response to environmental changes. The researchers have successfully demonstrated the polymer as a matrix material for the shape and position control, acoustic and vibration control in both active and passive methods.The materials are normally subjected to dynamic loads, impact damage and creep resistance. More recent approaches uses shape-memory alloy reinforced composite that uses to metal or silicon as matrix materials.

Silicon rubber was selected as a matrix material because of its following properties.It is very soft and has low stiffness and High strain capacity >140%. Siliocn rubber can be cured at room temperature, so no residual thermal stresses and it is very stable against temperature variation (-40 to 170 degrees).

The SMA volume fraction should be higher than the Critical Volume Fraction.Thecomposite is transformed in austenite phase using activation method. Hence composite’s mechanical properties, theultimate strength and Young’s modulus in the austenite phase should be considered for calculating critical volume fraction..

$$V_{fcritical} = \frac{(\sigma_m)_u - E_m * (\varepsilon_f)_u}{(\sigma_f)_u - E_m * (\varepsilon_f)_u} \tag{1}$$

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= 0.012

(2)

Where, $(\sigma_m)_u$ is strength of matrix material, E_m is Youngs Modulus of matrix, $(\varepsilon_f)_u$ is strain at the failure of SMA and $(\sigma_f)_u$ is the strength of SMA.

The strength of the SMA composite can be evaluated using the volume fraction or based on the required strength of the composite, the volume fraction can be determined.

$$(\sigma_u)_{Comp} = (\sigma_f)_u * V_f + E_M * \varepsilon_f * (1 - V_f)$$

(3)

Where, $(\sigma_{comp})_u$ is the strength of the composite, and V_f is the volume fraction.

Based on the volume fraction, the number of wires and the diameter of reinforcement wires can be determined as:

$$V_f = \frac{V_{SMA}}{V_{Composite}} = \frac{A_{SMA} * L}{A_{composite} * L} = \frac{N * \frac{\pi}{4} * D^2}{A_{composite}}$$

(4)

Where V_{SMA} is the volume of SMA and $V_{Composite}$ is the volume of the composite. A_{SMA} is the total area of SMA fibres, and $A_{composite}$ is the total area of composite. N is the number of wires, and D is the diameter of the SMA wire.

For designing the composite, the volume fraction was limited to 0.02(>$V_{f critical}$) and the number of wires chosen is 12. The wires are reinforced at two positions: one above the neutral axis and one below from neutral axis.The wires are arranged at equal distance along the width and symmetrical about the neutral axis.

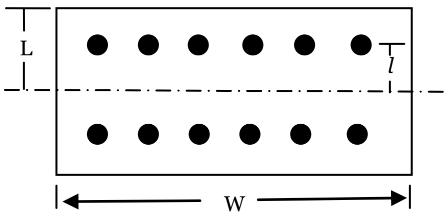

Fig 2. Cross section of a composite

Fig 1 shows the modes of SMA reinforced composite model. All the fibres are in the longitudinal direction of composite. The SMA wires of 1 mm diameter are used.


Fig 3. Mould for composite fabrication

Fig 2 shows the cross-section profile of the composite. A special mould was created using acrylic sheet.

Fig 4. Fabricating the Composite

First wires are passed through the mould and small current is passed through them. This straightens the wires. And then silicon rubber is poured to fill the mould completely.

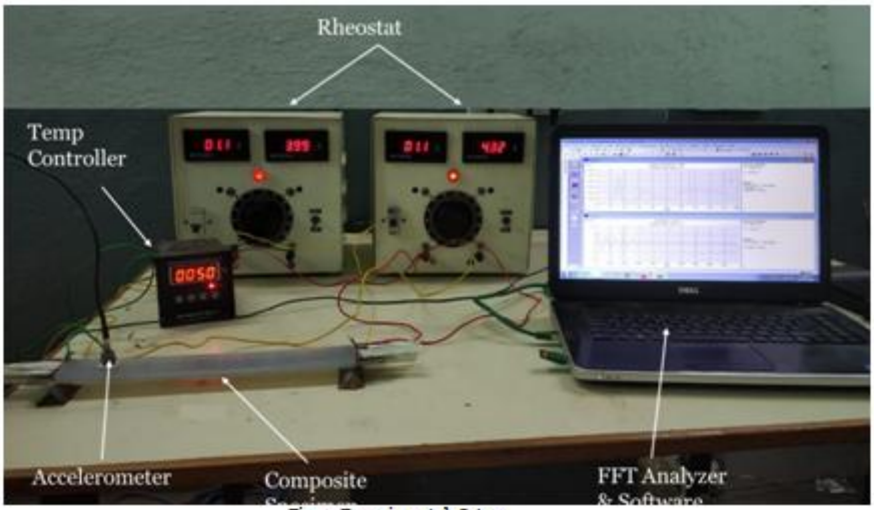

Fig 5. Experimental Setup

The composite was left to cure for 24 hours. The tests are conducted after 72 hours to ensure complete cure.

Experimentation

The setup requires an accelerometer, an FFT for vibration data processing and a computer for displaying the output. For the experiment, the composite is constrainedusing simply supported conditions. The composite is placed on two supports at the very end.

Fig 6. Composite Specimenp

The accelerometer is connected to the composite. The accelerometer is bonded to the composite using special lightweight glue. The accelerometer's output is fed into the FFT analyser. The FFT analyser sends the processed data to the Display. Once the setup is ready, the vibrations are generated by giving an impulse in the composite. FFT output provides two types of information. 1. Amplitude of vibration vs frequency and 2. Acceleration in time domain.The sample readings are shown in fig 11 anf fig 12. It can be seen that the amplitude of vibration is reducing with the time. There is significant damping in both martensite phase and austenite phase. The damping factor is calculated by logarithmic decrement method.

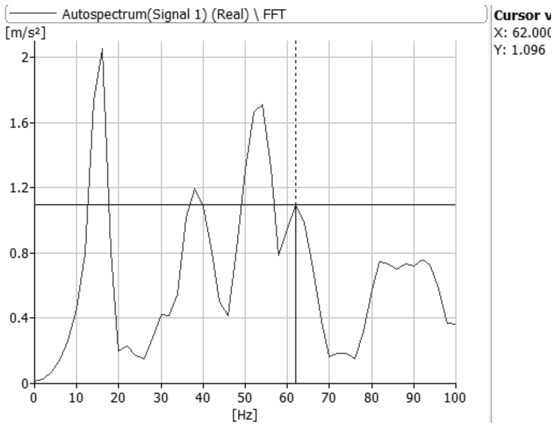

Fig 7. Amplitude vs Frequency

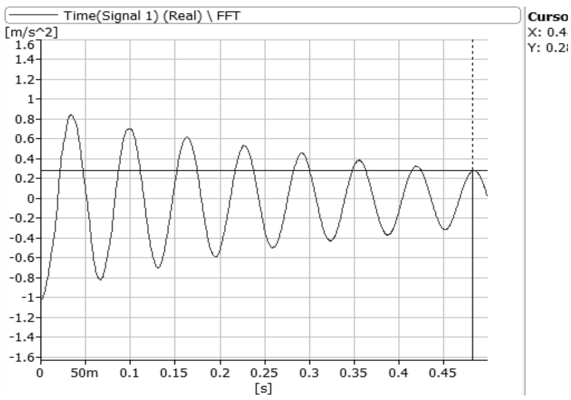

Fig 8. Amplitude vs Time

Readings are taken in several locations, such as 1/8th length from each side and at the centre of the composite.Several readings are taken. The frequency domain graphs shows the natural frequencies of first few modes. From the time domain graphs, the damping factor is calculated. Damping factor is calculated for several readings and average is taken to minimise the error. The process to calculate the damping factor is discussed in section 3.3 below.

Table 1

Experimental Modal Frequencies.

Mode Number	SMAMartensite (Hz)	SMA (Hz)	Austenite
Mode 1	14	16	
Mode 2	34	36	
Mode 3	58	64	

The experiment is repeated again, passing the current through the reinforcement wires to transform them into austenite phase. The current is passed continuously.A thermocouple is connected to one of the SMA wires to measure the temperature. It took a few minutes to reach the temperature range of 45-50 degrees C. The experiment is repeated, and damping factoris calculated.Table 3. shows the Modal frequencies in the martensite and austenite phases. In the study of transient vibration damping, it is necessary to evaluate the rise time and settling time. Table 4 compares the rise time, settling time and damping factor in martensite and austenite phase of SMA in composite.

Table 2

Experimental Results.

	SMAMartensite	SMA Austenite
Rise time	0.02448 sec	0.01923 sec
Settling time	1.18 sec	0.996 sec
Damping Factor	0.06	0.0694

3.2. Damping Factor Calculation of SMA Composite Experimentally

The composite is used to tune the vibration response of a structure. Therefore, it is necessary to understand the damping properties of the composite.

As shown in fig 8, the same experimental setup also provides the time domain response of the composite for the input impulse. It can be seen that the amplitude of vibration is reducing with the time. The damping factor is calculated by logarithmic decrement method. The logarithmic decrement method can be defined as the ratio of any two successive amplitude peaks. The logarithmic decrement shows the rate at which amplitude of free damped vibration decreases. When the amplitude of after number of cycles is known the logarithmic decrement can be calculated as

$$\delta = \frac{1}{n} \ln \left(\frac{X_0}{Xn} \right) \quad (5)$$

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where X_0 is the first amplitude peak and Xn is amplitude after 'n' no of cycles.

Using the logarithmic decrement, the damping factor is calculated as below

Damping Factor (ξ)

$$\xi = \sqrt{\frac{\delta}{4\pi^2 + \delta^2}} \tag{6}$$

The damping factor for martensite and austenite phase are shown in the table. These values are input in FEA analysis.

3.3. *Finite Element Analysis Method*

A transient analysis was performed in ANSYS Workbench 2020R2. Fig. 1 shows the 3D model of the SMA wire composite, Elastomer. By considering simply supported boundary condition, analysis was carried out. A geometry was created in Spaceclaim-Directmodeler. Section 3.1 discussed the consideration in the designing the composite. A solid model of dimension 300 x 40 x 10 and SMA wires of 1mm diameter are created. The wires are reinforced at two layers one above and one below from the neutral plane of bending of the composite. The analysis was done at martensite phase and austenite transformation temperatures. And the effect of change in Young's Modulus of SMA on natural frequency was studied.

The selected composite consists of the SMA wires, elastomer. The values of properties of materials are shown in Table3. The overall mesh quality has been checked with acceptable limits, and achieved values are within limits.

Table 3

Material properties.

Material	Density (kg/m^3)	Young Modulus (Pa)	Poisons ratio
SMA Austenite	6475	5.834E10	0.32
SMA Martensite	6475	3.388 E10	0.32
Elastomer	1100	1.32 E6	0.495

The displacement boundary condition is applied on the two edges created close to each end. To represent the simply supported condition, one end is fixed in all direction. The other end is free in longitudinal direction while fixed in other two direction.

The analysis was setup to be performed as ‘Mode Superposition Transient’ analysis. In this approach, first modal analysis is performed, and then transient response of structure is calculated by the superposition of mode shapes by the solver. In Analysis setting, damping control is used to define the damping factor. The damping control setting has’ Damping Ratio’ option which should be defined as equal to half the damping factor.To create the impulse excitation, an acceleration was defined for very small period of time. The response of the composite model to this input excitation was plotted in the postprocessing. The graph is shown below.

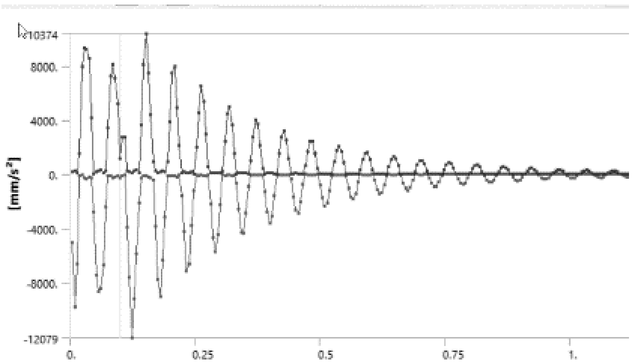

Fig 9. Transient Response of Composite

Table 4 shows the rise time and settling time comparison of martensite and austenite phase of SMA composite. From the response plots in FEA results, the initial impact time should be subtracted to get the correct rise time and settling time.

Table 4

FEA Results.

	SMAMartensite	SMA Austenite
Rise time	0.028 sec	0.023 sec
Settling time	1.247 sec	1.014 sec

4. Results anddiscussion

Experimentally calculated damping factor, rise time and settling time are shown in the Table 2.The damping factor is calculated based on logarithmic decrement method. Rise time is the time needed for the composite’s response to reach the 100% of its maximum amplitude. The settling time is time needed for the response of the composite to reach the value near steadystate. There are several readings are taken for experimental calculation. For each reading damping factor, rise time and settling time is calculated. The Table 2 shows the average values for the several reading taken in both martensite and austenite phase. The FEA results are shown in Table 4 for both the martensite and austenite phases.From Table 2 and Table 4, it can be seen that the analysis results closely match the experimental result.

5. Conclusion

The result shows that there is increase in damping when martensite is transformed into austenite. It is established that in the fully austenitic temperature region, the SMAs are transformed isothermally into martensite due to stress-strain. Thus,in the austenitic region, the SMAs are still good dampers. The increase in the damping property could be also attributed to change the properties of the elastomer due to heating. Therefore further study is necessary to study the effect of temperature rise on the damping properties of the matrix material. Higher input current generates higher resistance heat and thus expedites the martensite to austenite phase transformation. The FEA method used for transient analysis generates results which closely match the experimental results. The FEA method can be used to analyse several SMA-silicon composites configurations and run parametric studies.

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