Structural Health Monitoring of an asymmetrical SMA reinforced composite using embedded FBG sensors

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Abstract

Embedded actuator and sensor technology provides accurate structural health monitoring and proper structural response of a structure at any harsh servicing situation. This paper describes the fabrication of a smart composite by embedding shape memory alloy (SMA) wires and fibre Bragg grating (FBG) sensors into a glass fabric reinforced polymeric composite. Mechanical performances of the composite under martensitic and austenitic stages of the SMA wires were studied, and its natural frequencies were also measured accordingly. The result shows that the shift of the natural frequency arises from temperature change, thus changing the mechanical

properties of the SMA wires. The changes of strain, stress, curvature and damping ratio were predicted from an asymmetrical lamination model. It has found that this model demonstrates certain attractive effects including the mechanical properties, the change of shape and the natural frequency upon activation of the SMA wires.

1. Introduction

The potential of glass fibre reinforced plastics (GFRPs) in global market is enormous, and this global market will grow up to a total of US \$ 29.4 billion in 2013[1]. GFRPs have already been employed widely in aerospace, automotive engineering, railway and wind energy industries for many years. However, their main disadvantage is the complex failure mechanisms. Smart materials have attracted growing interest as it responds to environmental stimuli in particular conditions and leads to many potential applications. Embedded sensor and actuator technology is a promising solution to provide active control on composite structures. Therefore, the market tends to focus on the development of smart composites whose properties are altered appropriately in response to environmental fluctuations rather than conventional GFRPs. These smart composites are defined as an integrated structure consisting of actuating and sensing devices to form a smart system similar to a human body [2-4].

Fibre reinforced composites with embedded shape memory materials have been extensively focused on because of their superior potentials for the applications of vibrational and structural controls [5]. The advantages of shape memory alloy (SMA) in the field of actuating system include (1) high reversible strain, (2) high damping capacity, (3) large reversible change of mechanical and physical characteristics and (4) high recovery stresses [6]. SMA composites demonstrate their extraordinary performances in adjusting their shape, vibration, acoustic transmission and impact resistant through a centralized control system; for instance, vibration control can be

achieved by controlling the stiffness of SMA wires with heat, and thus the whole composite structure [7].

Fibre Bragg grating (FBG) sensor is one of the optical fibre sensing technologies, which has drawn enormous attention for over twenty years [8-11]. The advantages of the FBG sensors include (1) light in weight, (2) small in size without the degradation of the structural integrity, (3) insensitive to electromagnetic interference, (4) high degree of multi-plexability and (5) ability to be used in environmentally unfavorable conditions [12]. Embedding a FBG sensor into a composite helps to monitor the curing temperature of its structure during the manufacturing process, which can be subsequently used for life time performance monitoring [13].

A multi-layer asymmetric composite structure starts to be bent when subjected to a temperature change. Asymmetric structure is formed by orientating fabric layers in different directions or constructing the structure using distinct materials with different mechanical properties and coefficients of thermal expansion (CTEs). The asymmetrical lamination of a composite can result in the combined effect of bending moment and laminate extension. Another phenomenon is the formation of curvature resulting from an action to bending of an asymmetrical laminate under temperature change [14]. An undesirable formation of the curvature is unfavorable to a composite structure if it is applied to real life engineering applications. Korakianitis et al. [15] have found that the change of curvature of a composite blade affects the aerodynamic profile of the blade seriously, which in turn induces some problems of vibration and stalling of airflow. Besides, they have also found that an appropriate blade curvature design results in maximizing the aerodynamic performance with a prevention of flow separation [15].

However, existing studies of SMA reinforced composites have revealed the lack of basic understanding of the effect on their temperature change, especially the issues concerning the generation of distinct thermal expansions because of their hybrid materials' properties. Therefore, the mechanical and acoustic properties of these composites have to be well understood before implementing them for real-life engineering applications. In this paper, the mechanical and dynamic properties of an asymmetric SMA reinforced composite subjected to a temperature change have been investigated through experimental and theoretical approaches.

2. Experimental study

2.1 Materials

Ni-Ti alloy SMA wires with the diameter of 0.2 mm were used in the current study. Polymeric matrix GY251 epoxy resin mixed with GY 956 hardener was supplied by Shing Hing chemical Co., Ltd. The ratio of the epoxy resin to the hardener was 5:1. Plain weave glass fabrics (style AF218) that were used to make a composite were supplied by Colan, Australia.

The FBG sensors used in this study were written in polyimide-coated, standard monomode optical fibres. The gratings were fabricated and centered in $\lambda_B = 1540$ nm, 1536 nm or 1530 nm with the gauge length of 8 mm.

2.2 Sample manufacturing

The optical fibres and SMA wires were cleaned by ethanol applied lint-free wipe to remove contaminants including dust particles, human hand oils and so on in order to enhance the adhesion of the optical fibre and SMA wires with surrounding epoxy matrix.

Composite samples were made by hand lay-up process, which was followed by vacuum bagging and mounted inside a frame. The frame was used for pre-straining and aligning the SMA wires and optical fibres in the right direction. A total of eight plies of glass fabrics were used. The length, width and thickness of the composite beam for the calibration and tensile tests were 200mm $\times$ 30mm $\times$ 1.94mm respectively. Two types of lamination symmetric and asymmetric composites were prepared. Symmetrical composite beams were fabricated for temperature and strain calibration tests. The SMA wires and the optical fibre were embedded in the same plane and at the mid-thickness of the composite beam as shown in figure 1a. The asymmetric composite beam was fabricated as indicated in figure 1b.

For the composite beam fabricated asymmetrically, six layers of glass fabrics were underneath the SMA wires and the optical fibre and two layers were placed above. The interval between the SMA wires and the optical fibre with a pre-written FBG grating (FBG sensor) was 5 mm. A total of five SMA wires were embedded in parallel into the composite.

2.3 FBG detection system

An array of at least 2 FBG sensors was used in each composite samples. One of the FBGs was embedded inside the composite beam as a strain sensor while another was attached to the composite beam's surface as a mechanical-strain-free sensor to compensate for thermal strain effect. A pigtail of the array was spliced into a patchcord and connected to an interrogator. A PC with LabView program was connected to the interrogator for the data acquisition. The interrogators models sm125 and sm130 from Micron Optic Inc. were used in the experiment for static and dynamic measurements respectively. The sampling frequency and measurement

resolution of the static machine were 1 Hz and 1 pm, and the corresponding values for the dynamic machine were 2000 Hz and 5 pm.

2.4 Symmetrical composites

2.4.1 Temperature and strain calibration of the FBG sensors

A FBG sensor can be made from different fabrication techniques and consequently different sensing properties are obtained. Therefore, the strain and temperature sensitivity coefficients of the FBG sensor should be determined experimentally by conducting the calibration test prior to any property test of the composite beams. In this study, the calibration of strain and wavelength shift of the sensor was determined by performing a simple uniaxial tensile test of the sample shown in figure 1 at room temperature. The change of strain was measured by a surface mounted strain gauge. The wavelength shift induced by the applied strain ϵ at constant temperature is given by the following equation [16],

$$\Delta\lambda_B = \lambda_B (1-P_e)\epsilon = K_\epsilon \epsilon \quad (1)$$

Where P_e is the photoelastic coefficient of the fibre, K_ϵ is strain sensitivity. The linear correlations between the change of $\Delta\lambda_B / \lambda_B$ with the change of applied load, and the change of $\Delta\lambda_B / \lambda_B$ with the change of strain are shown in figure 2a & 2b. K_ϵ is obtained as the slope of the graph of $\Delta\lambda_B / \lambda_B$ versus the strain variation ($\mu\epsilon$), which is equal to $7.5 \times 10^{-7} [(pm/pm)/ \mu\epsilon]$. The result indicates that every 1.16 pm shift of the Bragg wavelength of the FBG sensor corresponds to 1 $\mu\epsilon$ in the case of 1541 nm wavelength.

For calibrating the thermal-induced strain of FBG sensor, the composite beam was heated up by the embedded SMA wires via electrical resistance heat, that is to apply the current to the wires and their electrical resistant properties in order to generate

heat themselves. Since the SMA wires were embedded into the composite beam which is relatively thin, the surface temperature of the composite beam at the location where the wires were embedded should be very close to the temperature of the SMA wires. The simultaneous wavelengths of the strain-free FBG were recorded from room temperature to 35 °C. According to the temperature change measured by thermocouples, the corresponding wavelength shift is given by [16],

$$\Delta\lambda_B/\lambda_B = S_T\Delta T \quad (2)$$

Where the temperature sensitivity coefficient $S_T = \alpha + \xi$, in which α is the thermal expansion coefficient and ξ is the thermo-optic coefficient. The linear correlation between the change of $\Delta\lambda_B/\lambda_B$ and the temperature is shown in figure 3. S_T was obtained as the slope of the graph of $\Delta\lambda_B/\lambda_B$ versus the change of temperature. From the figure 3, it shows that the S_T is $6.2 \times 10^{-6} [(pm/pm)/^\circ C^{-1}]$. This result demonstrates that every 9.55 pm shift of the Bragg wavelength of the FBG sensor corresponds to 1 °C in the case of 1541 nm wavelength.

2.5 Unsymmetrical composites

2.5.1 Mechanical properties

A tensile test was conducted to obtain the Young's modulus of the composite beam as shown in figure 1b. The composite beams were mounted onto the MTS testing machine (Alliance RT/50) with tailor-made supporting fixtures for the test. The crosshead speed of the test was 1.5 mm/min. The phase transformation temperatures of the SMA wires were measured by using differential scanning calorimeter (DSC) and the results are listed in table 1. A DC supplier was used to supply electrical current into the wires to generate electrical resistant heat to specified temperature. The properties of the composite beams at the SMA's transformation temperatures, namely

martensite finish temperature (M_f) and austenite finish temperature (A_f), are shown in Table 1.

Figure 4 shows the stress-strain curve obtained from the tensile test and conducted at (a) room temperature and (b) 50 °C. Notwithstanding the Young's modulus of the composite beam at $T < M_f$ is higher than that measured at $T > A_f$, the strength of the composite beam at $T < M_f$ is lower than that at the temperature above A_f . This result confirms that the composite beam is more ductile when the SMA wire is in its martensitic state as compared to that at full austenitic phase.

At the beginning of the tensile test, it is interesting to see that the force required to generate strain is lower as expected. This phenomenon is due to the re-alignment of a curved composite beam that was formed by the differential thermal expansions of plies inside the composite beam upon heating. Therefore, the force was initially used for straightening the composite beam instead of stretching the SMA wires. Therefore, the Young's modulus of the composite beam measured during the tensile testing at the temperature above A_f was lower than that at temperature below M_f . Most of previous studies ignored this thermal distortion effect, which however is a crucial factor for any precise smart control system. After the curved composite beam was aligned, the stress started increasing as the SMA wires effectively took part of the load via stress transfer mechanism between the wires and surrounding matrix [17].

Figure 5 shows the strain responses at the top surface of the composite beam when temperature increases from room temperature to 35 °C. Since both ends were fixed by the pre-designed testing fixture, no longitudinal expansion was allowed during the heating process. Instead, the unsymmetrical nature of the composite beam induced bending of the composite beam's surface due to unsymmetrical thermal expansions of the top surface and the bottom surface. Therefore, the longitudinal strain of the top

surface was lower than that strain of the bottom surface when the composite beam was heated up by the SMA wires.

As seen from figure 6, a good bonding at the interfaces between the optical fibre and matrix, and SMA wire and matrix was obtained so that the stress could be transferred from the matrix to the SMA wire. It is proved that the shift change of wavelength of FBG is due to the change of temperature.

2.5.2 Change of strains

A SMA reinforced composite beam for longitudinal and transverse strain analyses is shown in figure 7. Figures 8a-c depict the reflected spectra of a FBG sensor extracted at room temperature, $\Delta T=20^{\circ}\text{C}$ and $\Delta T=40^{\circ}\text{C}$. Figure 8d-f show the reflected spectra of FBG 1, FBG 2 and FBG 3 obtained according to the change of the temperature. The change of the strain shifts the Bragg wavelength by dilating or compressing the grating and changing the effective index of light in the optical fibre. In the figure 8e, it shows that reflected light intensity is increasing as the temperature rises. As the composite beam was deformed owing to distinct thermal expansion of the asymmetric lamination, it induced a pressure shift in the composite. The composite was bent due to the thermal expansion, and thus the intensity of reflected light was changed.

2.5.3 Change of natural frequency

The natural frequencies of the composite beams were measured by Brüel & Kjær (B&K) accelerometer for calibration. The configuration of the B&K set-up included accelerometer, charge amplifier, pulse front-end pulse dongle and a computer for time signal and spectrum analysis. The frequency range of the set-up was 0-250 Hz.

A series of cantilever composite beams were impacted at a distance of approximately 15mm from the clamped end. The frequency response functions of the clamped-free

sample recorded by an accelerometer and FBG sensor are plotted in figure 9. Obviously, the natural frequencies obtained by two different techniques are the same. The response peak is sharp and it represents the natural frequency of 29.1 Hz for the composite at room temperature .

Figure 10 shows the comparison of natural frequencies of the samples obtained from the FBG sensor at $T < M_f$ and $T > A_f$. The natural frequency of the cantilever composite beam is shifted from 29.1 Hz to 26.5 Hz when $T > A_f$. During the experiment , it was found that the embedded SMA wires could regulate the natural frequency of the cantilever composite beams. The natural frequency of the cantilever composite beams depends on their dimension and constitution, the number of embedded SMA wires and their transformations temperatures. However, the decrease of the natural frequency of the cantilever composite beams at $T > A_f$ was mainly due to the generation of an internal compressive stress by the mismatch of thermal expansions between the layers of glass fibre/epoxy, SMA wires and optical fibre [18-19]. Since the SMA wires and the optical fibre were not embedded in the neutral axis of the samples, the mismatch of the thermal expansion would therefore cause the bending of the sample accordingly upon heating.

Figure 11 illustrates the vibration response of the cantilever composite beam subject to a localized impact loading. The damping properties of the cantilever composite beam at $T < M_f$ and $T > A_f$ were analysed by FFT analyser. In figure 11, it can be seen that when the temperature increases, a reduction in the vibration amplitude occurs. Besides, the excitation is attenuated when the temperature increases. During the experiment, it was found that the damping properties and natural frequency of the cantilever composite beams could be modulated by increasing their temperature. This

phenomenon was due to the change of the modulus, induced internal stress and geometry of the cantilever composite beam.

3. Theoretical analysis

3.1 The relationship of temperature and curvature of the unsymmetrical composite

Figure 12 shows the theoretical model of an unsymmetrical composite plate. For thin plates subjected to small deformations, the fundamental assumptions of Kirchhoff hypothesis for plates are summarized as follow [20-23],

1. Deflections of the mid-surface are relatively small compared to the thickness of the composite plate, and the slope of the deflected plate is small.
2. The mid-plane is unstrained ($\epsilon=0$) when the plate is subjected to pure bending.
3. Plane sections are initially normal to the mid-plane remain normal to the mid-plane after bending.
4. Normal out- of- plane strains are assumed to be zero when plate deflections are due to bending.
5. The condition of $\sigma_z = 0$ is assumed to be valid.

For a thin laminated plate, the total laminate thickness is usually small compared to other plate dimensions, the plane stress relationship between Cartesian stresses and strains,

$$\begin{Bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{Bmatrix} = [\bar{Q}] \begin{Bmatrix} \epsilon_x \\ \epsilon_y \\ \gamma_{xy} \end{Bmatrix} \quad (3)$$

Where ϵ , σ , τ , γ are strain, stress, shear stress and shear strain, respectively. $[\bar{Q}]$ is the in-plane elements of the stiffness matrix under plane stress condition. Each laminate through the thickness may have a different fibre orientation and consequently a different $[\bar{Q}]$, $[\bar{Q}]_{GF}$ and $[\bar{Q}]_{SMA}$. Under conditions of plane stress the

Cartesian components of stress in the k^{th} layer are

$$\begin{Bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{Bmatrix}_k = [\bar{Q}]_k \left(\begin{Bmatrix} \varepsilon_x^0 \\ \varepsilon_y^0 \\ \gamma_{xy}^0 \end{Bmatrix} + z \begin{Bmatrix} \kappa_x \\ \kappa_y \\ \kappa_{xy} \end{Bmatrix} \right) \quad (4)$$

The above relationship is assumed to be valid for any layer of the laminate. However, the strain variation through a laminate is a function of both mid-surfaces strain and curvature, and is continuous through the plate thickness; whereas the stress is not required to be continuous through the plate. The loads and the moments incorporated with thermal loads and thermal moments are expressed as,

$$\begin{Bmatrix} N \\ M \end{Bmatrix} = \begin{bmatrix} A & B \\ B & D \end{bmatrix} \begin{Bmatrix} \varepsilon^0 \\ \kappa \end{Bmatrix} - \begin{Bmatrix} N^T \\ M^T \end{Bmatrix} \quad (5)$$

Where N is the external load, M is the external moment, N^T is the thermal load and M^T is the thermal moment.

$$[A] = \sum_{k=1}^N [\bar{Q}]_k (z_k - z_{k-1}) \quad (6)$$

$$[B] = \frac{1}{2} \sum_{k=1}^N [\bar{Q}]_k (z_k^2 - z_{k-1}^2) \quad (7)$$

$$[D] = \frac{1}{3} \sum_{k=1}^N [\bar{Q}]_k (z_k^3 - z_{k-1}^3) \quad (8)$$

$$\begin{Bmatrix} \varepsilon^0 \\ M^T \end{Bmatrix} = \begin{bmatrix} A^* & B^* \\ C^* & D^* \end{bmatrix} \begin{Bmatrix} N^T \\ \kappa \end{Bmatrix} \quad (9)$$

$$[A^*] = [A]^{-1} \quad (10)$$

$$[B^*] = [A]^{-1} [B] \quad (11)$$

$$[C^*] = [B][A]^{-1} \quad (12)$$

$$[D^*] = [D] - [B][A]^{-1}[B] \quad (13)$$

$$\begin{Bmatrix} \varepsilon^0 \\ \kappa \end{Bmatrix} = \begin{bmatrix} A' & B' \\ C' & D' \end{bmatrix} \begin{Bmatrix} N^T \\ M^T \end{Bmatrix} \quad (14)$$

$$[A'] = [A^*] - [B^*][D^*]^{-1}[C^*] \quad (15)$$

$$[B'] = [B^*][D^*]^{-1} \quad (16)$$

$$[C'] = -[D^*]^{-1}[C^*] \quad (17)$$

$$[D'] = [D^*]^{-1} \quad (18)$$

When a two-phase model consisting of the austenite and martensite phases connected in series is applied the elastic modulus of the SMA wire can be expressed as [24],

$$E_L = \frac{E_A E_M}{E_M + \xi(E_A - E_M)} \quad (19)$$

Where ξ , E_A and E_M are volume fraction of martensite, elastic moduli of parent phase and martensite phase, respectively. If the volume fraction of martensite is assumed to be linearly proportional to the temperature, longitudinal thermal expansion coefficient [20] can be obtained as

$$\bar{\alpha}_1 = \frac{v_f E_{f1} \bar{\alpha}_{f1}}{E_1} + \frac{v_m E_m \bar{\alpha}_m}{E_1} \quad (20)$$

Transverse thermal expansion coefficient is given by [20],

$$\bar{\alpha}_2 = v_f \bar{\alpha}_{f2} + v_m \bar{\alpha}_m + v_f v_{f12} (\bar{\alpha}_{f1} - \bar{\alpha}_1) + v_m v_m (\bar{\alpha}_m - \bar{\alpha}_1) \quad (21)$$

According to the data listed in Table 1, the theoretical responses of strain and stress at different layers with the change of temperature are shown in figure 13. The neutral axis is shifted and no longer exists in the middle through the thickness of the model. The difference of the strain between the bottom layer and the upper layer increases when the temperature is increasing. The composite plate was bent because of the distinct thermal expansion to cause strain decreasing at the upper layers but increasing at the lower layers. Figure 14 shows the curvature in the longitudinal and transverse directions as a result of the temperature change.

In figure 15, it is found that the strains in both cases decrease, but stresses increase with increasing the volume fraction of embedded SMA wires. The magnitude of stresses provides a general trend from positive to negative values when varying from

bottom layer to the upper layer. It is apparently attributed to a generated internal compressive stresses in the upper layer and a tensile stress in the bottom layer of the composite plate. Figure 16 exhibits that the curvature decreases with increasing the volume fraction of SMA wires in the SMA reinforced the composite so that the modulus of the composite increases.

3.2 Damping ratio and damping coefficients of the compoistes:

The damping ratio of the composite under the change of temperature can be evaluated by measuring the vibration amplitude in free vibration motion using the damping equation [19] below

$$\zeta = \frac{\delta}{\sqrt{(2\pi)^2 - \delta^2}} \quad (22)$$

where $\delta = \ln \frac{u_1}{u_2}$, δ is the natural logarithm of the ratio of any two successive displacement amplitudes (u_1 and u_2) in the same direction. Figure 17 shows the damping ratio of the composite plate with the change of temperature. The internal damping of the material was changed according to the different temperatures. The maximum damping ratio is achieved when $\Delta T = 60^\circ\text{C}$. Damping ratio tends to increase when the temperature and the curvature of the composite plate increase resulting from the thermal expansion of asymmetric laminate. Additinally, the energy dissipation arises from the internal friction at the interface of the stress-induced martensite. After $\Delta T > 60^\circ\text{C}$, damping ratio decreases which is ascribed to the polymer softening as the glass transtition temperature starts at around 65°C .

The mathematical expression of natural frequency of the composite is shown as [22,25],

$$f = \frac{\omega_1}{2\pi} = \frac{1}{2\pi} \sqrt{\frac{\lambda^2 EI}{\sigma A R^4}} \quad (23)$$

Where E is the Young's modulus, I is the moment of inertia, A is the cross sectional area, R is the radius of the curved composite beam, σ is the density of the composite, and λ is equal to 1.875 for the first mode of vibration. Figure 18 shows that the natural frequency increases with the temperature change from 0 to 15°C owing to the thermal expansion of the composite. When the temperature changes above 15 °C, the decrease of the natural frequency can be mainly due to the reduction of the Young's modulus.

4. Conclusion

The mechanical and dynamic properties of a smart asymmetric composite made by glass fibre reinforced epoxy with embedded SMA wires and FBG sensor were studied in this paper. The experimental and theoretical analyses have shown that the composite underwent abnormal shift of its neural axis due to the formation of curvature upon heating up the SMA wires, and thus the composite. The natural frequency decreased as the temperature of the composite above the austenite finish temperature of SMA wires. However, due to the change of the Young's modulus of the SMA wires, the damping ratio increases with the increase of temperature until reaching the glass transition temperature of epoxy. The formation of curvature was due to the differential thermal coefficients of expansion of different materials in the composite and thus, induced an internal stress to deform the composite. In this study, it proves that SMA wires and FBG sensors can be effectively used as intrinsic actuator and sensor for a smart composite system. However, the formation of internal stresses, which may alter the geometry of a composite structure, is an issue that has not been thoughtfully discussed elsewhere in the past. The use of embedded sensor can provide

reliable information to the system in any case that the deformation may reach to a critical status.

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Figure 1. Model of the composite for (a) the strain and temperature calibrations and (b) the experimental and theoretical analyses. (G represents a layer of glass fabric)

(a)

(b)

Figure 2. $\Delta\lambda_B/\lambda_B$ versus (a) the applied load and (b) the strain variation in the strain calibration test at the room temperature.

Figure 3. Temperature calibration for the FBG sensor.

(a)

(b)

Figure 4. Result of the tensile test under (a) the room temperature and (b) $T > A_f$ (50 °C).

Figure 5. Strain response when the temperature increases under the strain gauge investigation (number of layers = 9).

(a)

(b)

(c)

Figure 6. SEM micrographs of (a) a SMA wire, (b) an optical fibre (c) the sample comprising a SMA wire, an optical fibre and the glass fibre reinforced epoxy.

Figure 7. An experimental model of the composite for the longitudinal and transverse strain analyses. (G represents a layer of glass fabric)

Figure 8. Reflected spectra of a grating extracted at (a) the room temperature, (b) $\Delta T = 20^\circ\text{C}$ and (c) $\Delta T = 40^\circ\text{C}$. Reflected spectra of (d) FBG 1, (e) FBG 2 and (f) FBG 3 obtained according to the change of temperature.

Figure 9. Natural frequencies obtained from the FBG sensor and a B&K system.

Figure 10. Natural frequencies obtained from the FBG sensor at different temperatures.

(a)

(b)

Figure 11. Settling time of the composite at (a) $T < M_f$ and (b) $T > A_f$.

Figure 12. Laminate stacking sequence nomenclature. (G represents a layer of glass fabric)

(a)

(b)

(c)

Figure 13. Responses of (a) a longitudinal, (b) a transversely strain and (c) a stress at different layers with the change of temperature.

(a)

(b)

Figure 14. Generation of curvature in (a) a longitudinal and (b) a transverse direction as a result of the temperature change.

(a)

(b)

Figure 15. Responses of (a) a strain and (b) a stress at different layers with different

SMA volume fraction at $\Delta T > A_f$.

Figure 16. Generation of curvature in (a) a longitudinal and (b) a transverse direction at $\Delta T > A_f$ as a result of the different SMA volume fraction.

Figure 17. Damping ratio of the composite with the change of temperature.

Figure 18. Natural frequency of the composite with the change of temperature.

Table 1. material and mechanical properties of the SMA and composite materials.

Description	
SMA	
Coefficient of thermal expansion (CTE)	
Marten site (/°C)	6.6 X 10 ⁻⁶
Austenite (/°C)	11 X 10 ⁻⁶
Transformation temperatures (°C)	
Martensite finish (°C)	20
Martensite start (°C)	35
Austenite finish (°C)	60
Austenite start (°C)	45
Glass fibre epoxy composite	
Young's modulus (GPa)	25
CTE of glass fibre (m ³ /°C)	4X 10 ⁻⁶
CTE of epoxy (m ³ /°C)	55 x 10 ⁻⁶
SMA composite	
Young's modulus at RT(MPa)	2900
Young's modulus when T> A _f (MPa)	2470
Density (kg/m ³)	2500