Vibration Characteristics of Composite Plate Embedded with Shape Memory Alloy at Elevated Temperature

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Keywords: Modal testing, smart composite structure, vibration control

Abstract. Unique functional material of shape memory alloy has attracted tremendous interest from researchers, thus has been broadly investigated for a wide range application. Current research effort extends the use of SMA for the design of smart composite structures due to its shape memory effect, pseudo-elasticity and high damping capability. This paper presents an assessment of applications of the SMA materials for structural vibration controls, where the influence of SMA as reinforcement in the composite plate at different temperature are investigated. Four cases of composite plate are studied, which two of them are SMA-based composite fabricated at 0° and 45° angles, and the other two plates are neat (without SMA wires) and built with local stiffener. By using modal testing, the free vibration analysis is carried out to determine the vibration characteristics of composite plates. The results show that infusing SMA wires into composites increased the natural frequencies of the plate considerably, while decreased slightly for damping percentage. However, when SMA wires are heated, the damping percentage improved tremendously due to the phase transformation temperature of SMA from martensite to austenite. The outcome of this study reveals the potential of SMA materials in active vibration control.

Introduction

Since the new millennium, a number of researches for the structures using smart materials has been investigated to improve the structural performance [1-3]. One of the popular examples of smart materials is a shape memory alloy (SMA). The SMAs have engrossed in many applications because of its exceptional properties, such as a high elasticity, power density, a tuneable stiffness and a high fatigue resistance. In fact, SMA can be a passive or active component when integrated with other structures to reduce damage caused by environmental impacts. Even though research activities of SMA applications in engineering structures are still in early laboratory stage, only a few is found effective and has been implemented in actual engineering fields [4].

SMA has a unique characteristic known as shape memory effect; resulted in large recoverable deformations when SMA is heated. This ability is caused by martensite transformation to austenite phase that transpired in the material. A significant advantage of SMA compared to other actuator materials is it has larger recovery force generated by phase transition when initial deformation is applied. It is said that a maximum recovery force of SMA can reach to 700 MPa [5]. The generated force per unit volume is amazingly high which is more 10 times higher than commercially available smart actuators such as traditional electro-hydraulic servo mechanical actuator and laminated PZT.

Nowadays, embedding SMAs into composite materials have attracted attention from researchers around the globe. SMA-based composites have the ability to change material properties by inducing large internal forces in the materials and modify the structure's stress and strain. These characteristics are found useful for structural vibration control. For example, in the study by Zhang et al. [6] used SMA wires to control vibration and damping properties of laminated composites. Amor [7], on the other hand investigated the influence of SMA location on the composite plate where the greatest performance is observed when the SMA wires are fitted within the extreme...
layers of the plate. There are also researches have been done on composite with SMA short fibres. From Ni et al. research [8], elasticity modulus was increased with more SMA short fibres. Similarly, the use of a SMA layer as actuator was studied by Choon et al. [9].

However, there have been few studies dealing with the vibration characteristics of the composite plate embedded with SMA fibres at elevated temperatures. It has been indicated in the research by Jones [10] that temperature effects are very important in the determination of system frequency and loss factor. This, in turn, could have major impact upon control of systems employing SMA material. For this reason, understanding the temperature effects on the structural control employing smart damping treatment is of important. In this paper, the importance of temperature effects on frequency and damping for a composite plates embedded with SMA wires are investigated. The dynamic mechanical properties of composite plates were evaluated by impact hammer vibration test. By measuring the first vibration mode of a composite plate, the influences of both SMA orientations and temperatures on the vibration characteristics of the plates are also discussed.

Materials and Preparation
The present study employs the composite made of woven roving fiberglass reinforced into epoxy matrix. The percentage of material composition used is 50% fibre glass and 50% epoxy resin and hardener. The SMA wires choose for the study is Ni-Ti-Cu alloy from Dynalloy Inc. with a diameter of 0.5 mm and maximum pull force of 34.94 N. In this work, a hand lay-up technique is employed in preparation of composite specimen. The process of making layer of composite will be made manually until the required thickness of composite is obtained. As aforementioned, four types of composite plates are fabricated as tabulated in Table 1 where each plate having a similar dimension of 180 x 180 x 2 mm. The SMA wires which embedded in both of the composite plates are arranged in two different orientations which are 0° and 45°, respectively as illustrated in Fig. 1.

<table>
<thead>
<tr>
<th>Sample Abbrev.</th>
<th>Classification</th>
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<tbody>
<tr>
<td>S1</td>
<td>Plate without SMA wires</td>
</tr>
<tr>
<td>S2</td>
<td>Plate with local stiffener</td>
</tr>
<tr>
<td>S3</td>
<td>Plate embed with unidirectional SMA at 0° angle orientation</td>
</tr>
<tr>
<td>S4</td>
<td>Plate embed with unidirectional SMA at 45° angle orientation</td>
</tr>
</tbody>
</table>

![Fig. 1. Orientations of SMA wires embedded in composite plate](image-url)
Experimental Procedures
In this study, a modal free-free vibration arrangement is implemented to determine the dynamic characteristics of the composite plates. Sixteen grid points are created in the plate as shown in Fig. 2 to give adequate spatial resolution for the global structural mode shapes. The roving impact hammer test was employed with one single output of acceleration measured at point 1. The frequency response functions (FRF) are measured for multiple inputs using dBA Suite software in the range of 0–2000 Hz. All the measured FRFs are curve fitted followed by exporting to the MEScope software in Universal File Format.

![Fig. 2. Nodal point dividing on specimen plates](image)

Result and Discussion
(a) Vibration analysis of composite plates at ambient temperature
Table 2 tabulates the natural frequencies and the corresponding damping characteristics of composite plates extracted from the modal analysis testing. Only the first five fundamental frequencies are observed, as these frequencies are significantly important to the plate dynamic’s behaviour. It is found that the presence of epoxy resin in composite exhibits low stiffness which resulted in a lower natural frequency for sample S1 particularly. However, samples S2, S3 and S4 show higher natural frequencies due to additional mass to the plate, eg. local stiffener and SMA wires.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Natural frequencies (Hz)</th>
<th>Damping ratio (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>S1</td>
<td>S2</td>
</tr>
<tr>
<td>Mode 1</td>
<td>144</td>
<td>127</td>
</tr>
<tr>
<td>Mode 2</td>
<td>497</td>
<td>582</td>
</tr>
<tr>
<td>Mode 3</td>
<td>553</td>
<td>829</td>
</tr>
<tr>
<td>Mode 4</td>
<td>780</td>
<td>886</td>
</tr>
<tr>
<td>Mode 5</td>
<td>980</td>
<td>1390</td>
</tr>
</tbody>
</table>

Overall, sample S3 (refer Table 1 for abbrev.) displays the highest natural frequencies for all modes. This result elucidates the significant effect of SMA wires on the natural frequencies thus its potential role in increasing the stiffness of composites material. In terms of damping ratio, sample S2 shows a higher value compared to the others. It is explained that adding local stiffener to the plate could reduce the plate's bending motion as well as absorbing vibration motion. By contrast, embedding SMA wires to the composite plates reduce the damping ratio considerably, although it can be seen that different orientations of SMA wires produce significant damping effect to the composite plate. This result suggests that the structures with a high stiffness tend to have a low damping percentage. And this is absolutely correct since the damping percentage is inversely depending on the stiffness and mass of the structure, as shown in Eqs. 1 and 2.
\[ \omega_n = \sqrt{\frac{k}{m}} \]  
(Eq. 1)

\[ \zeta = \frac{c}{c_c} = \frac{c}{2\sqrt{km}} \]  
(Eq. 2)

where \( \omega_n \) is natural frequency, \( \zeta \) is damping percentage, \( k \) is stiffness, \( m \) is mass, \( c \) is damping coefficient and \( c_c \) is critical damping.

Meanwhile, the corresponding mode shapes of the composite plates were calculated using MEScope software. It is found that the mode shapes obtained are similar and to be independent of the types of composite plates; the first mode of free edges plate is torsion and the remaining two are bending (refer Table 3).

<table>
<thead>
<tr>
<th>Mode 1</th>
<th>S1</th>
<th>S2</th>
<th>S3</th>
<th>S4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mode 2</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Mode 3</td>
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</table>

Table 3. Mode shapes of composite plates

(b) Vibration analysis of SMA-based composites at elevated temperature

Fig. 3 shows the natural frequencies and damping ratios of composite plates S3 and S4 which embedded with SMA at elevated temperature. Only the first mode is considered in this analysis since it is the critical mode with relatively large displacement. The result in Fig. 3a shows that sample S3 has higher natural frequencies than S4 at all imposed temperatures; the highest frequencies obtained is at 40.5°C before decreases slightly at 50.5°C for S3. It is found that the reduction of natural frequency is caused by SMA's phase transformation to austenite which in agreement with [11,12] that showed the phase transformation temperature for austenite of Ni-Ti-Cu alloy is \( \sim50°C \). Thus this result concludes that the martensite phase of SMA increases the stiffness of composite material, but when it transforms to the austenite phase, it slowly decreases the material stiffness. By contrast, S4 shows reduction natural frequencies till 40.5°C before increases at 50.5°C. This result clearly indicates the significant effect of SMA wires orientation on the stiffness of composite material.
As aforementioned, one of the beneficial characteristics of SMA is their good damping property at super-elastic status. That is by embedding SMA in one composite material, it can increase damping property of the composite. Fig. 3b shows the result of damping percentage of SMA-based composites. It is shown that the damping percentage of sample S3 gradually increases with increase temperature; until at 50.5°C it drops slightly. A similar trend is observed for sample S4. This is explained by the hardening effect of austenitic phase transformation which begins at 50°C, and a high stiffness in SMAs within austenite phase at elevated temperature will further contribute to low damping percentage for these samples. Overall, the damping percentages obtained for S4 are much higher than S3 due to different orientation of SMA wires embedded in composite plates. These results reveal the potential of SMA in improving the damping properties of composite plates and control their natural frequency.

Conclusion
This paper investigated the functional of smart memory alloys (SMAs), its orientation embedded in the composite materials and the temperature effect on vibration characteristics of composite plate. From the study, the infused SMAs show a significant effect to natural frequency and damping percentage of composites due to the ability of shape memory effect. This is further concluded that the functionality and orientation of SMAs embedded in composite plate play important role in controlling vibration response because different orientation of SMA wires can produced different natural frequency and damping percentage. The temperature is also found to play role on system natural frequency and damping percentage of the composite plate as both martensite and austenite phase of SMA show strong effects in their stress–strain curves for loading–unloading cycles and dissipation of energy. Upon heating, the embedded SMA wires increase the stiffness of the structure, thus can actively tune the structure's natural frequency. By tuning the natural frequency, the resonance frequency of the structure can be avoided, as well as reduce the structural vibration at its resonant frequency. So, this is the basic principle of SMAs for active structural vibration control. If it combines with the application of the damping control, the SMA wires may reduce the vibration levels of the structure significantly.

Acknowledgement
IZ thanks Universiti Tun Hussein Onn Malaysia for the support under Short Term Grant, vote 0441 and provides facilities for this research.
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Advances in Manufacturing and Mechanical Engineering
10.4028/www.scientific.net/AMM.393

Vibration Characteristics of Composite Plate Embedded with Shape Memory Alloy at Elevated Temperature
10.4028/www.scientific.net/AMM.393.655