Influence of Ni–Ti shape memory alloy short fibers on the flexural response of glass fiber reinforced polymeric composites

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Abstract

Polymeric composites are structures reinforced with particles, fiber and whiskers. In this study, as a unique attempt GFRP composites are selectively reinforced with Ni–Ti shape memory alloy (positioned at a section below the neutral axis) for enhancing the flexure resistance. Under static loading condition, up to 4 wt% of shape memory alloy reinforcement, the GFRP exhibit enhanced flexure resistance. However, under dynamic loading, the shape memory alloy reinforced composite exhibit a mixed mode of response. It is observed that combination of wt% with loading frequency such as 2 wt% with 60 Hz and 4 wt% with 120 Hz facilitates better possible performance.

Keywords GFRP · SMA · Shape memory characteristics · DMA · Mechanical properties

1 Introduction

The binary Ni–Ti alloys have been intensively investigated during the last three decades, since they are the most important commercial shape memory alloys (SMAs) owing to their exclusive shape-memory performance, good processibility, and excellent mechanical properties. In addition, the alloys have very good corrosion resistance and biocompatibility, which enable them to be widely used in the biomedical field. Because the Ni–Ti alloys can be readily fabricated into various forms and sizes, it is technically feasible to make them an active element in various composites. In particular, Ni–Ti thin films, particles, long fibres and porous bulks have been successfully fabricated in recent years, and these materials, either in the monolithic form or in combination with other materials, have exhibited some exciting application potentials in micro-electro-mechanical systems, medical implants, intelligent materials and structural systems [1–5]. More detailed introduction to the SMAs and their unique attributes and the

resulting potential for many applications can be found in the literature [6–13]. Early investigation focused mainly on the characterization and discovery of the mechanical phenomena for their unique properties. Recently, development and studies of SMA composites have attained significant growth because SMAs possess both sensing and actuating functions leading to many potential applications. Many studies have shown that SMA composites have significant potential applications for vibration and structural controls [14–19]. However, some problems are encountered. The interfacial failure between the SMAs and the resin occurs easily because the fabrication process results in high residual stress within the SMA composites when cooled down to room temperature. However, discontinuous SMAs have an advantage of dispersing the residual stress owing to the random distribution/orientation of SMA fillers in epoxy resin matrix. Also, the discontinuous SMA composites can be easily fabricated by hand-layup methods at low-cost. Only limited studies on

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composites filled with SMA short fibres or SMA particles have been reported [20–24].

The main objective of this study is to investigate the influence of the SMA short fibers on the GFRP composites with embedded discontinuous fibres on mechanical properties of the composites. The SMA/GFRP composites were fabricated and static and dynamic flexural properties are investigated since the flexural behaviour is more important for the laminated composite structures.

2 Experimental techniques

2.1 Specimen fabrication

Plain GFRP and GFRP selectively reinforced with Ni–Ti alloy SMA were fabricated for the study. Both plain and SMA reinforced GFRP composites were prepared by hand layup process. Plain composite is a layup of 4 layers of cross ply orientation $[0/90]_4$ constituting a total cross section of 3 ± 0.1 mm thickness. In the case of SMA reinforced GFRP composites short fibres (2–3 mm, long 1.35 mm wide and 0.292 mm thick) of Ni–Ti SMA were placed at a depth of $\frac{3}{4}$ th thickness of the composite specimens. The SMA fibers were randomly distributed and of 2, 4 and 6 wt%. The position of the SMA is to reinforce the tensile region of the sample during flexure. The matrix used was LY 556 epoxy resin and hardening agent was HY951. After hand layup sufficient care was taken to ensure good wetting without entrapped air and also to remove any excessive resin. The structure of the composite is heterogeneous with glass fibres in 0° and 90° orientation sequentially across the cross section and randomly oriented SMA reinforcement at $\frac{3}{4}$ th cross section.

2.2 Experimental tests

The study is concerned with flexure characterization and DMA of the chosen composites. Samples of size $80 \times 10 \times 3$ mm were cut (as per standard) and the cut edges were trimmed to avoid any edge defect. These samples were subjected to normal three point bend test carried out by standard Instron Universal testing machine. With 0° fibers orientation the structure response to flexure could be influenced by the load carrying fiber with effective crack arresting. It was possible to carry out three points bending without crazing and transverse shearing. Apart from three points bending tests, DMA tests were also carried out. For DMA both plain GFRP composite and SMA reinforced GFRP composite specimens of size $30 \text{ mm} \times 5 \text{ mm} \times 3 \text{ mm}$ were prepared for 3 point bend test in DMA Apparatus. The test was carried out with different loading frequencies of 15, 30, 60, and 120 Hz at temperature from ambient to 200°C .

3 Results and discussions

3.1 Characterization of SMA

Typical shape memory effect of the chosen SMA is illustrated in Fig. 1. It is seen that with specimen temperature less than the A_s (austenitic start temp.) the SMA in Martensite state will undergo pseudo elastic deformation during load-unload cycle with energy dissipation. This can influence the response to flexure of the composite under mechanical loading; also the SMA will transform to Austenite around T_g glass transition temperature (for

Fig. 1 a Stress–strain relation of SMA and b schematic of shape memory effect [23]

Ni–Ti 50–50 in 72 °C). Thus, with thermo mechanical loading the SMA will undergo pseudo elastic deformation, while experiencing phase change around glass transition temperature. Concurrently the composite will undergo matrix crazing with fibre undergoing breakage/tend to arrest the cracking of the matrix material, which will influence the flexural response of the composite specimen. Typical glass transition and phase transformation with Ni–Ti is illustrated in Fig. 2 (supplier reference). It is seen that around 71.5 °C A_s (austenite start) and around 78 °C A_f (austenite finish) takes place in respective temperatures for the chosen Ni–Ti SMA. Thus it can be inferred that with thermo mechanical loading the SMA reinforced composite will respond to the loading influenced by the composite structure (fiber–matrix interaction angle) and the status of the SMA under loading environment.

3.2 Flexure response

Polymeric composites are structures reinforced by dispersion/fibers. Dispersion strengthened composites exhibit enhanced wear resistance while fiber reinforcement is normally for enhancement of flexure resistance. It is to be noted that during flexure the composite structure undergoes both tensile and compressive loading. Thus, the reinforcing fiber not only serve as load carrying member but also facilitate effective crack arresting in the structure. Hence, in the present study both plain and SMA reinforced GFRP composites were subjected to three points bend test on standard specimens (specified earlier). For repeatability/consistency 3 specimens were tested for each trial. Data on bending load and corresponding deflection were noted. A scatter of $\pm 5\%$ was noticed. The average values were graphically plotted.

Fig. 2 Phase transformation of SMA strip

Fig. 3 Loading–deflection curves for SMA/GFRP composites

Figure 3 represents typical Load (bending)—deflection relationship for all the composite specimens. It can be seen that with SMA addition bending resistance of composite specimen increases up to 4 wt% followed by a reduction with 6 wt% addition. It is to be noted that the layup of the composites present 90° orientation of the glass fiber in the outer envelope experiencing maximum tensile stress during flexure. However, presence of the SMA reinforcement at $\frac{3}{4}$ the thickness of the test specimen (in the tensile loading zone) undergoes pseudo elastic strain enhancing thereby the flexure resistance. A limit of up to 4 wt% SMA reinforcement can be seen for the observed enhancement. With higher % reinforcement, probably due to higher order energy absorption, a reduction in flexure resistance has been observed. It is seen from the Table 1 that the peak value of flexure modulus is the same for both 2 wt% and 4 wt% (but for different frequencies). It can be the ultimate for the chosen composites. The observed significance of the SMA addition is further supplemented by the DMA results in the following section.

Table 1 Significance of wt% and frequency on flexure modulus (e+009)

Weight %	Flexure modulus (e+009) at different frequencies			
	15 Hz	30 Hz	60 Hz	120 Hz
0	2.25	2.12	2	1.65
2	1.85	1.35	3.3	1.8
4	1.8	1.73	1.6	3.3
6	1.6	1.65	1.65	1.7

3.3 DMA observation

Apart from flexure response the GFRP composites were subjected to DMA trials. As stated earlier, separate specimens were prepared to conduct flexure studies in standard DMA set up. Also for repeatability 3 specimens were tested for each trial. Data obtained had a scatter of $\pm 7\%$. Figure 4 illustrates the response to Thermo Mechanical loading (under flexure) of the plain GFRP and SMA reinforced composite with different wt% of SMA. It is observed from the Fig. 4a that the storage modulus is influenced by the loading frequency and the environment/test temperature for plain GFRP. The plain GFRP has 0° and 90° orienting fiber sequentially arranged/laid up constituting the structure of the composite is known that the response of polymeric composite is largely related to the fiber matrix interaction angle with smaller (0° orientation) the response is largely due to the load carrying fiber.

With higher interaction angle (greater than $20^\circ/25^\circ$) the matrix play a significant role in response to the present surface layup has 0° orientation there by the flexure load is borne/resisted by the reinforcement. This has prompted to go in for three point bending flexure. It is also seen that with all frequencies the storage modulus is invariant with temperature up to around 100°C which is glass transition temperature (T_g) of the polymer matrix. Around T_g , the storage modulus drops down visibly up to 150°C almost which the matrix polymer changes its state (from glassy to rubbery state). The influence of the loading frequency on modulus could be attributed the energy absorption with cyclic loading. Increased energy absorption with loading frequency has resulted in the observed reduction in modulus with increasing loading frequency. From the illustration, it can be inferred that the storage modulus of plain GFRP composite is significantly influenced by thermo-mechanical working environment such as loading

Fig. 4 Variation of storage modulus as a function of temperature at different loading frequency

frequency and test temperature especially around glass transition temperature T_g .

Figure 4b presents the outcome of DMA for GFRP composites reinforced selectively (positioned at $\frac{3}{4}$ section thickness in the tensile loading region during flexure) with 2 wt% of Ni-Ti SMA; the reinforcement was randomly oriented over the section. Referring to the illustration the Flexural modulus exhibits a trend of variation differing from that in Fig. 4a. Barring the curve for 15 Hz the flexure modulus tends to vary only marginally with temperature of testing for loading frequencies of 30, 60 and 120 Hz, respectively. The modulus tends to drop down around 150 °C around which the polymer changes its state to rubbery state causing the drop. The marginal variation could be attributed to the role of the reinforcement in containing the defects generated during the thermo mechanical loading (crack arresting mechanism). Regarding loading frequency, 2 wt% SMA reinforced GFRP composite exhibits higher modulus with 60 Hz (higher than the plain GFRP) while with 30 Hz frequency flexure modulus smaller than the plain GFRP has been observed. It is to be noted that up to the glass transition temperature (around 70 °C) the SMA with Martensite phase will undergo pseudo elastic strain sustaining the modulus up to that temperature. With low frequency of 15 Hz, a reduction in modulus (compared to plain GFRP for 15 Hz) has been observed; also the modulus drops down above 70 °C, the glass transition of SMA. In addition to the response of the plain GFRP the presence of the SMA and consequent energy absorption (in addition to that of GFRP) causes the observed drop.

With 30 Hz loading frequency, also a reduction in flexure modulus can be seen. Rise in structural heating due to increased loading frequency superposed on the test temperature results in the phase transformation in SMA (martensite to austenite) and concurrent change of state of polymer to rubbery state and sustain the modulus to around 150 °C followed by a drop. With 60 Hz, the higher order heating of the structure facilitates austenitic transformation in SMA; the resultant increased stiffness causes the observed appreciable rise in modulus. With 120 Hz, considerable rise in the heating affects the polymer and consequent modulus. The thermal influence on the matrix causes the observed reduction in modulus; these observations are supplemented by the illustration on loss factor (Fig. 5b). The significance of 4% (wt.) SMA addition to GFRP composite on storage modulus is illustrated in Fig. 4c. It is seen that the storage modulus for all frequencies tends to drop down after around 70 °C (the glass transition of SMA) illustrating the significance of SMA addition and DMA test conditions. Frequencies 15–60 Hz resulted in overall reduction in modulus compared to the plain GFRP for identical frequencies. However, with higher frequency of 120 Hz a visible rise in modulus has been observed. An increased %

reinforcement SMA requires higher order heating for fully transformed austenite phase and consequent increased stiffness. This result in the observed rise in modulus has also been supplemented in loss factor (Fig. 5c).

3.4 Significance of 6 wt% SMA reinforcement

Typically monitored variation of storage modulus as influenced by the addition of 6 wt% of SMA reinforcement to GFRP composite is illustrated in Fig. 4d. It is observed that with 6 wt% addition of SMA, there is deterioration in the DMA response of the composite for all loading frequencies. Obviously for such large addition of SMA, the combined heating (due to test temperature and internal heating due to loading frequency) is not adequate to effect a phase change in the SMA; with the result the SMA with martensite structure will undergo pseudo elastic straining with energy absorption causing reduction in storage modulus mostly invariant with frequency of loading. The illustrations on loss factor for corresponding DMA study (Fig. 5d) also supplements the observation on storage modulus. The two illustrations on storage modulus and loss factor show reduced values for both storage modulus and loss factor. Thus it can be inferred that higher addition of SMA is not compatible with chosen GFRP structure. This also supports the observation on the critical value of SMA addition i.e. 4 wt% for maximizing the flexure resistance of the GFRP composite.

3.5 Significance of SMA addition on loss factor

Figures 5a–d illustrates the significance of loss factor in response to the addition of SMA on GFRP. Figure 5a illustrates the variation of loss factor for plain GFRP composite as influenced by the loading frequency. It is seen that for all frequencies the loss factor tends to raise around 100 °C the glass transition of polymeric composite. The peak value occurs mostly around 150 °C i.e. the rubbery state of the matrix polymer. Figure 5b illustrates the variation of loss factor for 2 wt% SMA addition. Compared to plain GFRP composite, there is a reduction in the peak value of the loss factor. The illustration shows trend change around 70, 100, 125 and 150 °C. With 15 Hz, it is around 70 °C while change has occurred around 100, 125 and 150 °C with other frequencies. The least value of loss factor (around 0.2) occurs for 60 Hz while the maximum occurs for 30 Hz. Typical variation of loss factor for 4 wt% SMA addition is shown in Fig. 5c. The peak values of loss factor occur around 125 °C the temperature around which the matrix mobility such as locale movement, stretching and sliding occurs influencing the loss factor. Figure 5d shows the variation of loss factor for 6 wt% addition of SMA to GFRP composite. It is seen that for all frequencies only a

Fig. 5 Variation of loss factor as a function of temperature at different loading frequency

marginal variation in the peak value of loss factor occurs. The observed reduction in loss factor combined with reduction in storage modulus for 6 wt% addition of SMA indicates the incompatibility with structural response. Referring to the illustrations on loss factors, it is observed that with 2 wt% SMA addition, the reinforced composite, exhibit a raise in loss factor around the glass transition of SMA (80 °C) and up to 150 °C. However, the composite exhibits mostly a steady/marginally varying storage modulus up to 150 °C and the loss factor is least at 60 Hz of loading frequency. Further, it is observed that with 4 wt% SMA reinforced composite exhibit least order of loss factor with 120 Hz of loading frequency. This supplements the observation on storage modulus. With higher wt% (6 wt%), there is no improvement in loss factor or storage modulus with loading frequency. This may be due to insufficient

phase transformation activity due to reduced order of heating of specimen of SMA.

4 Conclusions

The present study is concerned with enhancement of flexure characteristics of GFRP composites through selective reinforcement of SMA (Ni–Ti) with varying wt%. From the study, the following conclusions have been arrived.

- Under static loading, up to addition of 4 wt% of SMA, GFRP composites exhibit enhanced flexure resistance. It is to be noted that the reinforced GFRP composites exhibit relatively higher bending load and corresponding deformations.

- Under dynamic loading, plain GFRP composite exhibits a reduction in flexure resistance with increase in loading frequency. Further, the GFRP tends to lose its flexure resistance around the glass transition temperature.
- Addition of SMA reinforcement results in mixed mode of response. As in the static case, only up to 4 wt% SMA addition, it is possible to enhance the flexure resistance. However, a critical condition of wt% and loading frequency has been observed to realize best result. It is also observed that 2 wt% SMA addition with 60 Hz loading frequency and 4 wt% SMA addition with 120 Hz loading frequency are the combination for best response.
- Based on static and dynamic response, GFRP reinforced with 4 wt% of SMA and loading frequency of 120 Hz exhibit best response to flexure loading.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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