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Nanoparticle type effects on flexural, interfacial and vibration properties of GFRE composites

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Abstract Damping improvement in composite structures via introducing nanofillers generally has remarkable negative effects on the other mechanical properties. Therefore, in the present work, SiC and Al_2O_3 nanoparticles' infusion effects on the flexural, interfacial and vibration properties of epoxy matrix and glass fiber reinforced epoxy (GFR/E) laminates were investigated. Unidirectional (UD-GFR/E) and quasi-isotropic (QI-GFR/E) laminates with $[0/\pm45/90]_s$ and $[90/\pm45/0]_s$ stacking sequences were hybridized by the optimum nanoparticles percentages. Results from off-axis flexural strengths of UD-GFR/E demonstrate good fiber/nanophased-matrix interfacial bonding. The interlaminar shear stress between the adjacent layers with different orientations/strains of ductile QI-GFR/SiC/E laminates results in decreasing the flexural strengths respectively by 24.3% and 9.1% for $[0/\pm45/90]_s$ and $[90/\pm45/0]_s$ stacking sequences and increasing the dissipated interfacial friction energy and thus the damping by 105.7% and 26.1%. The damping of QI-GFR/E, QI-GFR/SiC/E and QI-GFR/Al_2O_3/E laminates with $[90/\pm45/0]_s$ stacking sequence was increased by 111.4%, 29.7% and 32.9% respectively compared to $[0/\pm45/90]_s$ stacking sequence.

1. Introduction

Recently, several studies related to the enhancement of the mechanical properties of epoxy matrix by introducing SiC[1–7] and Al_2O_3[2,8–12] nanoparticles have been conducted. The nanophased epoxy matrix cannot be used alone for high-performance structural applications due to their limited mechanical properties. For that purpose a limited number of researchers have explored the SiC[7] and Al_2O_3[8,11,12] nanoparticles impacts on the mechanical properties of nano-hybrid fiber reinforced composites, which is one of the objectives of this study. A key question is, to what extent the improvement in the damping properties of the nano-hybrid FRP composites can affect the other mechanical properties? To the best of the author's knowledge, the answer to this question is not fully addressed yet in the literature and accordingly, is the subject of this study.

Chisholm et al.[7] studied the influence of infusion of 1.5 wt% and 3 wt% of SiC nanoparticles into SC-15 epoxy on the

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tensile properties of nanophased epoxy (nanocomposites) and nano-hybrid woven carbon fiber composite laminates. They reported that with 3 wt% loading of SiC nanoparticles the mechanical properties were degraded. They attributed this result to the agglomerate, which reduced the cross-linking density and increase void content in the nanocomposite. The enhancements in stiffness and strength of 1.5 wt% SiC-nanocomposite were 45% and 16% respectively compared to neat epoxy. For nano-hybrid woven carbon fiber composites, the improvements in the stiffness and strength were 23.5% and 11.6% respectively. The present work showed contrary behavior for the stiffness of glass fiber reinforced epoxy (Y 1092-1) infused with 1.5 wt% SiC nanoparticles.

Rodgers et al.[1,3] investigated the effect of incorporation 0.5 wt%, 1 wt% and 1.5 wt% of SiC into SC-15 epoxy on the glass transition temperature (T_g) and flexural properties of the fabricated nanocomposites. Their results showed that the optimum loading of the SiC was about 1 wt% at which the best thermal and mechanical properties were observed. Their results also showed that the glass transition temperature (and thus chemical cross-linking density) of the modified epoxy with 1.5 wt% of SiC nanoparticles was decreased by 8 °C and there is hardly any gain in flexural strength. Faleh et al.[6] attributed the decrease of cross-linking density to the fact that the presence of nanoparticles in epoxy resin develops a strong molecular interaction between them and epoxy molecules that hinder the interaction between epoxy resin and hardener molecules. This impedes the formation of the final cross-linked structure of the matrix during curing.

Uddin and Sun[9] showed that introduction of 1.5wt%–3wt% of Al_2O_3 into DGEBA epoxy resin incorporates brittleness into the nanophased matrix (nanocomposite) and hence, the flexural strain at rupture was reduced by 6%–10% while, flexural modulus and strength were increased by 5%–9%. In that context, Zhao and Li[10] showed that inclusion of 1.5wt% Al_2O_3 nanoparticles in DGEBA epoxy resin has an insignificant effect on the glass transition temperature and thus chemical cross-linking density. In addition, rigid Al_2O_3 nanoparticles can act as physical cross-links for the epoxy molecular chains in the nanocomposites and accordingly, the fractured surfaces of Al_2O_3 nanocomposites show brittle failure. Mohanty et al.[11] reported a contrary behavior to that reported by Uddin and Sun[9] for Bondtite PL-411epoxy resin filled with 1wt%–5wt% Al_2O_3 nanoparticles. From the literature it has been shown that incorporation of different nanofiller types onto epoxy resin can play a key role in the ductility/brittleness and thus the mechanical properties of nanocomposites, which are combined in the present work with the damping performance of the fabricated nanocomposites and nano-hybrid GFRE laminates was investigated.

The interfacial bonding plays a significant role in transferring the load from the epoxy matrix into higher strength/stiffness nanoparticles and hence, increasing the mechanical properties of the nanophased matrix. Several techniques can be used to characterize the interfacial bonding that includes microdebonding/microindentation technique[3] and embedded single fiber test. For bulk composites, there are off-axis flexural and tensile tests,[13] off-axis fracture toughness test,[8] short beam shear test and the transverse Iosipescu shear tests. In the present study, the interfacial bonding was characterized via off-axis flexural tests of unidirectional GFRE laminates.

One promising approach to modify a brittle epoxy matrix is the incorporation of stiff nanoparticles like SiC, Al_2O_3, carbon nanotubes (CNT), which significantly improve the fracture toughness.[8,13–15] Nanoparticle-related toughening mechanisms like crack deflection and crack pinning at the nanoparticles, nanoparticle pull-out, or nanoparticle-matrix debonding followed by plastic deformation of the matrix were observed depending on the nanoparticle type and morphology.[14] These mechanisms enable the material to absorb more energy and accordingly, improve the damping properties. Improving the damping performance of the structural composite materials via introducing nanofillers generally has remarkable negative effects on the other mechanical properties. Therefore, any modifications in the constituent materials of the structural composites for optimizing their dynamic properties must be based on tradeoff between damping, stiffness and strength.[13,16]

The objective of the present work is to investigate the effect of nanoparticle types on the flexural, interfacial and vibration properties of nano-hybridized GFRE laminates. To achieve this objective, a unidirectional and angle-ply GFRE laminates were hybridized with optimum weight percentages of SiC and Al_2O_3 nanoparticles. The interfacial bonding of the nano-hybrid GFRE laminates was investigated via off-axis flexural tests in which the failure is a matrix-dominated property. The effect of stacking sequences ($[0/\pm45/90]_s$ and [90/±45/0] s) and the nanoparticle type on the flexural properties (strength, modulus and ultimate failure strain), and on the dynamic properties (damping, frequency, storage modulus) of the nano-hybrid GFRE laminates was investigated experimentally. The correlation between the flexural moduli determined by the static distractive test and the nondestructive vibration technique was investigated.

2. Experimental work

2.1. Materials

In the present work, twelve different composite materials with different configurations were fabricated from PY 1092-1 epoxy resin, Huntsman Advanced Materials Ltd. Details about the configurations of the fabricated panels and their constituent materials were illustrated in Table 1.

Eight of the fabricated materials were used to investigate the nanoparticles' effect on the mechanical properties of both epoxy bulk composites and GFRE composite laminates with different configurations. In parallel, four control panels were also fabricated following similar routes without any nanoparticle infusion. The used nanoparticles materials were 1.5 wt% SiC and 1.5 wt% Al_2O_3. The selected weight percentages of the nanoparticles (1.5 wt%) were based on the optimum values that were determined earlier by Khashaba et al.[2] In addition, this weight percentage showed enhancements in the mechanical properties of SiC/E and Al_2O_3/E nanophased epoxies by some investigators.[4,7–9] The properties of the used nanoparticles are indicated in Table 2.

The epoxy resin was first modified by 1.5wt% nanoparticles (SiC or Al_2O_3) using 750 W Ultrasonic Processor, Cole–Parmer, Inc., USA. Sonication parameters play a critical role in the dispersion of SiC and Al_2O_3 nanoparticles in epoxy resin. These parameters include the sonication temperature, sonication power and amplitude, sonicator probe diameter and immersing depth, sonication mode, sonication energy and container dimensions and materials. The contribution of each