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Modal analysis on nanoclay epoxy-based fiber-glass laminates

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Abstract

This paper focuses on the vibration analysis of fiber glass/epoxy/nanoclay nanocomposites. The modal analysis was performed using a grid of 35 response measurement points. For modes 1 and 7, where the bending-twisting shape mode is observed, the damping coefficient increases by about 27%, on average. For modes 2 through 6, where bending is noticed, the average increase is around 68%, with peaks of 169%. A new shape mode comes out at 600 Hz frequency when the nanoclay content reaches 2%. A crossing mode, mode 4 with inferior frequency than mode 3, for the 5% and 10% nanoclay content is also observed. For events where high frequencies are generated, the nanoclay content of 2% leads to a higher energy dissipation.

Keywords: Nanocomposites; Modal analysis; Laminates; Nanoclay

1. Introduction

High performance polymeric composites are a valuable alternative to conventional materials due to their high specific mechanical properties, i.e. stiffness-to-weight and strength-to-weight, tailor-ability, and damage tolerance. These composite materials and/or structures during their service life undergo various loading conditions. Among them, the most critical condition is the impact loadings due to the laminated nature of these structures.

According to Luo et al. [1], the damage in composite structures resulting from impact events is one of the most important aspects to be considered in the design and applications of composite materials. Impact events can be classified according to the impact velocity, i.e. low and high velocities. As mentioned by Naik and Shrirao [2], low velocity impact events occur when the contact period of the impactor is longer than the time period of the lowest vibration mode. In high velocity impact, the contact period of the impactor is much smaller than the time period of the lowest vibration mode of the structure. As a consequence, the response of the structural element is governed by the local behavior of the material in the neighborhood of the impacted zone, the impact response of the element being generally independent of its support conditions. On the other hand, high and low velocity impact can also be classified according to the energy threshold. To be able to explain this alternative classification, a brief discussion about damage threshold is required.

As mentioned by Shyr and Pan [3], the first damage threshold is probably due to the initiation of delamination failure. Furthermore, as recognized by Zhao and Cho [4], matrix cracking and delamination failure are associated to each other. Therefore, a pre-condition to occurrence of the first damage threshold is the matrix cracking. This phenomenon is due to the matrix loss of load transferring capacity as a result of cracking origination/propagation. It is a well known fact, that damage nature and extension are dependent on impact parameters, e.g. impact velocity, impactor mass, impact angle, nose shape and target material configuration. Zhou [5] considered such parameters and he has able to establish a relationship between the incident kinetic energy (IKE) and the damage threshold. He also mentioned that although the IKE values for a high velocity/low mass and low velocity/high mass impact

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events could be the same, the results were completely different. According to Aslan et al. [6], an invisible damage (internal delamination) can be created in a laminate composite when a low-velocity impact with enough energy is performed. Moreover, Jiang and Shu [7] associated such internal damage to the transverse matrix cracking in which delamination is usually induced. However, when the mass increases without a correspondent increase in velocity, the bending effect must be taken into consideration. Johnson and Holzapfel [8] demonstrated that, for low velocity/high mass impact events, a significant plate bending followed by extensive delamination was observed. Furthermore, they also reported that such extensive delamination also reduced the fiber damage and the impactor penetration. Lee et al. [9] mentioned that when the high velocity/low mass impact event occurs in addition to delamination, an extra local fiber breaking is induced into the composite due to local bending/compressive loadings and wave propagation. Based on the foregoing discussion, the low/high velocity impact classification based on absorbed energy threshold and the damage characterization seems to be more effective than the one proposed by Naik and Shrirao [2]. High velocity impact events lead to localized damaged regions, while in the case of low velocity impact the damaged region is considerably larger. When nanocomposites are analyzed another factor must be considered, i.e. the nanoparticle effect. As recognized by Ávila et al. [10], the impact response of laminated materials is dependent on the dispersion of small amounts of nanoclays into the matrix.

Luo and Daniel [11] suggested that nanoclays such as organically modified montmorillonite (Cloisite 30B) can be dispersed into epoxy systems without major efforts. However, in many cases the complete exfoliation or a fully dispersed intercalated structure formation is virtually impossible, even though the benefits in terms of improvement in stiffness and strength are significant. Yasmin et al. [12] also studied influence of nanoclay on epoxy systems. They varied the amount of Cloisite 30B in weight from 1% up to 10% and an increase in the elastic moduli was observed to a maximum of 80%. A more appealing result using nanoparticles into epoxy system was reported by Isik et al. [13]. In this case, the usage of nanoparticles enhanced both stiffness and toughness. However, for their binary system, resin – diglycidyl ether of bisphenol *A* and cure agent – triethylenetetraamine, the maximum impact strength obtained was at 1% in weight of montmorillonite content. The difference between the results obtained by Yasmin et al. [12] and Isik et al. [13] can be attributed to the mixing process, shear mixing in Yasmin's case and direct mixing for Isik's conditions. Liu et al. [14], however, demonstrated that an octadecyl amine modified montmorillonite, e.g. nanomer I30E from Nanocor, is more suitable for dispersion into epoxy systems and can lead to better results. These results were also corroborated by Ho et al. [15], who also studied modified montmorillonite with epoxy base systems.

A detailed investigation on nanoclay-epoxy composites was performed by Haque and Shamsuzzoha [16], since they evaluated both mechanical and thermal properties. Their main conclusions were that thermo-mechanical properties mostly increase at low clay loadings (1–2% in weight) but decrease at higher clay loadings ($\geqslant$5% in weight). They also observed a degradation of properties at higher clay loadings. This phenomenon can be due to the phase-separated structures and defects in cross-linked structures. Furthermore, these problems can be caused by the heating phase during the manufacturing process. It is important to mention that in all studies mentioned previously, but for Ref. [3] heating was present during the nanocomposite synthesis procedure. By abolishing the heating procedure, Ávila et al. [10] were able to obtain better nanoclay (Nanomer I30E) dispersion without epoxy system degradation. Ávila and Duarte [17] using the same methodology proposed by Ávila et al. [10] studied a series of fiber glass-epoxy-nanoclay systems. They were able to establish a relationship between the type of nanostructure formed inside the nanomodified epoxy system and the overall composite natural frequencies.

Another issue that must be addressed is how the stacking sequence and the boundary conditions affect the natural frequencies. One approach to obtain these relations is the finite element method. Ramtekkar and Desai [18] developed a finite element model based on a six node plane stress mixed element and by applying the Hamilton's energy principle; they were able to obtain the natural frequencies of laminated beams. Their results were in good agreement with data available in the literature. Gubran and Gupta [19] went further, as they demonstrated that natural frequencies are directly affected by the angle ply formation and the stacking sequence. Moreover, the bending-twisting effect is more evident for the angle ply configuration and associated to the Poisson effect and the shear-normal coupling. The largest reduction, $\approx$87%, on the natural frequency is considered to be a $\pi/6$ angle ply when the bending-twisting effect is associated to the shear-normal coupling.

According to Aydogdu and Timarci [20], when the boundary conditions from simple-supported/clamped changed to simple-supported/free a decrease around 400% on frequencies is observed. As mentioned by Lam and Chun [21], when impact loading is considered, the target boundary conditions have direct influence on the materials response to low velocity impact tests. Tan et al. [22] verified that clamped laminate plates undergo deflection and stretching during the impact process, while for simply supported conditions stretching does not occur. From the previous discussion, it is possible to conclude that not only natural frequencies, but also the overall plate response to low velocity impact loadings are affected by boundary conditions.

The main goal of this research is to investigate the nanoclay influence on the vibration behavior of a fiber glass-epoxy laminate composite. To be able to perform such