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Material Properties

# Out-of-plane shear properties of glass/epoxy composites enhanced with carbon-nanofibers

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ABSTRACT

The role of adding carbon-nanofibers (CNFs) to glass/epoxy composites and their effects on the out-of-plane shear properties of CNF/glass/epoxy composites have been studied. Neat glass/epoxy and 0.25 wt% CNF/glass/epoxy composite specimens were fabricated using vacuum assisted hand layup, and were subsequently evaluated in terms of shear strength and modulus by means of short beam bending (SBB) and Isopescu shear testing methods. In order to achieve a uniform dispersion of nanoparticles in the resin, online monitoring of suspension viscosity as a function of the sonication time was used. The experimental findings revealed that, at a level of 0.25 wt% CNF, the value of shear strength $S_{13}$ was improved by 18% and 19.5% in the SBB and Isopescu shear testing methods, respectively. Also, the values of shear modulus $G_{13}$, shear strength $S_{23}$ and shear modulus $G_{23}$ were increased by 38%, 18% and 34%, respectively. FESEM photographs confirmed that roughness enhancement of the resin due to the CNFs addition was the main source of properties improvement in out-of-plane directions.



## 1. Introduction

Polymeric composites are widely used in many industrial fields. With high strength to weight ratio, composite materials reduce the weight of structures significantly [1]. A new generation of multi-scale customized lightweight composite structures have been developed by incorporating nanoparticles into the traditional polymeric composites. It has been reported by many researchers that adding nanoparticles, especially carbon nanoparticles, can considerably improve the mechanical properties of polymeric composites while producing high performance structural components [2–7]. Recently, many investigations have been performed to reveal the effect of nanoparticles on mechanical properties of composites such as tensile strength and modulus, fatigue life and fracture characteristics. However, there are limited data on shear properties of composites enhanced with nanoparticles. This could be due to the complexities of shear tests and emergence of undesirable failure modes during the test [8]. The effect of adding nanoparticles on shear properties and interlaminar shear strength (ILSS) of composites have been investigated by some researchers [9–12]. Chandrasekaran et al. [9] studied the effects of multi-walled carbon nanotubes on the ILSS of glass/epoxy composites experimentally, and noticed a considerable improvement in the average ILSS value. Hossein et al. [10] considered the effects of carbon nanofibers (CNF) on thermal and interlaminar shear responses of E-glass/polyester composites, and added different amounts of CNF particles in order to evaluate the effects of CNFs on the ILSS values of glass/polystyrene composite. The research attributed 49.5% increase of the ILSS values to better interfacial bonding between the fiber and matrix in the presence of CNF. Davis et al. [11] studied the shear behavior of carbon/epoxy composites with carbon nanotubes. They used a nanoparticle spray method to modify the resin and fabricate the samples using 12 bi-directional 0/90 carbon layers. They observed that, by adding 0.05 wt,% of single wall carbon nanotubes (SWCNT), the ILSS decreased by 5%. Sagar and Ayewash [12] investigated the ILSS of carbon/epoxy composites reinforced by SWCNT. They sprayed nanoparticles in the mid-plane and observed that, by adding 0.05 wt % SWCNT, the shear strength decreased by 1%. Surprisingly, they found that, in some reinforced layers, a major crack initiated in the upper plane of the middle layer.

The SBB and Isopescu tests have usually been used as the testing method [12–14]. Sagar and Ayewash [12] emphasized that using a short beam bending test method is not reliable in all conditions. They mentioned that alternative methods need to be implemented to verify the results. Whitney and Browning [13] investigated the SBB method analytically and experimentally. They concluded that

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the considerable impact of compressive stresses in the area of maximum shear stress postpones the emergence of inter-layer cracks. They recommended using testing methods with pre-vertical cracks in the shearing area. Humberto et al. [14] evaluated different methods of obtaining shear properties of laminated composites and proposed that the Isopescu shear testing method exhibited more auspicious features, possibly due to a more uniform shear stress state during testing against SBB test.

A comprehensive survey on the available data revealed that less attention was given to study the effects of nano additives on out-of-plane shear properties of polymeric composites. The current manuscript deals with the study of CNF influence on the out-of-plane shear response of laminated composites considering different material orthotropic planes. In order to fulfill this target, three sets of experiment were conducted. Firstly, the out-of-plane shear strength in 1–3 plane of glass/epoxy laminated composites and CNF/glass/epoxy laminated hybrid nanocomposites was tested by means of the SBB test. Secondly, the out-of-plane shear strength and modulus of both materials in 1–3 plane were determined using the Isopescu shear test. Finally, the shear strength and modulus in the 2–3 plane were determined for both materials. Eventually, the effect of CNF presence on out-of-plane shear characteristics of laminated hybrid nanocomposites in the 1–3 and the 2–3 planes was explored using SEM micrography.

## 2. Materials specification

### 2.1. Epoxy resin

ML-526 (Bisphenol-A) epoxy resin was used to fabricate the specimens due to its low viscosity and extensive industrial applications. The low viscosity of the matrix makes the dispersion of additives easier. Physical and mechanical properties of ML-526 epoxy resin are shown in Table 1. The curing agent was HA-11 (Polyamine). The ML-526 resin and the HA-11 polyamine hardener were supplied by Mokarrar Company, Iran.

### 2.2. Nanoparticles

The CNFs were utilized as carbon based nanofiller and were provided by Grupo Antolin SL, Spain. The physical properties of CNF are represented in Table 2. These particles have an average diameter of approximately 20–80 nm with length lower than 30 μm. The Scanning Electron Microscopy (SEM) and Transmission Electron Microscopy (TEM) images of CNF nanoparticles are illustrated in Fig. 1.

### 2.3. Glass fibers

The unidirectional E-glass fibers in plain weave pattern with an average surface density of 223 g/m$^2$ and filled thread count of 17.8 per inch was supplied by Interglass, Germany.

**Table 2**
CNF specifications.

| Properties | Unit | Value |
|---|---|---|
| Fiber diameter (TEM) | nm | 20–80 |
| Fiber length (SEM) | μm | >30 |
| Bulk density | g/cc | >1.97 |
| Apparent density | g/cc | 0.060 |
| Surface energy | mJ/m$^2$ | ≈100 |
| Graphitization degree | % | ≈70 |
| Electrical resistivity | Ω m | $1 \times 10^{-3}$ |
| Metallic particles content | % | 6–8 |

## 3. Test equipment and standards

### 3.1. Static testing instruments

A Santam universal testing machine STM-150 was utilized for three point bending and double V-notch shear tests in accordance with ISO 14130 and ASTM D5379 standards, respectively. Experiments were conducted using 20 kN and 50 kN load cells. Furthermore, the cross head speed was set at 1 mm/min. To analyze CNF/glass/epoxy hybrid laminated nanocomposites, gold sputtered samples were used. Field-Emission Scanning Electron Microscopy (FESEM) photographs were taken using a Zeiss-Germany Sigma Microscopes.

### 3.2. Standards and experimental setups for out-of-plane shear properties

#### 3.2.1. Three-point bending method (SBB method)

Three-point bending test (Fig. 2) determines the short beam strength of high-modulus fiber-reinforced composite materials. This test can be used for quality control and process specification purposes [15]. Moreover, the method is commonly used for measuring ILSS (out-plane shear in plane or component). In a short beam under three-point bending load, both bending stress and out-of-plane shear stress are developed. With small ratio of span to thickness specimens, bending stress diminishes and shear yielding takes place at the neutral plane (see Fig. 2). However, one drawback is that the concentrated loading on the beam and the anchoring points cause stress concentration throughout the length of short beam. For a beam with a rectangular cross section A, the maximum shear stress is represented as following expression [15]:

$$S_{13} = \frac{3}{4} \times \frac{F}{A} \tag{1}$$

where, is the applied load on the beam knowing that the active shear force in the middle of the beam is equal to F/2.

On the other hand, the possibility of using samples with small geometrical dimensions, the lack of sensitivity to the cutting quality of specimen edges, simplicity in the preparation of the equipment, quick tests, no need for a strain gauge and positive economic aspects are the advantages of the SBB method.

In this study, SBB samples of both glass/epoxy composites and CNF/glass/epoxy hybrid laminated nanocomposite were prepared and tested to measure the out-of-plane shear strength in the 1–3 direction.

**Table 1**
Properties of ML-526 epoxy resin.

| Physical properties | | Mechanical properties | |
|---|---|---|---|
| Viscosity at 25 °C (Centipoise) | Glass transition temperature (°C) | Tensile modulus (GPa) | Tensile strength (MPa) |
| 1190 | 72 | 2.6 | 60 |