International Journal of Impact Engineering 47 (2012) 39–47

Contents lists available at SciVerse ScienceDirect

International Journal of Impact Engineering

journal homepage: www.elsevier.com/locate/ijimpeng

Low-velocity impact of thin woven carbon fabric composites incorporating multi-walled carbon nanotubes

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ARTICLE INFO

Article history:
Received 20 September 2011
Received in revised form
31 December 2011
Accepted 7 March 2012
Available online 23 March 2012

Keywords:
Carbon nanotubes
Low-velocity impact
Woven fabric
Damage

ABSTRACT

The low-velocity impact response of thin carbon woven fabric composites reinforced with functionalized multi-walled carbon nanotubes (MWCNTs) is investigated. Three loadings of MWCNTs by weight of epoxy are examined; 0.5%, 1.0%, and 1.5%. The composite plates are subjected to five levels of energy; 15, 24, 30, 60, and 120 J. The time history response of load, displacement, velocity, and energy are measured and reported. Moreover, the composite damage, associated with each energy level, is quantified and compared between different MWCNTs loadings. It is observed that the functionalized MWCNTs enhanced the impact response and limited the damage size in the woven carbon fiber composite. The addition of 1.5% MWCNTs resulted in 50% increase in energy absorption.

1. Introduction

Over the last century, fiber reinforced polymer (FRP) composites have been widely used in structural components subjected to quasi static loading due to their superior specific strength and stiffness. However, in many occasions, the composite structures used in aerospace, pipelines, and military applications are prone to high strain rate loadings when subjected to impact or blast events [1,2]. In this regard, the performance of composite components is usually poor and brittle when compared to other ductile materials such as metals. One of the major causes of such brittle fracture is the premature failure of composites due to matrix transverse cracking or fiber/matrix interface debonding. The poor inter-laminar shear strength (ILSS) and toughness of composites has limited their use in high strain rate applications. As a result, many studies have addressed the behavior of composite structures subjected to impact loading. These investigations studied various types of composites including laminated [3–5], sandwich [6], and woven fabric structures [7–9].

The woven fabric composite has attracted interest of researchers due to its relatively high impact resistance [10–16]. Naik et al. [10] conducted analytical study to investigate the low-velocity impact behaviour of woven fabric composites by means of modified hertz law. It was observed that multiple contacts occur between the impactor and the composite plates during the impact event. In addition, the magnitude of the compressive stresses at the top plies is higher than the tensile stresses at the bottom plies [10]. The effect of thickness on the low-velocity impact response was investigated. It was found that the force required for delamination follows power law for thickness with exponent of 1.5. It is also reported that the delamination energy due to the local deformation at the contact point increases with the increase of thickness [11]. Environmental conditions such as the effect of water immersion on the low-velocity impact strength of woven fabric were also investigated. The integrity of the composite microstructure was examined by water immersion. While no effect was observed on the threshold damage of fiber/matrix debonding [12], the after-impact strength of the impacted woven fabric composites was proven to decrease with the increase of damage area [13]. The behavior of 3D woven basalt/aramid hyprid composites subjected to low-velocity impact is examined. It is reported that placing the basalt and aramid yarns in different layers (interply hybrid configuration) yielded better impact performance than placing the basalt and aramid yarns in the same layers [14]. Atas and Sayman [15] also examined low-velocity impact response of woven E-glass/epoxy composites subjected to various levels of impact energy. The effect of weaving angle of woven fabric on the impact response was reported [16]. The impact response can be significantly improved (~40%) by reducing the weaving angle between the yarns from 90° to 20°.

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0734-743X/$ – see front matter
doi:10.1016/j.ijimpeng.2012.03.002

Discovered in 1991 [17], carbon nanotubes (CNTs) have been the focus of research by many scientists worldwide to investigate their performance and develop techniques to increase their production capacities. Because of their distinguished mechanical properties compared with conventional structural materials, a large portion of the CNTs research is oriented to their use in polymer nanocomposites. Achieving good dispersion and creating strong interfacial bond between the CNTs and the polymeric matrix are reported as the major challenges for producing nanocomposites. Various techniques are developed to overcome these challenges such as non-covalent [18–20] and covalent [21–23] functionalization. The covalent functionalization involves impregnating functional groups on the surface of nanotubes. The functional groups are expected to react with the polymer matrix and increase the interfacial bond significantly. A review for the use of functionalized CNTs in polymeric matrices can be found elsewhere [24–26]. Several studies reported good improvements in FRP mechanical properties when CNTs are used in epoxy nanocomposites. The improvements of FRP composites include the tensile and shear behavior of glass fiber reinforced polymer (GFRP) composites [27] and mode I and mode II fracture toughness [28,29].

Few studies examined the use of nanoparticles to improve the impact response of FRP composites. Hosur et al. [30] examined the impact response of woven carbon/epoxy–nanoclay nanocomposites and observed no change in the impact response with the addition of nanoclay. However, a reduction in the damage size was reported. These observations were confirmed later by Iqbal et al. [31] upon testing carbon fiber reinforced polymer (CFRP) laminates reinforced with nanoclay. Avila et al., 2007 [32] studied the behavior of nanoclay GFRP laminated plates under low-velocity impact. With the addition of nanoclay, 48% and 4% increase in the absorbed energy were reported when low and high velocity impact tests were performed respectively. A constitutive model for the impact response of CNTs/poly-vinyl-ester-epoxy/E-glass fiber composites was developed and a relatively small improvement in the ballistic performance was reported [33]. Kostopoulos et al. [34] investigated the impact response of quasi-isotropic CFRP laminates enhanced with 0.5% pristine MWCNTs and reported no effect on the absorbed energy or delamination area. In many studies, the nanoparticles limited the damage size however; they did not improve the impact response. In the reported literature, the use of pristine MWCNTs did not enhance the impact response as expected. The impact response needs further investigations when functionalized carbon nanotubes are used. This article further examines the use of multi-walled carbon nanotubes to improve the low-velocity impact response of FRP composites. In this study, the use of a wide range of functionalized MWCNTs loadings in epoxy carbon woven fabric composites is examined.

2. Experimental methods

2.1. Materials

The carbon fiber fabrics were AS4 supplied by Hexcel™. The fabric is AGP193-P, balanced plain bidirectional weave, PAN based fiber, 3k tow size and 0.25 mm thick with filament diameter of 1.0 μm. The tensile strength of the raw carbon fibers is 4.48 GPa and the tensile modulus is 231 GPa. The epoxy was EPOTUF® 37-127 epoxy system supplied by Riechhold®, Inc. The epoxy resin is diluted liquid epoxy resin based on Bisphenol-A and containing EPOTUF® 37-058 ($C_{12} - C_{14}$ glycidyl ether) while the hardener is aliphatic Amine. The resin to hardener mixing ratio was 2:1, the set time was 5–6 h and curing time of 24–28 h at room temperature. This particular epoxy has relatively low viscosity which facilitates the impregnation of the carbon fibers during the fabrication process. Furthermore, its relatively long pot life of 30–45 min and setting time of 5–6 h allow adequate time for the impregnation and the application of the vacuum environment before the epoxy partially hardens. The tensile strength and tensile elongation for the epoxy are 65 MPa and 2.5% respectively. Functionalized

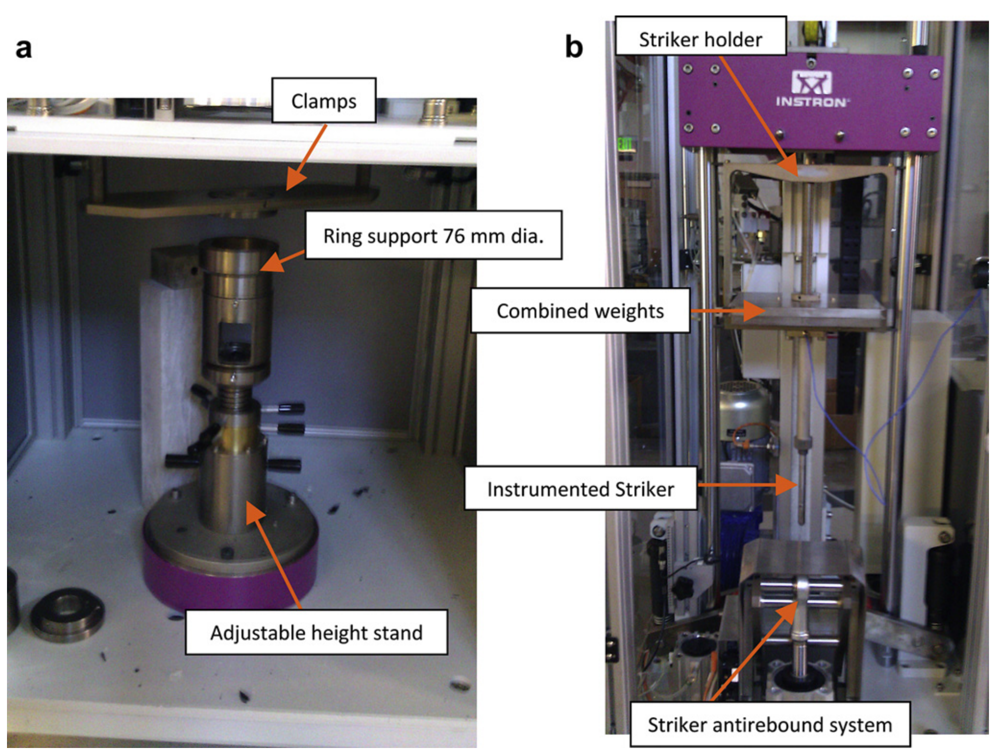

Fig. 1. CEAST® 9350 impact tester (a) test chamber, and (b) turret.