Composites: Part A 71 (2015) 59–71

Contents lists available at ScienceDirect

Composites: Part A

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

Analysis of adhesively bonded CFRE composite scarf joints modified with MWCNTs

U.A. Khashaba *,[1], A.A. Aljinaidi, M.A. Hamed

Department of Mechanical Engineering, Faculty of Engineering, King Abdulaziz University, P.O. Box 80204, Jeddah 21589, Saudi Arabia

ARTICLE INFO

Article history:
Received 16 June 2014
Received in revised form 6 November 2014
Accepted 1 January 2015
Available online 13 January 2015

Keywords:
A. Polymer-matrix composites (PMCs)
B. Environmental degradation
C. Finite element analysis (FEA)
E. Joints/joining

ABSTRACT

The main objective of the present work is to improve the performance of bonded joints in carbon fiber composite structures through introducing Multi-Walled Carbon Nanotubes (MWCNTs) into Epocast 50-A1/946 epoxy, which was primarily developed for joining and repairing of composite aircraft structures. Results from tension characterizations of structural adhesive joints (SAJs) with different scarf angles (5–45°) showed improvement up to 40% compared to neat epoxy (NE)–SAJs. Special attention was considered to investigate the performance of SAJs with 5° scarf angle under different environments. The tensile strength and stiffness of both NE-SAJs and MWCNT/E-SAJs were dramatically decreased at elevated temperature. Water absorption showed a marginal drop of about 2.0% in the tensile strength of the moist SAJs compared to the dry one. Cracks initiation and propagation were detected effectively using instrumented-SAJs with eight strain gauges. The experimental results agree well with the predicted using three-dimensional finite element analysis model.

1. Introduction

The weight and fuel savings offered by polymeric composite materials, due to their high specific strength and stiffness, makes them attractive not only to the military, but also to the civilian aircraft, space, and automobile industries. In these industries the adhesive joints are extensively used as a primary method of forming structural joints. Because there is a discontinuity of reinforcing fibers at the joint interfaces [1], the scarf joint becomes usually the weakest part of the structure. In the adhesively bonded joints, prediction the failure stress, enhancing the joint strength, and monitoring the progress of the joint damage are very important to prolong the structure's life and prevent their catastrophic failure. These issues are the main goals to be addressed in the present work.

Recently, many researchers have focused on the improving of epoxy materials using carbon nanotubes (CNTs) for practical application, as laminated composite structures [2–7] and adhesives for the structural joints [1,8]. Kwon [1] investigated the effect of multi-wall carbon nanotubes infused in epoxy matrix on the performance of the bonded scarf joints. Their results showed that the enhancement in the adhesive joint depends on the size of CNTs (length and diameter), the type of CNTs, and the adherend type. In general, he reported that most of the used CNTs provide enough enhancements in strength along the joint interface that is the weakest portion of the adhesive scarf joint.

Kumara et al. [9] showed that the theoretical strength of bonded scarf joint with small scarf angle (2–3°) have higher values compared to the larger scarf angles. Experimentally, small scarf angle required extremely large repair lengths, which verified laminate failure predominantly by fiber fracture and pull-out [9,10]. Therefore, in the present work the minimum scarf angle was 5°, which result in 57.15 scarf length for 5 mm adherends thickness (5/tan 5°).

Many investigators studied the effect of bond line thickness on the strength of bonded joints/repairs [10–18]. Xiaoquan et al. [11] showed that when the adhesive film thickness is about 0.15–0.25 mm, the ultimate stress of the scarf repaired plate reaches the highest value. Bond line thickness ranging from 0.2 to 0.25 mm is recommended by some researches [10,13–15]. Therefore, in the present work bond line thickness of 0.25 mm was adjusted for all the test samples. This value recommended for aircraft bonded composite joints [16,17].

Finite element is very powerful in determining the stress within the scarf joints. The main advantageous of the finite element software is to model each lamina separately to simulate the lamina nature of the adherends. Finite element analyses (FEA) showed large shear and normal stress concentrations at the extremities

* Corresponding author. Tel.: +966 553507515; fax: +966 26952181.
E-mail addresses: khashabu@zu.edu.eg, khashabu@hotmail.com (U.A. Khashaba).
[1] On Leave from: Mechanical Design and Production Engineering Department, Faculty of Engineering, Zagazig University, P.O. Box 44519, Zagazig, Egypt.

http://dx.doi.org/10.1016/j.compositesa.2015.01.004
1359-835X/

of the scarf joint [19,20]. The effect of material homogeneity assumptions made to enable analytic solutions was significant in finite element modeling, particularly when considering adhesive bonds between highly inhomogeneous adherends such as composite materials [21–23]. More details about the finite element analysis of adhesively bonded joints were discussed in a book recently published in Advances in Numerical Modelling of Adhesive Joint [24].

The main objective of the present work is to improve the tensile properties of adhesive joints in composite structures through introducing MWCNTs to Epocast 50-A1/946 epoxy, which was primarily developed for joining and repairing of composite aircraft structural components. Carbon fiber reinforced epoxy (CFRE) composite laminates were fabricated using prepreg technique. Neat epoxy (NE) and nanophased epoxy (MWCNT/E) were used to fabricate CFRE structural adhesive joints (SAJs) with different scarf angles (5°, 10°, 15°, 30°, and 45°). The tensile properties of the fabricated SAJs were determined at different temperature levels and water absorption. Cracks initiation and propagation were monitored through instrumented CFRE SAJ with eight strain gauges for each scarf angle and adhesive material. Finite element analysis of CFRE SAJs with both neat epoxy (NE) and nanophased epoxy (MWCNT/E) adhesives were modeled under uniaxial tensile loading and the results are compared with experimental data.

2. Experimental work

2.1. Materials

The used epoxy is bisphenol A diglycidyl ether resin consists of two parts, which are epoxy part-A (Epocast 50-A1 resin) and epoxy part-B (Hardener 946) manufactured by Huntsman Advanced Materials Americas Inc. The epoxy system is an unfilled, solvent-free, easy-to-handle material for the manufacture and repair of composite structures. The mixing ratio is 100 g from epoxy part-A: 15 g part from epoxy part-B. The viscosity of the epoxy system is 2400 cP at 25 °C. The used Multi-Walled Carbon Nanotubes (MWCNTs) were manufactured by Timesnano, Chengdu Organic Chemicals Co. Ltd, Chinese Academy of Sciences. MWCNTs have an average length of 30 μm, outer diameter <8 nm and purity above 95 wt%.

Carbon fiber reinforced epoxy (CFRE) composite laminates were fabricated using prepreg technique with 25 layer of T300-3k plain woven carbon fiber fabrics (200 g/m^2) and YPH-120-23A/B epoxy matrix. The laminate thickness is 5 ± 0.1 mm. The adherends were cut from CFRE laminates at different scarf angles (5°, 10°, 15°, 30°, and 45°).

2.2. Optimum weight percentage of MWCNTs

Four MWCNT/E nanocomposite panels were fabricated using different weight percentages of MWCTs ranging from 0.25% to 1.0 % with 0.25% increment. The MWCNTs were dispersed in epoxy resin using a high intensity Ultrasonic Processor (750 W), Cole–Parmer, Inc., USA. The test specimens were cut and tested in accordance with ASTM D 638. Details about the sonication parameters, fabrication procedure of the nanocomposites, machining the standard tension test specimens, and characterization procedure were described elsewhere, Khashaba et al. [2]. Their results showed that the MWCNT/E nanocomposite with 0.5 wt% MWCNTs has the highest improvements in the tensile properties compared to the other MWCNTs loading percentages. The in-plane shear properties of 0.5 wt% MWCNT/E nanocomposite were determined according to ASTM D5379 using Iosipescu test fixture and double V-notch specimens. The experimental results showed that the tensile and shear strengths were improved by 7.5% and 5.5% respectively, while the enhancement in the tensile and shear moduli were 18.2% and 10.3% respectively compared to the NE [2].

2.3. Characterizations of the CFRE composite adherends

2.3.1. Tension tests

Tensile properties of CFRE adherends were determined in accordance of ASTM D 3039. The dimensions of the test specimen are illustrated in Fig. 1. Five test specimens were cut into strips with 250 mm long and 25 mm width. Four rectangular aluminum end tabs were bonded to the griping length (65 mm) of the test specimens using a cold-hardening epoxy resin. These end tabs not only reduce the stress concentration from the serrated grips but also prevent the slipping of the test specimen from the grip, where the serration of the grip indented the aluminum tabs and engaged with it. End-tabs also smoothly transfer lateral compressive loads from machine grips to the specimen and accordingly, prevent crushing test specimen between the grips [25–27]. To measure the actual strain, modulus, and Poisson's ratio during the tensile test, two samples were equipped with longitudinal and transverse strain gauges. The strain gauges were connected to PC via 4-channel data acquisition model 9237 NI to monitor and record the longitudinal and transverse strains during the tension tests. All the strain gauges used in this work were BF120-3AA type with 2.1 gauge factor, 120 Ω gauge resistance, 3 × 2.44 mm^2 grid dimension and 6.6 × 3.4 mm^2 backing dimension.

2.3.2. Shear tests

In-plane shear properties of CFRE composite adherends were determined in accordance with ASTM D5379 using Iosipescu test fixture and double V-notch specimens as shown respectively in Fig. 2a and b. The principle of the test is to apply a set of prescribed displacements on the V-notch specimen, so that the central region of the sample is under a state of predominant shear [27]. These displacements are achieved through relative movement of the movable grip with respect to the fixed grip as shown in Fig. 2a. To measure the shear strain (γ_{xy}) and shear modulus (G_{xy}) two strain gauges were bonded at +45° and −45° at the center of the test

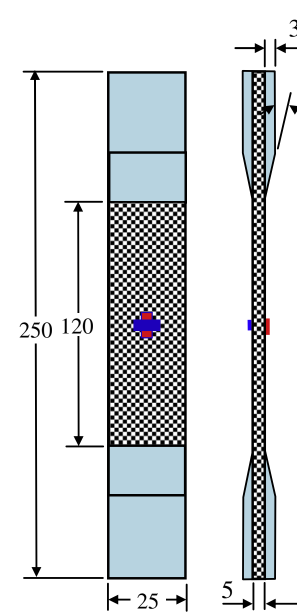

Fig. 1. Dimensions of tension CFRE specimen, ASTM D 3039. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)