Composites: Part A 84 (2016) 256–265

Contents lists available at ScienceDirect

Composites: Part A

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

Assessment of carbon nanotube yarns as reinforcement for composite overwrapped pressure vessels

Jae-Woo Kim [a,*], Godfrey Sauti [a], Roberto J. Cano [b], Russell A. Wincheski [c], James G. Ratcliffe [d], Michael Czabaj [e], Nathaniel W. Gardner [f], Emilie J. Siochi [b,*]

[a] National Institute of Aerospace, Hampton, VA 23666, USA
[b] Advanced Materials and Processing Branch, NASA Langley Research Center, Hampton, VA 23681, USA
[c] Nondestructive Evaluation Sciences Branch, NASA Langley Research Center, Hampton, VA 23681, USA
[d] Durability, Damage Tolerance and Reliability Branch, NASA Langley Research Center, Hampton, VA 23681, USA
[e] Department of Mechanical Engineering, The University of Utah, Salt Lake City, UT 84112, USA
[f] Analytical Services & Materials, Inc., Hampton, VA 23666, USA

A R T I C L E I N F O

Article history:
Received 2 November 2015
Received in revised form 21 January 2016
Accepted 5 February 2016
Available online 9 February 2016

Keywords:
Carbon nanotube
A. Nanocomposites
E. Filament winding
B. Mechanical properties

A B S T R A C T

Carbon nanotubes (CNTs) are one-dimensional nanomaterials with outstanding electrical and thermal conductivities and mechanical properties. Recent advances in CNT manufacturing have made bulk forms such as yarns, tapes and sheets available in commercial quantities to permit the evaluation of these materials for aerospace use. The high tensile properties of CNT composites can be exploited in tension-dominated applications such as composite overwrapped pressure vessels (COPVs). To investigate their utility in this application, aluminum (Al) rings were overwrapped with thermoset/CNT yarn, thermally cured under a vacuum bag, and their mechanical properties measured. Fabrication parameters such as CNT/resin ratio, tension applied during winding, and the number of CNT yarn layers were investigated to determine their effects on the mechanical performance of overwrapped Al rings. Mechanical properties of the CNT composite overwrapped Al rings (CCOARs) were measured under static and cyclic loads at room, elevated, and cryogenic temperatures to evaluate their performance relative to bare Al rings. The ultimate load carried by the composite overwrap in the CCOARs increased with increasing number of wraps. The wet winding process for the CCOAR fabrication improved load transfer compared to the dry winding process due to enhanced interfacial adhesion between the CNT yarn and the applied resin. Wet winding Al rings with CNT yarn/thermoset overwraps resulted in ~11% increase in weight relative to the bare ring and increased the room temperature breaking load by over 200%.

1. Introduction

Carbon nanotubes (CNTs) have been studied for various applications due to their excellent electrical [1,2], thermal [3,4], and mechanical [5–8] properties. However, the mechanical properties of bulk forms of CNTs have not been sufficient to justify their consideration in structural applications. Recently, CNT assemblages such as yarns, tapes, and sheets, manufactured using a continuous floating iron catalyst chemical vapor deposition technique (Nanocomp Technologies, Inc.) have become commercially available at specific strengths that warrant their assessment for structural applications. In this process, the as-produced CNT web is condensed physically and chemically to create yarns, tapes, and sheets suitable for fabricating structural composites [9–13]. These new forms of CNTs show potential for use in tension-dominated applications such as composite overwrapped pressure vessels (COPVs) [14–19] where thin walled liners are wrapped with composites reinforced with fibers such as Kevlar®, carbon and glass fibers [16,19]. Improvement of strength-to-weight ratio over state-of-the-art carbon fiber reinforced polymer (CFRP) composites could yield significant weight savings that minimize the mass of spacecraft and launch vehicles.

Here, a lab-scale test matrix was developed to assess new materials for potential use in the COPV application. In this work, thermoset/CNT yarn composite was wrapped around aluminum (Al) rings to assess their performance as COPV reinforcement. The CNT composite overwrapped Al rings (CCOARs) were fabricated under various winding conditions including “dry” and “wet”

* Corresponding authors.
E-mail addresses: jae-woo.kim-1@nasa.gov (J.-W. Kim), emilie.j.siochi@nasa.gov (E.J. Siochi).

http://dx.doi.org/10.1016/j.compositesa.2016.02.003
1359-835X/

winding process with various resin contents and various winding tensions using a custom-built filament winder. The effects of these processing parameters on the mechanical performance of the CNT yarn layers were determined under various temperatures (elevated, room, and cryogenic temperatures) and loading conditions (static, fatigue, and stress-rupture). The quality of the wound CNT composites was also investigated using X-ray computed tomography. In addition, results from CCOAR testing were compared to the mechanical properties obtained from both carbon fiber tow and unidirectional prepreg composite overwrapped Al rings.

2. Experimental

2.1. Materials and custom-built filament winder

Thermoset/CNT yarn composite overwraps were prepared by direct winding of commercially available highly-densified CNT yarns (Nanocomp Technologies, Inc., 4 ply) onto bare aluminum rings (McMaster-Carr multipurpose aluminum tubing with 3.8 cm outside diameter, 3.63 cm inside diameter, and 0.91 cm width) using a custom-built filament winder (Fig. 1). The custom-built filament winder was constructed in-house by modifying a commercially available desktop filament winder (X-Winder®, Cincinnati, OH, USA) as the starting platform. This winder was originally designed for winding conventional carbon, Kevlar and glass fibers. Modifications made to convert the as-received X-Winder 2.0 for fabrication of CCOARs included incorporation of (a) a fine filament guide, (b) a filament feeder system (breaker with a tension controller to handle the CNT spools), and (c) winding substrate mounting hardware. These alterations provided greater control of the winding process and tailored the apparatus to handle CNT yarns. The filament winder was operated by X-Winder® provided Designer and Executor software with some modifications to the G-code produced by the Designer to enable custom builds. The CNT yarns were wound in the hoop direction of the Al rings. Winding tension applied to the CNT yarn ranged between 2.4 and 26.7 N. Tension was measured and monitored by a custom-built 2-Zone system consisting of a pair of 45 N load cells connected to a signal conditioner and digital display modules (Montalvo, RF-series). Thermoset resins such as API-60 (Applied Poleramic Inc.) and Epon 828 with Epikure W cure agent (Hexion Inc.) were applied onto the as-received CNT yarns by a "dry" or "wet" method. In the dry winding process, CCOARs were prepared by applying resin directly onto each layer of the wound dry CNT yarn using a paintbrush with a 70 wt.% Epon 828 or 50 wt.% API-60 solution in methyl ethyl ketone (MEK, Sigma–Aldrich). In the wet winding process, CNT yarn was passed through a resin bath containing a 70 wt.% Epon 828 solution in MEK, and then directly wound onto an Al ring to produce Epon 828/CNT yarn composite overwrapped Al rings. Prior to winding the CNT yarn with resin, excess resin was removed by a metering blade located in the travel path of the CNT yarn. After depositing the desired length (measured as the number of turns) of CNT yarn, the as-prepared thermoset/CNT overwrapped Al ring (Fig. 2a) was removed from the winder, placed in a vacuum bag and cured at 177 °C for 2 h with a 1 h hold at 100 °C before ramping to 177 °C. Fig. 2b shows CCOARs in a vacuum bag after the curing process. The cured CCOARs (Fig. 2c) were kept at ambient conditions while awaiting further characterization. A summary of the various specimens studies is given in Table 1.

Dry carbon fiber (CF) tow and carbon fiber prepreg tape wrapped Al rings were also prepared for comparison with the CNT yarn reinforced rings. Desired lengths (30, 61, 76, 91, and 122 cm) of unsized dry IM7 carbon fiber (CF) tow (Hexcel, 12 K tow, tensile strength: 5.66 GPa, tensile modulus: 276 GPa, density: 1.78 g/cm^3, linear density: 446 g/km, tow cross-sectional area: 0.25 mm^2) [20] were wrapped around bare Al rings. API-60 (50 wt.% in MEK) was then applied using a paintbrush and cured under the same conditions as the CCOARs to obtain unidirectional API-60/CF composite overwrapped Al rings. For the case of IM7/8552 prepreg tape (Hexcel, 0-degree tensile strength and modulus 2.72 GPa and 164 GPa, respectively, resin content in prepreg: 33–38%) [21] overwrapped Al rings, desired lengths (15, 30, 46, and 61 cm) of as-received IM7/8552 prepreg tape were wrapped around bare Al rings and then cured as described above to obtain unidirectional CF/8552 composite overwrapped Al rings.

2.2. Characterization

A hoop tensile test method based on ASTM standard D2290 (standard test method for apparent hoop tensile strength of plastic or reinforced plastic pipe by split disk method) was utilized to evaluate the composite overwrapped Al rings. In this method, tensile load is applied to the ring primarily in the region between split disks fitted into the cylinder (Fig. 2d). The physical dimensions and

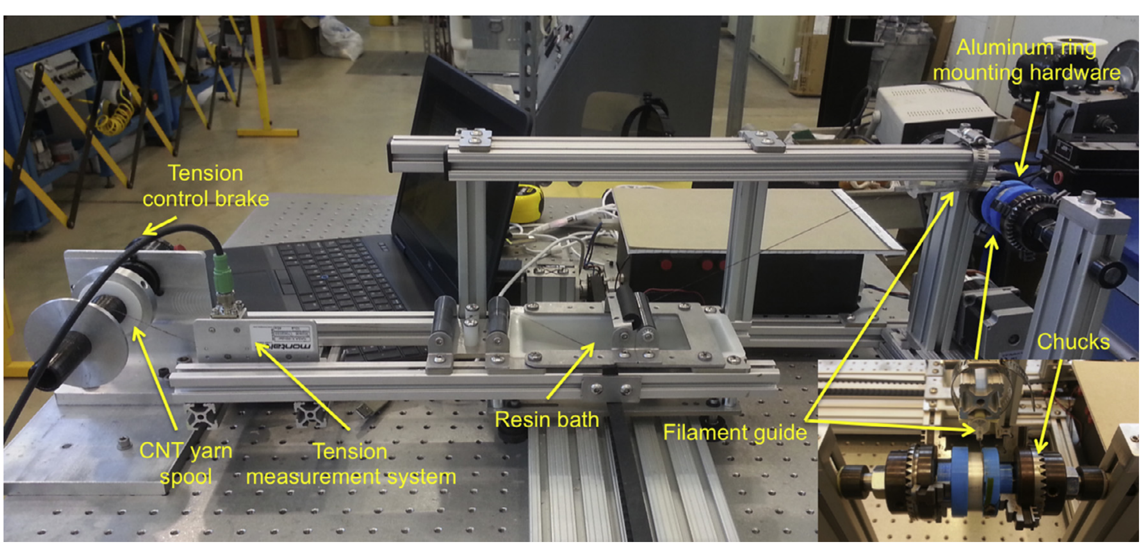

Fig. 1. Photograph of a custom-built filament winder for CCOAR fabrication. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)