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Evaluating the effectiveness of nanofillers in filament wound carbon/epoxy multiscale composite pipes

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ABSTRACT

The performance of filament wound (FW) composite pipes is considered to be fundamentally governed by fiber properties and winding angles; however, matrix dominated properties such as axial and hoop strengths are also responsible in design of FW composite pipes. This paper presents the experimental results of a project aiming to assess the benefits of addition of carbon nanotubes (CNTs) and/or boron nitride nanoplates (BNNPs) as nanofillers within epoxy matrix of FW carbon fiber composite pipes. The nanofillers enhance the burst and hoop strengths up to 17.0% and 31.7%, respectively, over the control samples. Failure analysis revealed that the morphologies of nanofillers play an important role on the matrix toughening and strengthening the fiber–matrix interface. Highest mechanical performance of the multiscale composite pipes was obtained with the addition of CNTs and BNNPs within the epoxy matrix concurrently related with the synergetic effect of the two different nanofillers.

1. Introduction

Filament wound (FW) fiber reinforced pipes have many advantages such as high specific stiffness and strength. The efficiency of filament winding process and above mentioned advantages have made this type of pipes good candidates for the storage of compressed hydrogen or of compressed and liquefied natural gas lines [1,2] Carbon fiber is a good choice for FW pipes because of its low density and high strength. Generally, FW composite pipes are made of carbon fiber/epoxy since smooth internal surface FW pipes lead lower friction during fluid flow. However carbon fiber reinforced plastics have some shortcomings such as brittleness and low resistance to crack propagation. Mechanical and failure behaviors of FW pipes have extensively investigated in the literature [3–9]. It is reported that mechanical properties mainly governed by fiber properties and winding parameters such as an optimum winding angle of 55° was recommended for close ended pipes [10,11].

It is well known that the mechanical properties of matrix become important since the damage of FW pipes initiates as matrix damage followed by formation of leakage path, delamination and finally fiber breakage occurs [3,5,6]. Interfacial properties for fiber reinforced composites are a matrix dominant property and usually limit the design [15]. The addition of nanofillers was considered as the most efficient way to enhance mechanical properties of fiber reinforced polymer composites, since the combination of conventional fiber and nanofillers in polymer matrices had led to a new generation of multiscale, multifunctional, three-phase materials with high performance [12–14]. Among various nanofillers, carbon nanotubes (CNTs) have served as an ideal filler for high performance composites due to their unique physical properties like high strength and aspect ratio [15,16]. It is reported that interlaminar shear strength [17], fracture toughness [18–20] and load transfer ability [21] can be enhanced by addition of CNTs such as pullout, rupture, and crack bridging [22,23] mechanisms.

Many researchers have focused on development of CNTs containing fiber reinforced polymers [24,25]. The effects of morphology and type of nano particles upon interfacial strength between matrix and reinforcement have been investigated [26–29]. In addition, the effects of volume fraction of the nano reinforcements [30] and dispersion quality [31] upon mechanical properties of materials have been also studied.

Boron nitride has been paid attention due to its high thermal and low electrical conductivities [32–34]. The crystal structure of hexagonal boron nitride is very similar to graphite except for the

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difference in the stacking sequence of layers [35]. In our previous study [36], it was showed that boron nitride addition into epoxy resin can result in notable increase of tensile strength. It is reported that the highest strength increase has obtained at 0.3% BN content while highest toughness increase has been obtained at 0.5% BN content.

The literature survey revealed that, the effects of nanofiller modification upon mechanical behaviors of FW pipes have received little attention. In this study, MWCNTs and/or BNNPs filled epoxy resin matrix FW carbon fiber composite pipes were successfully fabricated with winding angle of 55°, and the variation of burst and hoop strengths were evaluated with the standard tests. The effectiveness of nanofillers with different morphologies on damage development of carbon fiber composite pipes and their micro-reinforcing behavior were proposed.

2. Experimental

2.1. Materials

The nanofillers, MWCNTs (purity >95%, diameter 30–50 nm, length 10–30 μm) and BNNPs (diameter ~250 nm and thickness ~50 nm) were provided from Times Nano Company and BORTEK, respectively. The reinforcement, carbon fibers (800 tex) were purchased from DowAksa, Turkey. The preferred resin system is Araldite MY 740/HY 918/DY062 (Vantico Ltd) bisphenol-A epoxy resin system with 100:85:0.5 weight ratios.

2.2. Fabrication of the FW composite pipes

In collaboration with a manufacturer of composite pipes and tubes, carbon fiber reinforced epoxy composite pipes were manufactured by filament winding to allow experimental manipulation of the fabrication process. For getting a control group one group of pipes were produced without adding nanofillers. The amounts of nano particles were chosen based on our previous study [41]. Firstly, the epoxy resin system with agents was prepared, following, the required amount of nanofillers were added into the epoxy resin and mixed mechanically for 30 min and additional 30 min with ultrasonically. The temperature of epoxy resin was maintained as 35 °C in order to reduce the viscosity of resin for obtaining complete wetting and better saturation. Table 1 shows the composition of nanofiller added epoxy resin used for filament winding operation. Secondly, FW carbon fiber composite pipes were fabricated using a filament winding machine at the winding angle ±55° on a preheated (60 °C) mandrel as shown Fig. 1. The pipes were cured in an oven for 80 °C/2 h + 120 °C/4 h, and then cooled down to room temperature, subsequently. The average internal diameter and wall thickness of filament wound pipes were measured as 72 mm and 3 mm, respectively.

2.3. Characterizations

2.3.1. Burst pressure tests

The short time hydraulic burst pressure tests were performed with at least five samples according to ASTM D1599-99 standards. A lab made open ended apparatus was used to utilize the short time hydraulic burst pressure. The apparatus allows the pipe to shrink and expand in diameter freely which results regarding the axial stress as zero (Fig. 2). The internal pressure was generated by a PLC controlled hydraulic pump. During the tests, the pressure was continuously and uniformly increased until failure occurs. Test durations were measured until specimen fails to specify loading rates individually in order to develop burst damage within the range of 60 and 70 s of loading time for all specimens.

Table 1
Compositions of modified epoxy resin.

Case	% MWCNT (by weight)	% BNNP (by weight)	Epoxy
1	0	0	All Of
2	0.3	0	Remaining
3	0	0.5	Remaining
4	0.3	0.5	Remaining

Fig. 1. Filament winding process of carbon fiber/epoxy composite pipes. The inset represents winding angle as ±55°.

The burst strengths are also determined according to Equation (2)

$$S = P(d + t)/2t \quad (1)$$

Where;

S hoop stress (MPa), P internal pressure (MPa), d average inside diameter (mm), t average wall thickness (mm). So, the burst pressures have been converted to burst strength values.

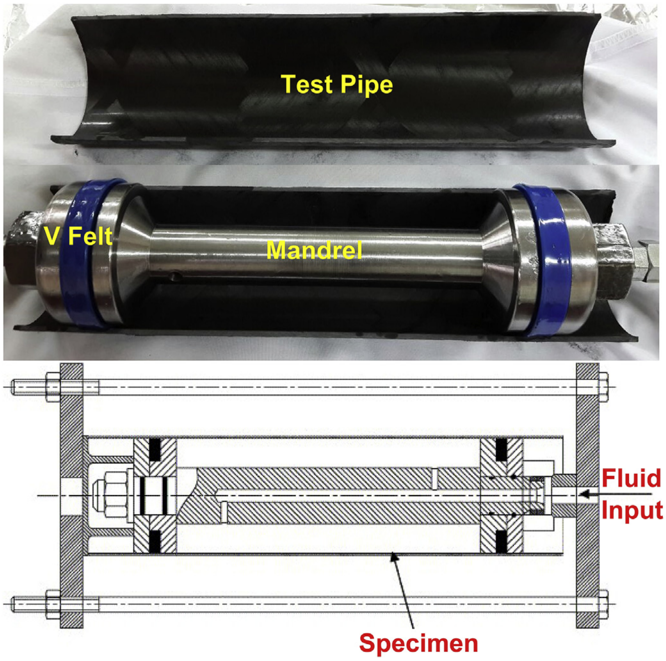

Fig. 2. Open ended short time hydraulic burst pressure test apparatus with schematic presentation showing the fluid input during bust tests.