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The effect of stress ratio on the fracture morphology of filament wound composite tubes

L.A.L. Martins [a], F.L. Bastian [b,*], T.A. Netto [c]

[a] *Federal Center of Technological Education, CEFET/RJ, Brazil*
[b] *Federal University of Rio de Janeiro, PEMM/COPPE/UFRJ, Brazil*
[c] *Federal University of Rio de Janeiro, PEnO/COPPE/UFRJ, Brazil*

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ABSTRACT

A comparative study was done between two typical loading conditions (closed-end and restrained-end condition) in the pipeline and piping systems manufactured by filament wound composite tubes with the objective of studying the influence of loading condition on fracture morphology. Four thin-walled E-glass fiber epoxy tubes with different wind angles were produced to perform hydrostatic tests under restrained-end condition. The results were compared with composite tubes tested under closed-end condition in previous work. Unlined tubes were first tested to obtain the leakage failure and then tubes lined with PVC were tested for burst failure pressure under restrained-end condition. The results showed that the fracture morphology of filament wound composite tubes hold a direct relationship to the stress ratio (σ_{Hoop}:σ_{Axial}).

1. Introduction

Composite materials have been used for building pipeline and piping systems for potable water, sewage treatment, power generation, oil and chemical transportation with a long history of reliability [1]. The word "piping" generally refers to process piping or utility piping which are located inside a plant facility. The word "pipeline" refers to a long pipe running over distances transporting liquids or gases [2].

Pipeline and piping systems which often operate under corrosive environment, severe thermal loading and high pressures are becoming highly sophisticated therefore needing advanced methods for their analyses and design. Normally composite tubular products are customized by tailoring the variables considered to the particular job in such a way that the custom producer is able to provide a more reliable product and longer life [3]. Consequently, the designer using composite materials must perform a careful selection of constituent materials and to define the lay-up, fiber volume fraction, fiber orientation and manufacturing processes, among other things. This is not an easy task and therefore it is also suggested to the design engineers to search references in the literature. The reader is encouraged to consult published guides like one of Edwards [4] which cover the main aspects of the design for composite materials.

In pipe stress analysis two loading conditions have particular interest. They are produced by biaxial loading (internal pressurization and different pipe end conditions). The first is an closed-end loading condition (similar to pressure vessel) and represented by stress ratio 2H:1A. The second is a restrained-end loading condition that produces a plane strain state. This loading condition although frequent in pipeline and piping systems has being poorly investigated for composite materials. This loading condition is common in pipelines and piping systems because they use pipe restraints as anchors and guides to counter forces and moments resulting from gravity, thermal displacement, wind, earthquake, vibration and dynamic pulsations such as water hammer [2]. Typically, all cross sections experience identical deformation and the displacement are restrained along the pipe length.

Structural failure in composite tubes is caused by overload on the tubular structure during operation or even in the installation. The failure region must be preserved because it contains information of practical importance to the understanding of the failure process of composite tubes. Fracture morphology holds a direct relationship with the stresses sustained by the composite tubular structures allowing to determine the stress ratio in a failure process.

Filament wound composite tubes have been tested for several uniaxial and biaxial loadings [5–7]. The failure envelope obtained from these tests is used in design and can give some information on the fracture morphology.

Meijer and Ellyin [8] performed multiaxial stress tests in ±60° filament wound composite tubes. These authors found that under tensile loading (0H:1A) and biaxial loading (1H:1A), the fracture morphology is a helical crack occurring along the edge of an external filament wound band.

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* Corresponding author. Tel.: +55 21 2562 8757.
E-mail address: fbastian@metalmat.ufrj.br (F.L. Bastian).

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Naik [9] conducted a study on the effect of environmental conditions on the burst pressure in composite tubes under open-end condition and represented by stress ratio 1H:0A (hoop pressure loading). During these tests localized yielding in the polymer occurs resulting in thinning of the wall in a localized region of the tube (typically at the point where the wall thickness is smallest). This is followed by localized expansion (“*ballooning*’) leading to final failure at the newly oriented polymer structure in the “*balloon*” to result in the typical “*Parrot’s Beak Failure*”.

Tarakcioglu et al. [10] studied the fatigue failure behavior of glass/epoxy ±55° filament wound pipes under open-end condition and hoop pressure loading (1H:0A). The specimens presented fracture morphology similar to the results obtained by Naik [9]. Gemi et al. [11] performed similar study with glass/epoxy $(\pm 75^\circ)_2$ filament wound pipes under same loading condition. They obtained the same results calling the final shape as “ *triangular leaf-shaped openings*”.

Results published [12,13] on burst failure of composite tubular structures under closed-end condition and biaxial pressure loading (2H:1A) have shown that a crack is formed parallel to one set of fibers and fiber fracture occurs in other set.

The aim of present work is to investigate the structural and functional failure pressure of composite tubes during hydrostatic tests for a restrained-end loading condition and the fracture morphology with results obtained from previous work [14]. Furthermore, an alternative damage model based on the model proposed by Linde et al. [15] was used to predict the structural failure pressure. This damage model is implemented in user subroutine (UMAT) for use with ABAQUS/Standard nonlinear finite element analysis. The numerical and experimental results were also compared in order to evaluate the applicability of the damage model for this loading condition.

2. Materials and fabrication

Glass fiber reinforced polymer (GFRP) tubes were fabricated using a filament winding machine (Fig. 1) produced by Tecservice (Brazil). This machine has the capacity of producing parts up to 3000 mm of length and 500 mm in diameter. The mandrel employed in this work is collapsible in order to allow removing the composite tubes without introducing damage. This mandrel was built in steel with 2000 mm length and 101.6 mm diameter.

Owens Corning 111A Type 30 1100 Tex E-glass fiber roving with 16 μm diameter was used as reinforcement. Six rovings were used forming a band width approximately 18 mm wide. Araldite MY 750 epoxy resin was used as matrix material with HY 2918 anhydride hardener and DY 062 as accelerator. The physical properties and mix ratio of the resin system are according to Table 1.

Table 1
Properties and mix ratio of the polymer system used.

Components	Parts by weight	Viscosity at 25 °C (mPa s)	ρ (g/cm^3)
Araldite MY 750	100	12,000–16,000	1.16
Hardener HY 2918	85	50–100	1.16–1.20
Accelerator DY 062	2.5	⩽50	0.90


Fig. 1. Filament winding machine.

Four tubes were fabricated with different winding angles. Four layers were utilized in each tube. The tubes have the following lay-up configurations: $[\pm 45^\circ]_4$, $[\pm 55^\circ]_4$, $[\pm 60^\circ]_4$ and $[\pm 75^\circ]_4$.

After the winding process, the tubes were cured inside an oven (Fig. 2) according to the recommended cure schedule (2 h/80 °C + 2 h/120 °C) the tubes rotated during the entire cycle to prevent dripping and sagging.

The tubes were cut and mapped (Fig. 3) to obtain the dimensions to be used in the models built for simulation in ABAQUS. 10 points with a gap of 18° between them were measured in the sections marked (100 mm of spacing) to obtain the external diameters. In both ends, the same procedure was used to measure the internal diameters. Vernier caliper (300 mm range) was used in the measurements. Table 2 shows the average dimensions mapped for each tube.


Fig. 2. Composite tube inside oven for cure.

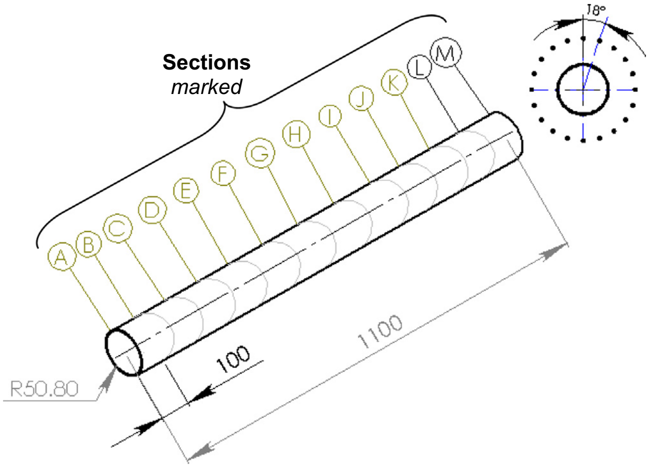

Fig. 3. Schematic view and mapping points of the tubes.