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Reviewing some design issues for filament wound composite tubes

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ABSTRACT

This article discusses important aspects of the design of composite tubes manufactured by filament winding. The work was divided into three parametric studies. The first study was conducted to determine the minimum length that can represent an infinite tube in hydrostatic testing. The second study was conducted in order to find the optimum wind angle of composite tubes subjected to internal pressure under different end conditions. The purpose of the last one was to study the influence of diameter and thickness on the failure pressure during tube burst tests. A progressive failure analysis was performed using ABAQUS software employing a damage model implemented by a user subroutine (UMAT). The models used were validated using experimental data obtained from tube burst tests in previous studies. The results provide a better understanding of the behavior of composite tubes under internal pressure thereby making possible to improve design practices used in industry.

1. Introduction

Fiber-reinforced polymer composites are recognised as possessing superior specific mechanical properties when compared to conventional engineering materials. However, the widespread use of these materials by design engineers is still limited [1] although this attitude tends to change due to increasing performance and weight saving demands for equipments and structures.

The customization of composite tubular products requires sophisticated tools to perform the analysis during the design. Parametric studies are necessary to evaluate the behavior of composite materials by changing some variables under diverse loading conditions. This approach allows the design engineer to estimate the failure envelope of the evaluated structures and to predict their response. The designer can investigate the optimum wind angle, lay-up (stacking sequence), diameter, thickness and other variables for the specific loading conditions in order to obtain the best configuration. Nowadays, a numerical analysis considering progressive failure offers faster results for those tasks and cost saving when compared to experimental work [2].

One of the most important parametric studies is to find the optimum winding angle for a given loading condition. The literature shows that some efforts have already been done to reach this goal particularly to find the optimum wind angle for pressure vessels. Netting analysis is a first attempt to optimize composite tubular structures. This tool is a very simple analytical technique but it has some restrictions. In this technique, it is assumed that all loads are supported by the fibers alone, neglecting the contribution of the matrix and the interaction between the fibers [3]. The optimum wind angle of 54.74° obtained from this technique is normally used to manufacture composite tubular structures under close-end loading condition (similar to pressure vessel) represented by a stress ratio (hoop to axial stress) of 2H:1A.

Evans and Gibson [4] conducted a careful study to understand why netting analysis does not offer accurate results to predict the optimum wind angle for thermosetting matrix composites. Their study concluded that the stable angle of inclination of the fibers, where no fiber rotation occurs with increasing strain, differs from the ideal angle of netting analysis by an amount that depends on the matrix-to-fiber-stiffness ratio. Thus, netting analysis approach is accurate only when the stiffness of the matrix is very small with respect to the reinforcement as occurs with rubber hose and thermoplastic matrix composites. Rosenow [5] studied composite tubes under uniaxial and biaxial loading. He performed experimental work and used the lamination theory to predict the optimum wind angle through stress/strain analysis up to the point of non-linearity. From his study, it appears that filament wound composite tubes should be wound at 54.75° for closed-end tubes, 75° for open-end tubes and at the lowest possible angle for tensile loading. Bhavya et al. [6] performing failure analysis of an anti-symmetric composite cylinder under open-end condition found similar results. Parnas and Katirci [7] developed an analytical procedure based on classical laminate theory to design and predict the behavior of fiber reinforced composite pressure vessels. From that procedure for internal pressure loading, they found optimum wind

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angles ranging between 52.1° and 54.2° depending on the geometry and failure criteria used.

Hydrostatic testing or numerical studies on open-end tubes help to understand the response of the material but this loading mode does not represent a common condition in applications such as pipes and pipelines. This is because there will always be some axial stress on the tubular structure due anchors and guides to counter forces and moments resulting from gravity, thermal displacement, wind, earthquake, vibration and dynamic pulsations such as water hammer [8]. The loading condition that best represents these practical situations is known as restrained-end condition and has particular interest in pipe stress analysis.

Design engineers have already some optimization tools available for designing composite tubular products. Some commercial software offer the possibility of introducing nonlinear effects and use of built-in models to describe the damage evolution in fiber-reinforced materials or to develop progressive failure formulations to be implemented in user subroutine. These resources offer better results in predicting the response of specific composite structures under given loading conditions allowing also optimizing and customizing these structures.

Various material degradation models have been proposed and tested for laminated composite structures. Generally, these models may be categorized into two main groups: heuristic models based on a ply-discounting material degradation approach and models based on a continuum damage mechanics [9].

In ply-discount approach one or more of the material properties (or constitutive components) of a damaged region is set equal to zero or reduced to a fraction of the original values. Degradation factors are used to define a percentage of the stiffness retained. Since degradation level depends among other factors on crack density and lamination sequence, an accurate evaluation of degradation factors is a difficult task which complicates the implementation of numerical methods in macroscopic damage modeling [10].

Sleight [11] describes a simple strategy to perform the gradual degradation of the material properties using the ply-discount approach. The model is used to predict the nonlinear response and failure of laminated composite structures. The C^1 plate and shell elements based on classical lamination theory are used to calculate the in-plane stresses. The methodology is implemented into a general purpose finite element analysis code called COMET (Computational Mechanics Testbed). Knight [9] also implemented a material degradation model based on the ply-discounting approach in a user subroutine (UMAT). The model makes it possible selecting the failure initiation criterion, the material degradation factor and the type of degradation (instantaneous or gradual). Antoniou et al. [12] validated a material constitutive model that employed the concept of sudden zeroing upon failure onset (instantaneous unloading). The model was implemented in the numerical procedure by comparison with experimental data from biaxial loading tests on tubular specimens.

Damage mechanics is the most used approach to capture the nonlinear behavior of laminates due to damage accumulation.[13]. Matzenmiller et al. [14] proposed a constitutive model (called MLT model) based on the use of a Weibull function to describe the statistical nature of internal defects and the ultimate strength of a fiber bundle within a composite lamina. Shuecker and Pettermann [15] developed a ply-level continuum damage mechanics for damage due to matrix dominated failure modes. A scalar evolution law and a tensor relation describing the effect of different damage modes on material stiffness were defined. Mori–Tanaka Method [16,17] was used to phenomenologically describe the variation of the compliance tensor due to material degradation in a thermodynamically consistent way. Maimí et al. [18] proposed a constitutive damage model that has its foundation in irreversible thermodynamics for the prediction of the onset and growth of intralaminar failure mechanisms in composite laminates under plane stress. More recently, Flatscher and Pettermann [19] performed an analysis using a constitutive ply model to simulate an open hole specimen subjected to uniaxial tensile loading combining damage and plasticity.

A comprehensive review on the recent developments for damage modeling and finite element analysis of composite laminates was published by Liu and Zheng [20]. Such review includes specially, the methodologies that solve numerical convergence problems using Newton–Raphson method. A problem with this method is that it fails to trace the nonlinear equilibrium path through the limit point, because in the vicinity of a limit point the tangent matrix $[K_T]$ becomes singular, and the iteration procedure diverges [21]. The discussion conducted by Liu and Zheng [20] showed that the arc-length algorithm originally proposed by Riks [22] and Wempner [23] can ensure highest solution precision for instability cases displaying negative stiffness ("snap-through" phenomenon) as occurred in the present study.

The aim of the present paper is to provide a better understanding of the behavior of composite tubes under internal pressure thereby improving design practices used in industry through parametric studies. An alternative damage model based on the model proposed by Linde et al. [24] was used. This damage model was implemented in user subroutine (UMAT) for use with ABAQUS/Standard nonlinear finite element analysis.

2. Materials and mechanical properties

Modeled glass fiber reinforced polymer (GFRP) tubes were fabricated using the filament winding process and cured inside an oven according to the recommended cure schedule (2 h/80 °C + 2 h/120 °C) [25,26]. The length and internal radius of the tubes are given in Fig. 1. Owens Corning 111A Type 30 1100 Tex E-glass fiber roving with 16 μm diameter was used as reinforcement. Araldite MY 750 epoxy resin was used as the matrix material with HY 2918 anhydride hardener and DY 062 as accelerator.

The burst pressure was used to obtain the hoop stress in numerical analysis.

The hoop stress was calculated using the following equation:

$$\sigma_H = \frac{P_i d_i}{d_e - d_i} \qquad (1)$$

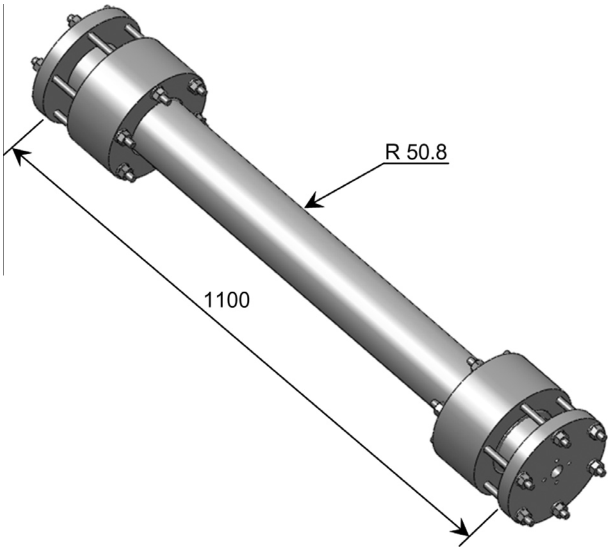

Fig. 1. Schematic view of tubes assembled for hydrostatic tests.