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Experimental study of the thermomechanical behavior of wound notched structures

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ABSTRACT

In the scope of the Osirhys IV project led by the French Alternative Energies and Atomic Energy Commission (CEA), this study has focused on the behavior of notched composite structures. The specific manufacturing of these structures, performed by CEA, has given rise to an architecture representative of the hyperbaric wound vessels dedicated to hydrogen storage. The objective of the test campaign carried out on these samples at different temperatures was twofold: the damage type and evolution undergone by a wound composite subjected to strong stress gradients was studied, and a wide experimental database was constituted in order to test and validate the capabilities of the damage models developed by the partners of the project. In order to provide a large quantity of information about the damage modes and kinetics, the mechanical tests were instrumented with acoustic emission and digital image correlation, and micrographic observations of the samples were performed.

Introduction

The past years, the use of composite materials (for example, carbon fibers in an epoxy matrix) has become generalized in the industry, in particular in the transportation sector. The anisotropy of this type of material makes it possible to adapt its behavior to the mechanical requirements of the structures [1]. Moreover, the very high specific properties of composite materials permits a significant weight reduction in secondary and, nowadays, primary structures. In parallel with the evolution of composite materials, many different manufacturing processes have been developed [2], each leading to a particular composite architecture. Among these processes and related architectures, one can cite pultrusion, sheet molding compounds, laminates, RTM (resin transfer molding), sandwich structures, etc ...

The present paper is devoted to wound composite materials, obtained by filament winding. This process is particularly well adapted for manufacturing structures with a revolution axis [3,4] such as pipes or pressure vessels. The material architecture of wound composites is different from that of laminates, in particular because of the presence of zones of interlaced fibers in helical layers [5], as shown in Fig. 1a.

Furthermore, the wound composites differ from laminates not only in their architecture but also with regard to

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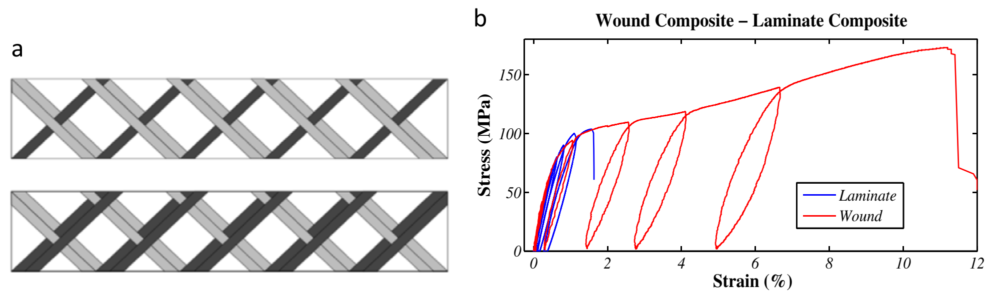

Fig. 1 – a) Interlaced fiber zones from a filament winding process; b) comparison of a laminate vs a wound composite for a [±45$_4$] sample subjected to tension.

mechanical behavior [6]: Fig. 1b presents the axial stress – axial strain curves of a laminate and a wound sample (both specimens were made of the same kinds of fibers and resin and had the same stacking sequence [±45$_4$]) subjected to tension. Even if both curves were perfectly superimposed up to the fracture of the laminate, the laminate sample exhibited a maximum elongation of about 1.5% while the fracture of the wound composite sample occurred at 11%. The wound architecture modifies the mechanical response since the interlaced zones stop crack propagation and delamination: thus, the sample can undergo larger strains.

Damage of laminate structures is a complex phenomenon combining different mechanisms, starting from the microscale and leading to macroscopic failure. The main mechanisms are the following:

- At microscale, decohesion at the interface fiber/matrix is one of the first damage mode, which occurs when matrix undergoes a significant enough loading. From these defects initiate microcracks at the ply scale by coalescence [7]. The origins of this decohesion are numerous (microdefects on the interface fiber/matrix, local stress due to fiber distribution [8], ...).
- Intraply microcracking appears in plies which are misoriented with respect to the loading axis. An abundant literature describes this phenomenon ([9–11] among others). The direction of the matrix cracks depends on the orientation of the fibers and the stacking sequence. In straight samples (as in the aforementioned works), cracks initiate in general from free edges and propagate in the depth and the width of the sample.
- The different orientations of the plies in the laminates lead to delamination (separation of two adjacent plies) because of interply stress. Delamination also initiates at the free edges because of the stress singularity and causes stiffness drop [12]. Notched samples are particularly sensitive to delamination.
- Fiber breakage occurs in a brutal way in the plies in which the axial stress is high enough (mostly in the loading direction). Intraply cracks contribute to this failure, by generating stress concentration [13]. Fiber breakage is in general the ultimate stage before final fracture.

Contrary to the mechanical behavior of laminates which is a subject abundantly described in the literature ([14–17], among many others), wound composites have been less studied and few investigations have focused on this type of material [18,19]. Nowadays, several research projects have been carried out in the framework of hydrogen energy development as an alternative to fossil fuels. These projects have been oriented towards two different challenges: the development of cheap and efficient fuel cells and hydrogen storage.

In the second challenge, the OSIRHYS IV project, funded by the French National Research Agency, aims at developing a simulation tool in order to properly predict failure of wound composite vessels and then propose optimized tanks. In this context, a test campaign comprising two parts has been carried out on samples manufactured in the same way as the wound vessels. First, tests on classical rectangular samples aim at providing data in order to identify the material parameters involved in the models [20,21]. A specific procedure was then set up by our partner CEA (French Atomic Energy Commission) to manufacture rectangular, flat, notched samples representative of the interlaced architecture of wound composite. Tensile tests were performed on these samples, and the results and analysis of the tests are the subject of the present article.

The purpose of the test campaign performed on these notched samples is twofold:

(i) Since the presence of the notch leads to a complex stress state with gradients, a single sample undergoes high levels of damage of different nature and it is possible to study the influence of the particular architecture on the onset and evolution of the damage. Knowledge of the kinetics of these different damage modes is pivotal in order to predict tank burst: even if fiber breakage in the cylindrical part of the tank is the main cause of burst, other damage modes may modify the kinetics of this mechanism, in particular in the dome, for which the structure and stress state are complex. A complete characterization of each damage mode is necessary to accurately predict the way the tank bursts.

(ii) The simulation of the behavior of these complex samples (which are structures) is a genuinely discriminating and validating test for the models developed by the partners of the Osirhys IV project. Moreover, the thermal response of wound composite is studied in order to correctly represent the damage behavior and its dependency on temperature, since the working