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Numerical/experimental impact events on filament wound composite pressure vessel

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ABSTRACT

Impacts on pressure vessels, produced by winding glass fibre with vinyl ester resin over a polyethylene liner, were numerically and experimentally investigated in the current work.

Pressure vessels were experimentally tested under low velocity impact loads. Different locations and incident energies were tested in order to evaluate the induced damage and the capability of the developed numerical model.

An advanced 3-D FE model was used for simulating the impact events. It is based on the combined use of interlaminar and intralaminar damage models. Puck and Hashin failure theories were used to evaluate the intralaminar damages (matrix cracking and fibre failure). Cohesive zone theory, by mean of cohesive elements, was used for modelling delamination onset and propagation.

The experimental impact curves were accurately predicted by the numerical model for the different impact locations and energies. The overall damages, both intralaminar and interlaminar, were instead slightly over predicted for all the configurations.

The model capabilities to simulate the low velocity impact events on the full scale composite structures were proved.

1. Introduction

Composite materials are becoming more and more attractive for several different applications mainly due to the corrosion properties and weight saving capabilities. Nowadays a very popular commercial application of composite is represented by pressure vessel.

In the last decades, filament winding composites (both carbon and glass fibre) have been progressively replacing metal for pressurized vessels [1] in both high tech and commercial applications. The increasing use of composite, coupled with the design complexy of such material, is increasing the demand of specialized tools capable to simulate the structural behaviour of these components reducing the necessity of expensive tests.

For pressure vessel, one of the most critical safety issues is the failure induced by low velocity impact of foreign objects (always happening during the production and/or in the service life). These events can severely affect the structural integrity leading to dangerous situations. According to the standard EN 14427 [2], the ability of the vessel design to withstand loadings other than internal pressure need to be demonstrated by a series of experimental impact/dropping tests. These need to be performed on both the cylindrical and the dome section of the vessel in order to verify the most critical part of the structure. This is one of the most severe design requirements that need to be fulfilled for their commercialization. In this scenario, the availability of numerical tools capable of properly simulate the impact event can reduce the experimental costs during the design phase. Even more, the composite layup/constituents and more generally the complete vessel design can be simply numerically optimized in order to fulfil the same safety requirements but reducing the production cost (high benefit considering the amount of produced units).

The effect of impact on filament wound structures is still not well understood and even more its numerical simulation is extremely complicated. A first numerical investigation was conducted by Changliang et al. [3] where 3D finite element (FE) model was used to evaluate the impact induced damage on metal liner composite vessel. Parametric analyses, varying the incident energy and the internal pressure, were carried out. Matrix cracking and delamination were evaluated by the use of Chang and Chang criteria [4]. Even if the results were consistent with the physical

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behaviour, the model accuracy was not verified against experimental data.

There is more available literature concerning the impact on filament wound composite structures (not specifically for pressure vessel). Alderson and Evans [5,6] compared the damage induced by an impact event against simple static tests on thin filament wounded E-Glass/Epoxy tubes with a ±55° winding angle. They observed that the first modes of damage were always delamination and local crushing, just like for carbon composites [7]. Geometrical effects, such as boundary conditions and curvature are also important for impact induced damage [3,4]. Christoforou et al. [8] and Curtis et al. [9] investigated the influence of impact damage on the burst pressure for thin composite pipes. Both researches showed a drastic reduction of the pressure resistance due to impact damage. Ozdil et al. [10] investigated the influence of defects and impact damage on the external (implosion) pressure. It was shown that the damage produced by low energy impact leads to a reduction of the implosion pressure. Tarfaoui et al. [11–14] carried out an extensive test program, arriving at the same conclusion that the impact damage reduces considerably the implosion pressure. Moreover, the same author [15] was able to predict the impact curves with good accuracy, using finite element model with progressive failure analysis (based on Hashin failure criterion [16]). The model was not intended to predict the onset and the propagation of delamination. A more complex numerical model was used by Zou et al. [17] and Li et al. [18] that investigated the impact induced damage on filament wounded pipes. A progressive interlaminar approach was used, based on a stress criterion for the damage onset and principles of fracture mechanics for the damage propagation. The numerical predictions showed good agreement with the experimental data for both the size and the shape of delaminations.

No numerical models (with the simultaneous evaluation of interlaminar and intralaminar damages) have been used so far, to simulate the impact event/damage on filament wound component/structures.

In the current work several experimental impact tests were carried out on commercial filament wound composite vessel with internal polyethylene liner. Different impact configurations (energy and position of impact) were experimentally testes in a fully instrumented drop weight machine. All the tests were also recorded by a high speed camera. The experimental tests were then accurately simulated using a commercial finite element software coupled with an advanced damage model for composite material. This, developed for the commercial software ABAQUS Explicit [19], was based on a combination of: interlaminar (by means of the cohesive zone approach) and intralaminar models (by a combination of Puck [20–22] and Hashin [16] strength based failure criteria).

2. Methodology

2.1. Pressure vessels

All the experimental/numerical tests were performed on filament wound pressure vessels. The vessels were produced with an internal polyethylene liner covered by E-Glass fibre and vinyl ester resin composite produced by filament winding.

The vessels were also equipped with an inlet/outlet brass valve for the pressurization. For safety reason, the samples were not pressurized during the impact tests; a low overpressure was anyway present (approximately 2 bar) in order to keep the proper sample's shape.

The vessels presented a height of 460 mm (including the main valve), maximum diameter of 300 mm (measured in the central section) and a engineering/nominal thickness varying from 1.3 mm to 3.4 mm (central and dome section respectively). More details about the layup orientations in the different sections of the vessel are reported in the following sections.

2.2. Material properties

The vessels were made of three distinct parts: the internal liner, the external composite shell and the main valve. In order to proper simulate the impact events, the material properties of the different parts were required.

The properties of the internal liner and the valve were provided by the material supplier and reported in Table 1. The properties of the composite were instead measured for the specific material/production process by means of a full campaign of experimental tests. Split disk [23] and biaxial [24–26] tests were carried out in order to evaluate the material moduli and strengths. The results of the material characterization are reported in Table 1.

Currently, no test techniques are available for the evaluation of the critical fracture toughness energies (G_{Ic}, G_{IIc} and G_{IIIc}), fundamental for the evaluation of the interlaminar damage (delamination). A first attempt to evaluate these values was carried out by the author and reported in [27]. The curved double cantilever beam test technique used in [27] was not usable in the present work for the specific material. The data used here (reported in Table 1) were defined using data evaluated on similar material previously characterized.

2.3. Experimental impact tests

Following the general suggestion of the EN 14427 [2] standard, two different configurations were defined for the impact tests.

- *Central section*: the impact position was located in the cylindrical section of the vessel (more details in Fig. 1). This section is characterized by the presence of both helical and hoop layers.

Table 1
Material properties.

Properties	Value
Composite properties	
Fibre volume fraction	45.7%
Density	1230 kg/m^3
Elastic properties	$E_1 = 61.54$ GPa; $E_2 = E_3$[a] $= 13.93$ GPa; $G_{12} = G_{13}$[a] $= G_{23}$[a] $= 1.43$ GPa; $\nu_{12} = \nu_{13}$[a] $= 0.30$; ν_{23}[a] $= 0.5$;
Strength (MPa)[b]	$X_t = 837$; $X_c = 414$; $Y_t = Z_t$[a] $= 25.8$; $Y_c = Z_c$[a] $= 100.2$; $S_{12} = S_{13}$[a] $= S_{23}$[a] $= 44.24$;
Interlaminar properties:	
Elastic properties[c]	$K_{nn} = 13.93$ GPa; $K_{ss} = K_{tt} = 1.43$ GPa
Strength[c] (MPa)	$t_n = 25.8$; $t_s = t_t = 44.24$;
Fracture toughness[d] (N/mm)	$G_{Ic} = 0.83$; $G_{IIc} = G_{IIIc} = 3.15$
Mode interaction[c] – BK	$\eta = 1.40$
Liner properties:	
Density	1230 kg/m^3
Elastic properties	$E = 3.5$ GPa; $\nu_{12} = 0.30$;
Valve properties:	
Density	1230 kg/m^3
Elastic properties	$E = 7$ GPa; $\nu_{12} = 0.30$

[a] Assumed.

[b] Note: *X* is the fibre direction, *Y* is the matrix direction, *t* is for tension and *c* for compression; *S*12 is for shear.

[c] See section "Interlaminar damage model" for more detail.

[d] Data from similar material (E-Glass/Epoxy produced by filament winding) from [39].