Composite Structures 185 (2018) 573–583

Contents lists available at ScienceDirect

Composite Structures

journal homepage: www.elsevier.com/locate/compstruct

Stochastic prediction of burst pressure in composite pressure vessels

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ARTICLE INFO

Keywords:
Composites
Pressure vessels
Theoretical modeling
Finite element analysis
Stochastic analysis
Progressive damage modeling

ABSTRACT

The main objective of this research is to predict burst pressure of composite pressure vessels subjected to internal pressure taking into account manufacturing uncertainties. Firstly, first-ply-failure (FPF) of composite pressure vessels with/without liner is studied comparing performance of different failure criteria. Then, burst pressure of the vessels are deterministically predicted using progressive damage modeling based on continuum damage mechanics approach. Both theoretical modeling approaches on predicting FPF and burst pressure are validated using available experimental data. Finally, stochastic modeling is conducted to estimate burst pressure of composite pressure vessels taking into account fiber volume fraction, winding angle and mechanical and strength properties as random parameters resembling manufacturing-induced inconsistencies. Statistical data analysis shows the importance of taking into consideration manufacturing variability.

1. Introduction

Inspired by the technological development in military section, composite pressure vessels are adapted for a widespread applications in civil sector. Exhibiting outstanding properties such as high strength/stiffness-to-weight ratio, remarkable fatigue endurance and excellent durability against corrosion have also expanded their commercial market from aerospace and aviation industries to automotive, medical and sport segments. Moreover, the design customization feature of composite structures accomplished by modifying ply orientation and sequence have enabled engineers to design and manufacture suitable composite vessels for various missions.

The technological evolution of pressure vessels for holding liquids and gases under pressure has advanced through the five generations so far. Type I is a full metallic pressure vessel suffering from high weight and low resistance against fatigue in comparison with other types. Type II and type III are composite overwrapped pressure vessels (COPV) with metallic liner. In the former, the cylindrical section of the liner is just overwrapped with composite in the hoop direction while in the later the liner is fully overwrapped with composite. Known as a full composite pressure vessel, a polymeric liner is fully overwrapped with composites in type IV. In types II, III and IV, liners play the role of barrier between the internal fluid and composite layers preventing leakage through the micro-cracks in matrix and ensuring gas permeability through the wall-thickness of the vessels in high pressures. The overwrapped composites provides required stiffness/strength as structural components. Most recently, an innovative liner-less pressure vessel has been introduced as type V for spacecraft applications wherein nano-particles are incorporated into the matrix system [1].

The growing interest and in fact the worldwide demand for reducing emissions and global warming has promoted compressed natural gas (CNG) and hydrogen fuelled vehicles in automotive industries. Consequently, a huge potential has been recently emerged for the high pressure storage of CNG and hydrogen in filament wound composite pressure vessels as the key requirement of these fuel systems. Particularly, automotive and aerospace industries are in need of lighter COPVs to increase the payload and the distance travelled by vehicles without refueling. Furthermore, the higher levels of weight reduction are achieved relying on the design optimization process and thus the cheaper COPVs can be fabricated from economical point of view.

Weight consideration of COPVs is mainly governed by the failure pressure as one of the most important design factors. Defining the load-carrying capacity, the burst pressure of COPVs is of great importance from reliability perspective. Consequently, accurate simulation of damage progress and prediction of ultimate strength are fundamental steps to achieve the safe and cost-effective design of COPVs.

The early attempts for investigating failure of composite pressure vessels were limited to predicting the first-ply-failure pressure using different failure criteria suitable for composite materials [2–6]. Some recent studies concentrated on predicting the burst pressure of composite vessels based on either experimental study or computational modeling techniques [7–17]. A nonlinear FE analysis was conducted by Sun et al. [7] to estimate the burst pressure based on maximum stress failure criterion and a stiffness degradation model. Onder et al. [8] have

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https://doi.org/10.1016/j.compstruct.2017.11.068
Received 2 October 2017; Received in revised form 2 November 2017; Accepted 24 November 2017
Available online 26 November 2017
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performed experimental measurement and theoretical modeling to study the effect of temperature and winding angle on the burst pressure of composite vessels. The stiffness were degraded constantly independently from the damage variables in their study [8]. Liu and Zheng [9] proposed an energy-based stiffness degradation method to evaluate the progressive failure properties. The progressive failure analysis was conducted using a nonlinear 3D FE analysis [9]. The predicted results were compared with experimental data [9]. In another research [10], the same researchers have proposed an universal algorithm on the basis of last-ply failure criterion to evaluate the damage evolution and the burst strength of composite pressure vessels. Elastic-plastic stress analysis of the aluminum liner and elastic stress analysis of the composite laminate were performed [10]. Xu et al. [11] conducted a comparison study on the influence of different failure criteria on predicting initiation of failure in composite vessels using 3D FE model and the results were compared with experimental data. They have concluded that the most accurate failure prediction is achieved when Tsai-Wu failure criterion is used for identifying failure initiation. They have considered the sudden degradation of mechanical properties after occurrence of failure in each layer [11].

Prediction of the burst pressure in composite pressure vessel is necessarily in need of progressive damage modeling capturing damage evolution in laminated composites. Increasing the internal pressure in composite vessels, matrix cracking preliminary appears. As the pressure increases, matrix cracking continues and interface debonding happens progressively. Burst pressure in composite pressure vessels implies on a specific level of pressure where large number of fiber breakage occurs. Wang et al. [12] have integrated material property degradation method and cohesive elements in commercial FE package to predict ultimate load-bearing ability of composite vessels addressing intralaminar and interlaminar failure modes. Progressive damage modeling was done by Leh et al. [13] using commercial FE package and two FE models. One model contains only solid elements and the other is a mixed of solid and shell elements for liner and composite layers, respectively. Ramirez et al. have conducted a series of investigation on type IV high pressure composite pressure vessels for hydrogen storage application [14–16]. A continuum damage mechanical model was proposed taking into account different damage modes [14]. The developed model was employed to simulate the behavior of notched filament wound composite structures and a comparison with experimental observation revealed the capability of model in recognizing various damage modes [15]. Incorporating developed damage model into commercial FE model, the burst test was simulated using 3D and axisymmetric elements in order to compare the advantages of each FE model [16]. Gentilleau et al. [17] have developed a probabilistic damage behavior law for composite materials used in fabrication of pressure vessels taking into account both fiber strength and volume fraction variability based on the previously developed thermo-mechanical model [18]. Rabczuk and his coworkers have done series of investigations dealing with the burst failure of structures which also accounts for fluid-structure interaction [19–22].

The main objective of this research is to estimate the burst pressure of filament wound composite pressure vessel taking into account the inconsistencies associated with production process. Namely, random volume fraction, winding angle and mechanical properties are taken into account and thus stochastic modeling is conducted. As it can be seen from literature survey [23], no attempt has been done to investigate the influence of production inconsistencies on the burst pressure of filament wound pressure vessels.

2. Problem statement

From practical point of view, fiber volume fractions and winding angles cannot be accurately fixed on design values during the filament winding process. Therefore, it is important to study the degree to which the aforementioned uncertainties can affect expected burst pressure of COPVs. The mechanical properties of constructing plies are truly influenced by variations of fiber volume fractions. Moreover, the fluctuation of fiber winding angle can significantly affect the structural properties of COPVs and their mechanical performance. These two parameters are considered as the most dominant influential design parameters. Therefore, in this study the burst pressure of COPVs are stochastically determined.

At the first stage, first-ply-failure (FPF) of both liner-less composite pressure vessels and COPV with liner are estimated using deterministic technique. Implying on the burst pressure, the associated pressure with last-ply-failure (LPF) of both vessels are predicted using progressive damage modeling afterward. Developed modeling procedure is validated using available experimental data in literature. After establishing the confidence toward appropriate modeling procedure for estimating burst pressure, stochastic implementation of modeling is accomplished treating fiber volume fraction, winding angle and consequently mechanical and strength properties as random variables.

3. Stress analysis

Prior to predicting FPL, stress analysis is conducted to obtained in-plane stress components. Finite Element (FE) analysis is performed for this purpose using Abaqus commercial FE package [24]. For modeling the liner-less composite pressure vessel, conventional shell elements (S4R) is employed. For COPV with liner, cubic solid element (C3D8R) is used for constructing liner and conventional shell element (S4R) is employed for constructing overwrapped composite layers on the liner. For this model, the reference surface is defined as the top surface of solid elements and node-offset feature for shell element is adjusted to the bottom of shell elements while the normal direction of them are defined outward. Consequently, the top surface of liner coincides with the bottom surface of FRP layers. A local spherical coordinate is also defined for both end caps and the tangential vector defining fiber direction is placed along circumferential direction. The size of elements are chosen sufficiently small to avoid any dependency of the results to the mesh density.

Isotropic behavior is considered for the liner and composite layers are treated as a transversely-isotropic material.

Internal hydrostatic pressure is uniformly applied on the inner surface of the model and a nipple node on one of the caps is restricted from any movements and rotations avoiding rigid body motion.

The obtained in-plane stress components are compared with analytical solution using simple Classical Lamination Theory (CLT) [25]. Implementing CLT for a liner-less composite vessel is a straight-forward task. For the COPV with liner, stress portioning needs to be accomplished for extracting the induced stress in liner and composite layers, separately. Equilibrium equation on the wall thickness of COPV with liner in cylindrical section is expressed as:

$$\sigma_h \cdot t = \sigma_h^{liner} \cdot t_{liner} + \sigma_h^{FRP} t_{FRP} \tag{1}$$

where t, t_{liner} and t_{FRP} stand for the total thickness of pressure vessel, liner thickness and the thickness of Fiber Reinforced Plastic (FRP) layers, respectively. subscript “h” denotes hoop direction. Induced hoop stress from internal pressure can be also obtained with a very good level of accuracy using simple below formulation:

$$\sigma_h = \frac{pr}{t} \tag{2}$$

where p and r imply on internal pressure and the radius of vessel, respectively.

Assuming perfect bonding condition between FRP layers and internal layer, following equation is governed as compatibility equation:

$$\varepsilon_h = \varepsilon_h^{Liner} = \varepsilon_h^{FRP} \Rightarrow \frac{\sigma_h^{liner}}{E_{liner}} = \frac{\sigma_h^{FRP}}{E_{FRP}|_h} \tag{3}$$

where E_{liner} and $E_{FRP}|_h$ show Young's modulus of the liner and apparent

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