INTERNATIONAL JOURNAL OF HYDROGEN ENERGY 47 (2022) 38862–38883

Available online at www.sciencedirect.com

ScienceDirect

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

Review on optimization design, failure analysis and non-destructive testing of composite hydrogen storage vessel

Wei Zhou [a,b,c,*], Jie Wang [a,b,c], Zhi-bo Pan [a,b,c], Jia Liu [a,b,c,**], Lian-hua Ma [a,b,c,***], Jia-yi Zhou [a,b,c], Yi-fan Su [a,b,c]

[a] Non-destructive Testing Laboratory, School of Quality and Technical Supervision, Hebei University, Baoding 071002, China

[b] National&Local Joint Engineering Research Center of Metrology Instrument and System, Hebei University, Baoding 071002, China

[c] Hebei Key Laboratory of Energy Metering and Safety Testing Technology, Hebei University, Baoding 071002, China

HIGHLIGHTS

- Composite hydrogen storage vessels of type III and type IV are compared.
- Reviewed the optimized design in the cylinder, dome and liner of composite vessels.
- Summarized burst failure, fatigue failure, and impact failure of composite vessels.
- Damage assessment by various non-destructive testing techniques.

ARTICLE INFO

Article history:
Received 6 June 2022
Received in revised form
24 August 2022
Accepted 3 September 2022
Available online 24 September 2022

Keywords:
Composite hydrogen storage vessel
Optimization design
Failure analysis
Non-destructive testing
Detection and evaluation

ABSTRACT

Composite hydrogen storage vessels have been increasingly applied to hydrogen fuel cell vehicles. This review focuses on optimization design, failure analysis and nondestructive testing for enhancing the safety of composites hydrogen storage vessels in service. The optimization designs of the composite vessel components help to improve the durability and strength of composite vessels subjected to burst pressure and fatigue loads. In complex service environments, composite vessels may suffer from various failure forms (burst failure, fatigue failure and impact failure) which involve different damage processes and influence factors. More importantly, this review discusses the applications of acoustic emission, digital image correlation, optical fiber in studying the residual performance (burst pressure and fatigue life) and damage modes of the composite vessel. It is expected that the combination of nondestructive testing techniques plays an increasingly important role in developing the composite vessel for structural health monitoring.

* *Corresponding author*. Non-destructive Testing Laboratory, School of Quality and Technical Supervision, Hebei University, Baoding 071002, China.

** *Corresponding author*. National&Local Joint Engineering Research Center of Metrology Instrument and System, Hebei University, Baoding 071002, China.

*** *Corresponding author*. Hebei Key Laboratory of Energy Metering and Safety Testing Technology, Hebei University, Baoding 071002, China.

E-mail addresses: zhouwei@hbu.edu.cn (W. Zhou), liujia@hbu.edu.cn (J. Liu), lhma@hbu.edu.cn (L.-h. Ma).

https://doi.org/10.1016/j.ijhydene.2022.09.028

Contents

Introduction

Hydrogen is emerging as an important renewable and sustainable energy because of its advantages such as zero-emission characteristics, high-energy conversion rate and infinite source. However, hydrogen storage technology has always been a key problem in the energy wide utilization process [1,2]. There are several hydrogen storage ways including high-pressure storage vessels, liquid hydrogen tanks, metal hydrides and chemical hydrogen storage [3]. High-pressure hydrogen storage is the mainstream method that requires a compromise between technical performance and cost competitiveness [4,5]. To consider the targeted weight efficiency for on-board storage in vehicles (about 4.8 wt %), the working pressure needs to be raised to 70 MPa [6,7]. This can be achieved by using a Composite Overwrapped Pressure Vessel (COPV) of Type III or IV [3,4,8]. The typical structure of Type III and IV composite pressure vessels is shown in Fig. 1. For such vessels, the fiber reinforced composites are mainly used as protective shells to resist internal loads, and the liners provide barriers between the gas and the composite, preventing leakages. Type III composite vessels have higher strength and superior sealability. Type IV composite vessels are equipped with polymer liners, which have the advantages of lightweight and resistance to damage from liner collapse. The main characteristics and failure modes of two types of pressure vessels are shown in Table 1.

Due to the complex structure of composite vessels, various manufacturing processes and design structures can significantly influence the mechanical properties [11,12]. Therefore, it is necessary to put forward some methods to improve the pressure resistance of composite hydrogen storage pressure vessel. Over the past decades, many researchers have systematically studied the optimization of composite shells and liner to reduce weight and cost while enhancing reliability and safety for a variety of applications [13–15]. The optimization for the concerned components of composite hydrogen storage pressure vessel is shown in Fig. 2. The optimal design of the composite layer can improve the quality of the laminate and the bursting pressure of the pressure vessel [16]. With the liner optimization, the accumulation of composite thickness can be reduced at the dome, and thus the economic efficiency is improved.

Compared to traditional pressure vessels, the damage modes of composite vessels are more complex. From the point

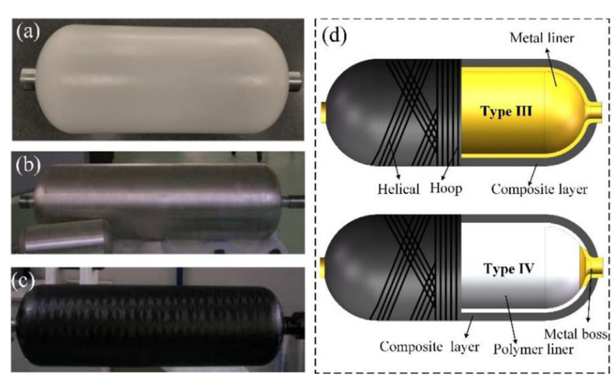

Fig. 1 – (a) Polymer liner [9], (b) metal liner, (c) the hydrogen vessel obtained by filament winding process [10], (d) typical structures of type III and IV composite vessels.

Table 1 – The comparisons between types III and IV composite vessels.

Type	Components	Advantage	Disadvantage	Failure
III	Metallic liner	High strength; Reliable sealing	Perishable; Heavyweight	Hydrogen embrittlement; Premature failure for fatigue
	Full composite over-wrap	_	_	Fiber breaks; Delamination; Matrix cracking
IV	Polymer liner	Lightweight	Thermolabile	Leakage; Collapse
	Full composite over-wrap	_	_	Fiber breaks; Delamination; Matrix cracking

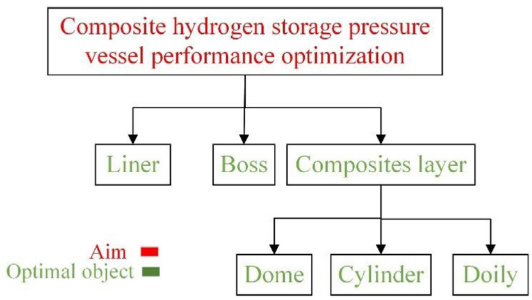

Fig. 2 – The optimization of typical components of the composite hydrogen storage pressure vessel.

view of the microscale level, the damage mechanisms of composite materials include fiber breakage, matrix cracking and fiber/matrix interface debonding [17–19]. Therefore, the identification damage evolutions and the prediction of burst pressure provide the basis of the structural optimization design of composite hydrogen storage cylinder. It is urgent to study the failure behavior of the composite hydrogen storage vessel for realizing the safe and economic design of such equipment [15,20]. Generally, the finite element analysis (FEA) is employed for the investigation of mechanical properties, failure modes and structural optimization on account of its strong design function and ability of reliable simulation [21–24]. The bursting pressure evaluation and remaining life prediction are two key problems in the failure analysis of the composite vessels. In addition, the damage analysis by developing multi-scale thermodynamic model under pressurization and heat source was systematically studied by considering the effect of thermo-mechanical pressure [25,26].

From the experimental point of view, some researchers used Non-destructive testing (NDT) technology to perform damage detection and performance evaluation of the composite hydrogen storage vessels. The NDT techniques can be used to detect damages of composite vessels in multiple aspects based on the characteristics and advantages of different detection methods. Specifically: (1) NDT technologies can be used to identify and locate defects and to assess the quality of the newly produced composite vessel. (2) Residual properties of composite vessels can be well tested using NDT technologies. (3) A combination of multiple NDT techniques was used to monitor the real-time damage state for structural health monitoring (SHM) of composite vessels.

In this review, typical methods for optimization design, failure analysis and non-destructive testing of high-pressure hydrogen storage vessels were summarized, and the application of the FEA and NDT technologies for predicting service life and revealing damage mechanisms were discussed.

Optimization design of composite hydrogen storage vessel

Optimization of composites layer

The composite layer design is one of the main factors that directly influence the bearing pressure and fatigue performances of composite hydrogen storage vessels. Consequently, many scholars have investigated and designed the composite layer to reduce the cost and weight of composite vessels while increasing the burst pressure and fatigue life. As shown in Fig. 3, many optimization studies for cylinder, dome and doily have been conducted [27–29]. The optimal design of such components is the challenge and focus to improve the performance of composite hydrogen storage pressure vessels [30]. The investigations on the structural design of typical components of the composite vessel are mainly discussed in the section.

Cylinder

In the fiber winding process, layer thickness [31,32], winding angle [33], layup sequence [34] and fiber winding technology [35,36] are considered to be design factors that have significant effects on the performance of the composite hydrogen storage vessel fiber layer as shown in Fig. 3. These key parameters determine the mechanical property of the composite vessels under internal pressure [37]. Therefore, many optimization designs have been carried out for the composite layer of the vessel [38,39]. Specifically, the structural optimizations of

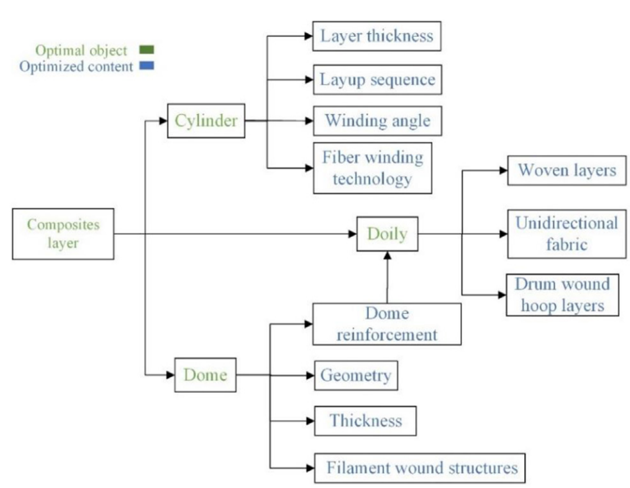

Fig. 3 – Three optimization focuses of the composite layer of the composite hydrogen storage vessel: cylinder, doily and dome.

cylindrical shell portion and the corresponding effects are summarized as shown in Table 2. Lin et al. [40] combined the simplified conjugate gradient method (SCGM) and a genetic algorithm (GA) with the FEA method to design the optimum winding angle and thickness in order to achieve minimal stress concentration. Nguyen et al. [41] studied the influences of winding angle of helical layer on damage evolution and burst pressure of composite vessels by developing a predictive modeling tool for damage analysis and structure design. It is found that the appropriate fiber direction can greatly reduce the early matrix cracking of cylindrical shells. Chapelle et al. [42] analyzed the effects of various winding angles and liner thicknesses on burst pressure considering the thermal gap and the residual stresses during the manufacturing process. The results show that the optimal winding angle increases with the increase of liner thickness. Wu et al. [43] accurately analyzed the effect of layup thickness, layup sequence and winding angle of the composite layers on the fatigue life of high-pressure hydrogen storage vessel by FEA with the consideration of the effects of design factors and autofrettage pressure. Generally, the optimization effect of winding angle and thickness is examined by evaluating the burst pressure and fatigue life of composite vessel.

In addition, the appropriate fiber winding angle and laminate thickness can be determined by optimizing the layup sequence, which is of great significance for reducing manufacturing difficulty and improving structural efficiency [44]. Nebe et al. [16] analyzed the influences of layup sequences (high angle layers and low angle layers) on structural surface deformation and burst pressure of composite pressure vessels. It is found that there is a 67% difference in burst pressure of composite vessels with different layup sequences. Subsequently, the effect of circumferential ply drop locations on burst pressure was investigated to improve the performance of composite vessels [45]. Hu et al. [34] analyzed the effect of different layup designs on burst pressure by establishing finite element models of composite components with 12 different layup sequences based on netting theory. The results showed that the various layup sequence accounted for 15% of the influence on burst pressure. Mian et al. [46] elucidated the optimization of layup sequences for composite pressure vessels by FEA. The optimal effect was reflected in the layup sequences $[\pm\theta]_{ns}$ which reduce weight of composite vessels and improve the failure strengths. Ellul et al. [47] optimized the layup sequence of two different types of cylindrical composite laminate through the Big Bang-Big Crunch (BB-BC) algorithm. It is found that the BB-BC algorithm is an effective tool for the optimization of layup sequences of the composite shell. It is clear from the above that the geometrical parameters (layer thickness, wounding angle and the layup sequence) will significantly influence the burst, fatigue and mechanical properties of composite vessels in various ways.

Besides, fiber winding technology has a significant effect on the mechanical properties and bearing pressure performance of composite pressure vessels due to the different filament winding technology and parameters [48,49]. Zheng et al. [50] analyzed the stress distribution of the thick cylinder under internal pressure and optimized the winding technology of composite vessels by adjusting the fibers' pretension. Lasn et al. [51] discussed the relationship among the microstructure, mechanical properties and filament winding process by considering the winding speed and thickness. Based on the winding process and cured residual stress, Liu et al. [52] proposed an optimization model to obtain a better bearing capacity of composite vessels to achieve the optimal fiber winding angle and tension. Therefore, the combination of appropriate winding speed and tension can greatly improve the bearing pressure of composite vessels by the optimized fiber winding technology.

It is summarized that inappropriate values of key design factors, such as layer thickness, wounding angle, the layup sequence and fiber winding technology will reduce the burst pressure and fatigue life of composite vessels, and that reduces the durability and strength. It is important to choose the most suitable design parameters for the composite cylinder to improve the pressure bearing performance and service life of composite pressure vessels.

Dome

Due to the simple shape of the cylindrical part, the winding angle and composite layer thickness can be readily available. On the dome, impregnated bundles of fibers are wound along the meridian line. Therefore, the winding angle and thickness in the different dome position are not easily accessible, which leads to some difficulties in structural optimization and performance prediction. It is well accepted that the performance of the dome is mainly affected by the filament wound structures, dome reinforcement, geometry and thickness [53,54]. The optimization parameters concerning these four aspects of such composite vessel dome are summarized in Table 3.

As for filament wound structures of the dome, some scholars have done work on fiber path predictions and structural analyses [55,56]. The main purpose is to reduce the weight of the composite vessels while increasing the pressure bearing capacity. Alcántar et al. [57] applied two optimization methodologies (genetic algorithms and simulated annealing) in finite element analysis to achieve light weight and high stiffness. Liu et al. [58] proposed an artificial immune system (AIS) for the optimal design for the purpose to minimize the weight of Type III vessels. Compared to genetic algorithm and simulated annealing, the AIS method exhibits more excellent optimization efficiency and accuracy. Zu et al. [59,60] analyzed the shapes and fiber path trajectories of composite pressure vessels based on non-geodesic trajectories using nonconstant slippage coefficients. Zhou et al. [61] studied the optimal structure of dome components based on the geodesic winding and non-geometric winding methods. It was found that in comparison with the geodesic winding, the optimized dome components by the non-geometric winding have an appropriate shape factor. They applied related algorithms to optimize filament wound structures of composite vessels, in order to improve the mechanical properties of the dome and minimize the weight.

In addition, the dome reinforcement (DR) [62] and insertion of a doily layer may be optimized to enhance the dome strength and improve the burst pressure and fatigue life performances of composite vessels. Hu et al. [63] applied DR technology to optimize the weight of the composites layer and

Table 2 – Optimization of the cylinder and corresponding effects.

Analysis methods	Material of liner	Material of composite layer	Optimization parameters of Cylinder	Main conclusions	References
FEA (Burst pressure)	Aluminum	Glass/Epoxy and Carbon/Epoxy	Winding angle	The optimal winding angle grows from 55° to 65 °as liner thickness increases.	[42]
FEA	Aluminum alloy	Carbon fiber resin composite	Fiber winding technology (fibers pretension)	–	[50]
FEA and experiment	–	Carbon/epoxy	Winding angle	Fibers oriented at 50° exhibited less shear failure in the coupons.	[33]
FEA	–	S-glass/epoxy, Kevlar/epoxy and Carbon/epoxy.	layup sequences	Angle-ply [±54] ns layup sequences is more effective in reducing the weight of the pressure vessel.	[46]
FEA	Aluminum	Carbon fiber/epoxy	Winding angle and layer thickness	The best combination of winding angle and layer thickness is 36.54° and 1.6 mm respectively.	[40]
FEA (Burst pressure)	–	Graphite/epoxy	Layer thickness	The damage to the cylinder is mainly caused by the tensile stress in the circumferential direction.	[31]
FEA	–	Chopped strand mat and direct roving	Layup sequence	The Big Bang-Big Crunch algorithm can effectively optimize the layup sequence of composite vessels.	[47]
FEA	Aluminum alloy	Carbon/epoxy	Fiber winding technology (residual stresses)	The thickness and material of composite layers greatly influence the optimal winding angle and tensions.	[52]
Experiment	Polyamide 6	Carbon/epoxy	Layup sequence	The stacking sequence can have a significant effect on surface deformation and burst pressure.	[16]
FEA	Aluminum alloy	Carbon/epoxy	Fiber winding technology	The thickness accumulation on the dome was reduced base on the mandrel-profile-updated method.	[35]
FEA	–	Carbon fiber	Layer thickness	–	[32]
Experiment	–	Carbon/epoxy	Fiber winding technology	The void content is a useful assessment indicator for various impregnation methods	[51]
FEA and experiment	Plastic	Carbon/epoxy	Layup sequence	The layup sequence affects up to 15% of the burst pressure.	[34]
FEA	Steel	Carbon fiber/epoxy	Winding angle	The winding angle plays an important role in matrix crack development.	[41]
FEA and experiment	Aluminum	Carbon/epoxy	Winding angle and layer thickness	A fatigue prediction method is proposed to optimize the design parameters	[43]

Table 3 – Optimization of the dome and corresponding effects.

Analysis methods	Material of liner	Material of composite layer	Optimization parameters of the dome	Main conclusions	References
FEA	Nonmetallic	–	Filament wound structures and geometry	The nine-degree winding angle produces better mechanical properties for geodesic heads.	[66]
FEA	Aluminum	Carbon fiber/epoxy	Filament wound structures	–	[58]
FEA	–	–	Thickness	The thickness of the dome can be effectively predicted using the cubic spline function.	[65]
FEA	High-density polyethylene	Carbon fiber	Dome reinforcement	The stress near the open end of the vessel is reduced using the doily.	[73]
FEA	High-density polyethylene	Carbon/Epoxy	Dome reinforcement	–	[62]
FEA	–	–	Geometry	The domes of higher shape factor and lightweight were obtained.	[71]
FEA	–	Carbon/Epoxy	Filament wound structures	The structural performance of the dome was improved using non-geodesics.	[59]
FEA	High-density polyethylene	Carbon fiber	Filament wound structures	Both genetic algorithm and simulated annealing can demonstrate similar optimal solutions for model optimization.	[57]
FEA	–	Carbon/epoxy	Filament wound structures	Compared to the geodesic winding pattern, the non-geodesic winding can achieve better performance.	[61]
Experiment	–	Glass fiber reinforced plastic	Geometry	The geometry of hemispherical pressure vessels exhibits the best impact resistance.	[72]
FEA and Experiment	Aluminum	Carbon fiber/epoxy	Filament wound structures	–	[60]
FEA	Polyethylene	Carbon/epoxy	Thickness	–	[68]
FEA	Aluminum	–	Thickness	The composite thickness at the port can be reduced by the proposed thickness prediction method.	[67]
FEA and Experiment	Nylon	Carbon fiber	Dome reinforcement	DR technology can help reduce the use of carbon fiber by nearly 5.5%.	[63]
FEA and Experiment	Aluminum	Carbon/epoxy	Dome reinforcement	Adding the carbon woven layers to the doily layer can improve the burst pressure.	[64]

to increase the burst pressure of composite vessels by FEA. Kartav et al. [64] used both numerical and experimental methods to examine the influences of doily layers on the failure mode and burst pressure performance of composite vessels. Their study found that the integration of the carbon woven layers into the doily layers during the wound process can improve the burst pressure of composite vessels. Roh et al. [39] determined the optimal dome shape of composite vessels by constructing FE model and examined the effects of the reinforcing doily on the stress distributions in the composite. Furthermore, an integral end cap is designed to strengthen the dome section and reduce stress concentration in the dome. The stress distribution and burst damage under the internal pressure of the composite vessel were analyzed using the FEA, and the weak positions of the composite vessel were analyzed. The composite layer of composite vessels can be optimized by dome reinforcement technology during the wound process. This is a promising and meaningful method to increase the burst pressure and reduce the cost of composite vessels.

From the previous studies, the dome thickness and geometry have an important influence on the mechanical properties of composite vessels. Many optimization works for the dome thickness [65] and geometry [66] have been reported. Chen et al. [67] precisely estimated rapidly altering the thickness of dome at composites layer for Type III composite vessels. The feasibility of the dome thickness prediction method was verified by analyzing stress distribution and damage behavior of composite pressure vessels. Zhang et al. [68] accurately predicted the thickness of dome for a 70 MPa type IV composite vessels by a cubic spline function. Accurate prediction of dome thickness is an urgent requirement for dome thickness optimization and failure analysis. By considering the blocking effect of cylinder dome ports on sliding fibers, Wang et al. [69] proposed a method for predicting dome thickness with higher prediction accuracy by introducing thickness correlation. Furthermore, the dome geometry also plays an important role in the optimization design. This is due to the fact that the dome part bears the highest stress under internal pressure and the dome is the key location to preventing structural failure [70]. Paknahad et al. [71] investigated the optimum design of dome geometry for composite vessels to obtain the dome with higher shape factor using the inertia weight particle swarm algorithm (IPSO) optimization technique. Furthermore, the algorithm can be optimized by considering the effects of fatigue damage and thermal stresses. Sharifi et al. [72] analyzed the influences of hemispherical, torispherical, and ellipsoidal domes on damage intensity and failure modes under low-velocity impact. The results showed that the hemispherical dome has the best impact resistance.

Due to the fact that the winding angle and thickness of the dome section are not constant, the most problematic aspect of dome optimization is the accumulation of fiber layers at the dome top. Therefore, the selection of the appropriate geometry and filament wound structures, the control of the composite layer of dome thickness and the addition of the dome reinforcement are effective ways to optimize the dome of the composite layer, which are helpful to enhance the burst pressure and service life of composite vessels.

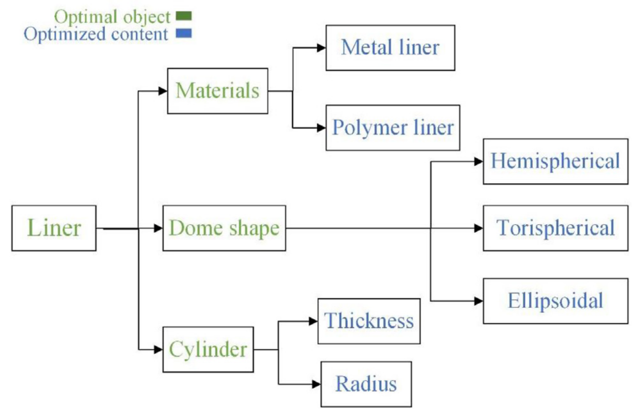

Fig. 4 – The optimization of liner on composite hydrogen storage vessel.

Optimization of liner

The liner is an indispensable part of the composite hydrogen storage vessel, which is generally manufactured with ductile metals (e.g. aluminum) and polymer materials to meet the gas-tight performance and fatigue performance requirements of hydrogen storage pressure vessels. To achieve lightweight and long life of hydrogen storage pressure vessels, some optimization studies have been conducted on liners in terms of materials, dimensions and dome shapes [72,74,75], as shown in Fig. 4.

The combination of metal lining and fiber wound composite layer increases the service pressure of the pressure vessel while maintaining air tightness. However, the studies on the lightweight design and reliability of improved metal liners are very limited. Vafaeesefat [76] proposed an adaptive response surface method by combining a genetic algorithm and response surface method to optimize the thickness and shape of composite vessels with metal liner. It was found that the optimum design of composite vessels with metal liner and a great decrease in computation time can be obtained by the adaptive response surface method. Almeida et al. [77] analyzed the effects of different thicknesses and shapes on the load sharing ability of aluminum and stainless steel liners for composite vessels and obtained stress and strain distributions of all regions of the liner under loading conditions by finite element methods. He et al. [78] proposed a lightweight optimization design method of metal liner based on a shear field theory for a hydrogen storage tank, which can further improve the shear performance and reduce the cost of the hydrogen storage tank.

Polymer liners are also commonly used in hydrogen storage vessel to avoid the hydrogen embrittlement of metal liners. The polymer liner has the characteristics of lightweight and long fatigue life [8]. Therefore, the optimization of polymer liners is also one of the hot topics of research. Park et al. [75] designed the dome shape of polymer liner with isotensoid-spherical curves to prevent slippage of the filaments in the dome area during filament winding, and the structural safety of the optimal dome shape was verified by FEM. Neto et al. [79] studied the failure behavior of LLDPE/HDPE liner (a polymer blend of low linear density polyethylene and high-density polyethylene) under burst pressure by experiments and simulations to optimize and determine the adequate parameters of polymeric liner.

It is well accepted that he polymer liner tends to cause deformation and collapse due to the gases permeating through the polymers [80,81]. Some scholars have investigated the collapse mechanism of the polymer liners, which helps in the optimal design of composite vessels. The collapse mechanism was systematically investigated not only by using the common computational tomography analysis but also by calculating the solvent pressure at the interface between the polymer liner and the composites layer to predict the collapse of the composite vessels [82,83]. Sohn et al. [84] proposed a simulation method to predict the collapse pressure and investigated the damage mechanism of collapse behavior. Pepin et al. [85] studied the key parameters of polymer liner for collapse analysis in hydrogen storage pressure vessels and pointed out that the differential pressure between the inner and outer surfaces of the polymer liner is the main factor resulting in the collapse of the polymer liner.

For the optimization of the metal liners, the thickness and shape are mainly optimized for purpose of the lightweight and high strength design. For the optimization of polymer liners, shape optimization can prevent filaments slippage during the winding process, and the thickness optimization can ensure the air tightness of the composite vessels and prevent the collapse of the liner.

Failure analysis of composite hydrogen storage vessel

Composite vessels suffer from different forms of failure and are eventually failed in complex service environments [86–88]. In what follows the three aspects (burst failure, fatigue failure, and impact failure) of the failure analysis of composite vessels are briefly reviewed. The damage processes and influence factors of various failure forms are shown in Fig. 5.

Burst failure

Composite hydrogen storage vessels have received high attention due to the advantages of lightweight and high strength, however, the complex vessel structure, anisotropic composite materials and progressive failure characteristics jointly lead to the complexity of damage mechanisms of composite vessels [89,90]. Therefore, the research on burst pressure and damage behavior is particularly important for the safe application of composite high-pressure hydrogen storage vessels [91]. Many scholars have conducted related researches through burst experiments. Harada et al. [92] conducted burst pressures tests on composite pressure vessels with different volume fractions of carbon fiber and proposed a burst pressure prediction method considering the irregularity of carbon fiber reinforcement. A full-scale composite vessel burst test is the best way to study the burst pressure and damage behavior, but it entails a rigorous experimental environment and high costs, hence a hoop ring test method with a new reinforcement design is essential to accurately measure the strength of the hoop material and

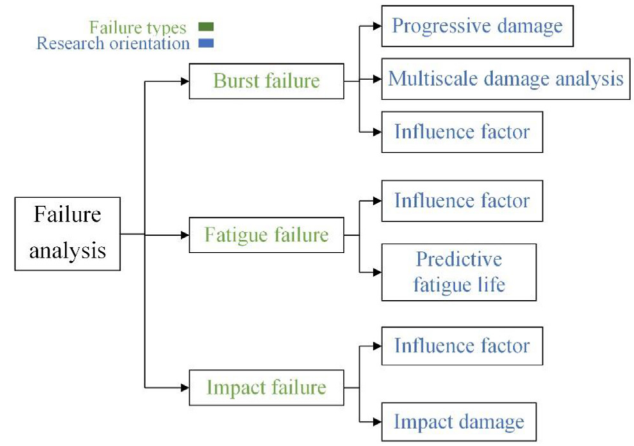

Fig. 5 – Three aspects of failure analysis: burst pressure, fatigue failure and impact failure.

burst pressure of the composite vessels [93]. Kim et al. [94] redesigned a ring burst test device to improve the pressure uniformity of the ring specimens, and the stress variation and failure behavior of ring specimens were evaluated by the digital image correlation (DIC) method during the burst test. In addition, acoustic emission (AE) can also provide a new perspective for evaluating the bursting pressure of composite pressure vessels [95]. Wang et al. [96] investigated the relationship between AE signal characteristics and damage behavior (matrix cracking, fiber/matrix debonding, fiber breakage) of hydrogen storage pressure vessels during hydrostatic burst tests with multi-step loading. The full-scale burst test (or ring burst test) combined with acoustic and optical sensors can be used to obtain the real burst pressure and damage evolution behavior of composite vessels.

The burst failure tests of composite hydrogen storage vessels have exorbitant costs and a long design cycle. The virtual FEA provides an effective approach with high design flexibility to conduct the progressive failure analysis and burst pressure prediction of composite vessels [97,98]. The core elements of the progressive failure analysis by the FEA are the development of constitutive models of the typical materials used in the composite vessels [99], the adoption of the material property degradation method [100–102], the selection of the failure criterion [103,104], the study of the damage evolution [105] and finally the prediction of the burst pressure of composite vessels [106]. The flow chart of the progressive failure analysis is shown in Fig. 6. Progressive failure analysis and burst pressure prediction of composite vessels have been conducted by many scholars using FEA [25,107]. Son et al. [108] analyzed the modeling technology of the composite pressure vessels with three different metal liner, including a laminate-based modeling technique, a hybrid modeling technique and a full ply-based modeling technique. The results show that the full ply-based modeling technique can acquire a more precise stress distribution for the composite vessels. Park et al. [31] investigated accurately the stresses of a thick multilayered composite cylinder by developing a three-dimensional elasticity solution under multiple loading, and the predicted stresses can be used to evaluate the burst pressure by the stress-based failure criterion. Rafiee et al. [109] used a

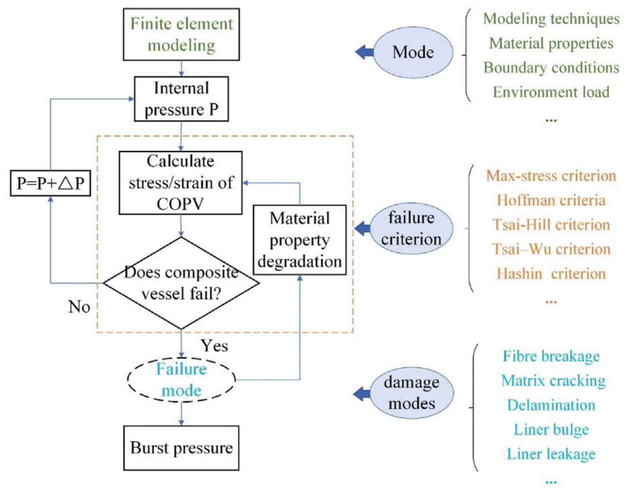

Fig. 6 – The finite element analysis flow chart for the progressive failure of composite vessel.

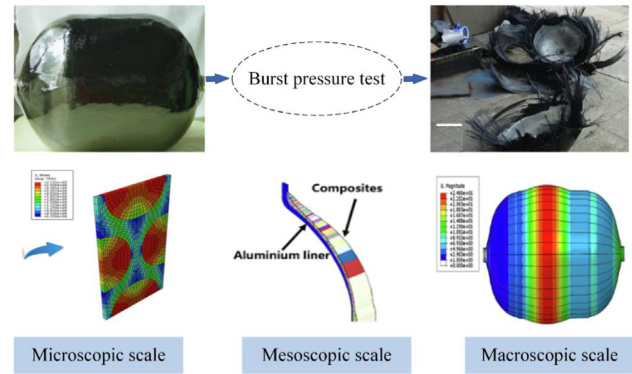

Fig. 7 – The Multi-scale failure analysis of composites vessel [121].

progressive damage model to predict the burst pressure of composite pressure vessels and investigated the effects of the manufacturing uncertainties on the burst strength of the composite pressure vessels by setting random parameters. Therefore, the stress calculation and progressive damage analysis are essential for the burst pressure prediction of the composite vessel. In other words, the burst pressure prediction is the ultimate goal for the progressive damage analysis.

In addition, some scholars have investigated the burst pressure prediction and the complex damage behavior of composite vessels based on the continuum damage models. Liu et al. [110] investigated the failure behavior and burst strength of cylindrical laminate structures of the composite vessels with different sizes (15 L, 74 L, 150 L) by using an explicit FEA based on the continuum damage model. The favorable computational efficiency and superior agreement of the explicit FEA were demonstrated by the comparisons among the explicit FEA, implicit FEA and experimental test. By developing a specific continuum damage mechanical model to simulate the burst behavior of composite vessels, it is possible to predict not only the overall mechanical behavior of composite vessels but also the complex damage modes (fiber breakage, matrix cracking, delamination, etc.) at the mesoscale [111,112]. Wang et al. [113] predicted the burst strength and complex failure behavior of the aluminum-carbon fiber/epoxy composite vessels in the context of continuum damage mechanics. The results showed that the dominant failure modes of the hoop wound layers and spiral wound layers were fiber breakage and matrix cracking, respectively, while delamination failures between the outer composite layers were more serious. Jebeli et al. [114] performed a progressive damage analysis of a Type IV composite pressure vessel by considering the debonding of the composite/liner layer and the variation of fiber thickness and angle in the dome section, and the results pointed out that the initial debonding did not influence the progressive damage process of the composite layer of the cylinder. To sum up, the stress distribution and damage evolution behavior under the internal pressure of composite vessels can be obtained by the progressive damage method, which can adopted to optimize the structure of composites vessel [115]. In the case of damage, matrix cracking and delamination first occur and then a large number of fibers breakages foreshadow the occurrence of the bursting behavior with the increase of internal pressure.

For the composite hydrogen storage vessels, various defects are potentially exist in the fibers and matrix during the manufacturing process, and different failure forms of the fibers and matrix may be produced during the internal pressure loading. Therefore, the stiffness degradation characteristics of composite layers are considered to be macroscopic manifestations of microscopic damage and failure accumulation, which indicates that it is not sufficient to study the macroscopic failure performance of composite structures simply by adopting continuous damage mechanics and composite homogenization theory [116]. Therefore, it is necessary to conduct multi-scale failure analysis for composite vessels by further combining the microscale and meso-scale mechanical properties of the composites [92,117–119]. As shown in Fig. 7, a representative volume element (RVE) was established to investigate the microscopic damage evolution, and a meso-scale model is used to study the progressive failure modes of the composite layers and a macroscopic model is used to predict the burst pressure of the composite pressure vessel. Liu et al. [120] proposed a multiscale damage model for failure analysis and burst pressure prediction of the composite pressure vessels, wherein the stiffness degradation model is used to associate the macroscopic stiffness degradation of composite vessels with the microscopic failure characteristics of the representative volume element. Lin et al. [121] proposed a meso-macro finite element progressive damage model based on the Puck failure criterion that can effectively predict the bursting pressure of the composite pressure vessels and accurately simulate the progressive damage. The results showed that matrix cracking and delamination occurred successively and they are finally expanded to fiber breakage with the increase of internal pressure. Based on the real composite vessels characteristics, multi-scale finite element models can be established by linking microscopic and macroscopic models which can effectively analyze the damage evolution behavior and burst pressure of composite vessels. However, it becomes potentially difficult to obtain all microscopic failure mechanisms through the experimental tests.

In addition, defects, structure, service conditions and other external factors affect the burst pressure of composite pressure vessels during manufacture and service [36,122]. Makinson et al. [123] studied the effects of cuts flaws on composite vessels' burst pressure. Compared with the circumferential flaw, the longitudinal flaw reduced burst performance more significantly. Kangal et al. [124] investigated the effects of interlayer hybridization on the burst pressure of composite pressure vessels and showed that the hybridization of the hoop layer had a positive influence on the radial deformation, while it did not have any significant effects on the burst pressure performance of composite vessels. Chou et al. [125] investigated the effects of pressurization rate on the burst strength of composite pressure vessels and showed that the faster pressurization rate resulted in the higher burst pressure due to the viscoelasticity of the matrix. Blanc-Vannet [126] investigated the effects of impact damage on the burst pressure of composite pressure vessels, by taking the absorbed energy as a measure of the negative effect of impact damage on burst pressure. When the absorbed energy is below the threshold range, the burst pressure did not appear to be a significant reduction. Defect detection and structural optimization can guarantee the excellent and stable mechanical properties of composites vessels. Furthermore, composites vessels may undergo impact, pressurization, heating and other complex environments during the service and filling. The research of the impact of various factors on the burst performance, which is the basis of the damage assessment and safety evaluation of the composite vessels.

Fatigue failure

Composite hydrogen storage pressure vessel is usually subjected to high temperature, cyclic load pressure, aging and other complex environments during the charging and service [127,128]. Therefore, the composite vessels are vulnerable to fatigue damage reducing the safety in service. In addition to focusing on the burst performance of newly produced composites vessels, it is essential to perform fatigue failure analysis on the composite vessels in long-term service. Over the past decades, many scholars have studied the fatigue performance of composites vessels mainly in two aspects: factors affecting fatigue life and fatigue life prediction. Many previous works have mainly focused on the influences of composites layer [43,129], liner [130], damage [131], environment [132,133] and other factors on fatigue life, as shown in Fig. 8. The structural optimization of composite vessels by introducing the influencing factors is for the purpose of improving the service life and reliability of the composite vessels [134].

Furthermore, the fatigue life prediction was investigated by experimental [135] and numerical [116] methods. On the one hand, the fatigue tests were conducted to obtain the service condition and fatigue damage of the composite vessels and then to analyze the residual performance and assess reliability of composite vessels. Zheng et al. [136] studied the thermo-mechanical fatigue property and failure behavior of hydrogen vehicle cylinders by establishing a real hydrogen fatigue test system. The results showed that the ultimate strength of the composite cylinder decreased by 15% after 500 times fatigue tests of the hydrogen charging and discharging. However, the ultimate strength reduction was not significant after the hydraulic fatigue test [137]. On the other hand, fatigue failure of the composite vessel was studied by using FEA. The energy method [138], critical surface method [43], and matrix creep damage method [116] can be employed to predict the fatigue life of composite vessels as shown in Fig. 8. Wang

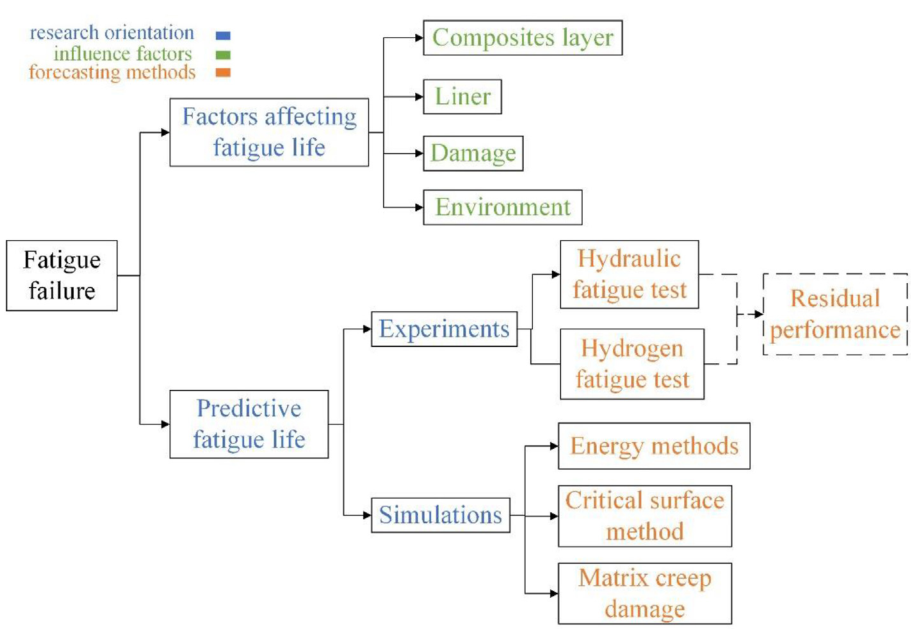

Fig. 8 – Fatigue life prediction method and affecting factors of composite vessels.

et al. [139] proposed the combined micromechanics of failure and time-temperature superposition principle approach to evaluate the fatigue life of composite hydrogen storage vessels under cyclic loading and temperature variation working conditions. Ataabadi et al. [138] performed critical stress analysis and residual strain energy analysis to predict the fatigue life of composite vessels with various materials and the results pointed out the location of the minimum fatigue life and its determinants. During long-term service and repeated filling, the mechanical properties of the composite hydrogen storage vessel are inevitably reduced. Therefore, it is noteworthy and important to explore the fatigue failure of composites vessels undergoing complex service environments based on the failure modes, residual performance and fatigue life prediction.

Impact failure

The composite hydrogen storage vessel may be subjected to low-velocity impacts such as a drop impact and foreign object impact during transportation, dismount and service [140]. The impact damage mechanism of composite vessels in a real environment are complex. Impact energy [141,142], impact position [143], impact temperature [144] and vessel structure [145] will affect the severity of impact damage. Many scholars have studied the influences of different factors on impact damage by experimental test and numerical simulation to achieve the optimized vessel structure and the impact damage mechanism. Furthermore, the residual properties of impact damaged composite vessel were characterized by burst pressure [144–146] and fatigue behavior [147]. The selection of a suitable impact damage characterization method is an important step in assessing the safety level of composite vessels after impact.

Due to the anisotropic characteristics of composite materials, impact loading can cause complex damages in composites vessel, such as matrix cracking, dents, fiber breakage and delamination [148,149]. Impacts result in multiple damage modes such as in-plane and out-of-plane damage of composites vessel are shown in Fig. 9. The simultaneous occurrence of multiple damage modes makes the progressive failure analysis of impact damage very difficult. Some scholars have carried out progressive failure analysis of impact damage by distinguishing in-plane and out-of-plane damage modes [150]. Liao and Perillo et al. [143,145,151] investigated the mechanical properties and failure mechanism of composite vessels under low-velocity impact based on the combination of interlaminar and intralaminar damage models, where Puck and Hashin failure criteria were used for matrix cracking and fiber failure and cohesive zone model was used to evaluate delamination damages. Rafiee et al. [152,153] proposed a theoretical solution for predicting the failure of composite vessels under low-velocity impact. In comparison with finite element results, the theoretical solution is more accurate for predicting the failure of impact damage. Long et al. [154] conducted low velocity impact tests by winding composite pressure vessels. The results show that delamination damage occurs mainly between the wound and hoop layers, and the fiber overlapping area is the weak part of the composite vessel. To summarize, the residual strength of composite vessels can be affected by various damage modes. Slight delamination and matrix cracking do not result in a significant reduction in residual burst performance. At high energy impact levels, the occurrence of fiber breakages in shear bands caused a considerable reduction in residual burst performance [155]. In addition, the numerical simulation for the progressive failure of composites have been carried out by considering low-velocity impacts. The numerical study on the low-velocity impact of composite vessels is still in the development.

Non-destructive testing

To ensure the safety of composites hydrogen storage vessels in service, it is essential to understand the damage mechanism of fiber winding structures and effectively evaluate the structural integrity of composite vessels. Thus, various NDT technologies have been used to detect damage and evaluate residual properties of composite vessels. Thereinto, the AE [156], DIC [157], Optical fiber [158], X-ray radiography [80], Ultrasonic [159], Ultrasonic guided waves [160,161] are generally

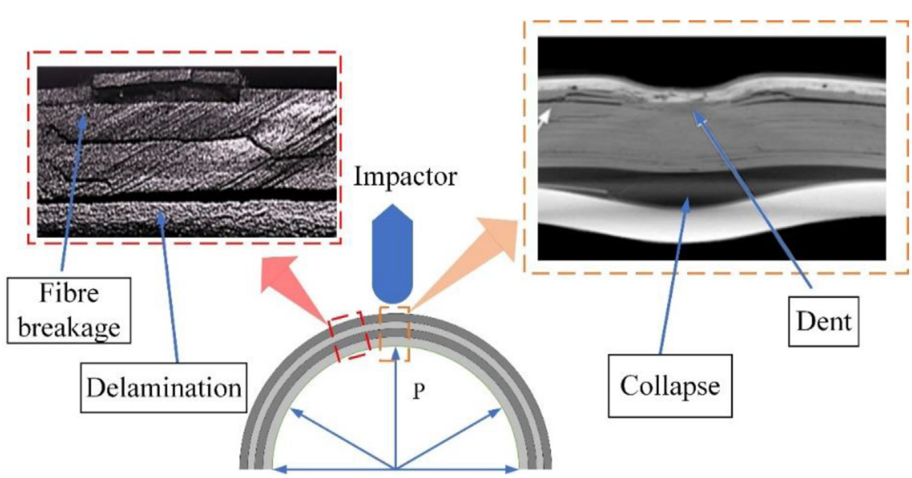

Fig. 9 – Schematic diagram of the failure mode of composite vessels during impact [147,149].

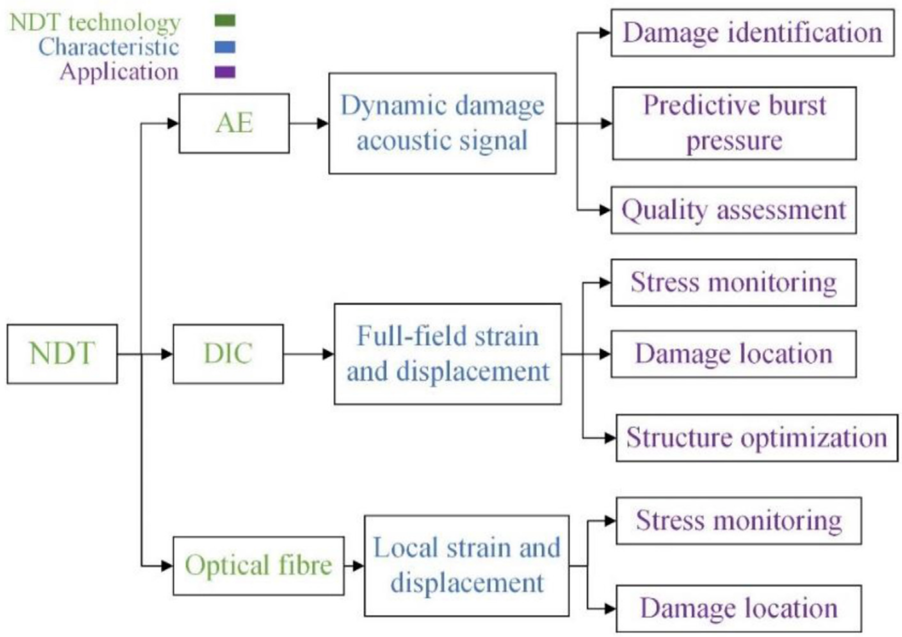

Fig. 10 – The characteristics and application of NDT technology.

used for damage detection and performance evaluation of composites vessel. In this section, the applications of NDT technologies on damage assessment and mechanical property prediction of composite vessels are summarized as shown in Fig. 10. The advantages and functions of three commonly used nondestructive testing methods for safety evaluation of the composite vessel are summarized.

Acoustic emission

The AE technology in the NDT application of filament winding composites is of great significance for detecting transient elastic waves [162–164]. Hence, the quality assessment, damage identification and burst pressure prediction for composite vessels using such technology are constantly reported. Fig. 11 shows the schematic diagram of classical AE detection for composites hydrogen storage vessel. While the acoustic emission technology is used to detect the damage state, the hydrotest of composite vessels are required. Generally, some parameters such as accumulation of damage events and Felicity ratio are used to evaluate the damage state and mechanical properties of composite vessels [165]. Joselin et al. [166] summarized the early studies on the application of AE to predict burst pressure of composite pressure chambers in chronological order. Chou et al. [156] evaluated the damage situation of composites vessels using AE detection technology under the conditions of cyclic and constant internal pressure. The analysis of mechanical property and accumulation of damage under internal pressure loading revealed that the accumulation counts of AE signals can be used to assess the mechanical integrity of composite vessels rather than as a reliable indicator of evaluating residual performance.

Qualitative assessment of damage state of composite vessel is possible, but it is more difficult to achieve quantitative assessment of composite vessels through AE signal trends and cumulative events. With the development of AE technology for damage detection of filament winding composites layer, the correspondence between AE activity and damage evolution is established, which is significant for the in service safety assessment of composite vessels [132,167,168]. Hill et al. [169] classified the AE signals from the hydraulic burst test into four subsets corresponding to different damage mechanisms by self-organizing map (SOM) and performed analysis of AE signals for low pressure condition by employing the backpropagation neural network (BPNN) to predict the burst pressure of composite vessels. Lepikhin et al. [170] studied the damage evolution of the composite shell of metal-composite pressure vessel (MCPV) from microscopic damage to burst failure with AE monitoring. It is found that the AE signal of fiber breakage is mainly characterized by long duration and low-frequency components, which could be used as a criterion for MCPV safety assessment. Jiang et al. [171] investigated the damage modes of composites vessel in progressive loading hydraulic tests using modal acoustic emission, where the damage evolutions of such vessel were characterized by fracture damage modes of fibers. Wang et al. [96] investigated the AE characteristics and damage evolution behavior of Type IV hydrogen storage vessels in multi-step loading tests and hydraulic burst tests. The K-means algorithm was performed to classify AE signals and the wavelet packet transform was used to verify the reliability of damage pattern recognition. These studies demonstrated the sensitivity of AE for detecting microscopic damage in composite vessels. However, due to the attenuation of the acoustic emission signal in propagation, it is instructive and meaningful to conduct area detection with multiple AE sensors for the composite vessel structures. As a consequence, it is promising to establish safety evaluation criteria for quality assessment, damage detection, and residual performance prediction of composite vessels based on AE technology.

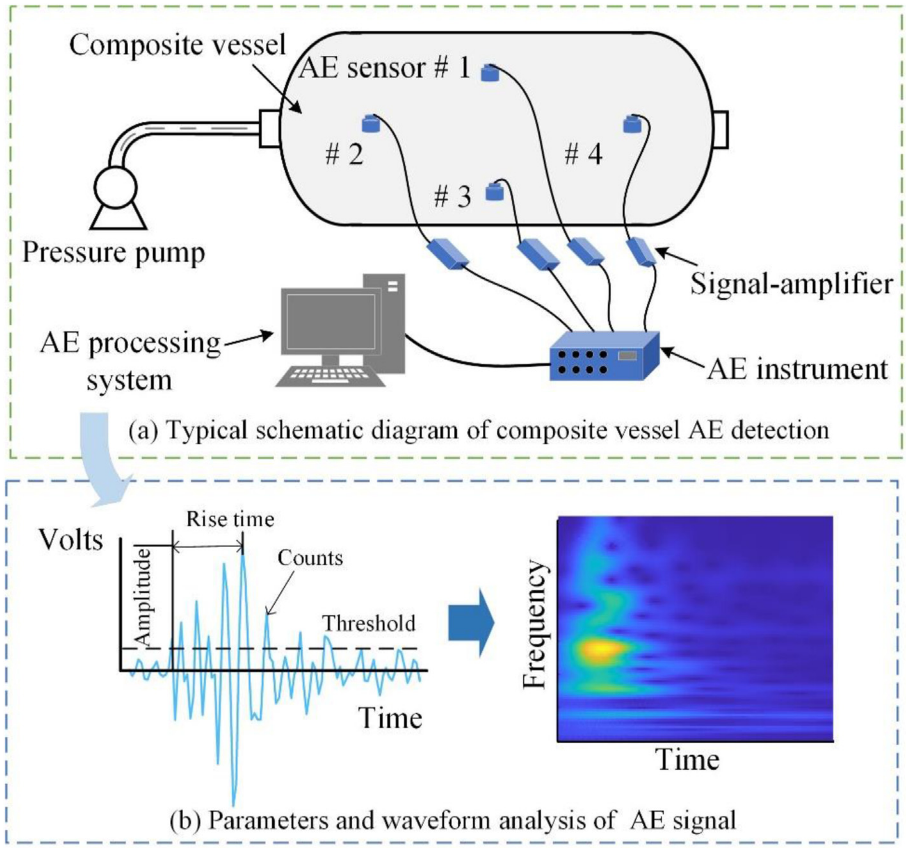

Fig. 11 – Schematic diagram of acoustic emission detection for composites vessel.

Digital image correlation

Due to non-contact, simple device and full-field measurements, the DIC technique is widely used for mechanical analysis of composite structures, such as strain concentration, damage location and crack propagation [172]. Depending on the structural characteristics of the composite material, two-dimensional (2D) or three-dimensional (3D) DIC techniques can be selected to measure the displacement and strain fields on the surface of the composite material [157,173,174]. With the widespread application of composite hydrogen storage pressure vessels, 3D DIC technology has gradually being used for strain monitoring and damage assessment of composite vessels [175]. The schematic diagram and flow chart of the data analysis for a typical 3D DIC measurement are shown in Fig. 12. The 3D DIC technique uses two cameras (CMOS camera 1 and CMOS camera 2) to record the undeformed and deformed speckle images of the composite pressure vessel at different angles. The stereo vision technique and the conventional DIC technique are combined to achieve 3D shape information and strain field measurements of the composite vessel [176–178]. Several scholars have conducted strain monitoring, damage assessment and structural optimization of composite vessels by using 3D DIC technology [9]. Nimdum et al. [179] investigated the effect of the gap between the boss and the composite layer on the mechanical behavior of the composite vessel by combining DIC and FEA and the results showed that local deformation and nonlinear mechanical behavior occurred before the gap contact. Garcia-Martin et al. [180] combined the DIC measurement and probabilistic approaches to conduct reliability analysis of composite pressure vessels. Nebe et al. [16] established the relationship between various stacking sequences and surface strain of composite vessels by DIC technology to optimize the layup structure of composite layer. It is found that the strain information in the transition region between the cylinder and the dome is the focus for the failure analysis of the composite vessel. In general, 3D DIC technology applies to the strain measurement of composite pressure vessels. The damage status and defect location inside the composite material are inferred from the strain field on the surface of the composite vessel, but the damage modes cannot be identified. Therefore, the combination of 3D DIC technology and other NDT methods can be used to identify the damage modes and evaluate the residual properties of composite vessels.

Fiber optic detection

To predict the lifetime of composite vessels, multiple embedded sensors have been developed to monitor the strain and pressurization state of composite vessels [181–185]. Wherein, fiber optic sensors can be arranged to reliably detect the strain of large-scale composite structures, and such technology plays an important role in structural health monitoring of composite high-pressure hydrogen storage vessels during gas filling and working service [158,181,186]. The schematic diagram of fiber optic monitoring of typical

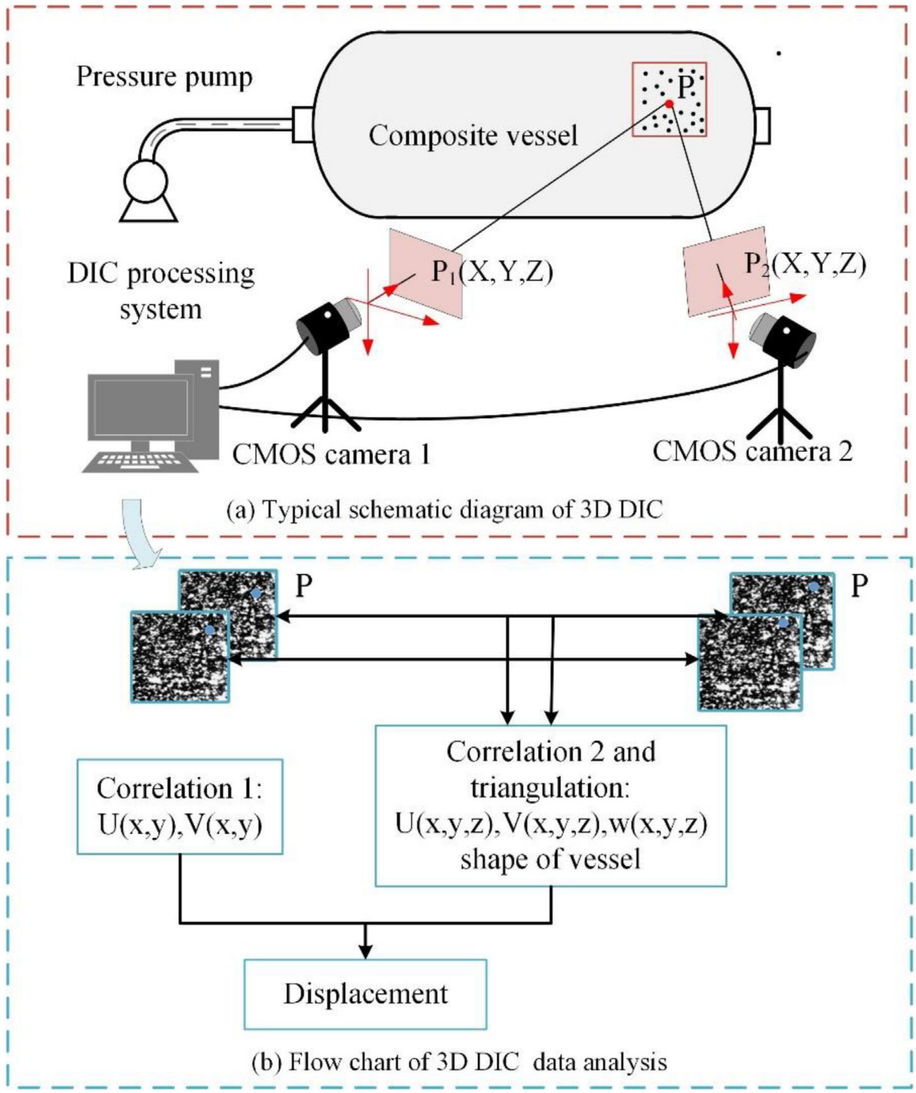

Fig. 12 – Schematic diagram and flow chart of the digital image correlation measurement of composites vessel.

composite vessels is shown in Fig. 13. The principle of fiber optic detection is that the deformation of the composite vessel is deduced from the offset of the wavelength. Several scholars have investigated the evaluation and localization of impact damage, fatigue damage and burst damage of composite vessels through fiber optic sensors [187,188]. Park et al. [189] monitored the internal strain of the composites vessel and analyzed the damage response by fiber Bragg grating (FBG) sensors during the impact test and quasi-static loading test. Souza et al. [190] studied the bursting process of the type IV composite vessel through the core fiber optic sensor. The results showed that the change rate of strain in the dome regions reasonably predicted the location of the burst damage. Frias et al. [191] analyzed the applicability of damage detection and monitoring strategies during cyclic loading of composite vessels by FBG sensors and polyvinylidene fluoride (PVDF) polymeric piezoelectric sensors, respectively. The previous studies show that the barely visible damage can be detected by the fiber optic sensors, which achieve the assessment of the pressurization state of the composite vessel and the prediction of the burst failure location.

Fiber optic sensors can be integrated into composite vessels to real-time monitor the structural situation of the composite vessel throughout its whole service life. Therefore, it is essential to investigate the parameters of the embedded optical fibers (optical fiber orientation, optical fiber depth, optical fiber position) and the failure of the optical fiber for optimizing the monitoring sensitivity [190,192]. The experimental comparison with various embedding orientations showed that the optical fiber wrapped along the ring orientation was most effective for damage detection [192]. Further research on mass-produced scale composite vessels embedding optical fibers can help to reduce damage and defects in optical fibers and improve the reliability of distributed optical fiber monitoring for composite vessels. In general, fiber optic sensor can be used for the detection and localization of damage by capturing the strain in composite vessels, which is expected to be an essential technology for monitoring the service status of composite vessels. The damage initiation and propagation occurred in composite vessels can be revealed by fiber optic sensors under different loads, and this provides an alternative approach for structural health monitoring of composite vessels.

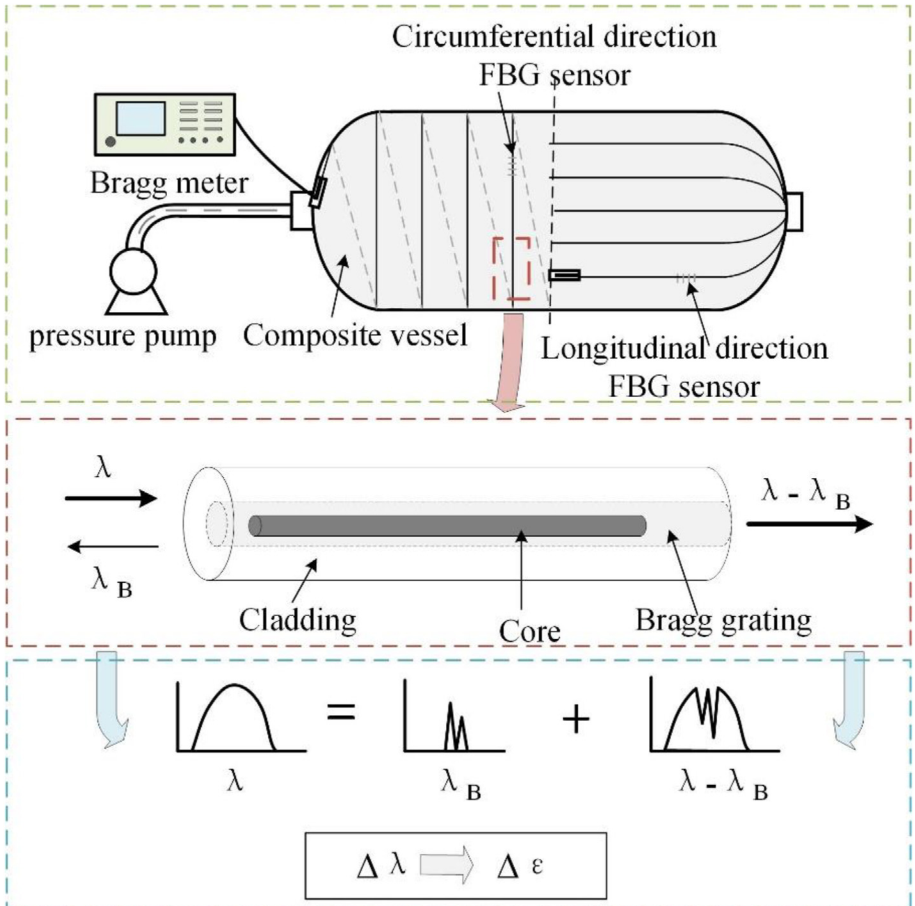

Fig. 13 – Schematic diagram of the fiber Bragg grating detection for composites vessel.

Combination of NDT methods

With the increasing demand for hydrogen energy, there is a growing requirement for regular detection and SHM of the composite hydrogen storage vessel. To guarantee the reliability of the high-pressure composite hydrogen storage vessels in service, it is important to evaluate the real-time safety situation of composite vessels. Hence it is essential to construct an efficient structural health monitoring system for composite vessels [193]. The previous studies indicated that the SHM of composite vessels is mainly examined in terms of displacement/strain field measurements and damage identification, as shown in Fig. 14. Some scholars have used fiber optical technology in combination with DIC technology to measure the local and full-field strain information of composite vessels to achieve defect identification (bubbles and inclusions, etc.) and damage localization [9,172]. Gąsior et al. [175] proposed a strain measurement method for composite hydrogen storage vessels based on a complementary optical detection by FBG and DIC, in which the full-field strains were measured by the DIC technique to determine the critical status of the composite vessel and guide the optimal installation of the FBG sensor. It demonstrated that the combination of optical fiber and DIC measurements can accurately identify the locations of defects and damages of composite vessels.

In addition, AE techniques can be used to monitor the initiation and propagation of damage produced in composite vessels in real-time and conduct damage classification and assessment. Several scholars have adopted AE techniques combined with optical methods (optical fiber and DIC) for the SHM of composite vessels [194]. Munzke et al. [187] conducted fatigue tests of load cycles and burst tests on the composite vessel, furthermore, the fiber optic sensors and AE sensors were used to monitor the entire fatigue damage process. Their results indicated that the strain information and AE signal captured before the bursting of the composite vessel can explicitly identify the failure location and vessel malfunction. Tapeinos et al. [195] investigated the mechanical properties and failure behavior of type IV composite pressure vessels under different environmental conditions based a combination of DIC, AE, and FBG. From their study, the strain gradient and damage evolution can be effectively evaluated for the pressure window of the composite vessel. In their work, the AE technique can be used to reveal different damage modes of the composite vessel under the internal pressure, the optical fiber detection and the DIC measurement can be conducted to predict the damage location and identify the defect. Therefore, the combination of AE, optical fiber, and DIC technologies can be used for achieving accurate damage localization and safety assessment of composite vessel [158]. Micro-CT,

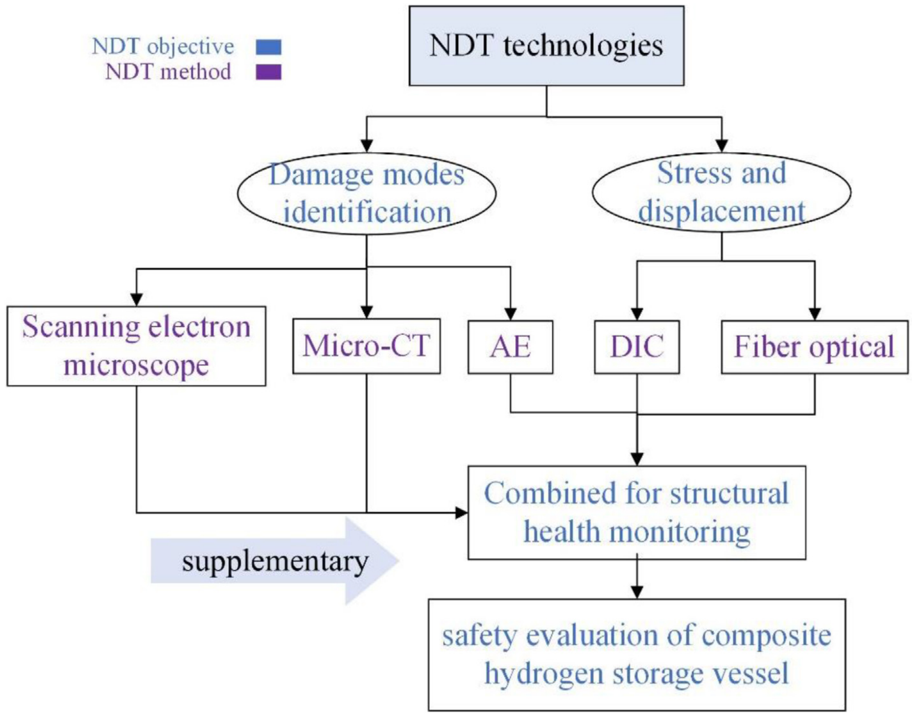

Fig. 14 – Application of multiple NDT technologies on the composite vessels.

scanning electron microscopy and other methods were used as supplements to verify the damage modes of the composite vessel [196]. In general, the combination of multiple NDT methods can be used to capture the damage information in a complementary way, and provide more accurate damage localization and assessment. Thus, it is significant and prospective to establish a detection technique combining multiple NDT methods for damage assessment and structural health monitoring of composite vessels.

Conclusions and future prospects

Conclusions

The application of composite hydrogen storage vessels in the field of the vehicle is becoming more and more widespread, hence it is urgent to develop effective structural optimization and nondestructive testing techniques for improving the reliability of such composite vessels in service.

This work attempts to provide a comprehensive review for three significant aspects of composite vessels, including optimization design, failure analysis and non-destructive testing. First, we review the design factors e.g. layer thickness, winding angle, the layup sequence, fiber winding technology, geometry and dome reinforcement, which can be optimized to improve the durability and strength of composite vessels. Then, we summarize the experimental and numerical studies on burst pressure, fatigue life, impact damage and progressive failure analysis of the composite vessels. Also, the residual performance and the optimization effects of such vessels are evaluated. Finally, we conduct a review for the development of the application of NDT technology on composite hydrogen storage vessels. Various NDT technologies (AE, DIC and fiber optical, etc.), contributing to quality assessment and residual performance prediction, are examined for locating damage and identifying damage modes in composite vessels in detail. In addition, the combination of multiple complementary NDT methods can provide more accurate damage localization and assessment, which is expected to be a prospective means for the structural health monitoring of composite hydrogen storage vessels.

Future prospects

From the previous works, the improvement of mechanical properties and structural optimization (layer thickness, layup sequence, winding angle, fiber winding technology, geometry, adding doily) of composite vessels have been receiving increasing attention. By reviewing the progress of mechanical property evaluation and optimization methods for composite vessels in terms of both structural design and failure analysis, the future prospects are focused on the following three aspects: (1) the development of dome reinforcement technology in the performance optimization of composite vessels, (2) the experimental verification for performance evaluation and failure analysis of composite hydrogen storage vessels, (3) the progressive failure analysis of multiple failure modes of composite vessels with impact damage. Furthermore, by reviewing the application of NDT technologies for composites hydrogen storage vessels, the future prospects are mainly focused on the following three aspects: (1) a combination of multiple NDT techniques for SHM of composite vessels, (2) the real-time online NDT technology for automotive composite hydrogen storage vessels, (3) the development of embedded sensor-based detection technology in the field of composites vessels, (4) the development of ultrasonic technology for damage detection of composites vessels.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors gratefully acknowledge the financial support of the National Natural Science Foundation of China (grant no. 12172117) and the Interdisciplinary Research Program of Natural Science of Hebei University (Grant No. DXK202015).

REFERENCES

[1] Reddi K, Elgowainy A, Rustagi N, Gupta E. Techno-economic analysis of conventional and advanced high-pressure tube trailer configurations for compressed hydrogen gas transportation and refueling. Int J Hydrogen Energy 2018;43:4428–38.
[2] Weisberg AH, Aceves SM, Espinosa-Loza F, et al. Cold hydrogen delivery in glass fiber composite pressure vessels: analysis, manufacture and testing. Int J Hydrogen Energy 2013;38:9271–84.
[3] Hassan IA, Ramadan HS, Saleh MA, Hissel D. Hydrogen storage technologies for stationary and mobile applications: review, analysis and perspectives. Renew Sustain Energy Rev 2021;149:111311.
[4] Rivard E, Trudeau M, Zaghib K. Hydrogen storage for mobility: a review. Materials 2019;12(12):1973.
[5] Johnson K, Veenstra MJ, Gotthold D, et al. Advancements and opportunities for on-board 700 bar compressed hydrogen tanks in the progression towards the commercialization of fuel cell vehicles. SAE Int J Altern Powertrains 2017;6:201–18.
[6] Weisberg AH, Aceves SM, Espinosa-Loza F, et al. Delivery of cold hydrogen in glass fiber composite pressure vessels. Int J Hydrogen Energy 2009;34:9773–80.
[7] Öztas KA, Kunze K, Jois K, et al. A numerical approach to design a type II box-shaped pressure vessel with inner tension struts. Int J Hydrogen Energy 2022;47:3927–38.
[8] Barthelemy H, Weber M, Barbier F. Hydrogen storage: recent improvements and industrial perspectives. Int J Hydrogen Energy 2017;42:7254–62.
[9] Gąsior P, Wachtarczyk K, Błachut A, et al. Validation of selected optical methods for assessing polyethylene (PE) liners used in high pressure vessels for hydrogen storage. Appl Sci 2021;11(12):5667.
[10] Parodi M, Fiaschi C, Memmolo V, et al. Interaction of guided waves with delamination in a bilayered aluminum-composite pressure vessel. J Mater Eng Perform 2019;28:3281–91.
[11] Echtermeyer AT, Lasn K. Safety approach for composite pressure vessels for road transport of hydrogen. Part 2: safety factors and test requirements. Int J Hydrogen Energy 2014;39:14142–52.
[12] Zhao X, Yan Y, Zhang J, et al. Analysis of multilayered carbon fiber winding of cryo-compressed hydrogen storage vessel. Int J Hydrogen Energy 2022;47:10934–46.
[13] Teng TL, Yu CM, Wu YY. Optimal design of filament-wound composite pressure vessels. Mech Compos Mater 2005;41(4):333–40.
[14] Akhtar MK, Qureshi WA, Jamshed R, Raza M. Analytical modeling and numerical analysis of the effect of mosaic patterns on composite pressure vessels with dome. J Reinforc Plast Compos 2021;40:621–31.
[15] Leh D, Saffré P, Francescato P, Arrieux R. Multi-sequence dome lay-up simulations for hydrogen hyper-bar composite pressure vessels. Compos Appl Sci Manuf 2013;52:106–17.
[16] Nebe M, Asijee TJ, Braun C, et al. Experimental and analytical analysis on the stacking sequence of composite pressure vessels. Compos Struct 2020;247:112429.
[17] Zhou W, Zhao WZ, Zhang YN, et al. Cluster analysis of acoustic emission signals and deformation measurement for delaminated glass fiber epoxy composites. Compos Struct 2018;195:349–58.
[18] Zhang PF, Zhou W, Yin HF, Shang YJ. Progressive damage analysis of three-dimensional braided composites under flexural load by micro-CT and acoustic emission. Compos Struct 2019;226:111196.
[19] Zhou W, Ji XL, Yang S, et al. Review on the performance improvements and non-destructive testing of patches repaired composites. Compos Struct 2021;263:113659.
[20] Bouvier M, Guiheneuf V, Jean-marie A. Modeling and simulation of a composite high-pressure vessel made of sustainable and renewable alternative fibers. Int J Hydrogen Energy 2019;44:11970–8.
[21] Hwang TK, Hong CS, Kim CG. Size effect on the fiber strength of composite pressure vessels. Compos Struct 2003;59(4):489–98.
[22] Dahl E, Becker JS, Mittelstedt C, Schürmann H. A new concept for a modular composite pressure vessel design. Compos Appl Sci Manuf 2019;124:105475.
[23] Solazzi L, Vaccari M. Reliability design of a pressure vessel made of composite materials. Compos Struct 2021;279:114726.
[24] Ebermann M, Bogenfeld R, Kreikemeier J, Glüge R. Analytical and numerical approach to determine effective diffusion coefficients for composite pressure vessels. Compos Struct 2022;291:115616.
[25] Hu J, Sundararaman S, Menta VGK, et al. Failure pressure prediction of composite cylinders for hydrogen storage using thermo-mechanical analysis and neural network. Adv Compos Mater 2009;18:233–49.
[26] Wang L, Zheng C, Wei S, Wei Z. Micromechanics-based progressive failure analysis of carbon fiber/epoxy composite vessel under combined internal pressure and thermomechanical loading. Compos B Eng 2016;89:77–84.
[27] Ghouaoula A, Hocine A, Chapelle D, et al. Analytical prediction of damage in the composit part of a type-3 hydrogen storage vessel. Mech Compos Mater 2012;48(1):77–88.
[28] Chapelle D, Perreux D. Optimal design of a Type 3 hydrogen vessel: Part I—analytic modelling of the cylindrical section. Int J Hydrogen Energy 2006;31:627–38.
[29] Baris Kalaycioglu, Dirikolu M, Husnu. Investigation of the design of a metal-lined fully wrapped composite vessel under high internal pressure. High Pres Res 2010;30(3):428–37.
[30] Azeem M, Ya HH, Alam MA, et al. Application of filament winding technology in composite pressure vessels and challenges: a review. J Energy Storage 2022;49:103468.
[31] Ramos I, Ho Park Y, Ulibarri-Sanchez J. Analytical and numerical studies of a thick anisotropic multilayered fiber-reinforced composite pressure vessel. J Pressure Vessel Technol 2019;141(1):011203.
[32] Park YH, Sakai J. Optimum design of composite pressure vessel structure based on 3-dimensional failure criteria. Int J Material Form 2020;13:957–65.

[33] Salavatian M, Smith LV. Matrix damage in composite pressure vessels with a bias fiber orientation. J Compos Mater 2012;46:2793–802.
[34] Hu Z, Chen M, Zu L, et al. Investigation on failure behaviors of 70 MPa Type IV carbon fiber overwound hydrogen storage vessels. Compos Struct 2021;259:113387.
[35] Zu L, Xu H, Jia X, et al. Winding path design based on mandrel profile updates of composite pressure vessels. Compos Struct 2020;235:1111766.
[36] Zaami A, Baran I, Bor TC, Akkerman R. New process optimization framework for laser assisted tape winding of composite pressure vessels: controlling the unsteady bonding temperature. Mater Des 2020;196:109130.
[37] Daghia F, Baranger E, Tran DT, Pichon P. A hierarchy of models for the design of composite pressure vessels. Compos Struct 2020;235:111809.
[38] Liu PF, Chu JK, Hou SJ, et al. Numerical simulation and optimal design for composite high-pressure hydrogen storage vessel: a review. Renew Sustain Energy Rev 2012;16:1817–27.
[39] Roh HS, Hua TQ, Ahluwalia RK, et al. Optimization of carbon fiber usage in Type 4 hydrogen storage tanks for fuel cell automobiles. Int J Hydrogen Energy 2013;38(29):12795–802.
[40] Lin DTW, Hsieh J-C, Chindakham N, Hai PD. Optimal design of a composite laminate hydrogen storage vessel. Int J Energy Res 2013;37:761–8.
[41] Nguyen BN, Roh HS, Merkel DR, Simmons KL. A predictive modeling tool for damage analysis and design of hydrogen storage composite pressure vessels. Int J Hydrogen Energy 2021;46:20573–85.
[42] Chapelle D, Perreux D. Analytical modelling of the metal vessel reinforced by filament winding for hydrogen storage. Sci Eng Compos Mater 2005;12:43–54.
[43] Wu E, Zhao Y, Zhao B, Xu W. Fatigue life prediction and verification of high-pressure hydrogen storage vessel. Int J Hydrogen Energy 2021;46:30412–22.
[44] Samuel BO, Sumaila M, Dan-Asabe B. Multi-parameter optimization (grey relational analysis) and modeling of a cellulosic plant/glass fiber hybrid reinforced polymer composite (P(x) G(y) E(z)) for offshore pressure vessels development. Funct Compos Struct 2022;4(3):035001.
[45] Nebe M, Johman A, Braun C, van Campen JMJF. The effect of stacking sequence and circumferential ply drop locations on the mechanical response of type IV composite pressure vessels subjected to internal pressure: a numerical and experimental study. Compos Struct 2022;294:115585.
[46] Mian HH, Wang G, Dar UA, Zhang W. Optimization of composite material system and lay-up to achieve minimum weight pressure vessel. Appl Compos Mater 2013;20:873–89.
[47] Brian Ellul, Duncan Camilleri. The applicability and implementation of the discrete Big Bang-Big Crunch optimisation technique. Int J Pres Ves Pip 2018;168:39–48.
[48] Weisberg A, Aceves SM. The potential of dry winding for rapid, inexpensive manufacture of composite overwrapped pressure vessels. Int J Hydrogen Energy 2015;40:4207–11.
[49] Kim J-W, Sauti G, Cano RJ, et al. Assessment of carbon nanotube yarns as reinforcement for composite overwrapped pressure vessels. Compos Appl Sci Manuf 2016;84:256–65.
[50] Zheng CX, Lei SH. Mechanical analysis and optimal design for carbon fiber resin composite wound hydrogen storage vessel with aluminum alloy liner. J Pressure Vessel Technol 2009;131(2):021204.
[51] Lasn K, Mulelid M. The effect of processing on the microstructure of hoop-wound composite cylinders. J Compos Mater 2020;54:3981–97.
[52] Liu C, Shi Y. Design optimization for filament wound cylindrical composite internal pressure vessels considering process-induced residual stresses. Compos Struct 2020;235:111755.
[53] Leh D, Magneville B, Saffré P, et al. Optimisation of 700 bar type IV hydrogen pressure vessel considering composite damage and dome multi-sequencing. Int J Hydrogen Energy 2015;40(38):13215–30.
[54] Madhavi M, Rao KVJ, Rao KN. Design and analysis of filament wound composite pressure vessel with integrated-end domes. Defence Sci J 2009;59(1):73–81.
[55] Huang Z, Ma W, Jia C, et al. Gradient design of tubular of the fiber-reinforced composites pressure vessel for diminishing of the edge effect. Int J Pres Ves Pip 2021;192:104398.
[56] Cho S-M, Kim K-S, Lee S-K, et al. Effect of dome curvature on failure mode of Type 4 composite pressure vessel. Int J Precis Eng Manuf 2018;19:405–10.
[57] Alcantar V, Aceves SM, Ledesma E, et al. Optimization of Type 4 composite pressure vessels using genetic algorithms and simulated annealing. Int J Hydrogen Energy 2017;42(24):15770–81.
[58] Liu P, Xu P, Zheng J. Artificial immune system for optimal design of composite hydrogen storage vessel. Comput Mater Sci 2009;47:261–7.
[59] Zu L, Wang J, Li S. Influence of fiber slippage coefficient distributions on the geometry and performance of composite pressure vessels. Polym Compos 2016;37:315–21.
[60] Zu L, Xu H, Wang H, et al. Design and analysis of filament-wound composite pressure vessels based on non-geodesic winding. Compos Struct 2019;207:41–52.
[61] Zhou J, Chen J, Zheng Y, et al. Dome shape optimization of filament-wound composite pressure vessels based on hyperelliptic functions considering both geodesic and non-geodesic winding patterns. J Compos Mater 2017;51:1961–9.
[62] Madhavi M, Venkat R. Predicting structural behavior of filament wound composite pressure vessel using three dimensional shell analysis. J Inst Eng: Ser C 2014;95:41–50.
[63] Hu ZY, Chen MH, Pan B. Simulation and burst validation of 70 MPa type IV hydrogen storage vessel with dome reinforcement. Int J Hydrogen Energy 2021;46(46):23779–94.
[64] Kartav O, Kangal S, Yücetürk K, et al. Development and analysis of composite overwrapped pressure vessels for hydrogen storage. J Compos Mater 2021;55:4141–55.
[65] Rongguo W, Weicheng J, Wenbo L, Fan Y. A new method for predicting dome thickness of composite pressure vessels. J Reinforc Plast Compos 2010;29:3345–52.
[66] Vafaeesefat A, Khani A. Head shape and winding angle optimization of composite pressure vessels based on a multi-level strategy. Appl Compos Mater 2007;14:379–91.
[67] Che J-l, Han M-G, Chang S-H. Prediction of composite layer thickness for Type III hydrogen pressure vessel at the dome part. Compos Struct 2021;271:114177.
[68] Zhang Q, Xu H, Jia X, et al. Design of a 70 MPa type IV hydrogen storage vessel using accurate modeling techniques for dome thickness prediction. Compos Struct 2020;236:111915.
[69] Wang H, Fu S, Chen Y, Hua L. Thickness-prediction method involving tow redistribution for the dome of composite hydrogen storage vessels. Polymers 2022;14(5):902.
[70] Sharma P, Sharma S, Bera T, et al. Effects of dome shape on burst and weight performance of a type-3 composite pressure vessel for storage of compressed hydrogen. Compos Struct 2022;293:115732.
[71] Paknahad A, Fathi A, Goudarzi AM, Nourani R. Optimum head design of filament wound composite pressure vessels using a hybrid model of FE analysis and inertia weight PSO algorithm. Int J Material Form 2016;9:49–57.
[72] Sharifi S, Gohari S, Sharifiteshnizi M, et al. Fracture of laminated woven GFRP composite pressure vessels under

combined low-velocity impact and internal pressure. Arch Civ Mech Eng 2018;18:1715–28.
[73] Roh HS, Hua TQ, Ahluwalia RK. Optimization of carbon fiber usage in Type 4 hydrogen storage tanks for fuel cell automobiles. Int J Hydrogen Energy 2013;38(29):12795–802.
[74] Zheng C-x, Yang F, Zhu A-s. Mechanical analysis and reasonable design for Ti-Al alloy liner wound with carbon fiber resin composite high pressure vessel. J Zhejiang Univ - Sci 2009;10:384–91.
[75] Park G, Jang H, Kim C. Design of composite layer and liner for structure safety of hydrogen pressure vessel (type 4). J Mech Sci Technol 2021;35:3507–17.
[76] Vafaeesefat A. Optimization of composite pressure vessels with metal liner by adaptive response surface method. J Mech Sci Technol 2011;25:2811–6.
[77] Almeida JHS, Faria H, Marques AT, Amico SC. Load sharing ability of the liner in type III composite pressure vessels under internal pressure. J Reinforc Plast Compos 2014;33:2274–86.
[78] He C, Yu R, Sun H, Chen Z. Lightweight multilayer composite structure for hydrogen storage tank. Int J Hydrogen Energy 2016;41:15812–6.
[79] Barboza Neto ES, Chludzinski M, Roese PB, et al. Experimental and numerical analysis of a LLDPE/HDPE liner for a composite pressure vessel. Polym Test 2011;30:693–700.
[80] Murray BR, Leen SB, Semprimoschnig COA, Brádaigh CMÓ. Helium permeability of polymer materials as liners for composite overwrapped pressure vessels. J Appl Polym Sci 2016;133(29):43675.
[81] Liu Guanjun, Fan Yang, Liu Wenbo, et al. Crystalline polymer functionalized non-oxidized graphene flakes for high gas barrier composites. Int J Hydrogen Energy 2021;46(7):5472–84.
[82] Pépin J, Lainé E, Grandidier J-C, et al. Replication of liner collapse phenomenon observed in hyperbaric type IV hydrogen storage vessel by explosive decompression experiments. Int J Hydrogen Energy 2018;43:4671–80.
[83] Blanc-Vannet P, Papin P, Weber M, et al. Sample scale testing method to prevent collapse of plastic liners in composite pressure vessels. Int J Hydrogen Energy 2019;44:8682–91.
[84] Sohn JM, Hirdaris S, Romanoff J, Kim SJ. Development of numerical modelling techniques for composite cylindrical structures under external pressure. J Mar Sci Eng 2022;10(4):466.
[85] Pepin J, Lainé E, Grandidier J-C, et al. Determination of key parameters responsible for polymeric liner collapse in hyperbaric type IV hydrogen storage vessels. Int J Hydrogen Energy 2018;43:16386–99.
[86] Hübner F, Brückner A, Dickhut T, et al. Low temperature fatigue crack propagation in toughened epoxy resins aimed for filament winding of type V composite pressure vessels. Polym Test 2021;102:107323.
[87] Hocine A, Chapelle D, Boubakar ML, et al. Experimental and analytical investigation of the cylindrical part of a metallic vessel reinforced by filament winding while submitted to internal pressure. Int J Pres Ves Pip 2009;86:649–55.
[88] Choi IH. Low-velocity impact response analysis of composite pressure vessel considering stiffness change due to cylinder stress. Compos Struct 2017;160:491–502.
[89] Gentilleau B, Villalonga S, Nony F, Galiano H. A probabilistic damage behavior law for composite material dedicated to composite pressure vessel. Int J Hydrogen Energy 2015;40(38):13160–4.
[90] Park WR, Fatoni NF, Kwon OH. Evaluation of stress and crack behavior using the extended finite element method in the composite layer of a type III hydrogen storage vessel. J Mech Sci Technol 2018;32:1995–2002.
[91] Sapre S, Pareek K, Vyas M. Investigation of structural stability of type IV compressed hydrogen storage tank during refueling of fuel cell vehicle. Energy Storage 2020;2(4):e150.
[92] Harada S, Arai Y, Araki W, et al. A simplified method for predicting burst pressure of type III filament-wound CFRP composite vessels considering the inhomogeneity of fiber packing. Compos Struct 2018;190:79–90.
[93] Hwang T-K, Park J-B, Kim H-G. Evaluation of fiber material properties in filament-wound composite pressure vessels. Compos Appl Sci Manuf 2012;43:1467–75.
[94] Kim WT, Kim SS. Design of a segment-type ring burst test device to evaluate the pressure resistance performance of composite pressure vessels. Compos Struct 2020;242:112199.
[95] Nebe M, Soriano A, Braun C, et al. Analysis on the mechanical response of composite pressure vessels during internal pressure loading: FE modeling and experimental correlation. Compos B Eng 2021;212:108550.
[96] Wang D, Liao B, Hao C, et al. Acoustic emission characteristics of used 70 MPa type IV hydrogen storage tanks during hydrostatic burst tests. Int J Hydrogen Energy 2021;46:12605–14.
[97] Leh D, Saffré P, Francescato P, et al. A progressive failure analysis of a 700-bar type IV hydrogen composite pressure vessel. Int J Hydrogen Energy 2015;40:13206–14.
[98] Hu J, Chandrashekhara K. Fracture analysis of hydrogen storage composite cylinders with liner crack accounting for autofrettage effect. Int J Hydrogen Energy 2009;34:3425–35.
[99] Son D-S, Hong J-H, Chang S-H. Determination of the autofrettage pressure and estimation of material failures of a Type III hydrogen pressure vessel by using finite element analysis. Int J Hydrogen Energy 2012;37:12771–81.
[100] Hong J-H, Han M-G, Chang S-H. Safety evaluation of 70MPa-capacity type III hydrogen pressure vessel considering material degradation of composites due to temperature rise. Compos Struct 2014;113:127–33.
[101] Hu J, Chen J, Sundararaman S, et al. Analysis of composite hydrogen storage cylinders subjected to localized flame impingements. Int J Hydrogen Energy 2008;33:2738–46.
[102] Burov AE, Lepikhin AM. Numerical simulation of carrying capacity of the high-pressure metal composite vessel. J Mach Manufact Reliab 2016;45:443–50.
[103] Onder A, Sayman O, Dogan T, Tarakcioglu N. Burst failure load of composite pressure vessels. Compos Struct 2009;89:159–66.
[104] Xu P, Zheng JY, Liu PF. Finite element analysis of burst pressure of composite hydrogen storage vessels. Mater Des 2009;30:2295–301.
[105] Goldin Priscilla CP, Selwin Rajadurai J. Failure phenomena in metallic and metal-lined polymer composite pressure vessels for aerospace applications. Trans Can Soc Mech Eng 2021;45(3):479–86.
[106] Kang Huairong, He Pengfei, Zhang Cunman. Stress–strain and burst failure analysis of fiber wound composite material high-pressure vessel. Polym Polym Compos 2021;29(8):1291–303.
[107] Liao B-b, Wang D-l, Jia L-y, et al. Continuum damage modeling and progressive failure analysis of a Type III composite vessel by considering the effect of autofrettage. J Zhejiang Univ - Sci 2018;20(1):36–49.
[108] Son D-S, Chang S-H. Evaluation of modeling techniques for a type III hydrogen pressure vessel (70 MPa) made of an aluminum liner and a thick carbon/epoxy composite for fuel cell vehicles. Int J Hydrogen Energy 2012;37(3):2353–69.

[109] Rafiee R, Torabi MA. Stochastic prediction of burst pressure in composite pressure vessels. Compos Struct 2018;185:573–83.
[110] Liu PF, Xing LJ, Zheng JY. Failure analysis of carbon fiber/epoxy composite cylindrical laminates using explicit finite element method. Compos B Eng 2014;56:54–61.
[111] Berro Ramirez JP, Halm D, Grandidier J-C, Villalonga S. A fixed directions damage model for composite materials dedicated to hyperbaric type IV hydrogen storage vessel – Part I: model formulation and identification. Int J Hydrogen Energy 2015;40:13165–73.
[112] Berro Ramirez JP, Halm D, Grandidier J-C, et al. 700 Bar type IV high pressure hydrogen storage vessel burst – simulation and experimental validation. Int J Hydrogen Energy 2015;40:13183–92.
[113] Wang L, Zheng C, Luo H, et al. Continuum damage modeling and progressive failure analysis of carbon fiber/epoxy composite pressure vessel. Compos Struct 2015;134:475–82.
[114] Ahmadi Jebeli M, Heidari-Rarani M. Development of Abaqus WCM plugin for progressive failure analysis of type IV composite pressure vessels based on Puck failure criterion. Eng Fail Anal 2022;131:105851.
[115] Lasn K, Echtermeyer AT. Safety approach for composite pressure vessels for road transport of hydrogen. Part 1: acceptable probability of failure and hydrogen mass. Int J Hydrogen Energy 2014;39:14132–41.
[116] Blassiau S, Thionnet A, Bunsell AR. Micromechanisms of load transfer in a unidirectional carbon fibre-reinforced epoxy composite due to fibre failures: Part 3. Multiscale reconstruction of composite behaviour. Compos Struct 2008;83:312–23.
[117] Nguyen BN, Merkel DR, Johnson KI. Modeling the effects of loading scenario and thermal expansion coefficient on potential failure of cryo-compressed hydrogen vessels. Int J Hydrogen Energy 2020;45(46):24883–94.
[118] Rafiee R, Salehi A. A novel recursive multi-scale modeling for predicting the burst pressure of filament wound composite pressure vessels. Appl Phys A 2022;128(5):388.
[119] Zhang N, Gao S, Song M, et al. A multiscale study of CFRP based on asymptotic homogenization with application to mechanical analysis of composite pressure vessels. Polymers 2022;14(14):2817.
[120] Liu PF, Chu JK, Hou SJ, Zheng JY. Micromechanical damage modeling and multiscale progressive failure analysis of composite pressure vessel. Comput Mater Sci 2012;60:137–48.
[121] Lin S, Yang L, Xu H, et al. Progressive damage analysis for multiscale modelling of composite pressure vessels based on Puck failure criterion. Compos Struct 2021;255:113046.
[122] Magneville B, Gentilleau B, Villalonga S, et al. Modeling, parameters identification and experimental validation of composite materials behavior law used in 700 bar type IV hydrogen high pressure storage vessel. Int J Hydrogen Energy 2015;40:13193–205.
[123] Makinson J, Newhouse NL. Flaw testing of fiber reinforced composite pressure vessels. J Pressure Vessel Technol 2014;136(4):041409.
[124] Kangal S, Kartav O, Tanoğlu M, et al. Investigation of interlayer hybridization effect on burst pressure performance of composite overwrapped pressure vessels with load-sharing metallic liner. J Compos Mater 2020;54(7):961–80.
[125] Chou HY, Bunsell AR, Mair G, Thionnet A. Effect of the loading rate on ultimate strength of composites. Application: pressure vessel slow burst test. Compos Struct 2013;104:144–53.
[126] Blanc-Vannet P. Burst pressure reduction of various thermoset composite pressure vessels after impact on the cylindrical part. Compos Struct 2017;160:706–11.
[127] Sharma Pranjali, Bera Tapan, Kaladhar Semwal. Theoretical analysis of design of filament wound type 3 composite cylinder for the storage of compressed hydrogen gas. Int J Hydrogen Energy 2020;45(46):25386–97.
[128] Simonovski I, Baraldi D, Melideo D, Acosta-Iborra B. Thermal simulations of a hydrogen storage tank during fast filling. Int J Hydrogen Energy 2015;40:12560–71.
[129] Bertin M, Touchard F, Lafarie-Frenot M-C. Experimental study of the stacking sequence effect on polymer/composite multi-layers submitted to thermomechanical cyclic loadings. Int J Hydrogen Energy 2010;35:11397–404.
[130] Comond O, Perreux D, Thiebaud F, Weber M. Methodology to improve the lifetime of type III HP tank with a steel liner. Int J Hydrogen Energy 2009;34:3077–90.
[131] Kim Y-S, Kim L-H, Park J-S. The effect of composite damage on fatigue life of the high pressure vessel for natural gas vehicles. Compos Struct 2011;93:2963–8.
[132] Lin S, Jia X, Sun H, et al. Thermo-mechanical properties of filament wound CFRP vessel under hydraulic and atmospheric fatigue cycling. Compos B Eng 2013;46:227–33.
[133] Gentilleau B, Touchard F, Grandidier JC. Numerical study of influence of temperature and matrix cracking on type IV hydrogen high pressure storage vessel behavior. Compos Struct 2014;111:98–110.
[134] Zhang Q, Wang ZW, Tang CY, et al. Analytical solution of the thermo-mechanical stresses in a multilayered composite pressure vessel considering the influence of the closed ends. Int J Pres Ves Pip 2012;98:102–10.
[135] Mair GW, Becker B, Wang B, Gesell S. Monte-Carlo-analysis of minimum load cycle requirements for composite cylinders for hydrogen. Int J Hydrogen Energy 2019;44:8833–41.
[136] Zheng C-x, Wang L, Li R, et al. Fatigue test of carbon epoxy composite high pressure hydrogen storage vessel under hydrogen environment. J Zhejiang Univ - Sci 2013;14:393–400.
[137] Wang D, Liao B, Hua Z, et al. Experimental analysis on residual performance of used 70 MPa type IV composite pressure vessels. J Fail Anal Prev 2019;19:204–11.
[138] Ataabadi Abdulreza Kabiri, Jeyed Ghadir Ahmadi. Strength analysis and fatigue life estimation of composite pressure vessel (CPV) based on the residual strain energy (RSE) approach. Int J Comput Methods Eng Sci Mech 2021;22(2):81–102.
[139] Wang L, Wang B, Wei S, et al. Prediction of long-term fatigue life of CFRP composite hydrogen storage vessel based on micromechanics of failure. Compos B Eng 2016;97:274–81.
[140] Han M-G, Chang S-H. Failure analysis of a Type III hydrogen pressure vessel under impact loading induced by free fall. Compos Struct 2015;127:288–97.
[141] Weerts RAJ, Cousigné O, Kunze K, et al. The initiation and progression of damage in composite overwrapped pressure vessels subjected to contact loads. J Reinforc Plast Compos 2021;40:594–605.
[142] Han M-G, Chang S-H. Evaluation of structural integrity of Type-III hydrogen pressure vessel under low-velocity car-to-car collision using finite element analysis. Compos Struct 2016;148:198–206.
[143] Perillo G, Grytten F, Sørbø S, Delhaye V. Numerical/experimental impact events on filament wound composite pressure vessel. Compos B Eng 2015;69:406–17.
[144] Demir İ, Sayman O, Dogan A, et al. The effects of repeated transverse impact load on the burst pressure of composite pressure vessel. Compos B Eng 2015;68:121–5.

[145] Liao B, Du Y, Zheng J, et al. Prediction of residual burst strength for composite pressure vessels after low velocity impact. Int J Hydrogen Energy 2020;45:10962–76.
[146] Alam S, Yandek G, Lee RC, Mabry J. A study of residual burst strength of composite over wrapped pressure vessel due to low velocity impact. Int J Pres Ves Pip 2021;194:104511.
[147] Sepetcioglu H, Tarakcioglu N. Fatigue behavior of graphene nanoplatelets reinforced and unreinforced basalt/epoxy composite pressure vessels subjected to low-velocity impact under internal pressure. J Compos Mater 2021;55:4361–73.
[148] Sepetcioglu H. Experimental study on the effect of graphene nanoplatelets on the low-velocity impact response of prestressed filament wound basalt-based composite pressure vessels. Polym Compos 2021;42:5527–40.
[149] Allen T, Ahmed S, Hepples W, et al. A comparison of quasi-static indentation and low-velocity impact on composite overwrapped pressure vessels. J Compos Mater 2018;52:4051–60.
[150] Weerts RAJ, Cousigné O, Kunze K, et al. A methodological approach to model composite overwrapped pressure vessels under impact conditions. Compos Struct 2021;276:114482.
[151] Liao BB, Jia LY. Finite element analysis of dynamic responses of composite pressure vessels under low velocity impact by using a three-dimensional laminated media model. Thin-Walled Struct 2018;129:488–501.
[152] Rafiee R, Ghorbanhosseini A, Rezaee S. Theoretical and numerical analyses of composite cylinders subjected to the low velocity impact. Compos Struct 2019;226:111230.
[153] Rafiee R, Rashedi H, Rezaee S. Theoretical study of failure in composite pressure vessels subjected to low-velocity impact and internal pressure. Front Struct Civ Eng 2020;14:1349–58.
[154] Long B, Yang N, Cao X. Low-velocity impact damages of filament-wound composite overwrapped pressure vessel (COPV). J Eng Fibers Fabr 2022;17:111–20.
[155] Weerts RAJ, Cousigné O, Kunze K, et al. Novel material model to predict the residual strength of a composite overwrapped pressure vessel after impact. Int J Impact Eng 2022;160:104055.
[156] Chou HY, Mouritz AP, Bannister MK, Bunsell AR. Acoustic emission analysis of composite pressure vessels under constant and cyclic pressure. Compos Appl Sci Manuf 2015;70:111–20.
[157] Bois C, Pilato A, Wahl J-C, Perry N. Proposal for a smart pressurised ring test to study thick composite produced by filament winding. Compos B Eng 2013;53:382–90.
[158] De Waele W, Degrieck J, Moerman W, et al. Feasibility of integrated optical fibre sensors for condition monitoring of composite structures Part II. Insight 2003;45(4):266–71.
[159] Lee Y-J, Ahmed H, Lee J-R. Filament-wound composite pressure vessel inspection based on rotational through-transmission laser ultrasonic propagation imaging. Compos Struct 2020;236:111871.
[160] Yang B, Xiang Y, Xuan F-Z, et al. Damage localization in hydrogen storage vessel by guided waves based on a real-time monitoring system. Int J Hydrogen Energy 2019;44:22740–51.
[161] Memmolo V, Maio L, Ricci F. Assessment of damage in composite pressure vessels using guided waves. Sensors 2022;22(14):5182.
[162] Babu MR, Prakash TVB. Characterisation of fiber failure mode in T-700 carbon fiber reinforced epoxy composites by acoustic emission testing. Russ J Nondestr Test 2014;50(1):45–57.
[163] Zhao WZ, Zhou W. Cluster analysis of acoustic emission signals and tensile properties of carbon/glass fiber-reinforced hybrid composites. Monit Int J 2019;18(5–6):1686–97.
[164] Barile C, Casavola C, Pappalettera G, et al. Damage assessment of carbon fibre reinforced plastic using acoustic emission technique: experimental and numerical approach. Struct Health Monit Int J 2020;20(3):1090–101.
[165] Newhouse NL, Rawls GB, Rana MD, et al. Development of ASME section X code rules for high pressure composite hydrogen pressure vessels with nonload sharing liners. J Pressure Vessel Technol 2012;134(3):030402.
[166] Joselin R, Chelladurai T. Burst pressure prediction of composite pressure chambers using acoustic emission technique: a review. J Fail Anal Prev 2011;11:344–56.
[167] Berro Ramirez JP, Halm D, Grandidier J-C. Assessment of a damage model for wound composite structures by acoustic emission. Compos Struct 2019;214:414–21.
[168] Gorman Michael R. Modal AE analysis of fracture and failure in composite materials, and the quality and life of high pressure composite pressure vessels. J Acoust Emiss 2011;29:1–28.
[169] Hill EvK, Iizuka J, Kaba IK, et al. Neural network burst pressure prediction in composite overwrapped pressure vessels using mathematically modeled acoustic emission failure mechanism data. Res Nondestr Eval 2011;23:89–103.
[170] Lepikhin AM, Moskvichev VV, Chernyaev AP. Acoustic-emission monitoring of the deformation and fracture of metal–composite pressure vessels. J Appl Mech Tech Phys 2018;59:511–8.
[171] Jiang P, Liu X, Li W, et al. Damage characterization of carbon fiber composite pressure vessels based on modal acoustic emission. Materials 2022;15(14):4783.
[172] Berro Ramirez JP, Halm D, Grandidier J-C, Villalonga S. A fixed directions damage model for composite materials dedicated to hyperbaric type IV hydrogen storage vessel – Part II: validation on notched structures. Int J Hydrogen Energy 2015;40:13174–82.
[173] Yao XF, Meng LB, Jin JC, Yeh HY. Full-field deformation measurement of fiber composite pressure vessel using digital speckle correlation method. Polym Test 2005;24:245–51.
[174] Meng LB, Jin GC, Yao XF, Yeh HY. 3D full-field deformation monitoring of fiber composite pressure vessel using 3D digital speckle correlation method. Polym Test 2006;25:42–8.
[175] Gąsior P, Malesa M, Kaleta J, et al. Application of complementary optical methods for strain investigation in composite high pressure vessel. Compos Struct 2018;203:718–24.
[176] Wang Y, Zhu C, Zhang B, et al. Full-field deformation characteristics of anisotropic marble under compression revealed by 3D digital image correlation. Lithosphere 2021;SI:1098235.
[177] Zhang X, Li D, Wang R. Active speckle deflectometry based on 3D digital image correlation. Opt Express 2021;29:28427–40.
[178] Camacho-Reyes A, Vasco-Olmo JM, James MN, Diaz FA. Characterization of non-planar crack tip displacement fields using a differential geometry approach in combination with 3D digital image correlation. Fatig Fract Eng Mater Struct 2022;45:1521–36.
[179] Nimdum P, Patamaprohm B, Renard J, Villalonga S. Experimental method and numerical simulation demonstrate non-linear axial behaviour in composite filament wound pressure vessel due to thermal expansion effect. Int J Hydrogen Energy 2015;40:13231–41.
[180] Garcia-Martin R, Bautista-De Castro Á, Sánchez-Aparicio LJ, et al. Combining digital image correlation and probabilistic approaches for the reliability analysis of composite pressure vessels. Arch Civ Mech Eng 2019;19:224–39.

[181] De Waele W, Degrieck J, Moerman W, et al. Feasibility of integrated optical fibre sensors for condition monitoring of composite structures - Part I Comparison of Bragg-sensors and strain gauges. Insight 2003;45(4):266–71.
[182] Lin L, Wang X, Yang B, et al. Conditionmonitoring of composite overwrap pressure vessels based on buckypaper sensor and MXene sensor. Compos Commun 2021;25:100699.
[183] Xiaoqiang W, Lunyang L, Shaowei L, Bohan L. Condition monitoring of composite overwrap pressure vessels using MXene sensor. Int J Pres Ves Pip 2021;191:104349.
[184] Zhang L, Qu X, Zhao Z, et al. Health monitoring of composite pressure vessels through omnidirectional buckypaper sensor array. Appl Phys Mater Sci Process 2022;128(3):178.
[185] Zhang L, Qu X, Lu S, et al. Damage monitoring and locating of COPV under low velocity impact using MXene sensor array. Compos Commun 2022;34:101241.
[186] Modesto AJ, Birgul R, Werlink RJ, Catbas FN. Damage detection of composite overwrapped pressure vessels using ARX models. Int J Pres Ves Pip 2021;192:104410.
[187] Munzke D, Duffner E, Eisermann R, et al. Monitoring of type IV composite pressure vessels with multilayer fully integrated optical fiber based distributed strain sensing. Mater Today Proc 2020;34:217–23.
[188] Choi B-H, Seo D-C, Kwon I-B. Detecting impact traces on a composite pressure vessel with aluminum-coating optical fiber using a phase-modulated BOCDA sensor. Compos Sci Technol 2017;142:264–74.
[189] Park SW, Kang DH, Bang HJ, et al. Strain monitoring and damage detection of a filament wound composite pressure tank using embedded fiber Bragg grating sensors. Key Eng Mater 2006;321–323:182–5.
[190] Souza G, Tarpani JR. Using OBR for pressure monitoring and BVID detection in type IV composite overwrapped pressure vessels. J Compos Mater 2021;55:423–36.
[191] Frias C, Faria H, Frazão O, et al. Manufacturing and testing composite overwrapped pressure vessels with embedded sensors. Mater Des 2010;31:4016–22.
[192] Saeter E, Lasn K, Nony F, Echtermeyer AT. Embedded optical fibres for monitoring pressurization and impact of filament wound cylinders. Compos Struct 2019;210:608–17.
[193] Bulletti A, Giannelli P, Calzolai M, Capineri L. An integrated acousto/ultrasonic structural health monitoring system for composite pressure vessels. IEEE Trans Ultrason Ferroelectrics Freq Control 2016;63:864–73.
[194] Laine Eric, Jean-Christophe Dupre, Jean-Claude Grandidier, et al. Instrumented tests on composite pressure vessels (type IV) under internal water pressure. Int J Hydrogen Energy 2021;46(1):1334–46.
[195] Tapeinos IG, Rajabzadeh A, Zarouchas DS, et al. Evaluation of the mechanical performance of a composite multi-cell tank for cryogenic storage: Part II – experimental assessment. Int J Hydrogen Energy 2019;44:3931–43.
[196] Shao Y, Betti A, Carvelli V, et al. High pressure strength of carbon fibre reinforced vinylester and epoxy vessels. Compos Struct 2016;140:147–56.