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Prediction of First Ply Failure of Composite Pressure Vessels Under Internal Pressure: A review

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ABSTRACT

Composite pressure vessels (i.e. types III and IV) are widely used for compressed natural gas (CNG) vehicles, as storage cylinders to reduce the weight while maintaining high mechanical properties. These vessels can achieve 70-80% of weight saving, as compared to steel vessels (type I). So, prediction of first ply failure and burst pressure of these vessels is of great concern. Thus, this paper involved a review of literature regarding the first ply failure and burst pressure of composite pressure vessels (types III and IV). The review included the researches related to the simulation, mathematical modeling, and experimental analysis. The study focused on simulation-related research more than others due to the complexities of mathematical modeling of such problems in addition to the high cost of experimental tests. The results indicated that the stacking sequence of layers, vessel thickness and the type of selected composites were the main factors that mainly affect the vessel burst pressure performance. Accordingly, the optimization in the vessel structure (composite fabric architecture) parameters plays an important role in the performance of burst pressure. This in turn will lead to a high vessel durability, longer life-time and better prediction of burst pressure. Furthermore, the study showed that the prediction of first ply failure is more important than burst pressure knowledge of pressure vessels because it gives an initial prediction of vessel failure before the final failure occurrence. This in turn, may prevent the catastrophic damage of vessel.

1. Introduction

The use of composite pressure vessels (CPVs) has growth more attention in many industrial fields over the metallic vessels due to the wide range applications of these vessels such as aerospace, medical and transportations etc. The pressure vessels normally used to store fluids or gases under a service pressure. The materials used for manufacturing of pressure vessels are either metallic or composite materials which in turns may be brittle or ductile. Metallic pressure vessels are restricted in their usage basically due to high weight and corrosion problems. Otherwise, composite vessels are widely used in the industrial fields because of high strength and stiffness to weight ratio, better corrosion and fatigue resistance. The design of pressure vessels is extremely complex although its looks simple in shape. Because of the different behaviors effected on the pressure vessel such as composites behavior and variables, plasticity of metallic boss and distribution of layup orientation in the dome etc., the pressure vessel considered a very complex structure during the analysis. For the pressure vessels used in high pressure applications, two failure modes should be considered accurately through the design of these vessels. The first ply failure mode which occurs when the deformation increases excessively till reach a permanent value, while the

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other style of failure occurs when the pressure increasing gradually until cause bursting of a pressure vessel and catastrophic failure [1, 2]. Hence, prediction of burst pressure in the pressure vessels design is an essential consideration concerning the safety and reliability aspects. In addition, the burst pressure assessment gives an indication on the factor of safety available over the maximum expected operating pressure (MEOP).

The burst pressure is the minimum pressure required to cause permanent damage on the cylinder by bursting. It is calculated when the internal pressure is only applied to the vessel structure and in this case it will be resisted only by the strength of vessel wall. The pressure vessels can be classified into four categories, according to the composite material sharing in the structure. These four types of pressure vessels are used basically as storage cylinders of compressed natural gas (CNG) in automobiles. Type I vessels (CNG1) are full metallic materials, while Type II vessels (CNG2) represent hoop wrapped metallic pressure vessels with an outer reinforcement area of composite materials. Type III pressure vessels (CNG3) are fully wrapped metallic pressure vessels reinforced with external area of composites and the latest stage of PVs development is the all-composite pressure vessel (CNG4) with plastic internal liner [3]. Moreover, according to the dimension of structure, the pressure vessels may also be thin or thick shell structure depending on the internal diameter of vessel to the thickness ratio.

Pressure vessels include the open and closed vessels and have wide applications such as transportation gas, steam or fluids, thermal and nuclear power plants, aerospace systems and chemical industries etc. Type IV composite pressure vessels are usually made of internal plastic liner of HDPE overwrapping with composite materials which sustain a high range of pressure loading, more safety, lighter and longer lifetime compared to type III vessels [4]. Figure 1 shows the main application of composite CNG pressure vessels in automotive.

In the present article, the cylindrical composite pressure vessels specifically, type III and type IV will be mainly reviewed in terms of vessel composites architecture for different analysis methods i.e. FE simulation, mathematical and experimental approaches.

Figure 1. Application for Composite PVs in busses [5]

2. Literature Review

Due to the increasing demand of industry for using types III and IV composite pressure vessels as these vessels have superior properties such as high strength and stiffness, weight saving, corrosion resistance and long lifetime. These properties make it a successful alternative for the metallic pressure vessels [6, 7]. As such, the current review will be focused mainly on the prediction of burst pressure and first ply failure for composite pressure vessels specifically types III and IV.

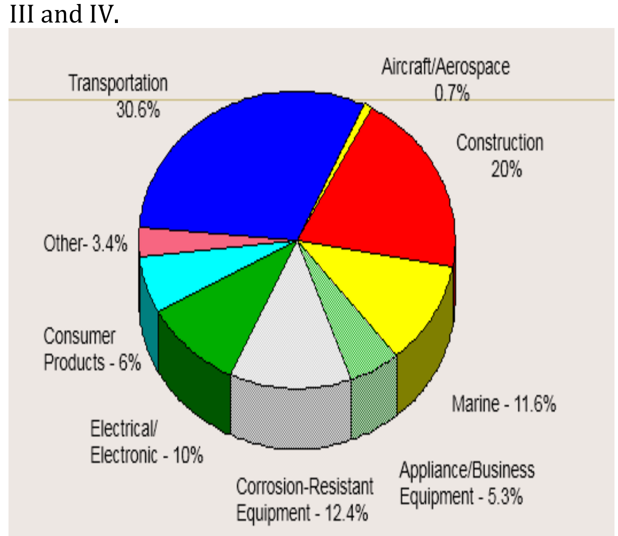

Figure 2. Applications of FRPs for both reinforced thermoset and thermoplastic resin composites (reinforcements and fillers) [8]

In types III and IV vessels, internal liners are normally made of elastic materials while the fiber reinforced polymers (FRP) layers are made of elasto-plastic materials such as carbon, glass and/or Kevlar etc. fibers reinforced composites. Recently fiber reinforced polymer composites have a wide range of industrial and technological applications as compared to the other kinds of reinforced composites. Figure 2 shows the main applications of fiber reinforced polymers (FRP) for both thermoset and thermoplastic reinforcement.

The thickness of liner and the load applied are the main parameters that the designed pressure vessels with liners based on. During the hydrostatic pressure test, the inner liner has a significant job in preventing leakage and maintaining the structure of cylindrical pipe. However, the burst pressure failure mode and mechanical strength of vessel are affected partly by the existence of the liner as reported by [9]. Thus, it is explained that the load carrying capacity is not mainly affected by the contribution of the vessel liner under the impact and internal pressure loading [10]. The literature review can be divided into three sections simulation, mathematical modeling, and experimental analysis based on the discussed literature.

2.1. Simulation Literature

The burst pressure of composite pressure vessels has been numerically studied comprehensively. However, it requires further investigation to achieve the required safety along with regulatory standards for the pressure vessels. A numerical simulation and experimental analyses were investigated by Önder A. [11] to determine the optimum winding angles of composite cylinder and failure of composites based on Tsai-Wu failure criterion. Symmetrical and unsymmetrical samples of composite pipes made of E-glass/epoxy with four layers of total thickness 1.6 mm were used. It was found that, ±55° gave the optimum winding angle for laminates composite PVs at corresponding burst pressure of 7.20 MPa. Wang Y. et al. [12] studied first ply failure of type III pressure vessels made of carbon fiber reinforced polymer (CFRP) with Aluminium liner. Numerical analysis was conducted using ANSYS software to predict burst pressure of vessel based on the maximum stress criteria. Furthermore, an experimental analysis has been done on the real pressure vessel for verification purpose. It has been found that when the internal pressure reaches 65 MPa, the vessel will be completely failed.

Sinha M and Pandit SN [13] studied the burst pressure of cylindrical section composite pressure vessel made of carbon fiber reinforced polymer (CFRP) through FEA utilizing ANSYS software. The modeling is performed at four layers with different fiber orientation angles for both helical and hoop winding of pressure vessel. Tsai-Wu failure criteria was utilized to predict burst pressure for each used fiber orientation. Sulaiman S. et al. [14] studied the burst pressure and the optimum winding angle of type III pressure vessels with aluminum liner. Finite element method using ABAQUS software was used to model carbon fiber reinforced epoxy composite vessel. Tsai-Wu, Tsai-Hill and maximum stress failure criterion were employed for analyzing results. The results showed that the maximum burst pressure was 15.5 -16 MPa corresponding to ±55° fiber angle for a total vessel thickness of 4.57 mm. A theoretical and FEA investigations of burst pressure prediction for CFRP composite pressure vessels were analyzed by Rayapuri A. et al. [15]. Different angles of fiber orientation were used with vessel configuration composed of 8 layers and internal liner with 64 mm total thickness. The maximum internal pressure was 207 MPa which represented the burst pressure of vessel at the fiber orientation ±25° in a symmetrical stacking sequence. Shanmugavel M. et al. [16] predicted the first ply failure of glass fiber reinforced polymer (GFRP) pressure vessel through finite element using ANSYS software. An axis-symmetric model with a solid element 186 was used for 12 layers of 12.8 mm vessel thickness. The results showed that the burst pressure was 35 MPa depending on Tsai-Wu failure criterion. Farhood NH et al. [17] investigated numerically the burst pressure of type IV composite pressure vessels used in automotive as a compressed natural gas (CNG) storage cylinders. The study predicted first ply failure of CFRP vessel reinforced with polymeric liner under different stacking sequence laminates based on Tsai-Wu and maximum stress failure theories. The results showed that the laminate (A) of sequence [90°2/±15°16/90°2] sustained a maximum burst pressure than laminate (B) of sequence [90°/±15°]ns for similar vessel thickness.

Haris HM et al. [18] performed an optimized lay-up composite pressure vessel under internal pressure by using finite element analysis (FEA) code ANSYS to estimate the weight saving of composite PVs with a metallic one. Three types of composite materials S-glass/epoxy, Kevlar/epoxy and Carbon/epoxy were used for optimization under variable stacking sequence, laminate thickness and angle orientation. The analyzed lay-up sequence for laminated were cross-ply $[0_m/90_n]_s$, angle-ply $[\pm\theta]_{ns}$, $[90/\pm\theta]_{ns}$ and $[0/\pm\theta]_{ns}$. For a verification purposes, a developed code in MATLAB based on classical lamination theory was used to predict first ply failure based on Tsai–Wu failure criterion. For all the composite material systems considered, the final results shows that the angle-ply [±θ]_ns is the optimum lay-up also the FE results were compared with theoretical results and very close results were shown. Another study by Wu QG et al. [19] studied the stress and damage behaviors for a composite pressure vessel with aluminum liner utilizing a numerical simulation under internal pressure loading. Carbon fiber of T-700/epoxy was used with a stacking sequence of $[90°_2/±14°_2/90°_2/±14°_2/90°_2/±14°_2/90°_2]$ for the cylinder model through FEA. Four failure modes of damage (the fiber tension and compression, the matrix tension and compression) were adopted by a progressive failure mode. The burst pressure predicted by fiber tensile fracture criterion was in a good agreement with maximum strain criterion, also, the middle part of the cylinder showed the highest values of hoop and axial stresses under service pressure condition. Kangal S. et al. [20] analyzed the burst pressure of carbon-glass hybrid composites for type III composite pressure vessels. Numerical and experimental approaches were used to predict burst pressure and progressive damage of pressure vessel. Two configurations of vessels are fabricated through filament winding machine, fully overwrapped vessel with glass fibers and a similar vessel with additional two layers of CF on the hoop cylindrical section with constant stacking sequence of $[±11°/90°_2]_3$. The results showed good agreements between FEA analysis through ANSYS software and experimental work. Besides, the metallic liner have mainly enhanced the load carrying capacity of burst pressure, while the hybridization of carbon fiber layers did not have significant effect on the results. Some of simulation literature have been summarized with their outcome results in Table 1.

More recently, a parametric analysis was made by Kang H. et al. [21] on type III composite pressure vessel to predict burst strength and stress distribution. FE simulation was established by combining MATLAB and ANSYS software. Hoop and helical winding patterns were used to model two cases of vessel. The results showed that the stresses of the dome were much lower than those of the cylinder. Moreover, a plenty of matrix failure occurred on the helical wound layers followed by fiber failure on the hoop wound layers. Nebe M. et al. [22] studied numerically and experimentally the burst pressure and mechanical behavior of Type IV composite pressure vessels under internal pressure. The effects of stacking sequence and the locations of circumferential ply drop were aimed in the study. The analysis was performed via a commercial filament winding software and compared to the strains on the outer layers captured by 3D digital image correlation. The results showed a better performance of vessel strength when the circumferential and high-angle helical layers placed at the innermost layers rather than the outermost layers. Furthermore, a significant effect of stacking sequence was observed on the burst performance. As such, the degradation of ply drop locations was obtained where the circumferential layers are located as outermost sequence.

Table 1. Literature summary of burst pressure prediction

Author	Vessel specification	Used methodology	Findings and conclusions
Wang Yingjun [2010]	Type III PV with Al-6061-T6 liner, composites used was CFRP.	FE analysis using ANSYS software with a shell element 99 was performed.	The results showed that the burst pressure was 65 MPa and ultimate tensile strength of the first ply of CFRP vessel reached 1210 MPa.
Medhavi [2012]	Composite tube with CFRP (300/LY5052) hoop and helical winding of layups: ± (25°, 35, 45, 55, 65, 75°).	FEA with ANSYS software was used, SHELL 99 with four layers of uniform thickness. Tsai-Wu failure criteria was used.	PV can sustain the maximum internal pressure of 207 MPa at fibers orientation of ± 45° in symmetrical stacking based on the Tsai-Wu failure criteria.
Shanmug-avel [2013]	E-glass/LY556 composites was used. The total thickness 12.8 mm divided on 12 layers.	ANSYS software of solid element 186 is used. Failure theories of maximum stress, Hoffman, Tsai Hill and Tsai Wu were applicable.	The burst pressure was 35 MPa based on the maximum stress theory.
S. Sulaiman [2013]	Type III PV of Al-liner (Al-6061), carbon/epoxy composite (300-LY5052 with six layers of 4.57 mm in thickness.	FEA with ANSYS software was utilized. Tsai-Wu, Tsai-Hill and maximum stress failure criteria were employed for analyzing results.	The obtained maximum burst pressures were 15.5 MPa, 15.6 MPa and 16 MPa for Tsai-Wu, Tsai-Hill and maximum stress theories respectively corresponding to 55° optimum orientation.

Rayapuri Ashok [2013]	Cylindrical CPV with hoop and helical windings made of CFRP T300/LY5052 at various orientation for 9 layers of 64 mm total thickness.	Theoretical and FEA analyses by using ANSYS software were applicable. And Tsai-Wu failure criterion is applied.	The vessel can withstand 207 MPa maximum internal pressure when the fibers are orientated at ± 25° without failure.
Farhood N. [2017]	Type IV vessel of Toray T700 CFRP with hoop and helical patterns with 12 mm total thickness.	FEA with ANSYS software. SHELL 181 with 20 layers of uniform thickness was used. TWSI failure criteria was used.	Results showed a maximum burst pressure of 55 MPa for laminate sequence A, while laminate B was give 45 MPa burst pressure for similar vessel thickness.

2.2. Mathematical Literature

Despite of the analysis complexities of composite pressure vessels under internal pressure, several researchers have investigated first ply failure of pressure vessels via theoretical approach. An analytical and experimental analyses were done by Kam TY et al. [23] in order to study the laminates strength of composite pressure vessels. First-ply failure strength of the pressure vessel laminates was predicted based on the first order shear deformation theory and the classical plate theory together with various failure criteria. Different orientation angles with various number of plies for six laminated composite pressure vessels were tested until failure. It was observed that the optimal designed pressure vessel gave the highest first-ply failure strength and ultimate burst strength for a similar number of plies. Moreover, the results showed that the ultimate burst pressure is generally much higher than first-ply failure pressure which the latter pressure can be considered important condition in the composite pressure vessel designs. Liu PF et al. [24] evaluated the burst pressure and lifetime of composite pressure vessels via analytical and experimental approaches. In order to predict the failure patterns of composite vessels, strength, reliability and stiffness degradation, a progressive failure analysis and damage modelling were conducted.

Camilleri D et al. [25] used the design of experiments technique based on the analytical models of filament wound cylindrical composite pressure vessels to predict the failure load. Experimental and numerical approaches were used for comparison purpose. An optimization for symmetrical and unbalanced laminates with different lay-up sequence was conducted based on the classical lamination theory and numerical predictive techniques. The numerical results predicted fairly well the failure load for symmetrical and unbalanced laminates through TWSI criterion. Furthermore, the design load was accurately established by classical lamination theory for both used laminates of specified material properties. Chang RR. [26] studied the first-ply failure strength on symmetrical laminated composite pressure vessels via analytical and experimental approaches. Optimal angle-ply orientations for the symmetrical shell designed was investigated for different numbers of layers and radius-to-thickness ratios subjected to uniform internal pressure loads. The acoustic emission (AE) system was used to determine the first-ply failure pressure loads of the laminated composite pressure vessels. It is noted that the optimal angle-ply orientations are $[\pm 54°]_{2s}$ for eight-layer cylindrical shells under the considered loading.

2.3. Experimental Literature

To clearly understand the burst pressure events, the experimental analysis must be implemented and analyzed, although the high cost of manufacturing and tests specifically for type IV composite pressure vessels. Cohen D. et al. [27, 28] stated that the strength of the pressure vessel depends not only on composite fibers type used but also on the orientation of fiber and winding techniques. Shen FC [29] proved that the manufacturing of composite pressure vessels through the filament winding technique has to be the most suitable production for components requiring high energy absorption. Most of the previous researches conducted using filament winding technique have been proved the optimum winding angle was ± 55° for the burst pressure loading [30, 31]. Another research was studied by Leh D. et al. [32] to examine the burst simulation of hydrogen pressure vessels manufactured by filament winding. A progressive failure model of burst simulations was conducted on several hydrogen storage vessel and compared to the experimental results to validate displacement and pressure values from modelling. The results demonstrated that modelling was well adapted, for the lay-up tested, to representing the damage behavior of the vessel on condition that certain properties are reset using experimental trials on vessels. Krishnan P et al. [33] investigated the effects of winding angle on the behavior of glass/epoxy composite tubes under multi-axial cyclic loading. Filament wound $[\pm 45°]_4$, $[\pm 55°]_4$, and $[\pm 63°]_4$ pipes were subjected to multi-axial cyclic loading under five stress ratios ranging from pure axial, a hoop to axial, pure hydrostatic, quad hoop to axial, to a pure hoop. The experimental results indicated that each winding angle dominates a different optimum pressure loading condition, namely, $[\pm 55°]_4$ for pure hydrostatic loading, $[\pm 45°]_4$ for hoop to axial loading, and $[\pm 63°]_4$ for quad hoop to axial loading, also three diverse failure modes, i.e. localized leakage failure, tensile axial failure, and weepage failure were observed during the tests.

Ramadhan AA [34] studied experimentally the burst pressure of Kevlar-29/epoxy composite thin wall cylinders under internal pressure loading. The effects of layering numbers on the pressure increase ratio (PIR) of composite pressure vessels was studied. Hand lay-up method has been used to fabricate the specimens and all of them were tested by using the hydraulic pump subjected to a uniform internal pressure loading. It was found that PIR for Kevlar-29/Epoxy Specimens increased with increasing number of layers from 2L to 4L. The results also identified that the pressure increase ratio (PIR) of Kevlar/epoxy composite cylinders was highest ratio from the others cylinders. Also, the results provided considerable advantage for using woven roving fibers in pressure vessels applications. Ramirez JPB et al. [35] investigated the burst pressure of type IV high pressure hydrogen storage vessel and damage modes. An experimental study was conducted on the composite pressure vessel and compared with simulation analysis of developed model based on continuum damage model. The burst pressure was occurred mainly due to the fiber breakage failure mode. Furthermore, the simulation analysis through a complex damage model proved that the vessel also effected by matrix cracking and/or delamination which in turn influenced on the burst pressure. The comparison ratio between the simulation and the experimental burst pressure was 7.74% which is acceptable ratio.

Joselin R. et al. [36] predicted on failure pressure of GFRP composite pressure vessels utilizing the acoustic emission technique under cyclic loading. When the burst pressure reaches 50% of its theoretical value, the acoustic emission data are collected. Then based on the received inferences, a relation was developed to predict the burst performance of this class of vessels. This novel technique can be applied to any other material system to predict the failure pressure and can send out warning signals well before failure occurrence. Sumana BG et al. [37] investigated the burst pressure effects on the carbon and glass fiber reinforced polymer for pressure vessel of internal metal liner under high pressures. An experimental study utilizing high pressure test rig with acoustic emission system was used on aluminum vessel structure at ±55° orientation angle through the filament winding machine. The results declared four types of responses viz, elastic, elasto-plastic, ultimate response and final failure for both tubes thickness of 3 mm and 4 mm. Burst pressure values of carbon/Al FML cylinder were 80% and 82% higher than glass/AL FML cylinder for 3 mm and 4 mm, respectively.

Shao Y. et al. [38] studied the burst pressure of type III composite pressure vessel of Al-liner with winding pattern of ± 15°/90° for two types of matrix resins, an epoxy and vinyl-ester reinforced with carbon fibers. The effect of two matrixs system on the the burst pressure and damage scenario of vessels is experimentally investigated. The results showed a better performance of carbon/vinyl ester vessel compared to carbon/epoxy vessel at 20% for the same fiber content. Moreover, through the microscopic observations the cracks initiation observed first on the carbon/epoxy vessel that other type with many cracks at longitudinal and hoop directions. A more recent literature, Wang D. et al. [39] studied experimentally the residual burst strength of type IV hydrogen composite pressure vessels used in vehicles. The study involved a series of static tests for polymeric liner and later examined the burst test and hydraulic fatigue test for whole vessels. The results showed that the temperature has a significant effect on the mechanical properties of polymeric liner. Besides, the burst pressure tests showed a decreasing values after the long-term fatigue tests. Lainé E. et al. [40] examined experimentally burst pressure of type IV high-pressure vessels through the non-destructive instrumented tests. The study used the acoustic emission together with an optical measurements (3D displacement measuring) to evaluate the pressure vessel behavior. The results showed the importance of combining 3D displacement measuring with acoustic emission for the pressure vessels assessment and comparison them with simulation analysis. Finally, Nebe M. et al. [41] investigated the laminates effectiveness, vessel distortion and burst pressure through the variation of stacking sequence for type IV composite pressure vessels. Experimental and analytical analysis were conducted based on first ply failure criterion. The experimental results stated that there is a difference of 67% in burst pressure between the investigated stacking sequences. As such, the study emphasized a great influence of stacking sequence on the laminate performance.

3. Discussion of literature

From the previous sections of literature, the researchers were mainly focused on the simulation analysis in order to predict first ply failure and/or burst pressure of composite pressure vessels under hydrostatic internal pressure. Despite that, most of simulation investigations have been enhanced using either experimental or mathematical approach in order to adequately validate the results. Based on the reviewed analysis, the concluded results showed that the burst pressure of composite vessel is highly influenced by the fiber orientation of composites and thickness of vessel geometry. Moreover, Tsai-Wu failure criterion showed an accurate prediction of results among the other failure criteria. As well as, the fiber angle ±55° gave the optimum winding angle for composite PVs which cause the highest burst pressure among the other fiber orientations. Generally, the composite vessels fabricated with carbon/epoxy composites sustain higher burst pressure values and showed better response of first ply failure versus the higher cost of manufacturing such vessels.

Furthermore, although many researchers have worked on the composite pressure vessels subjected to internal pressure, but few of them focused on the investigation of burst pressure of the hybrid composites especially for type IV pressure vessels. Hence, this issue is specified as the gap analysis in this field and an additional work need to be investigated considering the effects each of carbon/glass, Kevlar/glass and/or carbon/basalt fibers etc. on the burst pressure analysis of FRP pressure vessels using Tsai-Wu failure criteria to predict the first ply failure and Hashin damage failure criteria to examine the damage initiation of composites.

4. Conclusions

In this paper, a review study for the first ply failure and burst pressure prediction of composite pressure vessels (types III and IV) under internal pressure loading has been conducted. The current work is involved three main approaches to evaluate the first ply failure and burst pressure namely, simulation, mathematical modelling and experimental. Amongst different analyses available, simulation is the more economic analysis and can give reliable and accurate results. Besides, the analytical approach have many difficulties especially with variation of fabric architecture of composites and prediction of damage modes while the experimental evaluation is more accurate analysis but costly and dangerous. In the FE analysis, the results showed that Tsai-Wu and Hashin failure criteria had the best evaluation of first ply failure and damage modes, respectively. Additionally, the stacking sequence of layers, vessel thickness and the type of composites used have the main influence on the first ply failure and burst pressure prediction of composite pressure vessels. As such, lay-up sequence of ±55° showed the optimal orientation under internal pressure loading. Furthermore, the review showed that the prediction of first ply failure is more significant and safe than burst pressure prediction of composite pressure vessels, which can be considered the basis for the burst pressure prediction. Further work should be devoted to investigate the burst pressure and first ply failure on the hybrid composite pressure vessels i.e. types III and IV) and the potential to enhance the structure strength and reducing the cost using hybrid fibers.

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