Engineering and Applied Science Research 2022;49(2):272-287 Review Article

Engineering and Applied Science Research

https://www.tci-thaijo.org/index.php/easr/index

Published by the Faculty of Engineering, Khon Kaen University, Thailand

A comprehensive review on the performance analysis of composite overwrapped pressure vessels

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Received 23 December 2020
Revised 3 May 2021
Accepted 24 May 2021

Abstract

In recent decades due to the emerging use of composites, earlier metallic vessels have moved to composite overwrapped design. Even though the weight reduction is possible over earlier metallic vessels, various factors such as fluid-wall interaction, failure modes and effect of winding pattern in composite overwrapped pressure vessels need to be very seriously considered for getting a successful design. This paper provides a detailed review on various works carried by the researchers to evaluate the performance of composite overwrapped pressure vessels under various design and environmental factors. These variables include the geometry factors (size & shape of dome, length of cylindrical section), design factors (winding angle, winding thickness, thickness of the liner & overwrap, materials for liner & overwrap, interviewing), defects (notches, flaws), loading conditions (internal & external pressure, axial load, torsion, impact, fatigue, vibration) and the performance parameters (burst pressure, fatigue life, failure modes, leaks, deformations).

Keywords: Composite overwrapped pressure vessels, Finite element model, Failure analysis, Performance evaluation

1. Introduction

Composite materials are ultimate choice for lightweight constructions due to its unique properties such as specific density, specific stiffness, etc., A composite overwrapped pressure vessel (COPV) is a vessel consist a metal or plastic liner on which the composite is overwrapped to contain the pressurized fluid. The liner acts as a barrier between the fluid and composite to prevent leakage through micro cracks of composite matrix. Liner also avoids the chemical degradation of composite due to the fluid stored in pressure vessel. The primary advantage of composite overwrapped pressure vessel is the reduced weight approximately 50% compared to earlier metal vessels. The mechanical understanding of COPV is so difficult and it requires unique design, manufacturing as well as test requirements. This is because of the liner-composite interface and non-existence of homogeneity as well as isotropy. The failure modes of composite overwrapped vessels will significantly differ from metal vessel which makes the designer difficult to the identify and design the pressure vessels.

COPV is a composite structure wherein the fibers provide tensile strength and the matrix take shear load. Matrix also acts as an adhesive to hold successive fiber layers. Liner is a barrier over which the composite is wrapped and it may be a plastic or a metal. A strong liner shares the pressure acting on it along with fibers. There are some significant differences between the COPV and metal vessels and those are:

The burst strength of composites like carbon, Kevlar and glass will get reduced due to impact.

Composites will fail by stress rupture when holding the pressure and which is well below the ultimate limit for exposing an extended period. This failure is sudden, catastrophic and the mechanism is difficult to understand.

2. History

In the early 1970s, NASA initiated a program called Firefighter's breathing system program along with various fire service agencies in USA to develop a breathing system for firefighters [1]. Initially the metal vessels are proposed and due to physical constraints in it, the researchers are forced to develop a light weight and high-volume vessels at low manufacturing and maintenance costs. Later the invention of high strength fibers like Kevlar and Carbon made the weight reduction possible. Also, the properties of overwrapped vessels increased more for storing the high-pressure gases like helium and nitrogen in space shuttles. Due to increase in high-end applications of COPV, various test requirements have been emerged to state the load sharing behavior of metal liner and composite overwrap.

COPV may use a metal liner with soft metals like aluminum with minimum load sharing capability and sometimes high strength metals like high strength steels, titanium, inconel to increase the load sharing capability [2]. Later the plastic liners came in to play instead of metals to achieve further weight reduction [3].

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doi: 10.14456/easr.2022.29

3. Design of composite overwrapped pressure vessels

The general design of COPV consists of four phases, namely system requirement analysis, operating parameters analysis, material selection and optimized damage prevention.

System requirement analysis: This phase includes the identification part of service environment parameters (thermal, acoustic, shock and vibration), expected operating parameters (operating pressure and differential pressure) and physical parameters (shape of the vessel, size of the vessel and the type of fluid used in it) [1].

COPV design parameters: This step determines the operational envelope and necessary inputs that are required for design and qualification. This includes the parameters like burst factor, burst pressure, proof pressure, life and various 'ilities' of the pressure vessel [4].

Damage prevention and control: This step identifies the sources of various damages and the effects of it in pressure vessel service with necessary analysis. It also suggests for effective methods to control the damage during design, manufacturing and service phases. This phase also suggests various additional damage protections like damage indicators, covers, etc.., [1].

Material selection: Material selection for pressure vessels will be done based on the proven compatibility and material properties. The effect of various parameters like fabrication, load, corrosion and other environmental conditions are carefully examined to suggest the materials for vessel fabrication, for making the vessel desired in its service life [1].

4. Test methods of composite overwrapped pressure vessels

Testing of pressure vessels being done to establish the assurance and reliability. This is essential for verification, qualification and certification of pressure vessels to accomplish the specified service life at specified service conditions [1]. The various standard tests are described below:

Non-Destructive testing: Various NDT tests like visual, eddy current, ultrasonic, X-ray, radiography are used to determine the internal flaws of liner and overwrap as well as buckling of liner under service conditions [5, 6].

Physical envelope test: This includes the verification of linear dimension, mass and capacity of vessel based on the stated requirements [1].

Proof test: In this test, the vessel is pressurized until the proof pressure at a rate similar to pressurization rate of service and allowed to settle for some time for checking the stability of vessel. During proof test the vessel should not leak or attain any determinable deformation and this will be verified by visual or other NDT methods [7].

Leak test: Leak test is performed at maximum expected operating pressure and during this the vessel should not leak above the specified rate [8].

Pressure cycle test: Pressure cycle test is performed at maximum expected operating pressure for four times of specified life cycle at the critical temperature. The static strength and fracture toughness are verified for worst case temperature [9, 10].

Burst test: Burst test is used to verify the design burst pressure. During this test, the vessel is pressurized until design burst pressure at a specific rate and allowed to settle for time. Further the pressure is increased until the burst occurs [11].

Vibration and external load test: In this, the vessel is allowed to service life vibrations and pressure loads. The external loads are applied with combination of internal loads and relative magnitude as well as destabilizing strains are evaluated along with reaction loads of mounting [12].

5. Manufacturing of composite overwrapped pressure vessels

The manufacturing process of composite overwrapped pressure vessel consist two parts. One is the fabrication of liner and the second one is providing overwrap. Composite overwrapped pressure vessels are constructed over a liner on which the fibers are wrapped. The center portion of pressure vessel is generally prepared by filament winding technique consist of helical and hoop layers. Whereas the domes may be spherical and doilies. Providing the filament winding at domes is little bit difficult, hence drum wound hoop layers are preferred. Initially the liner material is preprocessed and fiber layers are wrapped using a suitable matrix. The carriage unit of filament winding machine moves front and back on a rotating mandrel and places the wet fibers on mandrel. For a unit move of carriage both +ve and-ve weaves will be placed on mandrel and make many crossovers in the vessel. It is possible to produce the vessel with specified capacity and configuration with different weaving patterns depending upon the flexibility of weaving machine.

Then the liner is pressurized and allowed to stretch over its elastic limit. The inner layer of liner will have some residual stresses and will continue its deformed position. The outer layer also stretched but not beyond elastic limit due to lack of intensity of pressure source at outer most point. Then the vessel is allowed to a low temperature heat treatment to increase its elastic limit. Pressure is applied again to test the inner layer with a magnitude which will not allow the inner layer to stretch beyond its elastic limit. This process is to ensure the inner surface having enough residual compressive strength to balance the tensile tresses induced during discharge. This process also increases storage volume and resistance to stress corrosion cracking.

The fibers made passed into resin and wound over the liner in relation to one another, normally in longitudinal, helical and hoop directions with respect to the axis of liner. The wounding consists of several serious factors like wound pattern with respect to the axis of liner, winding tension and resin content.

6. Types of pressure vessels

Type I: Full metallic pressure vessel
Type II: Metallic liner with hoop-wrapped composite pressure vessel
Type III: Metallic liner with fully overwrapped composite pressure vessel
Type IV: Polymer lined composite pressure vessel
Type V: Linerless composite pressure vessel

The schematic of different pressure vessel types was shown in Figure 1. Initially the vessels are formed from monolithic metals and problems associated with this are weight and tendency for corrosion from external environment. Then the usage of composites in pressure vessel has started and earlier drawbacks are reduced. Among which type III vessels unlike the type IV and Type V, shares a significant amount of load among the liner and composite overwrap. The optimum distribution of load between liner and composite is an ultimate factor in type III vessel design. In type II vessels, the composites are overwrapped only in hoop direction of cylindrical portion. But in type III vessels, the wounding will be on both helical and hoop directions. Also, winding will be on both cylindrical and dome portions of the vessel. The optimum winding angle to hold the hoop versus axial loads in the ratio of 2:1 under internal pressure is 54.7° [13]. But it is not possible in the dome portion because, the filament will not stand in dome portion with that much of winding angle. So, practically minimum winding angles are used in dome portion of type III vessels. Type IV cylinders are the plastic liner overwrapped vessels and uses high-density polymers such as high-density polyethylene as liner. In type IV vessels, the liner will not provide rigid support to the membrane of composite overwrap and they are susceptible to impact damage.

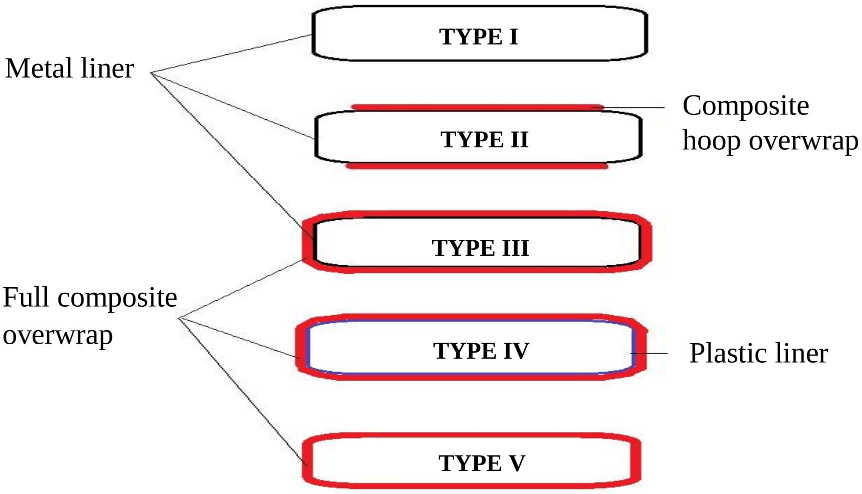

Figure 1 Types of pressure vessels

The weight saving capability of the pressure vessel was measured with a parameter called performance index. It describes the performance of the pressure vessel for given operating conditions with respect to the vessels weight.

$$Performance\ index\ = \frac{PV}{m}$$

where P is operating pressure, V is volume of the vessel and m is mass of the vessel. High performance index shows the vessel good for required operating conditions with low weight. Among all types, the plastic liner vessels have high performance index. The performance index of various pressure vessels were shown in Figure 2 [14].

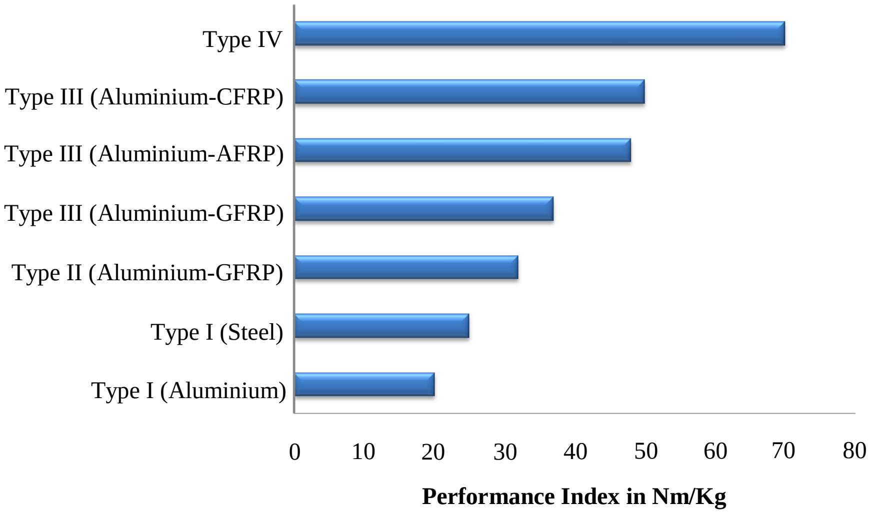

Figure 2 Performance indices of different pressure vessels

7. Applications

Compressed gas storage tanks for cryogenic operating environments used in satellites and space shuttles [15, 16]
Air suspension and pneumatic pressure reservoir for passenger rails [17]
Portable water and air reservoir for rails and aircrafts
Tanks for firefighting helicopters and shoulder fire extinguishers [17]
Storage tank for aggressive chemicals [18]
Storage tanks for compressed natural gas [19]
Casing of gas generators and rocket stages [20]

8. Standards for composite overwrapped pressure vessels

The failure of pressure vessel can be catastrophic and this should be avoided by design. To avoid sudden bursting, some fail safe mechanism should be used and in that the crack initiation pressure should made lower than the burst pressure from design. Many regulatory standards such as ISO [ISO 16528-1:2007 & ISO 16528-2:2007], AIAA [ANSI/AIAA S-080A-2018 & ANSI/AIAA S-081B-2018], MIL-STD [MIL-STD 1522A], EU [2014/68/EU & 2009/105/EC], UN [ASME Code & NASA-STD-8719.17], etc., are there to establish the guidelines in design, manufacturing, testing and certification of pressure vessels.

The generalized requirements from regulatory bodies for certification are listed below:

Service pressure: A specified service pressure for all environmental conditions with nearly 100% reliability & safety.

Service conditions: A specified life time with regulated environmental conditions such as temperature, load and humidity.

Burst pressure: The minimum burst pressure will vary from standard to standard and the vessels burst pressure should be higher than minimum burst pressure. The burst safety factor requirement of various pressure vessels was shown in Figure 3 [14].

Fatigue performance: The cylinders should perform up to the specified cycles under service pressure during that the failure should occur by liner leakage and not by the burst.

Composite flaw tolerance: This standard is used to demonstrate the flaw damage tolerance of COPV. In this, the artificial flaws are introduced and pressures are applied. During this process, the vessel is allowed to leak and should not fail by rupture.

Impact damage resistance: The vessels after the impact may fail by leakage and should not by rupture or burst.

Bonfire resistance: This regulates the vessel during fire. Excessive storage pressure should not build up in vessel due to the temperature rise and should activate the pressure relief mechanism fitted in it when the critical pressure level is reached.

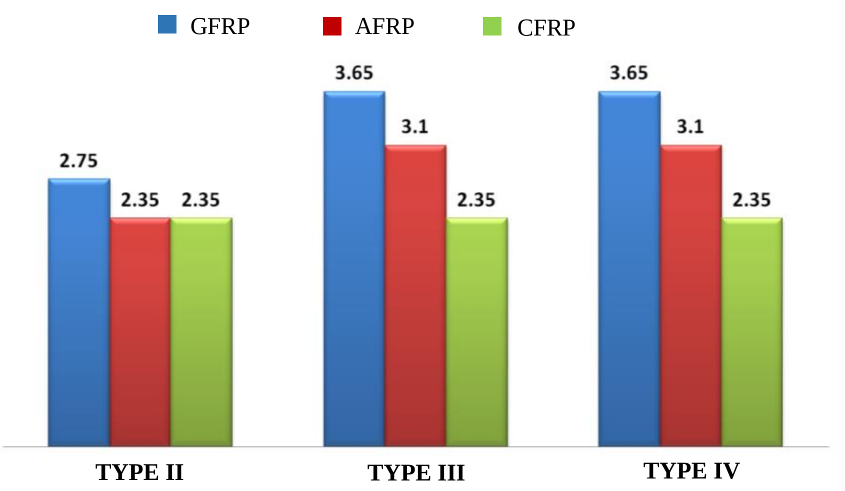

Figure 3 Burst safety factor requirement for various pressure vessels

9. Failure modes of composite overwrapped pressure vessels

The pressure vessels which are made by the continuous fibers will feel tension when it is subjected to the internal pressure. This leads to failure of the vessel including fiber breakage, interlaminar matrix crack and interfacial cracks. The hoop stresses introduced by internal pressure will lead to the most critical failure mode called fiber breakage due to tensile force induced in it. The hoop stress developed in the cylinder is given by

$$\sigma_h = \left[\frac{\left(P_i r_i^2 - P_o r_o^2\right)}{r_o^2 - r_i^2}\right] - \left[\frac{r_i^2 r_o^2 (P_o - P_i)}{r^2\left(r_o^2 - r_i^2\right)}\right] \tag{1}$$

Where p and r denote the pressure and radius respectively. The subscripts i and r are denoting the variables at inner and outer most layers respectively.

Generally, the failure of COPV will be classified into two categories. One is burst and the other one is leak before burst. Leak before burst should be provided with additional care in all the stages of design, manufacturing and service. Non-Destructive Techniques are used to find out the leak before burst at an initial point of failure. At any stage, stating the failure mode of a COPV with certainty is more difficult when compared to metal vessels due to the interaction of liner with composite. The common failure modes of COPV are:

Stress rupture failure of composite overwrap: Stress rupture is a sudden failure that can occur in normal operating conditions. The complete failure mechanism of stress rupture is still not understood. The state, mode and location of the stress rupture is generally random and not detectable prior to the damage. The amount of pressure, duration of pressure and temperature experienced will contribute to the degradation towards failure.

Burst from Over pressurization: This type of failure occurs at design burst pressure with leakage or rupture. The burst pressure will be calculated as the function of burst factor, environmental correction factor and MEOP (Maximum expected operating pressure).

Fatigue failure of the metallic liner: Fatigue failure will occur due to the loads acting on various parts of COPV. The vessels will undergo some detrimental deformation or leakage or rupture in their specified service life. Unlike the stress rupture failure, this can be well understood and the effects of this could be analyzed with good accuracy. The analysis will incorporate the material properties, number cycles, stress amplitude and residual stresses.

Burst due to the damage: In this case, the operating loads (pressure) will induce a great potential for damage to grow. The minimum length of crack should be determined by evaluating the potential of a flaw. When the flaw become as a thick damage, it will lead to burst of COPV. In the case of overwrap design, if liner leaks, then composite will allow the leaking fluid to pass through it. So, the composite rupture will not occur.

10. Mechanics of composite overwrapped pressure vessels

The theory of thin shells provides theoretical framework for understanding the mechanics of COPVs. The stress distribution of COPVs is non-uniform because of various factors like liner geometry, overwrap winding patterns, composite-liner interface characteristics, etc., The elastic-plastic behavior of liner is also an important factor in determining the stress state of overwrap. The detailed procedure of COPV finite element analysis was shown in Figure 4. Assuming the linear elasticity, the stress distribution in the composite over wrap can be defined as

$$\sigma_c(x, P_c) = f(x)\sigma_c^n(P_c) \tag{2}$$

where $f(x)$ is the form function of the spherical coordinate vector x and $\sigma_c^n(P_c)$ is the nominal stress value of the composite overwrap as the function of overwrap pressure load. The total pressure applied on the vessel will be the sum of pressure on the overwrap and pressure on the liner.

$$P = P_l + P_c \tag{3}$$

Where the subscripts l and c denote liner and composite respectively.

By taking R is radius and t is thickness, for thin shell analysis $R_c \approx R_l > t_c, t_l$ and the membrane stresses are given as

$$\sigma_l = P_l \frac{R_l}{2t_l} \tag{4}$$

$$\sigma_c = P_c \frac{R_c}{2t_c} \tag{5}$$

According to shell theory, the mid plane radii overestimates the stresses when compared to elasticity solutions and inner radii holds good results with stresses on inner wall from the above equations. From the fundamental netting assumption, the stress on fiber was given by,

$$\sigma_f = \frac{\sigma_c}{v_f/2} = \sigma_c \frac{2t_c}{t_f} = P_c \frac{R_c}{t_f} \tag{6}$$

Where subscripts f and c denotes fiber and composite respectively.

From the basic design fact of composite, the following condition should be met to avoid failure,

$$\frac{\sigma_f^u}{P_c} > \frac{R_c}{t_f} \tag{7}$$

Where the superscript u gives the variable at ultimate point.

And the load carrying capability of liner after yield point is given by

$$P_l^y = \sigma_l^y \frac{2t_l}{R_l} \tag{8}$$

Where superscript y gives the variable at yield point.

If the liner is perfect after yield point, the liners load carrying capability will be constant and the load carried by the composite is given by

$$P_c = P - P_l^y \tag{9}$$

Then the burst pressure of composite could be found from above equation and it is given by

$$P_B = P_c^u + P_l^y \tag{10}$$

Also the pressure carried by composite at burst is given by

$$P_c^B = P_B - P_l^y \tag{11}$$

and the ratio P_c^B/P_c^u is called as strength efficiency of composite overwrap [12].

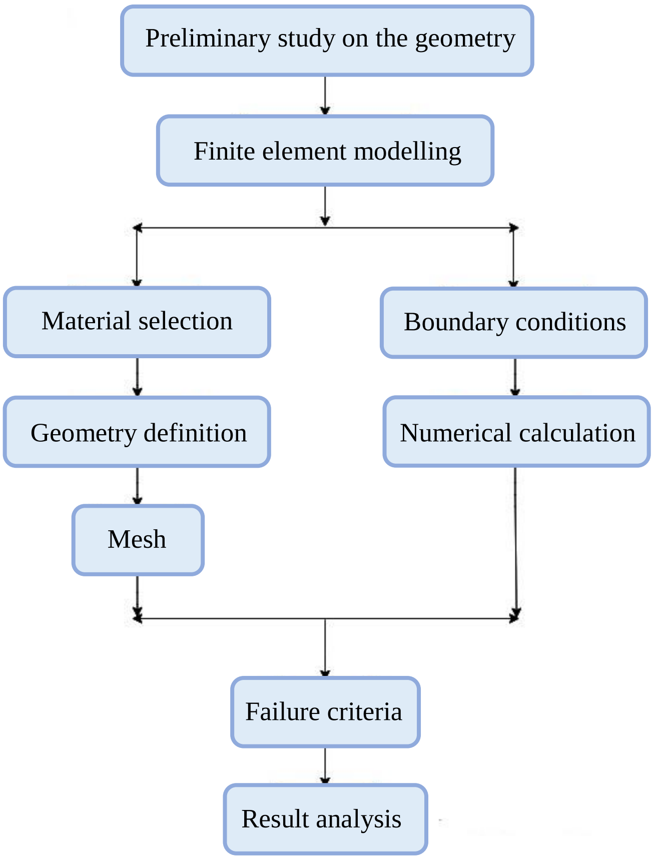

Figure 4 Steps involved in the finite element analysis of COPV

11. Performance analysis of composite overwrapped pressure vessels

11.1 Buckling

Buckling is one of the primary failure modes in pressure vessels, occurs due to elastic instability. Since the stability is primary concern in many applications, analysis of buckling loads is essential for reliable functioning of vessel. Generally, the experimental output is used in pressure vessel design, but there are few cases in which the design is entirely rely on empirical data. The best example for the empirical based design is externally pressurized hemispherical/tomispherical dome based pressure vessels. Combescure et al. conducted an experimental buckling study on 42 pressure vessels having different geometries and found large discrepancies between experimental findings and theoretical predictions. The deviations are found to be vary from -30% to 40% and the details are shown in Figure 5 [21]. These discrepancies between the experimental and theoretical critical buckling loads urged the research community to fine tune the experimental techniques for buckling tests. Now, the experimental methodologies are well improved for buckling studies and matches well with the theoretical as well numerical predictions [22]. Initial geometric imperfections, nonlinear pre-buckling and effect of combined loads are few areas having scope to investigate further. However, the sensitivity of the initial imperfections can be reduced by surrounding the pressure vessel with a compliant core [23]. In fact, the high-speed photography and photoelasticity are also employed in the buckling analysis of pressure vessels. A large number buckling studies were conducted on the externally pressurized cylindrical shells with corrosion and artificial damages. These studies suggested, the pressure vessels with corrosion damage should go for repair or the vessels should be operated within the modified safe regions and the studies also cautioned that repair in the pressure vessels may induce residual stresses, geometrical distortions, etc., [24]. Apart from the external pressure loads, the vessels which are subjected to axial compression, also investigated a lot by researchers. The complication of uneven load will arise when there is segment to segment interaction under axial compression and this can be reduced by filling the segment gap by shimming [25]. Eliminating the gap will lead to variable hoop contact and then to localized plastic deformation under axial compression followed by asymmetric buckling. Figure 6 shows the drop in the critical buckling load of three different cylinders having sinusoidal waviness with amplitude (A) at the ends, denoted by wave number (N) under axial compression. Typical imperfect cylinders with amplitude of waviness to thickness ratio 1, can able bear only 40% of the estimated buckling load. The axial length imperfection plays a dominant role in reducing the buckling load rather than number of sinusoidal wave [26]. But expecting load in the form pressure or axial load alone during service is a very limited case and one should look for performance of vessel under combined loading. In the case of combined loading, the initial imperfections having minimal effect over buckling strength under internal pressure than other sources. In many instances, stable post buckling behaviour was noted under the combined influence of internal pressure and bending. With combinations other than bending, the internal pressure induces accelerated elasto-plastic buckling [27]. When come to numerical analysis of composite pressure vessels under buckling, the shear deformation theory can be adopted to identify the transverse shear effects in delamination buckling and post buckling of composite cylindrical shells [28]. The cylinders will not recover initial buckling pressure after buckling and that leads to the collapse. The failure mode in that case, depends on helical winding angle [29]. The delamination size and shape plays a vital role in delamination growth rate, growth direction and buckling load of the cylinder than others [30]. The winding pattern has dominant effect on buckling pressure than the layer thickness [31].

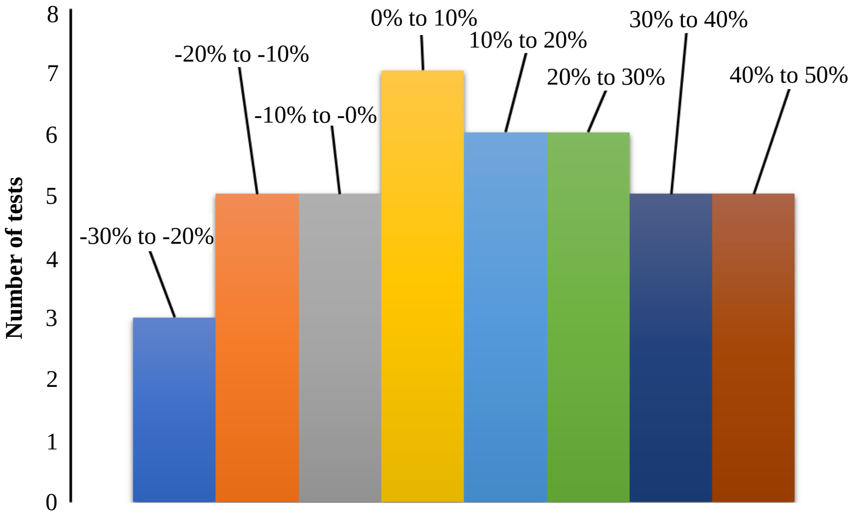

Figure 5 Error % of 42 conducted experimental buckling tests

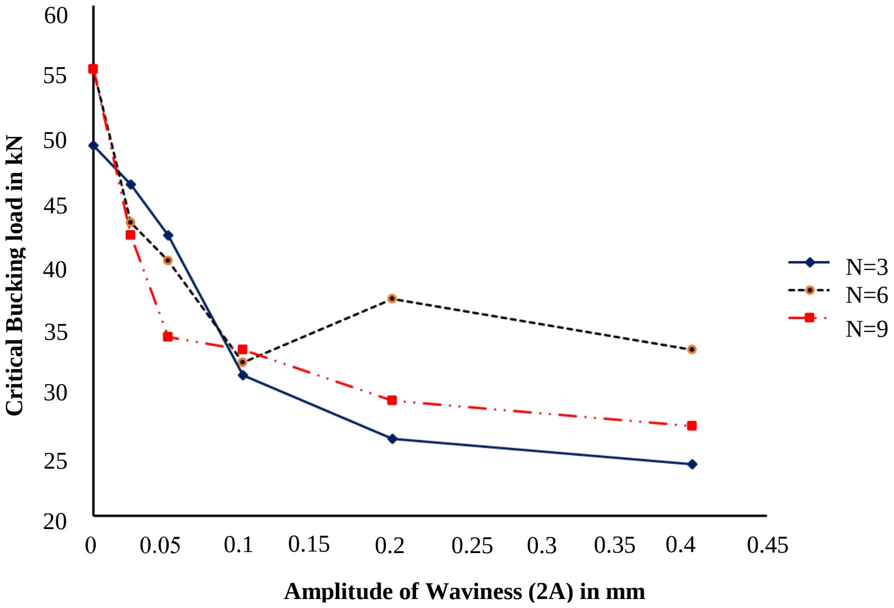

Figure 6 Effect of waviness in the critical buckling load under axial compression

11.2 Impact

The COPVs which are used in unmanned vehicles and spacecrafts may subject to impact damage. Impact loading on loaded pressure vessels will induce catastrophic failure than any other type of loadings. In many instances, failure occurs in the form propagated damage under influence of internal pressure of vessel rather than direct impact rupture. The direct rupture is not an acceptable one in view of pressure vessel design and the damage may be acceptable under proper design optimizations. Since the composite overwrapped pressure vessels have plenty of applications in the cryogenic conditions, the temperature effects also need to be considered during impact analysis. But the safety standards limits the number of high velocity impact studies conducted on pressure vessels under cryogenic conditions [32]. Over the years, the impact studies were conducted on pressure vessels subjected to different internal pressure starting from vacuum, under different temperatures. On instances, the velocity of impact, geometric parameters and material properties are also considered as variables for impact study. The walls of pressure vessels will be subjected to bi-axial stress state because of internal pressurization. This makes the impact analysis of pressure vessels complicated than the impact analysis of other elements. But, within the range of operating conditions the stress field on the wall of vessel will not affect the probability of perforation under impact. However, the internal stress field accelerates the extend of damage after impact [33]. By carefully considering the operating conditions and material properties along with impact conditions, it is possible segregate the effect of impact into rupture and non-rupture regions [32]. Figure 7 shows the NASA’s Ballistic Limit Equation (BLE) 1993 & 2001 for normal and 45^{o} oblique impacts to segregate perforated and nonperforated regions of pressure vessel under ballistic impact. Studies suggest that the design parameters should be chosen based on the operating conditions and projectile nature [34].

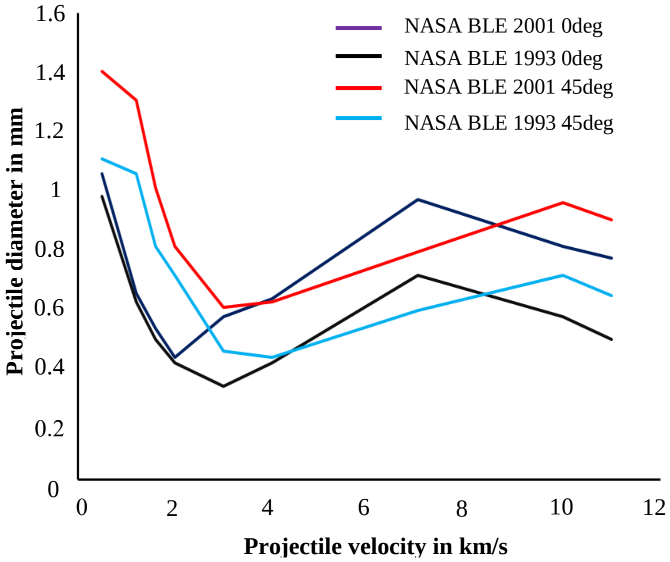

Figure 7 NASA’s BLE for normal and oblique impacts

High degree interweaving usually eliminates the propagation of delamination when compared to low degree interweaving. The fiber undulations will be formed on the crossovers of filament winding. It reduces the stress wave propagation as well as the inter-ply shear stresses during impact. Propagation of delamination away from the impact will be induced by local shearing through the stress waves along the filament band interface at impact [35]. Higher impact energy will give higher penetration depth and higher rate of preloading will affect the performance of specimen significantly [36, 37]. Burst predictions mostly depend on the strength properties of material during impact [38]. Peeling of the vessel is high in the low-density weaved specimen when compared to the high-density weaved specimen. The damage area is small in the high-density weaved vessel when compared to the low-density weaved specimen and it varies depend on impact conditions. When the specimens are preloaded, high-density weaved specimen is less sensible to impact at lower energy level when compared to the other. Number of crossover weaving limits the damage tolerance of vessel with inverse proportionality. When the COPV shell is perforated with high velocity impact, the waves will be induced in the fluid stored in it. This may also affect the damage and failure due to the pressure pulses generated by shock wave [39]. Even though plenty of literature is available for the design of pressure vessels under impact, the research is still lagging for the systematic approach to attack design problems [40]. Since many of the studies are based on the orthotropic walls, its applicability should be checked for the complex interweaving patterns through numerical and analytical means.

11.3 Stress-strain behavior

Stress-strain behavior of vessel will define the performance ultimately under any kind of loading condition. Usually, the linear theory is preferred for analysis by considering little elastic deformation. But in reality, for larger pressure, deformation will beyond the elastic limit that will completely differ from linear theory. In many studies, the netting analysis also have been used for predicting the stresses. In general, the helical layers are not preferred to handle the axial stresses than doilies and the doilies can able to bear the radial stresses too. The axial and hoop stress distribution of multilayer cylinder at ply interfaces will vary with respect to the fibre orientations [41]. Geometric non-linearity, material nonlinearity, dome geometry and dome thickness will play a vital role in the stress distributions [42]. Under internal pressure, the metallic liner has considerable effect in resultant stress and displacement [43, 44]. The winding angle and layer thickness will also affect the stress distribution of vessel under internal pressure [45]. Ply based modeling will determine the stress distribution accurately in numerical analysis when compared to others [46]. The increase in number of layers will proportionally reduce the strains in liner [47]. Multi-layer cylindrical composite pressure vessels under internal, external and interlaminar pressures will have stress variation across the thickness [48].

11.4 Health monitoring

Health monitoring in structures avoids catastrophic failures with prior intimation and it is required for certifications too. Usually, the pressure vessels will be tested for every 2-5 years through pressure test to get certification. A pressurized fluid will be applied on the vessel to check its structural integrity by comparing with tolerance limit. This is costly and time consuming one for the industry sector. To avoid the pressure test recertification, many health monitoring techniques have been proposed. Structural health monitoring techniques looks for the changes induced in the structure due to damage for identification, localization, and quantification of the damage. Early in 1970’s health monitoring has been started to use for damage assessment and maintenance fields. Health monitoring system employs a wide range of sensors to collect information from the structure and the collected information was processed by data acquisition system. The process of structural health monitoring in pressure vessels was shown in Figure 8. But the capability of health monitoring systems relies on sensors which are being employed and statistical means used to process the data for potential detection of damage. The anisotropic nature and complex wound patterns of pressure vessel makes the extraction of damage signatures difficult. But the fabrication process allows a path to embed the sensors within vessel for in-situ health monitoring. Since the COPV uses composite materials, the health monitoring system should be capable to detect the delamination, debonding, matrix cracking and fiber breakage to become an optimal system [49]. Well established NDT techniques such as radiography, thermography and electro-magnetic techniques are not preferred in COPV in-situ inspection because of its non-applicability and higher cost requirement. Even though the acoustic based techniques such as acoustic emission and lamp wave techniques are employed in pressure vessels, determining the reasons for transient acoustic emissions is little bit involved due to Kaiser effect [50]. Hence, the inbuild electromechanical sensor networks such as strain gauges, fiber optic sensors, piezo electric sensors are highly recommended for pressure vessel problems. But acoustic based methods are found to useful in the fatigue analysis of pressure vessels [51]. Guided waves are also employed in the pressure vessels for damage detection. Piezo electric transducers attached on the outer wall of pressure vessels are used to generate such guided waves [52]. Recently optic based whole field non-contact health monitoring methods also receiving attention towards the pressure vessel problems. Digital image correlation, Speckle interferometry, Laser doppler vibrometer are the typical examples for non-contact type whole field methods. The prime difference between conventional NDE methods and whole field technique is that the whole field technique is looking for global structure signature for health monitoring. Wherein the NDE methods concentrate on local signatures and applicable for component level only. Most of the global health monitoring techniques are using vibration response of structure for the structural health evaluation. Few of the vibration characteristic that are used in pressure vessel analysis are natural frequency, modal damping, mode shape, mode shape derivatives, modal strain and modal strain energy [53]. But the sloshing effect of pressure vessels from the internal fluid should be carefully considered while extracting the damage signatures [54]. In addition to sloshing effect, the environmental factors such as pressure, temperature, humidity also need to be considered carefully for long term measurements. While concerning the long-term measurements, wireless sensor networks provides significant potential for health monitoring systems over conventional wired systems. Strain gauges, gyroscopes, piezoelectric transducers, laser doppler vibrometer, fiber optic sensor are the most used sensors in vibration based health monitoring systems. Multi-axis fiber optic sensors have been employed for measuring the axial and transverse strain fields to quantify the delamination on pressure vessels subjected to impact [55]. Circumferentially overwrapped fiber optic sensors embedded in the helical direction of pressure vessel are also used for damage detection of pressure vessels [56]. Eddy current based MWM-Array's monitoring is well proven method used to analyze the performance of pressure vessels during cyclic pressure loading. It shows the conductivity of composite decreases when the pressure is applied on composite and decrement will be more in helical direction when compared to hoop direction [57]. Fiber optic sensor embedded high-definition strain gauges are also used for the health monitoring systems. In this technique, strain gauges are placed in hundreds of locations of pressure vessel in the manufacturing stage of vessel. By using Optical Frequency Domain Reflectometry technology, the strain readings from various gauge locations are obtained through telecommunication cables to monitor the structural integrity and identify the damages in the flask, when the vessel in rack itself [58, 59].

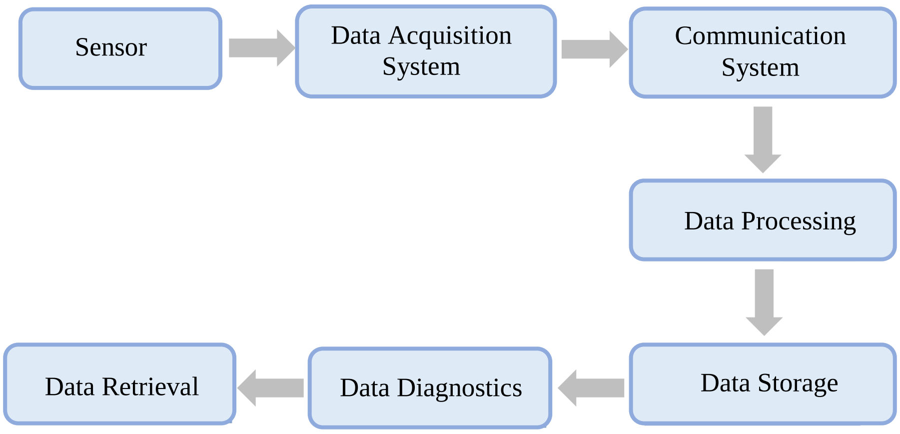

Figure 8 Process of structural health monitoring

11.5 Burst pressure

Early attempts on the pressure vessel analysis primarily concentrated on first ply failure. But recent studies shifted the focus from first ply failure to burst pressure for better characterization of pressure vessel. Burst pressure is the primary measure for estimating efficiency of pressure vessel. Maximum stress failure criteria, Stiffness degradation model, First ply failure criteria and Tsai-Wu failure theory are consistently used in literature for finding out the burst pressure [60]. In burst pressure estimation, the stiffness properties were noted to be degrading independently from damage variables [61]. Burst pressure induces the matrix cracking and leads to debonding at interfaces. The ultimate load bearing capability of pressure vessel can also be calculated with burst pressure by carefully addressing the interlaminar and intralaminar failure modes [62]. Tsai-Wu failure theory finds the burst pressure in numerical analysis with higher accuracy [63]. The designs which are utilizing the tensile strength of fibres for resistance against loads induced by the gases will have better performances than others [64]. As like the other measuring variables, burst pressure is also primary dependent of vessel material and stored content [65, 66]. Increase in fiber volume ratio tends to increase the fiber strength that leads to higher burst pressure [67]. The burst pressure of pressure vessels can be varied by taking the winding thickness and angles as design variables [68]. The damage propagation and rupture life are highly variable under constant pressure, also there is some significant changes in the energy emission during failure [69]. Composite failure and liner failure are the primary burst failure modes and fibre orientation has a strong influence on the shape of damaged zone [70]. The braided reinforcement configuration has the highest damage potential than others under the static pressure [71]. Burst strength will vary when winding angle and layer thickness changes. The burst pressure will be a depending factor of initial defect and vessel will have highest burst pressure which having less initial defect. The liner will have high strength and leak resistance when the composite shell is stiffer.

11.6 Temperature

Since pressure vessels having variety of applications, its working temperature will play a vital role in performance. Generally, the materials are insensitive to sharp notches under a range of temperature. But the performances of plain metallic and plain polymeric liners are unsatisfactory [72]. The cryogenic cyclic pressure and vacuum environment will not degrade the structural integrity of vessel

[73]. The burst pressure will change depend upon the material under temperature variations, generally will get degraded [74]. The performance of vessel linearly degrades with increase in temperature under static pressure [75]. The effect of temperature in burst pressure will vary the rate of fiber breakage, matrix cracking, plasticity and delamination [76].

11.7 Load sharing

The load sharing between the liner and the overwrap will define the performance of pressure vessel under same states. For higher internal pressure load, the stress on liner will be low because of the effect of composite load sharing. The Von-Mises stress along the longitudinal axis of vessel will peak at dome region for the liner and at shoulder region for the composite overwrap. Elastic compression-tension mode will be in liner and tension-tension mode will be at composite overwrap at the low-pressure levels [77].

11.8 Debonding

The debonding tendency of pressure vessel will leads to catastrophic failure and makes the vessel ineffective irrespective of configuration, environment and loading conditions. The effect of debonding in membrane region is less and, in the weld and transition regions, it is critical. In these regions the stresses in composite increases and may lead to fiber failure. When the de-bond size increases the stress also increase and chance of continuing de-bond in nearby regions [78].

11.9 Fatigue

The cyclic loadings introduced in vessels during operation will yield the brittle failure of vessel within small stipulated time. Most seen failure modes of pressure vessels under fatigue are whitening, leak and burst. Charging and discharging the fluid content inside the vessel will also contribute to vessel fatigue. Stored content of pressure vessel significantly influences the fatigue life of vessel [79]. For determining the fatigue life of composite overwrapped pressure vessel, the hydrostatic fatigue tests were used primarily [80]. In practical applications, filling fluid content inside the vessel will induce thermal fatigue along with direct fatigue stresses [81]. The success of fatigue analysis relies on the exact prediction of service cycle loads. Lower service loads employed in the fatigue modelling may overestimate the fatigue life of vessel. The vessels should be inspected on a regular basis for service induced defects and their effects should be included in fatigue analysis. When the vessel approaching near to the predicted fatigue life, NDE methods also should be employed to detect the service induced damages for safe operation of vessel [82]. Obtaining the fatigue life experimentally is a time consuming process. Hence numerical and analytical frameworks are required for the proper design of pressure vessel in minimized time frame against fatigue [83]. The detailed procedure of PDM based fatigue analysis was given in Figure 9 [83]. But the available literature for the theoretical fatigue life prediction was so limited. Implementation of the statistical methods such Progressive damage modelling (PDM), Taguchi method, Stochastic fatigue modelling have refined the fatigue analysis for better life prediction [84]. Along with the fatigue life, other essential factors such as stiffness degradation, random fatigue life are also possible with statistical methods.

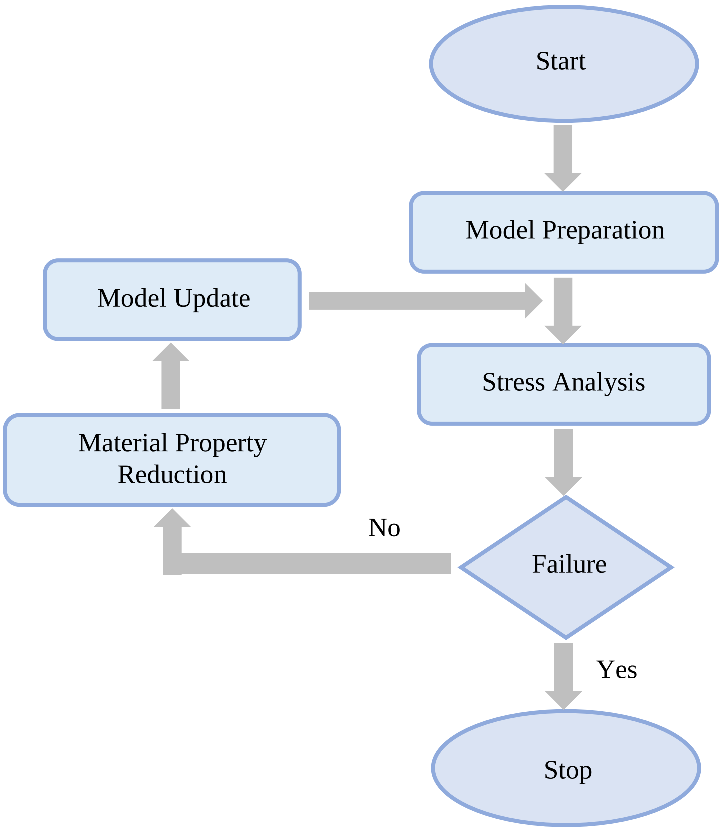

Figure 9 Process of PDM based fatigue analysis

Progressive damage modelling is a theoretical framework for the fatigue modelling. Along with fatigue life model, PDM uses material degradation rules and failure criteria to predict and analyse the damage behaviour. Under fatigue loading, the damage will accumulate cycle by cycle and finally will lead to the fracture [85]. Due to complex damage mechanism of composites, it very difficult to relate the small damages such as micro cracks and small strains to fatigue loading. PDM helps to overcome this issue by relating the small damages into physical parameters such as stiffness and strength, for defining the damage variables. PDM calculates ply by ply damage variables by analysing stresses in the layers. Hence, cycle by cycle degradation of vessel properties are obtained from calculated damage variables. Figure 10 shows the detailed process of PDM based fatigue analysis. Figure 10 shows the comparison between the PDM based fatigue life with the experimentally obtained fatigue life values [84].

Since many standards are suggesting the constant amplitude cyclic loading for fatigue life prediction, it will not help much to predict the real-life fatigue behavior. The stochastic analysis providing the way to analyze variable amplitude loading spectrum as seen in the service environments [86]. The detailed process of stochastic fatigue life prediction was given in Figure 11 [86]. Stochastic fatigue analysis essentially implements PDM by treating the loading as random scheme. In the stochastic fatigue analysis, loading history and sequence are captured and fatigue modelling was performed at each sub part of overall loading spectrum. For the variable amplitude fatigue loading, load spectrum, maximum and minimum amplitudes of loading are chosen randomly in the stochastic analysis.

The parameters like tensile strength, interlaminar shear strength and fracture toughness are degrading with the elevated temperature also produces significantly large plastic deformations when compared to the vessel in normal temperature under fatigue loading. Fatigue also results the reduced burst pressure of pressure vessel. The hydraulic fatigue results matrix cracks and interlaminar debonding and the damage are more in initial cycles when compared to final stage of cycles [80].

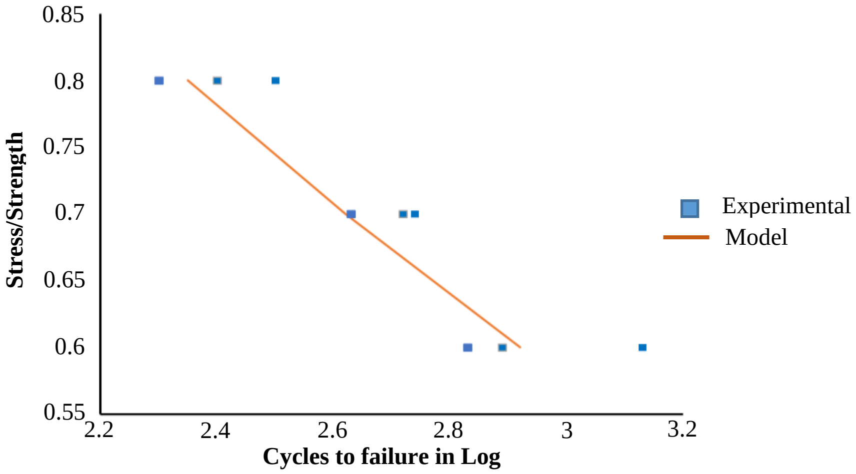

Figure 10 PDM Based fatigue life comparison with experimental data

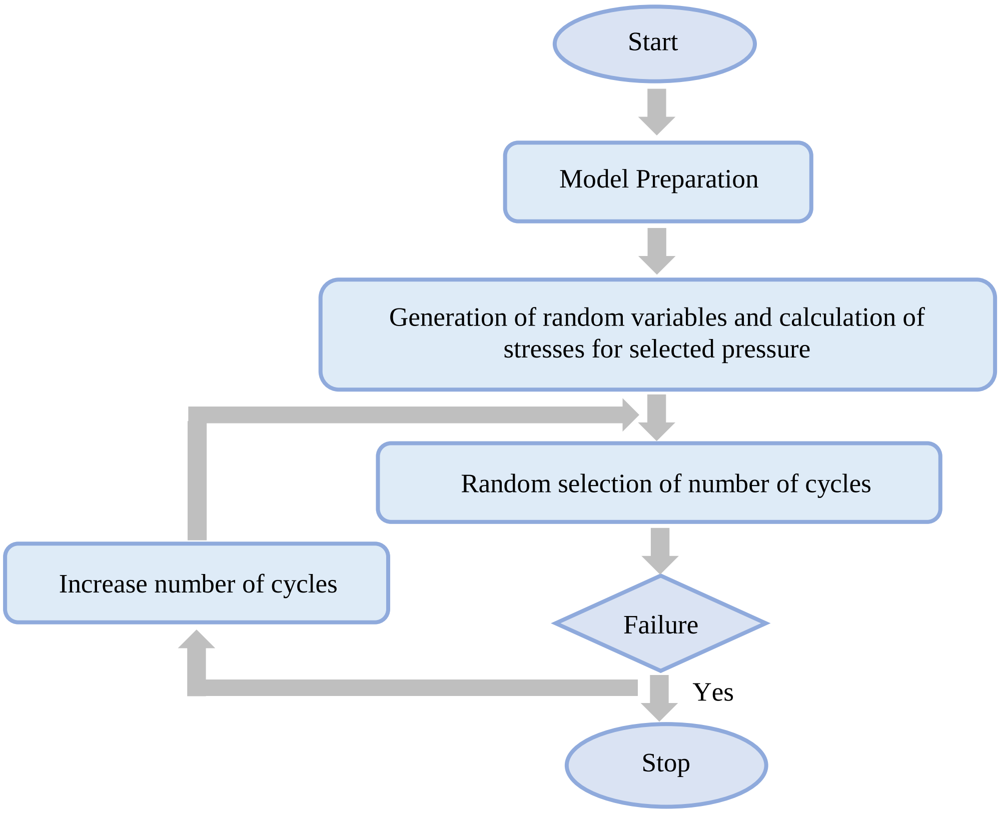

Figure 11 Process of stochastic fatigue life prediction

11.10 Property prediction

COPV need to satisfy different design requirements posted by normative international standards. The performance of pressure vessels was validated by different quality control tests. One of the important such test is hydrostatic proof test and failure modes such as weepage, leakage, fracture are validated by this [87]. The pressure vessels must exhibit sufficient amount of resistance against the compressive transverse loadings and cracks should not get formed under diametric deflections for proper performance. Since various layup patterns are employed in COPVs, it should have sufficient strength in both axial and circumferential directions. Estimating the directional properties are so important for calculating the resistance to short term hydraulic pressure [88]. In very limited literatures, it has been proved that analyzing the directional properties will help to avoid overdesign of pressure vessels [89]. For predicting directional properties, the sudden degradation rules can be employed for failed elements. The directional properties are found to be helpful in defining the static failure criteria and fatigue life too [90]. Failure parameters like matrix failure mode, burst pressure can be identified using netting analysis and classical lamination theory [91]. Multi layup simulation can be used for predicting the characteristics of multi layup domes. Varying configurations such as winding angle, material, etc., can be accommodated effectively using multi layup simulation by predicting the properties of single layup [92].

11.11 Design validation

Shell equations have good accuracy in predicting the stresses under combined action of axial load, torsion and internal pressure [93]. Bimodal Weibull distribution function gives much more accurate results for determining the fiber strength [94]. Manufacturing variables of pressure vessel are the key things in achieving specific performances and reliability parameters [95]. The effect of thickness of liner in the burst pressure will be in same range with same metal liner with different overwrap material [96]. Novel analytical method called Composite overwrapped pressure vessel Stress Analysis Program through multi-step non-linear finite element modeling can be used for better prediction of burst pressure, fatigue and fracture [97]. Reinforcement and matrix materials influence the internal pressure and crack size on the fracture behavior and transverse modulus of composite is an essential factor for determining the strength of composite cylinder [98]. Thickness to radius ratio and material properties under internal pressure significantly alter the first ply failure loads of vessels [99]. The vessels with varying dome geometries and material offers weight reduction [100]. Under temperature-moisture gradients, the vessel performance will vary under the action of internal pressure, axial load and applied torque. 3D failure criteria found to be effective in determining the optimum values of winding angle, burst pressure, maximum axial load and maximum rotational speed with hygro-thermal effects [101]. Semi-geodesic path equation can be used to study the effect of filament winding angle and slippage between fiber and mandrel under internal pressure [102]. 50^o to 54^o is the optimum winding angle when subjected inter pressure alone. When the rotation comes into play it greatly increases the stresses in hoop direction and tends to move the optimum winding angle nearly 90^o. Axial forces oppose the effect of body forces and tends to decrease the winding angle of vessel. Also, the thermal and moisture induced stresses decreases the performance of vessel with a certain proportionality [103]. For low end commercial applications, it is recommended to create the pressure vessels with winding of fibre tapes in longitudinal and transverse directions instead of vessels made by winding of unidirectional bands [104]. The burst pressure and hoop strain will be well dependent factor of the material and manufacturing technique. Thickness of the composite layer and strength in longitudinal direction are the ultimate factors in determining vessels life [105]. Width of the winding band and winding process parameters can be used for improvement of performance of dome geometry [106]. The performance of pressure vessels was also influenced by stress, temperature, time in the rupture, residual and spatial stress distribution of overwrapped pressure vessel [107]. Cubic spline function represents the effect of dome thickness in COPV performance with good accuracy [108]. Insufficient strength of the liner and poor design in transition area from cylinder to valve will degrade the vessel life [109]. CPT with gradual damage, enumerative optimization, finite element method with Reddy's progressive damage law, genetic algorithm with the results of CDM theory and 3D finite element technique can be used for identifying the merits and demerits of design rules and calculation methods [110].

The first type V liner less pressure vessel was built by U. S. Air Force Research Laboratory in association with university of Texas in 2010. The tank was filament wounded with carbon/epoxy to store argon gas for satellite applications. When compared to the Type IV vessel, it is 20% lighter and having significant payload capacity with lesser cost due to the elimination of liner. A critical consideration should be done during design because, the stored gases impermeable to the barrier layer and it could be achieved by special type of matrices like KIKBKO toughened resins. The pressure vessels which are made up of single material by filament winding to get required structural integrity more concentration should be made on fibre volume, winding angle and winding thickness.

12. Conclusion

The evaluation of pressure vessels from metallic to the fully composite is a boon for the CNG and transportation industries. The type I vessels requires little design considerations since the material used in this is homogenous and isotropic. Hence the mechanics & damage behaviour involved are simpler with the penalty of weight. The type II & type III vessels has excellent performance characteristics with reduced weight when compared to vessels of type I. But the care should be taken more in design and mechanics of dome region for better performance due to the existence of high material non linearity in that section. Type IV vessels have reduced material non-linear property along the longitudinal axis of the cylinder with increased performance and reduced weight when compared to type III vessels. Type IV vessels has significant performance when compared to earlier type vessels, but the interaction of fluid-plastic liner should be reduced. The type V liner less vessels are under development with toughened resins to avoid the fluid-composite wall interaction with the absence of barrier liner. When the type V vessels came into play, the weight of the vessels will be reduced further and the hardly predictable performance of liner-overwrap interaction region would be eliminated.

13. Acknowledgement

We as the authors of this review article conveys our heartfelt thanks to the colleagues and management of GKM College of Engineering & Technology and MVJ College of Engineering, for their encouragement and support to carry out this work.

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