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Performance Evaluation of Composite Pressure Vessel Due to Delamination

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ABSTRACT

Polymeric composites play a significant role in the aerospace industry, with one crucial application being the utilization of filament-wound composite cases for Pressure vessels (PV). These cases are designed to sustain very high pressure and temperature environments generated and are intended to perform adequately at any time during their service life. The performance of PVs can be affected by environmental conditions at different stages of their life cycle. This study focuses on evaluating the performance of PVs equipped with composite cases, specifically examining delamination issues caused by various environmental factors. The test matrix considers different delamination lengths and ply sequences while maintaining consistent cylindrical volume and thickness. Through the FEM analysis and experimental data, it is found that as the initial crack length increases, the Von-Mises stress also increases irrespective of ply sequence angle. For the same initial crack length, the Von-Mises stress initially increases until the ply sequence angle is 0/45° and then starts to decrease. During the PPT, Strain measurements were conducted at various points across the CPV, focusing particularly on the delaminated region at strain gauge locations (S8T) (between L8 and L10) and corresponding areas without delamination, strain gauge locations S8R, S8B, S8L situated circumferentially in the same plane, the results aligned with the predictions made during the FEM analysis. Upon completion of the burst pressure test, it was observed that the NE dome experienced circumferential hoop failure. This type of failure occurred around the circumference of the dome region.

Keywords: Pressure vessel; Finite element analysis; Failure modes; Delamination; Load carrying Capability

NOMENCLATURE

PV	: Pressure vessels
CPV	: Composite pressure vessels
FEM	: Finite element method
PPT	: Proof Pressure Test
ASTM	: American society for testing and materials
RT	: Radiographic tests
MERS	: Modified epoxy resin system
VCCT	: Virtual crack closure technique
UT	: Ultrasonic testing
CRMC	: Composite rocket motor casing
UTM	: Universal testing machine

1. INTRODUCTION

A PV is employed in various industries for the storage or processing of dynamic pressure with a differential pressure compared to the atmosphere. These vessels are used in diverse sectors such as power plants for coal-based power generation, petrochemical firms for crude oil storage and processing, and rocket motors[1]. As these systems are critical and intended for prolonged use, their post-deployment lifespan is a significant concern. In modern technology, composites are widely used in structural and thermal applications for missile and space systems.

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Composite materials offering exceptional strength and stiffness properties while maintaining a lightweight profile. Composites offer advantages over metal counterparts, including high specific strength, specific stiffness, tailorable strength characteristics, corrosion resistance, and fatigue resistance[2]. This advantage is due to their anisotropic nature, which enables an efficient distribution of mechanical characteristics. One of the key features of composite structures is their laminated construction, which allows for precise control over mechanical properties. However, this layered configuration introduces challenges in the form of weak interfaces between adjacent layers, often resulting in resin-rich regions. Lightweight CPVs are particularly well-suited for these applications. In this process, resin-impregnated continuous filaments are wound under tension over a rotating mandrel to create a surface of revolution with the desired thickness and ply sequences, forming a composite case for the PV[3].

A CPV consists of a cylindrical body with two end domes, as well as polar bosses and skirts acting as end fittings for interfacing with other subsystems and load transfer[4]. The in-service performance of polymeric composites is influenced by environmental factors, and these structures are susceptible to various forms of damage such as matrix cracking, delamination, debonding, porosity, fibre buckling, and fibre breakage. Environmental conditions can degrade the mechanical properties and structural performance of polymeric composites. When subjected to out-of-plane or transverse shear

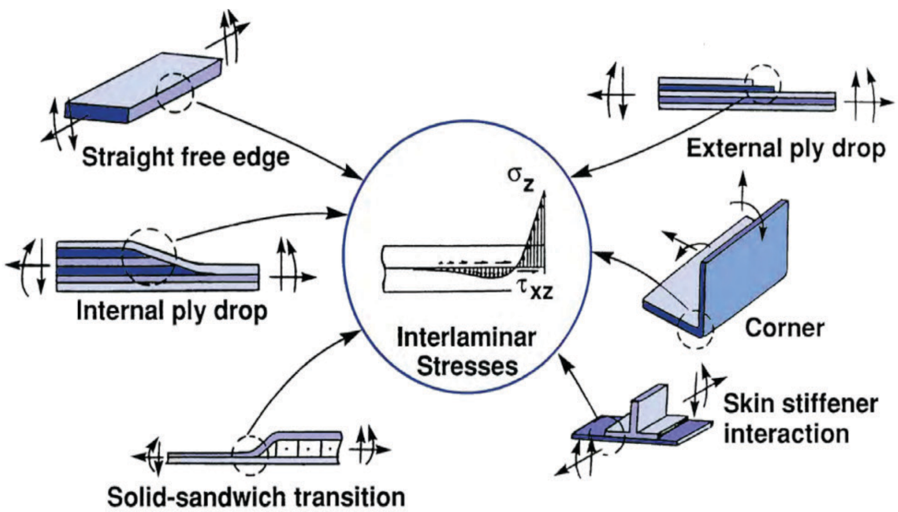


Figure 1. Examples of delamination-critical regions[5].

stresses that exceed the material strength at these interfaces, a phenomenon called delamination occurs. Delamination involves the separation of layers along these weak interfaces and can propagate under continued loading, ultimately leading to structural failure. Although delamination is just one of the potential failure modes in composite laminates, it is a prevalent issue encountered in numerous applications highlighting the critical need for accurate techniques to predict and mitigate this mode of failure.

Delamination can also occur during the service life of the composite structures, impacting their integrity. Therefore, it is crucial to comprehensively understand the effects of environmental conditions on the structural performance of composites to ensure safety and durability.

The extensive use of composite structures in the aerospace sector necessitates the development of trustworthy numerical techniques that take damage effects, including delamination, into consideration. Although cohesive elements are a flexible and physically accurate method of simulating delamination, their typical form necessitates the presence of at least three components in the narrow cohesive zone, which limits their use. The current models' incapacity to represent the deformation of the delaminating substrates is the cause of this constraint. The implementation and testing of CPV using compatible cohesive elements and hexagonal and mapped substrate elements that meet C1-continuity at their boundary are the main objectives of the current effort[6].

The enhanced regularity satisfies the Kirchhoff Plate Theory's condition for continuity. The whole model is checked for delamination once the cohesive element and CPV have been verified separately using PPT and burst test. CEs are used to find very accurate forecasts of the limit load and fracture propagation phase. Cohesive elements are a useful tool in delamination analysis because of their capacity to forecast the beginning and spread of cracks in both brittle and ductile materials. However, a strict mesh density requirement keeps this technique from being adopted in practical practice. The so-called cohesive zone, which often stretches a few millimetres, if not tenths of millimetres, forward of the crack tip, does require a minimum number of elements. The mesh density constraint is a requirement that results from ordinary CEs' incapacity to replicate the cohesive zone's severe stress gradients, unless incredibly small elements are employed.

This necessitates detailed characterization and the identification of suitable Non-Destructive Testing (NDT) methods for process control and defect diagnosis. The main objective of this study is to qualify CPVs with different initial delamination lengths and ply sequence angles, comparing their performance with virgin CPVs. The study focuses on evaluating the best layup sequence for performance assessment by keeping the ply sequence constant and varying the associated ply angle, along with considering the initial crack length as a delamination initiator. Additionally, delamination analysis was conducted to determine the load-bearing capability of CPVs with different initial crack lengths and ply angles[7].

Detecting damage in composite structures throughout their service life is crucial for ensuring structural reliability. In this context, a through-transmission Ultrasonic Testing (UT) and RT methodology has been developed for the detection of delamination in large-sized CPVs. While there is existing literature on the design, development, and qualification of CPVs, a comprehensive work focusing on structural integrity assessment using the aforementioned technique is lacking. This paper aims to provide insights into delamination caused by process parameter variations during manufacturing and its detection using UT and RT[8]. However, the lack of a foolproof methodology and reference standards in the public domain poses significant challenges.

To address this, customized reference blocks simulating defects such as delamination and varying thickness have been fabricated, and their ultrasonic responses have been characterized. The radiographic response of full-scale CPVs has been studied, and an overview of the structural integrity assessment of CPVs is presented. The impact behaviour of CPVs under internal pressure has been a subject of interest for a limited number of researchers. Most studies have focused on either FEM analysis or experimental evaluation. However, in experimental evaluations, researchers typically use only

Proof Pressure Testing (PPT) to validate their results, as PPT is commonly used for acceptance testing[7]. In contrast, our study incorporates PPT along with burst testing for both acceptance and qualification tests of CPVs[10-13]. To investigate how different conditions and ageing affect composites' performance, a thorough literature review is conducted. Regretfully, there are very few attempts to use static firing to comprehend the behaviour of the composite case under various situations in the literature that is currently available. Consequently, the impact of environmental factors on the structural performance of CRMC was investigated using the burst test method. Nevertheless, the explosion does not replicate combustion conditions and an instantaneous pressure rise.

As anticipated during flight, a static test, on the other hand, closely mimics real operational conditions. In order to better understand the overall impact of ageing and environmental factors on CPV performance, the current study has been conducted at the subsystem level, which is similar to the actual flight hardware configuration. The aim is to analyze the data in a manner that ensures close agreement between the FEM results and analytical design, validating the design and ensuring the absence of failures in the CPV. Consequently, this study has been conducted at a subsystem level, replicating the actual hardware configuration. The overall effect of delamination on the performance of CPVs has been experimentally evaluated in an integrated manner, aiming to establish a comprehensive understanding of the structural integrity of CPVs[14].

2. METHODOLOGY

The research work presented in this paper is divided into two main parts, as depicted in Fig. 2. The first part focuses on conducting FEM analysis to identify the most critical ply sequence and initial delamination length that leads to critical Von-Mises stress in delaminated CPVs. To accomplish this, we employed APDL software as our tool of choice. To validate the FEM results, various experiments, were conducted. The outcomes of these experiments were then compared with the FEM results. Stress calculations were performed in both cases, considering models with and without delamination, in order to evaluate the performance degradation caused by delamination. Additionally, this study compares the extent of degradation resulting from different ply sequences and initial delamination lengths[15].

3. MATERIAL SELECTION

Filament-wound CPVs are well-suited for the utilization of Carbon epoxy and Glass epoxy composites[16-17]. In this study, Carbon fibre T-700 with Modified Epoxy Resin System (MERS) (LY556 & HY5200) with a volume fraction (Vf =60 %) is utilized. Specimens are fabricated using filament winding, following the same curing process as that of CPVs, and subsequently tested to evaluate various physical and mechanical properties, Longitudinal specimens were subjected to tension tests (Fig. 3) as per ASTM D3039 to determine the longitudinal tensile strength, modulus, and major Poisson's ratio. For assessing the transverse tensile strength and transverse tensile modulus, tension tests were conducted on flat (90°) transverse specimens[18].

The test results for Carbon fibre T-700 with Modified Epoxy Resin System (LY556 & HY5200) (Vf=60 %) are given in Tables 1 and 2 respectively.

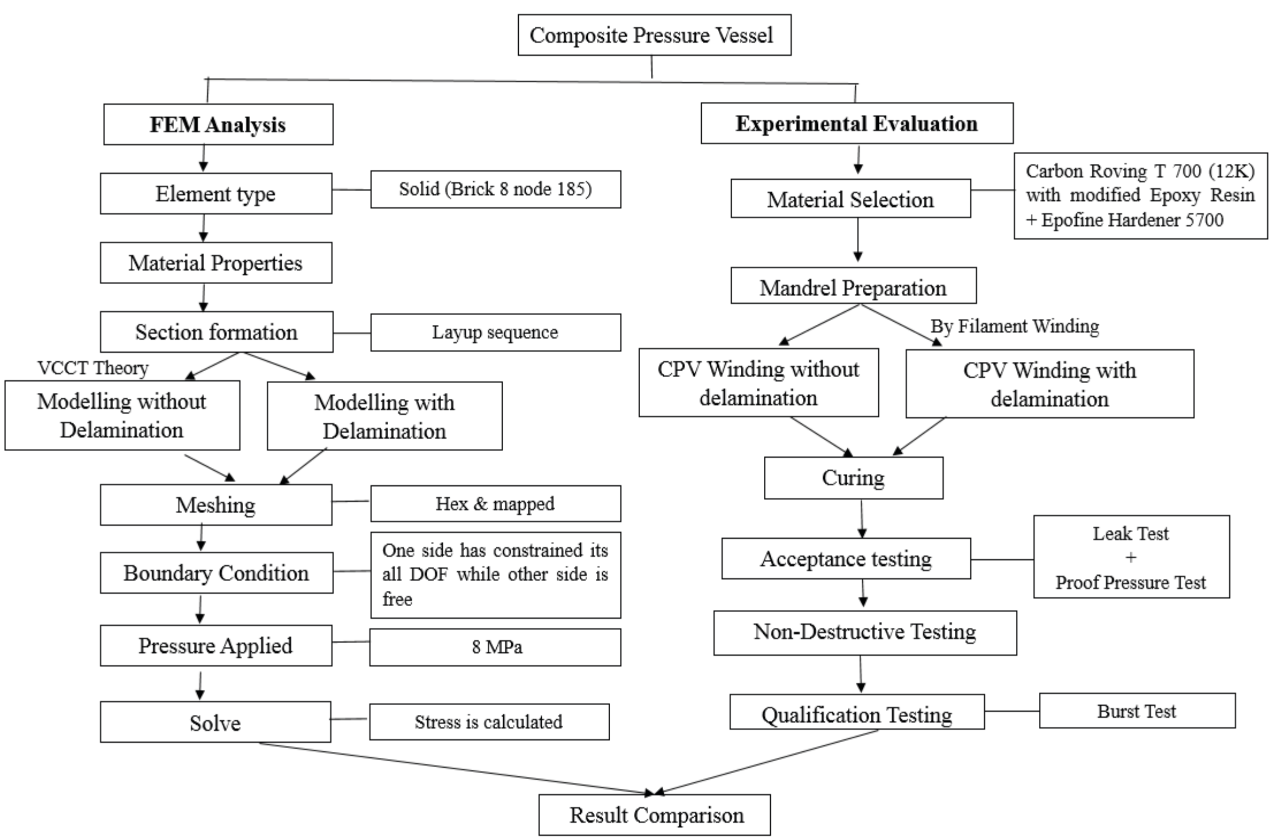


Figure 2. Flow chart of study methodology.

Figure 3. Failure modes of test results of composite specimens (Vf = 60 %).

Table 1. Mechanical properties

Property	T 700 / Modified Epoxy resin composite
Longitudinal tensile strength, MPa	2000
Longitudinal tensile modulus. GPa	128
Poisson's ratio	0.29
Transverse tensile strength, MPa	14
Transverse tensile modulus, GPa	9.0
Longitudinal compressive strength, MPa	800
Transverse compressive strength, MPa	60

Table 2. Physical properties

Properties	ASTM Std. No.	Tested value
Tex, g/km	D 3800	804
Density, g/cc	D 3800	1.785
Filament diameter, micron	-	6.98
Tensile strength of fibre, MPa	D 4018	4800
Tensile modulus of fibre, GPa	D 4018	225

4. ANALYSIS OF CPV

4.1 FEM Methodology

Initially, CPV is modelled in AUTOCAD as shown in Fig. 4. and then exported as a STEP file with solid as an option.

The applied model was based on the modelling approach developed and extended for Mixed Mode. Two types of CPV were modelled in AUTOCAD (one with delamination and other without any type of delamination) . The detail of CPV is given in Table 3.

Table 3. Specifications of CPV

Parameter	Value
Diameter	1400 mm
Length	2200 mm

Two types of CPV models were considered for analysis. Although analytical methods are useful for preliminary design phases and numerical approaches are essential for accurately capturing complex structural deformations. In the first type, delamination was intentionally created between the 4th and 5th layers from top surfaces, while the second type represented a perfect CPV without any defects. The objective was to study the performance degradation of CPV due to delamination. Sixteen different pre-damaged (delaminated) models were created to investigate this. In the pre-damaged models, delamination was induced on the cylindrical portion. The ply sequence angle between the laminates was fixed at 0/0° initially, and the stress values were analyzed by varying the initial delamination length. The initial delamination lengths ranged from 80 mm to 110 mm in steps of 10 mm. Additionally, four different ply sequence angles (0/0°, 0/30°, 0/45°, and 0/60°) were considered to analyze their effect on the CPV performance. The same methodology was applied to each ply sequence angle as in the 0/0° case. Explicit finite element simulations were conducted using the APDL software.

In computational mechanics, Finite Element (FE) analysis is widely employed to study intricate structural behaviors. Within this framework, cohesive elements (CEs) are utilized in numerical models to investigate interface degradation, particularly in delamination analysis. Cohesive elements offer

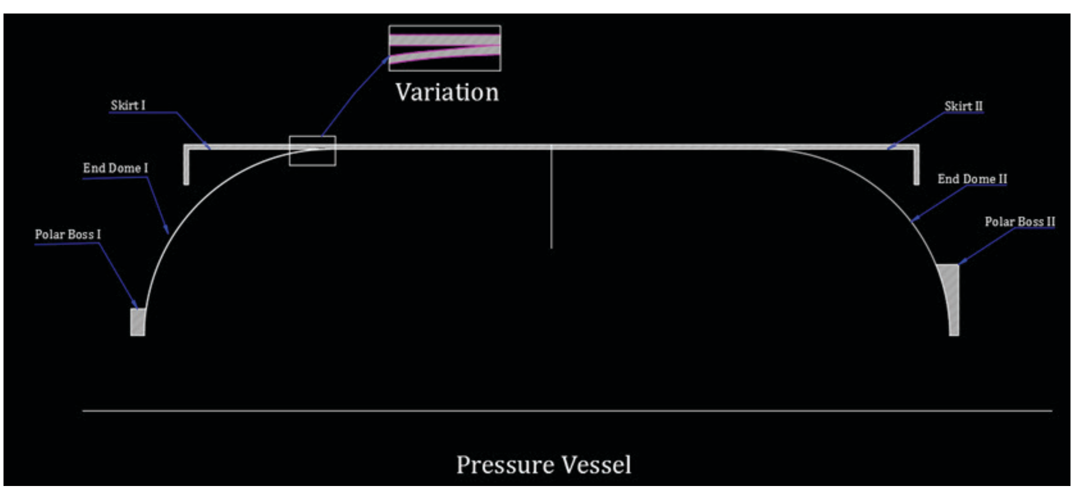


Figure 4. Location of delamination.

the capability to predict crack initiation and propagation in both ductile and brittle material[19].

The CPV geometry was simplified as a cylinder, and the composite material was discretized using thick shell and cohesive elements. SOLID185 and INTER205 elements were utilized to simulate the interface between surfaces and the subsequent delamination process.

The nomenclature used refers to both quadrilateral and triangular elements. The triangular version is derived from the quadrilateral element through degeneration, meaning they share the same geometrical parametrization. These elements are based on the Reissner-Mindlin theory and are designed to be C0 continuous. In simpler terms, both quadrilateral and triangular elements are named under the same classification. Triangular elements are a specialized form of the quadrilateral element, sharing identical geometric characteristics and formulation. The mechanical properties required for the FEA were obtained from Table 1 and Table 2. Cohesive elements were employed to model delamination initiation and growth, allowing for capturing the intralaminar material behaviour of the composite.

Various layup orientations were analyzed to determine the best model (layup sequence) for maximum LCC. The interelement was considered, and nodes were separated at the patch location to facilitate delamination analysis. The Virtual Crack Closure Technique (VCCT) was used to carry out the delamination analysis. Figure 5 illustrates the CPV model presented in this study. This means that during each increment of a FEA, the energy release rate is calculated by multiplying the separations of the nodes just ahead of the crack tip with the nodal forces acting at the crack tip. This method allows for the simulation of crack growth in a manner that reflects the physical behavior of the material, accounting for both normal and shear opening modes during crack propagation. The VCCT approach is valuable for studying fracture mechanics and predicting crack paths in structural components subjected to complex loading conditions.

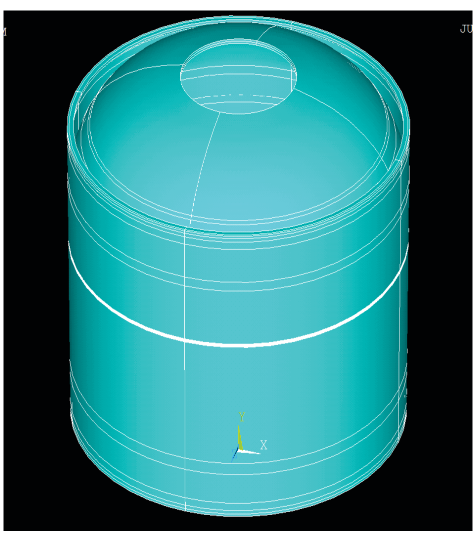


Figure 5. 3D CPV model in APDL.

4.2 Meshing

To achieve higher result accuracy, the Hex mapped mesh tool was utilized for meshing. Approximately 850,000 nodes and 800,000 elements were employed to model the CPV, comprising 400,000 thick shell elements and 400,000 cohesive elements. A finer mesh generally yields more precise results compared to a coarser mesh. In our case, convergence was observed when the stress value reached a relatively stable state, which occurred at approximately 336,035 elements. This convergence point indicated that further refinement of the mesh was unnecessary. The finest region of the mesh had an element size of approximately 2.5 mm, while the coarsest region had an element size of 20 mm. Figure 6 illustrates the meshed model of the 20° exploded side.

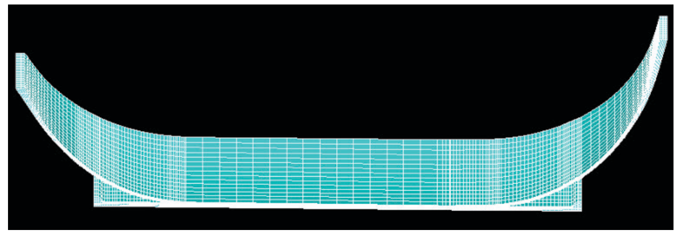


Figure 6. Meshed model of 20° exploded side.

4.3 Boundary Conditions

In the FEM analysis, a specific boundary condition was applied to the CPV model. One end of the CPV was fixed, while the other end was free from all degrees of freedom. This boundary condition ensured that the results remained consistent. For our analysis, the 20° exploded side of the CPV was chosen, and a symmetric boundary condition was applied to maintain result stability. The analysis was conducted for two types of CPV models: one without any defects and the other with delamination. Four different ply sequences (0/0°, 0/30°, 0/45°, and 0/60°) were considered, and the delamination length was varied from 80 mm to 110 mm. The fixed support was applied to one end of the CPV, and a pressure of 8 MPa was exerted on all inner faces of the CPV, as depicted in Fig. 7.

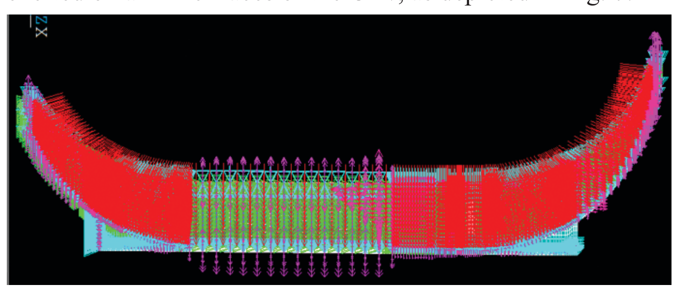


Figure 7. Boundary conditions.

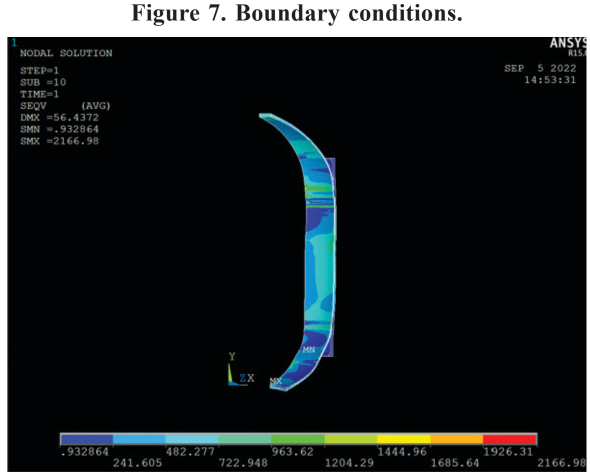


Figure 8. Stress distribution of CPV.

4.4 FEM Results

To evaluate the best layup sequence for LCC of CPV, stress analysis for different types of layup sequence angle by varying the initial crack length has been carried out. With the help of FEA, we have studied the actual stress distributions in the different components of CPV and the actual behaviour of CPV. The stress analysis results are shown in Fig. 8.

Table 4 shows the variations of Von-Mises stresses in each case are given as follows.

Table 4. Stress analysis results

Initial crack length	Ply sequence angle	Without delamination (Von-mises stress) (MPa)	With delamination (Von-mises stress) (MPa)
80 mm	0/0°	1400	1571
	0/30°	1623	1698
	0/45°	1854	2106
	0/60°	1735	2094
90mm	0/0°	1400	1647
	0/30°	1623	1774
	0/45°	1854	2118
	0/60°	1735	1856
100 mm	0/0°	1400	1746
	0/30°	1623	2166
	0/45°	1854	2333
	0/60°	1735	2080
110 mm	0/0°	1400	2016
	0/30°	1623	2308
	0/45°	1854	2468
	0/60°	1735	2412

As from Table 4, it was observed the stress increases continuously as the ply sequence angle increases and it reaches the maximum value at a ply sequence of 0/45° and then starts decreasing. The stress concentration level also gets the maximum value when the initial delamination length reached the maximum value of 110 mm. It was also observed that the stress increases continuously for initial crack length of 80 mm as ply sequence angle increase from 0/0°, 0/30° and reaching maximum value at 0/45°. It may be due to load carrying fibre, σxx stresses along the fibre and σyy perpendicular to the fibre are same. Hence, net Von mises stresses will be more and starts decreasing to ply sequence angle 0/60°, it may be because of biaxial state of stress. The similar stress pattern for other delamination length of 90, 100 and 110 mm are shown for ply sequence of 0/0°, 0/30°,0/45°, 0/60°. The stresses for with delamination CPV were observed more than the CPV without delamination, it may be due to no load carrying at delamination zone and at tip of delamination zone to sudden offer resistance to load/ pressure.

5. METHODOLOGY

To validate the results and analysis obtained from the FEM test, an experimental test was conducted. The purpose of this experimental validation was to provide a reference for future studies. In the experimental validation, the same material with evaluated mechanical properties was utilized. Specifically, Carbon Roving T700 with MERS was chosen for the CPV manufacturing process. The CPV was manufactured using a wet filament winding process, as illustrated in Fig. 9. This process was selected because it offers improved control over fiber placement, thanks to the increased tack of the tow-preg material. As a result, it allows for greater design freedom and more accurate predictions of burst pressure. Filament wound CPVs are widely employed due to their high-performance characteristics. By conducting the experimental test with the chosen material and manufacturing process, the aim was to verify the accuracy and reliability of the FEM analysis. This experimental validation serves as a valuable reference for future endeavors.

Manufacturing 16 different types of CPVs, each with unique ply sequence angles and initial crack lengths is not only costly but also impractical for experimental purposes. Therefore, to optimize resources and efficiency, we prioritize the production of the CPV configuration that presents the most critical scenario. This entails selecting the CPV design characterized by a ply sequence angle of 45° and an initial crack length of 110 mm. This decision was made to replicate the conditions where delamination occurs between the L10 and L8 regions as shown in Fig. 10. By focusing on this configuration, we ensure that our manufacturing efforts are aligned with addressing the most significant structural challenges identified through simulation.

To introduce delamination between 4^{th} and 5^{th} layers of the CPV, Teflon material is inserted during the filament winding process. The CPV was manufactured using the same layup sequence (0/45°) at delamination and initial delamination length of 110 mm. Once the filament winding was completed, the CPV is subjected to a curing cycle to ensure proper bonding. The curing cycle follows the same parameters as provided in Table 5. By incorporating Teflon during the winding process and following the specified curing

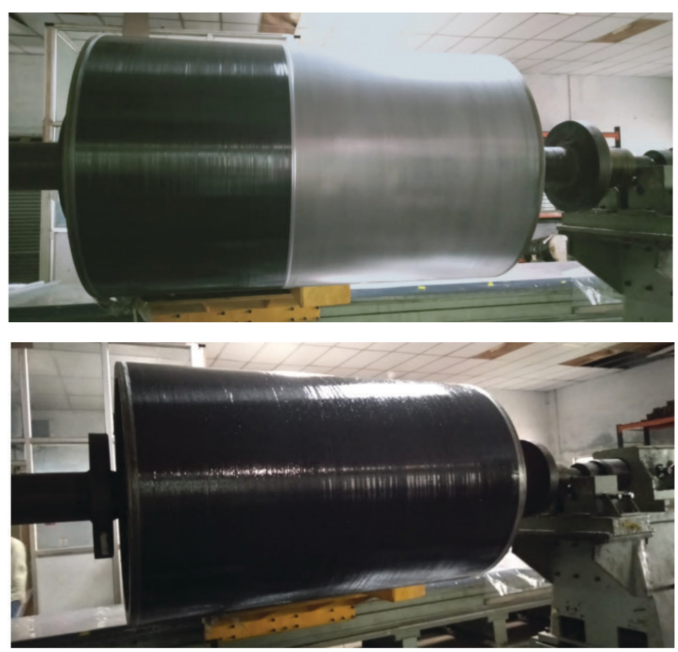


Figure 9. Manufacturing of CPV through filament winding.

cycle, the desired delamination between the layers of the CPV was achieved. This method allows for controlled delamination and enables further analysis and investigation of its effects on the CPV's performance.

Table 5. Curing cycle for CPV

Initial temperature (°C)	**Final temperature (°C)**	**Time (min.)**	**Remarks (heating rate per min.)**
Room temperature	120	30	2 to 4 °C
Hold at 120°C		180	
120	160	30	2 to 4 °C
Hold at 160 °C		180	
Switch off the oven and allow the component to cool naturally.			
Open the door and remove mandrel when it is below 40°C.			

After curing, CPV was gone through series of qualification and acceptance test to validate FEM test results and to evaluate the degradation in performance due to delamination in CPV.

6. RESULT AND ANALYSIS

Experiments are conducted to validate the FEM results and to study the impact behaviour on CPV. To validate the design following test is carried out:

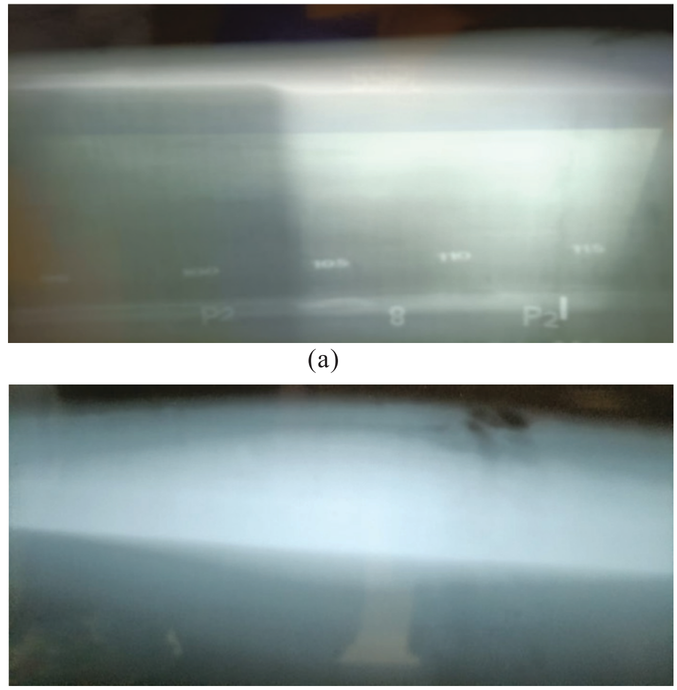
- As a part of acceptance tests, Leak test and PPT was done for CPV.
- As a part of qualification test, burst test was conducted for the most critical CPV.

6.1 Leak Test

To ensure the integrity of all the joints between the ends, it was necessary to perform a leak-proof check. The primary objective of the leak test is to verify that the CPV's fluid containment systems are free from leaks. The CPV must pass the leak test by demonstrating that it can maintain specified pressure levels without any significant drop, ensuring that it meets safety and performance standards before deployment or further testing. To prevent any leakage, the CPV was fully lined with rubber from the inside, as the casing itself has a porous nature. For the leak-proof test, the casing was pressurized up to a pressure of 1.0 MPa and held at this pressure for a duration of two minutes. During this pressurization and hold period, the casing joints were physically inspected to detect any signs of leakage. No visible indications of leakage or abrupt pressure drop were observed. Post RT was also carried out to find out any change in delamination length if any. No any major change was observed. Post RT result after leak test is shown in Fig. 10.

6.2 Proof Pressure Test (PPT)

The testing process involved pressurizing the casing using water as a medium. The pressure was gradually increased from 0 to 1 MPa, and then depressurized back to 0 MPa. This pressurization and depressurization cycle was repeated three times, allowing the strain gauges to stabilize. The entire test was conducted with the CPV in a vertical position. The primary objective was to measure strain and dilation at critical regions, specifically the areas of delamination and subcritical locations.



(a)

(b)

Figure 10. RT result (a) Before; and (b) After leak test.

To achieve this, a strain gauge setup was implemented, as illustrated in Fig. 11. Strain measurements were conducted at various points across the CPV, focusing particularly on the delaminated region at strain gauge locations (S8T) (between L8 and L10) and corresponding area without delamination, strain gauge location S8R, S8B, S8L situated circumferentially opposite (between S3 and S4) in the same plane. In composite materials, fibers are typically oriented in two main directions: hoop and longitudinal.

The hoop direction refers to fibers running circumferentially around a structure, while the longitudinal direction involves fibers aligned along the length of the structure. In practical applications, especially where hoop stresses dominate over longitudinal stresses, strain gauges are primarily installed or oriented in the hoop direction. This approach is chosen because the strain (and consequently the strain measurement) in the longitudinal direction tends to be much lower or negligible compared to that in the hoop direction. Therefore, to accurately capture and measure the predominant strain field experienced by the composite material, strain gauges are strategically placed and oriented along the hoop direction. This focused measurement approach ensures reliable and meaningful data related to the material's performance under the primary loads and stresses encountered in its operational environment. The experimental setup utilized strain gauges arranged to effectively treat the CPV as two distinct entities: one with delamination and the other without.

This setup facilitates comparative analysis, allowing for the assessment of performance degradation in the CPV attributed to delamination. By simultaneously monitoring strain levels in both delaminated and non-delaminated sections, the impact of delamination on the CPV's structural integrity and mechanical behavior can be accurately evaluated.

This approach provides valuable insights into the effects of delamination on CPV performance, aiding in the development of strategies to mitigate such issues and enhance overall vessel durability and reliability. By subjecting the casing to multiple pressurization and depressurization cycles, the strain gauges were able to settle and provide accurate measurements of strain and dilation at the designated critical regions.

To ensure the integrity of all the joints, a thorough leak check was conducted once again. Three pressure gauges were utilized: one on the pressurization system, another near the test article, and a third on the exit hose. These pressure gauges facilitated accurate pressure readings throughout the test. The

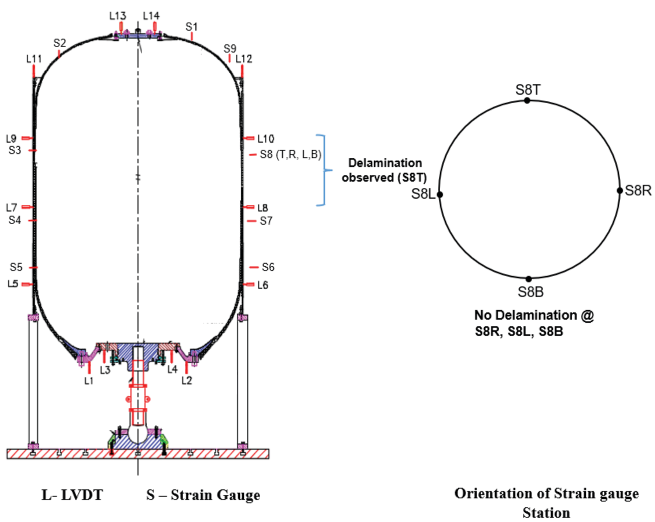
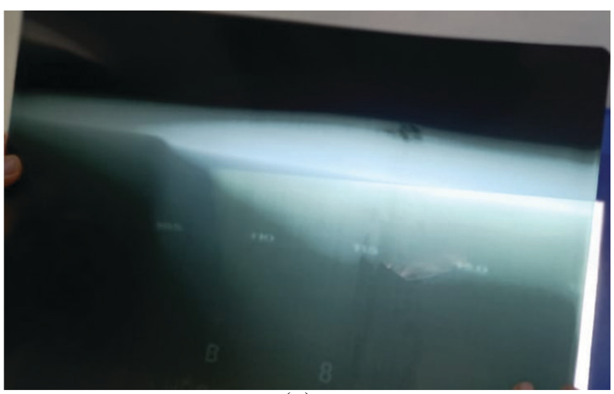
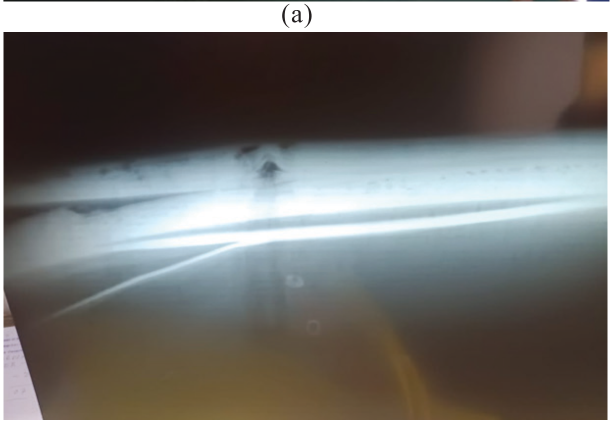


Figure 11. PPT strain gauge location plan.



(a)



(b)

Figure 12. (a) Pre PPT RT-Result; and (b) Post PPT RT result.

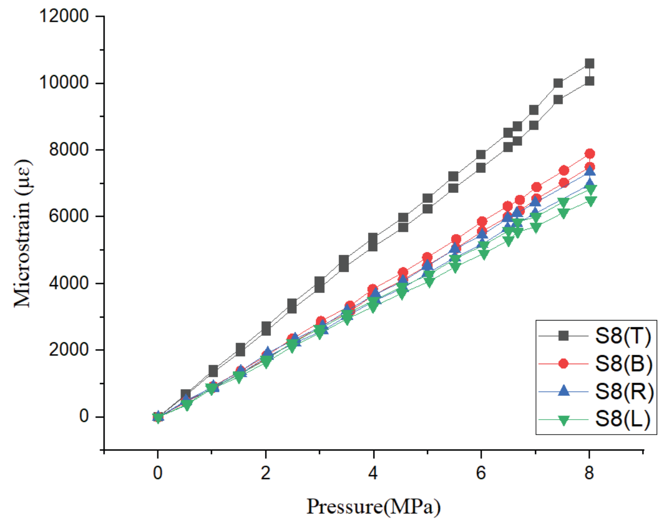


Figure 13. Strain graphs during PPT.

casing was pressurized in incremental steps: 0, 1, 2, 3, 4, 5, 6, 7, and 8 MPa. Each step of pressurization, except for the proof pressure (8 MPa), allowed sufficient time to record the strain gauge readings. The hold time at 8 MPa was set to 2 minutes. The pressure measurement accuracy was ±0.05 MPa (minimum). During the PPT, strain gauges and LVDT (Linear Variable Differential Transformer) were strategically positioned at various locations to continuously measure strain and dilation. As the pressure was gradually released during depressurization, residual strains and dilations were continuously recorded across all channels. Upon completion of the PPT, the water within the casing was completely drained, and all systems were switched off. No visible signs of leakage or abrupt pressure drops were observed during the pressurization process.

Post-PPT was also carried out to find any growth in delamination length. No major change was found in perfect CPV and minor growth was observed in delaminated CPV as shown in Fig. 12.

During PPT strain gauge were placed at different critical locations and results are found as predicted. Pressure Vs microstrain graphs, pressure vs dilation was recorded at different location during each test. The results are given in Fig. 13. Figure 13 displays the strain values recorded at stations 8 at top, bottom, right and left point.

6.3 Burst Test

To verify the integrity of the CPV and determine a safety margin, a specific test was conducted with the closure plates sealing both ends of the CPV. The main objective of the burst test is to evaluate the structural strength and maximum pressure capacity of critical components of CPV. The burst test establishes

Table 6. Duty cycle of burst test

Starting pressure	End pressure	Rate of pressurization
0	8 MPa	3 MPa/min
8 MPa	Up to burst pressure (9.4MPa)	120 MPa/min

Figure 14. CPV after burst test.

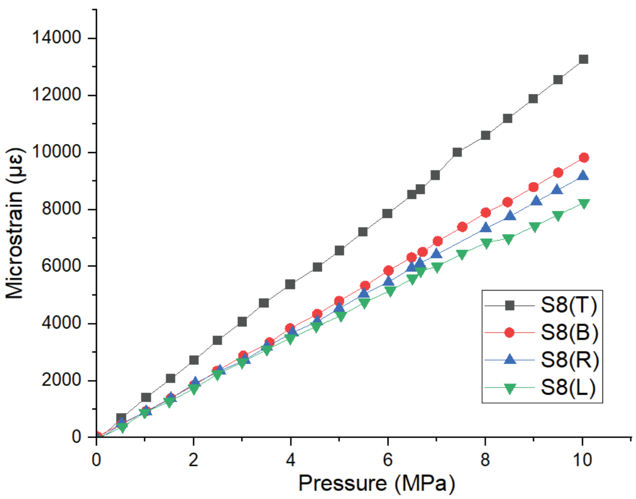


Figure 15. Strain graphs during burst test.

the maximum pressure that a component can withstand without failing catastrophically. The strain at delamination location (S8T) and without delamination locations at S8R, S8B and S8L. This test was performed on a limited number of CPVs, specifically one CPV with delamination. Water was used as the medium for pressurization. The test involved applying internal hydraulic pressure to the CPV and gradually increasing it until failure, known as burst. The duty cycle used for the burst test is outlined in Table 6. By subjecting the CPV to this burst test, its maximum pressure capacity and performance under extreme conditions were evaluated.

The CPV underwent pressurization until it reached its bursting point. Throughout the pressurization process, strains and dilation were continuously measured at critical locations to monitor the CPV's behaviour under increasing pressure. Upon completion of the burst pressure test, it was observed that the NE dome experienced circumferential hoop failure. This type of failure occurred around the circumference of the dome region. The CPV, following the burst test, is depicted in Fig. 14. The burst pressure test allowed for the determination of the CPV's maximum pressure capacity and highlighted the failure mode in the NE dome section.

No major visual signs of failure of matrix/roving observed in other areas. Strain was measured at different locations. Strain was compared at the location where delamination was embedded to the perfect location. Variation of strain at location S8T (delamination) and S8R, S8B & S8L (without delamination) were plotted as shown in Fig. 15.

7. DISCUSSION

The FEM analysis carried out with delamination and without delamination for ply sequence of 0/0°, 0/30°, 0/45°, and 0/60° with delamination length of 80mm. Similarly, the other delamination lengths of 90, 100 and 110 mm were carried out for all ply sequence. The experiment test of CPV were carried out for ply sequence of 0/45°, with delamination length of 110mm.The FEM & experimental results are discussed below.

- In FEM analysis, composite laminate with a ply sequence angle of 0/45°, the layers are oriented such that one ply is aligned with the loading direction (0°), while the adjacent ply is oriented at a 45° angle to the loading direction. This configuration leads to complex stress distributions due to the interaction between the different ply orientations. The 0° ply primarily carries the load in the loading direction, while the 45° ply contributes to both tensile and shear stresses. The combination of tensile and shear stresses from the two orientations can result in stress concentrations, particularly at the interface between the plies, leading to higher Von Mises stress compared to other ply sequence angles 0/0°, 0/30° and 0/60°. The higher concentration of σxx and σyy is particularly around the crack region. Due to this reason only, at a ply sequence angle of 0/45°, the Von Mises stress tends to be higher in FEM results
- The presence of delamination significantly affects the stress distribution and leads to stress concentration at the crack tip. As the crack length increases, the stress concentration at the crack tip becomes more severe. According to fracture mechanics principles, the stress intensity factor (K) at the crack tip increases with crack length. Higher stress intensity at the crack tip results in higher stress levels in the vicinity of the crack, contributing to an increase in Von Mises stress. Additionally, longer cracks provide more opportunities for stress concentration and propagation, further exacerbating the stress state in the material. The greater the crack length, the greater the stress intensity and the proportion of the delaminated area. Due to this reason only, irrespective of ply sequence angle, Von- Misses stress is higher at 110 mm as observed in FEM results
- In PPT, it was evident that the macrostrain exhibited a higher magnitude in delaminated CPV in comparison to intact CPV. This discrepancy can be readily attributed to the diminished inter-fiber strength resulting from delamination. Essentially, delamination weakens the bonds between fibers, rendering them more susceptible to fracturing under lesser applied force.

8. CONCLUSION

The delamination effect on LCC of CPV were studied using combination of FEM and experimental values. FEM analysis of 16 different cases of delamination on CPV for ply sequences of 0/0°, 0/30° , 0/45° and 0/60° and for delamination length varies from 80 mm to 110 mm instep of 10 mm. The Von mises stress were observed maximum for 0/45° with 110 mm delamination in FEM analysis. The experiment of CPV with 0/45° and 110 mm delamination were carried out. The following points are concluded:

- As the initial crack length increases, the Von-Mises stress also increases irrespective of ply sequence angle
- The ply sequence angle also influences the results as expected. For the same initial crack length, the Von-Mises stress initially increases until the ply sequence angle is 0/45° and then starts to decrease
- It is noteworthy that the stress values for the delaminated CPV are higher than those for the perfect CPV
- During the PPT, Strain measurements were conducted at various points across the CPV, focusing particularly on the delaminated region at strain gauge locations (S8T) (between L8 and L10) and corresponding area without delamination, strain gauge location S8R, S8B, S8L situated circumferentially in same plane. the results aligned with the predictions made during the FEM analysis
- The test results were found to be consistent and comparable. A post-RT inspection was also performed after the burst test, revealing no major visual signs of matrix or roving failure
- The strain measurements also aligned with the predicted trends. Based on all the test results and analyses, it can be concluded that the CPV with a certain level of delamination remains safe for use
- Upon completion of the burst pressure test, it was observed that the NE dome experienced circumferential hoop failure. This type of failure occurred around the circumference of the dome region
- Although the load carrying capacity of pressure vessel reduced by 8%, but in this CPV on completion of the burst pressure test, it was observed that the NE dome experienced circumferential hoop failure. This type of failure occurred around the circumference of the dome region
- No major visual signs of failure of matrix/roving observed in other areas. Strain was measured at different locations. Strain was compared at the location where delamination was embedded to the perfect location.

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