

Investigation of crack initiation during the burst test of hydrogen storage composite overwrapped pressure vessels

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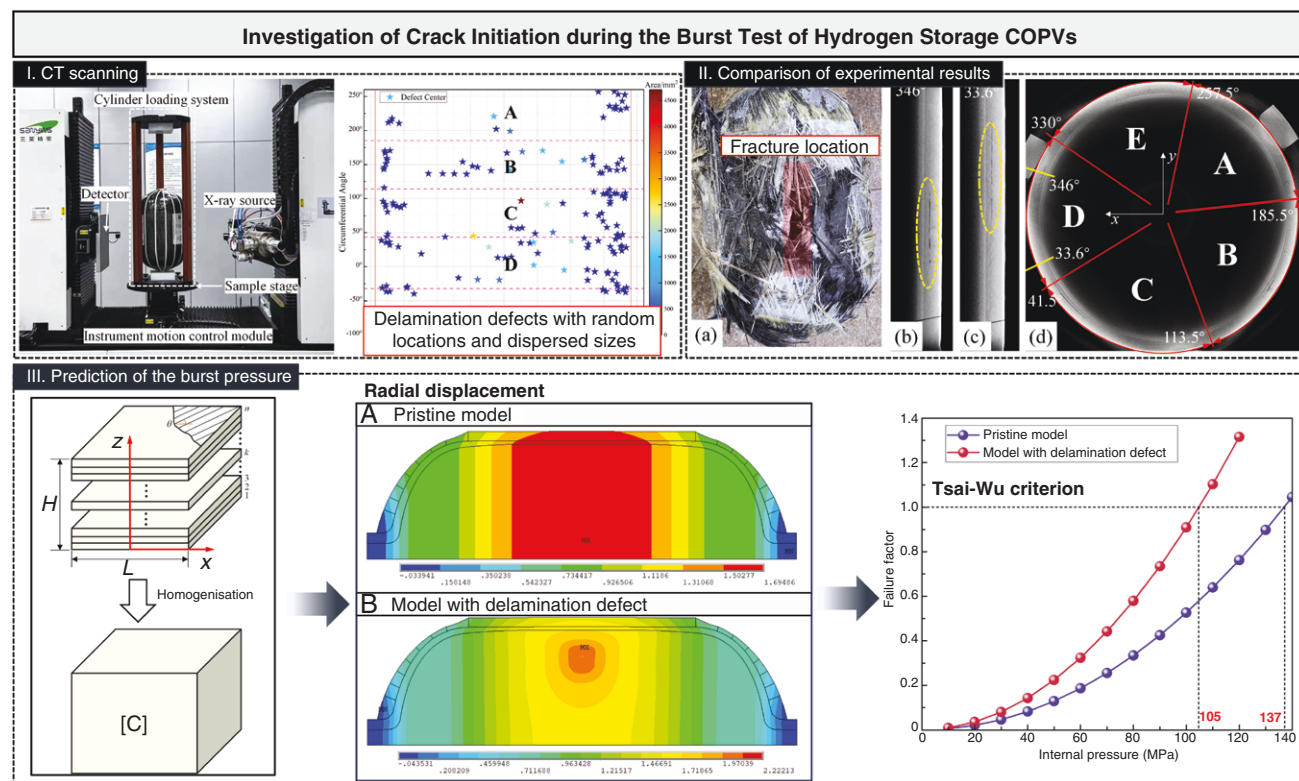
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Abstract

Hydrogen storage composite overwrapped pressure vessels (COPVs), as a core component of fuel cells, are widely used in the new energy vehicles and other fields. However, the service performance of COPVs, especially the burst pressure, has a great dispersion, which may come from the microscopic defects inside the vessels. In this paper, the industrial computed tomography scan was carried out on a type III hydrogen storage COPV with an aluminum alloy liner and a carbon fiber wound layer, and it was found that many delamination defects with random sizes and locations exist inside the fiber wound layer. Among these defects, there are 164 delamination defects with an area of $<500 \text{ mm}^2$ (accounting for 87.7% of the total number of defects), but the area of the defects only comprises 19.14% of the entire defects area. Delamination defects were the predominant type of manufacturing defect in the fiber wound layer of COPVs. Then the burst test of the COPV was carried out, which showed that the aggregated area of large-sized delamination defects located in the composite layer of the cylindrical part triggered the crack initiation during the burst test. Thus, in turn, directly affected both the burst pressure and the post-burst morphology. Finally, a 3D equivalent model of the laminated structure is proposed to model the expansion of the composite cylinder. By carrying out a finite element simulation of the COPV, the most dangerous area during the loading process of the COPV is confirmed. The experimentally measured burst pressure of the cylinder is 115.5 MPa, which deviates by 18.6% from the pristine model prediction and by 9.09% from the model with delamination defects.

Graphical abstract



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Keywords: COPV; delamination defect; CT scanning; burst test; crack initiation

1. Introduction

Given the limited availability of energy and the worsening environmental issues, it is crucial to prioritize the production and utilization of clean and renewable energy [1–3]. Hydrogen energy, in comparison to traditional fossil fuels, with abundant raw materials, a high heat value, and zero carbon emissions, makes it a very promising and environmentally friendly form of clean energy. However, hydrogen, as the lightest element in nature, is prone to leakage, spontaneous combustion, and even explosion. Additionally, hydrogen deteriorates the mechanical properties of metal materials, resulting in hydrogen embrittlement or hydrogen corrosion [4–6]. This, in turn, puts significant safety requirements on hydrogen storage vessels.

Currently, high-pressure gaseous hydrogen is the most mature technology for hydrogen storage [7]. It is extensively utilized in hydrogen energy vehicles and other fields. Composite overwrapped pressure vessels (COPVs), as crucial components of fuel cells for hydrogen-powered vehicles, have the advantages of being lightweight, having a large hydrogen storage capacity, and exhibiting excellent fatigue resistance [8–11]. Nevertheless, the complex manufacturing process inevitably generates manufacturing defects like wrinkles, delamination, and voids [12]. During the service process, these defects lead to a complicated localized mechanical behavior of COPVs, reducing the structural strength and lifespan of COPVs.

The safety performance criteria for COPVs primarily depend on the performance tests according to international standards/regulations [13–15]. However, some nondestructive testing (NDT) methods provided by the standards only focus on identifying exterior and internal surface defects, such as abrasion and impact damage, through direct visual examination or endoscopy. In terms of experimental research, the NDT techniques used to detect internal defects of COPVs include industrial computed tomography (CT) [16–19], ultrasonic testing [20, 21], and acoustic emission [22–25]. However, due to the multi-layer structure of COPVs, the acoustic signal is seriously attenuated at the inter-layer interface, which makes it difficult to carry out specific defect analysis and increases the probability of defect missing detection [26]. While industrial CT with the high penetrability of X-rays can effectively detect and accurately measure internal defects in composite structures, Zhu *et al.* found that industrial CT is effective in detecting cracks, delamination, and void defects on the surface of gas cylinders [17]. Nebe *et al.* observed delamination defects at the high-strain areas of the COPV by CT scanning, which are causally linked to the final failure [18]. Shi *et al.* established the industrial CT test method with the use of a filter and systematically researched the delamination defects at the cylinder [19].

The hydrodynamic burst test is essential for validating the design and ensuring the safety of COPVs. During the testing process, internal defects alter the local stress distribution, leading to stress concentration and crack initiation, which influence the burst behavior of gas cylinders. The impact of prefabricated defects, such as delamination and gap defects, on the burst behavior of small-volume gas cylinders was investigated [27]. In another study, the design, prototyping, and burst testing of thermoplastic COPVs led to the development of new models for composite stacking in the dome area, aimed at predicting the complex behavior of composite materials under operational stresses [28]. Further research determined the failure of the

composite layer in gas cylinders using the maximum stress criterion, and this design method was validated by hydrodynamic burst tests on small-volume gas cylinders to ensure its reliability and safety [29]. However, few experimental investigations have been conducted on the crack origin of commercial hydrogen storage COPVs, as predicting the burst behavior of commercial COPVs is challenging due to the variable sizes and randomly distributed defects of these COPVs.

Although the burst test of full-scale COPVs is the best method to investigate their burst pressure and damage behavior, it entails a rigorous test environment and high costs [30]. Therefore, the prediction of the bursting pressure is particularly important for the safety assessment of COPVs [31], which can provide an efficient and flexible design method for COPVs. Some failure criteria have been proposed for COPVs burst pressure prediction and damage simulation, such as maximum strain and maximum stress criterion [32–34], Hashin failure criterion [35, 36], Puck failure criterion [37–39]. For the modeling of COPVs, the traditional modeling approach is often complicated. In this study, the 3D equivalent theory based on the homogenization method is proposed to calculate the equivalent stiffness matrix of the fiber wound layer, instead of the complicated modeling process of COPVs. The burst pressure of COPVs can be predicted using the Tsai-Wu failure criterion, taking into account the stress variations in all directions of the cylinder.

In this paper, industrial CT scanning and a hydraulic burst test were conducted on a commercial type III hydrogen storage COPV. It was found that delamination defects were the most dominant type of manufacturing defects within the fiber wound layer of the COPV. By comparing the distribution of delamination defects with the crack location of the COPV burst, it can be found that the defects do have an effect on the crack initiation and the burst pressure of COPV. Additionally, the overall morphological characteristics of the COPV after the burst were investigated. A 3D equivalent model of laminated structure is proposed to investigate the response characteristics of the composite cylinder. By carrying out a finite element simulation of the COPV, the dangerous area during the loading process of the cylinders is confirmed, and the burst pressures of the pristine model and the model with delamination defect are predicted using the Tsai-Wu failure criterion.

2. Industrial CT scan of COPV

2.1 Experimental process

Figure 1 shows an experimental type III hydrogen storage COPV (product number CHG3-383-55-35 S/A, according to the Chinese standard GB/T 35544 [14]) with an outer diameter of 420 mm, a length of 700 mm, a volume of 55 L, and a nominal working pressure of 35 MPa, which includes 40 layers of carbon fiber wound and an aluminum liner.

X-ray-based industrial CT has a strong penetration, allowing it to scan objects and precisely measure their 3D internal structure. This enables accurate and intuitive observation of defects such as delamination, voids, and inclusions within the structure. In this paper, the experimental process utilizes industrial CT equipment (modified nanoVoxel-4000, Sanying Precision Instruments Co., Ltd) as shown in Fig. 2, which is equipped with an X-ray source with a maximum voltage of 225 kV and 4 μ m focal spot size, an

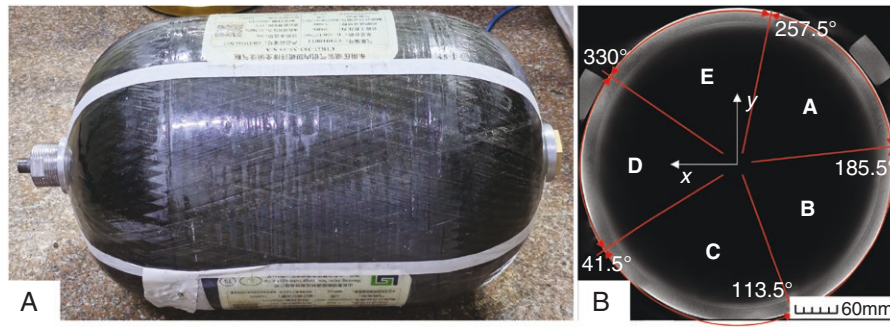


Figure 1. (a) Experimental COPV; (b) axial cross-section of cylinder.

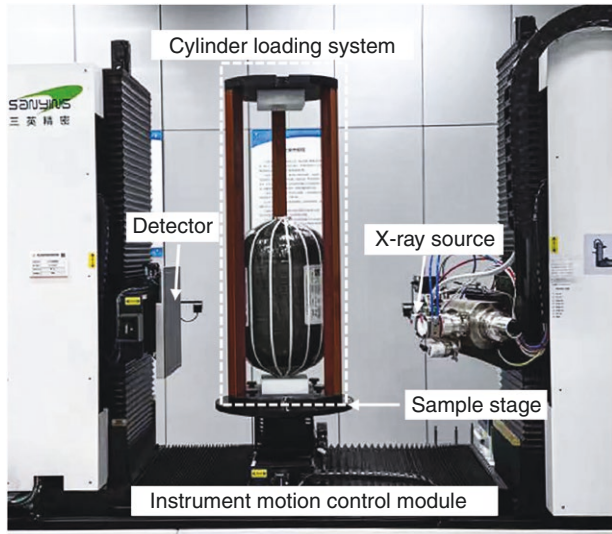


Figure 2. CT scanning of the hydrogen storage cylinder.

instrument motion control module, and a flat panel detector with 3072×3072 pixels and $140 \mu\text{m}$ pixel pitch. The geometric magnification of the CT scan and the voxel size of the reconstructed 3D model are determined by the distance between the X-ray source and the detector and the distance between the X-ray source and the scanning target. In order to facilitate the statistical analysis of the COPV defect detection data, the COPV is divided along the circumferential direction into five regions A, B, C, D, and E, as shown in Fig. 1b.

2.2 Scanning results

Generally, the brightness of a CT image is proportional to the density of the material, so different materials will present slightly different brightness, making it easier to discern delamination defects. Figure 3 shows the CT scanning results of the COPV. Through the scanning image, the overall structure of the COPV can be clearly seen: an aluminum liner, a carbon fiber composite reinforcement layer, and a glass fiber composite protective layer from inside to outside. The delamination defect in the cylinder part is indicated by the yellow circle in Fig. 3a, and the size and location of the defects can be measured and counted based on the scanning result.

Figure 4 shows the cross-section of the cylinder part with different angles. It finds that there are indeed a large number of delamination defects with random locations and dispersed sizes inside the fiber wound layer of the COPV.

2.3 Statistical analysis

In order to facilitate further statistical analysis of the CT scan results, the delamination defects from the CT scans were regularized, as shown in Fig. 5, into standard elliptical defects with the long semiaxis of a and the short semiaxis of b according to the shape and size characteristics. The area of the delamination defects can be further estimated according to Equation (1).

$$S = \pi \times a \times b \quad (1)$$

Figure 6 shows the statistical information of the position and area of the delamination defects in the cylinder part of the COPV, in which the horizontal coordinate corresponds to the axial length and the vertical coordinate is the angle corresponding to the annular unfolding. It can be found that there are a large number of small-size delamination defects in the transition region between the cylinder part and the dome, which is mainly caused by the change of the surface curvature in the transition region. Combined with Table 1, it can be found that the number of delamination defects in the middle section of the cylinder part is small, but the average size is large. On the other hand, the transition region on both sides has a large number of delamination defects, but they are small-sized delamination defects. By analyzing the relevant data, it is found that there are 164 delamination defects with an area of $<500 \text{ mm}^2$ (accounting for 87.7% of the total number of defects). Nevertheless, the area of the defects only comprises 19.14% of the entire defects area, and its impact on the overall mechanical property is negligible. Therefore, further statistics of the delamination defects with an area greater than 500 mm^2 , as depicted in Fig. 7, reveal that the number of defects obeys a normal distribution. These defects account for 80.86% of the total defect area and are primarily concentrated in the middle section of the cylinder part. It is inclined to cause stress concentration, which in turn adversely affects the overall mechanical properties of the structure.

Industrial CT scanning reveals that delamination defects with random locations and dispersed sizes inside the fiber wound layer are the most significant types of manufacturing defects. And the impact of these defects on the overall structural performance of the COPV cannot be ignored. Meanwhile, through the statistical analysis of the defect data, the middle section of the cylinder part has delamination defects with large areas (most of which are concentrated in area D), which may have a greater impact on crack initiation during the burst test of the COPV.

3. Burst test of COPV

3.1 Experimental procedure

According to the standard GB/T 35544-2017 [14] "Full-wrapped carbon fiber reinforced cylinders with an aluminum liner for the

on-board storage of compressed hydrogen as a fuel for land vehicles," hydrogen storage COPVs are subjected to a series of inspections and tests before leaving the factory. Among these, the hydrodynamic burst test is one of the most important test items.

In this part, a hydraulic burst test was conducted on a commercial type III hydrogen storage COPV according to the requirements of GB/T 35544 section 6.2.5 [14]. Figure 8a provides an overview of the experimental setup, where the COPV being tested is placed in an explosion-proof steel drum. Figure 8b illustrates the real-time monitoring of internal pressure and the control of

hydraulic loading rate using a high-pressure vessel/pipe pressure resistance testing system.

3.2 Results

During the test, the internal pressure of the COPV was monitored in real time by the high-pressure vessel/pipe pressure resistance testing system. The resulting pressure curve, shown in Fig. 8c, indicates the average pressure increase rate of 0.0874 MPa/s and the burst pressure of 115.5 MPa.

Figure 9 shows the overall shape of the COPV after the explosion. It can be seen that the location of the cylinder explosion is located in the cylindrical part, resulting in a circular rupture between the dome and the cylinder part. The fiber wound layer experienced fractures, while the liner rupture exhibited a tear-like pattern. No debris was generated as a result of the explosion. In summary, based on the preexperimentation of the circumferential direction area division, the burst occurred in the middle section of the area D of the COPV cylinder part, as shown in Fig. 9b.

3.3 Comparison of experimental results

The industrial CT scanning and hydraulic burst test revealed that the COPV burst crack originated in the middle section of the cylinder in the D area. As described in section 2.3, it can be found that the majority of large-sized delamination defects exist in the D area. Figure 10 reveals that the location of the COPV burst crack and the location of the dense area of large-size delamination defects have a high degree of correspondence. It can be seen that the delamination defects have a certain degree of influence on the crack initiation during the burst test.

4. Finite element method simulation

In this paper, the type III hydrogen storage COPV consists of a 6061 aluminum alloy liner and a T700 grade carbon fiber prepreg wound layer. The mechanical properties of 6061 aluminum alloy are shown in Table 2, and the mechanical properties of T700 grade carbon fiber-reinforced composites are shown in Table 3, in which the subscripts x denotes the direction of the fibers, while y and z represent the perpendicular direction to the fibers. The fiber wound layer contains 40 layers with the stacker sequence $[90_{22}/\pm 12.5_6/\pm 17.2_2/\pm 14.8_2/\pm 19_2/\pm 26.8_2/\pm 35.8_2/\pm 42.5_2]$.

4.1 Material model

Assuming ideal bonding between each layer, we propose a 3D equivalent theory to model the laminated structure [40, 41] and assign it as a material property to the finite element analysis (FEA) model.

The stiffness matrix C_{ij} of the unidirectional fiber-reinforced composite laminate in the global coordinate system is given by Equation (2).

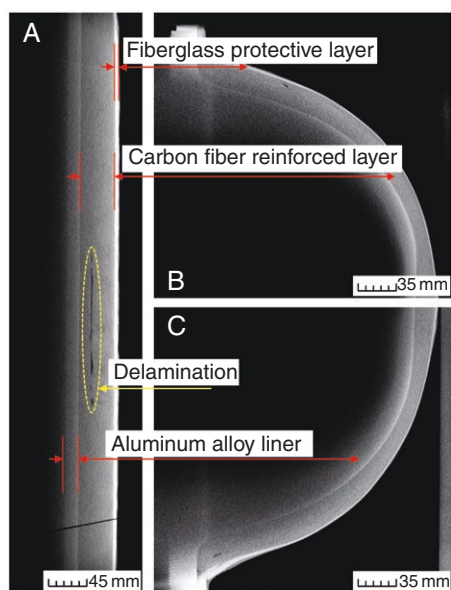


Figure 3. CT scan results correspond to different parts of the COPV.

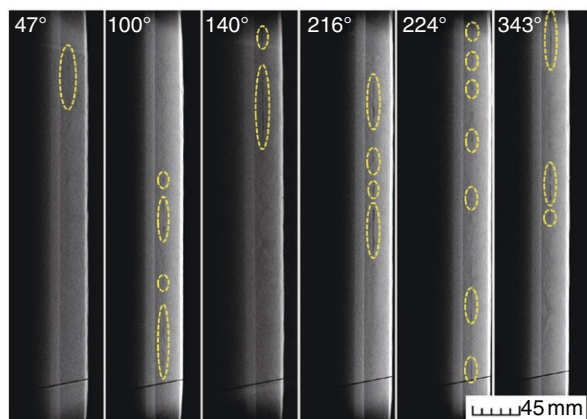


Figure 4. Delamination defects in cylindrical part.

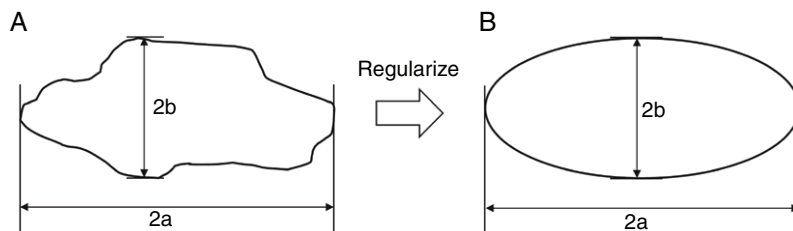


Figure 5. Regularization of defects: (a) shape of real defect; (b) regularized shape of defect.

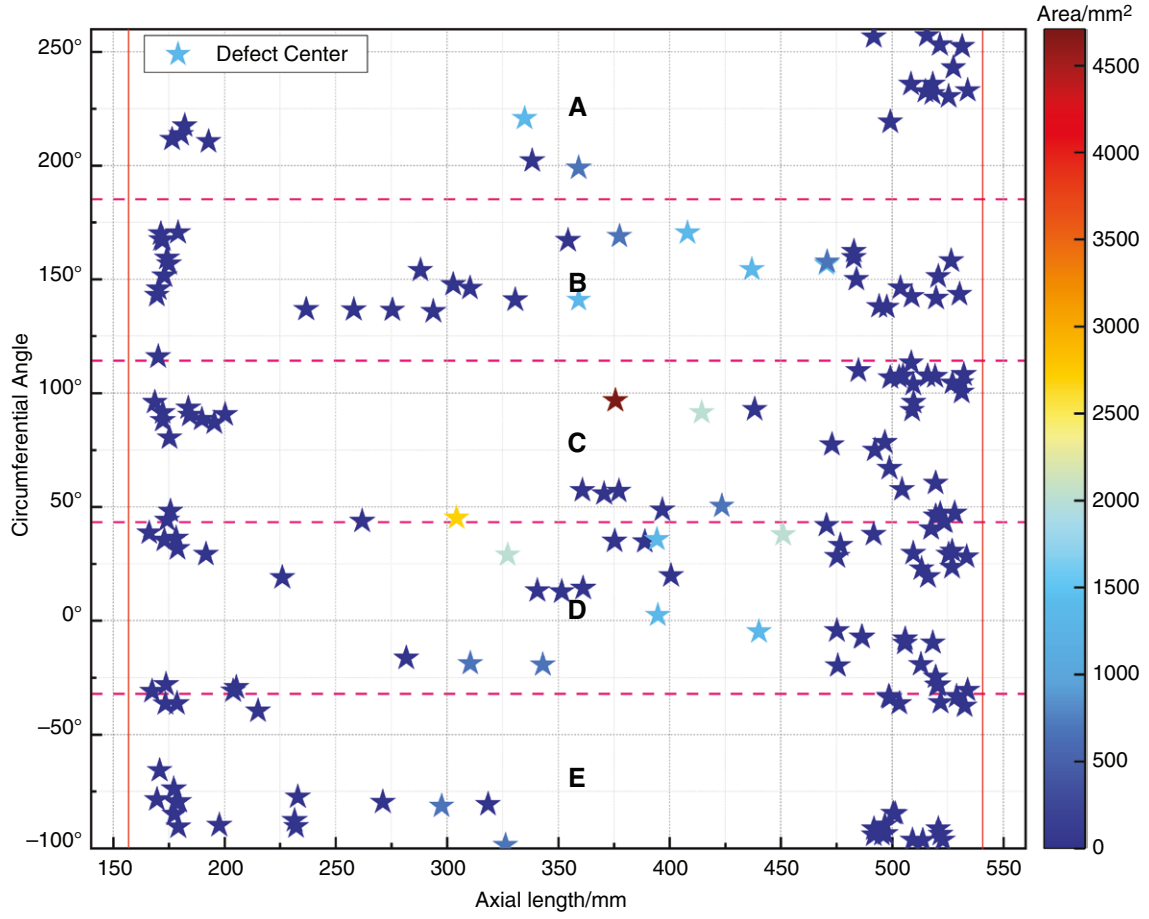


Figure 6. Distribution and areas of delamination defects in the COPV.

Table 1. Statistics of delamination defects.

Area/mm ²	0–500	500–1000	1000–1500	1500–2000	2000–2500	2500–5000
Number	164	7	10	3	2	1
Area Proportion	19.14%	11.69%	31.33%	14.12%	11.91%	11.81%

$$C_{ij} = T_{\theta}^{-1} C'_{ij} T_{\theta}^{-T} \quad (2)$$

where C represents the stiffness matrix of the unidirectional plate in the material coordinate system, and T_{θ} is the transformation matrix, in which the subscript θ denotes the in-plane angle of the layer. However, for the isotropic materials, the transformation of the coordinate system can be neglected. The transformation matrix T_{θ} can be expressed as:

$$[T_{\theta}] = \begin{bmatrix} \cos^2 \theta & \sin^2 \theta & 0 & 0 & 0 & 2 \sin \theta \cos \theta \\ \sin^2 \theta & \cos^2 \theta & 0 & 0 & 0 & -2 \sin \theta \cos \theta \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & \cos \theta & -\sin \theta & 0 \\ 0 & 0 & 0 & \sin \theta & \cos \theta & 0 \\ -\sin \theta \cos \theta & \sin \theta \cos \theta & 0 & 0 & 0 & \cos^2 \theta - \sin^2 \theta \end{bmatrix} \quad (3)$$

For the ideal laminate, the equivalent stiffness matrix C can be obtained directly by homogenization in the vertical direction (i.e.

in the direction of stacked hair) as shown in Fig. 11. It is assumed that stresses in the layers along the vertical direction are equal, and the in-plane deformation is continuous. Then the in-plane stresses and strains should be changed to average stresses and average strains, i.e. $\sigma_{zz} = \sigma_{zz}^*$, $\tau_{yz} = \tau_{yz}^*$, $\tau_{zx} = \tau_{zx}^*$, $\varepsilon_{xx} = \varepsilon_{xx}^*$, $\varepsilon_{yy} = \varepsilon_{yy}^*$, $\varepsilon_{xy} = \varepsilon_{xy}^*$.

Therefore, the constitutive relations of each layer can be expressed as:

$$\begin{Bmatrix} \{\sigma_A^*\} \\ \{\sigma_B^*\} \end{Bmatrix} = \begin{Bmatrix} [C_{AA}] & [C_{AB}] \\ [C_{AB}]^T & [C_{BB}] \end{Bmatrix} \begin{Bmatrix} \{\varepsilon_A^*\} \\ \{\varepsilon_B^*\} \end{Bmatrix} \quad (4)$$

where

$$\begin{aligned} \{\sigma_A^*\} &= \{\sigma_{zz}^* \quad \tau_{yz}^* \quad \tau_{zx}^*\}^T & \{\sigma_B^*\} &= \{\sigma_{xx}^* \quad \sigma_{yy}^* \quad \tau_{xy}^*\}^T \\ \{\varepsilon_A^*\} &= \{\varepsilon_{zz}^* \quad 2\gamma_{yz}^* \quad 2\gamma_{zx}^*\}^T & \{\varepsilon_B^*\} &= \{\varepsilon_{xx}^* \quad \varepsilon_{yy}^* \quad 2\gamma_{xy}^*\}^T \end{aligned} \quad (5)$$

$$[C_{AA}] = \begin{bmatrix} C_{33} & C_{34} & C_{35} \\ C_{43} & C_{44} & C_{45} \\ C_{53} & C_{54} & C_{55} \end{bmatrix}, [C_{AB}] = \begin{bmatrix} C_{13} & C_{23} & C_{36} \\ C_{14} & C_{24} & C_{46} \\ C_{15} & C_{25} & C_{56} \end{bmatrix}, [C_{BB}] = \begin{bmatrix} C_{11} & C_{12} & C_{16} \\ C_{21} & C_{22} & C_{26} \\ C_{16} & C_{26} & C_{66} \end{bmatrix} \quad (6)$$

Thus, Equation (4) can be rewritten as:

$$\begin{Bmatrix} \{\varepsilon_A^*\} \\ \{\sigma_B^*\} \end{Bmatrix} = \begin{Bmatrix} [C_{AA}]^{-1} & -[C_{AA}]^{-1}[C_{AB}] \\ [C_{AB}]^T[C_{AA}]^{-1} & -[C_{AB}]^T[C_{AA}]^{-1}[C_{AB}] + [C_{BB}] \end{Bmatrix} \begin{Bmatrix} \{\sigma_A^*\} \\ \{\varepsilon_B^*\} \end{Bmatrix} \quad (7)$$

$\{\varepsilon_A^*\}$ and $\{\varepsilon_B^*\}$ can also be obtained:

$$\begin{Bmatrix} \{\varepsilon_A^*\} \\ \{\sigma_B^*\} \end{Bmatrix} = \begin{Bmatrix} \{[C_{AA}]^{-1}\}^* & -\{[C_{AA}]^{-1}[C_{AB}]\}^* \\ \{[C_{AB}]^T[C_{AA}]^{-1}[C_{AB}]\}^* & -\{[C_{AB}]^T[C_{AA}]^{-1}[C_{AB}] + [C_{BB}]\}^* \end{Bmatrix} \begin{Bmatrix} \{\sigma_A^*\} \\ \{\varepsilon_B^*\} \end{Bmatrix} \quad (8)$$

$$\begin{cases} \{[C_{AA}]^{-1}\}^* = \frac{1}{H} \sum_{k=1}^n \int_{z^{k-1}}^{z^k} [C_{AA}]^{-1} dz \\ \{[C_{AA}]^{-1}[C_{AB}]\}^* = \frac{1}{H} \sum_{k=1}^n \int_{z^{k-1}}^{z^k} [C_{AA}]^{-1}[C_{AB}] dz \\ \{-[C_{AB}]^T[C_{AA}]^{-1}[C_{AB}] + [C_{BB}]\}^* = \frac{1}{H} \sum_{k=1}^n \int_{z^{k-1}}^{z^k} -[C_{AB}]^T[C_{AA}]^{-1}[C_{AB}] + [C_{BB}] dz \end{cases} \quad (9)$$

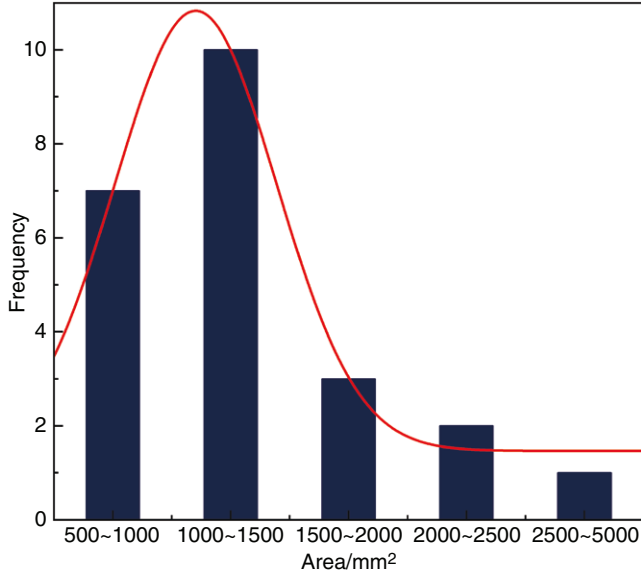


Figure 7. Statistical law of defects (area >500 mm²).

where n represents the total number of layers, z is the thickness direction coordinate, and H represents the thickness of the laminate.

Equation (8) can be rewritten as:

$$\sigma_i^* = \sum_{j=1}^6 C_{ij}^* \varepsilon_j^* \quad (10)$$

where C is the equivalent stiffness matrix after homogenization, $i = 1, 2, \dots, 6$.

The proposed 3D equivalence theory based on the homogenization method is an efficient way to calculate the laminate equivalent stiffness matrix. Then, the equivalent stiffness matrix is realized by MATLAB® programming according to the above equation, and Equation (11) is the calculated equivalent stiffness matrix of the fiber wound layer of the cylinder part.

$$[C] = \begin{bmatrix} 67.316 & 16.036 & 8.878 & 0 & 0 & 0 \\ & 96.254 & 9.345 & 0 & 0 & 0 \\ & & 15.669 & 0 & 0 & 0 \\ & & & 5.256 & 0 & 0 \\ & & & & 4.663 & 0 \\ \text{sym.} & & & & & 14.037 \end{bmatrix} \quad (\text{GPa}) \quad (11)$$

4.2 Finite element method model and failure criterion

Considering the symmetry of the COPV structure, a one-quarter-scale FEA (finite element analysis) model is built in ANSYS. Based on industrial CT scanning, a crack-like delamination defect, as shown in Fig. 12a, was incorporated into the model, distinguishing it from the ideal cylinder model. The boundary conditions are applied as shown in Fig. 12b. According to the 3D equivalent theory proposed in section 4.1, the equivalent

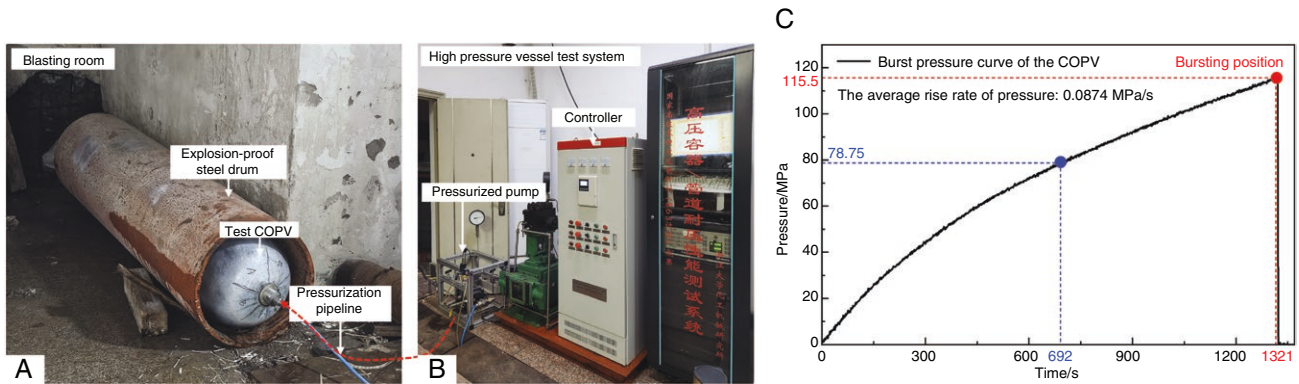


Figure 8. Burst test of COPV: (a) overview of the experimental setup; (b) the high-pressure vessel/pipe pressure resistance testing system; (c) pressure curve.



Figure 9. Three views of the COPV after the burst test: (a) left view; (b) front view; (c) right view.

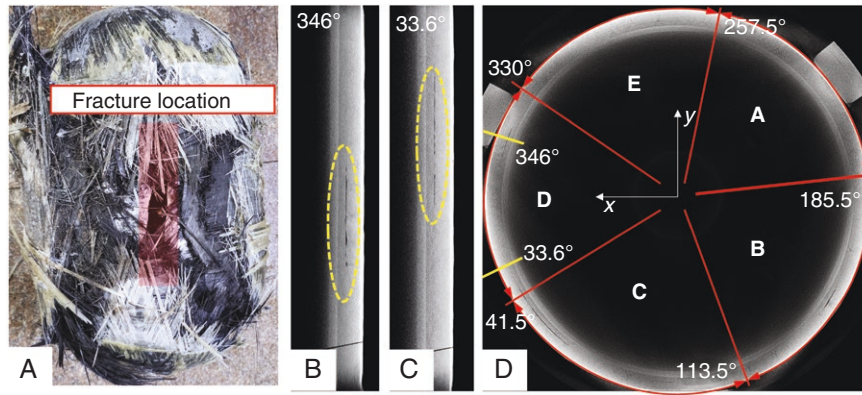


Figure 10. Comparison of measurements with burst test of the COPV.

Table 2. Mechanical properties of 6061 aluminum alloy.

Elastic Modulus/GPa	Poisson's Ratio
68.9	0.324

Table 3. Mechanical properties of carbon fiber-reinforced composite.

E_x /GPa	E_y /GPa	E_z /GPa	ν_{xy}	ν_{yz}	ν_{xz}	G_{xy} /GPa	G_{yz} /GPa	G_{xz} /GPa
154.1	11.41	11.41	0.33	0.49	0.49	7.092	3.792	7.092

stiffness matrix of the fiber wound layer is calculated and implanted as a material property in the FEA model. In order to avoid rigid body displacement, fixed constraints are imposed on both ends of the cylinder. Symmetrical constraints are imposed on x-z and y-z planes, and a uniform pressure load is exerted on the inner side of the aluminum liner. The aluminum liner and carbon fiber wound layer were meshed with the element type of Solid185 as shown in Fig. 12c.

For the prediction of the burst pressure of COPVs, many damage criteria can be employed [42, 43]. Among them, the Tsai-Wu criterion is most used to evaluate the deformability and potential failure risk of a material under specific loading conditions [44–46]. For orthotropic materials, the failure criterion is given by the following equation:

$$F_{11}\sigma_1^2 + F_{22}\sigma_2^2 + F_{66}\sigma_6^2 + F_1\sigma_1 + F_2\sigma_2 + 2F_{12}\sigma_1\sigma_2 \geq 1 \quad (12)$$

where

$$\begin{aligned} F_{11} &= \frac{1}{X_t X_c} & F_1 &= \frac{1}{X_t} - \frac{1}{X_c} \\ F_{22} &= \frac{1}{Y_t Y_c} & F_2 &= \frac{1}{Y_t} - \frac{1}{Y_c} \\ F_{66} &= \frac{1}{S^2} & F_{12} &= -\frac{1}{2} \sqrt{F_{11} F_{22}} \end{aligned} \quad (13)$$

Among them, σ_1 and σ_2 are the on-axis stresses in the longitudinal and transverse directions and σ_6 is the in-plane shear stress, while X_t , X_c , Y_t , Y_c , and S are the material strength parameters. The strength parameters of carbon fiber/epoxy composites are shown in Table 4. By combining the stresses in each direction from the finite element analysis results, failure occurs if the value of the entire equation exceeds 1.

4.3 Result

Figure 13 presents the finite element analysis results for both the pristine model and the model with delamination defect under an

internal pressure of 78.75 MPa. Figure 13a and b shows the radial displacement and circumferential strain distributions for the pristine model, respectively, while Fig. 13c and d illustrates the radial displacement and circumferential strain for the delamination defect model. From the radial displacement and circumferential strain contour plots, it is evident that the cylindrical section of the COPV is identified as the dangerous region, as it experiences significantly higher stress and strain values compared to the domes. Thus, for type III hydrogen storage COPVs, the cylindrical part is considered the critical region during the pressurization process. To predict the burst pressure of the COPV, we further analyzed the stress distribution in the filament winding layer of its cylindrical section.

The delamination defects within the filament winding layer of the cylinder alter the overall structural strength consistency, particularly in the out-of-plane direction. As shown in the contour plots mentioned above, compared to the pristine model, the results for the model with delamination defect show varying degrees of distortion in out-of-plane displacement and circumferential strain at the defect location. As the internal pressure increases during the loading process, these distortion characteristics become more pronounced at the defect sites, leading to a reduction in the burst pressure of the COPV. This, in turn, induces crack initiation at the defect locations, ultimately causing the COPV to fail.

Based on the stresses in various directions obtained from the cylinder model analysis and the Tsai-Wu failure criterion, Fig. 14 indicates that the burst pressure of the pristine model is 137 MPa, while the burst pressure of the model with delamination defect is 105 MPa. As shown in Section 3, the experimentally measured burst pressure of the cylinder is 115.5 MPa, which deviates by 18.6% from the pristine model prediction and by 9.09% from the model with delamination defects.

It can be seen that both the pristine model and the model with delamination defect exhibit a prediction error of 9% to 20% compared to the experimentally measured burst pressure. This discrepancy arises primarily because the pristine model assumes the material to be in a completely ideal state, with no defects or damage, leading to a predicted burst pressure that is 18.6% higher than the measured value. For the model with delamination defects, the modeling of defects does not perfectly match the actual conditions; the spacing between delamination in the model is larger than that detected by industrial CT scanning, resulting in a greater impact on the overall structure of the cylinder. Consequently, the predicted burst pressure is 9.09% lower than the experimentally measured value.

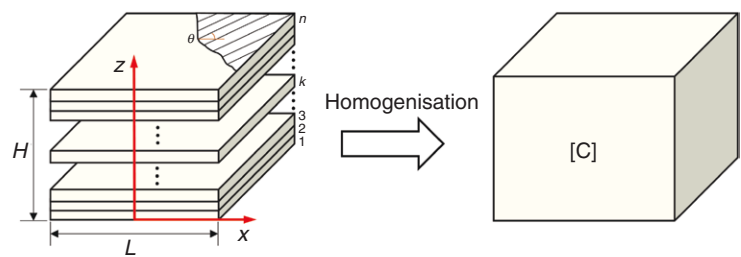


Figure 11. Establishment of material model.

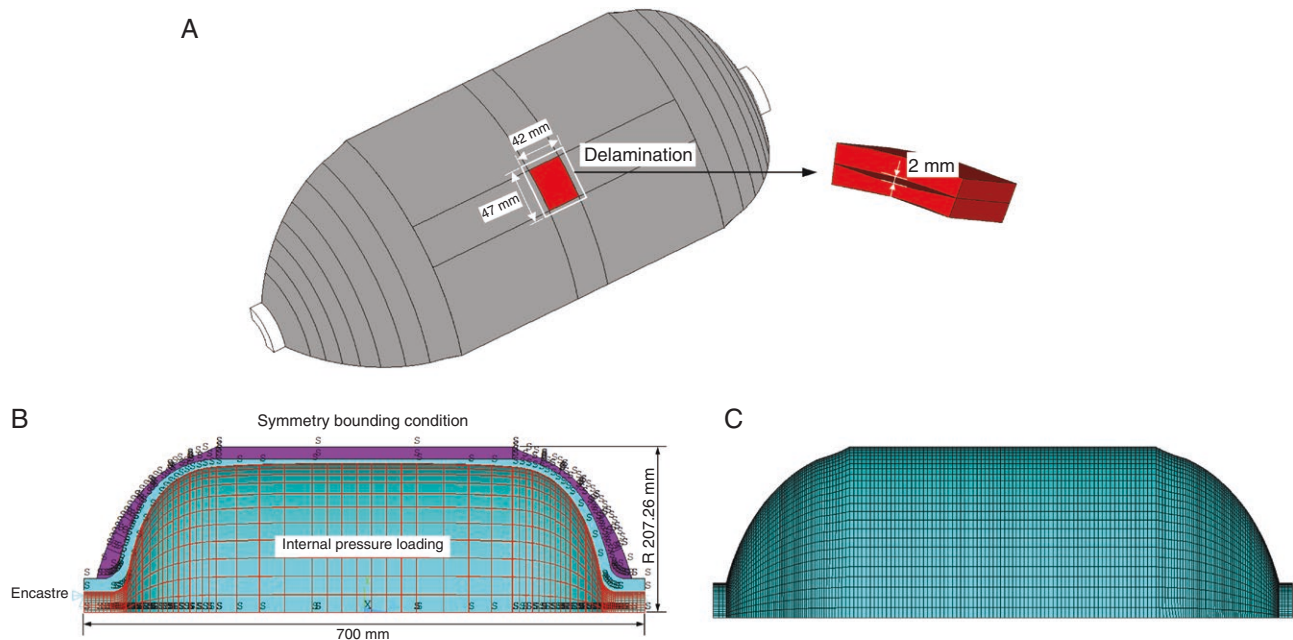


Figure 12. (a) One-quarter-scale FEA model of the COPV with delamination defect; (b) boundary conditions; (c) model after meshing.

Table 4. Strength parameters for T700/epoxy composite [47].

X_t (MPa)	X_c (MPa)	Y_t (MPa)	Y_c (MPa)	S (MPa)
2150	2150	298	298	778

Therefore, it can be concluded that delamination defects within the winding layer of the COPV affect the consistency of the overall structural strength, reducing the structural integrity of the COPV. During the actual loading process, these defects lead to localized stress, strain, and displacement distortions, which can trigger crack propagation during the bursting process, ultimately reducing the burst pressure of the cylinder.

5. Conclusion

In this paper, an industrial CT scan and a hydraulic burst test were carried out on a type III hydrogen storage COPV (product number CHG3-383-55-35 S/A). The industrial CT scan revealed

that a large number of delamination defects with dispersed sizes and random locations exist inside the fiber wound layer, and the overall area accounted for a relatively large proportion, which was the predominant type of manufacturing defect in the fiber wound layer of COPVs. Combined with the hydraulic burst test, it was found that the aggregated area of large-sized delamination defects in the cylinder part triggered the crack initiation during the test. The burst pressure of the COPV was measured at 115.5 MPa.

Finally, a method for calculating the equivalent stiffness matrix of composites based on 3D solid units is proposed, which greatly reduces the cost of modeling. By carrying out a finite element simulation of the COPV, it is confirmed that the cylindrical part is the most dangerous area during the loading process. The experimentally measured burst pressure of the cylinder is 115.5 MPa, deviating by 18.6% from the prediction of the pristine model and by 9.09% from the model with delamination defects. And, it can be found that the presence of delamination defects affects the uniformity of the overall structural strength of the COPVs, reduces its burst pressure, and influences the crack initiation during the burst process.

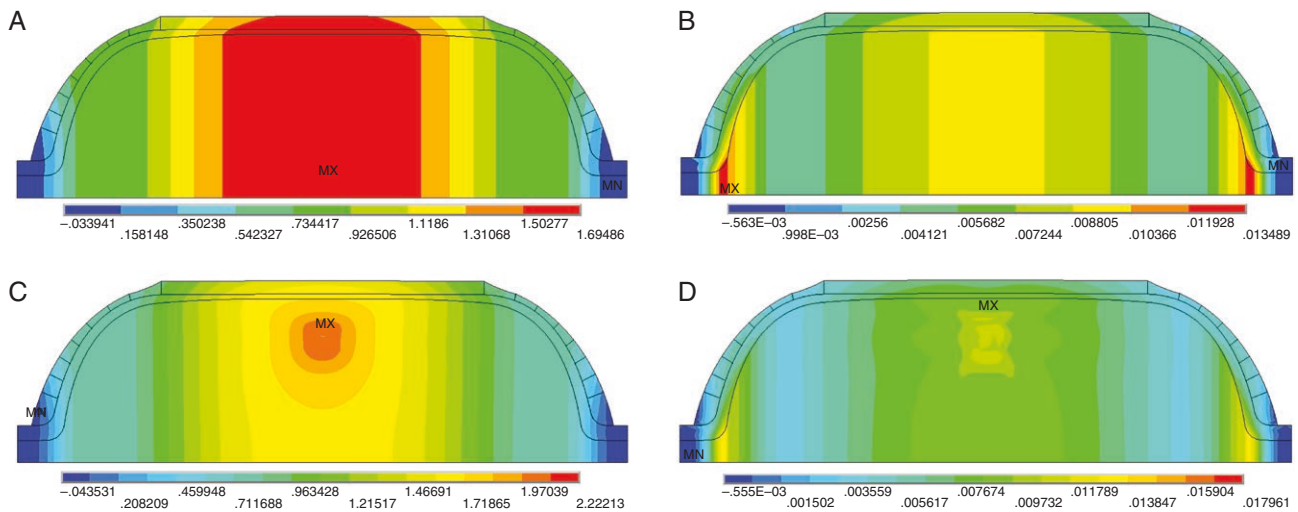


Figure 13. FEA results (78.75 MPa): (a) radial displacement of pristine model; (b) circumferential strain of pristine model; (c) radial displacement of model with delamination defect; (d) circumferential strain of model with delamination defect.

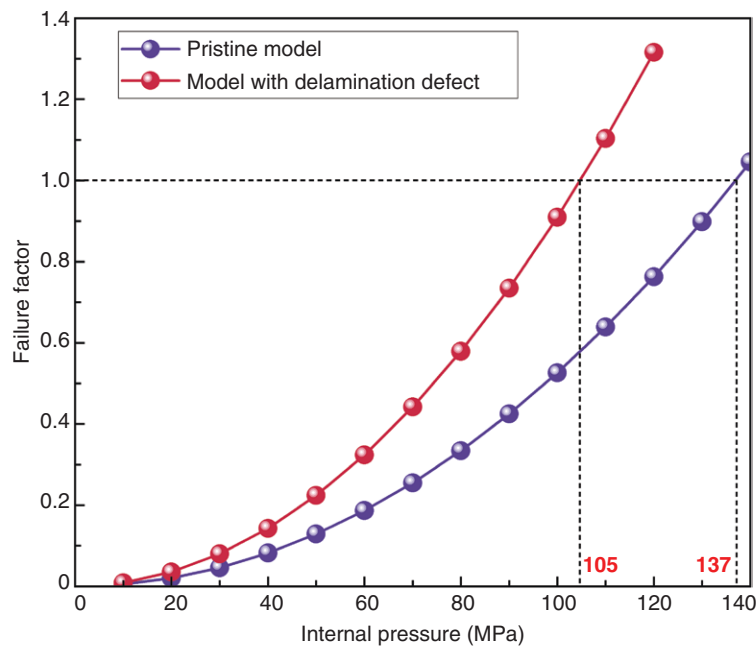


Figure 14. Variation of the failure factor with different inner pressures.

Author contributions

Changchen Liu (Formal analysis [equal], Investigation [equal], Methodology [equal], Software [equal], Writing—original draft [equal], Writing—review & editing [equal]), Zhihui Ouyang (Data curation [equal], Validation [equal]), Jiexiang Yu (Data curation [equal], Investigation [equal]), and LiMa (Funding acquisition [equal], Investigation [equal], Resources [equal], Supervision [equal], Writing—review & editing [equal]).

Conflict of interest statement

The authors declare no competing interests.

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Data availability

Data will be made available upon request.

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