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A CONTRIBUTION TO STRUCTURAL RELIABILITY ANALYSIS OF COMPOSITE HIGH-PRESSURE HYDROGEN STORAGE TANKS

Wkład w analizę niezawodności strukturalnej kompozytowych wysokociśnieniowych zbiorników do magazynowania wodoru

Abstract: *Although composite high-pressure tanks are a subject of growing interest, especially for hydrogen storage applications, a detailed structural reliability analysis still needs to be improved. This work aims to provide a probabilistic investigation of the mechanical response of composite high-pressure hydrogen storage tanks using the Monte Carlo Simulation method. A performance function based on the circumferential model of composite pressure cylinders is employed with five random design variables. According to the results, the internal pressure and the helical layer thickness are the foremost parameters significantly impacting the structural reliability of the tank, whereas, the helical layer thickness and winding angles have a minor influence. In addition, high coefficients of variation values cause the contraction of the safety margin potentially leading to the failure of the composite hydrogen high-pressure tank. The obtained results were validated with experimental tests available in the literature.*

Keywords: structural reliability, composite tanks, hydrogen storage, Monte Carlo simulation, safety margin

Streszczenie: *Chociaż kompozytowe zbiorniki wysokociśnieniowe są przedmiotem rosnącego zainteresowania, zwłaszcza w zastosowaniach związanych z magazynowaniem wodoru, szczegółowa analiza niezawodności konstrukcji wciąż wymaga poprawy. Niniejsza praca ma na celu zapewnienie probabilistycznego badania odpowiedzi mechanicznej kompozytowych wysokociśnieniowych zbiorników do przechowywania wodoru przy użyciu metody symulacji Monte Carlo. Zastosowano funkcję wydajności opartą na modelu obwodowym kompozytowych cylindrów ciśnieniowych z pięcioma losowymi zmiennymi projektowymi. Zgodnie z wynikami, ciśnienie wewnętrzne i grubość warstwy obwodowej są głównymi parametrami istotnie wpływającymi na niezawodność konstrukcyjną zbiornika, podczas gdy grubość warstwy spiralnej i kąty uzwojenia mają niewielki wpływ. Ponadto duże wartości współczynników zmienności powodują kurczenie się marginesu bezpieczeństwa potencjalnie prowadząc do awarii kompozytowego zbiornika wysokociśnieniowego na wodór. Uzyskane wyniki zostały zweryfikowane z badaniami eksperymentalnymi dostępnymi w literaturze.*
Słowa kluczowe: niezawodność strukturalna, zbiorniki kompozytowe, magazynowanie wodoru, symulacja Monte Carlo, margines bezpieczeństwa

1. Introduction

The emergence of composite tanks due to their distinctive characteristics has provided an excellent solution for transportation and gas storage in terms of safety and efficiency in several fields, especially for storing the so-called environment-friendly gases such as green hydrogen used for fuel cell vehicles. Nevertheless, composite pressure tanks present a severe challenge for reliable and economical design. To deal with this issue, much research emphasizes different aspects related to the optimal design of overwrapped cylindrical composite structures under internal pressure, such as composite failure behaviour [1], production and manufacturing techniques [2], optimization of winding angles [3] and geometrical shape of composite tanks [4]. Nonetheless, no existing studies have furnished a definitive design approach for composite high-pressure hydrogen vessels [5].

In current literature, deterministic methods for designing and analysing composite hydrogen tanks, incorporating safety factors, have garnered significant attention from many scholars. However, for a reliable design, it is crucial to consider the effect of randomness related to different design variables [6]. Undoubtedly, the structural reliability analysis of different engineering structures in general, which incorporates uncertainty, is a noticeable method in analysing safety margin distributions and reliability of the structure regarding its design requirements [7]. Despite this, according to the authors, no such study has been found in the literature on safety margin distributions of high-pressure hydrogen storage tanks wound with different helical winding angles. Nevertheless, some papers have been devoted to studying the structural reliability of cylindrical composite structures.

One of the earliest appreciable structural reliability contributions was made by Uemera, and Fukunaga [8]. They utilized the Monte Carlo Simulation method (MCSM) to predict the probabilistic burst failure pressure of filament wound composite cylinders, and the results from the probabilistic approach were in good agreement with the experimental outcomes of hydraulic burst pressure tests. The authors showed that the burst failure pressure of composite tanks corresponds to 50% of the probability of failure.

An analytical approach for assessing the probabilistic mechanical response of thick multi-layered composite pipes was presented by Bouhafs et al. [9]. According to the reliability analysis, the probabilistic distribution of hoop stress in laminated thick pipes is greatly affected by uncertainties in geometrical and mechanical properties. Later on, Hocine et al. [10,11] developed a sensitivity theoretical design using Monte Carlo simulations for composite pipelines and the theoretical sizing tool performed by the same author [12] in combination with MCSM. The developed study highlighted the key factors influencing the failure of axially symmetric composite structures.

Zhang et al. [13] are interested in predicting the burst pressure of overwrapped composite vessels using analytical and probabilistic approaches. The performance function developed in this manuscript is based on the maximum allowable pressure of composite overwrapped tanks. The accuracy of the performance function was well proven, and good agreement was found with experimental results. However, the author does not investigate the uncertainties' effect on the composite tank's safety margin distributions. Ghouaoula et al. [14] studied the safety margin distributions obtained by the probability density functions of a low-pressure compressed natural gas tank. The findings of the study revealed that the applied internal loading has a considerable impact on the probabilistic mechanical behaviour of the tank, while the elastic properties have little effect.

This paper aims to present a probabilistic investigation of safety margin distributions of composite hydrogen storage tanks under high pressure. The Monte Carlo Simulation method is used to predict the distributions for five random variables: the internal pressure, the direction angles of the fibres, and the thicknesses of the hoop and helical layers. Different scenarios have been proposed to investigate the effect of the uncertainties associated with design parameters on the structural reliability of the composite tank.

2. Problem formulation

Overwrapped composite vessels are considered axisymmetric structures of radius R_i subjected to internal pressure *(P)*. Essentially, they comprise an inner aluminium liner encased in many composite hoop layers and helical layers wound at various winding angles α. The fibre direction angles θ associated with the winding angles are given by θ = 90 - α.

In this research, the composite hydrogen storage tank analysis is based on the circumferential model of composite cylinders. The composite tank is assumed to be a succession of thin-walled stacked circles, as shown in Fig. 1. The following formula can provide the circumferential internal pressure of composite cylinders [13]:

$$2\pi R_i P_i = 2\pi R_0 P_0 + 2\pi R_1 P_1 + \cdots + 2\pi R_n P_n \tag{1}$$

Where P_i and P_n are the internal pressure and the pressure of the n^{th} layer, respectively. R_i and R_n are the internal radii and the radii of the n^{th} layer, respectively.

The radius of the composite tank can be expressed as:

$$R_n = R_i + t_1 + t_2 + \cdots + t_n \tag{2}$$

Where t_n is the n^{th} layer thickness.

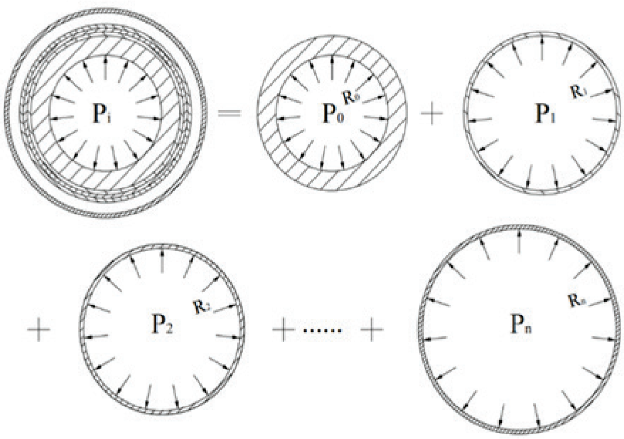

Fig. 1. Circumferential model for cylindrical hydrogen composite pressure tanks [13].

To simplify the mathematical modelling process, the ratio of the internal radius to the last cylinder radius $K_n = \frac{R_n}{R_i}$ is introduced. Thus, the expression (1) can be expressed as follows:

$$P_i = P_0 + K_1 P_1 + K_2 P_2 + \cdots + K_n P_n \tag{3}$$

The primary purpose of the liner is to prevent hydrogen embrittlement and leakage [15]. Therefore, the internal pressure is assumed to be borne solely by the composite material, without considering the liner's role ($P_0 = 0$) [13,15]. In addition, since the thickness of the composite layers is much less than the radii of the circles, K_n can be considered equal to one ($K_n = 0$). Therefore, equation (3) can be expressed as follows [13]:

$$P_i = P_1 + P_2 + \cdots + P_n \tag{4}$$

The internal pressure of n^{th} layer is given by [13]:

$$[P]_n = \frac{2t_n[\sigma]_n^*}{D_i + t_n} \tag{5}$$

Where:

$$[\sigma]_n^* = \begin{cases} \frac{X_t}{cos^2(\theta)}\ (0 < \theta \leq 20) \\ \frac{S_{tc}}{sin(\theta)\,cos(\theta)}\ (20 < \theta \leq 30) \\ \frac{Y_t}{sin^2(\theta)}(30 < \theta \leq 90) \end{cases} \tag{6}$$

Where D_i is the internal diameter, θ is the direction angle, X_t is longitudinal ultimate tensile strength, Y_t is transverse ultimate tensile strength, S_{tc} is the shear strength.

The axisymmetric pressure tank investigated in this paper has five composite layers. The five layers are divided into two helical layers and three hoop layers. Both hoop layers and helical layers have the same thickness. The thicknesses of the different hoop composite layers are $t_1 = t_3 = t_5 = t_{hoop}$. Moreover, the fibre winding angles of the different hoop composite layers are $\alpha_1 = \alpha_3 = \alpha_5 = 90°$. Therefore, the direction angles of the different hoop layers are $\theta_1 = \theta_3 = \theta_5 = 90° - 90° = 0°$. Subsequently, the thicknesses of each helical layer is equal to $t_2 = t_4 = t_{helical}$. The winding angles of the helical composite layers are α_2 and α_4. So, the fibre direction angles of the two helical layers are $\theta_2 = 90° - \alpha_2$ and $\theta_4 = 90° - \alpha_4$.

If the number of layers of the composite cylinder is equal to *k*, the burst failure pressure can be defined by two equations depending on whether the number of layers is even (*k=2m*) or odd (*k=2m+1*):

$$P_b = \begin{cases} 2t_{hoop}X_t \sum_m^1 \left[\frac{1}{D_i+(2n-1)t_{hoop}+2(n-1)t_{helical}}\right] + 2t_{helical}Y_t \sum_m^1 \left[\frac{1}{D_i+2nt_{hoop}+(2n-1)t_{helical}} \cdot \frac{1}{(sin\theta_{2n})^2}\right]; (k = 2m) \\ 2t_{hoop}X_t \sum_m^1 \left[\frac{1}{D_i+(2n-1)t_{hoop}+2(n-1)t_{helical}}\right] + 2t_{helical}Y_t \sum_{m-1}^1 \left[\frac{1}{D_i+2nt_{hoop}+(2n-1)t_{helical}} \cdot \frac{1}{(sin\theta_{2n})^2}\right]; (k = 2m+1) \end{cases} \tag{7}$$

Since the pressure tank investigated in this manuscript has five composite layers, which is an odd number, thus *m=3*.

The reader is referred to [13] for more details about developing the circumferential burst failure pressure model for composite vessels.

Generally, all failure probability analysis methods share a common starting point: a limit state function *g(X)* built upon the stress-strength interference model. The latter is defined as the difference between stress (*S*) and resistance of the structure (*R*) as follows [16]:

$$g(X) = R - S \tag{8}$$

Developing a limit state equation that adheres to the stress-strength interference model is challenging due to the anisotropy and structural configuration of composites. Thus, in this paper, instead of the stress and strength of the tank, the difference between the burst failure pressure P_b and the working pressure P_t is employed as a performance function:

$$g(X) = P_b - P_t = t_{hoop} X_t \sum_m^1 \left[\frac{1}{D+(2n-1)t_{hoop}+2(n-1)t_{helical}}\right] + 2t_{helical} Y_t \sum_{m-1}^1 \left[\frac{1}{D+2nt_{hoop}+(2n-1)t_{helical}} \cdot \frac{1}{(sin\theta_{2n})^2}\right] - P_t \quad (9)$$

The safety margin is defined such that $g(X) > 0$.

The probability of failure is defined as the integral of the probability density function $f_X(X)$ follows [16]:

$$P_f = \int_{g(X)\leq 0} f_X(X)dx \quad (10)$$

Structural reliability can be estimated by creating numerous axisymmetric composite tank models via random sampling. Thus, the probability of failure is determined by the relationship between the number of failed samples and the total number of samples. The Monte Carlo simulation method is used in this manuscript and 10^5 simulations are performed to obtain different safety margin distributions of the composite hydrogen storage tank.

3.Numerical application

The composite high-pressure tank studied in this paper consists of an aluminium liner fully wrapped with T700/epoxy composite layers with equal thickness. The configuration of the stacking sequence is [±90/±18.9/±90/±28.6/±90]. The experimental burst pressure of the composite high-pressure hydrogen storage tank is P_b=125~126 MPa [13, 17]. The burst pressure found in equation (7) equals 125.8 MPa. Thus, the analytical result is consistent with the experimental results. The direction angles of the composite layers are $\theta_1 = \theta_3 = \theta_5 = 0°$, $\theta_2 = 71.1°$ and $\theta_4 = 61.4°$. The operating pressure of the composite hydrogen tank is set at 70 MPa to investigate the composite vessel's probabilistic mechanical response under high pressure. The statistical properties of random design variables of the hydrogen tank are given in Tab. 1, and the material's mechanical properties are given in Tab. 2.

Table 1

Statistical properties of random variables

Random Variable	Mean	COV	Distribution
Operating pressure (MPa)	70	10%	Normal
Thickness of hoop layers t_{hoop} (mm)	0.84	10%	Normal
Thickness of helical layers $t_{helical}$ (mm)	0.84	10%	Normal
Helical direction angle θ_2 (°)	71.1	10%	Normal
Helical direction angle θ_4 (°)	61.4	10%	Normal

Table 2

Mechanical properties of carbon-epoxy composite material

Parameter	Value
Longitudinal ultimate tensile strength Xt (MPa)	2150
Longitudinal ultimate compress strength Xc (MPa)	2150
Transverse ultimate tensile strength Yt (MPa)	298
Transverse ultimate compress strength Yc (MPa)	298
Longitudinal ultimate shear strength Stc (MPa)	778

4. Results and discussion

Different graphical representations of probability density functions (PDF) of the performance function *g(X)* with various combinations of input random design variables illustrate the distribution functions of the mechanical response of a high-pressure hydrogen storage tank.

From Fig. 2, it can be seen that the distribution function of g(X) has a leftward tendency with a greater dispersion compared to P_b and P_t. It results from the difference between the two distributions. Moreover, this underlines the importance of analysing structural reliability and considering uncertainties when assessing the performance of high-pressure vessels.

Fig. 3. shows the probability density functions with multiple input design variables. The addition of random design variables increases the dispersion of the curves, resulting in a corresponding increase in the probability of failure. The most significant dispersion of the PDFs is obtained by introducing all the parameters of the composite tank into the limit state equation as stochastic variables. Moreover, it can also be noted that the probability of failure increases, especially when the thickness of the hoop layers and the internal pressure are added as random variables. This can reveal the critical effect of the hoop layer thickness and the internal loading on the structural reliability of high-pressure hydrogen storage tanks.

Fig. 4. shows the safety margin distributions of the pressure tank as a function of various internal pressure values. It is easy to notice that the dispersion of the PDF curves becomes more pronounced as the internal pressure of the tank increases. It is worth noting that when the pressure value reaches 125.8 MPa, corresponding to the burst pressure value, the curve becomes symmetrical to the origin line. Thus, 50% of the area of the curve is in the failure zone. Since the failure probability is the integral of the probability density function, as presented by equation (10), it could be deduced that the burst pressure coincides with 50% of the failure probability. Therefore, the results presented in this paper coincide well with probabilistic investigations, experimental tests, and the finite element analysis already mentioned in the literature [12, 13, 16].

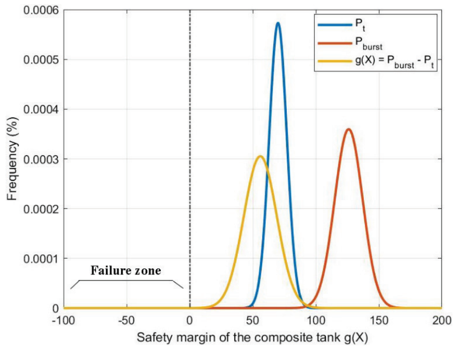

Fig. 2. Safety Margin distributions of the composite hydrogen tank

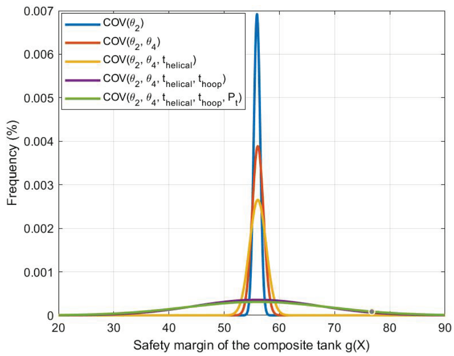

Fig. 3. Safety margin distributions of the composite hydrogen tank in terms of a different combination of input design variables

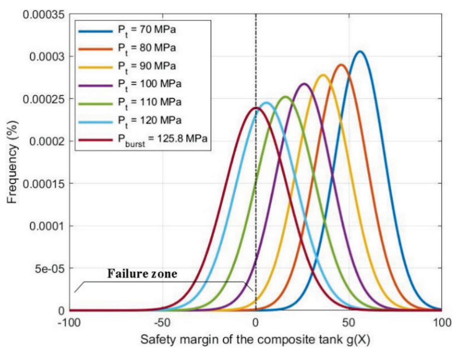

Fig. 4. Safety margin distributions with different internal pressures

The effect of the variation of the thickness of the hoop and helical layers on the structural reliability of the composite hydrogen tank is shown in Fig. 5(a) and 5(b), respectively. As the thickness of hoop layers increases from 0.6 mm to 0.90 mm, the PDFs of the limit state equation tend towards the right side and move away from the failure zone. Whereas for the same increase in the thickness of helical layers, the changes in the safety margin distributions are less pronounced. This means that the probability of failure is more sensitive to the variation of the hoop layers' thickness than the thickness of the helical layers.

Fig. 6(a) and 6(b) discuss the variation of the safety margin distributions of the composite hydrogen tank, respectively, in terms of the variation of the two direction angles θ_2 and θ_4. It can be observed that the variation of the direction angles from 50° to 75 does not overly affect the probability of tank failure.

In Fig. 7, three scenarios using three coefficients of variation (COV) were simulated to show the effect of uncertainties and fluctuations associated with design parameters on the structural reliability of the high-pressure hydrogen cylinder. When the coefficients of variation range from 8% to 20%, a non-negligible probability of failure can be inferred from the extensive interval covered by the dispersion. Therefore, effective management of uncertainties, particularly those related to the working pressure, is a prerequisite for ensuring the safety of the hydrogen composite storage tank.

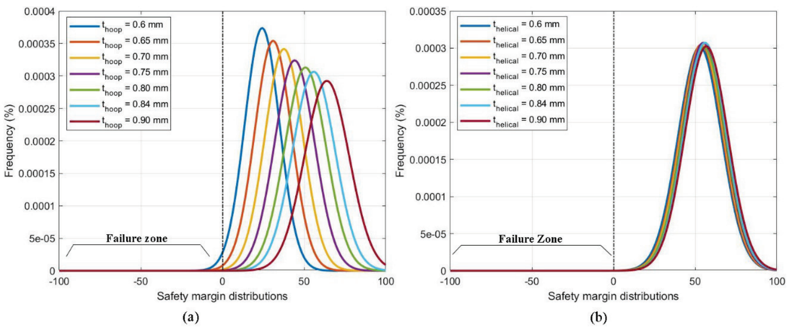

Fig. 5. Safety margin distributions of the composite hydrogen tank with different thicknesses of a) hoop layers and b) helical layers

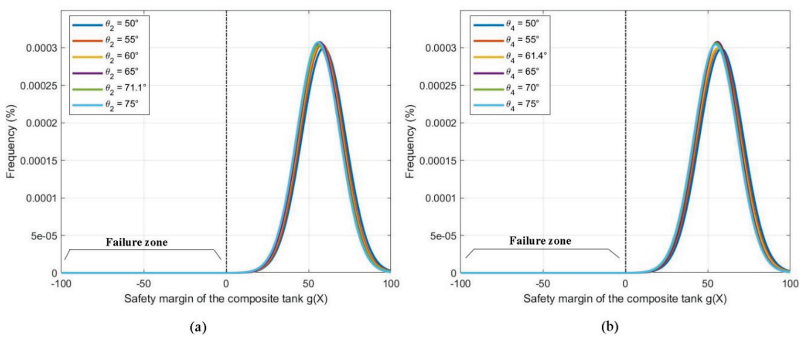

Fig. 6. Safety margin distributions of the composite hydrogen tank with different fibre direction angles a) θ_2 and b) θ_4

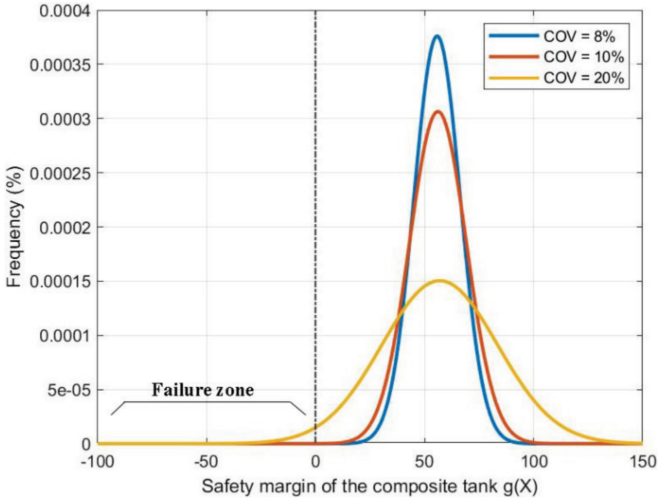

Fig. 7. Safety margin distributions of the composite hydrogen tank with different coefficients of variation of the design variables

5. Conclusions and summary

This manuscript aims to develop a probabilistic analysis of a composite hydrogen storage tank under high pressure. The Monte Carlo simulation method is used to investigate the safety margin distributions of the composite cylinder with different input random design variables combinations. The results showed the following:

- Structural reliability analysis can provide valuable insights into the behaviour of high-pressure composite tanks.
- Internal pressure and the thickness of hoop layers are the main parameters that affect the tank's structural reliability and increase the probability of failure.
- The burst pressure of composite tanks obtained by analysing the safety margin distribution is equal to $P_f \approx 50\%$; experiment tests have validated this result.
- Rigorous control of the uncertainties associated with the design parameters, especially the internal pressure, is mandatory since each time the COV increases, the probability of failure also increases. It can lead to failure of the cylindrical structure.

Furthermore, this simulation should be an essential guide for the manufacturer to design safe and reliable composite high-pressure vessels. The perspective of this research paper is dedicated to the failure probability analysis of composite high-pressure tanks to develop a structural reliability sizing tool devoted to the optimal design of composite tanks under different loading conditions.

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