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Research Article

Failure Probability Analysis of Composite Pressure Tanks Using Subset Simulation

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ABSTRACT

Composite pressure tanks have received increased attention across a number of civilian applications due to their lightweight and high strength. Traditionally, the design of composite vessels is based on deterministic analysis. However, the design of these structures is challenging and involves several kinds of uncertainties. In fact, different computational investigations have been carried out but no studies provide a resolution for small failure probability evaluation of composite pressure tanks. The aim of this study is to establish a computational framework to investigate small failure probability levels of composite tanks using the Subset Simulation method (SS). The model was developed in two steps, first, the development of limit state functions for hoop and helical layers using netting analysis, and afterwards, a probabilistic computation with six random variables. To quantify the effect of the randomness of different parameters on the structural reliability of composite tanks, a sensitivity analysis was performed using different values of coefficients of variation (COV). It was observed from the results that SS has the ability and the accuracy required to evaluate small failure probabilities which are commonly encountered in composite tank applications. In addition, the hoop strength, the internal pressure, and the thickness of the composite are the major design variables that have a great impact on the structural reliability of the axially symmetric composite tank whereas the fiber winding angle has little effect. Moreover, high COV values drastically reduce the safety zone, which could eventually lead to the burst failure of the composite pressure tank. Furthermore, this study implements a reliability-based design from the perspective of hoop and helical composite layer thicknesses, thus providing a rational assessment of the risk of structural failure.

1. Introduction

Designing pressure tanks with the highest efficiency, the longest life expectancy, and low cost is one of today's hot topics in the field of gas storage and transportation. In particular, overwrapped composite pressure tanks have been widely employed in different industries, and have provided an excellent solution for gas storage, including storage of the so-called environment-friendly gases such as compressed natural gas (CNG) and green hydrogen. Several

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approaches have been used to analyze composite tanks, such as the finite element method, classical lamination theory, artificial intelligence, netting analysis, etc. Nevertheless, the design of composite structures is an intricate task, mainly due to the presence of several design variables. These variables are influenced by variations in the geometrical and mechanical properties and loading conditions [1-13]. In the literature, research was mainly focused on composite failure behavior, manufacturing processes, winding angle optimization, and geometrical shape of tanks, however, none of these researches has given a definitive protocol for designing axially symmetric composite tanks [14].

In contrast to works using deterministic methods including global safety factors, which were extensively employed for the analysis and design of composite pressure tanks, the studies taking into account the effect of randomness associated with design parameters were less addressed. In fact, structural reliability holds a critical position in the analysis and design of engineering structures [15]. The primary goal of structural reliability is to estimate the probability of failure of structures, considering fluctuations and uncertainties in geometrical and mechanical design parameters [16]. One of the hardest computational problems in the field of structural reliability is the prediction of small failure probabilities. Of all the approaches used to calculate the probability of failure, the subset simulation is a powerful, accurate, and computationally efficient new method capable of predicting small failure probabilities [17]. Many researchers have employed this method in failure probability analysis of different structures, such as buildings, bridges, and heliostat systems [18-21]. So far, no such research study on failure probability analysis of composite pressure tanks has been found in the existing literature according to the authors' knowledge. Nevertheless, a number of probabilistic studies using different methods have been carried out within this framework.

One of the earliest appreciable probabilistic studies was conducted by Uemera and Fukunaga [22], in which they used the Monte Carlo (MC) simulation method to study the probabilistic failure strength of carbon fiber filament wound vessels. Good agreement was obtained between the probabilistic approach and the experimental hydraulic pressure tests. In this paper, the author showed that the burst pressure of laminated composite tanks corresponds to a 50% probability of failure.

To illustrate the influence of randomness on the fiber winding angle of laminated composite tanks, Béakou et al. [23] have scrutinized the impact of the dispersion of random design parameters to forecast the probabilistic strength of glass fiber laminated vessels using the traditional laminated shells analysis and utilized the Tsai-Wu quadratic failure criterion as the performance function. The major attention of this work was to prove that the common value of 55° did not permanently denote the optimal fiber winding angle. To forecast the deformation and the burst pressure of composite tanks subjected to uniform internal loading, Hwang et al. [24] employed the Edgeworth expansion method (EEM) and the MC simulations. In this work, the evolution of the failure probability has been represented by the cumulative distribution curves. The probabilistic model showed good agreement with experimental hydraulic tests for the hoop strain and the burst pressure of the ten composite tanks used in the study.

To investigate the reliability of composite cylinders under external pressure, Cai et al. [25] performed an experimental and analytical study of composite cylinders used in the field of offshore oil drilling. In this work, a limit state equation based on the critical buckling external pressure was formulated and then solved via the traditional theory of laminated shells. The probabilistic sensitivity analysis revealed that uncertainties associated with the external pressure have the greatest impact on the probability of the failure of the composite cylinder. In the recent work of Solazzi and Vaccari [26], the structural reliability-based design of composite vessels using the netting analysis has been performed. A comparative study between tanks made of isotropic materials and those made of composite materials was carried out, and the geometry and the strength of the pressure tanks were validated using the finite element method (FEM). It was shown that the weight of CFRP tanks is equivalent to 17% of isotropic tanks manufactured of steel.

There is also other interesting literature on the general theory of anisotropic composites combined with probabilistic methods. A theoretical approach was proposed by Bouhafs et al. [27] to calculate strains and stresses in helical wound pressure thick pipes. Afterward, a probabilistic sensitivity analysis of the mechanical response was conducted in this paper, using a performance function obtained by the difference between the hoop stress and the hoop strength. It has been observed that the safety of the pipeline is more sensitive to the uncertainties associated with small composite thicknesses compared to pipes with large thicknesses. Maizia et al. [28] studied the structural reliability of composite cylinders under hygro-thermo-mechanical loading. The study showed a reduction in the safety margin when all design parameters were treated as random. In addition, noticeable contributions of the failure probability-based approach for axially symmetric laminated composite pipes have been made by Hocine et al. [29,30]. The established work discerned the key design parameters that influence the probability of failure of cylindrical pipes under internal pressure, using the analytical sizing tool formulated by the same author [31]. Later on, Ghouaoula et al. [32] analyzed the probability density functions for different input random design variables of an overwrapped composite pressure vessel with an aluminum liner, used for natural gas storage applications. The outcomes of these researches have pointed out that the uncertainties related to elastic properties have no considerable impact on the safety margin of the axially symmetric laminated structure.

The aim of this work is to evaluate, under uniform internal pressure, the failure probability level of a composite tank designed in accordance with the netting theory, taking into consideration uncertainties related to different design parameters. To this end, the composite pressure tank is divided into two parts: helical and hoop layers. Each part has a limit state function obtained by netting analysis. Thus, the failure probability of the entire structure is calculated using the law of composition in structural reliability engineering. Different scenarios have been proposed, using different coefficients of variation (COV) to investigate the impact of uncertainties of the main design parameters on the structural reliability of the composite tank.

2. Materials and Methods

2.1. Netting Analysis

Much attention has been paid to mathematical models to analyze composite pressure tanks including the classical laminate theory [33] the general theory of anisotropic composites, where Lekhnitskii's works are an important reference [34], the finite element method [35] and netting theory [26, 36]. The latter is an analytical method used in the design of composite pressure tanks to determine the composite wall thickness with generally unknown reliability. It is based on the assumption that the pressure is carried only by the fibers, neglecting any contribution of the matrix to bearing the load and any interaction between the filaments. In this work, netting analysis is used to develop the limit state functions, which will be used for the failure probability analysis.

To formulate the problem, the composite tank is assumed to be an axially symmetric composite cylinder of a radius *r*, manufactured by a number of hoop layers with a winding angle of 90°, and helical layers with the angle-ply orientation of ± α. The cylinder is subjected to uniform internal loading *p*. Combinations of the hoop and helical layers in the hoop and axial directions are shown in Fig. 1.

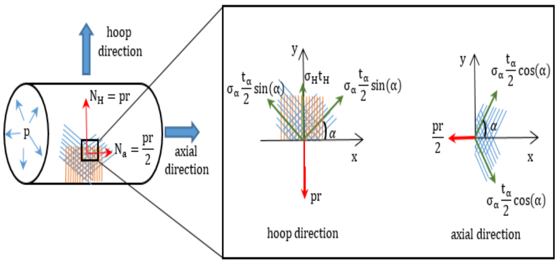

Fig. 1. Combinations of the hoop and helical layers in the hoop and axial directions

The internally applied pressure *p* generates load resultants in axial and hoop directions; N_a and N_H respectively:

$$N_a = \frac{pr}{2} \tag{1}$$

$$N_H = pr \tag{2}$$

where *p* is the internal pressure and *r* is the radius of the tank.

The stress resultants are given by the following expressions [37]:

- In the helical direction:

$$\sigma_\alpha t_{helical}(\cos(\alpha))^2(2\pi R) = p\pi r^2 \tag{3}$$

- In the hoop direction:

$$\sigma_\alpha t_{helical}(\sin(\alpha))^2 + \sigma_H t_{hoop} = pr \tag{4}$$

where s is the stress of fibers in the helical layers, σ_H is the stress of fibers in the hoop layers, $t_{helical}$ is the thickness of the helical layers, t_{hoop} is the thickness of the hoop layers and α is the winding angle.

The well-known expressions of the thicknesses of helical and hoop layers of the composite pressure tank can be expressed, respectively, as [38, 39]:

$$t_{helical} = \frac{pr}{2\sigma_\alpha(\cos(\alpha))^2} \tag{5}$$

$$t_{hoop} = \frac{pr(2-(\tan(\alpha))^2)}{2\sigma_H} \tag{6}$$

The expressions of stress in the helical and the hoop layers as a function of the internal pressure are, respectively:

$$\sigma_\alpha = \frac{pr}{2t_{helical}(\cos(\alpha))^2} \tag{7}$$

$$\sigma_H = \frac{pr(2-(\tan(\alpha))^2)}{2t_{hoop}} \quad (8)$$

In this study, the fiber tensile factor K in the helical layers is introduced, which can be expressed as [39]:

$$\sigma_\alpha = K\sigma_H \quad (9)$$

Therefore, the expressions of hoop stress in the composite pressure tank can be written as:

- For helical layers:

$$\sigma_{H1} = \frac{pr}{2Kt_{helical}(\cos(\alpha))^2} \quad (10)$$

- For hoop layers:

$$\sigma_{H2} = \frac{pr(2-(\tan(\alpha))^2)}{2t_{hoop}} \quad (11)$$

where σ_{H1} indicates the expression of hoop stress in the helical layers, and σ_{H2} indicates the expression of hoop stress in hoop layers.

According to the classical stress analysis, it was demonstrated that the hoop stress is twice as much as the axial stress [40]. As a result, the hoop strength plays a critical role in providing strength to the tank. To ensure the safety of the composite pressure structure, the hoop stress must be lower than the hoop tensile strength [29, 39]. The safety criterion for both the helical and the hoop layers is obtained respectively by the following inequalities:

- For helical layers:

$$\sigma_{H1} \leq \sigma_{TS} \quad (12)$$

- For hoop layers:

$$\sigma_{H2} \leq \sigma_{TS} \quad (13)$$

where σ_{TS} is the hoop tensile strength.

2.2. Reliability Formulation

Fundamentally, the reliability can be defined based on the stress-strength interference model using the performance function *g(X)* [21]:

$$g(X) = R - S \quad (14)$$

where R and S are the strength and the stress of the composite tank, respectively, and X is the vector of random design variables.

Based on equations (10) and (11), the following limit state functions are obtained for the helical and the hoop layers, respectively:

$$g_1(X_{helical}) = \sigma_{TS} - \sigma_{H1} \quad (15)$$

$$g_2(X_{hoop}) = \sigma_{TS} - \sigma_{H2} \quad (16)$$

where $X_{helical}$ represents the vector of random variables for helical layers $X_{helical} = \{\sigma_{TS}, p, r, t_{helical}, \alpha\}$ and X_{hoop} represents the vector of random variables for hoop layers $X_{hoop} = \{\sigma_{TS}, p, r, t_{hoop}, \alpha\}$.

The safety margin is defined such that $g_1(X_{helical}) > 0$ and $g_2(X_{hoop}) > 0$.

By definition, the failure probability P_f associated with a limit state equation *g(X)* can be written as:

$$P_f = P[g(X) \leq 0] \quad (17)$$

The probability of failure P_f can be calculated by solving the integral of the probability density function $f_X(X)$ as given by this expression [21]:

$$P_f = \int_{g(X)\leq 0} f_X(X)dx \quad (18)$$

The safety index is given by:

$$\beta = -\Phi^{-1}(P_f) \quad (19)$$

here $\Phi^{-1}(.)$ is the inverse of the standardized normal cumulative distribution function.

The previous integral can be resolved using different structural reliability algorithms. The subset simulation is emerging as a novel way to deal with very low failure probabilities which are encountered generally in composite structure applications while ensuring high computational efficiency. The basic concept of this method is to represent the low failure probability as a result of larger probabilities conditioned on intermediate events. Therefore, the simulation of a rare event is converted into a sequence of more frequent events. Given a failure event, F divided into n failure events, such as:

$$F_1 \supset F_2 \supset \ldots \supset F_n = F \quad (20)$$

Thus, for the obtained failure probability $P_f = P[X : g(X) \leq 0]$ can be rewritten as:

$$F = P\,[X : g(X) \leq C_i(X)] \quad (21)$$

where $C_1 > C_2 > \ldots > C_n = 0$.

By definition, the general expression can be written as follows:

$$P_f = P(F_1)\prod_{i=1}^{n-1} P(F_{i+1}|F_i) \quad (22)$$

The previous equation expresses the estimation of the probability P_f by estimating the quantities of the product of $P(F_1)$ and the sequence of conditional probabilities $P(F_{i+1}|F_i)$ where $i = 1, 2, 3 \ldots n$.

In the numerical procedure, the initial step involves the computation of conditional failure probabilities, which necessitates the simulation of samples from the conditional distribution within F_i. The probability P_1 can be estimated using the Monte Carlo simulation method.

In the subsequent phase, the computation of conditional probabilities is carried out through the use of Markov chain Monte Carlo simulation (MCMC), offering a robust approach for generating conditional samples within the failure zone.

For further information about this approach, the reader can be directed to [17, 18, 21, 41, 42].

2.3. Numerical Application

The cylindrical composite tank studied in this work is designed by netting theory and consists of a polymer liner fully wrapped with carbon fiber composite material [39]. The composite supports the internal pressure load and the liner serves as a barrier to prevent gas leakage. The composite part consists of hoop layers and helical layers with a fiber winding angle of 10°. The composite tank has a helical layer thickness of 6.06 mm, a hoop layer thickness of 9.61 mm, and a radius r of 152.5 mm. The hoop tensile strength of the material is equal to 570 MPa. The fiber strength factor in helical layers is K = 0.8. The working pressure p is equal to 20 MPa. In this study, to simulate the variation in the failure probability of the tank, the internal pressure is varied from 15 to 25 MPa since the tank is designed to withstand a load of 1.25 times the required load of 20 MPa. Fig. 2 shows a sketch of the composite pressure tank and layer orientation

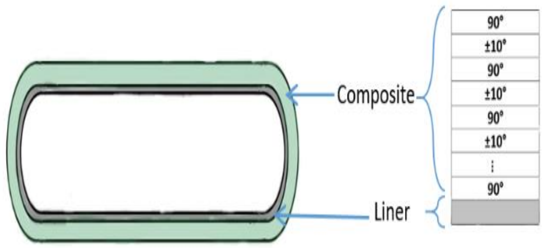

Fig. 2. A sketch of the composite tank and layer orientation

In general, the different statistical properties of the random design variables are obtained from experimental testing and measurement based on wide data collection and using different tools of statistical analysis. However, when there is a lack of sufficient and high-quality data sources, it is necessary to use professional skills and expertise. In this study, the different statistical properties of the random variables were estimated based on technical judgment and benchmark studies [25, 26, 29, 43], as shown in Table 1. As well, the design parameters that are used in limit state equations, are considered independent random design variables.

Table 1. Statistical properties of random design variables

Random variable	Mean	COV	Distribution
Internal pressure (MPa)	15-25	10%	Normal
Winding angle (°)	10	1%	Normal
Radius (mm)	152.5	1%	Normal
Helical thickness (mm)	6.06	1%	Normal
Hoop thickness (mm)	9.61	1%	Normal
Hoop tensile strength (MPa)	570	7%	Normal

3. Results and Discussion

The evaluation of the probability of failure is highly crucial in the case of composite pressure tank design. As presented previously, to investigate the low failure probabilities obtained by netting analysis, the composite tank is divided into two main parts: helical and hoop layers. Therefore, the probability of the failure of the composite structure is calculated using the law of composition in structural reliability engineering. The failure probability analysis is illustrated by the graphical plots corresponding to the changes in the calculated failure probability P_f and the safety index beta of the CFRP composite tank, with the variation of the internal pressure. The coefficients of variation were varied for each design variable to investigate the impact of uncertainties on the probability of failure of the structure. In this study, the subset simulation is carried out with N = 2000 samples.

Figures 3 and 4 show the evolution of the probability of failure P_f and the safety index beta of the composite tank, respectively, as a function of the internal pressure. It can be observed that the failure probability values of helical layers are slightly greater than those of hoop layers. It can also be seen that the values of the probability of failure obtained by netting analysis for both helical and hoop layers correspond to the order of 10^{-6} for a working pressure equal to 20 MPa. This demonstrates the effectiveness of netting analysis in the calculation of the thicknesses of helical and hoop layers of composite vessels.

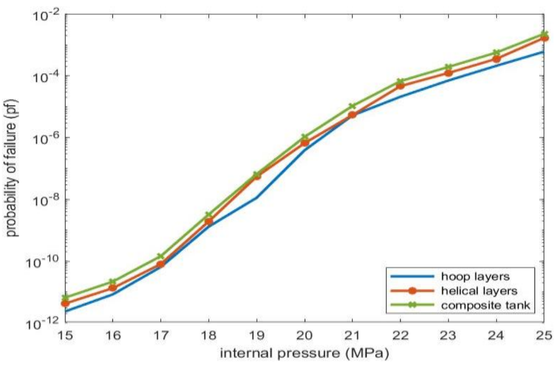

Fig. 3. Probability of failure of the composite tank in terms of internal pressure

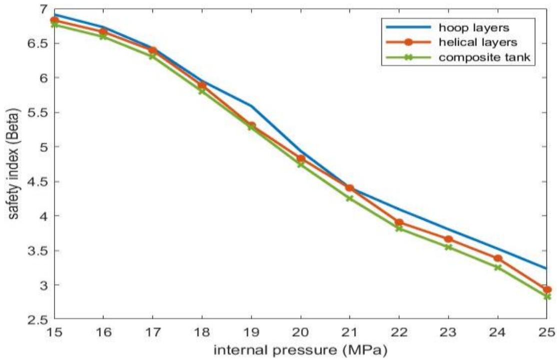

Fig. 4. Safety index of helical and hoop layers in terms of internal pressure

The changes in the probability of failure of the composite tank under different combinations of input random design parameters have been reported in Fig. 5. The probability of failure P_f of the composite cylinder rises when all the design parameters taken into account are treated as random design variables. As expected, the internal load is the main parameter that influences the probability of failure of the filament wound tank.

An analogous behaviour may be observed in Fig. 6 which represents the changes in the safety index as a function of the internal pressure. It is well known that the safety index beta is the point in normalized space where the failure surface is closest to the origin. Accordingly, when this distance is too close to the origin indicates that the safe zone is too small than the failure zone and the rupture occurs. This could illustrate the significant effect of uncertainties and fluctuations related to the uniform internal pressure on the structural reliability of the tank.

As mentioned previously, the hoop tensile strength plays an important role in providing strength to the composite cylindrical structure. Figures 7 and 8 represent, respectively, the changes in the failure probability P_f and the safety index as a function of different COV of the hoop strength. Each time there is an increase in the coefficients of variation values, the probability of failure P_f increases in parallel, which leads to the shrinkage of the safety zone. Thus, the selection of a high-quality material for the manufacture of CFRP tanks is one of the most important factors in avoiding the effect of randomness in mechanical properties.

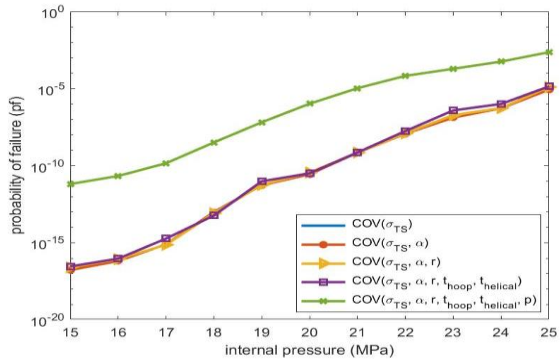

Fig. 5. Probability of failure under various considerations of random variables

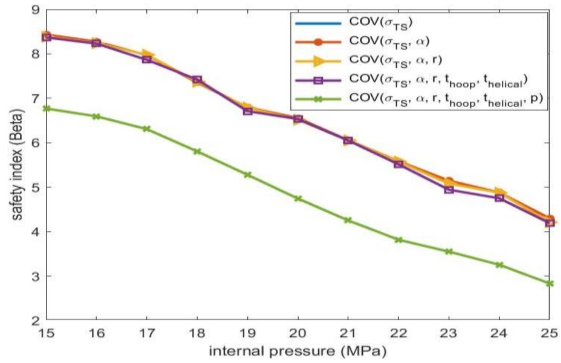

Fig. 6. Safety index under various considerations of input random design variables

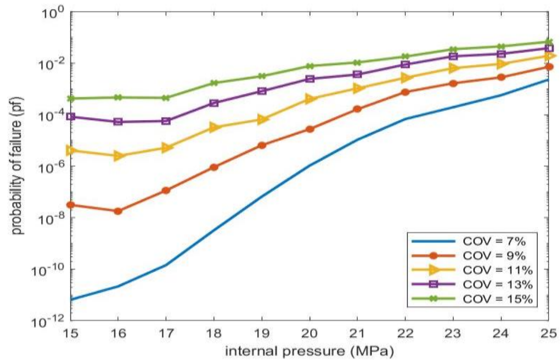

Fig. 7. Probability of failure in terms of the variation of the different COV of the hoop tensile strength

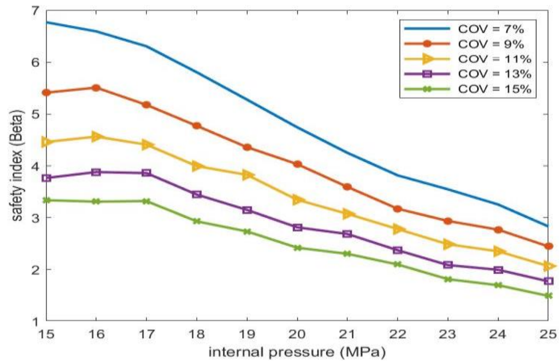

Fig. 8. Safety index in terms of the different COV of the ultimate strength

Figures 9 and 10 show, respectively, the changes in the failure probability and the safety index as a function of internal pressure loading for different coefficients of variation. It is visible that any increase in COV induces a reduction of the safety index. It was also noticed that the probability of failure increases with the increase in COV values. When the COV increases from 10% to 18%, the probability of failure increases by 10^{-6} to 10^{-4} for an operating pressure of 20 MPa. Similarly, the safety index decreases from 4.7 to 3.2. This probability margin is therefore very large, which explains the importance of taking into account the effect of randomness associated with the internal pressure in the design of composite tanks.

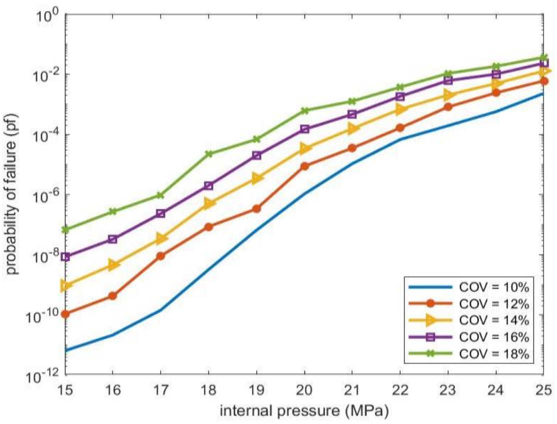

Fig. 9. Probability of failure in terms of COV of the internal pressure

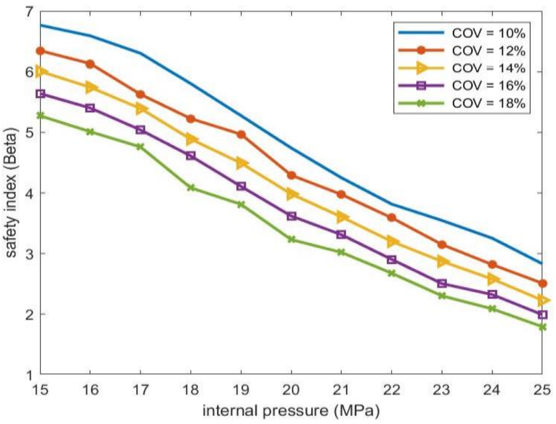

Fig. 10. Safety index in terms of the variation of the different COV of the internal pressure

Figures 11 and 13 present the influence of COV values of the composite wall thickness and the fiber winding angle, respectively, on the probability of failure of the filament-wound composite vessel. For a pressure equal to 15 MPa, it can be observed in Fig. 13 that the probability of failure P_f starts with the minimum value of the order of 10^{-12} when COV = 1% and reaches the P_f values corresponding to the order of 10^{-8} when COV = 8%. Fig. 10 shows a very slight evolution of the probability of failure for the same pressure value. This observation explains why the structural reliability of composite pressure tanks is more sensitive to the variation of COV of the thickness than those of the winding angle. Thus, the safety margin of the composite structure will be also more sensitive to the uncertainties related to the composite wall thickness as depicted in Figs. 12 and 14 related to the changes in the safety index in terms of the variation of the different COV of the composite wall thickness and the fiber winding angle, respectively.

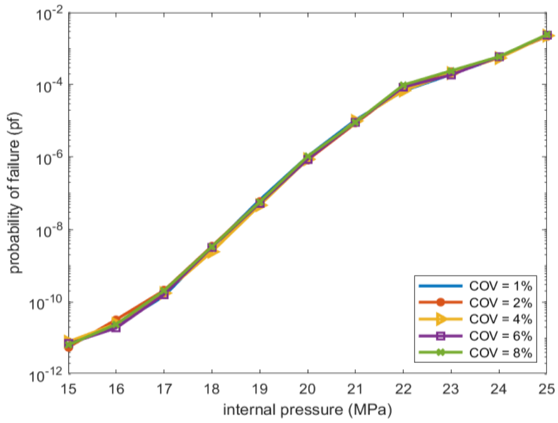

Fig. 11. Probability of failure in terms of different COV of the winding angle

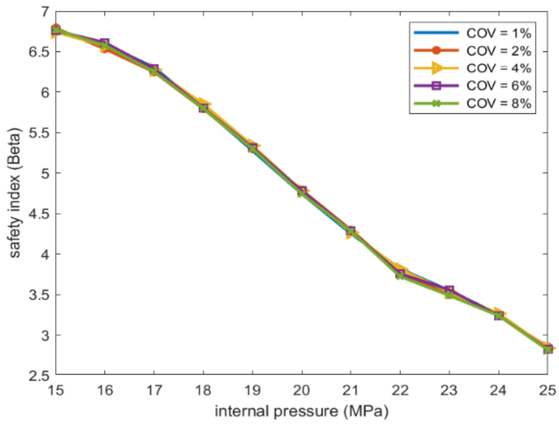

Fig. 12. Safety index in terms of different COV of the winding angle

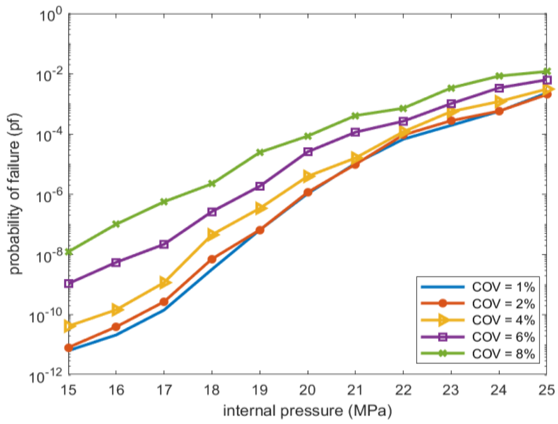

Fig. 13. Probability of failure in terms of the variation of different COV of the composite thickness

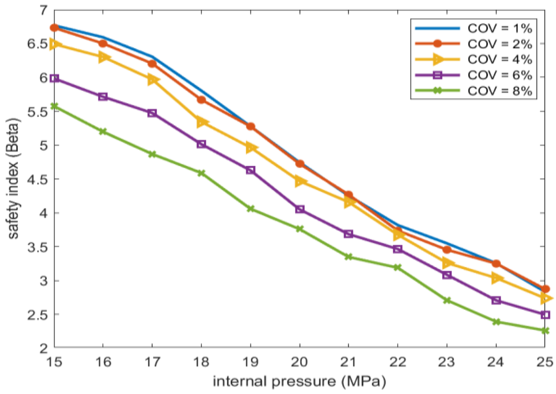

Fig. 14. Safety index in terms of the variation of different COV of the composite thickness

3.1. Reliability Based-Design

A similar study has been carried out for the evolution of the probability of failure P_f and the safety index beta of the helical layers and the hoop layers of the composite pressure tank, respectively, with the variation of the helical thickness and the hoop thickness in terms of different COV of the working pressure (P = 20 MPa).

From Figs. 15 and 16, It can be noticed that the failure probability of helical layers shifts downward and the safety index beta shifts upwards, respectively, when the helical thickness increases. It is clear that the highest failure probability is related to the smallest hoop thickness, while the lowest failure probability appears at the value of t = 9 mm. If the required reliability value is 0.999999, which means that an occasional failure of one tank in 1,000,000 is acceptable, the thickness value will be equal to 6 mm for an internal pressure COV equal to 10%. In other words, the thickness can be reduced or increased to any value corresponding to the desired failure probability, considering the uncertainties associated with the design parameters. On the grounds that reducing the thickness of the composite means reducing the cost and the weight of the composite tank.

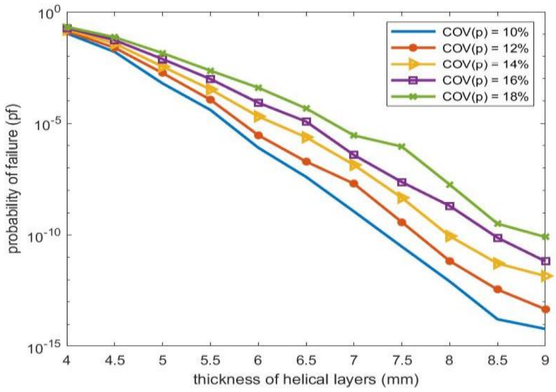

Fig. 15. Probability of failure of the helical layers of the composite tank in terms of helical thickness with the variation of different COV of the internal pressure (P=20MPa)

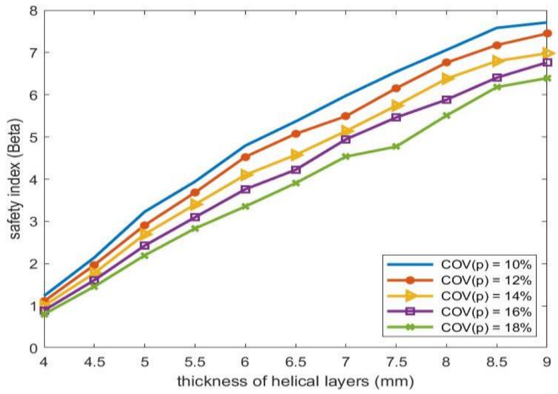

Fig. 16. Safety index of the helical layers of the composite tank in terms of helical thickness with the variation of different COV of the internal pressure (P=20MPa)

The same behavior can be deduced from Figs. 17 and 18 which represent the evolution of the probability of failure P_f and the safety index beta of the hoop part of the composite tank as a function of the hoop thickness. Therefore, this investigation depicts very well the effect of the variation of COV of the internal pressure on the thickness of hoop and helical layers, thus on the whole structural reliability of the tank. Hence, accurate supervision of the working pressure is critically necessary to maintain the reliability level of the axially symmetric composite tank.

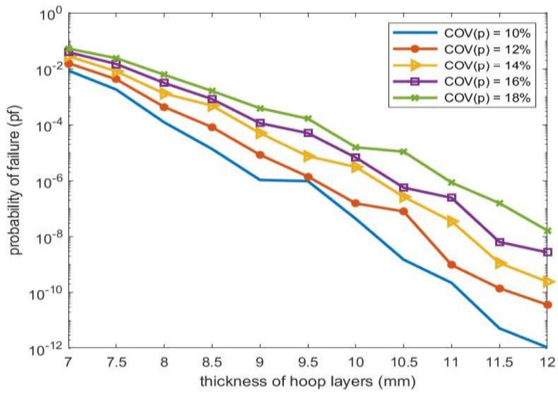

Fig. 17. Probability of failure of the hoop layers of the composite tank in terms of hoop thickness with the variation of different COV of the internal pressure (P=20MPa)

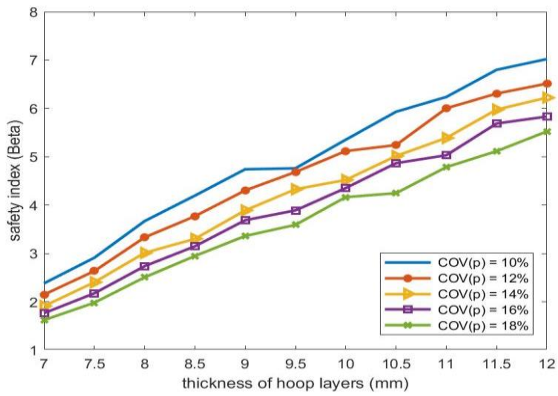

Fig. 18. Safety index of the hoop layers of the composite tank in terms of hoop thickness with the variation of different COV of the internal pressure (P=20MPa)

3.2. Validation and Comparison

The few studies on the probabilistic design of composite tanks quantify reliability in percentage terms, such as the work reported by Solazzi et al. [26] using safety factors, but none of these studies presents a method for solving the problem of assessing the low probabilities of failure of pressure vessels made of composite materials.

A prototype of a composite tank fabricated using the filament winding technique was described by Sharma et al [39]. The netting theory was applied to calculate the thicknesses of the hoop and helical layers, as expressed in equations (5) and (6). Nevertheless, the numerical and experimental investigation conducted in this study does not encompass the probabilistic aspect. In this work, it was shown that for a working pressure of 20 MPa, the calculated thicknesses of 6.06 mm for the helical layers and 9.61 mm for the hoop layers correspond to a failure probability of about 10^{-6} for an internal pressure COV equal to 10%, which proves the robustness of netting analysis as a design tool to estimate the thickness of composite tanks. For commercial applications, the basic design concept of composite tanks is to ensure maximum reliability and reasonable mass [44]. Therefore, a safe and optimal tank thickness can be expected when determining an acceptable level of failure probability as presented in Figs. 15 and 17. This procedure is very important to avoid oversizing the structure and then reducing the composite thickness which leads to a reduction in the mass of the tank while providing a rational assessment of the risk of structural failure.

4. Conclusions

In this paper, a combined netting analysis and subset simulation-based approach to analyze small failure probabilities of Type 4 filament wound composite tanks has been developed. The results of this study showed that:

- Failure probability analysis provides crucial information concerning the composite pressure tank behavior.
- Estimating small failure probabilities encounters a significant hurdle in simulating rare events. Nonetheless, the SS resolves this obstacle by decomposing the problem into the estimation of a series of larger conditional probabilities. Thus, the subset simulation can accurately assess the very low probability of failure of composite pressure vessels. It reached the order of 10^{-6} for a working pressure of 20 MPa.
- Uncertainties in geometrical parameters and randomness of the loading have a significant influence on the structural reliability of the composite tank, and high COV values lead to the shrinkage of the safety zone of the axially symmetric composite tank.
- Uncertainties associated with the hoop strength, the internal pressure, and the thickness of the composite have an important effect on the reliability of the tank more than those related to the winding angle.
- Failure probability analysis can offer an accurate method to evaluate the composite wall thickness according to any desired reliability threshold, which implies the reliable and economical design of composite tanks.

In addition, this simulation should provide an important guide for the manufacturer to design safe and reliable composite pressure tanks for various fields of engineering. The forthcoming paper is devoted to the prediction of the burst pressure and the safety margin distributions of high-pressure composite vessels to develop a structural reliability sizing tool dedicated to the optimal design of onboard composite tanks under various loading conditions.

Nomenclature

p	Internal pressure
r	The radius of the composite tank
α	Winding angle of helical layers
$t_{helical}$	Thickness of helical layers
t_{hoop}	The thickness of hoop layers
σ_{H1}	Hoop stress in helical layers
σ_{H2}	Hoop stress in hoop layers
σ_{TS}	Hoop tensile strength
P_f	Probability of failure
β	Safety index

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Conflicts of Interest

The author declares that there is no conflict of interest regarding the publication of this article.

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