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Structural reliability of axisymmetric composite gas storage tanks

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Abstract—**This paper aims to investigate and analyze the effect of uncertainties and fluctuations on the structural reliability of filament wound cylindrical composite gas storage tank using Monte Carlo Simulation method (MCS). A performance function using Tsai-Wu failure criterion, with seven random variables, has been developed wherein the random variables are the three elastic constants of the material (longitudinal modulus E_1, the transverse modulus E_2 and shear modulus G_{12}), the thickness of the laminate, the radius of the tank, the winding angle and the internal pressure. The safety margin distributions in terms of the coefficients of variation (COVs) of the composite gas storage tank are obtained. The results show that the internal pressure and the winding angle are the main parameters that affect the structural reliability of the tank and the probability of failure increases especially when all the parameters are treated as random. Furthermore, high values of coefficients of variation cause the shrink of the safety margin and can induce the failure of the axisymmetric structure.**

Keywords-structural reliability; gas storage; composite tank; uncertainties; Monte Carlo Simulation

I. INTRODUCTION

More attention has been paid to cylindrical composite tanks in recent years due to their interesting characteristics, which propose an excellent solution for safe gas storage in many engineering applications, ranging from aerospace, hydrocarbons and marine industries to the storage of green hydrogen.

Several research works have focused on composite materials and their damage behavior, in addition to winding optimization approaches in connection to tank shape and manufacturing processes, but none of these works have provided a definitive design guideline [1]. In recent literature, many scholars have placed great emphasis on deterministic methods, and different design approaches have been used to analyze axially symmetric filament wound composite pressure tanks including finite element analysis [2], classical lamination theory [3], netting analysis [4], theory of elasticity of anisotropic composites [5] and artificial intelligence [6].

Traditional design methods use global safety factors, but for a reliable composite tank design, it is important to take into account fluctuations and uncertainties associated with manufacturing, geometrical parameters, loading conditions, material properties and mechanical behavior. Therefore, structural reliability analysis plays a significant role in the analysis and design of different composite structures. However, few studies that examine the effect of randomness in mechanical properties and geometrical parameters of composite pressure tanks. In this way, different probabilistic models describing the strength of fiber reinforced composites have been reviewed by [7] to draw attention to the key features that are relevant for modelling and analyzing the behavior of composites structures.

Béakou and Mohamed [8] have considered the influence of the scattering of design variables (elastic constants, load cases, strengths…) on the optimal fiber winding angle of cylindrical laminated composite using the classical lamination theory, by adopting the Tsai-Wu failure criterion as the limit state function of the ply. The main objective of the study is to reveal that the widely used value of 55° does not always correspond to the optimal winding angle.

Hwang, Hong and Kim [9] have conducted probabilistic analysis and experimental tests to forecast the probabilistic deformation and strength of composite pressure tanks subjected to inner pressure loading, using three design random variables namely: the strength of the lamina, the composite elastic constants, and the helical and hoop layer thickness. Good agreement pointed out between the analysis and experiments for the hoop strain and the burst pressure.

Multivariate method combining composite micro and macro mechanics, finite element, durability and damage tolerance, and probabilistic methods was presented by [10] in order to evaluate the reliability of composite overwrapped tanks. The method could be used as a guide during test programs by identifying variables that influence on the design of pressurized composite tanks.

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In the field of reliability study of subsea blowout preventers manufactured by filament winding under external pressure, [11] used the reliability-based load and resistance factor design method for composite vessel subjected to buckling phenomenon. The performance function developed in this work used critical buckling external pressure which is solved by the classical lamination theory. The sensitivity analysis showed that the external pressure affect significantly the structural reliability of the axisymmetric composite tank under external loading.

Bouhafs, Sereir and Chateauneuf [12] proposed an analytical method to assess stresses and strains in filament wound thick composite pipe under internal pressure, and performed a probabilistic sensitivity analysis of the mechanical response, obtained by Monte Carlo simulations. The limit state function used in this study corresponds to the difference between the transverse strength and the induced hoop stress, since the hoop stress represents the most critical stress compared to the transverse strength.

The first order reliability method (FORM) have been employed by [13] using maximum stress failure criterion and Tsai-Wu failure criterion to predict failure in composites. However, the limitation of the suggested approach is that it is not able to handle random fields.

Appreciable contributions on the structural reliability based approach for axisymmetric composite pipeline have been made by [14] [15]. The developed work identified the main parameters that affect the failure of the composite tubular structures, using the analytical design tool developed by the same author [16] combined to Monte Carlo simulation method. In the recent work of [17], reliability design of a pressure tank manufactured by composite materials based on the netting theory and the filament winding technology has been developed and the geometry of tanks was verified through finite element method. The results show that the weight of composite pressure tanks manufactured by fiber carbon is equal to 17% to the one made of steel.

As reported in literature review, research works has generally been emphasized on probabilistic-based design for lightweight composite pressure tanks, and optimal design parameters. The major aim of this work is to study the different distribution functions of the mechanical response of an axisymmetric composite tank taking into account fluctuations and uncertainties associated with the mechanical proprieties and the geometrical parameters. This paper is based on the analytical model developed on previous work by [18] combined with the Monte Carlo simulation method. The Tsai-Wu failure criterion is used as a state limit function to estimate the safety margin of the probabilistic design. Seven random variables of the cylindrical composite structure are selected in this study, namely: the longitudinal modulus E_1, the transverse modulus E_2, the shear modulus G_{12}, the thickness of the laminate, the radius of the tank, the winding angle and the internal pressure.

II. STRESS ANALYSIS

The mathematical formulation for the axially symmetric composite shell manufactured by orthotropic layers with the angle-ply orientation of ± α and subjected to axisymmetric loading used in this work has been developed previously by [18]. The coordinate system used in order show the directions is as given in Fig. 1.

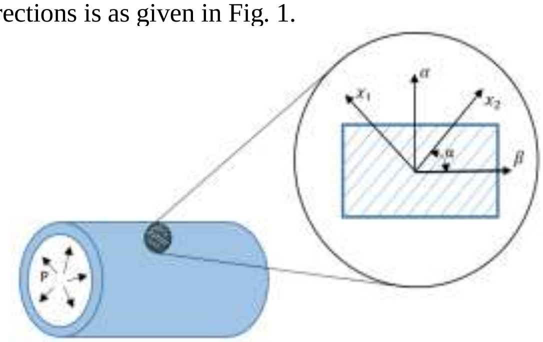

Figure 1. Relation of coordinate system between local axes and principal material axes.

The axes in α-β coordinate system are called the local axes, and the principle material coordinates are defined by x_1- x_2.

For a thin-walled cylindrical tank subjected to internal pressure, axial stress σ_α and hoop stress σ_β can be calculated easily as [18]:

$$\sigma_\alpha = \frac{pr}{2t} \tag{1}$$

$$\sigma_\beta = \frac{pr}{t} \tag{2}$$

Both the principal and local stresses, and the principal and local strains, are related to each other through the angle α. For the stress and strain transformation we employ here the following relationships [19]:

$$\sigma_\alpha = \sigma_1\cos^2(\alpha) + \sigma_2\sin^2(\alpha) - \tau_{12}\sin(2\alpha) \tag{3}$$

$$\sigma_\beta = \sigma_1\sin^2(\alpha) + \sigma_2\cos^2(\alpha) + \tau_{12}\sin(2\alpha) \tag{4}$$

And

$$\varepsilon_1 = \varepsilon_\alpha\cos^2(\alpha) + \varepsilon_\beta\sin^2(\alpha) \tag{5}$$

$$\varepsilon_2 = \varepsilon_\alpha\sin^2(\alpha) + \varepsilon_\beta\cos^2(\alpha) \tag{6}$$

$$\gamma_{12} = (\varepsilon_\beta - \varepsilon_\alpha)\sin(2\alpha) \tag{7}$$

The principal stresses and the principal deformations are related to each other with the help of material proprieties by Hook's law:

$$\varepsilon_1 = \frac{\sigma_1}{E_1} - \frac{\upsilon_{12}}{E_2}\sigma_2;\ \varepsilon_2 = \frac{\sigma_2}{E_2} - \frac{\upsilon_{21}}{E_1}\sigma_1;\ \gamma_{12} = \frac{\tau_{12}}{G_{12}} \tag{8}$$

Wherein E_1 is the longitudinal Young's modulus, E_2 is the transverse Young's modulus, G_{12} is the shear modulus,

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and υ_{12}, υ_{21} are the Poisson coefficients. It should be noticed that the symmetric condition is expressed by the following relation:

$$E_1\upsilon_{12} = E_2\upsilon_{21} \quad (9)$$

From (6), (7) and (8) the compatibility condition can be given as:

$$\varepsilon_1 - \varepsilon_2 + \gamma_{12}\cot(2\alpha) = 0 \quad (10)$$

The last equation with due regard to (8) can be expressed in the form:

$$\frac{\sigma_1}{e_1} - \frac{\sigma_2}{e_2} + \frac{\tau_{12}}{G_{12}}\cot(2\alpha) = 0 \quad (11)$$

Where $e_1 = \frac{E_1}{1+\upsilon_{21}}$ and $e_2 = \frac{E_2}{1+\upsilon_{12}}$

Equations (3), (4) and (11) are solved for σ_1, σ_2 and τ_{12}, in order to obtain the expressions of the principle stresses [18]:

$$\sigma_1 = \frac{1}{2c}\left[(\sigma_\alpha+\sigma_\beta)\left(1+\frac{2G_{12}}{e_2}\tan^2(2\alpha)\right)+\frac{(\sigma_\alpha-\sigma_\beta)}{\cos(2\alpha)}\right] \quad (12)$$

$$\sigma_2 = \frac{1}{2c}\left[(\sigma_\alpha+\sigma_\beta)\left(1+\frac{2G_{12}}{e_1}\tan^2(2\alpha)\right)-\frac{(\sigma_\alpha-\sigma_\beta)}{\cos(2\alpha)}\right] \quad (13)$$

$$\tau_{12} = \frac{G_{12}\tan(2\alpha)}{c\cos(2\alpha)}\left[\sigma_\beta\left(\frac{\sin^2(\alpha)}{e_1}+\frac{\cos^2(\alpha)}{e_2}\right)-\sigma_\alpha\left(\frac{\cos^2(\alpha)}{e_1}+\frac{\sin^2(\alpha)}{e_2}\right)\right] \quad (14)$$

Where $c = 1 + G_{12}\left(\frac{1}{e_1}+\frac{1}{e_2}\right)\tan^2(2\alpha)$

A. *Failure criterion*

Analyzing the strength of the composite pressure tank requires employing failure criteria. In this study the Tsai-Wu failure criterion has been considered; this failure criterion is commonly used to assess the failure of composites, and also known as the quadratic failure criterion, given by this expression [20]:

$$CF = F_1\sigma_1 + F_2\sigma_2 + F_6\tau_{12} + F_{11}\sigma_1^2 + F_{22}\sigma_2^2 + F_{66}\tau_{12}^2 + 2F_{12}\sigma_1\sigma_2 \quad (15)$$

The failure index CF is defined such that failure does not occur if CF < 1.
where σ_1, σ_2 and τ_{12} are stress components along the principal material directions.

And F_1, F_2 F_3, F_{11}, F_{22}, F_{66} are the various Tsai-Wu coefficients:

$$F_1 = \frac{1}{(\sigma_1^T)_{ult}} - \frac{1}{(\sigma_1^C)_{ult}};\ F_2 = \frac{1}{(\sigma_2^T)_{ult}} - \frac{1}{(\sigma_2^C)_{ult}};\ F_6 = 0;$$
$$F_{11} = \frac{1}{(\sigma_1^T)_{ult}(\sigma_1^C)_{ult}};\ F_{22} = \frac{1}{(\sigma_2^T)_{ult}(\sigma_2^C)_{ult}}; \quad (16)$$
$$F_{11} = \frac{1}{(\sigma_1^T)^2_{ult}};\ F_{12} = -\frac{\sqrt{F_{11}F_{22}}}{2}$$

Where

$(\sigma^T_1)_{ult}$ is the ultimate longitudinal tensile strength.
$(\sigma^C_1)_{ult}$ is the ultimate longitudinal compressive strength.
$(\sigma^T_2)_{ult}$ is the ultimate transverse tensile strength.
$(\sigma^C_2)_{ult}$ is the ultimate transverse compressive strength.
$(\tau_{12})_{ult}$ is the ultimate in plane shear strength.

III. DETERMINATION OF THE LIMIT STATE FUNCTION

The starting point for all the structural reliability methods is a performance function, which is given by [21]:

$$g(X) = R - S \quad (17)$$

Where R is the strength of the structure, S is the solicitation and X is the stochastic variable vector.

The Tsai-Wu failure criterion is defined such that failure does not occur if CF < 1, thus we can write the limit state equation as follows:

$$g(X) = 1 - CF \quad (18)$$

Such that the safety margin is defined when g(X) is greater than zero: g(X) > 0.
Where X represents the vector of random variables of the composite structure: $X = \{E_1, E_2, G_{12}, p, r, t, \alpha\}$.

Different methods have been developed by researchers in order to evaluate the structural reliability of structures. Compared with other reliability methods, Monte Carlo simulation method has the benefits of being accurate, insensitive to the complexity of limit state functions and straightforward to implement [22]. MCS method is used in this study, and 10^5 simulation trials are carried out in order to obtain different probability density functions for the limit state function g(X).

IV. NUMERICAL EXAMPLE

The numerical example used in this study is available in literature and was previously described by [23]. The composite pressure vessel has a radius r of 50 mm, a thickness t of 1 mm, a side-length L of 300 mm. The experimental failure pressure load of the laminated composite pressure vessel is 5.39 MPa. The working pressure is equal to 2.7 MPa. The orientations for eight-layer cylindrical shells are [54/-54/54/-54]s. Table I presents the proposal probability density functions for each uncertain parameter. The material strength properties of the composite are shown in table II.

In this study, seven random variables of the cylindrical composite structure are selected, expressly: the longitudinal modulus E_1, the transverse modulus E_2, the shear modulus G_{12}, the thickness of the laminate, the radius of the tank, the winding angle and the internal pressure.

TABLE I. STATISTICAL PROPERITIES OF RANDOM VARIABLES

Random variable	mean	COV	Distribution
Pressure (MPa)	2.7	10%	normal
Winding angle (°)	54	1%	normal
Radius (mm)	50	1%	normal
Thickness (mm)	1	1%	normal
Longitudinal modulus E_1 (GPa)	142.5	1%	normal
Transverse modulus E_2 (GPa)	9.79	1%	normal
Shear modulus G_{12} (GPa)	4.72	1%	normal

TABLE II. STRENGTH PROPRIETIES OF THE TANK

Parameters	Values (MPa)
$(\sigma^T_1)_{ult}$	2193.5
$(\sigma^C_1)_{ult}$	2457.0
$(\sigma^T_2)_{ult}$	41.3
$(\sigma^C_2)_{ult}$	206.8
$(\tau_{12})_{ult}$	78.78

V. RESULTS AND DISCUSSION

The response of the thin-walled cylindrical composite vessel is depicted by the graphical representation belonging to probability density functions of the limit state function in terms of different combinations of uncertainties of materials proprieties and the geometrical parameters.

Fig. 2 shows the safety margin distribution in terms of different combination of axisymmetric composite tank uncertainties. It is easy to see that the lowest dispersion appears when the three elastic properties of the material (the longitudinal modulus E_1, the transverse modulus E_2, the shear modulus G_{12}) are taken alone as random variables, as well as this low dispersion corresponds to the highest frequency value. An increase in dispersion relative to the combination when adding winding angle, composite thickness and the radius of the tank as random variables. It can be noticed that the safety margin decreases when all the uncertainties of materials proprieties and geometrical parameters are involved in the limit state function. As expected, the internal pressure is the main parameter that affect the structural reliability of the tank and can lead to failure of the vessel. This could illustrate the influence of loading on the structure's strength.

Safety margin distribution in terms of different COVs of the composite tank elastic constants is shown in Fig. 3. It is clear that each time the COVs increase the dispersion increases in parallel and the probability of failure increases accordingly, thus it can be noted that the safety margin shrinks. The frequency is also affected, a decrease from 0.16% when COV=1% to less than 0.14% when COV=8% is observed. An excellent quality of materials employed in the manufacture of the composite pressure tanks could be required to avoid the effect of randomness in mechanical properties, thus the choice of materials is a key parameter for the design of composite tanks.

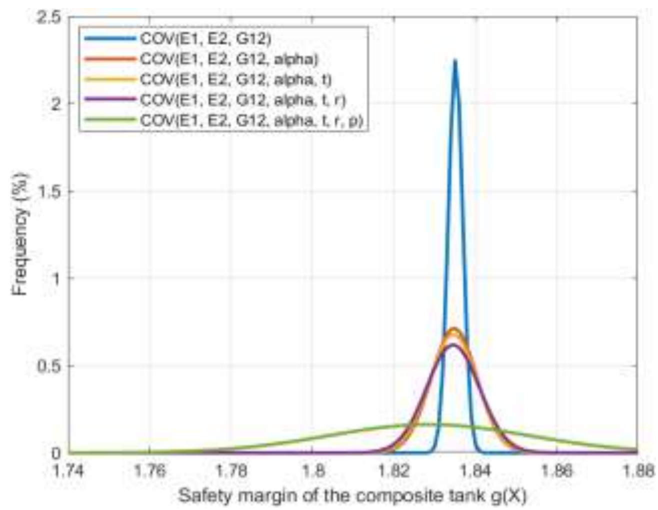

Figure 2. Safety margin distribution in terms of the different cylindrical composite tank uncertainties.

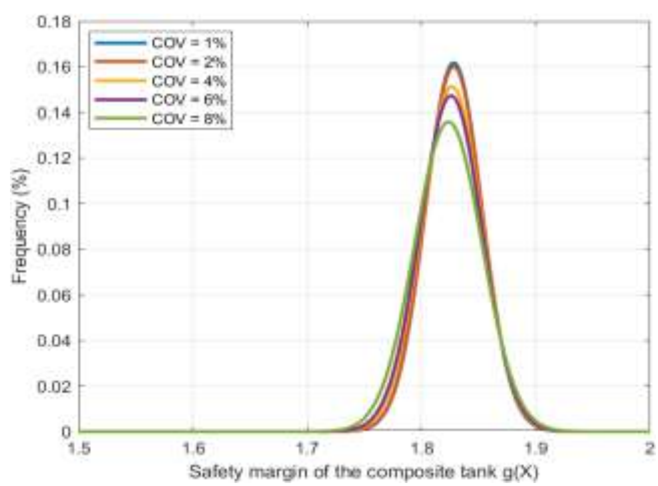

Figure 3. Safety margin distribution in terms of the different COVs of the composite tank elastic constants.

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The probability density functions of the safety margin in terms of the coefficients of variation of the internal pressure has been presented in Fig. 4. It can be observed that when the coefficients of variation increases from 10% to 18% the dispersion increases and the curves tend to the left side which causes a decrease in the safety margin.

The same behavior may be observed in the Fig. 5 for the probability density functions in terms of the different coefficients of variation of the winding angle. The dispersion extends over a large interval and non-negligible probability of failure could be deduced when the coefficients of variation reach values greater than 4% for this structure. The shrink of the safety margin can generate the failure of the axisymmetric vessel, induced by the large effect of uncertainties related to the winding angle.

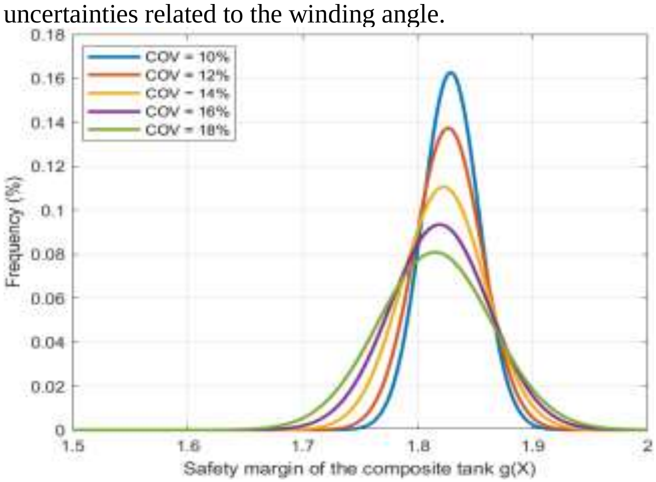

Figure 4. Safety margin distribution in terms of the diffrent COVs of the internal pressure of the composite tank

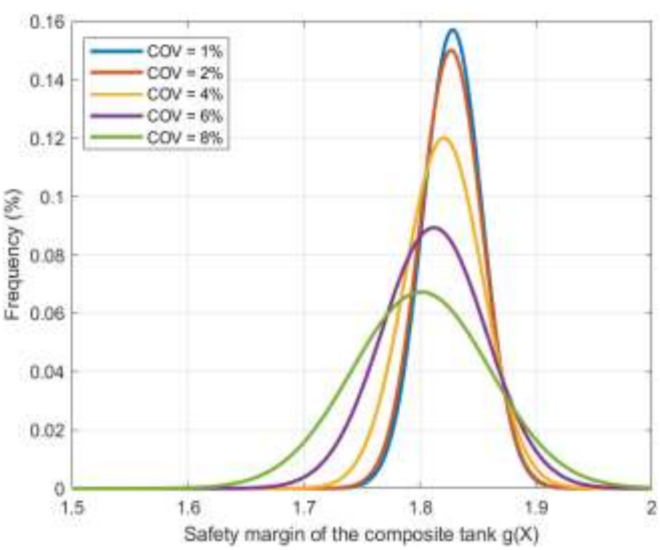

Figure 5. Safety margin distribution in terms of the different COVs of the winding angle of the composite tank

The probability density functions of the safety margin in terms of coefficients of variation of the thickness of the composite tank has been presented in Fig. 6. It can be seen that the influence of the thickness is less important than the influence of the winding angle. Fig. 7 shows the safety margin distribution in terms of different COVs of the radius of the composite tank. It can be observed that the frequency decreases when the coefficients of variation are varied from 1% to 8%. Accordingly, in literature [24], it is preferable when planning to increase the volume stored inside a pressure tank, to increase the length of the tank and not its diameter.

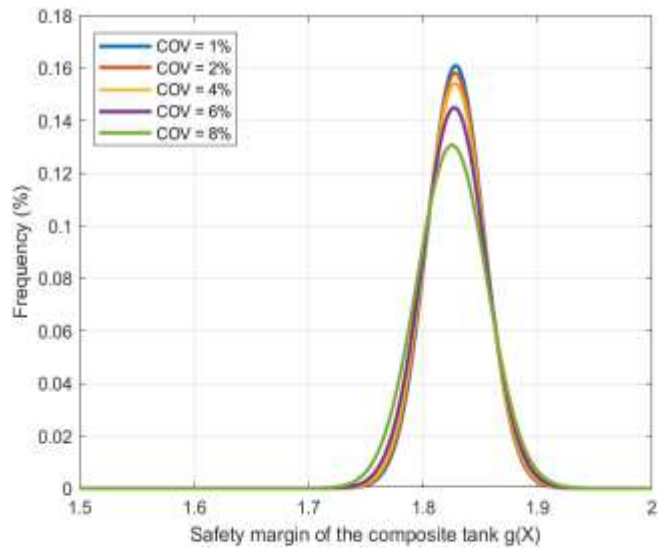

Figure 6. Safety margin distribution in terms of the different COVs of the thickness of the composite tank

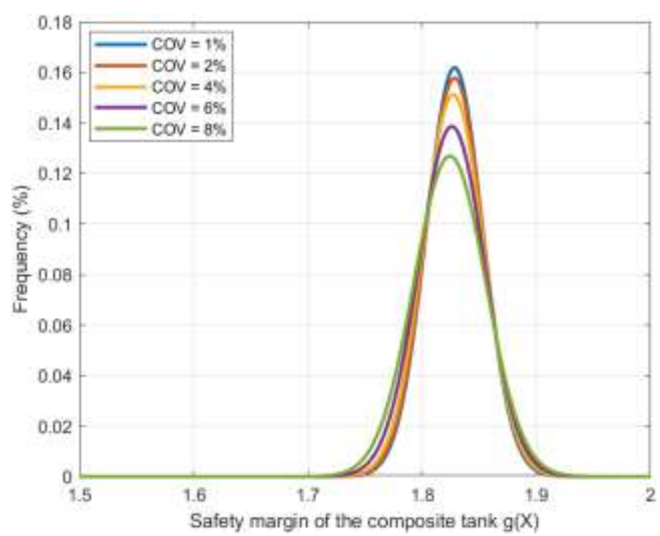

Figure 7. Safety margin distribution in terms of the different COVs of the radius of the composite tank

In a global way, the reliability decrease with the increasing of coefficients of variation of material proprieties and geometrical parameters. The results show that the dispersion related to elastic constants, composite thickness and the radius of the tank doesn't affect the safety margin compared to the dispersion generated by the winding angle and the internal pressure. The uncertainties associated to the winding angle makes it an important variable in the design of composite pressure tanks. In addition, a correct control of the operating pressure is absolutely imperative to ensure the safety of the axisymmetric structure.

VI. CONCLUSION

In this paper, structural reliability analysis of filament wound composite tank has been provided. Monte Carlo simulation method is used. Safety margin distribution in terms of different coefficients of variation of design parameters of the composite pressure tank was analyzed and investigated.

The results show that the structural probabilistic analysis provides an important information about the safety and reliability of the composite tank design. the internal pressure and the winding angle are the main parameters that influence the structural reliability of the tank, and the probability of failure increases especially when all the parameters are treated as random. Moreover, high values of coefficient of variation cause the shrink of the safety margin and can induce the failure of the axisymmetric structure.

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