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Numerical simulation of failure probability prediction: Application to cylindrical part of type III CNG storage vessel

Prédiction numérique de la probabilité de défaillance: Application à la partie cylindrique d'un réservoir de type III de stockage du GNC

Abdelhakim MAIZIA[a], Abdelkader HOCINE[a*], Abdelhamid GHOUAOULA[a], Mohamed HADJ MELIANI[b]

[a]Controls Laboratory Tests, Measurements and Simulations Mechanics, Hassiba Benbouali University of Chlef, Algeria

[b] Laboratory for theoretical Physics and Materials Physics, Hassiba Benbouali University of Chlef, Algeria

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ABSTRACT

The present paper focus on a numerical simulation failure probability prediction of cylindrical part of type III CNG storage vessel under pressure with end effect, which has a thin metallic envelope, called liner who is coated by a filament winding composite layers. First, a sensitivity analysis contribution was performed in order to identify the influence of the different parameters as: materials properties, geometry, manufacturing and loading, on the reliability of the Liner-Composite structure studied. Finally, the failure probability of this kind of storage structure is estimated by Monte Carlo method. In order to predict the main parameters which can be the origin of failure, we opted to a high number of drawings, $N=10^4$. The results obtained show that liner thickness and internal pressure have large significant influence on the security of the composite vessels type III in relation to the others manufacturing parameters.

RÉSUMÉ

Le présent article porte sur la prédiction numérique de la probabilité de défaillance d'un réservoir de stockage de GNC de type III sous pression interne avec effet de fond. La partie cylindrique du réservoir de type III, qui fait l'objet de ce travail, est constitué d'une enveloppe métallique mince, appelée revêtement, revêtue de couches composites d'enroulement filamentaire. Dans un premier temps, une analyse de sensibilité a été réalisée afin d'identifier l'influence des différents paramètres comme: propriétés des matériaux, géométrie, de fabrication et chargement, sur la fiabilité de la structure étudiée. Enfin, la probabilité de défaillance de ce type de structure de stockage est estimée par la méthode de Monte Carlo. Afin de prédire les principaux paramètres pouvant être à l'origine de la défaillance, nous avons opté pour un nombre élevé de tirage d'une grandeur de 10^4. Les résultats obtenus montrent que l'épaisseur du revêtement métallique et la pression interne du revêtement ont une influence très significative sur la sécurité de ce genre de structure de stockage.

1 Introduction

The state of the art shows that current applications of natural gas are extremely diverse. However, the rapidly growing application is Compressed Natural Gas (CNG) fuel for vehicles. At present, the primary storage options of CNG are Type I, Type II, Type III and Type IV vessels [1-2]. The literature shows that there are four categories of pressure vessels, based on their construction. Each type has assets and liabilities. The type I: All-metal construction, generally steel, which is the

* *Corresponding author. Tel.: 00213 5 42 32 56 25.*
E-mail address: a.hocine@univ-chlef.dz

least expensive. The Type II is made by mostly steel or aluminium with a glass-fiber composite overwrap in the hoop direction. The Type III is made by metal liner with full composite overwrap, generally aluminium, with a carbon fiber composite. It is important to know that the composite materials carry the structural loads. The last classified pressure vessel is Type IV, which is an all-composite construction featuring a polymer liner with carbon fiber or hybrid carbon/glass fiber composite. The composite materials carry all of the structural loads. In this paper, we focus on Type III pressure vessel reliability and it's presented by Figure 1, with two components metallic liner and filament winding composite.

The present paper focus on the Type III vessel, which is a combination of metal liner and filament winding composite external wrap, where all metallic envelope, called liner, is reinforced by filamentary composite layers.

The literature shows that, there is many design variables for the gas transport and storage structure. These variables are induced first by uncertainties of material properties, geometrical and the manufacturing process [3]. Numerous methodologies for estimating the reliability of fiber-reinforced structure have been published, where the most of them used, according to the literature are: Monte Carlo Method [3-4], First Order Reliability Method (FORM) [5-6], Reliability-based design optimization (RBDO) and robust design optimization (RDO) [7].

The beginning research of Hocine and al [8 and 9] conducted deterministic studies to analyze the composites vessel storage behavior under various loads using experimental, analytical and numerical models to describe the failure process, but neglect the randomness in mechanical properties, winding angle, loading and geometrical parameters. For the evaluation of the composite structure reliability, [10 and 11] focus on developing reliability model of composite piping, in order to get an optimal design of cylindrical composite structures. In this area, we are interested to study the effect of uncertainties parameters on the failure behavior of type III storage vessel. The present study concerns, developing a numerical sensitivity evaluation to geometrical and mechanical uncertainties through reliability approach. Using the hoop stress for each ply, the Monte Carlo method is used to predict the distribution function of mechanical response of type III vessel. In the second part, we try to estimate the probability of failure P_f of this type of structure. We used the Monte Carlo method available in the Probabilistic module (PDS) under the calculation code ANSYS. Nine random design variables with uncertainties are selected, namely: elastic constants of aluminium liner and composite materials parts, winding angles, thickness of the two parts and the mechanical loading (pressure).

2 Materials of Type III vessel

The Type III is made. In this section, we present the Type III pressure vessel by metal liner with full composite overwrap, generally aluminium, with a carbon fiber composite and it's presented by Figure 1.

Fig.1- Type III gas storage vessel.

2.1 Metallic Liner

The studied liner is made of aluminium 6061 where the mechanical properties are defined in Table 1. E_L and ν_L are respectively the liner Young modulus and Poisson coefficient. σ_0 and σ_r are the yield and rupture stresses.

2.2 Filament winding composite

The aluminium liner is overwrapped by a carbon/epoxy T300/5208 composite manufactured by filament winding (see Fig.1). Table 2 present the material properties of this impregnated carbon fiber.

Table 1- Materials properties of aluminium liner

	E^L [GPa]	ν^L	σ_0 [MPa]	σ_r [MPa]
Al	**72**	**0.25**	200	250

Table 2- Materials properties of composite

Parameter	T300/5208	Parameter	T300/5208
E_x (GPa)	181	X= X' (MPa)	1500
E_y (GPa)	10.3	Y (Mpa)	40
G_{zz} (GPa)	7.17	Y'(Mpa)	246
ν_{xy}	0.28	S (Mpa)	68

3 Reliability formulation

In order to analyze the vessel storage reliability, we propose a Mechanical reliability analysis which used the System of Probabilistic Design (PDS) existing in the commercial Code ANSYS "APDL". This system has allowed us to pair the method of Monte-Carlo and the method of finite elements (Figure.2).

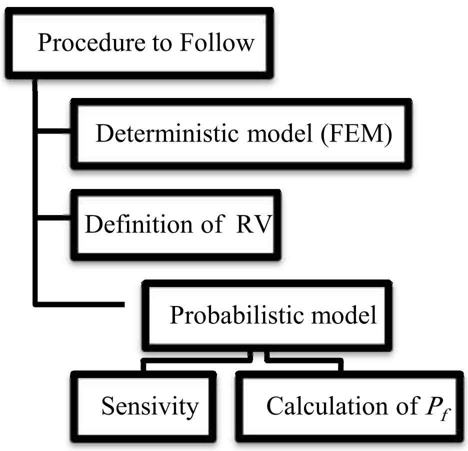


Fig.2- Steps of the analysis mecano-reliability [2].

The establishment of probabilistic model is in two main steps. First, we realize the deterministic model to verify the results, then we begin the probabilistic model. The latter takes place in two steps. The first step is performed to find the parameters that can play an important role in the reliability. The second step is performed in order to estimate the Failure Probability by Monte Carlo method.

3.1 Type III Vessel and uncertainties

The cylindrical type III vessel is submitted to an internal pressure, which is limited to 15 MPa, in order to not go far from the elastic area. The internal radius of the liner is of 33 mm and its thickness of 2 mm when each composite layer has a thickness of 0.27 mm. In the following, we study the $[\pm 55]_8$ stacking sequence of multilayered composite. The random parameters with their coefficients of variation (CV) are given in Table 3.

3.2. FEM Model representation

All finite element simulations run using ANSYS 18. Two 3D elements are used in our investigation, Solid95 for the isotropic material (Liner) and layered Solid186 for anisotropic material (composite). Fig. 3 emphases the complete FE model including its specificities. The deterministic results of hoop and radial stress are represented on local representation.

4 Results and discussion

4.1. Deterministic analysis

The figure 4 shows the distribution of radial and hoop stress through the thickness of the liner and composite. The wall thickness of type III vessel is subjected to compressive stress from the given internal pressure 15 MPa to zero, as shown by the radial stress. The distribution of the hoop stress shows that the liner part is more stressed than the composite part. So, if the failure occurs, the liner will be the first.

Table 3- Mechanicals properties uncertainties of Type III vessel

	Variable	Mean	Coefficient of variation (CV)
Composite	Ex	181 GPa	4%
	Ey	10.3 GPa	1%
	Gzz	7.17 GPa	12%
	Pi	16 MPa	10%
	Winding angle φ	55°	1%
	Layer Thickness Thc	0.27 mm	5%
Liner	E_L	72 GPa	4%
	G_L	7.17 GPa	12%
	Thickness Th_L	2 mm	5%

Structural representation	Local representation

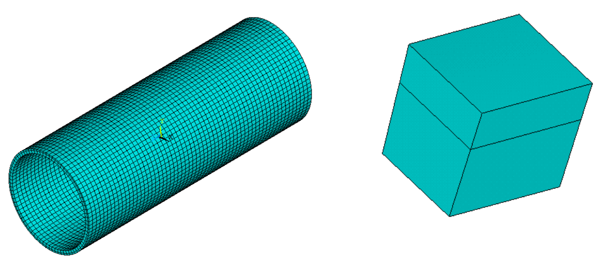


Fig.3- Structural and local representation of Type III vessel.

4.2. Sensitivity analysis

The sensitivity analysis represents an essential element of a reliability study. In fact, this analysis allows us to define the parameters that can be the origin of Type III vessel failure. Subsequently, we look primarily to these settings. To achieve this objective, we will put in place a probabilistic model of a Type III vessel. In order to estimate a better sensitivity of the reliability of the structure, we opted for a high number of drawings (N = 104).

The Fig. 5 represents the sensitivity of the hoop stress. The results show clearly that the Type III vessel reliability is affected by the significant influential parameters:

- Internal pressure;
- Thickness of Liner;
- Liner modulus of elasticity E
- Thickness of composite;
- Fibers winding angle;
- Liner shear modulus;

In the following, we will study the variation of the failure probability according to the three main parameters namely: Internal pressure, thickness and Modulus of elasticity E_L of liner.

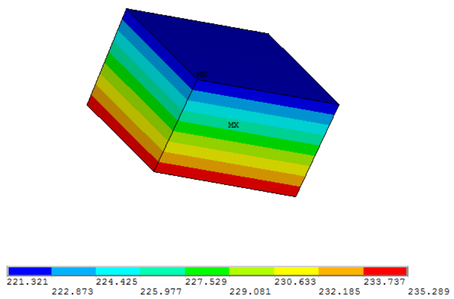
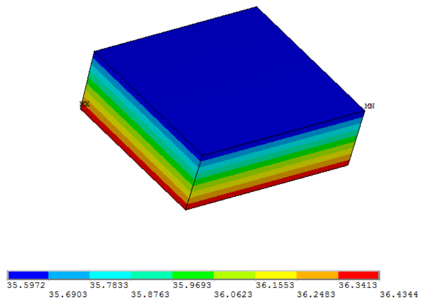
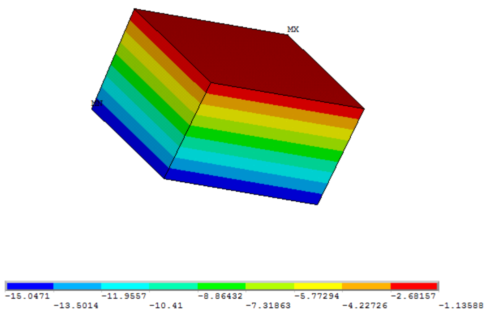
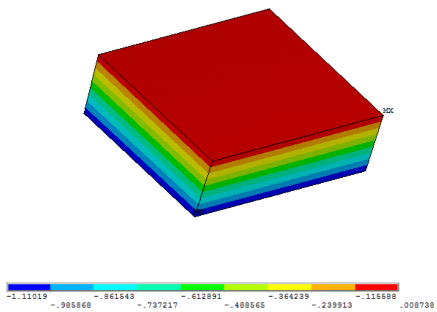
Stress	Liner	Composite
Hoop stress		
Radial stress		

Fig.4- The deterministic local results of hoop and radial stress

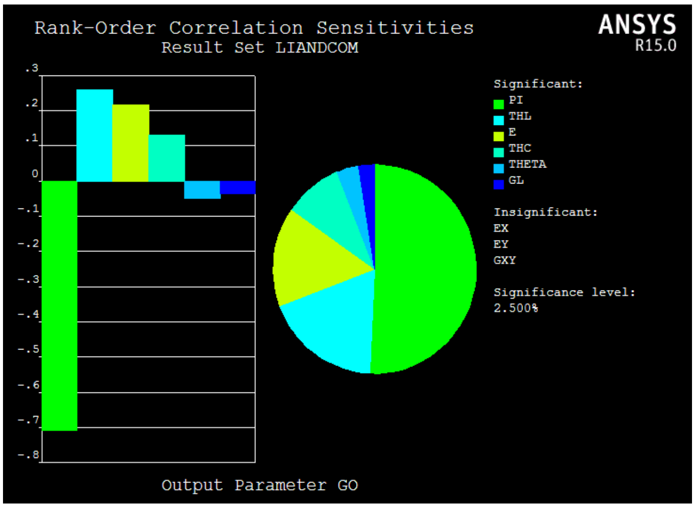


Fig.5- Sensibility of hoop stresses for $[\pm 55]_8$, with Pi=16 MPa.

4.3. Failure probability

Based on the results of the sensitivity analysis, the objective of this section is to study the variation of the failure probability (P_f) of the type III vessel under pressure. In order to define the safety zone of the structure and to achieve optimum design, we evaluated the effect of three main parameters mentioned above on failure probability.

4.3.1 Internal pressure influence

The Fig.6 presents the effect of the first significant parameter, which is the internal pressure random variable, on failure probability P_f for $[\pm 55]_8$ stacking sequence from internal and external wall of Type III vessel. For internal pressure random parameter, it is important to note that the increase in CV about 10% of internal pressure leads to a reduction in safety of vessel storage. It was noted that for the inner wall is the most stressed, where the failure probability decreases from the inner wall of liner to the outer wall of composite, where it's equal zero.

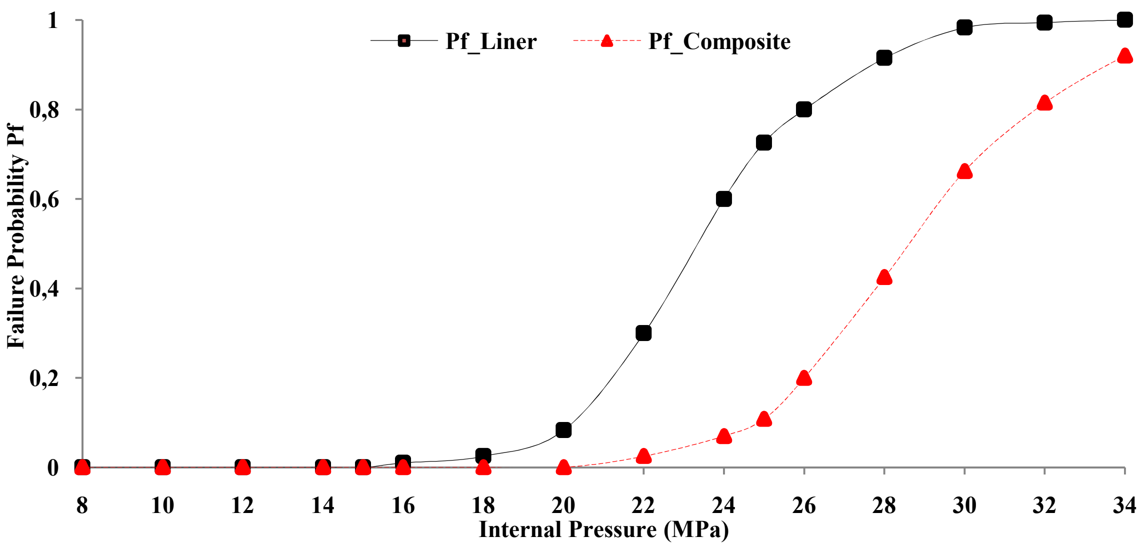


Fig.6- Evolution of failure probability Pf according to internal pressure (maximum stress criterion)

The results show that the liner is more sensitive to any variation of the internal pressure with respect to the filament winding. This observation requires the use intermetallic barrier between the liner and the composite multilayer, in order to stop leakage gas in case of the gas-proof failure of the liner which was the subject of the work of Hocine et al [2].

4.3.2 Metallic Liner Thickness influence

The results presented in Fig.7 show that any decrease in the liner thickness leads in failure of the two parts of Type III vessel. This result obtained, requires an optimization of liner thickness, to ensure the securing of this structure under pressure.

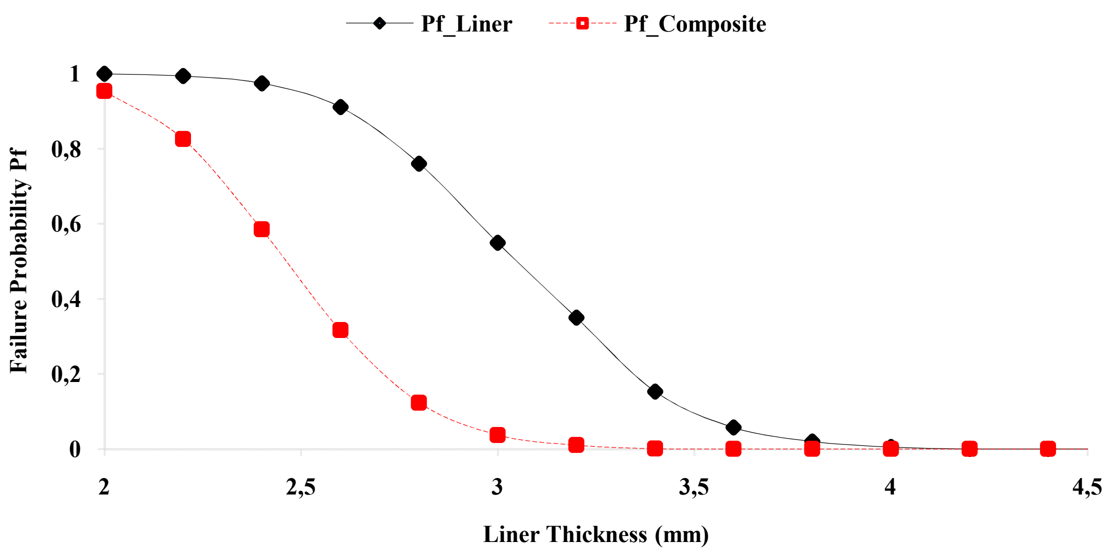


Fig. 7 - Evolution of failure probability according to Liner Thickness of Type III vessel.

5 Conclusion

The present paper has focus on a prevention of failure probability of Type III vessel under pressure. First a sensitivity analysis has shows the most significant parameters on the reliability of this kind of structure, which are resumed as: Internal pressure; Liner thickness; Liner modulus of elasticity; Composite thickness; Fibers winding angle; Liner shear modulus.

The last step deals to estimate the failure probability according to the three main significant parameters combinations of the above-mentioned random parameters.

The reliability analysis shows the very high variation of the probability of failure when the internal pressure and thickness liner are considered compared to the fourth significant parameters:

- Liner Modulus of elasticity ;
- Structure thickness of composite;
- Fibers winding angle;
- Shear modulus of Liner.

It is important to note that all properties of metallic liner are significant parameters on the reliability of Type III vessel. On the other hand, the probability of failure increases significantly when all the random variables of internal pressure and liner thickness are considered simultaneously.

These results obtained show that it's important to secure the gas storage, by including intermetallic envelope between the liner and filament winding composite. The intermediate layer aims to secure the hydrogen storage medium in case of the gas-proof failure of the liner. This subject can be a previous work, in order to get a reliability optimization procedure of the Type III vessel.

Nomenclature

Symbols		Greek Symbols	
E_L	Metallic's young modulus	ν_L	Metallic's Poisson coefficient
Ex	Young's modulus in x direction	ν_{xy}	Poisson coefficient
Ey	Young's modulus in y direction	ν_{xz}	Poisson coefficient
Ez	Young's modulus in z direction	ν_{yz}	Poisson coefficient
Gxy	Shear modulus in X-Y plane	z,θ,r	Cylindrical coordinate system
Gxz	Shear modulus in X-Z plane	k	Such as $k \in [1, w]$
Gyz	Shear modulus in Y-Z plane	w	The number of composite layers.
P_f	Probability of failure for mechanical loading.	φ	Winding angle
$G(X_i)$	The limit state function or performance	Thc	Layer Thickness
$G(X_i) \leq 0$	Safe domain	ThL	Liner Thickness
$G(X_i) > 0$	Failure domain.		

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