PROBABILISTIC EVALUATION OF FILAMENT-WOUND COMPOSITE PRESSURE VESSEL UNDER MATERIAL UNCERTAINTY

M.P. Alves[1], S.K. Ha[2] and C.A. Cimini Junior[3]

[1] Structural Engineering Department from UFMG, Belo Horizonte, Brazil, PhD student, maripimenta8@gmail.com

[2] Structural Engineering Department from UFMG, Belo Horizonte, Brazil, Professor, cimini@gmail.com

Keywords: Hydrogen storage, Filament Winding, Probabilistic structural design.

ABSTRACT

The application of hydrogen-based fuel cell vehicles in transportation offers a great alternative to address the urgent threats of environmental pollution and climate change. Nevertheless, the challenges are multiple when comparing the applicable design requirements for compressed hydrogen tanks with the ones associated with a typical gasoline container. Composite pressure vessels are currently the automotive industry's answer to the technological issues raised. This work consists in an investigation of the effects of uncertainties typically associated with material properties on the structural performance of filament-wound pressure vessels subjected to internal hydrostatic pressure. A probabilistic methodology to evaluate the burst behavior of type IV composite pressure vessels was developed, taking into account the effect of uncertainties in mechanical properties described in the lamina level. The analytical modeling approach reflected the assumptions usually made for preliminary design stages of such components and used Monte Carlo simulations for probabilistic assessment. An uncertainty analysis was first performed, quantitatively describing the possible outputs given the prescribed variation of the inputs. Later, a sensitivity analysis was conducted, determining which input parameters among the material properties contributed the most in the output variability.

1 INTRODUCTION

The worldwide quest for a global energy transition has elected hydrogen fuel cell (FC) technology as a viable, green, clean, emissions-free option to traditional internal combustion processes [1]. Motors powered by electricity have since assumed a pivotal role, with hydrogen-powered vehicles complementing battery electric alternatives in order to achieve a deep decarbonization of the transportation sector, which alone is responsible for the largest share of greenhouse gas emissions.

Light duty vehicles using compressed hydrogen have learned from the successful global growth of natural gas vehicles, and the first generation of FC vehicles has experienced commercial deployment in recent years, under the leadership of Honda, Toyota and Hyundai. Latterly, the focus of hydrogen fuel cell has been shifting from light duty compact cars to heavy-duty applications [2]. The gravimetric energy density of hydrogen makes it a great candidate for medium/larger vehicles operating longer trips, such as trucks and buses, for which battery size would become impractical. In addition, it allows refueling infrastructure challenges to be faced by concentrating stations.

Regardless of the vehicle weight class, the feasibility of hydrogen-based fuel cell vehicles particularly relies on the development of safe, lightweight and cost-competitive solutions for hydrogen on-board storage. The most prominent and costly component of the hydrogen storage system of a FC vehicle is the hydrogen tank and its fabrication processes may be challenged to ramp up fast enough for a large-scale market adoption [3]. The storage system of fuel cell vehicles requires a specialized pressure vessel, significantly different in function, size, and construction from a typical gasoline container. The automobile industry has adopted a Type IV pressure vessel configuration, which is composed of a thin polymer liner fully overwrapped with carbon fibers wound layers.

Reliability analyses are vital to quantify and evaluate structural safety. The most common application of probabilistic structural design revolves around the typical stress-strength reliability approach, where distributions of applied stress are compared to distributions of the strength resistance offered by the structure [4]. Fig. 1 represents the uncertain nature of both applied stresses and strength by probabilistic density functions. Failure occurs when the applied stress on a structure exceeds its strength, what would be represented by the interception of the two curves.

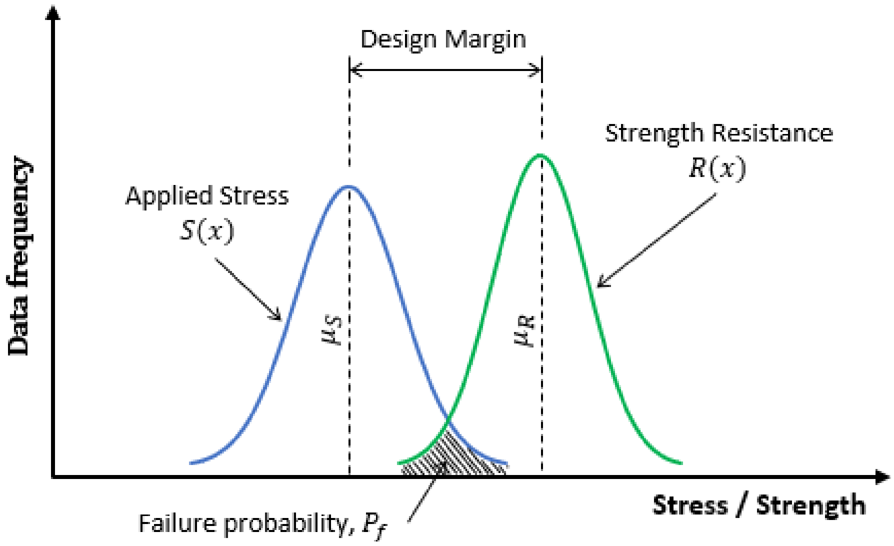


Figure 1: Stress-Strength analysis for reliability: Graphical representation of failure concept.

When dealing with composite materials, its mechanical behavior reflects the variability associated with their intricated structure and complex manufacturing processes. In the context of structural design, uncertainties can manifest from the variability in constituent properties, fiber distribution, part geometry, loading conditions, and also from manufacturing-related features [5]. During the design stage of composite structures, the influence of multiple design parameters on the product needs to be critically evaluated to achieve the desirable objective. There is thus a need to incorporate uncertainties effect so that structural performance can be assessed from a probabilistic perspective.

This work addresses an investigation of the effects of material uncertainties on the structural performance of filament-wound pressure vessels subjected to internal hydrostatic pressure. A probabilistic methodology to evaluate the burst pressure of type IV composite pressure vessels (COPV) was developed and validated, taking into account the effect of uncertainties in material properties. The modeling approach was focused on reflecting the initial assumptions usually made for preliminary design stages of composite pressure vessels, which employ lower levels of detail regarding material and structural definitions. As a result, a framework was built to probabilistically assess the design of a COPV, by means of both uncertainty and sensitivity analysis.

2 METHODOLOGY

2.1 Case study and general guidelines

This work utilized a case study from the current literature, focused on the design of filament wound COPV of type IV. Alam *et al.* [6] have performed finite element analysis and burst testing of a carbon fiber/epoxy pressure vessel. The geometry of the pressure vessel in question can be seen in Fig. 2. The analyzed COPV had a layup sequence of [-13°/+13°/+88°/-13°/+13°] and ply individual thicknesses of $t_{helical}$ = 0,8382 mm and t_{hoop} = 0,2286 mm.

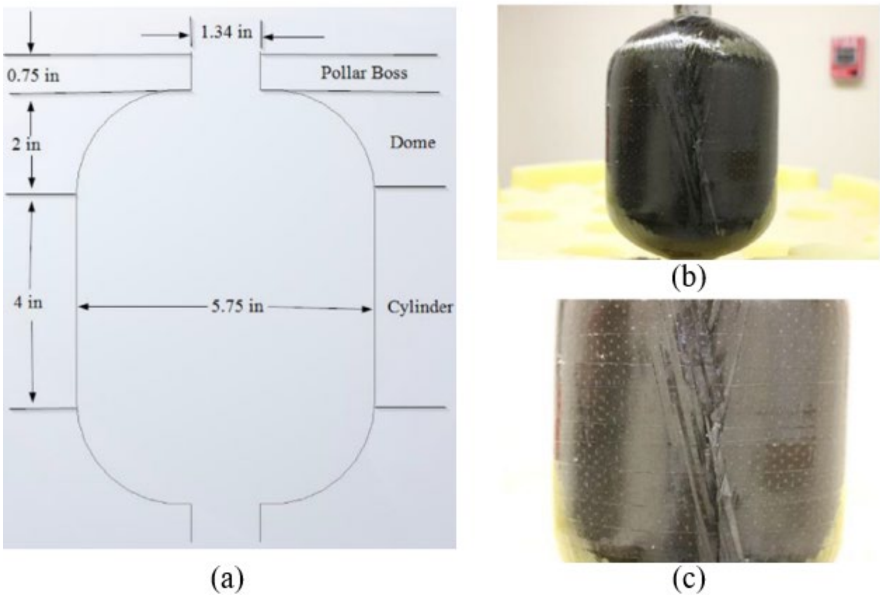


Figure 2: (a) COPV geometry; (b - c) Photographs of failed specimens [6].

The first task consisted in performing a deterministic stress analysis for the COPV using the input from [6] to demonstrate the accuracy of the developed tool. ELamX^2 [7], an open-source Java-written composite calculator developed by the Institute of Aerospace Engineering from the Technische Universität Dresden, was used in this calibration stage, by comparing local stresses values. The results showed a good agreement, with a very low discrepancy. The second task encompassed the probabilistic structural assessment of the COPV, taking into account the variation in material mechanical properties at lamina level, which were treated as random variables and statistically described.

The computational tool was built using a Microsoft® Excel® spreadsheet, with macro codes written in VBA in order to automate the repeated calculations involved in probabilistic analysis. Excel® Data Analysis ToolPack was used in data post-processing.

2.2 Strength analysis

The composite pressure vessel was analyzed under static condition, considering simplified linear elastic behavior. The structural load was considered to be carried totally by the composite layers, with the plastic liner sharing no load. Failure investigations approximated the burst pressure with First Ply Failure (FPF) condition. Stress-strain relations were obtained by employing Classical Laminate Theory formulations.

The vessel was considered thin-walled and only its cylindrical section was analyzed, an assumption backed by the fact that the dome section manufactured by filament winding usually exhibits fiber accumulation. No localized bending correction was here considered, so that the model displays a purely membrane biaxial tensile stress state. The observation of failed specimens from the case study indicated that the COPV in question has failed in the cylindrical section, as in accordance with the adopted assumption.

The employed material system consisted in towpreg carbon fibers (T800S-10E-24 K) / epoxy resin TCR UF3323 and its mechanical properties are statistically described in Table 1, following normal distributions. The mean values are the ones encountered in Reference [1]. In the absence of a stochastic experimental material characterization, standard deviation values (in terms of percentage of the mean values) were taken in accordance with the probabilistic study from Li *et al*. [8], that was originally based on information from Composite Materials Handbook Series [9].

Parameter	Mean	Standard deviation
Longitudinal modulus - E_1 [GPa]	176.8	8.0
Transverse modulus - E_2 [GPa]	10.336	0.519
Poisson's ratio in direction - ν_{12} [-]	0.3300	0.0208
In-plane shear modulus - G_{12} [GPa]	4.895	0.296
Longitudinal tensile strength - X^T [MPa]	3364.8	112.0
Longitudinal compressive strength - X^C [MPa]	1723.75	137.9
Transverse tensile strength -Y^T [MPa]	96.53	3.99
Transverse compressive strength - Y^C [MPa]	289.59	16.11
In-plane shear strength - S_{12} [MPa]	96.53	0.59

Table 1: Stiffness and strength mechanical properties for carbon fiber composite (T800/epoxy) [1,8].

Maximum Stress was taken as failure criteria, taking the Margin of Safety as zero. Equations (1) - (3) express failure condition in the form of subcriteria. This option makes it possible to also account for failure mode, by comparing three distinguished possibilities: Longitudinal failure (Eq. 1), Transverse failure (Eq. 2), and Shear failure (Eq. 3). Since the structure in question is an internally pressurized vessel, the deformation mode will imply in an expansion movement, that will be accompanied only by a resulting tension stress field. So, the evaluated Maximum Stress equations will refer only to tensile failure ($\sigma_1 > 0$ and $\sigma_2 > 0$).

$$\sigma_1 = \begin{cases} X^T, \text{when } \sigma_1 > 0 \\ -X^C, \text{when } \sigma_1 < 0 \end{cases}, \tag{1}$$

$$\sigma_2 = \begin{cases} Y^T, \text{when } \sigma_2 > 0 \\ -Y^C, \text{when } \sigma_2 < 0 \end{cases} \tag{2}$$

$$|\tau_{12}| = S \tag{3}$$

2.3 Probabilistic evaluation

The probabilistic structural assessment was performed by means of a Monte Carlo simulation with simple random sampling, so that its repeated calculations generated the database for probabilistic response. Uncertainty propagation was first performed, determining the impact of input uncertainties on the outcome of the model. Following Hwang *et al*. [10], 1000 simulations were performed.

Sensitivity analyses were later conducted in order to identify the key material properties of concern. Initially, a correlation analysis using Pearson's coefficients was made (Eq. 4), measuring the association between each input considered separately and the output. These dimensionless indexes ranging from -1.0 to +1.0 reflect the extent of a linear relationship between two data sets.

$$r_{xy} = \frac{\sum_{i=1}^{n}(x_i-\bar{x})(y_i-\bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i-\bar{x})^2}\sqrt{\sum_{i=1}^{n}(y_i-\bar{y})^2}}, \tag{4}$$

The level of correlation between two data sets can be classified in terms of the absolute values from Pearson's coefficients [11]: i) 0.00 – 0.19: very weak correlation; (ii) 0.20 – 0.39: weak correlation; (iii) 0.40 – 0.59: moderate correlation; (iv) 0.60 – 0.79: strong correlation; (v) 0.80 – 1.00: very strong.

Finally, a one-factor-at-a-time investigation was conducted, aiming to describe how perturbations near an input space influences the output. In this local sensitivity analysis, all other factors were held constant when one is varied. Once the input random material properties present different degrees of variability, the local sensitivity analysis ranged from the 5th percentile to the 95th percentile.

3 RESULTS AND DISCUSSION

Fig. 3 presents the histogram of the estimated burst pressure, describing the uncertainty quantification of the outcome. It includes a normal distribution curve with the mean and standard deviation calculated from a curve fitting of the generated database. The obtained outcome presents a medium value of $\mu = 9.695$ MPa and standard deviation of $\sigma = 0.5300$ MPa (5.5%). Alam *et al*. [6] have predicted a burst pressure value of 15.64 MPa for the vessel configuration in question, while the mean burst pressure values experimentally obtained from three specimens was 16.09 MPa. Both values surpass the maximum values from this work's probabilistic analysis by relatively far. This can be attributed to different hypotheses considered in the analysis procedure. Alam *et al.* [6] have used detailed finite element simulations of half quarter tank, including dome section. Nonlinear geometry was considered as well as a nonlinear material description, taking into account progressive damage modeling. This finding shows how important is to consider the effect of progressive damage evolution in burst pressure simulations. Fig. 4 shows the cumulative density function (CDF) of the failure condition.

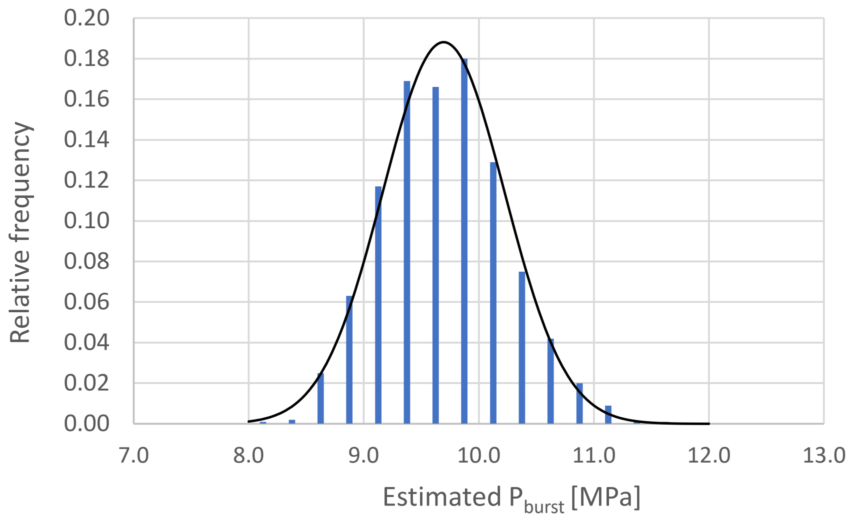


Figure 3: Probabilistic failure response of a COPV to material uncertainty – Histogram of estimated burst pressure.

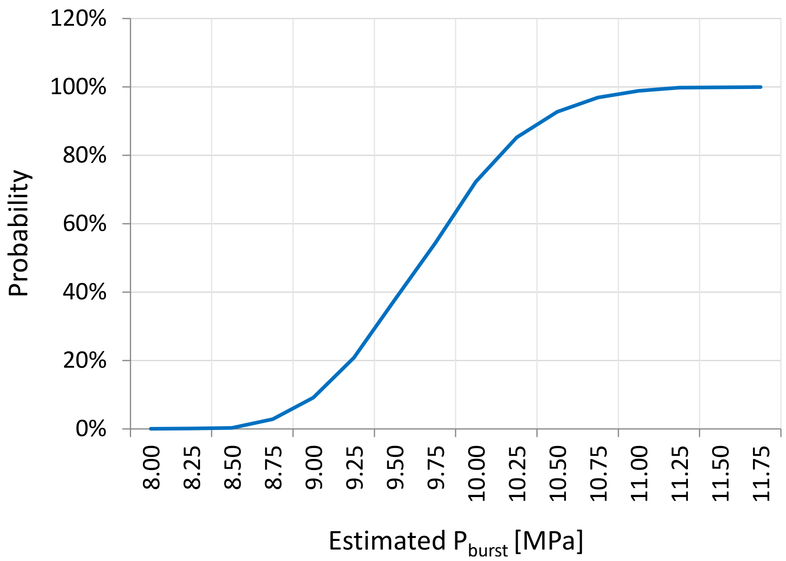


Figure 4: Probabilistic failure response of a COPV to material uncertainty – CDF of estimatedburst pressure.

Tab. 2 summarizes Pearson's correlation coefficients relating the estimated burst pressure with material uncertainty, presented in a descending order. Between all the material properties treated as uncertainties, Y^T, E_2 and E_1 are the ones associated with strong, moderate, and weak correlations, respectively. All other uncertainty parameters have shown very weak correlation properties. The highest absolute values of correlation coefficient indicate what parameters have a significant effect on the performance of the COPV. Therefore, designers should be paid more attention to them, and its variability should be well controlled.

Given the sign of Pearson's correlation coefficients, an increase in Y^T or E_1 would be accompanied by a resulting increase in burst pressure. On the other hand, an increase in E_2 will generate a decrease in resulting outcome. Such findings can be corroborated by the graphs presented in Fig. 5.

Parameter	Correlation coefficient
E_2	-0.4909
Y^C	-0.0589
X^C	-0.0540
S_{12}	-0.0447
X^T	-0.0263
ν_{12}	+0.0290
G_{12}	+0.0291
E_1	+0.3883
Y^T	+0.7485

Table 2: Correlation coefficients relating the estimated burst pressure with material uncertainty.

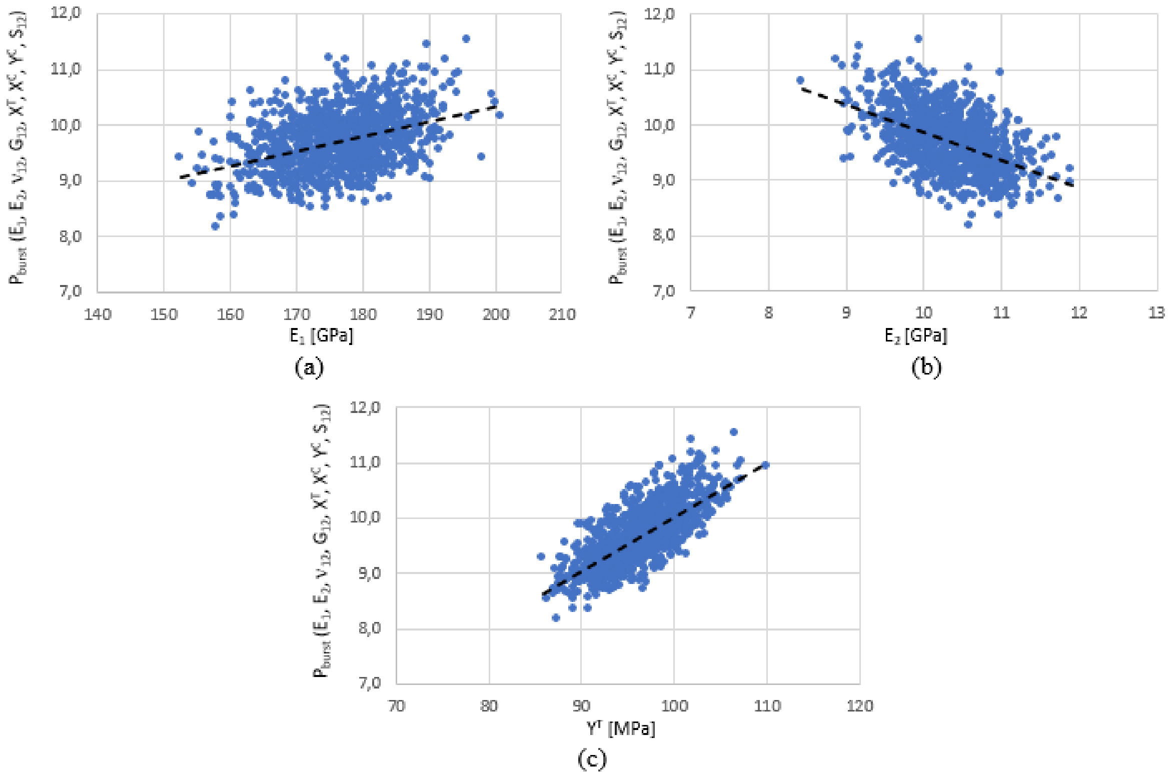


Figure 5: Distribution of estimated burst pressure with respect to: (a) Longitudinal modulus; (b) Transverse modulus; (c) Transverse tensile strength.

Fig. 6 collects the results from the one-factor-at-a-time analysis. The results were gathered in the form of a tornado plot, been displaced around the deterministic value of burst pressure. The input properties with negligible effect in the output variation were not presented in the graph. Once again, it reinforced Y^T as the input parameter that dominates the output response of the COPV in question. Its variation along the prescribed statistical range will reflect in a wider fluctuation of burst pressure.

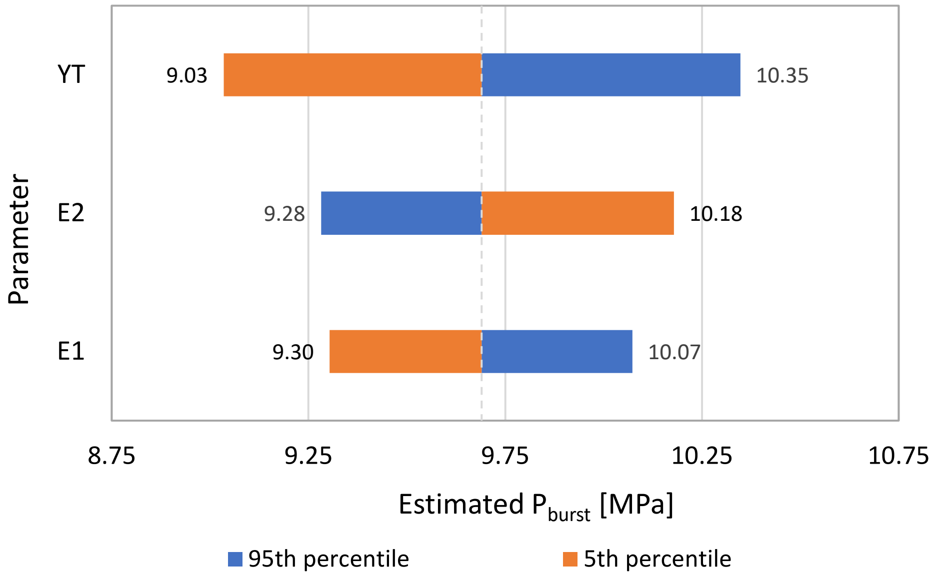
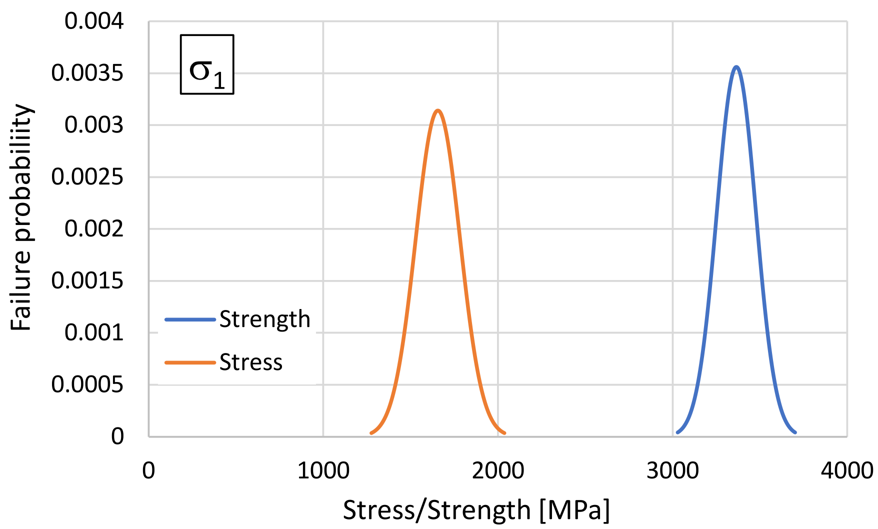


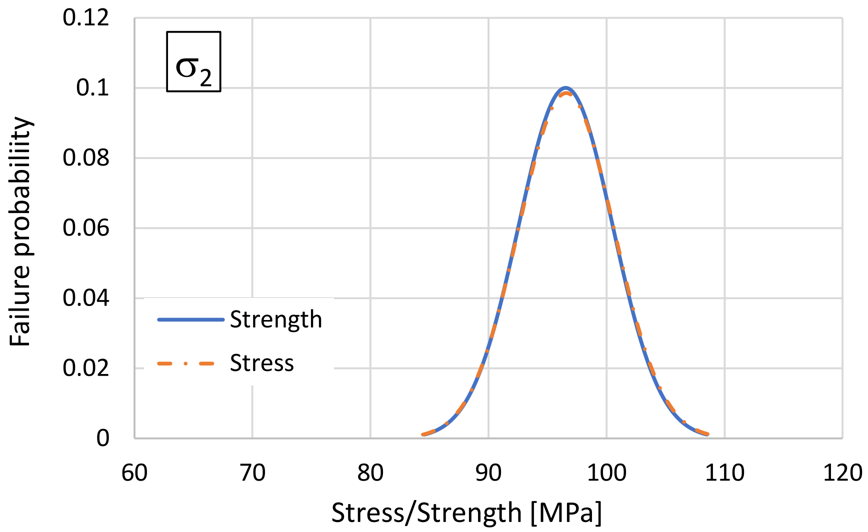
Figure 6: Sensitivity of burst pressure to random input material properties

Fig. 7 shows the stress-strength interference plots that can be derived from the three subcriteria that compose the Maximum Stress failure criterion. It can be seen that failure in the COPV in question was governed by transverse tensile failure, a response that can be attributed to a very low transverse stress allowable (circa 35 times lower than the longitudinal tensile value). This agrees with the deterministic simulations performed in eLamX2 for the prescribed layup. Once that the Margin of Safety was fixed as zero for this investigation, it was expected that strength and stress curves would superimpose, as observed in Fig 1.

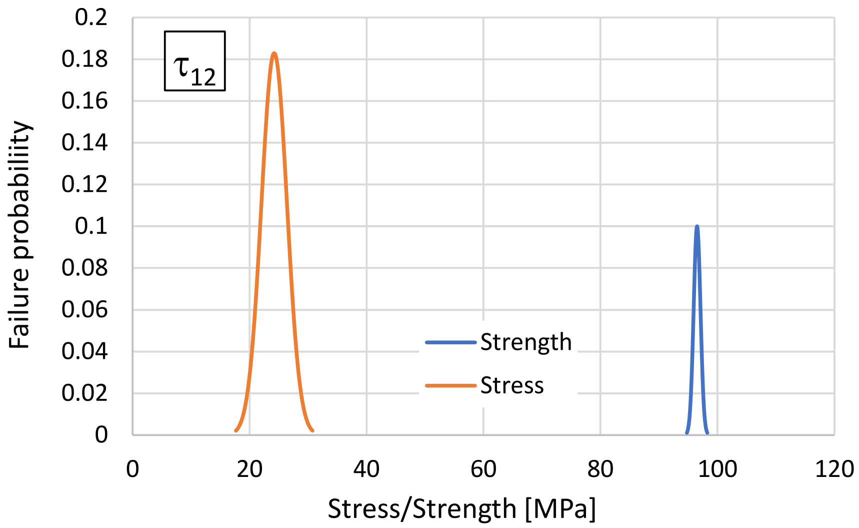


(a)

Figure 7: Stress-strength interference on local orientation: (a) Longitudinal normal stress-strength; (b) Transverse normal stress-strength; (c) In-plane shear stress-strength.



(b)



(c)

Figure 7: Stress-strength interference on local orientation: (a) Longitudinal normal stress-strength; (b) Transverse normal stress-strength; (c) In-plane shear stress-strength (*Continued*).

4 CONCLUSIONS

This work conducted a probabilistic investigation of strength analysis of a composite pressure vessel. The simplified analytical methodology proposed herein was able to describe the effect of uncertainties related to material properties on the predicted structural performance from the standpoint of uncertainty propagation and sensibility analysis. The allowable burst pressure of the vessel in question was shown to be most sensitive to transverse tensile strength, transverse modulus and longitudinal modulus, while other material properties on the lamina level showed little effect. This is valid for the current case study and may vary with changes in vessel geometry (such as layup, thickness, etc.), failure criteria, among others.

Studies like this allow a better understanding of the limitations of current deterministic preliminary design strategies and are particularly useful for anticipating variation in material properties. Probabilistic structural evaluations can then provide additional information about reliability and risks, while achieving less conservative results than the ones obtained by deterministic guidelines.

ACKNOWLEDGEMENTS

The authors are thankful for the assistance of the Structural Engineering Department of UFMG. This work was supported by CAPES, CNPq, and FAPEMIG.

REFERENCES

[1] M.P. Alves, W. Gul, C.A. Cimini Junior and S.K. Ha, A Review on Industrial Perspectives and Challenges on Material, Manufacturing, Design and Development of Compressed Hydrogen Storage Tanks for the Transportation Sector, *Energies*, **15**, 2022, 32 p. (doi: 10.3390/en15145152).

[2] D. Cullen *et al*., New roads and challenges for fuel cells in heavy-duty transportation, *Nature Energy*, **6**, 2021, pp. 462-474 (doi: 10.1038/s41560-021-00775-z).

[3] A. Weisberg and S. Aceves, The potential of dry winding for rapid, inexpensive manufacture of composite overwrapped pressure vessels, *International Journal of Hydrogen Energy*, **40**, 2015, pp. 4207-4211 (doi: 10.1016/j.ijhydene.2015.01.130).

[4] S. Easley *et al*., Finite element-based probabilistic analysis tool for orthopaedic applications, Computer Methods and Programs in Biomedicine, 85, 2007, pp. 32-40 (doi: 10.1016/j.cmpb.2006.09.013).

[5] Chamis, C.C. Polymer composite mechanics review - 1965 to 2006. *Journal of Reinforced Plastics and Composites*, **26**, 2007, pp. 987–1019 (doi: 10.1177/0731684407079419).

[6] S. Alam, G. Yandek, R.C. Lee and J.M. Mabry, Design and development of a filament wound composite overwrapped pressure vessel, *Composites Part C: Open Access*, **2**, 2020, 14p. (doi: 10.1016/j.jcomc.2020.100045).

[7] ELAMX². Available at: https://tu-dresden.de/ing/maschinenwesen/ilr/lft/elamx2/elamx. Accessed on 15/05/2023.

[8] H.-S. Li, S. Xia and D.-M. Luo, A probabilistic analysis for pint joint bearing strength in composite laminates using subset simulation, *Composites Part B: Engineering*, **56**, 2014, pp 780-789 (doi: 10.1016/j.compositesb.2013.09.025).

[9] MIL-HDBK-17-3: *Composite Materials Handbook. Polymer matrix composites materials properties. Vol. 3: Polymer matrix composites – Materials usage, design, and analysis*, Department of Defense, USA, 2002.

[10] T. Hwang, C. Hong and C. Kim, Probabilistic deformation and strength prediction for a filament wound pressure vessel, *Composites Part B: Engineering*, **34**, 2003, pp. 481-497 (doi: 10.1016/S1359-8368(03)00021-0)

[11] N. Meghanathan, Assortativity Analysis of Real-World Network Graphs based on Centrality Metrics, *Computer and Information Science*, **9**, 2016, p. 7 (doi: 10.5539/cis.v9n3p7).