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Probabilistic evaluation of filament-wound composite pressure vessel under material uncertainty

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Abstract

The application of hydrogen-based fuel cell vehicles offers a great alternative to address the urgent threats of environmental pollution and climate change. Nevertheless, the challenges are multiple when comparing design requirements for compressed hydrogen tanks with the ones associated with a typical gasoline container. This work is an investigation of the effects of uncertainties typically associated with material properties on the structural performance of filament-wound composite pressure vessels subjected to internal hydrostatic pressure. A probabilistic methodology to evaluate the burst behavior of type IV composite pressure vessels was developed, considering the effect of uncertainties in mechanical properties described in the lamina level. This analytical approach reflected the assumptions usually made for preliminary design 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.

Introduction

- Hydrogen fuel cell (FC) technology: clean and emissions-free [1]
- Motors powered by electricity assumed a pivotal role [1]
- Hydrogen-powered vehicles complementing battery electric cars [1]
- Hydrogen storage: key factor for feasibility of FC [1]
- Lightweight and cost-competitive solutions [1]
- Type IV pressure vessel adopted by automobile industry [1]
- Thin polymer liner overwrapped with carbon fibers wound layers [1]
- Reliability analyses quantify and evaluate structural safety [2]
- Stress-strength reliability approach [2]
- Distributions compared: applied stress to strength[2]
- This work:
  - effects of uncertainties on structural performance
  - filament-wound pressure vessels
  - burst pressure
  - type IV composite pressure vessels (COPV)
  - effect of uncertainties in material properties
  - probabilistic design: uncertainty and sensitivity analyses

Methodology

Case study and general guidelines

- COPV of type IV
- Deterministic analysis [3] [4]
- T800/epoxy
- layup [-13°/+13°/+88°/-13°/+13°]
- ply thicknesses:

  $t_{helical}$ = 0.8382 mm

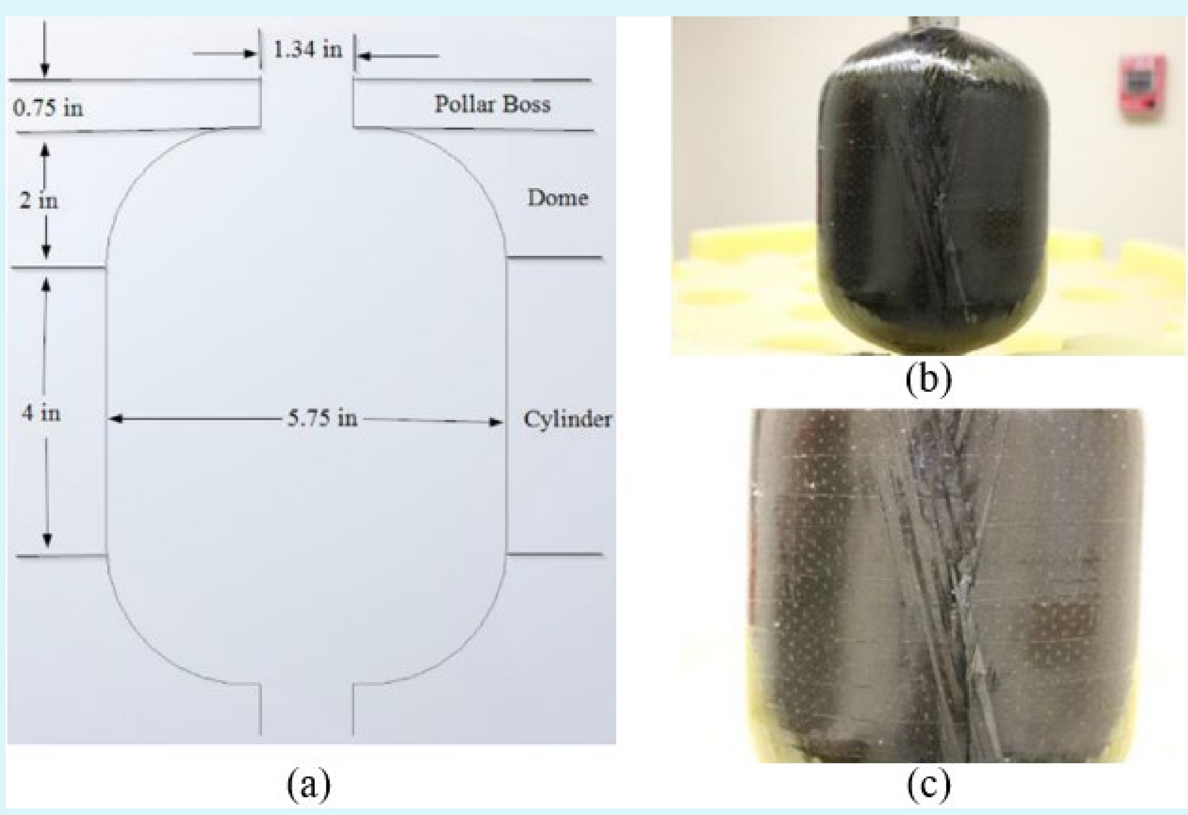
  t_{hoop} = 0.2286 mm

T800/epoxy [5]

Parameter	Mean	Standard deviation
E_1 [GPa]	176.8	8.0
E_2 [GPa]	10.336	0.519
ν_{12} [-]	0.3300	0.0208
G_{12} [GPa]	4.895	0.296
X^T [MPa]	3364.8	112.0
X^C [MPa]	1723.75	137.9
Y^T [MPa]	96.53	3.99
Y^C [MPa]	289.59	16.11
S_{12} [MPa]	96.53	0.59

Strength analysis

- Static, linear elastic
- Design: burst pressure
- Failure criterion: Max Stress
- First Ply Failure (FPF)
- Classical Laminate Theory
- Failure modes: longitudinal, transverse and shear



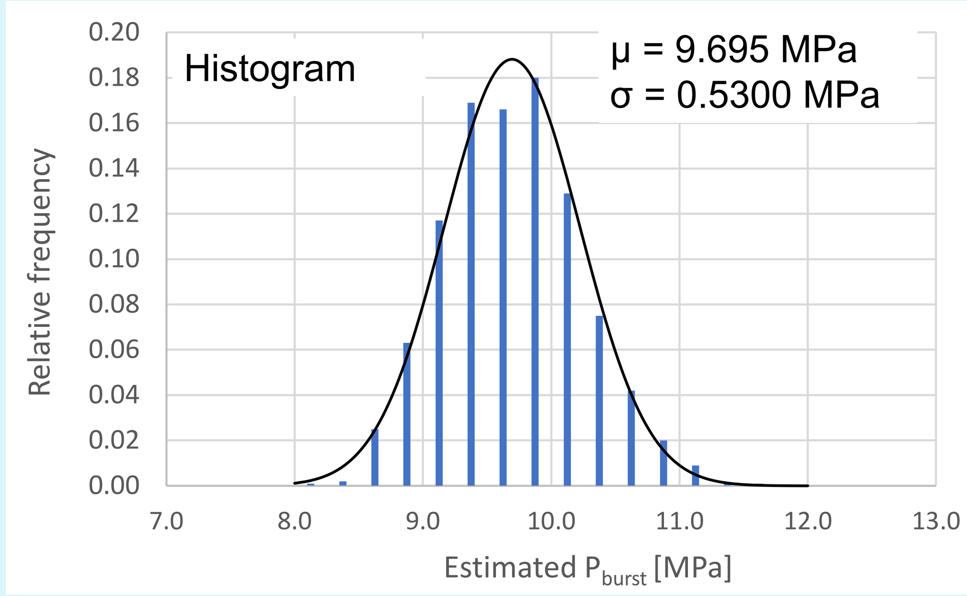
(a) COPV geometry; (b) and (c) Photographs of failed specimens [6]

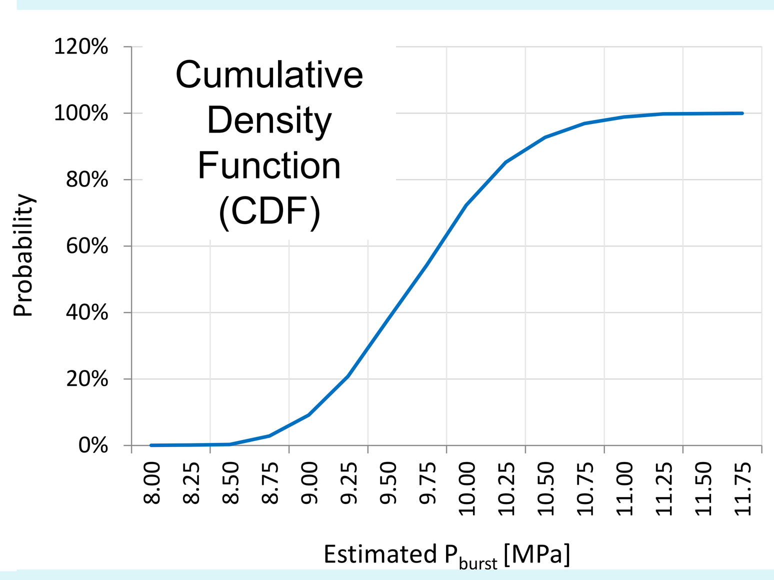
Probabilistic evaluation

- Monte Carlo Simulation with simple random sampling
- 1,000 simulations performed
- Uncertainty propagation first performed
- Sensitivity analyses later conducted
- Pearson's coefficients
- One-factor-at-a-time investigation conducted: all factors held constant, one varied from the 5th to 95th percentile.

Results

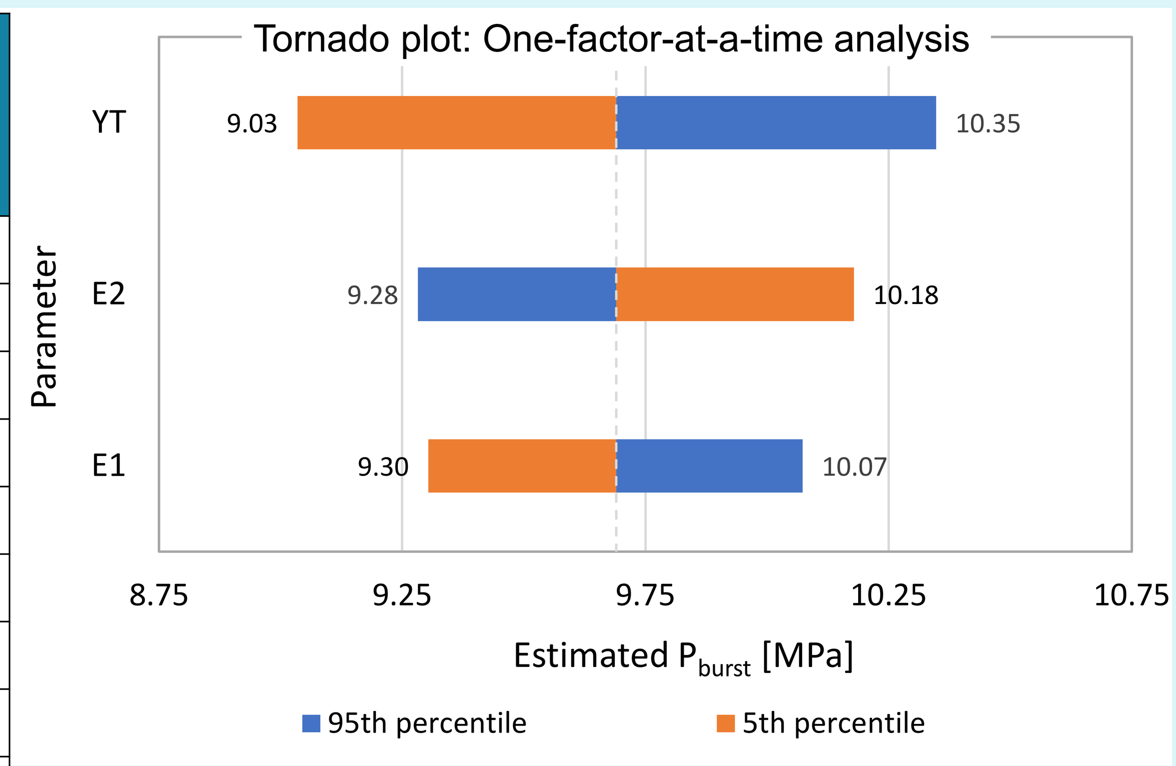
BURST PRESSURE





- Predicted burst pressure: 15.64 MPa [3]
- Experimental burst pressure: 16.09 MPa [6]
- Both values surpass the maximum values of this work's probabilistic analysis by relatively far. This can be attributed to different hypotheses considered (detailed finite element simulations of half quarter tank, including dome, as well as nonlinear geometry and material descriptions).

Parameter	Pearson's 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**



- Y^T, E_2 and E_1 associated with stronger correlations
- Y^T is the input parameter that dominates the burst response
- Its variation will reflect in a wider fluctuation of burst pressure

Conclusion

- Probabilistic investigation of strength of COPV conducted
- Simplified analytical methodology able to describe the effect of uncertainties of material properties on structural performance
- Uncertainty propagation and sensibility analysis
- Allowable burst pressure of COPV more sensitive to Y^T (most), E_2 and E_1
- Design may vary with changes in vessel geometry (such as layup, thickness), failure criteria, among others
- Better understanding of limitations of current deterministic design strategies

References

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