

Development of digital twin for composite pressure vessel

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Abstract. The present study is devoted to developing a digital twin for a composite overwrapped pressure vessel (COPV) used in electric propulsion engines of spacecraft. The digital twin is used to predict the future behavior and performance of a real physical object based on the currently available information without carrying out expensive and time-consuming full-scale prototyping and testing. Multiscale approach is employed to link the macroscopic stiffness degradation and failure with a progressive damage evolution at the microlevel of composite. The computational models for the stress state and failure analysis at different scale levels are presented. Based on a comparative analysis of the traditional approach for assessing the load-bearing capacity of the COPV and its digital analogue, the advantages of the latter are shown as the predicted burst pressure is in good agreement with the experimental results.

1. Introduction

At present, the metal-composite structures of pressure vessels (known also as composite overwrapped pressure vessels, COPVs) for various applications are widely used in aviation and space industries where a high strength/weight ratio is of prime importance. The low weight and high load-bearing capacity of COPVs allow to storage larger volume of working medium compared to all-metal analogues to ensure the operability of electric propulsion engines for a given period of active lifespan of spacecraft. However, the high level of operating pressures and strict requirements for the safety and reliability dictate the need for comprehensive calculations and experimental justification of COPV designs and operating performance.

A typical COPV consists of a composite power shell and a thin-walled metal liner. The liner serves as the permeation barrier, while the composite shell provides the strength and stiffness of the vessel structure. Composite filament winding is the most common method for manufacturing the power shell, which is the main load-bearing element in COPVs [1]. The combined deformation of an orthotropic, linear elastic composite shell and an isotropic, elasto-plastic metal liner determines the complex nature of the stress state of COPV and occurrence of such limit states that are not typical for all-metal pressure vessels or composite shells separately. This complicates the design and analysis of COPVs and requires developing more comprehensive computational models that would accurately reflect the mechanical behaviour of COPV elements and their interrelation.

At present, no single model or computational method can cover various scales involved in failure process of COPVs. An effective technique to simulate the deformation and fracture of COPV structures is a multiscale approach that has proven itself in the mechanics of composites [2–4]. Such structural hierarchy approach was used in [5] to predict failure properties and the ultimate (burst)



pressure of the aluminium alloy liner–carbon fiber/epoxy pressure vessel. Initially, a micromechanical kinetic model was employed to simulate the progressive failure of the representative volume element (RVE). Then, the relationship between the failure evolution in representative volume and the stiffness degradation of composite at the macro level is determined. A hierarchical model for the composite power shell was developed in [6] to analyse COPVs from micro- to macrostructural scale. The model includes three scale levels: micro level – elastic fiber in an elasto-plastic matrix, meso level – orthotropic composite layer and macro level – layered shell finite element. Based on the model, a parametrical study was carried out to assess the influence of mechanical properties of the composite constituents and winding parameters on the burst pressure values. Other examples of the multiscale simulation framework used to analyse the mechanical behavior of composite pressure vessels can be found in [7–8].

Despite the achievements in evaluating the structural integrity of COPVs provided by multiscale and other advanced computational approaches, there are issues still need to be addressed. This primarily relates to tracking and taking into account the history of operations and impacts that the COPV structure is exposed to during its lifetime. For instance, at the manufacturing stage, COPVs undergo a process called autofrettage which results in change of the COPV geometry and associated residual compressive stresses in the plastically deformed liner and tensile stresses in linear elastic composite shell. The autofrettage can also lead to a local buckling of the thin-walled liner and the loss of contact between the liner and composite layers. This, in turn, will influence the stress-strain state of COPV under the service loading [1, 9–10].

Traditionally, the analysis of deformation and failure processes in the COPV is carried out using the geometrical and mechanical parameters given at the design stage. Based on the design data, the COPV computational model is created and the structure behavior is predicted under boundary conditions that replicate the testing or operating loads. The simulation accuracy mostly depends on how realistic are the physical attributes included into the model. Variations in fiber volume fraction, winding angle, composite mechanical and strength properties resembling manufacturing-induced inconsistencies, as well as initial defects that can affect the vessel performance can be set a priori [11–12]. These data are based, as a rule, on experience from previous practices (historical information). However, at the manufacturing stage and, to the greatest extent, during qualification testing and following operation, the vessel is subjected to a number of influences that may affect the properties of liner and overwrap materials. It can result in a significant discrepancy between the real structural parameters and the design ones for a particular COPV. Moreover, the data on COPV from different stages and sources are fragmented and isolated. This determines the need to use new methods for analyzing the structural integrity of COPV, which capture on a continuous basis all information and data relevant to the COPV performance.

Such opportunity is provided by digital twin technologies, which have recently emerged as a new paradigm in data processing, simulation and engineering analysis [13–15]. Digital twin (DT), first conceptually presented by Michael Grieves [13], can be defined as a virtual object specified in the digital space, which has a mapping relationship with real object in the physical space in multiple dimensions which include but not limited to geometry, behavior, materials, requirements and functionality [15]. In ideal, any information that could be obtained from inspecting a physical manufactured product can be obtained from its digital counterpart [14]. The digital twin concept has proven to be useful and valuable for various applications in aerospace, automotive, construction and other domains [14–16].

The present study aims at developing a digital twin for a composite overwrapped pressure vessel used in electric propulsion engines of spacecraft (figure 1). The core of DT presented here includes the material models, micromechanical model, stress analysis model and long-term durability model. The goal of the DT is to evaluate the effect of the loading history on the strength and durability of COPVs. The DT was built in the ANSYS environment [17].

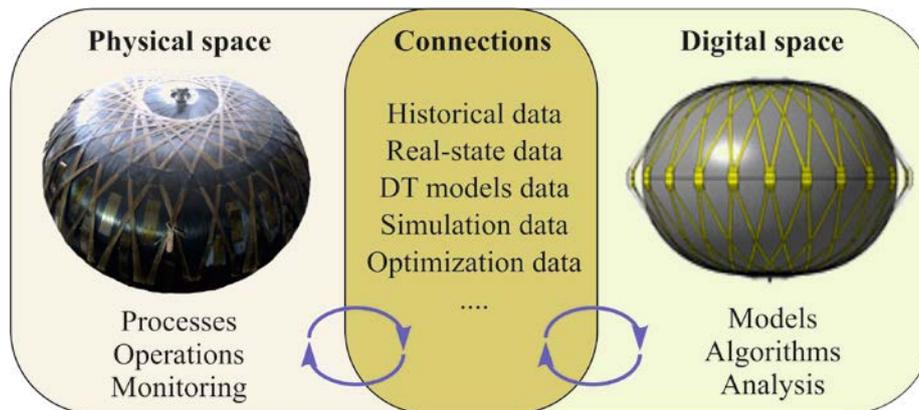


Figure 1. Conceptual scheme of the digital twin for COPV.

2. Research methods

The multiscale approach is adopted in this study to analyse the COPV. The parameters characterizing the damage level of a composite ply are determined directly from the finite element solution at the microscale, and the effective mechanical characteristics of the corresponding volume at the mesoscale are calculated based on the principle of averaging the components of stress and strain tensors. The flow chart of the multiscale failure analysis is shown in figure 2.

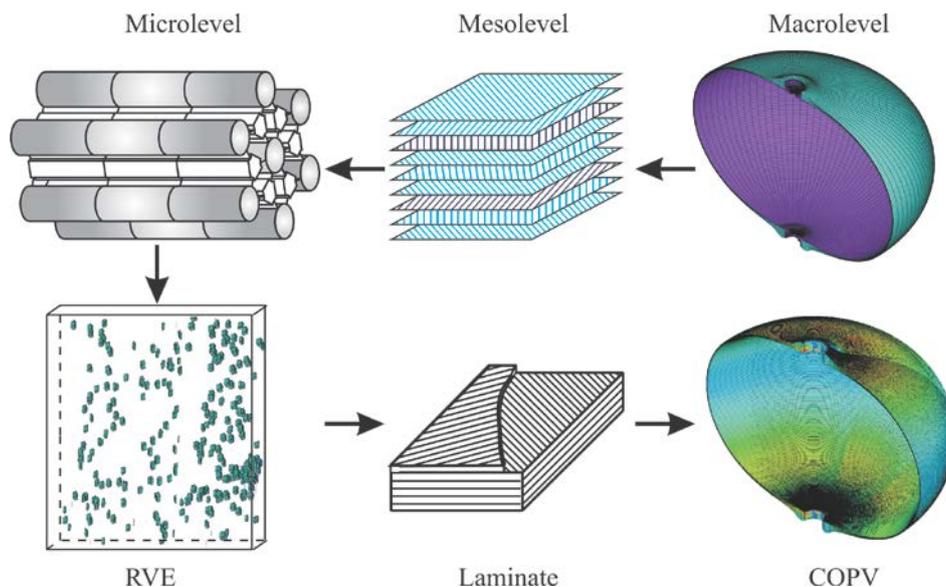


Figure 2. Multiscale failure analysis of COPV.

2.1. Micromechanical model of continuous fiber composite

In micromechanical progressive damage model the continuum of a unidirectional fiber composite is discretized with a set of finite elements representing fibers and matrix [18]. The strength of individual fiber and matrix elements is a stochastic variable assumed to follow the two parameter Weibull distribution:

$$F(\sigma_f) = 1 - \exp\left[-\frac{L_e}{L_0}\left(\frac{\sigma_f}{\sigma_0}\right)^m\right], \quad (1)$$

$$X_{f,m} = \sigma_0 \left[-\frac{L_0}{L_e} \ln(1-\eta) \right]^{1/m} \quad (2)$$

where F ($[0..1]$) stands for the probability of fiber (matrix) failure at the stress not exceeding the axial stresses σ_f (σ_m); η – a random number from 0 to 1; m – the shape parameter; σ_0 – the scale parameter; L_0 – the fiber base length; L_e – the length of the structural element; X – the material strength; subscripts f and m stand for the fiber and matrix elements, respectively. The failure of an element occurs when $|\sigma_f| \geq X_f$, $|\sigma_m| \geq X_m$.

The hexagonal arrangement with constant inter-fiber distance determined by the fiber volume fraction is assumed. The simulation starts from determining the stress state induced in the RVE by the internal pressure. The stresses in each of matrix and fiber elements of the RVE are compared with the corresponding strength value. If the failure criterion is met, the element is considered to be broken and its stiffness drops to a negligibly small value. The calculation repeats until no new broken elements are found. The failure of the whole RVE is reached when there is a spontaneous growth of the broken elements at a constant load.

2.2. Stress analysis model

The stress analysis model is constructed using a twenty-node finite element in the layered and structural solid form to represent respectively the composite shell and the liner (figure 3). Friction contact conditions are imposed between the outer surface of liner and the inner surface of composite shell. Due to the cyclic symmetry of the structure and load, only an axisymmetric section can be replicated with corresponding boundary conditions.

The initial (design) parameters for the thickness of the composite shell h and the geodesic winding angle φ are defined according to [1]:

$$h(r) = \frac{h_R R (1 - (r_0/R))^{1/2}}{w} \left[\cos^{-1} \frac{r_0}{r} - \cos^{-1} \frac{r_0 + w}{r} \right], \quad r_0 + 2w \leq r \leq R \quad (3)$$

$$h(r) = \sin^{-1} A_0 + A_1 r + A_2 r^2 + A_3 r, \quad r_0 \leq r \leq r_0 + 2w \quad (4)$$

$$\varphi(r) = \sin^{-1} \frac{r_0}{r} \quad (5)$$

where h_R is the thickness at the shell equator, w – the tape width, r_0 – the pole opening radius, A_i – coefficients of a polynomial function approximating the thickness distribution near the pole opening.

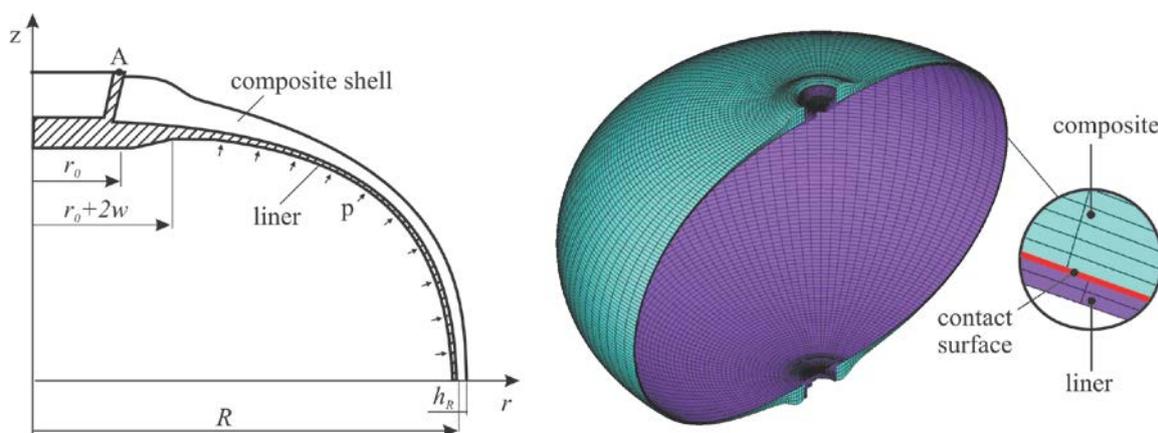


Figure 3. Finite element model of a COPV.

The liner is treated as an elasto-plastic material with the isotropic hardening assuming the Prandtl–Reuss equations and the Mises yield criterion are valid. Every finite element of the composite shell is a

laminate, each ply of which exhibits elastic orthotropic (transversely isotropic) properties. The effective stiffness characteristics of a particular element are calculated according to the winding pattern and number of plies enclosed in it. The evolution of damage on the microscale is used to obtain the properties of the laminate (mesolevel) as a function of its stress-strain-damaged state through the homogenization procedure.

3. Results and discussion

The computational models described above has been employed to simulate a pneumatic burst test performed on a 200 liter COPV, which was made of a carbon/epoxy tape wound over a thin (1 mm) titanium alloy liner. Only one half of the COPV structure is modelled. The following geometric and material properties were used in calculations: radius at equator $R = 416$ mm, $r_0 = 35$ mm, $w = 24$ mm, $h_R = 3.5$ mm; titanium alloy modulus of elasticity $E = 110$ GPa, yield stress $\sigma_{02} = 360$ MPa, ultimate strength $\sigma_{ul} = 450$ MPa; fiber volume fraction $V_f = 0.62$, fiber modulus $E_f = 300$ GPa, Poisson's ratio $\nu_f = 0.16$, matrix modulus $E_m = 3$ GPa, $\nu_m = 0.33$; the experimentally obtained parameters for the equation (2) [5]: $\sigma_{0f} = 3.9$ GPa, $m_f = 6.3$, $\sigma_{0m} = 92$ MPa, $m_f = 6.2$, $L_0 = 8$ mm, $L_e = 2$ mm; the parameters for the equation (4): $A_0 = -27.1$, $A_1 = 2.4$, $A_2 = -0.038$, $A_3 = 0.00018$.

No initial damage in the composite after the filament winding process is assumed. Following the history of processes and loading, the DT was updated and maintained in a state corresponding to its physical counterpart. The processes applied to a typical COPV during production, maintenance and testing phases, which can result in change of the vessel shape and/or properties of constituent materials, as well as the means of data acquisition are presented in table 1.

Table 1. Processes applied to COPV and the influenced parameters.

Processes	COPV parameters	Means of data acquisition
Liner welding, filament winding, curing, autofrettage, proof test, cyclic test, leak test, thermal cycling, climatic test, transportation, launch	Winding angle, composite thickness distribution, fiber volume fraction, strength and stiffness properties of composite, shape, elasto-plastic properties of liner material, composite damage state, defectiveness	Visual control, penetrant testing, ultrasonic inspection coupon tests, electron microscopy, x-ray spectroscopy, acoustic emission, laser profilometry, 3d laser scanning, infrared thermography, strain-gauging

The burst test of COPV was carried out by stepwise increasing the internal pressure ($\Delta P = 1-3$ MPa) until the moment of failure. During the test, measurements of displacement along the vessel axes were carried out using optoelectronic incremental displacement sensors. Parameters of the stress-strain state of the composite were controlled with tenoresistors located on the outer surface of the power shell. The integrity of the COPV was monitored with six acoustic emission sensors mounted at equal-angle locations on the equator. Before the burst test, the vessel has passed all operations required by the technical specifications. In total, the COPV has undergone about fifty pressurizing/depressurizing cycles at pressures ranging from 1.0 up to 1.4 times of the maximum expected operating pressure.

The results of the burst test simulation shown as the axial displacement of the polar boss (point A in the figure 3) are presented in the figure 4. The predicted burst pressure and deformation properties of the COPV are in good agreement with the experimental data. The final fracture of the COPV occurred at pressure P_f of 31.6 MPa which is quite close to the predicted value of 29.6 MPa. The fracture was initiated in plane of maximum radius as confirmed by a post-fracture analysis. It should be noted the features of mechanical behavior of the vessel under increasing pressure. At relatively low pressures, the COPV is deformed mainly in the direction of the axis of rotation (the z-axis in figure 3), striving to the spherical shape. On the final stages of loading, the COPV expands in the equator plane, while the elongation along the rotation axis decreases. As seen in figure 4, the calculation of the burst pressure performed without taking into account the load history and the corresponding damage state gives a higher value of the ultimate pressure than that obtained in the experiment. Moreover, in this

case the simulation predicts much stiffer response of the COPV to the applied pressure as a previous deterioration of the composite properties is not considered.

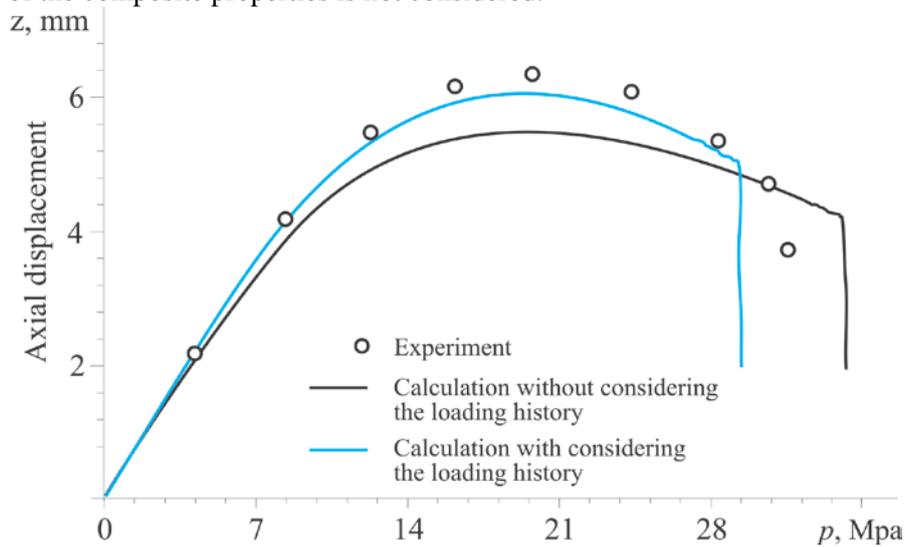


Figure 4. Displacement of the COPV along the rotation axis.

The evolution of damage in the RVE during the burst test is shown in figure 5. In the graphs, the number of failed elements at zero pressure is equal to the amount accumulated in simulations of all previous processes experienced by the COPV (autofrettage, proof test etc). Note that the bulk of the failed elements occurs at pressure levels close to the burst pressure, therefore a sharp degradation of the composite properties is observed within a relatively short loading interval.

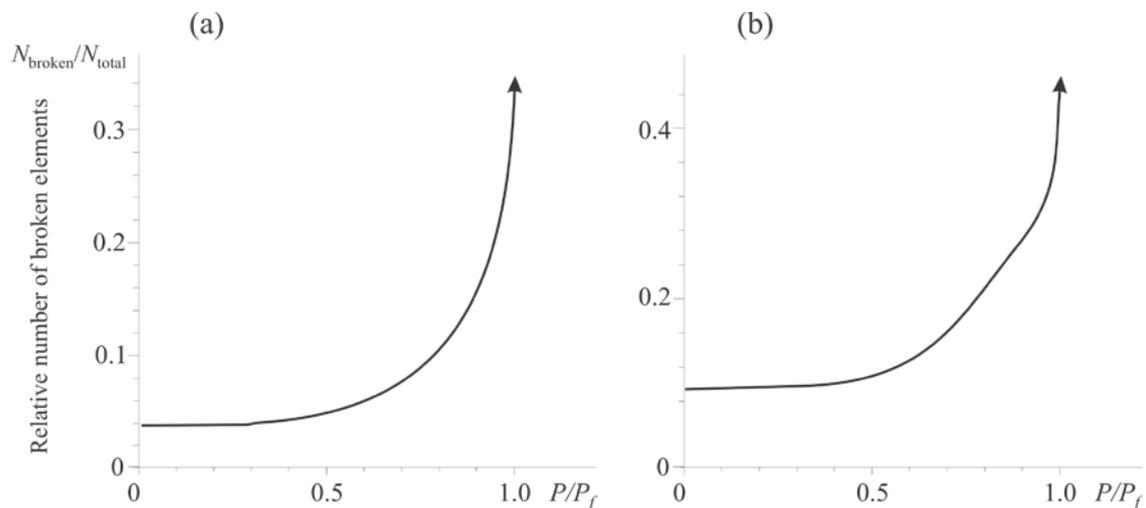


Figure 5. Damage evolution in the RVE: (a) fiber elements; (b) matrix elements.

From our point of view, there are two main reasons to employ the digital twin concept for COPVs used in aerospace applications. First, the use of DT would substitute or supplement costly physical prototyping, testing and inspections with virtual simulation especially when a direct access to the vessel is difficult or not possible such as during performing the burst test or operation phase, which lasts more than 10 years. Second, the COPV performance can be accurately simulated and predicted as DT integrates the historical and real-time data in a single environment, thus allowing to optimize the characteristics of COPV and helps in decision making. To be most effective, the concept of a digital twin should cover the entire COPV life-cycle or most important successive phases at least.

The DT model presented in this paper we consider as the first step in constructing a fully functioning digital analogue for COPVs. At present, the developed DT lacks some essential components. First of all, this concerns a continuous monitoring of the vessel performance and collecting the characteristics of its technical conditions in real-time. To do this, it is necessary to install sensors that monitor the parameter of the stress state of the liner and composite at the manufacturing phase. Currently, most of the data required for simulation of the COPV behavior we receive offline by means of coupon testing, studying past experience or post-fracture analysis. Also, technologies that are capable to process heterogeneous data from different sources and convert them into a format appropriate for the DT models should be developed. The elimination of these shortcomings is the subject of further research.

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