Burst pressure estimations of a composite pressure vessel accounting for the composite shell imperfections

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Abstract. The paper presents the numerical evaluation of the effect of possible imperfections on the burst strength of composite pressure vessel made by filament winding over a thin metallic liner. The damages and defects distributed over the composite volume that lead to deterioration of the mechanical properties or increase their scattering are considered. The burst pressure is predicted with finite element analysis by using progressive damage approach. The obtained results show a strong influence of initial imperfection in the composite laminate on the vessel strength. The performed calculations show that the failure of the weakest layers does not lead to loss of the load-carrying capacity of the composite shell and the structure burst occurs as results of the subsequent damage evolution process. Such phenomenon happens regardless of the level of initial imperfection.

1. Introduction
In recent years different types of composite pressure vessels made by filament winding (composite overwrapped pressure vessels - COPVs) have found a wide use in aviation, aerospace, chemical and automotive industries. They provide significant advantages over all-metal analogues due to outstanding properties of fibrous composites such as a high specific strength and stiffness, fatigue endurance and design tailoring [1]. Despite vast theoretical and experimental studies aimed at developing reliable and efficient composite pressure vessels, some issues related to thorough understanding of their mechanical behaviour are still open. In particular, very few studies have been conducted to investigate the impact of imperfections associated with production process on the failure pressure [2].

In engineering practice, the calculation of the ultimate loads for composite structures is often based on the first-ply failure theory [3-5] which implies that a laminated composite loses integrity when at least one of its layers is failed or cracked. Analytical and numerical methods based on this approach assume that the burst pressure for COPVs associated with the rupture of the composite shell depends only on the design parameters and criteria employed. The maximum operating pressure is then determined from the calculated burst pressure with a corresponding safety factor varied from 1.5 to 3 [1, 6].

Such interpretation of the limit state generally leads to very conservative estimates for the load-carrying capacity of COPVs. It is well known that the ultimate failure of laminated materials occurs as a result of a gradual, multi-stage process covering various scale levels and the fracture of the weakest layer is just its initiation [7-9]. In addition, by using the first-ply failure assumption it is not possible to directly account for the effect of material imperfections or defects on the COPV strength. Their probable occurrence, as well as other uncertainties related to technological and operational processes,
such as variability in geometric, mechanical and strength parameters or the load levels are taken into account by setting the increased value of the safety factor.

Imperfections in this study are understood as defects, damages or other deviations in the structure of composite shell from the design or technical documentation that lead to deterioration of the mechanical properties or increase their variability. A variety of imperfection types in the shell can be divided into two categories - technological, formed during the manufacturing process and operational, induced at the stages of installation, transportation, or testing. Depending on the size, one can also distinguish between micro, meso- and macro level imperfections. Microdamages such as single fiber breaks, local interface fracture etc. do not affect the average mechanical properties of the composite, but may contribute to their scattering. This type of imperfections, as well as defects at the macro level, the size of which is comparable to the shell thickness (large clusters of broken fibers, extended interlayer delamination, cracks), are not considered in this study. The greatest interest for us is defects distributed over the composite volume and whose dimensions are comparable with the thickness of the laminate layer. In filament wound composite shell they include but not limited to tow breaks, variation of fiber volume fraction and winding angle, porosity and fiber undulation (figure 1).

![Figure 1. Imperfections (indicated by arrows) of the composite shell fabricated by filament winding: (a) voids; (b) fiber undulation.](image)

The study aims to numerically estimate the influence of possible imperfections in the composite shell on the burst strength of a high pressure vessel made of carbon fiber/epoxy composite wound over a thin liner. The burst pressure is predicted with finite element analysis by using progressive damage modelling of the COPV with an initially damaged composite laminate.

2. Progressive damage model

The vessel under study is designed to hold 200 l of gas and operate at pressure of 10 MPa. The ellipsoid-like composite shells of revolution is formed by continuous winding of carbon-fiber/epoxy tows over a titanium alloy liner along the geodesic trajectories. The titanium alloy is considered to be isotropic and elastic-perfectly plastic material obeying the von-Mises criterion while the tow of carbon fibre/epoxy composite is linear elastic and transversely isotropic (1 – is the fiber direction).

The following geometrical parameters of the COPV and mechanical properties are used in calculations: radius at equator (the major radius) \( R = 416 \) mm; polar opening radius \( r_0 = 35 \) mm; composite and liner thickness at equator, respectively, \( t_R = 2 \) mm and \( t_l = 1.5 \) mm; titanium alloy – \( E=110 \) GPa, \( \nu = 0.32, \sigma_y =340 \) MPa; composite elastic properties – \( E_1 = 165 \) GPa, \( E_2 = E_3 =7.7 \) GPa, \( G_{12} =G_{13} =3.8 \) GPa, \( G_{23} = 3.4 \) GPa, \( \nu_{12} =\nu_{13} =0.26, \nu_{23} =0.45 \).

For an isotensoid shell with elastic-perfectly plastic liner the burst pressure \( p_f \) can be obtained analytically as shown by Vasiliev [1] using the netting model of composite

\[
p_f = \frac{2 \left( X_l t_R \cos^2 \varphi_R + \sigma_y t_l \right)}{R}\]

(1)
The value of 20.1 MPa calculated with equation (1), which is actually based on the first-ply failure assumption and the maximum stress criterion, will be compared with the burst pressure estimates obtained using the progressive damage approach.

The finite element model used in progressive damage analysis is built using custom procedures coded with ANSYS Parametric Design Language [10]. Taking advantage of axial symmetry, only a cyclically repeated 45° segment of the COPV structure is modelled. Eight-node layered shell and twenty-node structural solid elements are employed to represent the composite laminate and the liner, respectively. A similar numerical model was used by Burov and Lepikhin [11].

To simulate the COPV failure as a result of the damage evolution in the composite shell with initial imperfections three interrelated tasks are to be solved: 1) the transition of material from intact to damaged state (damage initiation) depending on a failure mode; 2) the law of damage accumulation once the damage initiation has occurred; 3) the relationship between the damage level and degradation of mechanical properties.

The damage initiation of individual laminate layers is determined by Hashin criteria [12] associated with a certain mode of failure (Table 1). In the Table 1, $X_t$, $Y_t$, $X_c$, $Y_c$ are the strength of composite lamina along and across fiber direction in tension and compression, respectively, $S$ is the shear strength.

### Table 1. Hashin failure criteria

| Failure mode          | Failure criterion                                                                 |
|-----------------------|-----------------------------------------------------------------------------------|
| Fiber in tension      | $\sigma_{11} > 0$                                                                 |
|                       | $\left( \frac{\sigma_{11}}{X_t} \right)^2 + \frac{\sigma_{12}^2 + \sigma_{13}^2}{S^2} \geq 1$ |
| Fiber in compression  | $\sigma_{11} < 0$                                                                 |
|                       | $\left( \frac{\sigma_{11}}{X_c} \right)^2 \geq 1$                               |
| Matrix in tension     | $\sigma_{22} + \sigma_{33} > 0$                                                  |
|                       | $\left( \frac{\sigma_{22} + \sigma_{33}}{Y_t} \right)^2 + \frac{\sigma_{12}^2 + \sigma_{13}^2}{S^2} + \frac{\sigma_{23}^2 - \sigma_{22}\sigma_{33}}{S^2} \geq 1$ |
| Matrix in compression | $\sigma_{22} + \sigma_{33} < 0$                                                  |
|                       | $\left( \frac{Y_c}{2S} \right)^2 - 1 \left( \frac{\sigma_{22} + \sigma_{33}}{Y_c} \right) + \frac{(\sigma_{22} + \sigma_{33})^2}{4S^2} + \frac{(\sigma_{23} - \sigma_{22}\sigma_{33})}{S^2} + \frac{(\sigma_{12}^2 + \sigma_{13}^2)}{S^2} \geq 1$ |

When the failure criterion is met, the material stiffness gradually decreases, following the measure of damage. The used linearly damage evolution law is based on fracture energy dissipation:

$$G_{ci} = \int_0^{\sigma_{eq}} \sigma_{eq} \sigma_{eq} du_{eq} = \frac{1}{2} \sigma_{eq}^2 u_{eq},$$

where $G_{ci} = G_{cf}$, $G_{cm}$ – critical energy release rate for fiber and matrix failure, $\sigma_{eq}$, $u_{eq}$ are equivalent stress and displacement, $\sigma_{eq}$, $u_{eq}$ – their critical values.

The damage parameter $d$ for each mode of fracture is calculated via the equivalent displacements:

$$d = 1 - \frac{\sigma_{eq}^0 (u_{eq}^c - u_{eq}^0)}{u_{eq}^c (u_{eq}^c - u_{eq}^0)}; \quad u_{eq}^0 \leq u_{eq} \leq u_{eq}^c,$$

where $u_{eq}^0$ is the equivalent displacement at damage onset.
For a damaged layer the relation between stress and strain takes the form of $\sigma = [D]_d \cdot [\varepsilon]$. For a plane stress state, the damaged stiffness matrix $[D]_d$ can be expressed via the elastic engineering constants:

$$
[D]_d = \frac{1}{\Delta} \begin{bmatrix}
(1 - d_f)E_1 & (1 - d_f)(1 - d_m)\nu_{21}E_1 & 0 \\
(1 - d_f)(1 - d_m)\nu_{12}E_2 & (1 - d_m)E_2 & 0 \\
0 & 0 & \Delta(1 - d_s)G_{12}
\end{bmatrix},
$$

(4)

where $\Delta = 1 - (1 - d_f)(1 - d_m)\nu_{21}^2$; $d_f$, $d_m$, $d_s = 1 - (1 - d_f)(1 - d_m)$ – damage parameters corresponding to fiber, matrix and shear failure.

The damage parameters range from 0 for the intact material to 1 for the completely damaged one.

The initial imperfection in the composite shell is formed by assigning in finite elements a “defective” layer (or layers) with the damage parameters of 0.2 and corresponding stiffness matrix as it is shown on the figure 1. The location of elements and defective layers within the composite shell are randomly selected. The initial imperfection level is defined as the ratio of conditionally damaged layers to the total number of layers in the composite shell. Given that the simulation of progressive damage process is sensitive to the initial distribution of imperfections in the composite shell, calculations for each level are performed 4 times with a different array of random numbers.

The progressive damage analysis procedure includes: 1) determining the stress-strain state; 2) verifying the failure criteria are met; 3) recalculating the elastic properties of the damaged layers; 4) increasing the pressure if the structure retains the bearing capacity. A pressure at which the number of failed layers is spontaneously increased is considered to be the burst pressure. Usually, it manifests in the termination of solution run.

3. Progressive damage analysis of COPV with initial imperfections

In order to assess the effect of imperfections on the burst pressure, the progressive damage analysis is first carried out assuming no predefined damages. The burst pressure for the initially intact COPV amounts to 22.3 MPa. Figure 2 shows the damage distribution in the composite shell for different load steps. There is an evident change of the dominant type of failure as the internal pressure increases. The nature of initiation and accumulation of damages is determined by anisotropy of elastic and strength
properties of unidirectional composite. Due to the lower strength across the fiber direction, damages first occur by the mechanism of matrix cracking under tensile $\sigma_{22}$ stress as shown in figure 2 (a). Starting with upper layers in the region near the polar opening, such damages develop with increasing internal pressure towards the equator (figure 2 (b)).

![Figure 3](image)

Figure 3. Progressive damage in the composite shell with increasing pressure:
(a) $p/p_f = 0.82$; (b) $p/p_f = 0.89$; (c) $p/p_f = 0.99$.

The occurrence of damaged zones leads to the stress redistribution and their concentration in the neighboring elements. This process results in the initiation of fiber failures, which upon accumulation lead to a significant stiffness degradation of the shell, a sharp growth of damages and ultimately to a complete loss of the load-bearing capacity of COPV (figure 2 (c)).

The calculated dependence of the burst pressure on the initial imperfection is presented in figure 3. The pressure values are normalized to the burst pressure computed for the intact COPV. The results of calculation show that the progressive damage scenarios differ depending on the level of initial imperfection. At a low level, the mechanisms and the failure mode sequence are similar to those of the intact composite shell. Accordingly, the burst pressure values accounting for the initial imperfection in the range of 0-0.08 decrease quite slowly.
As the proportion of initially damaged layers increases, there is a well-pronounced change in the dependence of the burst strength on the level of imperfection. This happens as a result of the emergence of a new mechanism of failure – the formation of clusters of failed elements near the initially damaged ones already at relatively early stages of loading. As result, the burst pressure drops 20% at the imperfection level of 0.15. The failure mechanism for COPV with such a high and concentrated initial imperfection corresponds to the limit state of composite structures with crack-like defects.

4. Conclusions
The paper presents the numerical evaluation of the influence of imperfections on the burst strength of composite pressure vessel. The burst pressure of the COPV with different level of initially damaged composite layers was predicted by using progressive damage approach. The dependence of the burst pressure on the initial imperfection has two characteristic ranges, each of which corresponds to the main mechanism of failure.

The performed calculations confirm the experimental observations that the failure of the weakest layers does not lead to loss of the load-carrying capacity of the composite shell and the burst of COPV occurs as results of the subsequent progressive damage process. This phenomenon happens regardless of the level of initial imperfection, which, however, strongly influences the strength of COPV.

5. References
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