The sensitivity of the burst performance of impact damaged pressure vessels to material strength properties

K Lasn, N P Vedvik and A T Echtermeyer

Norwegian University of Science and Technology (NTNU), Composites and Polymers, Department of Engineering Design and Materials, Richard Birkelandsvæi 2B, N-7491 Trondheim, Norway

E-mail: kaspar.lasn@ntnu.no

Abstract. This numerical study is carried out to improve the understanding of short-term residual strength of impacted composite pressure vessels. The relationship between the impact, created damage and residual strength is predicted by finite element (FE) analysis. The burst predictions depend largely on the strength properties used in the material models. However, it is typically not possible to measure all laminate properties on filament wound structures. Reasonable testing efforts are concentrated on critical properties, while obtaining other less sensitive parameters from e.g. literature. A parametric FE model is hereby employed to identify the critical strength properties, focusing on the cylindrical section of the pressure vessel. The model simulates an impactor strike on an empty vessel, which is subsequently pressurized until burst. Monte Carlo Simulations (MCS) are employed to investigate the correlations between strength related material parameters and the burst pressure. The simulations indicate the fracture toughness of the composite, hoop layer tensile strength and the yield stress of the PE liner as the most influential parameters for current vessel and impact configurations. In addition, the conservative variation in strength parameters is shown to have a rather moderate effect (COV ca. 7 %) on residual burst pressures.

1. Introduction

Composite overwrap pressure vessels (COPV) are often used in cars, buses and bulk transport vehicles. They can hold higher pressures and weigh less than steel pressure vessels. COPVs are today mainly used for natural gas storage and transportation. Additional prospective applications include the upcoming hydrogen economy where gaseous hydrogen needs to be stored [1] at internal pressures greater than 700 bars for economic feasibility.

The cylinders used for high pressure applications, and requiring long fatigue life, typically utilize carbon fibre composite overwrap. Liners of Type IV cylinders are made from polymers such as HDPE. They are resistant to hydrogen exposure and show good fatigue performance. The pressure vessels are often designed to fail in the cylindrical section. In the following, only this cylindrical section of the pressure vessel is investigated in detail.

The cylinders are often protected from mechanical interactions with the environment. However, accidental impacts are still of concern. Large impact damage, e.g. from a serious car accident or a rollover, is visually obvious. Vessels should thereafter be thoroughly inspected or taken out of service. Low-energy impacts may occur during handling and transport. Such events are: falling of the vessel, dropping of tools and impacts from forklifts. The consequences of low-energy and low-velocity events to residual performance are often unclear. To study the effect of flaws or damage, composite pressure
vessels can be experimentally burst tested [2]. Experimental studies however have limitations on the number of vessel and flaw configurations which can be studied. A numerical model can be applied to many different scenarios, but the models are complicated and confidence in the results needs to be established.

Numerical modelling by Finite Element Analysis is used here to study the effect from a given impact event on short-term burst strength. The model calculates first the damage created by the impact and subsequently its influence on the burst behavior. The FE model requires many material properties as input parameters which are not easy to measure. Material properties from flat laminates are not necessarily transferable to filament wound laminates, since fibre architecture and compaction is different. Obtaining a full set of material properties is more demanding for cylindrical specimens than for flat composites due to the lack of standardized methods and the geometry of the curved shapes incompatible with traditional tensile-testing/uniaxial test apparatuses. Consequently, it is desirable to focus testing efforts on a few critical material properties, obtaining other, less relevant parameters from flat laminates and literature.

This work studies the effect from 30 strength related parameters on the predicted burst pressure of the pressure vessel. This helps to determine strength properties which are most influential/critical to the short-term burst behavior.

2. Model description
The 3D FE model is developed in Abaqus 6.14-1, employing the explicit solver. Explicit is typically used for high speed dynamic problems such as impact, material degradation and failure. The description of the numerical model is divided into two sections: general description of the FE model, and discussion of material properties and other input parameters.

2.1. The FE model
The pressure vessel is modelled as an axisymmetric cylinder, attached to end domes, as illustrated in Figure 1. The cylinder consists of a relatively thick PE liner and a thin carbon fibre composite overwrap (Figure 2). The combination of thick PE liner and thin laminate is untypical for commercial pressure vessels. It was motivated by a specific design subjected to experimental studies in our laboratory. The impact and the failure initiation occurs in the middle of the cylindrical part.

![Figure 1. The geometry of the pressure vessel.](image1)

![Figure 2. Cross section of the cylinder.](image2)

The domes are simplified as two cylinders (i.e. disks) made of linearly elastic isotropic material. The pressure vessel is fixed at the external flat surfaces of the domes. During impact, all displacements of both surfaces are fixed. During pressurizing, axial displacements remain restrained for one end surface, while unconstrained for the opposite surface. The impactor tip is hemispherical and modeled as rigid, positioned to impact the midsection of the tube horizontally. It is given an initial velocity and inertia properties. The impactor is affected by artificial gravity and its vertical position is therefore slightly
offset, so the first contact occurs normal to the cylinder surface. Residual vibrations in the vessel are damped after the impact event. During subsequent pressurization, the pressure amplitude is increased according to Abaqus' in-built smooth step definition until $P_{\text{max}} = 300$ bar in course of 0.1 s.

The cylinder of the pressure vessel consists of concentric layers of liner, composite, and cohesive interfaces, modelled with solid and continuum shell elements. The PE liner is isotropic, with elastic-plastic material behavior. The composite layers have orthotropic material symmetry. The stress based Hashin’s failure criterion is used for the initiation of intralaminar fibre and matrix damage. Damage evolution is controlled by fracture energies and stabilized by viscosity coefficients. Cohesive layers are implemented between individual layers of composite and the liner. The damage in the cohesive elements is initiated by a quadratic stress criterion and the energy based Benzegagh-Kenane (BK) formulation is used as the fracture criterion. The cylinder layup [PE / $90^\circ$ / $+15^\circ$ / $-15^\circ$ / $90^\circ$] is generic, chosen to enforce the failure in hoop layers. The helical layers would be wound as two $\pm 15^\circ$ pairs in practice — the current layup is a simplified model version.

The connection between individual layers of the cylinder and from the cylinder to the domes is implemented by tie constraints. Contact interactions are prescribed for surfaces in possible contact during the analysis; between the tube elements and the impactor and neighboring composite plies. A hard contact is assumed in the normal direction, and a frictional penalty in the tangential direction.

The base element length for the FE model (see Figure 3) was chosen as $\delta = 1.7$ mm for the composite layers and the impactor, following a mesh convergence study. The tube elements not facing the impactor (backside of the tube) have length $5\delta$ in the circumferential direction. The liner is fairly thick and has three elements in the thickness direction, while the other cylindrical layers have a single element. The solid elements C3D8R in the domes have their linear dimensions set to approx. $4\delta$.

![Figure 3. The base mesh length $\delta$, element layout, and element types in the cylinder.](image)

2.2. Material properties
The material properties describe a typical filament wound carbon fibre composite. Specific values are based on the previous work in the Composite Group in NTNU [3-5], as well as information from manufacturers and literature [6-8]. Since this is a numerical study, the chosen material properties are generic. The properties of hoop and helical composite layers are assumed to differ due to different fibre volume fraction $V_f$, originating from the filament winding process. Helical layers have a lower $V_f$ and therefore larger thickness and lower fibre dominated strengths. Matrix dominated strengths are assumed to be the same for helical and hoop layers.

The material parameters are divided into constant properties and randomly sampled strength related properties. All elastic properties were taken as constant in this study to focus on strength. The sensitivity study for the strength properties is conducted by Monte Carlo Simulations (MCS). Random sampling creates a number of material datasets, with varying strength properties, for FE input. This enables to study the sensitivity of the burst pressure to changes in each individual strength parameter value. A large number of virtual experiments may be simulated to study the behavior of probabilistically sampled material parameters, e.g. as in [9]. Recently, Cai et al. [10] used MCS to study the critical buckling pressures for pressure vessels under external hydrostatic pressure. A similar approach is adopted here, even though the number of simulations has been relatively small so far, due to the high computing effort for each simulation. More simulations are in progress.
Table 1 describes the parameters of the model and materials, which are assumed constant in the sampling and the following calculations. These are the geometry, FE mesh size, pressure loading, mass densities, elastic constants and the friction properties in the model. The mass, velocity and shape of the impactor also remains constant in the calculations. It is well known that stiffness and strength of the composite become interconnected during the progressive failure of the material. Hereby, the initial stiffness of the undamaged material is kept constant. Progressive degradation of stiffness can still vary in separate simulations, depending on the sampled strength parameters.

Table 1. The model and material properties with constant values in Monte Carlo Simulations (MCS).

| Parameter group       | Specifics                                      | Notation | Generic values |
|-----------------------|-----------------------------------------------|----------|----------------|
| General               | Layup                                         | [ PE / 90° / +15° / -15° / 90° ]          | 300 [bar], 10⁻¹ [s] |
|                       | Maximum pressure and pressurization time with smooth step | P<sub>max</sub>, t<sub>Pmax</sub> | |
|                       | Base mesh size (composite layers)              | δ        | 1.7 [mm] |
|                       | Friction coeff.                               | μ        | 0.3 [-] |
|                       | Radius of the inner surface of the PE liner    | R₀       | 57.3 [mm] |
|                       | Length of the tube                            | L        | 0.3 [m] |
| Dome                  | Width                                         | w        | 50 [mm] |
|                       | Isotropic properties                          | ρ, E, ν  | 1200 [kg/m³], 100 [GPa], 0.3 [-] |
| PE liner              | Thickness                                      | ρ<sub>PE</sub> | 12.7 [mm] |
|                       | Isotropic properties                          | ρ, E, ν  | 960 [kg/m³], 1.1 [GPa], 0.45 [-] |
| Composite hoop layers | Thickness                                      | t<sub>hoop</sub> | 0.25 [mm] |
|                       | Density                                       | ρ<sub>hoop</sub> | 1550 [kg/m³] |
|                       | Elastic constants                             | E<sub>1</sub>, E<sub>2</sub> = E<sub>3</sub> | 130 [GPa], 11.0 [GPa] |
|                       |                                             | G<sub>12</sub> = G<sub>13</sub>, G<sub>23</sub> | 4.7 [GPa], 4.2 [GPa] |
|                       |                                             | ν<sub>12</sub> = ν<sub>13</sub>, ν<sub>23</sub> | 0.30 [-], 0.50 [-] |
| Composite helical layers | Thickness (half of the helical pair)          | t<sub>helical</sub> | 0.40 [mm] |
|                       | Density                                       | ρ<sub>hel</sub> | 1400 [kg/m³] |
|                       | Elastic constants                             | E<sub>1</sub>, E<sub>2</sub> = E<sub>3</sub> | 80 [GPa], 7.0 [GPa] |
|                       |                                             | G<sub>12</sub> = G<sub>13</sub>, G<sub>23</sub> | 3.0 [GPa], 2.7 [GPa] |
|                       |                                             | ν<sub>12</sub> = ν<sub>13</sub>, ν<sub>23</sub> | 0.30 [-], 0.50 [-] |
| Composite (hoop and helical) | Shear contribution coeff. in the Hashin criterion | α    | 1 [-] |
| Cohesive layers       | Density                                       | ρ<sub>COH</sub> | 1200 [kg/m³] |
|                       | Stiffness                                     | E, G<sub>1</sub> = G<sub>2</sub> | 3.0 [GPa], 1.1 [GPa] |
|                       | BK power parameter                            | η        | 1.4 [-] |
| Impactor              | Mass                                          | m        | 1.5 [kg] |
|                       | Velocity                                      | v        | 10 [m/s] |
|                       | Radius of the spherical nose                  | R<sub>imp</sub> | 15 [mm] |

Table 2 describes the strength related properties whose sensitivity is investigated by MCS. Each of the parameters in Table 2 is sampled by a normal distribution, defined by the mean and the coefficient of variation (COV). Although the COVs define sufficiently narrow parameter ranges, a small but necessary sampling bias was introduced to avoid the creation of non-physical negative parameter values. Whenever a negative value is sampled, the specific parameter is re-sampled to arrive to a set of all-positive values. The variation of properties in Table 2 is considered as the combined effect of both the lack of experimental data and the scatter in frequently encountered experimental values. Thus it is not aimed to distinguish between various sources and mechanisms of variability.
Table 2. Material properties with values sampled according to normal distributions in Monte Carlo Simulations (MCS).

| Parameter group | Specifics | Notation | Mean value in MCS | COV in MCS |
|-----------------|-----------|----------|-------------------|------------|
| PE liner | Elastic-plastic behaviour | True yield stress | 23.5 ; 161 [MPa] | 10 % |
|          |           | Plastic strain | 0 ; 1.93 [-] | 10 % |
| Composite hoop | Strengths | $X_1^T, X_1^C$ | 2700 [MPa], 1400 [MPa] | 5 %, 10 % |
|          |           | $X_2^T, X_2^C$ | 80 [MPa], 180 [MPa] | 20 % |
|          |           | $X_{12} = X_{13}, X_{23}$ | 100 [MPa], 80 [MPa] | 20 % |
| Composite helical | Strengths | $X_1^T, X_1^C$ | 1700 [MPa], 800 [MPa] | 5 %, 10 % |
|          |           | $X_2^T, X_2^C$ | 80 [MPa], 180 [MPa] | 20 % |
|          |           | $X_{12} = X_{13}, X_{23}$ | 100 [MPa], 80 [MPa] | 20 % |
| Composite all (hoop and helical) | Fracture toughness | $G_{tt}, G_{tc}$ | 150 [N/mm], 75 [N/mm] | 30 % |
|          | Viscosity, relax. time | $\eta_{ft}, \eta_{fc}$ | 0.83 [N/mm], 0.83 [N/mm] | 30 % |
|          | Constitutive thickness | $\eta_{inf}, \eta_{inf}$ | $10^{-8}$ [s], $10^{-8}$ [s] | 20 % * |
| Cohesive layers | Strengths | $\tau_0, \tau_0, \tau$ | 50 [MPa], 50 [MPa], 50 [MPa] | 20 % |
|          | Fracture toughness | $G_{lc}, G_{lfc} = G_{lc}$ | 0.83 [N/mm], 1.8 [N/mm] | 30 % |

* The exponent $x$ in $10^{-x}$ is sampled.

3. Results and discussion

3.1. General model behaviour

The behavior of 50 virtual specimens was simulated during the Monte Carlo study. These are specimens with constant parameters from Table 1 and randomly sampled parameters as described in Table 2. There are small differences in damage created by the impact and the sequence of events leading to failure in the individual simulations. However, the following characteristic behavior was confirmed from observing individual results from ca. half of the specimens.

At impact (Figure 4), three types of damage are created in the composite: matrix cracking (and fibre/matrix debonding), delamination and fibre failure. In addition, the thick PE liner yields and obtains a dent from the impact. Delaminations occur in three interfaces except between the liner and the composite, see Figure 5. The sizes and shapes of delaminations vary somewhat. The fibre failures occur in the external hoop layer, typically running as a one-element wide crack in the horizontal (axial) direction, as shown in Figure 6. There is at least one case where the fibre failure from the impact is asymmetrical, only on one side. Also, in multiple cases (not always), was a vertical crack of fibre failures created in both helical 15° layers. The internal hoop layer did not acquire fibre failures from the impact. Figures 4-6 describe the impact event for the reference case, with mean values as input parameters.

As the vessel is pressurized, there is very little to no material damage up to a certain point (hereby denoted by ‘DI’ as damage initiation). After this stage, damage accumulation increases — localized small cohesive failures, isolated fibre failures and some yielding of PE. As the pressure becomes critical, the external and internal hoop layers fail simultaneously by forming a long axial crack (see Figure 7). This event is distinct, and both, the kinetic energy and energy dissipated by material damage increase in approximately a step-like manner. This final failure is clearly recognizable by large scale fibre rupture in hoop layers and it is hereby denoted by ‘B’ for burst.

The behavior of the model is studied in terms of damage dissipation energy for the whole model (ALLDMD variable in Abaqus) which is accumulated during the pressurizing step. Threshold values of 0.5 J were chosen for damage initiation (‘DI’) and 100 J for burst (‘B’). Figure 8 shows how the internal pressure and the radial displacement of a single point (on the external back-surface of the tube, exactly
opposite to the impactor) are related for all 50 calculated samples. The scatter of burst pressures ‘B’ in Figure 8 has the COV of 7%. This shows that even as the scatter of strength properties was chosen to be large/conservative (Table 2), the scatter in the calculated burst pressure remains moderate. This is important from practical engineering point of view, indicating that the accuracy of each individual material parameter is not so important.

The pressurization begins with a small negative radial displacement because the damping of residual vibrations was conducted by external pressure in the timestep preceding the internal pressure. The influence on the final burst behaviour is considered negligible. The burst pressure can be estimated for the undamaged vessel as $P \approx X_1^T \cdot 2t_{\text{hoop}} / (R_0 + t_{\text{PE}}) = 2700 \cdot 0.5 / 70 = 19.3 \text{ MPa} = 193 \text{ bar}$ (hoop fibre mean $X_1^T = 2700 \text{ MPa}$). This agrees well with the calculated pressure of 190 bar from non-impacted modification of the FE-analysis. The burst pressures in Figure 8 are 160 ± 22 bar (2 standard deviations), thereby ca. 16% below the initial value, which is expected due to the damage.

In addition, Figure 9 shows how the damage dissipation energy develops during the final pressurizing step. In principle, the burst event could be defined by a different numerical value or by e.g. kinetic energy altogether. The choice of burst event being equivalent to $\text{ALLDMD} = 100 \text{ J}$ was made after investigating a range of possible kinetic and damage dissipation energies. The details of this substudy are hereby omitted for brevity.
3.2. Correlations

The correlation between sampled strength variables and burst strengths is evaluated by the coefficient of determination $R^2$ for linear regression. Values for $R^2$ can range from 0 to 1 and a higher value implies better correlation between the input parameter and the obtained burst pressure. This correlation does not provide hard evidence for causation, rather an indication which variables can be suspected of affecting the burst pressure more than others.

In general, the obtained correlation coefficients $R^2$ were fairly weak, as seen from Table 3 where four highest values are given. Figures 10 and 11 show the individual datapoints behind the coefficients which gave the highest $R^2$ values. This data shows considerable scatter. The scatter in data and the consequently low $R^2$ indicate that several material parameters affect the impact (therefore the damage) and the burst pressure simultaneously. None of the material parameters however seem to have a clearly superior effect on the burst pressure in current case.

Table 3. The highest correlation coefficients (sample of 50 specimens).

| Parameter                                      | Notation         | $R^2$ |
|------------------------------------------------|------------------|-------|
| Composite (hoop and helical) fracture toughness (compressive, longitudinal) | $G_{cl}$         | 0.189 |
| Hoop layer tensile strength                    | $X_{t}^T$        | 0.162 |
| Composite (hoop and helical) fracture toughness (tensile, longitudinal) | $G_{tl}$         | 0.141 |
| Yield stress of the PE liner                   | $\sigma_{y,0}$ PE | 0.100 |

Overall, the results in Table 3 are expected. The greatest influence comes from the compressive fracture toughness of the composite. This is due to impact which creates fibre failures on the external surface of the vessel (Figure 6). The effect from the hoop ply tensile strength and composite tensile fracture toughness are caused by the nature of burst: a hoop fibre tensile failure. The yield stress of the PE liner is an influential material parameter due to the configuration of this specific vessel – a thick liner overwrapped with a thin layer of composite.

It is important to note that since a large number of material parameters are investigated, several of which are influential simultaneously, analyses with small sample sizes can give misleading and strange...
correlations. This was experienced with this study for small sample sizes of 10-20. To verify that current outcome remains unchanged, more simulations (up to a sample of 100) are still in progress.

4. Conclusions
The following conclusions were drawn based on this numerical study.

- The most influential material parameters for the current vessel and impact configurations were determined (Table 3) as: longitudinal fracture toughness of the composite (both compressive and tensile), hoop layer tensile strength and yield stress of the PE liner.
- The FE prediction of burst pressure for a non-impacted vessel is consistent with hand calculation. The predicted drop in burst pressure from the impact damage was 16 ± 12 %, based on the variations of all parameters modelled. This variation may be acceptable for most engineering calculations.
- The modelling shows that the COV for calculated burst pressures remains fairly low, ca. 7 %, even for the conservative estimates of scatter in the strength properties. The variation of strength parameters has a rather limited effect on the predicted burst pressure, making the exact knowledge of any individual material parameter not so critical. Rather, a group of influential parameters needs to be known fairly well.
- Monte Carlo studies with small sample sizes can lead to erroneous conclusions. The current study and conclusions are based on a sample of 50 simulations. Still, 50 more configurations will be simulated to verify and confirm this outcome.

Acknowledgements
The research leading to these results has received funding from the European Union’s Seventh Framework Programme (FP7/2007-2013) for the Fuel Cells and Hydrogen Joint Technology Initiative under grant agreement n° 621194, http://www.hypactor.eu/.

The research was also supported in part with computational resources at NTNU provided by NOTUR, http://www.sigma2.no.

References
[1] Echtermeyer A T and Lasn K 2014 Safety Approach for Composite Pressure Vessels for Road Transport of Hydrogen. Part 2: Safety Factors and Test Requirements Int. J. Hydrogen Energ. 39 14142–52
[2] Makinson J and Newhouse N L 2014 Flaw Testing of Fiber Reinforced Composite Pressure Vessels J. Press. Vess-T. ASME 136 041409-1-5
[3] Shchebetov S, Vedvik N P and Echtermeyer A T 2013 Typical Static Ply Properties for Composites (IPM-CP-2012-2001 Rev. 01) NTNU, Trondheim.
[4] Perillo G, Vedvik N P and Echtermeyer A T 2014 Damage Development in Stitch Bonded GFRP Composite Plates under Low Velocity Impact: Experimental and Numerical Results J. Compos. Mater. 1-15
[5] Skaar M W 2015 Modeling and Testing of Impact Damage in Composite Pressure Vessels MSc Thesis at NTNU https://brage.bibsys.no/xmlui/handle/11250/2350300.
[6] Grafil 34-700 carbon fiber. https://www.rockwestcomposites.com/downloads/34-700.pdf.
[7] Hexion - EPIKOTE Resin MGS RIMR 135 and EPIKURE Curing Agent MGS RIMH 134–RIMH 137. https://www.hexion.com/Products/TechnicalDataSheet.aspx?id=8246.
[8] Daniel I M and Ishai O 2006 Engineering Mechanics of Composite Materials (Second Edition). New York: Oxford University Press
[9] Lasn K, Klauson A and Echtermeyer A T 2015 Back-Calculation of Elastic Moduli of a Ply from the Moduli of Cross-Ply Laminates Mech. Compos. Mater. 51 55–68
[10] Cai B, Liu Y, Liu Z, Tian X, Ji R and Zhang Y 2012 Probabilistic Analysis of Composite Pressure Vessel for Subsea Blowout Preventers Eng. Fail. Anal. 19 97–108