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Type approval of composite gas cylinders – Probabilistic analysis of standards' requirements concerning minimum burst pressure

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ABSTRACT

Gas cylinders made from composite materials receive growing popularity in applications where light weight is of advantage. At the same time manufacturers are interested in cutting cost and weight through material reduction for better acceptance of a product, e.g. H_2-vehicles. This requires a better understanding of safety relevant properties.

The safety determination of current standards is mainly based on the minimum burst pressure of a few specimens. Various research projects were conducted aiming at reducing minimum burst pressure requirements without compromising safety. No satisfying results were found. While looking at reliability aspects it could be concluded, that the minimum burst pressure of unused specimens is not a satisfying criterion for safety during service life.

This paper introduces first ideas for a method to determine one aspect of reliability of composite gas cylinders, employing probabilistic analysis of burst pressures of a sample of specimens. This can create potential for saving material cost while granting a higher safety level than the current method. Additionally, degradation over service time can be assessed.

Introduction

Gas cylinders made of continuous fibre reinforced plastics (composites) do have weight advantages over ones made from metal. This makes them suitable for mobile use like breathing apparatus for emergency services, fuel storage for gas powered vehicles or hydrogen transportation in battery vehicles or tube trailers. Weight advantages are most significant when carbon fibre material (CF) is used.

Unfortunately these gas cylinders also suffer from high production costs, particularly if they are made from CF. Also the determination of safety and reliability of composite gas cylinders is more complex than for ones made from metals, which increases the effort during approval process and for manufacturing quality control. The strength properties of composite gas cylinders are known to depend on a larger variety of design and production influences than the properties of cylinders made of metal. Also, composite material degradation is more complex, because of different failure mechanisms, which are mainly dependent on time and temperature.

Acknowledging this, methods for safety determination are becoming more sophisticated for good reasons. The ability to lower material consumption and production cost can justify

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extended efforts in this field. The minimum burst pressure as a safety criterion is criticized for keeping costs unnecessarily high, at least since the completion of the EU-project StorHy [1] in 2008. The principle of safety assessment for type approval is generally the same today. According to current standards, there are varying boundary conditions and required burst pressures, depending on the application.

For this reason it is illustrated in the following how the current specifications according to regulations, codes and standards (RC&S) can be evaluated regarding a required reliability incorporating scatter of burst strength. This assessment results from experience as competent authority and as project partner in EU-projects like StorHy [1], HyCube [2] and HyComp [3]. Employing the methods introduced in this paper, the safety level resulting from current standards as well as a potential reduction of current minimum requirements can be derived. The safety concerning load cycling can be analysed in a very similar manner to the following assessment of safety for a single quasi-static load test. According to [4], the most critical strength criterion (load cycle or static strength) depends on the design of the cylinders: High burst pressure does not guarantee high load cycle strength, particularly for gas cylinders with metal liner and vice-versa. For this reason, always both criteria have to be investigated. This paper refers to the criterion of burst strength, which is considered as primarily valid if a design type reliably withstands more than 50,000 load cycles [5]. The criterion of minimum burst strength is also employed to investigate the safety level resulting from current standards.

The performance chart for the probabilistic assessment of burst test results

To qualify the results of burst tests for an assessment, the test procedure has to be described very precisely. This guarantees the results to be reproducible and not just reflecting fluctuations of the experimental setup. Probabilistic assessments are based on the analysis of scatter. Scatter from fluctuations of the experimental setup would blur such an assessment. Also, there should be a unified system for assessments of such results. This would not only permit a reliability analysis of strength values of specimens from a single test sample, but a system for comparing various samples of one design type or even from different design types.

A sufficiently precise description of a test procedure is established in Ref. [6]. This procedure for a burst test is called "Slow Burst Test" (SBT) and is much more detailed and permits only a much narrower range of parameters than various relevant standards like EN 12245 [7], EN ISO 11119-3 [8] or EN ISO 11439 [9]. As a main difference to regular burst test, the pressure increase rate is selected slow enough for creep effects to have effect on the test results. This represents service loads better than regular burst tests with high pressure increase rates. Regular burst tests show more deviating and unexpected results than slow burst tests due to the time influence on composite strength. This phenomenon has been elaborated in Refs. [4,10] and was supported by micro mechanical analysis in Ref. [11]. All results analysed in this paper are derived from SBTs [6].

A performance chart for the systematic assessment of sample tests has already been used in Refs. [4,5,10]. It is re-introduced in this paper. This diagram consists of an x-axis (abscissa), displaying scatter, and a y-axis (ordinate), representing the mean value and is shown in Fig. 1. This layout is applicable independently of the load case criteria. It visualizes safety limits as lines of constant survival rate (called "iso-asfale") against burst at the maximum developed pressure; in this case for hydrogen at 85 °C.

The mean value of the burst pressure $p_{50\%}$ is that pressure, which half of the gas cylinders endured before rupture. Scatter is based on the pressure level $p_{10\%}$, which is endured by the "strongest 10%" of the gas cylinders and pressure level $p_{90\%}$, which is endured by the "strongest 90%" of the gas cylinders. Mean burst pressure as well as scatter values in this performance chart are normalized to test pressure PH. This normalization enables the use of the diagram and the analysis, to be introduced in this paper, independent of the pressure level.

$$\Omega \equiv \frac{p}{PH} \text{ and } \Omega_{SR=50\%} \equiv \frac{p_{50\%}}{PH} \quad \text{(Eq. 1)}$$

PH is defined in regulations as 150% of nominal working pressure (NWP). NWP expresses the maximum allowable filling at 15 °C settled temperature. In the field of dangerous goods transport (TDG), PH is commonly assumed to represent the highest pressure to be expected during normal service.

The developed pressure at maximum service temperature (MAWP) is usually lower than test pressure PH. MAWP results from accurate filling with a gas to working pressure at 15 °C, then heating up to a defined settled temperature. MAWP as used in Fig. 1 is exclusively suitable to "dedicated services" and represents real service load during filling and storage. This applies specifically to gas cylinders or fuel gas storage systems designed and approved for one particular gas; e. g. hydrogen. In the areas of transport of dangerous goods and on-board storage for CNG-vehicles the relevant temperature for MAWP is 65 °C, while for hydrogen vehicles it is 85 °C as shown in Fig. 1. Throughout this paper, these definitions are used.

In the following, (slow) burst pressures will be assessed. As a description of scatter the relative scatter spread ψ ("rel. Streumaβ") is introduced and defined as:

$$\psi \equiv \frac{p_{10\%}}{PH} - \frac{p_{90\%}}{PH} \text{ and } \psi \equiv \Omega_{10\%} - \Omega_{90\%} \quad \text{(Eq. 2)}$$

This definition of a relative scatter spread ψ can be used in conjunction with any kind of density function. For this reason, its use is more appropriate than the employment of standard deviation s_p. The use of the standard deviation s_p would imply the assumption of a GAUSSian normal distribution (ND).

In this paper, reliability of survival will be discussed as criterion for the safety of gas cylinders. It is often called survival rate (SR; complement to failure rate FR; SR = 1 − FR). Survival rate SR in this connotation means the probability of a gas cylinder to withstand a certain pressure without failure. A survival rate of for example 99% against PH means 1 out of 100 gas cylinders would fail (statistically) when filled to PH. When assessing composite gas cylinders, only extremely high survival rates ($\geq 1-10^{-6}$) are acceptable. In this case, the normal distribution is not always a good match or even a conservative