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Concept of interactive determination of safe service life for composite cylinders by destructive tests parallel to operation

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A R T I C L E   I N F O

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A B S T R A C T

There is evidence that composite materials degrade under static loads. Consequently there is no way to design composite gas cylinders for unlimited service life. Yet this fact is not reflected by design standards for composite receptacles approved for the transport of dangerous goods or for stationary application. Unnecessary cost and weight result from this.

Due to the degradation aspects of composites it is necessary to provide appropriate retesting procedures, which allow rejection of used vessels as is common practice for metallic receptacles. The current procedure of hydraulic tests appears to be an expensive procedure with serious doubts regarding its usefulness for composite cylinders.

Consequently, an efficient method is needed, which allows limiting the life time to its safe maximum. It is thus recommended to combine retesting with the assessment of residual life time. Since relevant non-destructive methods are not yet sufficiently matured and standardized enough, a concept featuring destructive tests on composite cylinders parallel to operation should be considered. An alternative concept introduced here, proposes to substitute the hydraulic testing of 100% of a population by a probabilistic evaluation of destructive tests on samples parallel to operation. Intensified pre-fill inspections should be an additional component of such a concept.

1. Introduction

For the most part, pressure vessels used for the transport of dangerous goods (“pressure receptacles, cylinders”) and for onboard storage of gaseous fuels (“fuel gas storage cylinders”, often spuriously called “tanks”) are currently made of steel. Depending on the region of the world, aluminium is also used to a certain degree. Composite materials for mobile pressure receptacles are not a complete novelty today. They were first approved in the USA and Canada and since the beginning of the 1980s also in Germany. There was, however, some initial uncertainty in handling these materials. Some explanations on relevant development of regulations can be studied in Refs. [1], while hints on weak points of these regulations and potential of improvement are shown in Refs. [2], based on [3].

Good reasons exist both for and against the use of composite vessels. The main argument against their widespread use is cost-related: the material, manufacturing, and testing costs are higher than those of steel cylinders. Nevertheless, the use of this expensive type of cylinder construction is still increasing due to their low weight.

With the advent of composite cylinders, new design and test requirements were established by CEN and ISO. Since a market was established before relevant standards the European industry used e. g. the draft version prEN 12245:1999 [4] before the standard was finalized. They partially accounted for the particularities of the material, yet did not deviate much from preconceptions and experiences derived from metal cylinders. This also holds true for the standards concerning periodic inspections for pressure receptacles and fuel gas storage cylinders. Based on insights gained from literature, experience, and plausibility considerations, fundamental differences can be found with regard to this particular aspect.

As opposed to steel cylinders, inspection intervals of composite pressure receptacles for dangerous goods transport are not regulated directly dependent on the type of gas. Rather they are to be

Acronyms: PH, test pressure equals 150% of nominal working pressure; LC, load cycle to failure; SR, survival rate of the population; $N_{10\%}$, number of LC at a SR of 10%; $N_{90\%}$, number of LC at a SR of 90%; T_N, Streuspanne spread of distribution = $N_{90\%}/N_{10\%}$.

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defined by a competent authority without specific criteria, according to RID/ADR. Internal inspection is mandatory for all composite pressure receptacles as is the case with steel cylinders. Whereas the hydraulic pressure or "proof" test can be replaced with a pneumatic test using an inert gas in combination with acoustic emission testing if the competent authority agrees. During the first years until the mid-1990s, a retest period of 3 years was almost exclusively found in the type approvals. This was in line with German regulations on cylinders. At that time, the same interval of 3 years was also mandatory for fuel gas storage cylinders in vehicles. Today however, the ratio of composite cylinders with inspection intervals of 5 and also 10 years has increased noticeably.

With an ordinary life time of 15 or 20 years and inspection intervals of 5 years (or 10 years, respectively), the majority of composite cylinders are subject to only one or perhaps two inspections during their entire life time – which is a considerable difference compared to the requirements for metal pressure receptacles without limited life. Nevertheless, there are numerous composite cylinders with a "non-limited" life time on European market.

If one wants to evaluate the advantages of the complex hydraulic pressure test common in Europe with respect to safety, the test method in particular and periodic inspection as a whole must be examined. First of all, the question needs to be raised whether the current inspection intervals are suitable for removing pressure receptacles from service reliably and early enough to prevent failure between inspections under normal operating conditions. To guarantee this, one of the following conditions must be met at the time of periodic inspection: Possibly existing damage must be detectable during this periodic inspection. If not detectable, it must not cause critical failure (leakage, rupture) until the next periodic inspection takes place.

In order to evaluate this aspect properly, in particular the development of damage to the laminate needs to be examined closer. For this purpose, the continuous development of a damage resulting from normal operating conditions (internal pressure, temperature, etc.) is designated "degradation" (see Refs. [2,5–7]).

2. Development of damage in composite cylinders

At first it is necessary to discuss the differences between damages to metallic liners and the degradation of composites.

2.1. Damage to metallic liners

According to [8,9], it can be assumed that the life time of composite pressure receptacles with metallic liners is mainly limited by the liner. This fact results from its lower fatigue resistance to cyclic strains as compared to that of e. g. carbon fibres.

In 2003, analytical studies found a mere internal pressure test not leading to additional knowledge on current degradation or safety status. Instead it may cause new or expand safety problems. In 2006, some research was published regarding the growth of cracks in metal liners (which are also used as winding cores) of composite cylinders [10]. Cracks in metal cylinders and liners commonly start at the inner surface of the metal liner and grow in axial and radial direction until reaching the outer surface, which means leakage. Liner cracks tend to grow noticeably more along the inner receptacle surface than going into the depth of the material, compared to cracks in metal cylinders (see Fig. 1). At the same time, plastic deformation on the crack tips is highly restrained. Rupture of the cylinder without prior massive fibre degradation or damage to the laminate is not to be expected. Non-destructive test methods such as ultrasonic examination or acoustic emission testing were investigated, too. NDT-methods were not found to be reliable in detecting an initial development of cracks in the liners of composite cylinders.

Reliable detection of cracks in the metallic liners of composite cylinder during periodic inspection thus remains an unsolved problem. Even with integral strain measurements, such as the volume expansion method, it is quite difficult to distinguish between different causes of increased expansion. This method cannot discriminate the local growth of cracks from an increase of strains in the whole cylinder resulting from acceptable degradation of the composite. Composite cylinders are continuously optimised aiming at a reduction of wall thickness and materials consumption. For this reason, the expected and accepted average strain resulting from elastic deformation and degradation of the composite is increasing. Thus the detection of liner cracks by volume expansion tests, as shown in Ref. [11] for steel cylinders, will become more and more impossible.

2.2. Degradation models of fibre-plastic composites

The first fibre-reinforced plastic materials were composed during World War II and used in aircraft construction for covering radar domes. The aeronautic industry was especially interested in using composites because the weight related fatigue strength of these new light materials was better than the one of metals, depending on the type of fibre. The degradation behaviour of composites, in the meaning of loss of strength or stiffness properties is much more complex with regard to relevant influences and to noticeable effects than the fatigue behaviour of metals. For this reason there are many different degradation models. A considerable number of them have been compiled in Ref. [12].

As opposed to metals, composite materials are subject to degradation under static load and thus to a limited stress rupture strength, even at room temperature. This is also referred to as "static fatigue" in literature. As a result, it is not possible to design composite pressure receptacles for an unlimited service life like it is common with metals, adhering to their technical fatigue endurance limit.

For space applications, NASA made considerable efforts in the 1970s to record the stress rupture behaviour for a service life of 30 years. At the beginning of the 1980s, the results were published in Refs. [13], among others. In the 1990s the results were summarised by the working group 17 of ISO/TC 58 for composite cylinders and included in the requirements for construction, design and testing for composite cylinders (see Ref. [14]).

The results of this survey were static safety factors today known as "stress ratios". The determination of these factors was primarily based on a maximum permissible failure rate of 10^{-6} during a service life under permanent load of 15–20 years. The necessity of these safety factors has once again become an object of extensive debate, particularly with regard to hydrogen storage containers for automotive application.

BUNSELL and THINNOET ([6,7]), among others, examined the properties of laminates under the aspect of cylinders used for propellant gas. He derived a degradation model mainly applicable to carbon fibre composites. Carbon fibres can be considered ideally elastic fibres. They do not show degradation, neither under static nor under cyclic loads.

In order to illustrate the concept behind the degradation model, pictures showing different states of an increasing degradation process have been summarised in Fig. 2. This process was simulated in a simplified manner using finite elements. In the first iterations of this model, visco-elastic-plastic matrix properties were not taken into account, while they play an important part in the recent versions. In brief, the main concept behind this degradation model is based on the assumption of a fibre-filament's strength being