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Gas cylinders — Guidance for design of composite cylinders —

Part 3:
Calculation of stress ratios

Bouteilles à gaz — Recommandations pour la conception des bouteilles en matière composite —

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Foreword

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The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

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This document was prepared by Technical Committee ISO/TC 58, *Gas cylinders*, Subcommittee SC 3, *Cylinder design*.

A list of all parts in the ISO 13086 series can be found on the ISO website.

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

Gas cylinders — Guidance for design of composite cylinders —

Part 3: Calculation of stress ratios

1 Scope

This document addresses the topic of calculation of stress ratios when analyzing filament wound composite cylinders. This document is applicable to cylinders of Types 2, 3, and 4. The calculation of stress ratios supports the development and revision of standards for fibre reinforced composite pressurized cylinders.

2 Normative references

There are no normative references in this document.

3 Terms and definitions

No terms and definitions are listed in this document.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— IEC Electropedia: available at http://www.electropedia.org/

— ISO Online browsing platform: available at https://www.iso.org/obp

4 Background

Stress rupture, also known as static fatigue, is the broadly defined mechanism where a material fails under sustained static load. Stress ratio, the ratio of maximum fibre stress at minimum cylinder design burst pressure divided by the maximum fibre stress at cylinder working pressure, allowing assessment of the likelihood of stress rupture of the reinforcing fibres. Other performance may be affected by the amount of fibre on the part, as reflected by the stress ratio, but there are other means to accomplish improvements in other performance areas (e.g. drop, impact, gunfire, flaw resistance), and performance testing is a better means to assess other performance factors. It is assumed that a time-based relationship between the applied static load and the breakdown of the material can be defined. The goal of defining a mathematical relationship between applied stress and time to failure is to make accurate predictions of the material's performance for safe use. In the simplest of terms, the greater the sustained load, the sooner the occurrence of failure (stress rupture). A full and accurate understanding of the material's working stress state in service is imperative in order to assure that the stress ratios are calculated accurately, and therefore the reliability of the cylinder in service is known.

Burst ratios and stress ratios are theoretically the same for Type 4 cylinders with a single structural reinforcing fibre, but not for Type 2 or Type 3 cylinders due to the effect of autofrettage. While use of a burst ratio for Type 2 and Type 3 cylinders is normally conservative, poor design and autofrettage practice may cause higher stress in the reinforcing fibre, causing premature failure by rupture. This unsafe condition can result when using non-traditional materials, very thick liner and/or thin composite materials, and/or high autofrettage pressures. Some amount of calculation is also required for Type 4 cylinders using hybrid construction, which is the use of more than one structural reinforcing fibre (see 6.3).

5 Stress ratio determination

Stress ratios can be determined by a burst ratio in some cases, and in all cases by analysis, where material properties and dimensions are known, and where the analysis is compared with strain and deflection measurements to confirm its accuracy. Stress ratios may also be determined by strain or deflection measurements. Validity of analysis or measurements should be established in all cases, particularly given the need to address safety concerns. Analysis and validation is easiest when the cylinder is assumed to fail in the cylindrical section, and not in the dome section. Burst location can be confirmed through burst testing, and the assumption is confirmed if at least a majority of the bursts initiate in the cylinder. In the event all failures initiate in the dome, additional validation may be required.

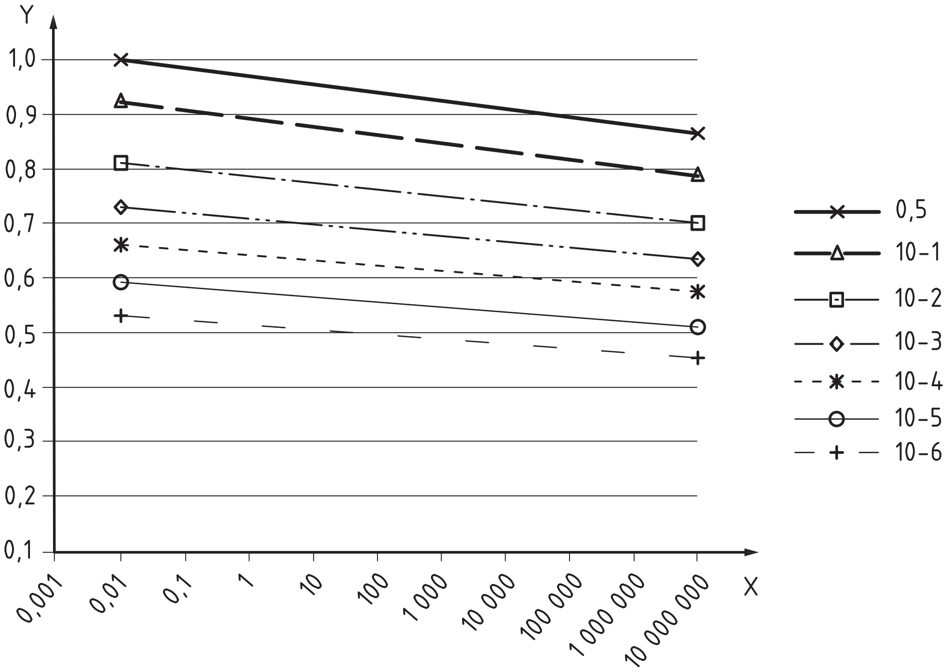
6 Stress ratio development and calculation

6.1 General

Stress ratio is defined as the stress in the material at ultimate load (burst pressure) divided by the stress in the material at the rated load (or nominal use pressure). Stress ratio is developed using the nominal burst pressure for the cylinders used in the test studies, but is often applied to the minimum design burst pressure to add a degree of conservatism, given that the coefficient of variation of burst pressure for a production batch of cylinders may be different than the coefficient of variation of burst pressure for the test study cylinders. Stress ratio is used in stress rupture analysis in the same manner as stress range is used in cyclic fatigue analysis to help set the reference conditions for the performance predictions.

$$\textit{Stress ratio} = \frac{\textit{Maximum fibre stress at specified minimum design burst pressure}}{\textit{Maximum fibre stress at working pressure}}$$

As provided in numerous technical papers in composite design, stress rupture resistance is developed on testing of individual strands or composite cylinders which are held to various percentages of their average ultimate strength. These studies[1] to [8] look to the intrinsic properties of the material to evaluate degradation rates from specific loads. Presentation of stress rupture has many formats but it always includes the stress ratio (or load fraction) and time to failure at the reference stress state as shown in Figure 1[9].



Key

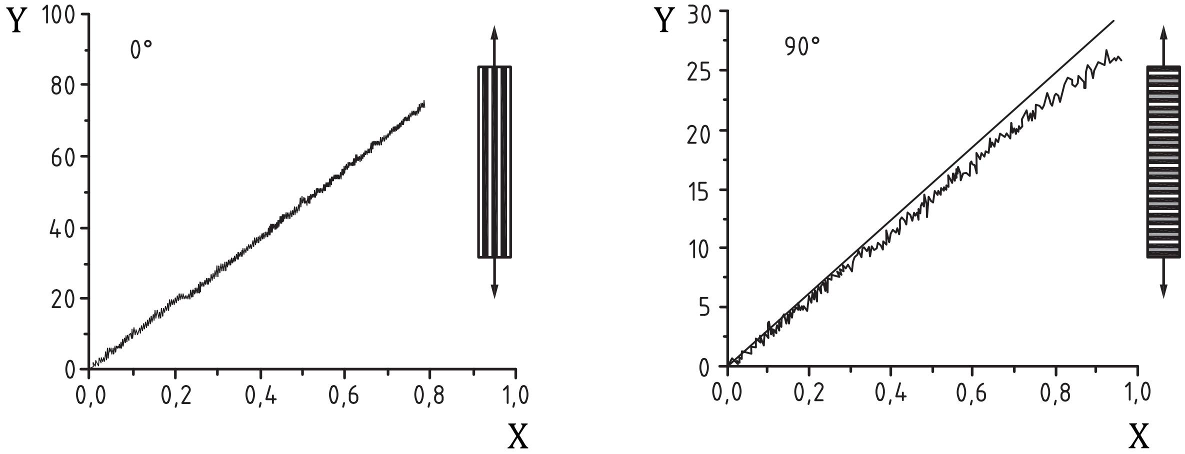
X time, hours

Y load fraction of median strength

Figure 1 — Carbon composite stress rupture chart

In addition, the nearly perfectly linear strain response of fibre composites under load provides another opportunity to limit the complexity of the stress rupture analysis. The linear stress-strain curve for carbon fibre is displayed in Figure 2. The material does not display a yield point so stress rupture curves as exampled in Figure 1 can accurately predict the material's response across wide ranges of applied stress. This response is typical for nearly all fibre reinforced composite materials and vessel types. This allows significant reduction of the complexity of the fatigue predictions at least as it relates to the individual fibres in the laminate itself. The basic assumption in any analysis of composites is that the reinforcement fibres dominate the viscoelastic response of the material. For resins with significant creep under load or credited for stress ratio compliance their stress rupture properties will also be evaluated in a comprehensive stress rupture analysis.

Different levels of difficulty are encountered in composite pressure vessel design when evaluating the actual stress state of a reinforcement. A common issue in all designs is to resolve the laminate stiffness in the fabricated cylinder in the principle directions. This is typically well estimated using classical lamination theory (macro-mechanics) coupled with a suitable micro-mechanics approach, e.g. rule of mixtures. In lamination theory, the local angle of the fibre reinforcement has a direct bearing on the stiffness of the laminate as shown in Figure 3.

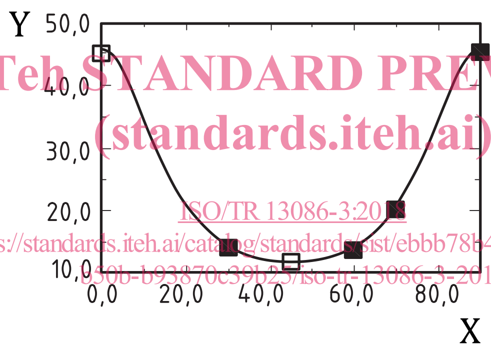


Key

X strain (%)

Y stress (Mpa)

Figure 2 — Typical stress-strain curves of carbon fibre composites at 0° and 90°[10]



Key

———	prediction
□	baseline data
■	verification data
X	orientation angle (degree)
Y	stiffness (GPa)

Figure 3 — Laminate stiffness vs. fibre angle

6.2 Use of pressure ratios

For cylinders with a non-load-sharing liner (Type 4) and with a single reinforcement fibre type, the materials have elastic behavior, and there is no bending in the cylinder section. The burst ratio is defined as the pressure at burst, divided by the working pressure, and is equal to the stress ratio.

$$Burst\ ratio = \frac{Burst\ pressure}{Working\ pressure} = Stress\ ratio\ \ for\ Type\ 4\ with\ only\ one\ material$$

6.3 Type 4 evaluation with hybrid construction

In Type 4 designs that are hybridized with multiple fibres of different classifications (e.g. carbon, glass, aramid), additional calculations will be applied to verify the proper stress ratio in the design. Hybrids may include using one material in each layer, and changing materials between layers, and it may include co-mingled fibres in a winding band. When evaluating co-mingled fibres, the strain in the fibre direction will be the same for each fibre in the band. Consideration will also be given to load share from external protection layers.

The stress in each reinforcement will be checked. Examples of hybridized cylinders are those constructed with both carbon and glass fibres where the glass may or may not be used for stress ratio compliance. A load sharing hybrid is one in which both fibres meet their required stress ratio at working pressure. A non-loadsharing hybrid is one in which the primary fibre was able to meet its stress ratio requirements if the secondary fibre was removed.

If the secondary fibre is considered non-structural its load share at burst will still be calculated to validate the proper stress ratio on the primary reinforcement. If all reinforcement fibres are considered structural in meeting demonstrated burst performance, then each reinforcement will be evaluated for stress ratio compliance.

Type 4 designs hybridized with multiple reinforcements, having a primary structural fibre and secondary non-structural reinforcement, the burst ratio will be corrected by the cross-sectional area of the non-structural fibre within the lamina. This is considered by defining a reinforcement stiffness ratio.

$$\textit{Reinforcement stiffness ratio} = RSR = \frac{E_P A_P}{E_P A_P + E_S A_S}$$

where

A is the cross-sectional area of the fibre in the lamina (primary or secondary as noted);

E is the elastic modulus of the fibre (primary or secondary as noted).

The minimum required demonstrated burst ratio for the cylinder is then calculated by

$$\textit{Burst ratio}_{(\textit{Minimum demonstrated})} = \textit{Burst ratio}_{(\textit{Single reinforcement})} * (2 - RSR)$$

For example, if the primary reinforcement is carbon fibre and it carries 90 percent of the structural load, as calculated by the RSR, and the secondary reinforcement carries 10 percent, the minimum burst ratio to be demonstrated = 2,25 * (2 – 0,9) = 2,25 * 1,1 = 2,475.

For Type 4 designs with multiple classes of reinforcement where all the fibres are used to demonstrate minimum burst performance, all of the reinforcements will be evaluated for stress ratio compliance. The reinforcement with the lowest strain to failure may be validated for an appropriate stress ratio with the burst test of the cylinder. All other reinforcements require knowledge of the failure strain for each reinforcement and the failure location. This may require separate cylinder burst tests for each reinforcement to explicitly determine its expected failure strain in the application. In addition, an analysis appropriate for the cylinder failure mode will need to be performed to determine the stress field in the laminate.

6.4 Analysis of Type 2 and Type 3 designs

For Type 2 or Type 3 designs the interaction of the liner with the composite shell will be included to develop an accurate understanding of the stress state of the reinforcement at any point in the pressure history. This requires an advanced understanding of the composite design process but it is still within the known state-of-the-art for good pressure vessel design practice. Generally, these advanced technics are numerical methods which includes finite element analysis (FEA), but may include other methodologies. The model will have sufficient capability and accuracy so as to yield acceptable results, as confirmed by strain gages, and will have the ability to perform non-linear analysis in order to model the yielding behavior of the metallic liner.

It is necessary to know certain information in order to have an accurate and valid analysis. This information includes:

— composite material properties, including elastic modulus in the principle directions and Poisson's ratio;

— composite strength in the principle directions;

— composite layer thicknesses;

— liner stress/strain behaviour over the full pressure range;

— liner thickness;

— cylinder inner diameter;

— autofrettage, test, working, and minimum burst pressures;

— inclusion of pre-stresses from winding tension, if significant.

A typical refinement in the cylinder model would be to investigate if internal (galvanic isolation) or external (impact shield) protection layers disturb the stress ratio calculations. In some national standards, these additive plies are limited to a total maximum load share at burst. This is a type of inter-ply hybridization that requires advanced techniques if the analysis is solely used to validate regulatory compliance. The generally recognized method to provide compliance is modeling the cylinder in a commercially available FEA software package. The FEA model for the cylinder will need to account for the varying liner and composite thickness, orientation of the fibres in the layers and the non-linear response (yield) of the liner material if autofrettage is used in the fabrication process and as analysis is done at the minimum burst pressure.

The designer needs to be able to evaluate the principle fibre and liner stresses at any point in the cylinder and maintain an accounting of those stresses at (a) autofrettage, (b) zero after autofrettage, (c) service, (d) test, and (e) burst pressure in the order (strain history) as they are accumulated in the actual cylinder. This is because strain history of the liner material is an integral part of the autofrettage process. The FEA also needs to have sufficient fidelity to model the failure mechanism and location at burst pressure. For cylinders limited to a mid-cylinder burst a simple axisymmetric shell model provides sufficient resolution. Where the failure location is part of the dome or port geometry then the additional complexity of the dome will be included to properly evaluate the liner response and the corresponding stress field of the composite.

Examples of studies conducted on Type 3 cylinders with metallic liners of increasing thickness and varying autofrettage pressures are provided in Figures 4 through 8. The process for developing these figures includes the following:

— Start with single fibre Type 4 design (no liner).

— Add liner (Composite ID maintained).

— Remove composite material to maintain common burst ratio with Type 4 design (step 1).

— Check new Type 3 design with varying levels of autofrettage pressure and calculate resulting fibre stress ratio.

— Repeat steps 2-4 with various liner thicknesses.

— The chart is the plot of various Type 3 designs, designed with the same burst ratio (line 1) but with different composite-to-liner thickness ratios.

— Each design has undergone a series of different autofrettage cycles and the subsequent stress ratio at service pressure has been plotted (lines 3 through to 7).

— Additionally, a simple liner burst calculation has been included for reference (line 2).

— The bottom horizontal axis shows the liner thickness of each design.

— The left vertical axis shows the stress ratio and the burst ratio of each design.

— The right vertical axis shows the composite thickness of each design.

— Every point along the bottom horizontal axis represents a new design with a different composite-to-liner thickness ratios.

— The vertical column of each horizontal position (design) shows you:

  — the design's liner thickness (horizontal axis);

  — the design's composite thickness (line 8, plotted on the right vertical axis)

  — the design's burst ratio (line 1, plotted on the left vertical axis) of the tank;

  — the design's liner burst ratio (line 2, plotted on the left vertical axis) of the tank;

  — the design's stress ratio without an autofrettage cycle (line 3, plotted on the left vertical axis) of the tank;

  — the design's stress ratio after different levels of autofrettage (lines 4 thru 7, plotted on the left vertical axis) of the tank.

Combinations of fibres, liners, and stress ratios (set at 5 % above nominal) evaluated include the following:

— Figure 4, carbon fibre, aluminum liner 2,36 SR;

— Figure 5, carbon fibre, aluminum liner, 3,00 SR;

— Figure 6, glass fibre, aluminum liner, 3,68 SR;

— Figure 7, carbon fibre, steel liner, 2,36 SR;

— Figure 8, glass fibre, steel liner, 3,68 SR.

The material properties used are as follows:

Aluminum		
68,95	GPa	modulus of elasticity
0,33		Poisson's ratio
200	MPa	proportionality limit
240	MPa	yield strength – 0,2 % offset
Steel		
200	GPa	modulus of elasticity
0,29		Poisson's ratio
648	MPa	proportionality limit
731	MPa	yield strength – 0,2 % offset
Resin		
3,17	GPa	modulus of elasticity
0,35		Poisson's ratio