TECHNICAL REPORT

# ISO/TR 13086-3

First edition
2018-09

# 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 —*



Reference number
ISO/TR 13086-3:2018(E)

ISO copyright office
CP 401 • Ch. de Blandonnet 8
CH-1214 Vernier, Geneva
Phone: +41 22 749 01 11
Fax: +41 22 749 09 47
Email: copyright@iso.org
Website: www.iso.org

Published in Switzerland

# Contents

Page

# Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

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).

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights. Details of any patent rights identified during the development of the document will be in the Introduction and/or on the ISO list of patent declarations received (see www.iso.org/patents).

Any trade name used in this document is information given for the convenience of users and does not constitute an endorsement.

For an explanation of the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT) see: www.iso.org/iso/foreword.html.

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

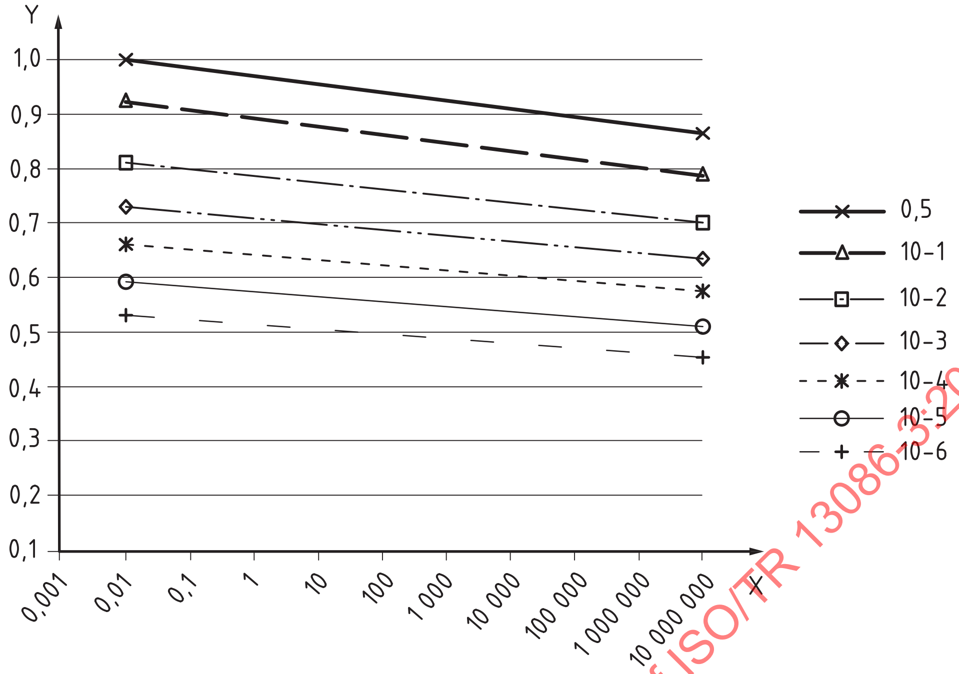
Stress ratio is defined as the stress in the material at ultimate load (burst pressure) divided by the stress in the material at the rated load (or nominal use pressure). Stress ratio is developed using the nominal burst pressure for the cylinders used in the test studies, but is often applied to the 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.

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

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**

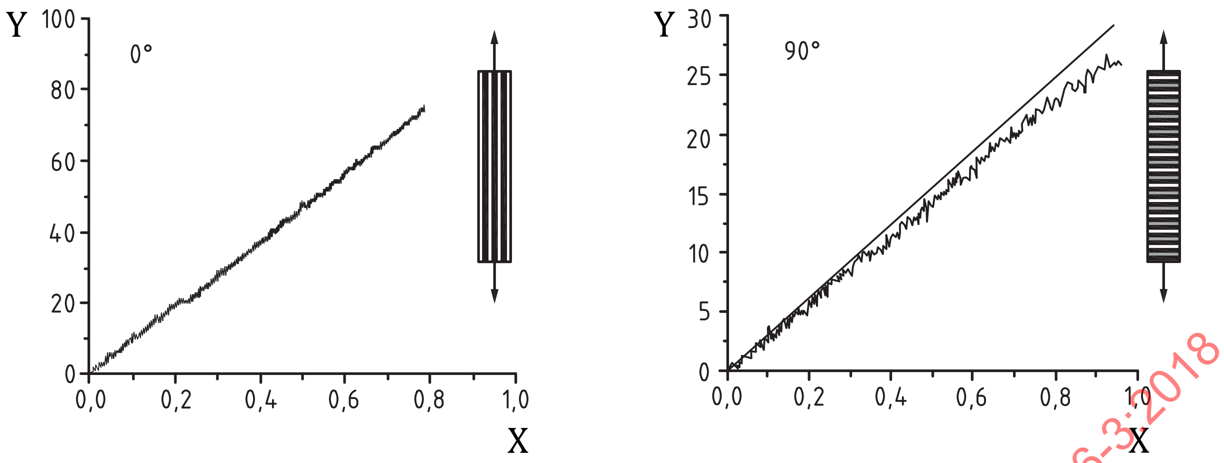
X time, hours

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.

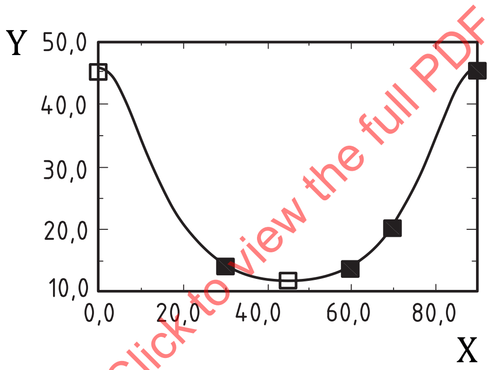



**Key**

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.

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

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

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

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 |

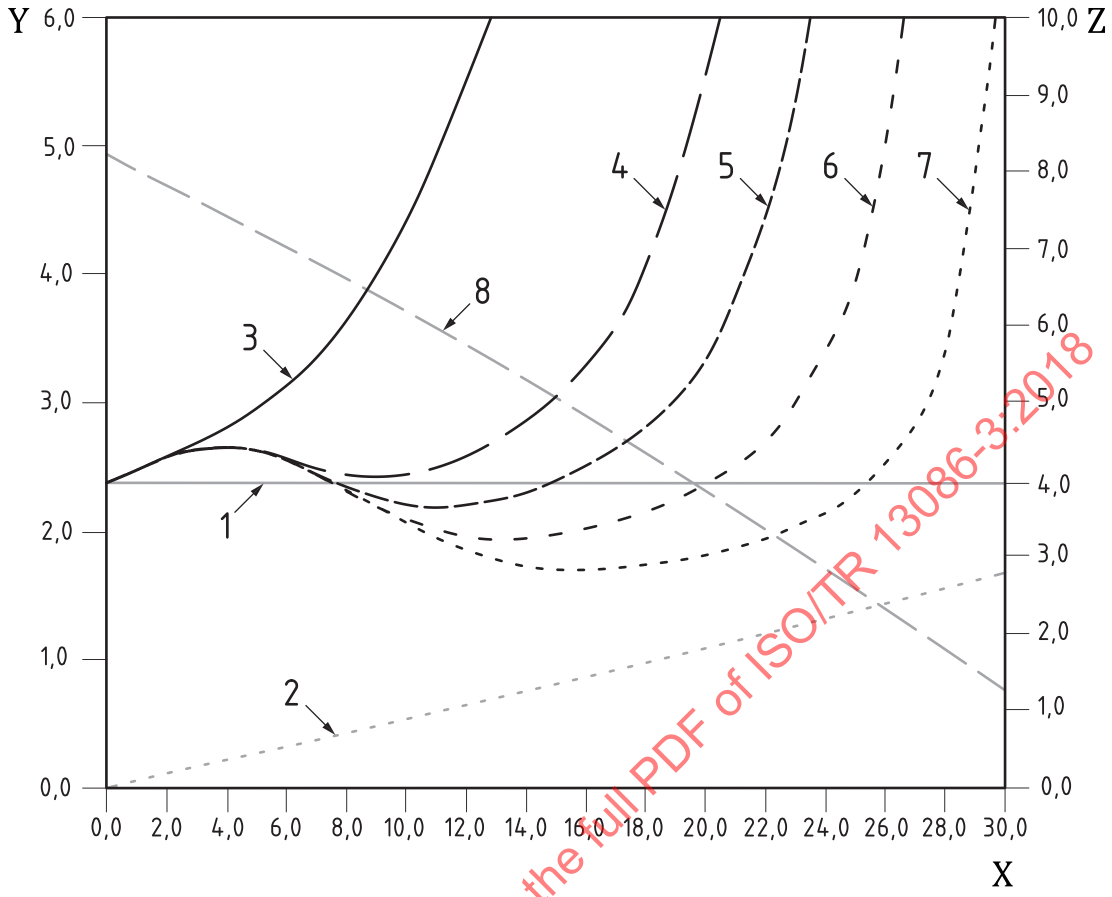
| | | |
|---|---|---|
| Carbon fibre | | |
| 230 | GPa | modulus of elasticity |
| 0,20 | | Poisson's ratio |
| Glass fibre | | |
| 82,7 | GPA | Modulus of elasticity |
| 0,22 | | Poisson's ratio |

The given material properties have been used to show the basic behaviour of the given designs. Results will vary when different properties, including yield strength, are used. The material properties will be reflective of the actual materials used in order to get valid results for the actual designs being analysed.

Observe that in each of the Figures 4 through to 8, the designs operating with portions of lines 4 through to 7 below line 1 indicating the burst ratio, are in fact operating below the intended stress ratio, and are therefore at risk of rupturing during their lifetime (except in Figure 5, where the burst ratio for carbon fibre is greater than normally required). This confirms that stress ratio and burst ratio are not the same for Type 3 tanks, and that the stress ratio will be calculated to ensure that burst will not be at high risk due to stress rupture.



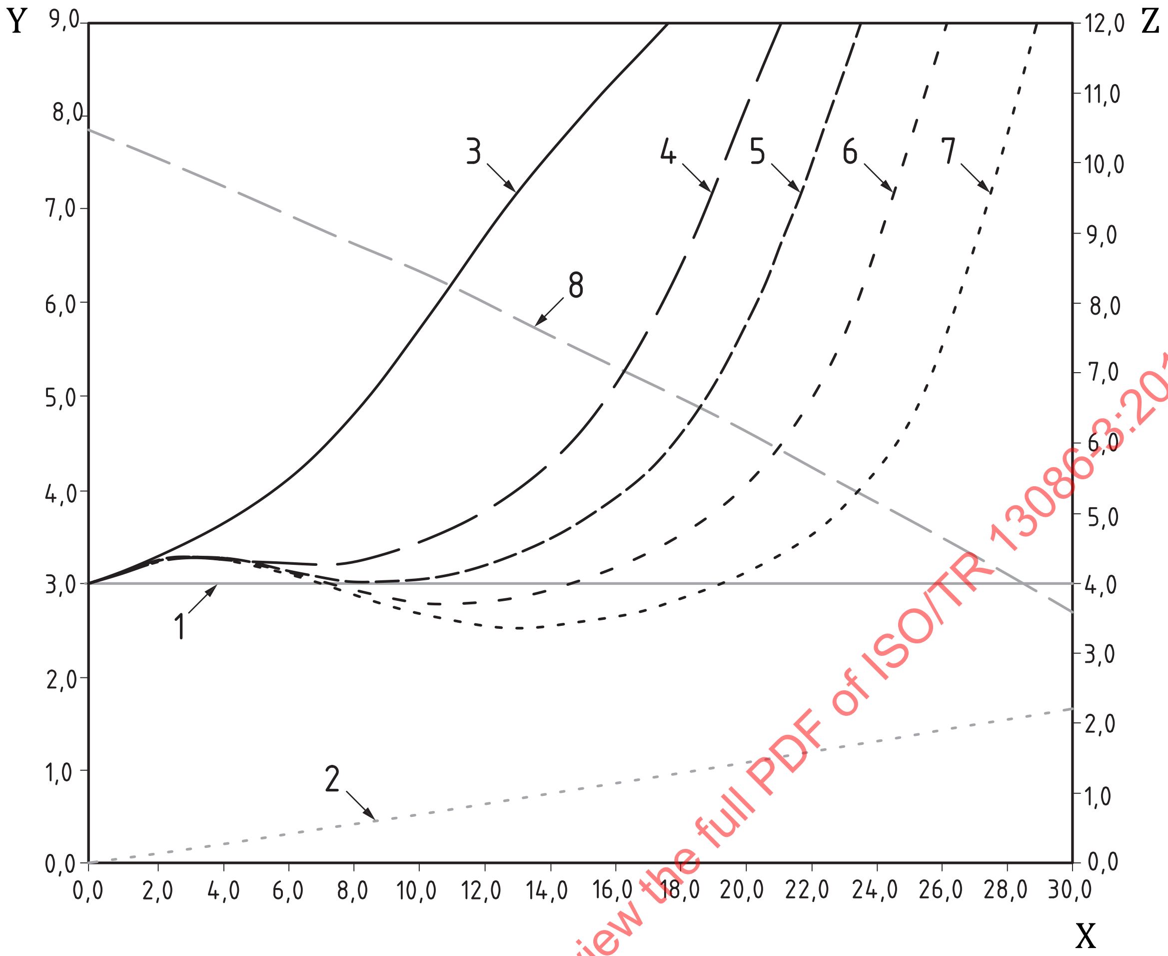
 




**Key**

1 vessel burst ratio
2 liner burst ratio
3 fibre stress ratio before autofrettage
4 fibre stress ratio after 1,50x autofrettage
5 fibre stress ratio after 1,67x autofrettage
6 fibre stress ratio after 1,83x autofrettage
7 fibre stress ratio after 2,00x autofrettage
8 composite thickness
X liner thickness (mm)
Y ratio (stress or burst)
Z composite thickness (mm)

**Figure 4 — Carbon fibre, aluminum liner, 2,36 SR**



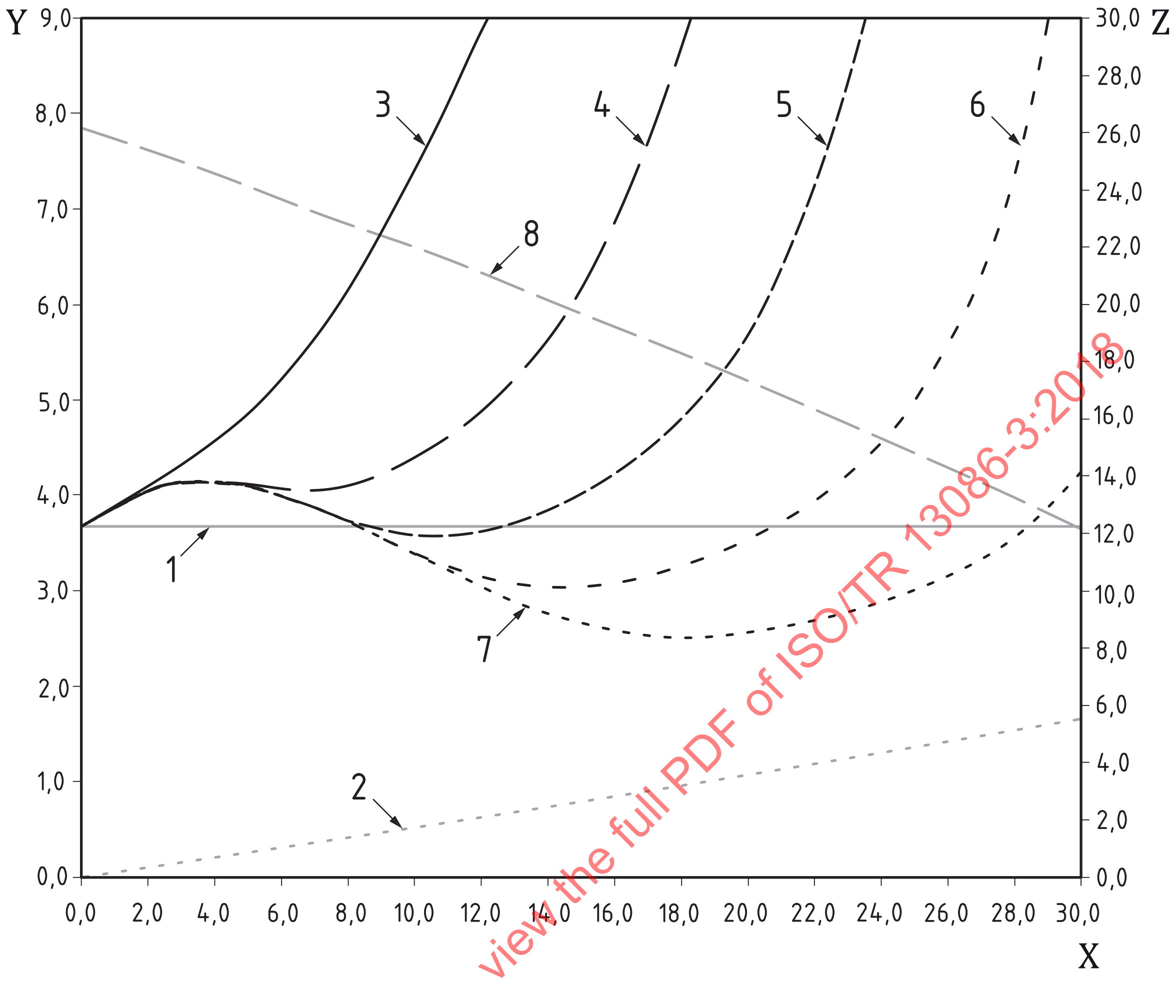

**Key**

1 vessel burst ratio
2 liner burst ratio
3 fibre stress ratio before autofrettage
4 fibre stress ratio after 1,50x autofrettage
5 fibre stress ratio after 1,67x autofrettage
6 fibre stress ratio after 1,83x autofrettage
7 fibre stress ratio after 2,00x autofrettage
8 composite thickness
X liner thickness (mm)
Y ratio (stress or burst)
Z composite thickness (mm)

**Figure 5 — Carbon fibre, aluminum liner, 3,00 SR**



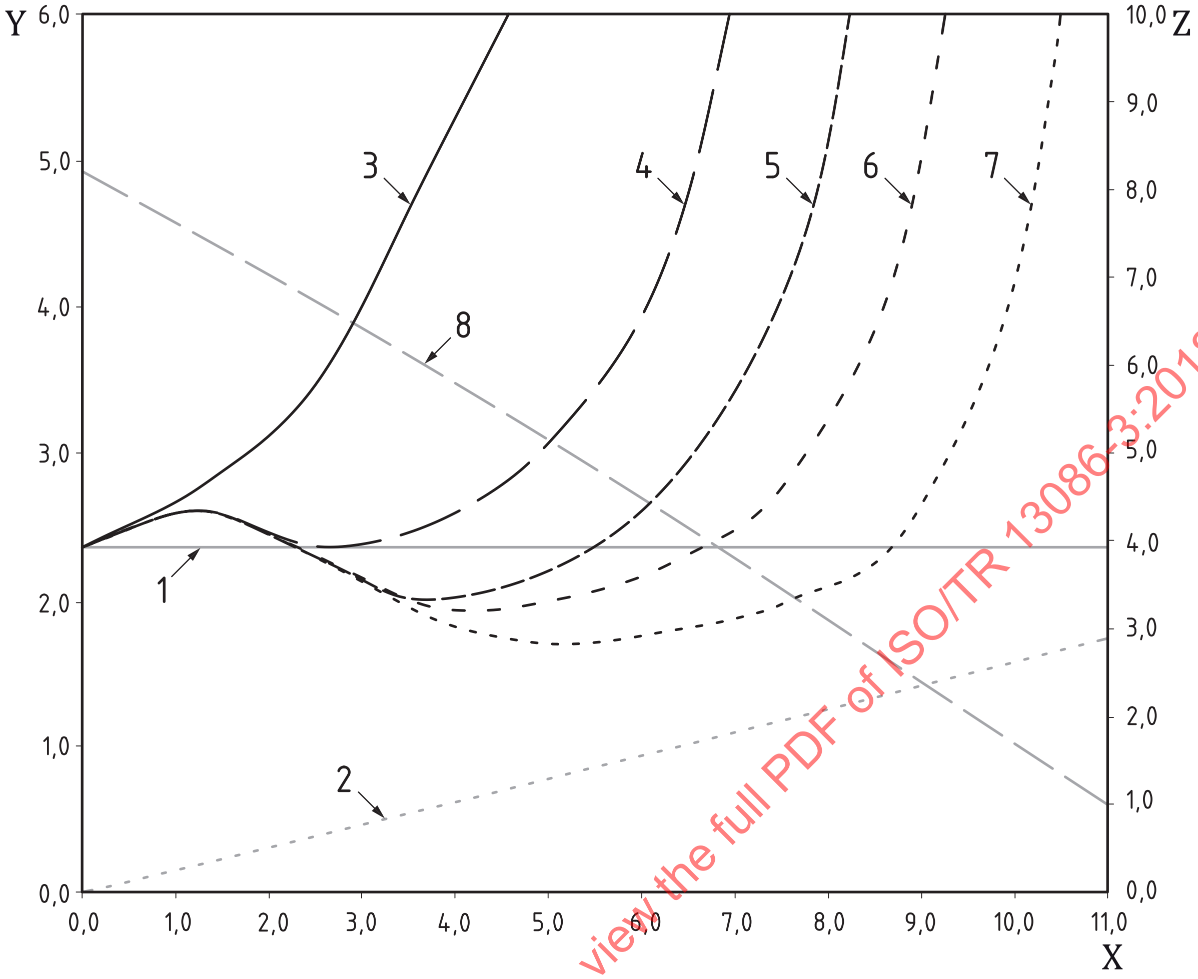
 




**Key**

| | |
|---|---|
| 1 | vessel burst ratio |
| 2 | liner burst ratio |
| 3 | fibre stress ratio before autofrettage |
| 4 | fibre stress ratio after 1,50x autofrettage |
| 5 | fibre stress ratio after 1,83x autofrettage |
| 6 | fibre stress ratio after 2,17x autofrettage |
| 7 | fibre stress ratio after 2,50x autofrettage |
| 8 | composite thickness |
| X | liner thickness (mm) |
| Y | ratio (stress or burst) |
| Z | composite thickness (mm) |

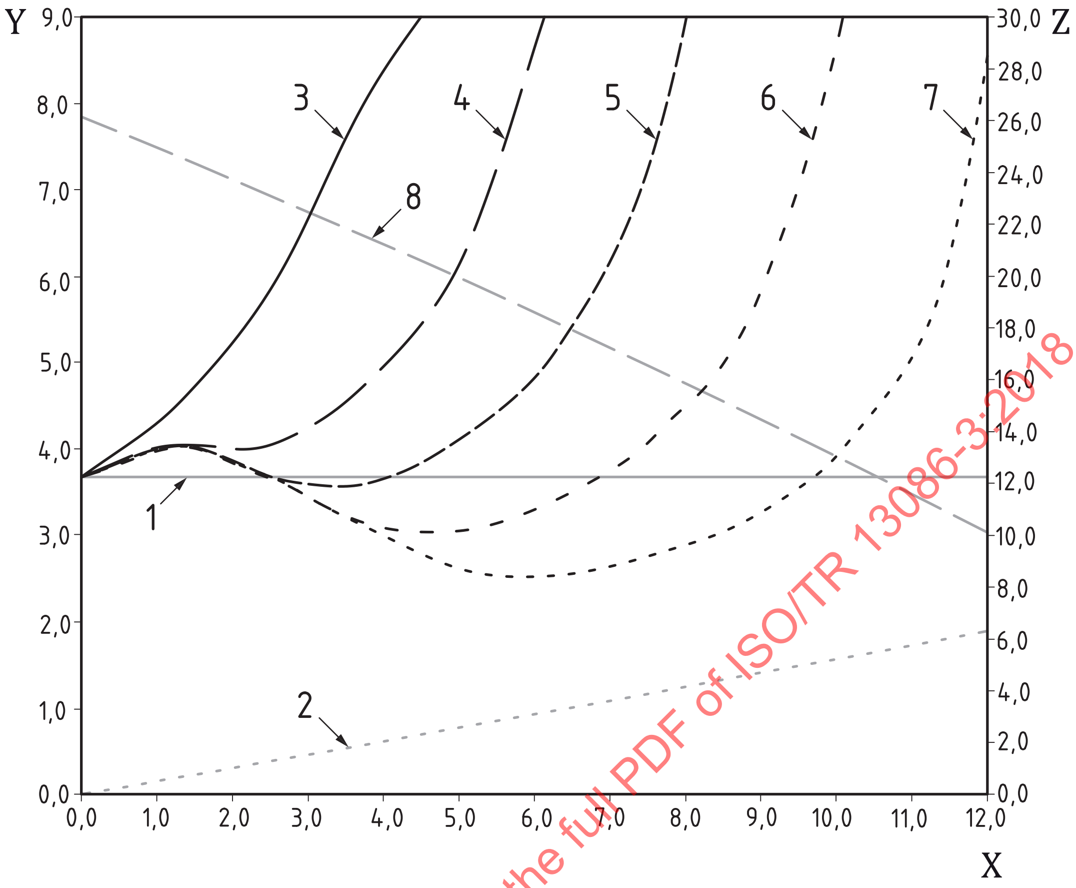
**Figure 6 — Glass fibre, aluminum liner, 3,68 SR**




**Key**

1 vessel burst ratio
2 liner burst ratio
3 fibre stress ratio before autofrettage
4 fibre stress ratio after 1,50x autofrettage
5 fibre stress ratio after 1,67x autofrettage
6 fibre stress ratio after 1,83x autofrettage
7 fibre stress ratio after 2,00x autofrettage
8 composite thickness
X liner thickness (mm)
Y ratio (stress or burst)
Z composite thickness (mm)

**Figure 7 — Carbon fibre, steel liner, 2,36 SR**




**Key**

| | |
|---|---|
| 1 | vessel burst ratio |
| 2 | liner burst ratio |
| 3 | fibre stress ratio before autofrettage |
| 4 | fibre stress ratio after 1,50x autofrettage |
| 5 | fibre stress ratio after 1,83x autofrettage |
| 6 | fibre stress ratio after 2,17x autofrettage |
| 7 | fibre stress ratio after 2,50x autofrettage |
| 8 | composite thickness |
| X | liner thickness (mm) |
| Y | ratio (stress or burst) |
| Z | composite thickness (mm) |



**Figure 8 — Glass fibre, steel liner, 3,68 SR**

There are other numerical methods, including closed form analysis that may require iteration to address non-linear material properties, which may give suitable results as well. The information required to conduct an accurate analysis includes the same values given above for finite element analysis, and the requirements for calculated outputs would be the same.

Accurate modelling can reduce development risk in the design phase but it also can be used to point to safe operational use of cylinders that might not be directly covered by published standards. This may occur with novel materials, processes or applications within the literal scope of the standards but not considered in the experience base of the industry at the time of publishing. In all cases, the designer is responsible for providing for the safe application of the design.

The key issue then becomes one of validating the calculated stress ratios within the fabricated cylinders. This is necessary because of potential errors in modeling and need for an independent verification of the design in performance based standards. Chief concern for a robust validation process is maintaining operational safety to prevent stress rupture. Operational safety in a performance based standard can be accomplished through several different approaches. As stated earlier for single reinforcing material Type 4 cylinders the burst ratio is directly the stress ratio. For Type 2 and Type 3 cylinder designs verification requires more knowledge of the cylinder's performance.

It should be recognized that while analytical methods are desirable, and with sufficient care and diligence they may be used to demonstrate regulatory compliance, it is necessary to conduct tests, and verify strains, displacements, and liner yield points with proper instrumentation. It may be to the advantage of the industry to develop a standardized set of input information that can be used to calibrate and/or assess whether a given software package can develop accurate output. A standardized set of input information would include material properties, dimensions, and pressures noted above. It would also include guidelines for consistent boundary conditions, application of pressure loads, and expected results.

## 6.5 Direct measurements methods

Guidance for the direct measurement of actual stress ratio in Type 3 cylinders has been given in several composite pressure vessel standards, such as in ISO 11439:2013 Annex F, provided below. This following procedure allows verification of stress ratios using strain gauges.

a) The stress-strain relationship for fibres is always elastic, therefore, stress ratios and strain ratios are equal.

b) High elongation strain gauges are required.

c) Strain gauges should be orientated in the direction of the fibres on which they are mounted (i.e. with hoop fibre on the outside of the cylinder, mount gauges in the hoop direction).

d) **Method 1** (applies to cylinders that do not use high tension winding)

1) Prior to autofrettage, apply strain gauges and calibrate.

2) Measure strains at autofrettage, at zero pressure after autofrettage and at working and minimum burst pressure.

3) Confirm that the strain at burst pressure divided by the strain at working pressure meets the stress ratio requirements. For hybrid construction, the strain at operating pressure is compared with the rupture strain of cylinders reinforced with a single fibre type.

e) **Method 2** (applies to all cylinders)

1) At zero pressure after winding and autofrettage, apply strain gauges and calibrate.

2) Measure strains at zero, working and minimum burst pressures.

3) At zero pressure, after strain measurements have been taken at the working and minimum burst pressures, and with strain gauges monitored, cut the cylinder section apart so that the region containing the strain gauge is approximately 125 mm long. Remove the liner without damaging the composite. Measure the strains after the liner is removed.

4) Adjust the strain readings at zero, operating, and minimum burst pressures by the amount of strain measured at zero pressure with and without the liner.

5) Confirm that the strain at burst pressure divided by the strain at working pressure meets the stress ratio requirements. For hybrid construction, the strain at operating pressure is compared with the rupture strain of cylinders reinforced with a single fibre type.

NOTE It is best practice that anyone doing this test first conducts a test on a known cylinder with known pressure history in order to confirm their ability to get accurate results.



See Annex A for further guidance on direct measurement methods.

## 6.6 Design limits

An alternative to stress ratio calculation as a means of addressing stress rupture reliability is to maintain the burst ratio across the board for all designs. But this requires additional prescriptive controls in the pressure vessel standards to ensure that the interaction between the composite shell and liner is appropriately controlled. Effectively for all designs this could be controlling the liner load share through a prescribed maximum liner to composite stiffness ratio.

In these discussions, we define the stiffness ratio as:

$$Stiffness\ ratio = \frac{Et(liner)}{Et(liner) + Et(composite)}$$

where

- $t$ is the thickness of liner or composite;
- $E$ is the modulus of liner, or Hoop modulus of composite (for designs where burst occurs in the cylinder section with failure of the circumferential reinforcement).

This is a simple relationship to obtain, as the modulus of the composite is easily calculated using classical lamination theory, which should be bounded between easily verified limits. The effect of the liner stiffness ratio in a design of a Type 3 pressure vessel is shown Figures 4 through 8. In these figures, multiple designs are plotted where the burst ratio is held to a level that represents the appropriate stress ratio for typical carbon or glass cylinders with a somewhat conservative design. In the example of a carbon fibre reinforced cylinder the safe maximum limit for the stiffness ratio would be about 50 %. This would limit the stress ratio to always be above the burst ratio for all autofrettage pressures.

Another alternative to stress ratio calculation to achieve safety in most instances would be to limit autofrettage pressure to 1,55 times working pressure or require the burst ratio to be greater than 3,0 in the case of a carbon fibre reinforced cylinder. Alternatively, the liner burst might be limited to about 0,25 times the working pressure. The autofrettage pressure of a glass fibre reinforced cylinder would be limited to 1,75 times working pressure, or the liner burst might be limited to about 0,25 times the working pressure.

While this method would be effective in limiting all cylinders to appropriate stress ratios it would also limit the competitiveness of certain designs in some applications. This may be viewed as technology limiting when sound engineering analysis is available to extend the safe range of those configurations.

## 6.7 Test methods

Another method of evaluating stress rupture is through testing. Data that was used to generate current recommended stress ratios was developed over a period of several years using a significant number of test specimens. It is not practical to do similar test programs for each new design. However, it may be possible to develop a shortened test procedure that can evaluate a particular design and determine if it will be safe. An advantage to this approach is that it integrates all elements of the design and fabrication into the program, and would address load sharing between reinforcements and the resin, residual stresses, scatter during manufacture, and similar concerns. A program of this sort might only use 30 to 50 cylinders, and require 6 to 12 months of testing. It would define the number of tests required, the load levels, the time at load, and temperatures during loading. It would also define pressurization rates during initial burst tests, which should be chosen as consistent with current practice, and with the idea that the pressurization rate would not artificially influence the data base of burst strength of a vessel. This approach is particularly of interest as new materials become available, by shortening the time to gather stress rupture data compared to programs that lasted several years.

## 7 Verification and validation

See ISO/TR 13086-1[9] for further information on the background and need for stress ratios as a means of evaluating and preventing stress rupture. Several methods have been presented for determining stress ratios. Some of these have been in use for many years. If the industry need additional confidence in these methods, it may be useful to establish “round robin” analysis and testing to compare results. Given the number of designs available, the different methodologies available, and the need to assure safety without eliminating viable designs, the industry should be capable of verifying the different methodologies.

Validation comes from success, or failure, in actual service as a means of confirming the methods for calculating stress ratios. Much can be learned from evaluating designs that have a long history, confirming stress rupture failures or lack thereof. Trying new designs that may push beyond traditional and/or recommended stress ratios can be dangerous, however, as it may be several years before there is sufficient history. If this history becomes negative, it may be necessary to recall cylinders that violate stress ratio recommendations before significant stress rupture failures occur.

## 8 Conclusions

Stress ratios address stress rupture, a phenomenon by which reinforcing fibres may fail under sustained loading. Burst ratios do not always correlate directly to stress ratios, and therefore they cannot be used to address stress rupture.

Determining the working stresses in a composite cylinder does require advanced techniques but those skills are widely published and understood within the pressure vessel industry. In all cases the manufacturer’s knowledge of the materials, construction geometry and fabrication techniques are key to the successful application of those analysis techniques. There are many acceptable analysis techniques available to the designer depending on the construction of the cylinder (Type 2, 3, or 4). At a minimum the capability of the analysis will be sufficient to resolve the stress field so that the appropriate stress rupture reference data (fibre or laminate) can be determined. The value of advanced analysis techniques is that they can be used to gain insight to the response of the cylinders in situations that are not directly covered (or envisioned) by performance based standards. In almost all cases analytical methods should be confirmed with strain gage measurements. Measurement of strains is an acceptable alternative to analysis as a means of determining stress ratios. Stress ratios can also be controlled by limiting design options.

Safety can be improved by specifying stress ratio requirements, thereby defining reliability of a cylinder over time. This is particularly true since it has been shown that stress ratios can drop to dangerously low levels even while meeting burst ratios that some in industry have felt address all safety issues.



# Annex A
(informative)

# Examples of direct measurement methods

## A.1 Method 1 (applies to cylinders that do not use high tension winding)



1) Prior to autofrettage, apply strain gauges and calibrate.

   a) High elongation strain gages are required.

   b) Strain gages should be oriented in the direction of the fibres on which they are mounted, the more precise the alignment, the better the results.

   c) If measurements are required across the fibres, a displacement transducer should be used.

   d) Gages should be away from discontinuities; mid-cylinder is recommended.

   e) Multiple hoop gages should be placed at the same axial position.

      i) Multiple readings increase confidence in results.

      ii) Some gages may fail during the testing.

   f) Pressurize the cylinder to pressures below the yield point of the liner and take strain gage readings.

      i) Compare results to confirm that readings are consistent and as expected.

      ii) Gages may not all agree, as there may be some differences in alignment and in composite structure below the gages, but the ratios of strains between two pressures should be consistent.

      iii) Replace gages that do not appear to be functioning properly.

2) Measure strains at autofrettage, at zero pressure after autofrettage and at working and minimum burst pressure.

   a) All gages should read “zero” before pressurizing.

   b) Pressurize to the autofrettage pressure.

      i) It is useful to stop at intermediate pressures and take readings to confirm that the gages are linear up to the point the metal liner (if present) yields, and that the gages read consistently before and after the yield point.

      ii) The autofrettage pressure should be held long enough that the strain readings do not change; it may take some time for the yielding of the metal liner (if present) to be completed, and for crazing of the resin matrix to stop.

   c) Reduce pressure to “zero”.

      i) It is useful to stop at intermediate pressures and take readings to confirm that the gages are still functioning properly, and to confirm the slope of the line as pressure decreases.

      ii) The resulting strains should be positive, due to yielding of the metal liner (if present) and crazing of the resin matrix.

iii) It is possible that a metal liner (if present) will yield in compression as it is depressurized; this is not a structural problem, be could indicate that the fatigue life of the liner will be limited.

iv) The cylinder should be held at “zero” pressure long enough for the readings to stabilize.

d) Pressurize to working pressure.

i) It is useful to stop at intermediate pressures and take readings.

ii) Hold at working pressure to confirm that readings are stabilized.

e) Pressurize to minimum burst pressure.

i) It is useful to stop at intermediate pressures and take readings are linear up to the point the metal liner (if present) yields, and that the gages read consistently before and after the yield point

ii) It is expected that the liner will yield again after pressurizing beyond the autofrettage pressure.

iii) The pressure should be held at minimum burst pressure long enough for the readings to stabilize.

iv) The cylinder can be depressurized after readings have been taken.

v) It is not necessary to take readings at “zero” pressure after holding at minimum burst pressure (the vaues will have changed due to the high pressure exposure, and do not represent service conditions).

3) Confirm that the strain at burst pressure divided by the strain at working pressure meets the stress ratio requirements. For hybrid construction, the strain at operating pressure is compared with the rupture strain of cylinders reinforced with a single fibre type.

a) As the gages are on the fibres, the fibre strain ratios will also be the fibre stress ratios.

b) Although individual gages may differ, the ratio of strains between two pressures should be consistent.

c) It is not uncommon for strain gages to fail at extreme strains, but this should be evident from the strain readings, particularly given that not all gages would fail at the same point in time.

## A.2 Method 2 (applies to all cylinders)

1) At zero pressure after winding and autofrettage, apply strain gauges and calibrate.

a) This method is particularly applicable for a cylinder that is removed from the field, and the autofrettage pressure is not known.

b) High elongation strain gages are required.

c) Strain gages should be oriented in the direction of the fibres on which they are mounted, the more precise the alignment, the better the results

d) If measurements are required across the fibres, a displacement transducer should be used.

e) Gages should be away from discontinuities; mid-cylinder is recommended.

f) Multiple hoop gages should be placed at the same axial position.

i) Multiple readings increase confidence in results.

