Technical Report

ISO/TR 13086-4

Second edition
2024-11

Gas cylinders — Guidance for design of composite cylinders —

Part 4: Cyclic fatigue of fibres and liners

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

Partie 4: Fatigue cyclique des fibres et liners

Reference number
ISO/TR 13086-4:2024(en)

ISO copyright office
CP 401 • Ch. de Blandonnet 8
CH-1214 Vernier, Geneva
Phone: +41 22 749 01 11
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 document 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).

ISO draws attention to the possibility that the implementation of this document may involve the use of (a) patent(s). ISO takes no position concerning the evidence, validity or applicability of any claimed patent rights in respect thereof. As of the date of publication of this document, ISO had not received notice of (a) patent(s) which may be required to implement this document. However, implementers are cautioned that this may not represent the latest information, which may be obtained from the patent database available at www.iso.org/patents. ISO shall not be held responsible for identifying any or all such patent rights.

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*.

This second edition of ISO/TR 13086-4 cancels and replaces the first edition (ISO/TR 13086-4:2019) which was technicall revised.

The main changes are as follows:

— editorial and technical changes throughout the document.

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 4:
Cyclic fatigue of fibres and liners

1 Scope

This document addresses the topic of cyclic fatigue of structural reinforcing fibres as used in composite cylinders, and cyclic fatigue of structural and non-structural liners in these cylinders. This document provides a basic level of understanding of these topics.

2 Normative references

There are no normative references in this document.

3 Terms and definitions

No terms and definitions are listed in this document.

NOTE Terms and definitions related to gas cylinders can be found in ISO 10286.

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

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

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

4 Background

Composite cylinders began service in the 1950s, initially as rocket motor cases with glass fibre reinforcement. This soon led to glass fibre pressure vessels with rubber liners, and then to glass fibre pressure vessels with metal liners. Metal liners were typically either aluminium alloy or steel. Eventually, new structural fibres, such as aramid and carbon, came into use for reinforcing pressure vessels. Today, typical reinforcements for composite gas cylinders are glass and carbon, either individually or together as a hybrid. Typical liner materials are steel, aluminium alloy or polymers, for example, high-density polyethylene (HDPE) or polyamide (PA); other materials could be acceptable.

Each of these materials is subject to cyclic fatigue based on the type of service and the construction of the cylinder. Cylinders used in transport service generally see full range cycles, with a limited number of cycles per year. Cylinders used as fuel containers typically see up to three pressure cycles per day for fleet vehicles, and less for private vehicles. Cylinders used in stationary applications such as refuelling cascades could see a very large number of partial cycles in a year. Some cylinders could see a combination of these conditions. Stationary cylinders used for fuel cells or emergency breathing applications could see a very limited number of cycles. Design working pressures for high pressure cylinders are typically in the range of 20 bar to 1 100 bar. Cylinders for liquified gases such as propane can operate at pressures up to 20 bar, and normally see fewer pressure cycles.

The different reinforcing fibres have different fatigue lives for a given stress or strain range. Liner materials can also have different fatigue lives for a given stress or strain range. The load-sharing characteristics of a liner material with a given reinforcement will affect their fatigue lives. An autofrettage cycle is used with metal lined cylinders to improve fatigue life. The low modulus of elasticity of polymer liner materials often results in the liner being in compression when the cylinder is pressurized, so their fatigue life could be very high. Welds in a liner, whether it is metal or polymer, can affect the fatigue life due to the different mechanical properties in a weld and in heat affected zones.

Surface quality and conditions such as roughness will affect cyclic fatigue, particularly crack initiation in Type 2 or Type 3 cylinders. Autofrettage generally blunts cracks, and adds surface compression, which will improve fatigue life.

Evaluation and understanding of cyclic fatigue will lead to improved designs and reduce the risk of cyclic fatigue failures without the need to overdesign the cylinders or conduct extensive qualification testing on each new design.

5 Cyclic fatigue evaluation

Cyclic fatigue of composite cylinders can be addressed with an understanding of

— service conditions and requirements,

— test conditions and specimens,

— fibre materials and their fatigue properties,

— liner materials and their fatigue properties,

— resin materials and their fatigue properties,

— composite/liner load sharing,

— autofrettage,

— analysis methods,

— leak before burst (LBB),

— damage tolerance,

— aging and environment,

— counting and combining different cycles, and

— qualification testing.

6 Elements of cyclic fatigue

6.1 Service conditions and requirements

6.1.1 Temperature and moisture

Service conditions depend largely on location and usage of the cylinder. If the cylinders are located and used outdoors, they must be able to withstand ambient conditions. Common conditions include temperature ranges from −40 °C to +85 °C (−40 °F to +185 °F), which include higher temperature exposure due to solar input and storage in confined spaces. This could include use in a vehicle or shipment in a rail car where direct sunlight will raise temperatures within the storage compartment. Surface absorptivity and emissivity of the cylinder can affect solar input to the cylinder and its equilibrium temperature. It is less common to require operation in temperatures to -55 °C (−67 °F), and in some cases to even lower temperatures.

Moisture levels in outdoor locations can range from very high to very low depending on ambient conditions. Some cylinders are actually located in a water bath. Moisture itself generally does not affect fatigue of structural materials used in cylinders, but can cause corrosion, which could affect fatigue life. Moisture can also be absorbed into polymer liners, and resulting property changes need to be understood by the cylinder designer. Moisture can also bring in chemicals that could affect material strength and fatigue properties, particularly those glass fibres that are not corrosion resistant.

Some cylinders are maintained in a controlled environment, such that temperature and moisture are monitored and controlled. However, conditions must be guaranteed if a controlled environment is needed to meet fatigue requirements. Otherwise, it is best to assume the cylinders will be exposed to worst-case conditions.

Temperature and moisture changes from a reference point can cause dimensional changes in the cylinder components, which can likely result in stresses within the cylinder. These stresses can result from either transient or steady-state conditions of temperature and moisture, as shown by Newhouse[2].

6.1.2 Pressure

Working pressures typically range from 5 bar to 20 bar for liquified gas applications, and up to 1 100 bar for compressed gas applications, with allowance for pressure increases due to temperature increases. The maximum allowable working pressure in stationary applications, more commonly known as the design pressure or maximum service pressure for this application, is the maximum pressure the cylinder can be exposed to. The pressure could be at the design limit regardless of the service temperature.

In transportable and vehicle fuel container applications, the working pressure is the settled pressure at 15 °C, and can increase up to about 130 % of the rated working pressure during extreme temperature conditions. Operating pressures will be below the rated working pressure when ambient temperature drops below 15 °C. Note that in North America, the reference temperature is usually 21,1 °C (70 °F).

Cylinders in various applications can also be subject to test pressures that are generally 150 % of the rated working pressure, but can range from 125 % to 167 % of the rated working pressure, with generally not more than 50 such cycles over a lifetime. Although some cylinder standards or regulations allow pressurizing to test pressure during fill, cylinders must not be filled with more gas than can settle to working pressure at 15 °C.

6.1.3 Pressure cycles

Some applications require only a limited number of cycles in a lifetime, so fatigue evaluation is not a significant concern. Such applications include emergency breathing cylinders, and fuel containers for fuel cells providing power when primary power is out of service. It can also include applications where the cylinder is in limited use, and could only experience one or two pressure cycles in a month.

Transportable cylinders are generally designed for a specified lifetime, either limited or non-limited, and qualified by conducting a specified number of cycles. A typical qualification test requirement is 12,000 cycles to test pressure, or in dedicated gas service 24,000 cycles to maximum developed pressure, for a non-limited life. For a limited life, cycling 250 times to test pressure, or in dedicated gas service 500 times to maximum developed pressure, per year of design life is a common requirement. Specific standards could require more or less cycles. Transportable cylinders are generally not expected to be filled more than once a day, and cycling to the test pressure provides a margin of safety.

Vehicle fuel tanks, containing either natural gas or hydrogen, could be filled two to three times a day in fleet use, such as in buses or medium- and heavy-duty trucks. This is the basis for qualification testing of 750 cycles to 1 000 cycles per year used in fuel container standards.

Stationary cylinders, generally referred to as pressure vessels, could be subject to a high number of pressure cycles. One such application is use as a refuelling cascade for natural gas and hydrogen powered vehicles. These cylinders could be in use continually as vehicles are brought in for refuelling, resulting in a high number of cycles per day. In some cases, the cylinders could be refuelled from another fuel reservoir, such as from a pipeline, as soon as the pressure begins to drop. These cylinders can see a very high number of partial cycles. Some cylinders can see a high number of partial cycles, combined with a given number of full cycles, in the course of a day.

6.2 Test conditions and specimens

Testing is generally conducted at ambient temperature. Care is taken to avoid testing at temperatures that can affect test results. Consideration is given to actual conditions, and how that can affect fatigue results.

Low temperatures can increase strength of the material being tested, but can also cause embrittlement that decreases the fatigue life. High temperatures can decrease the strength of material being tested. Extreme temperatures will also affect load share between liner and overwrap materials due to differences in thermal coefficient of expansion, and will also affect stress distribution if hybrid construction is used for the composite overwrap. For example, as temperature decreases, an aluminium alloy liner tends to decrease interface pressure with the composite overwrap, causing the liner to carry a larger percentage of the pressure load. Analysis needs to be conducted to evaluate the effect of temperature on stresses and strains within an actual cylinder.

Testing with liquid versus gas to pressurize a cylinder results in the same pressure on the inside of the cylinder, and therefore the same stress in the cylinder. However, there can be temperature differences resulting from the use of different fluids, depending on energy to compress the fluid. This could also be a consideration for the service conditions, although filling and discharge are generally over a longer time period in service compared with testing.

Fibre strength in the helical and hoop directions is the basic design criteria for design of the composite overwrap for the cylinder. As cylinder design pressure increases, laminate thickness is increased in order to maintain the stress and strain at the same level vs. their design stress and strain in the helical and hoop directions. Although the peak fibre stresses generally remain the same, the radial compressive stress increases in the inner part of the laminate. This change in stress conditions can have a significant effect on the fatigue life of the composite and of a metal liner. Therefore, consideration is given to test pressure versus service pressure when evaluating fatigue life.

Options for test specimens to evaluate laminate strength and fatigue resistance include flat coupons, tube sections, and cylinders. Each option has advantages and disadvantages. As the test specimen gets closer to the actual product configuration, the results will be more valid, but more difficult to obtain.

Flat coupons can include unidirectional specimens and cross-plied laminates. These specimens could be suitable for comparisons between fibres as to strength and fatigue properties, but are generally not suitable from which to predict cylinder performance directly. Loading is only in the principle direction, unlike the three-dimensional loading of a pressure cylinder. If loaded in tension, consider the stress concentrations caused by the grips, and the geometry of the specimen, including edge effects. If loaded in bending, consider that the specimen loading is further removed from the type of loading seen in a cylinder. Nevertheless, the ability to quickly test comparative specimens can have some value.

A flat coupon is not suitable for evaluating the interaction between a metal liner and a composite overwrap.

Tube specimens can include unidirectional specimens and cross-plied laminates. NOL[3] or ASTM[4] rings are one option for unidirectional tubular specimens. Tube specimens can also be wound with helical and/or hoop layers over a longer cylindrical mandrel. Cross-plied tube specimens could be tested in axial tension using end grips that interface with tube ends that have additional reinforcement to avoid grip failures. That is, the tube has similarity to a flat tensile specimen with wider or thicker ends (i.e. a “dog-bone” specimen).

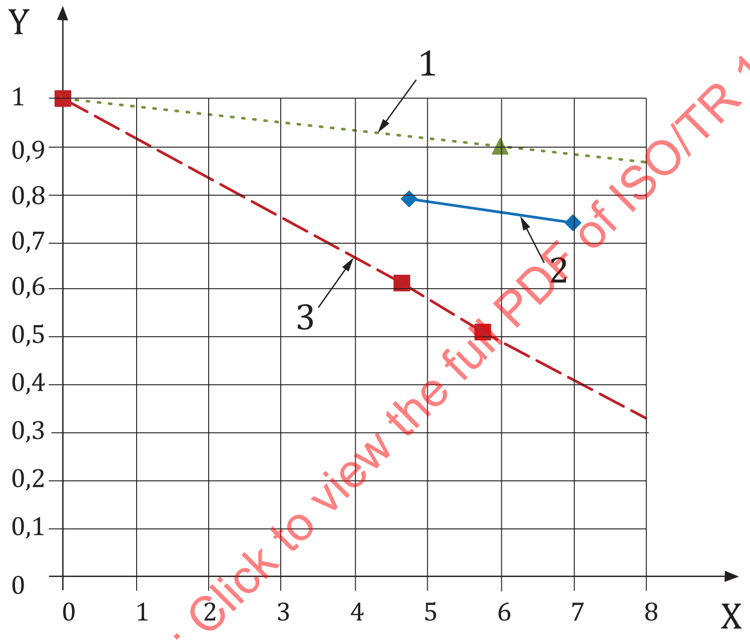
Tubular specimens can also be tested using internal pressure. The resultant will be hoop stress if the pressure source was contained within a double ended piston, so that axial load was contained within the piston. Alternatively, the tube will experience both hoop load and axial tension if the tube ends were closed such that the end closures apply tension to the tube, such as when doing an axial tension test, but using the internal pressure for loading.

A tubular specimen loaded in either axial tension or in hoop loading has advantages over a flat specimen given that it is testing of a curved specimen, but the single direction loading has limitations. As with a flat specimen, it is suitable for comparisons between fibres as to strength and fatigue properties, and gives more representative results, but is still not as accurate as an actual specimen. A tubular specimen loaded in both axial tension and hoop loading will have an even greater fidelity, with consideration to the level the laminate reflects the construction of an actual cylinder.

Cylinder specimens give the best fidelity when assessing strength and fatigue life. However, the relative cost can make them less attractive for a study involving many specimens. Subscale cylinder specimens offer an option for good fidelity at a lower cost than full scale cylinders.

Figure 1 shows how fatigue results can vary with the choice of test specimen. The upper line, with data from Mandell[5], reflects use of a unidirectional carbon fibre reinforced specimen loaded in tension. The middle line, with data from Liber and Daniel,[6] reflects use of a flattened tube with a symmetric laminate having longitudinal fibre layers and ±45° layers loaded in tension. This construction results in a more complex laminate, with more complex loading within the laminate. The data from this specimen shows a reduction in fatigue life compared with the test specimen using unidirectional fibre.

The lower line reflects cyclic pressure testing of high pressure gas cylinders. These cylinders have a more complex laminate and loading within the laminate than the test specimens of Mandell and of Liber and Daniel. The lower line reflects a reduction in life compared with the other two specimens, but it does contain some conservativism. The points plotted reflect test cycles conducted, but not necessarily with a resulting test failure. It therefore represents a lower limit on fatigue life, rather than an average life.



Key

X log cycles (10^x)

Y fraction of ultimate strength

1 mandell

2 liber and daniel

3 pressure vessel

Figure 1 — Fatigue results using different configuration test specimens

The data presented in Figure 1 reflects what was stated above, that cyclic fatigue performance depends on laminate construction, method of loading and other factors. Resin selection and laminate construction can also affect results, as load transfer through the wall is dependent on radial laminate properties. It is therefore accepted to demonstrate cyclic fatigue performance on a representative gas cylinder to properly address fatigue performance in service due to pressure cycling. Note that the lines from Mandell and Liber and Daniel reflect mean values, while the pressure vessel line reflects the methodology of this report.

The data presented in Figure 1 also indicates that cyclic fatigue testing can be accelerated by increasing the upper pressure limit. Sufficient cyclic fatigue data, over a range of stress levels, is needed to get representative results.

6.3 Fibre materials and their fatigue properties

6.3.1 Materials

Common composite reinforcing materials include glass, aramid and carbon fibres, generally filament wound with an epoxy or vinyl ester resin matrix. Other resin matrix materials could be suitable. Other reinforcing fibres could be available, but none have developed as being viable alternatives to glass, aramid and carbon fibre at this time.

Glass fibre was the first to be developed and was in use in the 1950s and 1960s. The most commonly used grade for gas cylinders is ECR-glass. This is fundamentally an E-glass, but has enhanced corrosion resistance resulting from removal of boron from the glass formulation. Other grades of glass fibre are suitable, but are less widely used. Glass fibre is essentially a super-cooled liquid, and is subject to creep flow and surface cracking. It has the least resistance to fatigue failure of the three commonly used fibre types.

Aramid fibre (aromatic polyamide) was developed in the 1960s and came into use in gas cylinders in the 1970s. It has greater strength, lower density and improved fatigue resistance compared with glass fibre. It has a long-chain molecular structure, with very high strength in the longitudinal direction, but relatively weak transverse properties.

Carbon fibre suitable for use in gas cylinders was developed in the 1960s and 1970s. It came into widespread use in commercial gas cylinders in the 1990s. Carbon fibre is more of a crystalline structure, and is generally processed from a PAN precursor. It has higher tensile strength and modulus than glass and aramid fibre. Carbon fibre has the best fatigue resistance of the commonly used fibre reinforcements, but is more sensitive to mechanical impacts.

6.3.2 Material properties and data

Table 1 provides typical properties for glass, aramid and carbon fibres. Actual fibres used could have higher or lower values, particularly for strength and modulus, depending on the characteristics of the fibre.

Table 1 — Typical fibre properties

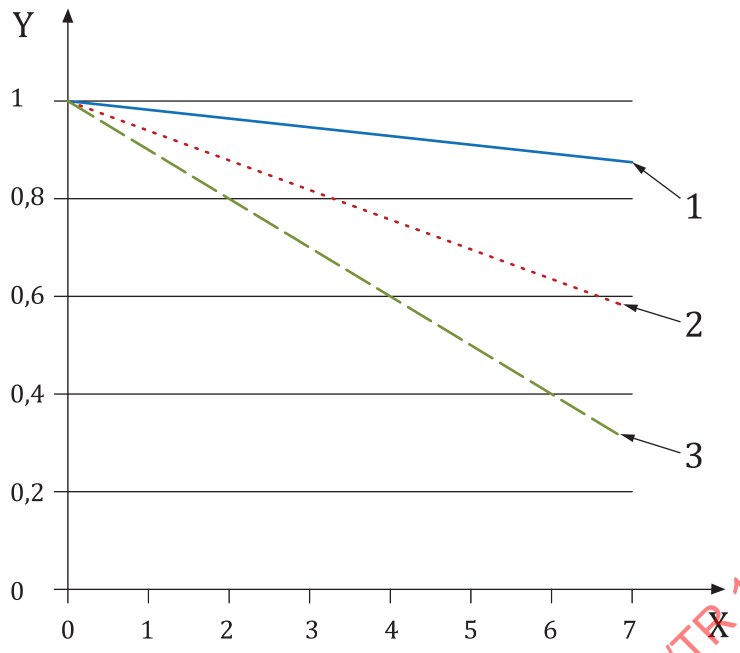
Property	ECR-Glass	Aramid	Carbon
Tensile strength, MPa (ksi)[a]	1 500 (220)	2 500 (360)	4 500 (650)
Working strength, MPa (ksi)[b]	430 (63)	830 (120)	2 000 (290)
Tensile modulus, GPa (msi)	72 (10,5)	131 (19)	220 (32)
Density, g/cc (pounds per cubic inch)	2,55 (0,092)	1,44 (0,052)	1,80 (0,065)

[a] Nominal design fibre strength in the hoop direction of a pressure vessel at minimum burst pressure.

[b] Nominal design fibre strength in the hoop direction of a pressure vessel at service pressure.

NOTE ECR refers to corrosion resistant E-glass, from which boron has been removed as a constituent.

Figure 2[5] compares nominal cyclic fatigue for glass, aramid and carbon fibre.



Key

X log (cycles to fail, N)

Y maximum stress/static strength

1 carbon

2 aramid

3 glass

Figure 2 — S/N data for carbon, aramid and glass reinforcement

6.3.3 Hybrid construction

Some gas cylinders are manufactured using hybrid construction. That is, using two or more different reinforcing fibres in the gas cylinder. This could be a combination of a glass and carbon fibre, or it could be a combination of two different carbon fibres. This can be in the form of intraply hybrids, where there are different fibres within a single winding band, or it can be alternating layers of fibres.

Hybrid construction is discussed here in terms of structural reinforcement. However, in some cases, materials such as glass fibre can be wound on the outside surface as a protective layer. This layer is generally not considered structural, but there is an awareness that it does have a contribution to the structure and could share load.

The evaluation and analysis of hybrid construction can be accomplished by considering the basic elements being evaluated. With a layered hybrid, each layer can be modelled using the properties of the single material, with consideration for orientation. With an intraply hybrid, consider the number of fibre tows of each material in the strand, the cross-sectional area of each tow, and the mechanical properties of each fibre, in order to calculate the equivalent properties.

The concept of generalized plane strain applies to calculation of mechanical properties and strain within the band and laminate. That is, all tows within the band have the same axial strain. The mechanical properties in the fibre direction are based on the effective area and modulus of each material. Once the strains for the laminate have been calculated, the strain in each fibre, along with the elastic modulus of the fibre, determine the stress in the fibre.

In-plane transverse property calculation is a bit more involved, as the materials are in series rather than in parallel. However, computer software is available that will evaluate the properties of a hybrid band. Also, the in-plane transverse stiffness of the laminate is less significant than the properties in the direction of the band, so the properties in the direction of the band dominate the laminate response to loading.

6.4 Liner materials and their fatigue properties

6.4.1 Materials used

Liners are generally made of metals or polymers. Aluminium alloys, carbon steel, CrMo steel or stainless steel are the most commonly used metal liner materials. Polymer liner materials are often high-density polyethylene (HPDE), or polyamide (PA) materials.

Metal liners generally carry part of the structural load, with consideration for liner thickness, as a result of their relatively high elastic modulus. Given that the composite material is the primary reinforcement material, it is generally the dominant factor in the strains seen at working pressure, and could result in the metal liner being used at strain levels in the liner that are greater than is used in an all-metal cylinder of the same material. High strain levels will have an influence on the liner fatigue life.

Polymer liner materials are generally non-load sharing, regardless of thickness. The strain in the liner is fully dependent on the composite. Given that the polymer elastic modulus is low, it is generally in a state of compressive stress at working pressure, as the Poisson's effects from radial pressure overcome the in-plane tensile strain.

Polymer liners generally have a metal end boss. Materials suitable for liners are generally suitable for end bosses. Many other metals or alloys are also suitable for use as an end boss on a polymer liner, as the end boss can be designed with more options for geometry than can the ends of one-piece (seamless) liners.

6.4.2 Material properties and data

Properties of some commonly used metal and polymer liner materials are given in Table 2 and Table 3. These properties are provided for general information, and can be confirmed before use in analysis. Other metal alloys or polymers are also suitable for use as liners.

Table 2 — Typical metal liner properties

Property	Aluminium alloy	Carbon steel	Stainless steel
Alloy-heat treat	6 061-T6	4 340	SS 316
Tensile strength, MPa[a]	260	690	580
Elongation, %	10	21	50
Tensile modulus, GPa	68	200	190
Poisson's ratio	0,33	0,30	0,29
Density, g/cc	2,71	7,85	8,03

[a] Nominal design strength in a pressure cylinder at minimum burst pressure.

Table 3 — Typical polymer liner properties

Property	HDPE	PA
Tensile strength, MPa	27	72
Elongation, %	600	100
Tensile modulus, GPa	0,97	1,45
Poisson's ratio	0,40	0,40
Density, g/cc	0,96	1,13

6.4.3 Issues with localized strain differences

The cylindrical portion of a gas cylinder is generally at a constant thickness, and generally has equal strain at all locations. Therefore, the fatigue characteristics of the composite and liner are nearly constant over this region. However, there are localized conditions that require more detailed evaluation for fatigue. Some examples are:

— The liner could have stress concentrations if it is welded.

— There could be bending stresses in the dome region that add to the extensional stresses.

— There are generally stress/strain discontinuities at the juncture of the cylinder and dome.

— The boss flange and neck could be different materials (as is the case with a polymer liner) and thicknesses than the liner membrane.

— The transition from the flange to the membrane thickness of the liner generally results in strain concentrations.

6.5 Resin materials and their fatigue properties

Resin matrix materials used in the composite construction are generally thermoset, but can also be thermoplastic. Thermoset materials are typically epoxy, vinyl ester or polyester. The resin matrix is primarily used to hold the fibre materials in place, and to facilitate transfer of radial compressive loads with the laminate.

The resin matrix does not contribute significantly to the in-plane strength of the laminate. It will generally micro-crack, or craze, when taken to test pressure, and this micro-cracking could progress further as the cylinder is pressure cycled. This micro-cracking could have some effect on the fatigue life of the laminate.

6.6 Composite/liner load sharing

The load sharing between the laminate and the liner, and between fibres within a laminate, will have an influence on fatigue. The in-plane strains, in particular, are affected by load sharing. Load sharing will depend on relative fibre stiffness within hybrid composites, and will depend on the stiffness of the laminate compared with the stiffness of the liner.

Load sharing could depend on manufacturing processes. One factor is the fibre tension during winding. High tension will apply a compressive pre-load to the liner. However, resin can flow out of the laminate during winding, reducing this compressive pre-load somewhat. Thermosetting resins can be more subject to such flow than thermoplastic resins.

A second factor in load sharing is the effective “stress-free” temperature of the composite and liner. The temperature during the winding process, and during the curing process, will affect the “stress-free” temperature. The difference between the “stress-free” temperature and the ambient temperature can result in tensile or compressive stresses in the liner or composite. Note that “stress-free” can be relative, as some thermally induced stresses could always be present in the laminate.

A third factor in load sharing involved the autofrettage process, which is discussed in 6.7. Autofrettage will result in residual compressive stress in the liner, and residual tensile stress in the composite.

6.7 Autofrettage

Autofrettage is one method of improving cyclic fatigue life of a metal liner. The cylinder is pressurized to achieve liner yielding. Autofrettage pressure can be held for a sufficient length of time that the liner does not yield further. A typical time is 1 min. This preload results in a net compression in the liner at zero pressure, thereby reducing the average stress in the liner while pressurized. A reduced average stress during pressure cycling increases the fatigue life of a metal liner. The yielding of the liner during autofrettage also blunts any stress concentrations (e.g. cracks), which will increase the fatigue life of the liner.

However, the compressive preload in the liner results in a tensile preload in the composite reinforcement. Care is taken to avoid putting too much preload into the composite, as it could result in excessive stress, resulting in violation of the stress ratio requirements, as explained further in ISO/TR 13086-3[7].

Autofrettage will not improve the cyclic fatigue life of a polymer liner, given that it is non-structural, and generally will not yield during pressurization.

6.8 Analysis methods

Fatigue performance of the composite reinforcement and the liner are generally confirmed by means of performance testing. However, analysis of the cylinder to determine stresses and strains, particularly where there could be localized stresses and strain peaks, is of great value in understanding margins of safety, and evaluate means to improve on the fatigue performance of the cylinder reinforcement and liner.

Finite element analysis is a generally accepted method of determining stresses and strains throughout the cylinder. There are closed form methods that can also be used, particularly in the cylindrical portion of the gas cylinder, where the stresses and strains are not dependent on axial or circumferential location.

Regardless of the analysis method, it is appropriate to validate the analysis results by means of strain gages, displacement gages, or other mechanical means to measure the actual strains and/or displacements.

Knowing the stresses and strains during cycling, the fatigue life of the composite reinforcement can be predicted by, and compared with, data such as that presented in Figures 1 and 2. The stresses and strains in a polymer can similarly be used to predict liner cyclic fatigue life. However, it is noted that, depending on the modulus of the polymer, the liner will likely be in compressive stress when pressurized, so there is little tendency for crack formation and growth.

For a metal liner, knowing the stresses and strains, and the effect of contained gases (such as hydrogen), will facilitate prediction of liner cyclic fatigue life. Fracture mechanics is one method to predict life of the metal liner. A second method is to use fatigue curves generated by testing, such as those in MIL-HDBK-5J[8]. A third method is to use empirical methods based on evaluation of data.

One such empirical method is the low cycle fatigue equation developed by S.S. Manson[9]:

$$\Delta\varepsilon = V_1 \cdot \frac{\sigma_{\text{ult}}}{E} \cdot N_{\text{f}}^{V_3} + \left[\ln \frac{1}{1-R_A}\right]^{V_2} \cdot N_{\text{f}}^{V_4}$$

where

N_{f}	is the fatigue life;
$\Delta\varepsilon$	is the strain range;
σ_{ult}	is the ultimate strength;
E	is the Young's modulus;
R_A	is the reduction of area for the metal material;
V_1	= 3,5;
V_2	= 0,6;
V_3	= 0,12;
V_4	= 0,6.

6.9 Leak before burst (LBB)

Leak before burst (LBB) is a term used to describe a preferred failure mode when a cylinder is pressure cycled to failure. LBB is not applicable to the failure mode in a burst test. A metal cylinder generally meets this requirement by use of a material that was ductile to a point where a through crack is not likely to propagate rapidly. It could also use an intentional flaw to initiate fatigue failure in a region of the cylinder that is resistant to rapid flaw growth.

Typically, the fatigue life of a metal liner is lower than that of the composite reinforcement. With proper material selection and design, liner fatigue failure results in leakage rather than rupture. However, if the liner carries a large enough fraction of the load, and a through crack results in rapid failure of the liner, it is possible to dynamically transfer the liner load into the composite reinforcement, resulting in a rupture.

It is generally accepted that if the margin against failure by pressure cycling is sufficiently high, such that the likelihood of fatigue failure is low, the cylinder is safe for use. The safety factor on cycling is generally 2 or 3 times the maximum number of cycles expected in the lifetime of the cylinder. Some standards have addressed LBB by pressure cycling to test pressure. Alternatively, a weak point could be designed into a component, such as an end boss, that results in failure by leakage before burst.

6.10 Damage tolerance

Damage tolerance of the laminate will affect its cyclic fatigue life. Impact damage, cuts and abrasions could directly cut or remove fibre in the laminate. This can reduce laminate strength at the points surrounding the damage, resulting in higher stresses locally, and propagate damage further into the laminate. Such damage can directly reduce the fatigue life of the composite.

Damage to the laminate effectively reduces the local stiffness of the composite. This in turn can transfer more load into the surrounding composite and into a metallic liner. A higher stress/strain in the liner in a localized area can effectively reduce the fatigue life of a metal liner or a polymer liner.

6.11 Aging and environment

One element of aging is stress rupture, discussed in ISO/TR 13086-1[10]. Stress rupture and pressure cycling each reduce the strength of the laminate, and will therefore interact to reduce the stress rupture life and the cyclic fatigue life.

The cyclic fatigue life of the cylinder can also be reduced by fluids found in the environment if those fluids reduced the strength or modulus of the laminate. Either the fibre or the resin can be affected by these fluids to a point of reducing fatigue life.

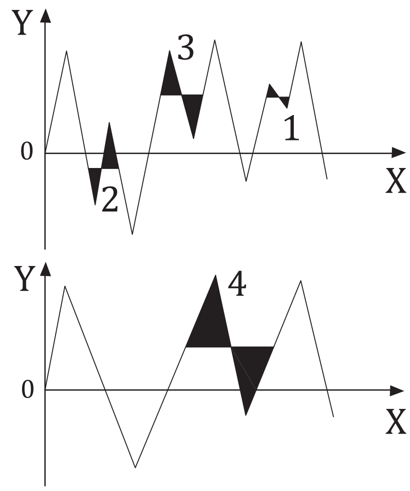
Temperature extremes can also affect cyclic fatigue life of the composite or the liner. Cold temperatures can cause embrittlement of the materials, thereby reducing fatigue life. High temperatures can directly reduce strength of the fibre, resin, and/or liner materials. High temperatures can also directly reduce fatigue life if the materials are subject to Arrhenius rate equation effects.

Exposure to ultraviolet light can also reduce strength of the laminate, and therefore reduce fatigue life. Such strength reduction is generally limited to the outermost layer of the composite.

6.12 Counting cycles

It is easy to count the number of cycles applied when a gas cylinder is subjected to cycles that are full range, which is typical of industrial gas cylinders. Similarly, if the cylinder is subjected to specific ranges, e.g. X cycles from 50 % to 100 %, and Y cycles from 0 % to 100 %, it is easy to count cycles.

When the cylinder is subjected to cycles with varying or random cycles, such as encountered by cylinders used in a natural gas vehicle refuelling cascade, counting models are generally used to evaluate fatigue. Two models in use are range pair cycle counting and rain-flow cycle counting, shown in Figures 3 and 4. Range pair counting starts with small ranges, then removes them, reconnects the ends and goes to the next smallest range, until all cycles are counted. The top half of Figure 3 shows the small ranges being identified, while the bottom half shows the ends reconnected. Rain-flow counting works by turning the cycle plot 90°. Consider each resulting line to be a "roof" from which water can flow down and over the tensile and compressive peaks. The half-cycles are counted, and tensile and compressive half-cycles paired. The bottom half of Figure 4 shows correlation between hysteresis cycles equivalent to some of the history in the top half. ASTM E 1049-85 (reaffirmed 2017)[11] has compiled and explained these and other procedures for cycle counting.



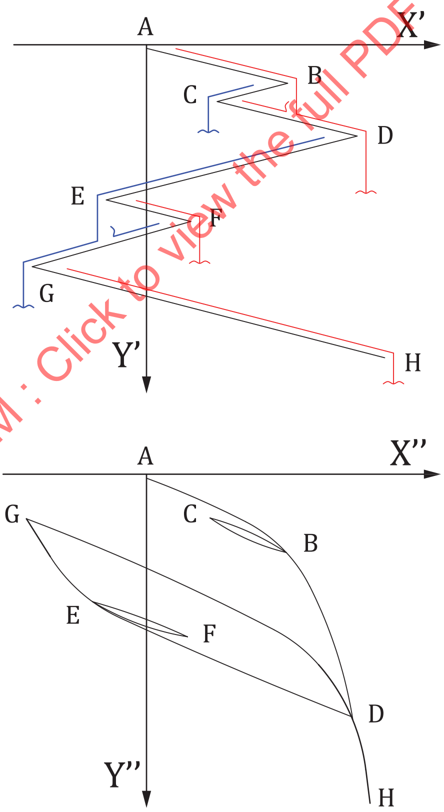
Key

1, 2, and 3 reflect small ranges that are counted and removed

4 reflects a range that can be removed once the ends from 1, 2, and 3 are reconnected

Y pressure

Figure 3 — Range pair cycle counting



Key

X' load

Y' time

X'' stress

Y'' strain

Figure 4 — Rain-flow cycle counting

6.13 Combining cycles

It is easy to determine the cycle testing protocol when all cycles are full range. The cycles are applied with the multiplier required by the standard being used. Is it similarly easy to determine the cycle testing protocol when a limited number of cycles, and a limited number of cycle ranges, are used. However, when the cycle requirements are somewhat random, and involve many small range cycles, the cycle testing protocol becomes more complicated.

It is not practical to treat all cycles as full cycles if there are a very high number of partial cycles, particularly when the range on the cycles is small. A cylinder with a nominal fatigue life of 50,000 cycles could safely be used for an application with 5 million cycles from 90 % to 100 % of the working pressure, but it is not reasonable to test the cylinder for 5 million cycles from 0 % to 100 % of working pressure. However, it is possible to effectively assess the cycles to be applied in service, and calculate a cycle testing protocol using an equivalent number of full pressure cycles to working pressure, to test pressure, or to an even higher pressure.

Goodman diagrams are a well-recognized and widely used means of evaluating equivalent fatigue cycles. A Goodman diagram can be developed from an S/N curve developed from test data. A Goodman diagram can be used to assess fraction of life used by any full or partial cycle range. A given number of cycles, say from 30 % to 80 %, 40 % to 100 %, or any selected range, can be equated to an equivalent number of full pressure cycles to working pressure or elevated pressure. This greatly simplifies qualification testing.

Annex A gives a detailed explanation of the development of an S/N curve, and from that a Goodman diagram. It provides best practices in developing these curves. It also uses the resultant Goodman diagram to provide an example of an assessment of combined full and partial cycles. There are other methods available to assess combined full and partial cycles.

6.14 Qualification testing

Burst and pressure cycling are the key qualification tests to assess fatigue capabilities of the cylinder. The burst test is conducted to assess compliance of the design to the requirements of the specification and the standard, and to confirm the anchor point for an S/N curve and Goodman diagram.

The pressure cycle testing directly confirms the ability of a cylinder to meet the specification and the standard requirements, with margin, in the case where full range pressure cycles are expected. The pressure cycle test, combined with an assessment using a Goodman diagram, confirms the ability of a cylinder to meet requirements for a combination of full and partial cycles.

7 Summary and conclusions

Each of the topics of Clause 5 have been addressed in the discussion in Clause 6. This provides a better understanding of the design, materials, testing and operating issues associated with fatigue life and testing of gas cylinders. Methods for counting partial cycles, and for assessing complex cycle requirements using a Goodman diagram to identify equivalent full range pressure cycles have also been identified.

The understanding developed, and analytical methods discussed, lead to better understanding of fatigue issues, improved safety, and more appropriate and effective qualification testing.

Annex A
(informative)

Equivalent pressure cycling

A.1 Purpose

This annex contains information regarding the development of S-N diagrams and Goodman diagrams for the purpose of evaluating equivalent full pressure cycles at elevated pressure, rather than testing all combinations of full and shallow cycles, so that the total number of test cycles be reduced, yet provide assurance that the pressure vessel can meet life requirements with high reliability.

A.2 Developing an S-N diagram (Strength – Number of cycles)

The pressure vessel manufacturer is responsible for developing the S-N diagram based on using the same materials and manufacturing approach used for the pressure vessels to be developed. The S-N curve, also known as a Wöhler curve, plots applied stress (S) against component life or number of cycles to failure (N). As this is an S-N diagram to evaluate fatigue characteristics of the total vessel, the failure mode is consistent, recognizing this generally results in composite failure for a Type 4 cylinder (i.e. all results are composite burst, not liner leakage), or liner failure for a Type 2 or Type 3 cylinder (i.e. all results are liner leakage, not composite burst).

The goal is to assess projected life for any type of pressure vessels, where the life is based on fatigue of vessel components. For Type 2 and Type 3 construction, the liner is the component likely to fatigue, creating a leak path through the liner, before the composite is fatigued to the point of failure. For Type 4 construction, the non-metallic liner is generally in compression, and not as likely to fatigue to a point of leakage prior to the composite reinforcement component reaching its point of failure. Regardless of which component of the pressure vessel fails, the approach to developing the S-N diagram is similar as long as the failure mode is consistent for the particular design or design family being evaluated. The pressure vessel manufacturer will have built the vessels tested for use in developing the S-N diagram and Goodman diagram.

For all cycle testing, it is accepted that cycle be no more than 10 cycles/min.

The following steps are used for a Type 4 cylinder:

a) Establish the mean burst pressure of the vessel used to develop the S-N diagram. A minimum of 10 units are used. Plot this point as 100 % stress, 1 cycle on the S-N diagram.

b) Cycle a minimum of 4 pressure vessels from no more than 10 % of nominal working pressure to a first specified pressure level for which the stress is known. Plot this point on the S-N diagram. The S value will be the stress relative to the mean burst, the N value will be either the point of first failure, or the point at which cycling was stopped if there was no failure.

c) Cycle a minimum of 4 pressure vessels from no more than 10 % of nominal working pressure to a second specified pressure level for which the stress is known. Plot this point on the S-N diagram as was done for the first specified pressure level.

d) Draw a line from the 100 %-1 point (burst) through the fatigue point that gives the lower of lines. This will be the characteristic line.

The following steps are used for a Type 2 or Type 3 cylinder:

a) Cycle a minimum of 4 pressure vessels from no more than 10 % of the design pressure to a first specified pressure for which the stress is known. Plot this point on the S-N diagram. The N value will be either the point of first failure, or the point at which cycling was stopped if there was no failure.

b) Cycle a minimum of 4 pressure vessels from no more than 10 % of the design pressure to a second specified pressure level for which the stress is known. Plot this point on the S-N diagram. The *N* value will be either the point of first failure, or the point at which cycling was stopped if there was no failure. The second cycle point could be at least 1 decade above the first cycle point, i.e., if the first failure point is at 1,000 cycles, the second point could be at least 10,000 cycles.

c) Cycle a minimum of 4 pressure vessels from no more than 10 % of the design pressure to a third specified pressure level for which the stress is known. Plot this point on the S-N diagram. The third cycle point could be at least 1 decade above the second cycle point as was done for the first specified pressure level.

d) Draw a best-fit line through the three fatigue points, then offset the line to be parallel such that each of the failure points is on or above the offset line. This will be the characteristic line.

The following criteria also apply:

— More than three points can be plotted. If the points are such that the three points are not linear, but indicate a curve or bi-linear result, consideration might be given to developing one or more additional data sets to better understand the cylinder's cycle life vs. pressure range, and thereby develop a more precise Goodman Diagram.

— For the data point plotted, either:

  1) one point has more than 10,000 cycles, and one point has more than 100,000 cycles, or

  2) partial cycles are projected to a limit of 20 times the point with higher cycles.

— Fatigue point data could be used from different pressure vessel designs, given that plotting is done as a percent of strength, providing the construction is sufficiently similar so as to give consistent fatigue results.

— To provide consistency of results, the test vessels meet the following criteria:

  1) Test vessels are at least 22,9 cm (9 in) in diameter.

  2) The cylinder length (total vessel length less domes and end features) has a cylinder length at least equal to the diameter.

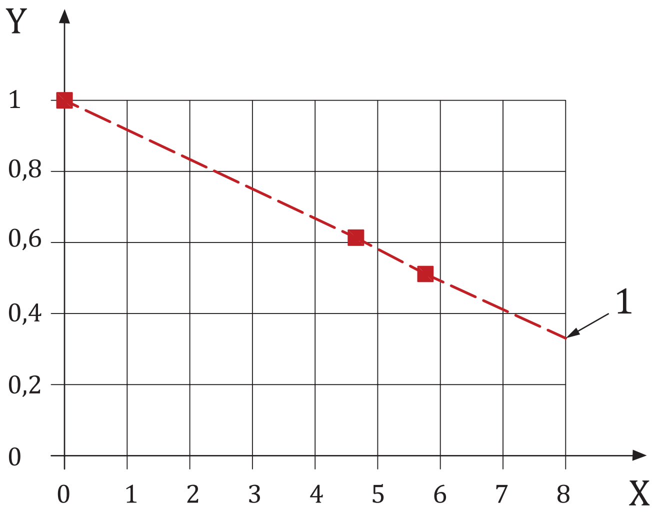
  3) The primary reinforcing materials are the same:

    i) Carbon reinforced vessel testing results can be used for carbon and carbon/glass intraply hybrid vessel evaluation.

    ii) Carbon/glass reinforced intraply hybrid vessel testing results can be used for carbon and carbon/glass intraply hybrid vessel evaluation.

    iii) All-glass reinforced vessel testing results can be used for all-glass vessel evaluation.

Figure A.1, illustrates an S-N diagram based on the above development.



Key

X log cycles (10^x)

Y fraction of ultimate strength

1 pressure vessel

Figure A.1 — Carbon composite fatigue life versus load level

In constructing Figure A.1, actual test data was generally used to develop the cycles versus the maximum pressure used in the test as follows:

a) The first data point is based on numerous burst test results from a number of vessels in a given design family (same materials = carbon fiber/epoxy resin, same factor of safety = 2,25 minimum, similar sizes, same working pressure = 240 bar). In this case, the mean burst pressure is 2,5× working pressure. This margin ensures that, with scatter of test results, there are no failures. Use of the nominal design burst is conservative when building the S/N diagram, as it makes the resulting line steeper when compared with using the minimum burst pressure.

b) The second data point is based on cycling to test pressure (1,5× working pressure) on a significant number of vessels in a given design family. Some standards for composite vessels require testing for 45,000 cycles to test pressure without rupture (Y = 0,6 = 1,5/2,5, X = log 45,000). The tests are generally stopped at this time, so the data point reflects a “no failure” condition.

c) The third data point is projected on cycling to 1,25× working pressure. The projected number of cycles for this test is about 600,000 cycles (Y = 0,5 = 1,25/2,5, X = log 600 000).

The above example reflects one design family from one manufacturer and is not intended to be used for other design families or beyond reasonable limits of actual testing. Each manufacturer develops an S/N curve and Goodman Diagram based on testing of their design family, as the data can likely differ from manufacturer to manufacturer.

A.3 Equivalent pressure cycling

The S-N diagram (Figure A.1) can be used to specify an alternate pressure to demonstrate fatigue resistance. For example:

— Assume the requirement for full cycles is 10^7 full pressure cycles (10,000,000). The vessel is designed so the stress is no more than 40 % of the mean burst pressure.

— The same vessel can be expected to withstand about 10^2 full pressure cycles (100) at about 80 % of the mean burst pressure. If the number of pressure cycles exceed 100 when cycled from 0 % to 80 % pressure without failure, the design is qualified.