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Gas cylinders — Guidance for design of composite cylinders —

Part 4: Cyclic fatigue of fibres and liners

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Foreword

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

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

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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 http://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 may 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 would 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 may 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 will 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. 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;

— 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 may 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 would 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 should 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 required 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 would 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 may 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 should not be filled with more gas than would 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 should be taken to avoid testing at temperatures that would affect test results. Consideration should be 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 would decrease 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 would tend to decrease interface pressure with the composite overwrap, causing the liner to carry a larger percentage of the pressure load. Analysis would need to be conducted to evaluate the effect of temperature on stresses and strains within an actual cylinder.

Testing with liquid vs. 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 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 should be 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 would generally not be suitable from which to predict cylinder performance directly. Loading would only be 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 would not be 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 would have similarity to a flat tensile specimen with wider or thicker ends (i.e. a “dog-bone” specimen).

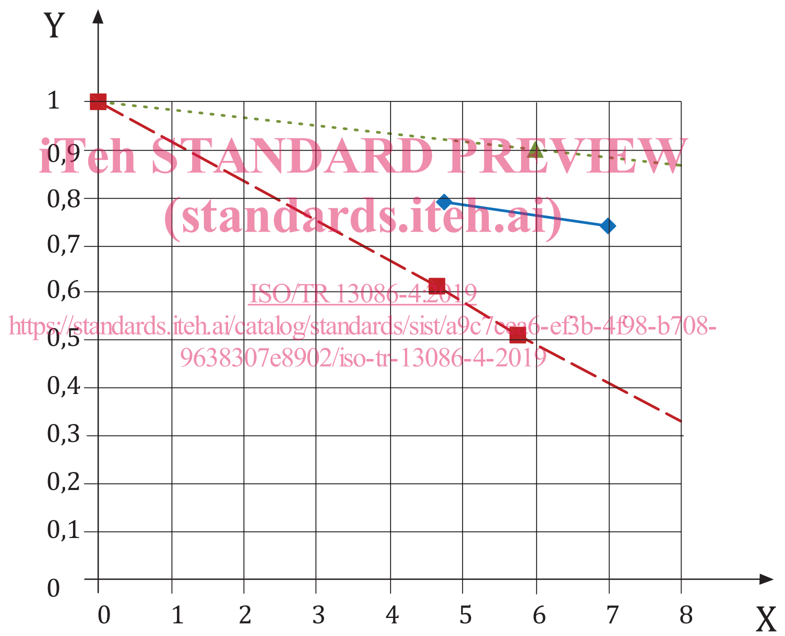
Tubular specimens can also be tested using internal pressure. The resultant would be hoop stress if the pressure source was contained within a double ended piston, so that axial load was contained within the piston. Alternatively, the tube could experience both hoop load and axial tension if the tube ends were closed such that the end closures would 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 would give 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-degree 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

···▲···	Mandell	X	Log cycles (10^x)
—◆—	Liber and Daniel	Y	Fraction of ultimate strength
– ■ –	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 necessary 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

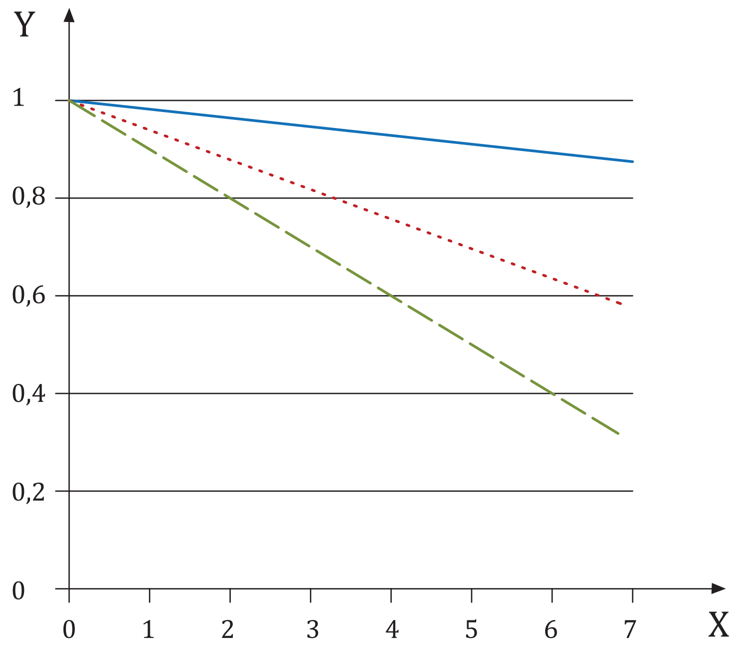
Property	ECR-Glass	Aramid	Carbon
Tensile strength, MPa (ksi)[a]	1 500 (220)	2 500 (360)	4 500 (650)
Working strength, MPa (ksi)[b]	430 (63)	830 (120)	2 000 (290)
Tensile modulus, GPa (msi)	72 (10,5)	131 (19)	220 (32)
Density, g/cc (pounds per cubic inch)	2,55 (0,092)	1,44 (0,052)	1,80 (0,065)

[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

——	carbon	X	Log (cycles to fail, N)
·······	aramid	Y	Maximum stress/static strength
– – –	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 may not be considered structural, but there should be 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 would apply to calculation of mechanical properties and strain within the band and laminate. That is, all tows within the band would 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.