# Filament-wound FRP pressure vessels — Materials, design, manufacturing and testing

The European Standard EN 13923:2005 has the status of a British Standard

ICS 23.020.30



British Standards

# National foreword

This British Standard is the official English language version of EN 13923:2005. Along with the publication of BS EN 13121-3, it will partially supersede BS 4994:1987. BS EN 13923:2005 is primarily for the design and manufacture of simple one piece GRP pressure vessels, with a minimum of branches fixed integrally within the dome ends and along the axis of the vessel.

The UK participation in its preparation was entrusted by Technical Committee PRI/5, UK steering committee for CEN/TC210 'GRP tanks', to Subcommittee PRI/5/1, Reinforced plastic tanks and vessels, which has the responsibility to:

— aid enquirers to understand the text;

— present to the responsible international/European committee any enquiries on the interpretation, or proposals for change, and keep UK interests informed;

— monitor related international and European developments and promulgate them in the UK.

A list of organizations represented on this subcommittee can be obtained on request to its secretary.

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**Summary of pages**

This document comprises a front cover, an inside front cover, the EN title page, pages 2 to 41 and a back cover.

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**This British Standard was published under the authority of the Standards Policy and Strategy Committee on 22 February 2006**



**ISBN 0 580 47538 7**

**Amendments issued since publication**

| Amd. No. | Date | Comments |
|---|---|---|
| | | |
| | | |
| | | |
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EUROPEAN STANDARD

NORME EUROPÉENNE

EUROPÄISCHE NORM

# EN 13923

November 2005

ICS 23.020.30

English Version

# Filament-wound FRP pressure vessels - Materials, design, manufacturing and testing

Récipients sous pression en PRV par enroulement filamentaire - Matériaux, conception, fabrication et essais

Fadengewickelte Druckbehälter aus textilfaserverstärkten Kunststoffen - Werkstoffe, Konstruktion, Herstellung und Prüfung

This European Standard was approved by CEN on 22 September 2005.

CEN members are bound to comply with the CEN/CENELEC Internal Regulations which stipulate the conditions for giving this European Standard the status of a national standard without any alteration. Up-to-date lists and bibliographical references concerning such national standards may be obtained on application to the Central Secretariat or to any CEN member.

This European Standard exists in three official versions (English, French, German). A version in any other language made by translation under the responsibility of a CEN member into its own language and notified to the Central Secretariat has the same status as the official versions.

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Ref. No. EN 13923:2005: E

# Contents

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# Foreword

This European Standard (EN 13923:2005) has been prepared by Technical Committee CEN/TC 210 "GRP tanks and vessels", the secretariat of which is held by DIN.

This European Standard shall be given the status of a national standard, either by publication of an identical text or by endorsement, at the latest by May 2006, and conflicting national standards shall be withdrawn at the latest by May 2006.

This European Standard falls under the Pressure Equipment Directive (PED) and supports essential requirements of this EC Directive.

For relationship with EU Directive(s), see informative Annex ZA, which is an integral part of this European Standard.

According to the CEN/CENELEC Internal Regulations, the national standards organizations of the following countries are bound to implement this European Standard: Austria, Belgium, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Norway, Poland, Portugal, Slovakia, Slovenia, Spain, Sweden, Switzerland and United Kingdom.

# Introduction

This European Standard specifies two design methods for filament wound GRP pressure vessels. In this European Standard only the winding is considered in the calculation of the strength and the stiffness of the shell.

Method A, describes the calculation of the reinforcement of the cylindrical shell and the end domes based on netting theory. The design is verified by prototype testing.

Method B, describes the calculation of the reinforcement of the cylindrical shell and the end domes based on laminate theory.

The design and manufacture of filament wound GRP pressure vessels involve a number of different materials, such as resins, thermoplastics and reinforcement fibres. It is implicit that vessels conforming to this European Standard should be made only by manufacturers and operators who are competent and suitably equipped to fulfil all requirements, using materials manufactured by competent and experienced material manufacturers.

This European Standard specifies stress and strain limits and the requirements for the acceptance testing.

## 1 Scope

This European Standard specifies the requirements for the design including raw materials, calculation, manufacturing including composite materials, and testing of seamless Glass Reinforced Plastic (GRP) pressure vessels with protective layer, using only multi-directional filament winding, made in a factory and for use above ground and for storage and processing of fluids.

This European Standard covers vessels subject to pressures below 20 MPa and temperatures between – 30 °C and 120 °C.

Excluded from this European Standard are transportation vessels, double wall vessels, vessels under negative pressure, vessels which are subjected to the risk of explosion or failure of which may cause an emission of radioactivity.

## 2 Normative references

The following referenced documents are indispensable for the application of this European Standard. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

EN 13121-1:2003, *GRP tanks and vessels for use above ground — Part 1: Raw materials — Specification conditions and acceptance conditions*

EN 13121-2:2003, *GRP tanks and vessels for use above ground — Part 2: Composite materials — Chemical resistance*

prEN 13121-3:2004, *GRP tanks and vessels for use above ground — Part 3: Design and work-manship*

EN ISO 527-4, *Plastics — Determination of tensile properties — Part 4: Test conditions for isotropic and orthotropic fibre-reinforced plastic composites (ISO 527-4:1997)*

EN ISO 14129, *Fibre-reinforced plastic composites — Determination of the in-plane shear stress/shear strain response, including the in-plane shear modulus and strength, by ± 45° tension test method (ISO 14129:1997)*

EN ISO 75-2:2004, *Plastics — Determination of temperature of deflection under load — Part 2: Plastics and ebonite and long-fibre-reinforced composites (ISO 75-2:2004)*

EN ISO 75-3, *Plastics — Determination of temperature of deflection under load — Part 3: High-strength thermosetting laminates (ISO 75-3:2004)*

ISO 2602, *Statistical interpretation of test results — Estimation of the mean — Confidence interval*

## 3 Terms and definitions

For the purpose of this European Standard, the following terms and definitions apply.

**3.1**
**manufacturer**
organisation that manufactures the vessel in accordance with this European Standard

**3.2**
**material manufacturer**
organisation that manufactures the specific material (e.g. resin, glass fibre or catalyst). The material manufacturer may also be the "supplier"

**3.3**
**purchaser**
organisation or individual that purchases the vessel

**3.4**
**supplier**
organisation that supplies materials or products to the manufacturer for use in manufacturing the vessel. The supplier may be either the material manufacturer or an intermediary

**3.5**
**pressure vessel**
housing designed and built to contain fluids under pressure including its direct attachments up to the coupling point connecting it to other equipment. A vessel may be composed of more than one chamber

**3.6**
**protective layer**
chemical resistant layer (CRL) or a thermoplastic lining (TPL) in accordance with Clause 4 of EN 13121-2:2003, intended to serve as a barrier against chemical attack of the structural laminate and to prevent leakage

**3.7**
**pressure**
pressure relative to atmospheric pressure, i.e. gauge pressure. As a consequence, vacuum is designated by a negative value

**3.8**
**maximum allowable pressure PS**
maximum operating pressure for which the equipment is designed, as specified by the manufacturer. This is identical to the design pressure

**3.9**
**maximum/minimum allowable temperature TS**
maximum/minimum temperature for which the equipment is designed, as specified by the manufacturer. The maximum allowable temperature is identical to the design temperature

**3.10**
**lamina**
ply or layer of glass reinforced thermosetting resin

**3.11**
**laminate**
composite structure consisting of one or more lamina

**3.12**
**filament winding**
production technique for winding of continuous filaments of glass fibre with the specified resin system applied in a systematic manner and cured on a mandrel or other supporting structure

**3.13**
**chemical resistant layer (CRL)**
protective layer in accordance with 4.3 of EN 13121-2:2003

**3.14**
**thermoplastic lining (TPL)**
protective layer in accordance with 4.4 of EN 13121-2:2003

**3.15**
**contact layer**
layer to increase adhesion between TPL and structural laminate

**3.16**
**hoop winding**
winding for which the fibre direction is perpendicular to the rotation axis of the vessel

**3.17**
**helical winding**
winding for which the angle between the fibre direction and the rotation axis is not 0° or 90°

**3.18**
**prototype**
pressure vessel with the same diameter and end domes, manufactured with the same material and winding specifications using the same manufacturing techniques as a production vessel, but used only for testing purposes

**3.19**
**pigment**
component added to change the natural colour of the resin

## 4 Symbols and abbreviated terms

For the purpose of this European Standard, the symbols and abbreviated terms shall be used according to Table 1.

**Table 1 — Symbols and abbreviated terms**

| Symbol | Term | Unit |
|---|---|---|
| $b$ | width | mm |
| $h$ | height | mm |
| $m_f$ | fibre content by mass | — |
| PS | design pressure | MPa |
| $p_{crit}$ | critical pressure | MPa |
| $r$ | radial co-ordinate | mm |
| $r_p$ | radius of polar opening | mm |
| $t$ | wall thickness | mm |
| $t_h$ | thickness of the helical windings | mm |
| $t_c$ | thickness of the circumferential windings | mm |
| $w_i$ | weight of part i of the shell | N |
| $A$ | material weakening factor | — |
| $A_1$, ... $A_5$ | partial design factors | — |
| $C$ | shape factor | — |
| $D_a$ | internal diameter of winding laminate | mm |
| $E_1$, $E$ | modulus of elasticity in the fibre direction | MPa |
| $E_2$ | modulus of elasticity perpendicular to the fibre direction | MPa |
| $l$ | length of shell | mm |
| $K$ | design factor | — |
| $M_f$ | fibre reinforcement content per square meter | kg/m² |
| $M_w$ | wind moment on the shell | Nmm |
| $M_\phi$ | bending moment in longitudinal direction | Nmm/mm |
| $M_\theta$ | bending moment in circumferential direction | Nmm/mm |
| $N_\phi$ | stress resultant in longitudinal direction | N/mm |
| $N_\theta$ | stress resultant in circumferential direction | N/mm |
| $P$ | probability | % |
| $R$ | radius of a end-dome | mm |
| $S$ | safety factor | — |
| TSHL | Tsai-Hill criterion | — |
| $V_f$ | fibre volume fraction | — |
| $\alpha$ | winding angle | ° |
| $\rho_f$ | density of the fibre | kg/m³ |
| $\rho_r$ | density of the resin | kg/m³ |

**Table 1** (*concluded*)

| | | |
|---|---|---|
| $\sigma$ | stress | MPa |
| $\tau$ | shear stress | MPa |
| $\varepsilon$ | strain | % |
| $\varepsilon_n$ | strain normal to the fibre direction | % |
| $\upsilon_{12}$ | Poisson's ratio | — |
| TS | design temperature | °C |
| HDT | heat deflection temperature | °C |
| $\varepsilon_{max}$ | maximum allowable strain | % |
| $\varepsilon_{lim}$ | strain limit | % |
| $G$ | in-plane shear modulus | MPa |
| $X_t$ | ultimate longitudinal tensile strength | MPa |
| $X_c$ | ultimate longitudinal compressive strength | MPa |
| $Y_t$ | ultimate transversal tensile strength | MPa |
| $Y_c$ | ultimate transversal compressive strength | MPa |
| $S_s$ | in-plane shear strength | MPa |

# 5 General

The manufacturer shall obtain from the purchaser sufficient information to undertake the product design and construction in accordance with the requirements of this European Standard:

— vessel volume and the vessel fluid;

— maximum operating pressure including the alternating pressure;

— maximum operating temperature including the alternating temperature;

— additional data shall be supplied on any stresses occurring as a result of operation (pressures, pipe work, extremes of temperature, fluids, wind etc.), sequential filling or emptying of the vessel, the application and removal of the pressure.

# 6 Materials

## 6.1 General

The composite materials, hereinafter referred to as "composites" are characterised by matrix materials based on thermosetting resins by the quantity and order of reinforcing fibre and by the laminating or the moulding process for the protective layer and the winding process for the structural laminate.

The components of composites hereinafter are referred to as "raw materials". Raw materials acceptance conditions and usage conditions shall be in accordance with EN 13121-1 and the exceptions or restrictions listed in 6.2.

The chemical resistance of composites shall be in accordance with EN 13121-2 and the exceptions or restrictions are listed in 6.3.

## 6.2 Raw materials

### 6.2.1 Reinforcements

In the structural laminate continuous roving in accordance with 6.6 and 9.11 of EN 13121-1:2003 shall only be used.

In the CRL chopped strand mats in accordance with 6.3 and 9.9 of EN 13121-1:2003 or chopped roving in accordance with 6.6 and 9.11 of EN 13121-1:2003 shall be used.

#### 6.2.2 Resins

In the structural laminate UP-resins in accordance with 4.1, 4.2, 9.1 and 9.2 of EN 13121-1:2003, VE-resins in accordance with 4.1, 4.3, 9.1 and 9.2 of EN 13121-1:2003 and EP-resins in accordance with 4.1, 4.4, 9.1 and 9.3 of EN 13121-1:2003 shall be used.

#### 6.2.3 Thermoplastic lining materials

In addition to those thermoplastic materials listed in 8.1 of EN 13121-1:2003, other thermoplastic materials may be used if they meet the requirements of workmanship and service conditions. Specifications and technological data for these materials shall be confirmed by the thermoplastic material manufacturer according to the general requirements in Clause 8 and 9.12 of EN 13121-1:2003.

The range of thickness of thermoplastic linings shall be specified by the manufacturer.

Using PE linings the minimum shear strength to the structural laminate shall be 5 $N/mm^2$ when tested at maximum operating temperature in accordance with D.8 of prEN 13121-3:2004. If necessary, a contact layer to the structural laminate may be used.

#### 6.2.4 Pigments

Pigments are allowed in the structural laminate only in case of vessels designed according to method A. The amount of pigment is restricted by recommendations from the supplier or resin manufacturer.

### 6.3 Chemical resistance

#### 6.3.1 Reinforcements

Type of fibre, listed in 6.2.1, shall be in accordance with A.3 of EN 13121-2:2003.

#### 6.3.2 Resins

Resins, listed in 6.2.2, shall be used in accordance with Clause 5 of EN 13121-2:2003. EP-resins are only to be used according to 5.3, 5.5 or 5.6 of EN 13121-2:2003.

#### 6.3.3 Thermoplastic lining material

Thermoplastic materials shall be used in accordance with Clause 5 of EN 13121-2:2003. Other thermoplastics are only to be used according to 5.4, 5.5 or 5.6 of EN 13121-2:2003.

### 6.4 Characteristics values for calculations

#### 6.4.1 General

The manufacturer shall determine the required mechanical properties of all reinforcing lamina. There are four elastic constants and five strength constants that can be determined for a lamina. For design calculations only the constants $E_1$, $E_2$, $G$, $\nu_{12}$, $X_t$, $X_c$, $Y_t$, $Y_c$ and $S_s$ (for definitions see Clause 4) needed shall be determined.

The mechanical properties of the individual lamina shall be used for the design calculations of the laminate according to Clause 8 and Clause 9.

### 6.4.2 Test specimen

Test specimen for filament wound laminate shall be made from a unidirectional wound flat panel made according to Annex A. The test specimen shall be made from the same materials as determined in the production specification. The flat test specimen shall have a representative thickness, the curved test specimen shall have a representative thickness to diameter ratio. The fibre content of the test specimen shall be as specified in Clause 8 and Clause 9 with a tolerance of + 0 % and – 10 %. Winding patterns shall be achieved to within ± 5° of the specified angle. The number of test specimen shall be in accordance with the value of the partial design factor for dispersion (see 7.2.2).

### 6.4.3 Elastic properties

#### 6.4.3.1 $E_1$-modulus

The $E_1$-modulus for a filament wound laminate shall be determined either by performing an uniaxial tensile test according to EN ISO 527-4 on a flat test panel according to Annex A. The Poisson ratio $\nu_{12}$ shall be determined from the same test, from the measurement of longitudinal and transverse strains.

#### 6.4.3.2 $E_2$-modulus

The $E_2$-modulus for a filament wound laminate shall be determined by performing a uniaxial tensile test according to EN ISO 527-4 on a test panel according to Annex A.

#### 6.4.3.3 $G$-modulus

The shear modulus $G$ for a filament wound laminate shall be determined by performing a shear test according to EN ISO 14129.

### 6.4.4 Strength properties

#### 6.4.4.1 The longitudinal strength

The longitudinal strength $X$ for a filament wound laminate shall be determined by performing a uniaxial tensile test according to EN ISO 527-4 on a test panel according to Annex A.

#### 6.4.4.2 The transverse strength

The transverse strength $Y$ for a filament wound laminate shall be determined either by performing a uniaxial tensile test according to EN ISO 527-4 on a test panel according to Annex A.

#### 6.4.4.3 The shear strength

The shear strength $S_s$ for a filament wound laminate shall be determined by a shear test according to EN 14129 on a flat test panel.

### 6.4.5 Test report

The results of the tests in accordance with 6.4.3 and 6.4.4 shall be documented in a report which shall become a part of the "Design documentation", as described in Clause 10.

# 7 Design

## 7.1 General

This European Standard contains two methods for the design of filament wound GRP pressure vessels.

The thickness of the vessel parts designed by method A shall be determined by the calculation method given in Clause 8 and the design shall be confirmed by prototype testing according to 8.3.

The thickness of the vessel parts designed by method B shall be determined by the calculation method given in 9.1.

Filament wound pressure vessels shall be designed so that any developing distortions and changes in material properties do not impair the safety of the component part, not even during long-term stressing. This shall be approved in tests according to Clause 6 and Clause 12.

The design shall take into account the maximum difference in fluid pressure which can occur under the service conditions as specified in the design specification, between the inside and the outside of the vessel wall or between two chambers.

The protective layer shall not be included in the determination of the required wall thickness. However, the weight of the protective layer shall be taken into account when determining loading other than pressure. The protective layer shall be designed so that it extends completely through all openings in the vessel.

## 7.2 The design factor

### 7.2.1 General

The allowable stresses in each layer of the load-bearing material are derived from the characteristic values for elasticity and strength, the material-independent safety factor $S$ and the partial design factors to account for the influence of inhomogeneities and dispersion ($A_1$), chemical environment ($A_2$), design temperature versus heat resistance ($A_3$) and long term behaviour ($A_5$). The protective layer shall be ignored in strength calculations. The design factor $K$ shall be determined from the Equation (1).

$$K = S \times A_1 \times A_2 \times A_3 \times A_4 \times A_5 \quad (1)$$

The safety factor $S$ shall be 2,0.

The partial design factors $A_1$ to $A_5$ in Table 2 apply only if it can be demonstrated that the requirements according to 6.4 and the conditions given in 7.2.2 to 7.2.6 are strictly observed.

The partial design factors $A_1$ to $A_5$ may be reduced if justified by long-term tests on representative material samples or by strain measurements or by long-term pressure tests on representative vessel samples and if such a reduction is confirmed by material quality specifications. The product of two or more partial design factors can be determined by one test.

The design factor $K$ shall not be less than 4,0.

**Table 2 — Partial design factors**

| Partial design factor | | Min. value | Max. value |
|---|---|---|---|
| Effect of inhomogeneities and dispersion | $A_1$ | 1,0 | 2,0 |
| Effect of vessel liquid and environment | $A_2$ | 1,1 | 1,8 |
| Effect of design temperature | $A_3$ | 1,0 | 1,4 |
| Effect of dynamic loading | $A_4$ | 1,0 | 1,1 |
| Effect of long term behaviour | $A_5$ | 1,25 | 2,0 |

### 7.2.2 The partial design factor for inhomogeneities and dispersion $A_1$

Taking a normal logarithmic distribution the 5 % fracture values shall be regarded as statistically significant for a probability of $P$ = 75 % in an evaluation of at least 5 single values, according to ISO 2602. The partial design factor $A_1$ = 1,0 can be adopted, provided that the 5 % value is employed. When the mean value is taken of at least 10 values, the partial design factor $A_1$ = 1,2 can be adopted. When measured values are used on a non-statistical basis the partial design factor $A_1$ = 2,0 shall be adopted.

### 7.2.3 The partial design factor for chemical environment $A_2$

The partial design factor $A_2$ for chemical environment shall be derived according to EN 13121-2.

### 7.2.4 The partial design factor for design temperature $A_3$

The partial design factor $A_3$ for the influence of the design temperature can be obtained from Equation (2).

$$A_3 = 1{,}0 + 0{,}4\,\frac{(T_\mathrm{D} - 20)}{(\mathrm{HDT} - 40)} \tag{2}$$

For service temperatures greater than 40 °C post-curing is required. Post-curing instructions are according to resin manufacturer's recommendations. HDT shall be determined according to EN ISO 75-2:2004 method C or EN ISO 75-3.

The partial design factor $A_3$ can also be confirmed experimentally by:

— measurements on the bending strength, deflection on fracture and/or modulus of elasticity according to EN ISO 14125 at 23 °C and at design temperature;

— measurements on strain in long term creep tests according to EN ISO 14125 at working stresses, at 23 °C and at design temperature over a minimum of 1 000 h;

— long-term destructive or non-destructive compression test according to 8.3.3 at 23 °C and at design temperature.

These tests can be included in the testing of $A_5$. The measured properties shall be extrapolated for the determination of the long-term behaviour according to Annex C.

### 7.2.5 The partial design factor for dynamic loading $A_4$

The partial design factor $A_4$ for dynamic loading is 1,0 if there is no dynamic loading and 1,1 in case of dynamic loading. Dynamic loading is defined as more than 10 000 pressure cycles over the service life of the vessel.

#### 7.2.6 The partial design factor for long-term behaviour $A_5$

The partial design factor $A_5$ is 2,0 for long-term behaviour up to $2 \times 10^5$ h, which can be reduced if the results from either of the following tests produces a lower value:

— creep tests according to EN ISO 14125 at working stress, over a minimum of 1 000 h;

— long-term non-destructive compression test according to 8.3.3 at 23 °C.

The measured properties shall be extrapolated for the determination of the long-term behaviour according to Annex C. However, $A_5$ shall never be less than 1,25.

#### 7.2.7 Combination of more than one partial design factor

$A_2 \times A_3 \times A_5$ can be confirmed by one test according to 8.3.3 when the vessel contents are in contact with the environment throughout the test. The product of these factors shall be calculated in accordance with Annex C.

### 7.3 Permissible strain

The permissible strain at design pressure of lined filament wound vessels shall be specified in accordance with the strain behaviour of the linings and with the medium. Micro-cracks in the supporting laminate are acceptable because of the protective layer. The maximum permissible strain in the structural laminate, including as well as bending effects is given in Equation (3):

$$\varepsilon_{\text{max}} = \frac{\varepsilon_{\text{lim}}}{A_5} \quad (3)$$

For media category 3 class IV and sulfuric acid as specified in EN 13121-2, the strain $\varepsilon_{\text{lim}}$ shall not be higher than 0,25 % for all type of protective layers.

In case of a chemical resistant layer consisting of a veil layer followed by a layer of sprayed fibres or chopped strand mat with a total mass per unit area of minimum 900 g/m² the limiting strain $\varepsilon_{\text{lim}}$ of the structural laminate shall be according to Table 3.

**Table 3 — Strain limits for thermosetting protective layers**

| Type of resin | $\varepsilon_{\text{lim}}$ |
|---|---|
| UP | min (0,1 × $\varepsilon_{\text{resin}}$ or 0,20 %) |
| VE | min (0,1 × $\varepsilon_{\text{resin}}$ or 0,25 %) |
| EP | min (0,1 × $\varepsilon_{\text{resin}}$ or 0,30 %) |

When the chemically loaded side of the laminate is protected by a thermoplastic protective layer, the limiting strain $\varepsilon_{\text{lim}}$ of the structural laminate is according to Table 4.

**Table 4 — Strain limits for thermoplastic protective layers**

| Protective layer material | $\varepsilon_{\mathrm{lim}}$ |
|---|---|
| PE | 0,60 % |
| PP | 0,50 % |
| PVC-C and PVC-RI | 0,40 % |
| PVC-U | 0,25 % |
| PVDF | 0,50 % |

When used in aggressive external environments a protective external layer of randomly oriented fibres of 450 g/m² or an elastic external coating shall be applied.

## 7.4 Stress resultants

### 7.4.1 General

When calculating the winding laminate, the stress resultants $N_\phi$ and $N_\theta$ and the bending moments $M_\phi$ and $M_\theta$ have to be determined. Bending moments can also be taken into account by a shape factor $C$.

This European Standard only considers the following recommended shapes:

— cylinders;

— spheres;

— hemispherical;

— isotensoidal ends.

### 7.4.2 Cylinder

The stress resultants in the cylindrical shell shall be determined in accordance with Equations (4) and (5) if weight, wind and internal pressure are considered as loads.

$$N_\phi = \frac{\mathrm{PS} \times D_\mathrm{a}}{4} \pm \frac{4\,M_\mathrm{w}}{\pi\,D_\mathrm{a}^2} \pm \frac{\sum_i w_\mathrm{i}}{\pi\,D_a} \quad (4)$$

$$N_\theta = \frac{\mathrm{PS} \times D_\mathrm{a}}{2} \quad (5)$$

### 7.4.3 Spheres

The stress resultants in the spheres shell shall be determined in accordance with Equations (6) and (7) when only internal pressure is considered as load.

$$N_\phi = \frac{\mathrm{PS} \times D_\mathrm{a}}{4} \quad (6)$$

$$N_\theta = \frac{\mathrm{PS} \times D_\mathrm{a}}{4} \tag{7}$$

### 7.4.4 Hemispherical ends

The stress resultants in the hemispherical ends shall be determined in accordance with Equations (8) and (9) if only internal pressure is considered as load, taking $C$ for bending moments into account.

$$N_\phi = \frac{\mathrm{PS} \times D_\mathrm{a} C}{4} \tag{8}$$

$$N_\theta = \frac{\mathrm{PS} \times D_\mathrm{a} C}{4} \tag{9}$$

$C = 1{,}2$

### 7.4.5 Isotensoid

This shape is strongly recommended for filament wound pressure vessels as it deals with the ideal stress situation for all fibre positions. The shape of the dome is a result of the fibre direction of the helical winding.

For a helical wound end-dome (see Figure 1) the relationship can be found by Equation (10).

$$\frac{R_2}{R_1} = \frac{2 - 3\,\frac{r_\mathrm{p}^{\,2}}{r^2}}{l - \frac{r_p^{\,2}}{r^2}} \tag{10}$$

where

$R_1$ and $R_2$ are the principal radii of curvature;

$r$ is the radial co-ordinate;

$r_\mathrm{p}$ is the radius of the polar opening.

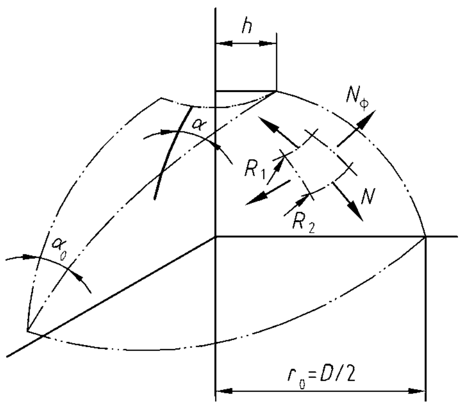



**Figure 1 — End-dome**

The stress resultants in an isotensiodical end-dome shall be determined in accordance with Equations (11) and (12) if only internal pressure is considered as load.

$$N_{\phi} = \frac{\text{PS} \times D_{\text{a}}}{4} \tag{11}$$

$$N_{\theta} = N_{\phi} \times \tan^2 \alpha \tag{12}$$

where

$\alpha$ = winding angle

# 8 Design analysis method A

## 8.1 General

This calculation method shall be confirmed by prototype testing according to 8.3.

## 8.2 Calculations

### 8.2.1 Evaluation of the stresses

This calculation method is only valid for a cylindrical pressure vessel with isotensiodical end-domes. Besides helical windings the cylinder shall also contain circumferential windings. In netting theory stresses perpendicular to the fibre direction are neglected. Stresses in the fibre direction of the helical winding shall be calculated according to Equation (13).

$$\sigma_{1,\text{h}} = \frac{N_{\phi}}{t_{\text{h}} \cos^2 \alpha_{0,\text{h}}} \tag{13}$$

where

$N_{\phi}$ is stress resultant at the equator;

$t_{\text{h}}$ is the thickness of the helical windings;

$\alpha_{0,\text{h}}$ is the winding angle of the helical winding at the equator;

$\sigma_{1,\text{h}}$ is the stress in the fibre direction of the helical winding.

Stresses in the circumferential windings on the cylinder shall be calculated according to Equation (14).

$$\sigma_{1,\text{c}} = \frac{N_{\theta} \left(1 - \frac{\tan^2 \alpha_{0,\text{h}}}{2}\right)}{t_{\text{c}}} \tag{14}$$

where

$t_{\text{c}}$ is the thickness of the circumferential windings;

$\alpha_{0,\text{h}}$ is the winding angle of the helical winding at the equator;

$\sigma_{1,\text{c}}$ is the stress in the fibre direction of the circumferential winding.

#### 8.2.2 Stress evaluation criterion

The allowable design stress shall be evaluated in accordance with the Equation (15).

$$\sigma_1 \leq \frac{\sigma_{ULT}}{K} \quad (15)$$

where

$\sigma_{ULT}$ is $X_T$ of either the helical or the circumferential winding.

#### 8.2.3 Strain evaluation

The strain in the fibre direction shall be calculated and evaluated in accordance with Equation (16).

$$\varepsilon_1 = \frac{\sigma_1}{E_1} \leq \varepsilon_{max} \quad (16)$$

### 8.3 Prototype testing

#### 8.3.1 Initial burst test

At least one prototype vessel shall be subjected to an initial burst test. The test fluid shall be water or another appropriate liquid at design temperature. The test pressure shall be applied at a uniform rate of 0,05 MPa/s for vessels below and equal 250 mm inner diameter and 0,02 MPa/s for vessels above 250 mm inner diameter.

#### 8.3.2 Cyclic pressure test

At least one prototype vessel shall be subjected to a cyclic pressure test followed by a burst test. The test fluid shall be water or another appropriate liquid at design temperature. The pressure shall be cycled from atmospheric pressure to the design pressure for a minimum of 100 000 cycles without leakage or failure.

After cycling the prototype shall be subjected to a burst test. The test fluid shall be water or another appropriate liquid at design temperature. The test pressure shall be applied at a uniform rate of 0,05 MPa/s for vessels below and equal 250 mm inner diameter and 0,02 MPa/s for vessels above 250 mm inner diameter.

#### 8.3.3 Long term pressure test

To determine the partial design factor for chemical environment and/or the design temperature and/or the long-term behaviour on a prototype vessel can be done as follows:

— test fluid shall be a liquid representing the chemical environment at appropriate temperature;

— test pressure shall be applied at a uniform rate so that the design pressure is reached and maintained over a minimum of 1 000 h;

— strain measurements shall be carried out at different locations and the first measurement shall be recorded after 6 min;

— following strain measurements shall be in accordance to Annex C.

#### 8.3.4 Test results evaluation

The maximum pressure reached during the tests described in 8.3.1 and 8.3.2 is called the qualification pressure. The qualification pressure shall be at least the maximum allowable pressure PS times the design factor $K$ for initial burst testing and times $0{,}7 \times K$ for burst testing after cyclic testing. During the test weeping or leakage is not allowed below the qualification pressure.

# 9 Design analysis method B

## 9.1 Calculation

#### 9.1.1 Evaluation of the stresses

With the obtained stress resultants, stresses and strains shall be calculated in the laminate, using laminate theory (see Annex B). This calculation is required at the most critical locations on the shell. These stresses shall be compared to their limit values. The "First Ply Failure Criterion" shall be used: the laminate is considered as failed when one lamina has failed.

#### 9.1.2 Theoretical thickness

Laminate thickness shall be calculated according to Equation (17).

$$t = \frac{M_\mathrm{f}}{\rho_\mathrm{f} \times V_\mathrm{f}} \qquad (17)$$

where:

$M_\mathrm{f}$ is the mass of the fibre reinforcement per square metre

The fibre content $V_\mathrm{f}$ or $m_\mathrm{f}$ shall be calculated according to Equation (18) or Equation (19).

$$m_\mathrm{f} = \frac{\rho_\mathrm{f}\ V_\mathrm{f}}{\rho_\mathrm{f}\ V_\mathrm{f} + \rho_\mathrm{r}\,(1 - V_\mathrm{f})} \qquad (18)$$

where

$\rho_\mathrm{f}$ is the fibre density;

$\rho_\mathrm{r}$ is the resin density.

$$V_f = \frac{m_\mathrm{f}}{\frac{\rho_\mathrm{f}}{\rho_\mathrm{f}} - \frac{\rho_\mathrm{f}}{\rho_\mathrm{f}}\ m_\mathrm{f} + m_\mathrm{f}} \qquad (19)$$

This theoretical thickness shall be used for dimensioning the laminate with a known reinforcement. A calculation example is given in Annex D.

### 9.1.3 Stress evaluation criterion

In case of a stress evaluation using laminate theory, stresses shall be calculated (see Annex B). The allowable design stress shall be evaluated according to Equation (20).

$$\left[\frac{\sigma_1}{\sigma_{1,\,\mathrm{ULT}}}\right]^2 - \frac{\sigma_1 \times \sigma_2}{\sigma_{1,\,\mathrm{ULT}}^2} + \left[\frac{\sigma_2}{\sigma_{2,\,\mathrm{ULT}}}\right]^2 + \left[\frac{\sigma_{12}}{S_S}\right]^2 \leq \left[\frac{1}{K}\right]^2 \quad (20)$$

where

$\sigma_{1,\,\mathrm{ULT}}$ is $X_\mathrm{T}$ , $X_\mathrm{C}$ of the lamina to be evaluated;

$\sigma_{2,\,\mathrm{ULT}}$ is $Y_\mathrm{T}$ , $Y_\mathrm{C}$ of the lamina to be evaluated.

The criterion shall be applied to each lamina, including CRL, separately, and if one or more lamina fail the criterion, the corresponding load on the vessel is not allowed.

In case micro cracks between the fibres are allowed and the elastic properties perpendicular to the fibre direction can be neglected, design method A in clause 8 should be applied.

### 9.1.4 Strain evaluation

The strain in all directions shall be calculated and shall be in accordance with Equation (21):

$$\varepsilon \leq \varepsilon_{\mathrm{max}} \quad (21)$$

### 9.1.5 Stability of the vessel

The stability of the vessel shall be designed according to prEN 13121-3 if necessary. The determination of the moduli of elasticity shall be obtained from test results or from laminate calculations, starting from known lamina properties.

### 9.1.6 Local reinforcements

A full stress analysis by finite elements of openings, nozzles and joints is required. Overlaps, distortions in the winding pattern and reinforcing pads shall be included in such analysis.

Calculated stresses and strains shall be evaluated according to 9.1.1 to 9.1.4.

For end-domes other then described in 7.4, a full stress analysis by finite elements is required.

The requirements for an acceptable design are:

— stresses at any point shall not exceed the limits stated in 9.1.3;

— strains at any point shall not exceed the limits stated in 7.3 and 9.1.4;

— average shear stress in overlays shall not exceed 3,5 MPa;

— for configurations where compressive stress occurs, the design shall meet the requirements for buckling.

## 10 Design documentation

The manufacturer shall, before commencing manufacture, prepare calculations, drawings and a construction specification in documented form to be made available as required.

The design documentation shall contain:

— main description of the pressure vessel;

— design and production drawings;

— results of design calculations;

— results of testing as described in 6.4;

— results of testing as described in 8.3;

— raw material documentation as required by EN 13121-1.

## 11 Manufacturing

### 11.1 Filament winding

#### 11.1.1 Materials

The matrix materials and fibre reinforcement shall comply with Clause 6.

#### 11.1.2 Mandrels

Mandrels shall be constructed in such a way that they remain structurally rigid throughout the winding and curing process. Removal of the mandrel shall not damage the protective layer or the structural windings.

#### 11.1.3 Details of the filament winding process

The laminators shall be approved in accordance with Annex E of prEN 13121-3:2004.

The required amount of resin, catalyst and any other ingredient, such as accelerator or permitted filler, shall be accurately measured and thoroughly mixed. The amount of mixed resin and the reinforcement fibres together with the specified winding pattern shall be recorded. The records shall be made available to the inspecting authority, where required. Specific winding patterns for the fibre reinforcement shall be used to ensure the strength and stiffness as calculated in Clause 8 or Clause 9.

The tension of the fibre reinforcement during the winding process shall be suitable to assure the correct winding pattern.

The bandwidth and spacing shall conform to those specified in Clause 8 or Clause 9 (see also Annex D). Winding patterns shall be achieved to within ± 5° of the specified angle.

The resin content by mass of the laminate shall be as specified ± 3 %. The minimum mass of the fibre reinforcement shall be as calculated in Clause 8 or Clause 9 (see also Annex D).

It shall be ensured that good adhesion is obtained between successive layers of the winding and between the shell and added fittings either by appropriate scheduling of the manufacturing process or by removing the surface of any cured resin to expose the fibres.

Adjacent pieces of laminate, e.g. local reinforcements around fittings, shall be overlapped with the winding by not less than 50 mm.

The length of individual fibres in local reinforcements shall not be less than 25 mm. When directionally biased reinforcement is used, care shall be taken to ensure that the fibres are correctly aligned.

#### 11.1.4 Curing

For all filament wound shells the cure times and temperatures shall conform to the resin manufacturers instructions.

If other than ambient temperature cure is employed, the design and operation of the curing equipment shall provide uniform heating over the entire surface of the vessel.

Wherever possible this shall be done at the manufacturers works. Where this is not possible due to size limitations or other reasons, the curing procedure shall be performed according to the design requirements and the resin system used.

### 11.2 Protective layers

#### 11.2.1 Materials

The protective layer may be made of thermosetting or thermoplastic materials. The details of the fabrication process shall be chosen to suit the selected protective layer material according to the material manufacturing specifications.

#### 11.2.2 Protective layer application

The protective layer may be applied to the mandrel prior to the start of the winding process. If applied to the mandrel before the winding operation begins, the thickness and hardness of the protective layer material shall be such that the filament orientation and tension will not be adversely affected by deflection or yield of the protective layer material. Alternatively, the protective layer may be applied to the completed vessel, in which case the restrictions on thickness and hardness do not apply.

#### 11.2.3 Protective layers of fibre-reinforced thermosets

Fibre-reinforced protective layers with thermoset matrix may be produced by e.g. hand lay-up, spray-up, injection or matched-die moulding. The processing conditions shall conform to the raw material manufacturers instructions.

In the case of laminates used as a chemical barrier, adjacent pieces of reinforcement shall be overlapped by not less than 25 mm. In the case of all structural laminates, e.g. when the protective layer takes up the winding loads and the loads occurring during the cure, adjacent pieces of reinforcement shall be overlapped by not less than 50 mm.

#### 11.2.4 Thermoplastic protective layers

The details of the fabrication process (e.g. blow moulding, injection moulding, welding of sheets) shall conform to the raw material manufacturers instructions.

The welders shall be approved in accordance with Annex F of prEN 13121-3:2004.

If surface treatment is necessary to facilitate bonding, the outer surface shall be treated in a suitable way to reach the minimum shear strength as specified in 6.2.3.

The manufacturer shall state the method to be employed when the materials of construction are agreed.

In the case of glass-backed materials the glass backing shall be stripped back for a distance of 3 mm to 6 mm on either side of the welds to ensure that no glass filaments are included in the welded joints.

### 11.3 Manufacturing specifications

The manufacturing specifications shall contain the following minimum requirements:

— raw material data;

— dimensional data;

— protective layer data;

— winding data;

— curing data;

— production personal.

## 12 Final acceptance testing

### 12.1 General

The manufacturer has the responsibility for conducting the tests stipulated in this clause.

The minimum tests shall consist of:

— acceptance test as specified in 12.2; and

— hydrostatic pressure test as specified in 12.3.

### 12.2 Acceptance testing for filament wound vessels

#### 12.2.1 Design dimensions

All vessels shall conform with the dimensions and tolerances given on the design drawings. Any dimension falling outside the specified limits shall be cause for rejection.

#### 12.2.2 Visual Inspection

Each vessel shall be visually examined to determine whether there are any imperfections of an unacceptable nature (see Table 5). This examination shall be carried out after the leakage test or hydrostatic test.

**Table 5 — Limits for imperfections in the laminate**

| Imperfection | Inner surface (thermoset linings only) | Structural laminate layers | Outer surface |
|---|---|---|---|
| Blisters | None | None | Max. 6 mm diameter and 1,5 mm high |
| Chips | None | None | Max. 6 mm diameter but not penetrating though the winding |
| Cracks | None | None | None |
| Micro cracks | None | Allowed | Allowed |
| Dry spots | None | None | None |
| Entrapped air | None at surface | Max. 1,5 mm diameter less than 2 per 100 $mm^2$ | Max. 3 mm diameter less than 3 % of the area |
| Exposed glass | None | None | None |
| Exposed cut edges | None | None | None |
| Foreign matter | None | None | None |
| Pits | Max. 3 mm diameter | None | Max. 3 mm diameter |
| | Max. 0,5 mm depth less than 1 per $10^4$ $mm^2$ | | Max. 1,5 mm deep |
| Scores | Max. 0,2 mm deep | — | Max. 0,5 mm deep |
| Surface porosity | None | — | None |
| Sharp discontinuity | Max. 0,5 mm | None | Max. 1 mm |
| Wrinkles | Maximum deviation 20 % of wall thickness but not exceeding 3 mm | None | Maximum deviation 20 % of wall thickness but not exceeding 4,5 mm |

Imperfections outside the limits given in Table 5 can be repaired following acceptance of a specific repair procedure. These procedures shall be technically endorsed, recorded on the drawings and made available for inspection as required. Moulded in threads or core holes shall be free of all visible defects.

#### 12.2.3 Vessel weight

The weight of the vessel shall conform the vessel specification, at least 95 % of the specified weight.

#### 12.2.4 Thermoplastic protective layer integrity

The protective layer shall be securely bonded to the winding and shall not show evidence of excessive heating.

### 12.3 Hydrostatic pressure test

Each vessel falling under Category II, III, or IV of the PED shall be subjected to the tests stipulated in this clause. Other vessels may be tested on a statistical basis.

The test pressure shall be no less than the greater of:

— 1,25 times the design pressure at maximum allowable temperature, or

— 1,43 times the design pressure.

In cases where it is known that hydrostatic testing of FRP vessels reduces the life expectancy of the vessel, such harmful tests may be avoided by carrying out a hydrostatic test with a lower test pressure of 1,1 times the maximum allowable pressure if an equivalent overall level of safety can be demonstrated by:

— design analysis and,

— means of prototype testing according 8.3 and,

— means of repeating this test during production on a statistical basis and,

— operating an approved quality system for production, final inspection and testing.

The vessel shall be tested using water or other suitable liquid as test fluid. The pressure shall be maintained for at least 1 min. The vessel shall be carefully examined for leakage. Vessels that leak shall be rejected. For vessels designed according to method B, the strains shall be measured at the critical locations and shall not exceed the specified strain by more than 5 %.

#### 12.3.1 Test conditions for pneumatic testing

Pneumatic testing may be used if the following precautions are taken:

— when the vessels are pneumatically tested under water:

  Leakage determination shall be made by testing the vessels while totally submerged in water, the pressure shall be applied to the vessels only while they are completely submerged in water, examination shall be accomplished by slowly rotating the vessel, so that the entire surface can be inspected.

— when free-standing vessels are pneumatically tested:

  The pressure shall be increased gradually to not more than one half of the test pressure, after which the pressure shall be increased in increments of one-tenth of the test pressure until the required test pressure has been reached.

  After the test pressure has been maintained for at least one minute, it shall be reduced to 75 % of the design pressure and maintained at that pressure for sufficient time to permit examination of the entire surface of the vessel for leakage by means of soapsuds applied thereto.

### 12.4 Test report

A reference to this European Standard, and to any deviations shall be given in the “Test report”.

# Annex A
(normative)

# Fabrication of flat filament wound test specimens

## A.1 General

This annex describes the fabrication of flat filament-wound panels with:

— unidirectional lamina for the determination of the material properties in 6.4.3.1, 6.4.3.2, 6.4.4.1 and 6.4.4.2; or

— $[0/90°]_s$ laminate for the cut-out of [± 45°] panels for the determination of the material properties in 6.4.3.3 and 6.4.4.3.

## A.2 Winding device

The same winding process as specified for the vessel shall be used the produce the panels. The accuracy of the winding equipment shall conform the minimum requirements of the test standards.

## A.3 Mandrel

The mandrel may be any material of sufficient size to produce the desired specimen. The mandrel shall be of sufficient strength not to vary under the tension of the reinforcement or under the compression in the mould.

## A.4 Mould

The mould may be any device providing two parallel flat surfaces of sufficient size to accept the mandrel. The mandrel is transferred from the winding device to the mould before the resin has gelled, and sufficient weight or pressure applied to achieve a cured, flat panel of uniform thickness. Misalignment of the fibres during the moulding shall be avoided.

## A.5 String guide — Tensioning system

This may consist of any device suitable for application of tension, and directing the strand of roving through the resin bath and onto the mandrel.

## A.6 Procedure

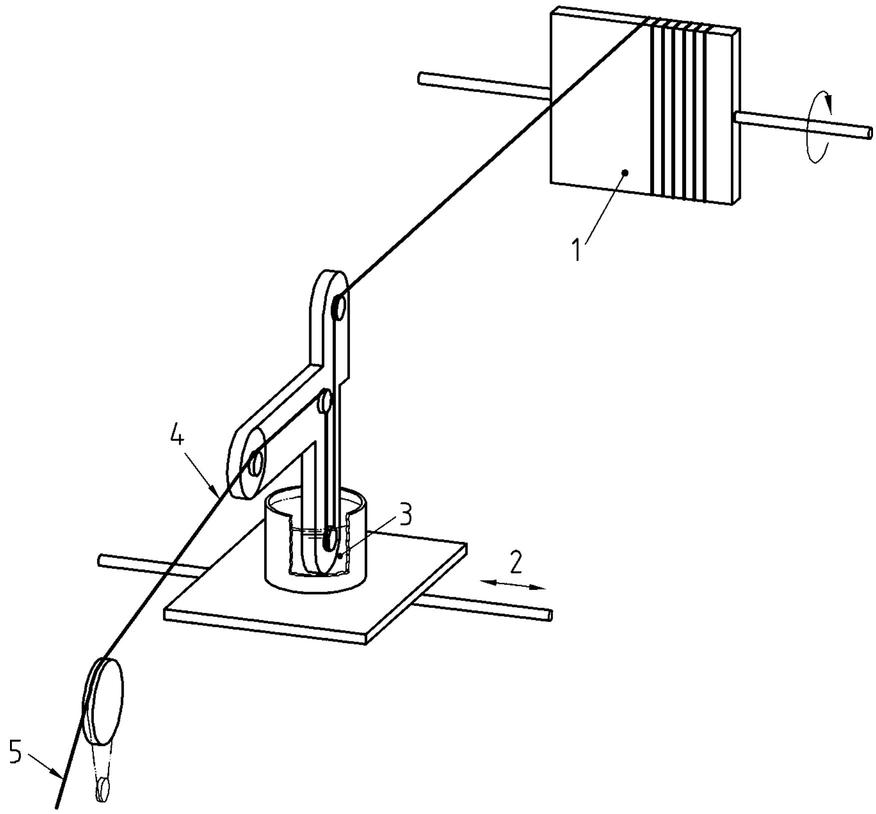
The package of reinforcement roving should be positioned to provide free flow of fibre to the winding mechanism. The reinforcement should be pulled through the resin bath by the rotation of the mandrel. As the reinforcement is pulled through the resin bath, remove excess resin by any convenient wiper method.

In Figure A.1 the string guide and resin bath are mounted on a carriage mechanism that has lateral travel parallel to the rotating axis of the flat mandrel. The lateral movement of the string guide should be such that each revolution of the mandrel axis will advance the string guide the equivalent of one fibre bundle strand width.

The strand velocity through the resin bath should be constant and slow enough to give good wetting of the reinforcement. Wind sufficient layers to produce a specimen of the desired thickness and fibre content.

After winding, and before the resin has gelled, transfer the mandrel and wet reinforcement to the mould and apply sufficient weight or pressure to achieve uniform flatness and thickness of the panel. Apply mould release to both the mandrel and the mould.

After the laminate has cured, saw through the over wrap at the top and bottom of the mandrel and remove the laminate.




**Key**

1 Flat mandrel
2 Carriage
3 Resin bath
4 String guide
5 Supply

**Figure A.1 — Winding device**

# Annex B
(informative)

# Laminate Theory

## B.1 General

Laminate theory is a mathematical treatment of the mechanics governing the behaviour of uni-directional orthotropic lamina and the interrelation between multiple lamina as they act together to form a multidirectional laminate. A winding pattern should be considered as a laminate. Laminate theory as addressed in this annex shall be used to:

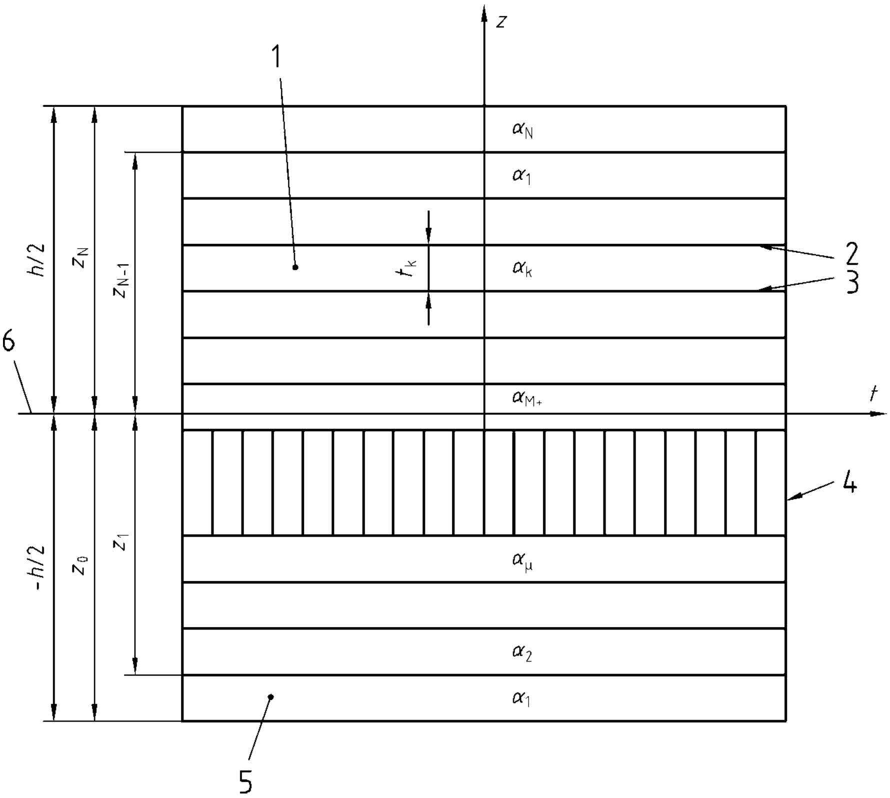
— determine the in-plane and flexural modulus components that define the stress-strain and moment-curvature relationships for laminates;

— examine the strength of a laminate based on the strain state of individual lamina reacting to imposed moment and stress resultants;

— determine the effective engineering constants of the laminates.

## B.2 Standard notation

A multidirectional general laminate is represented in Figure B.1.

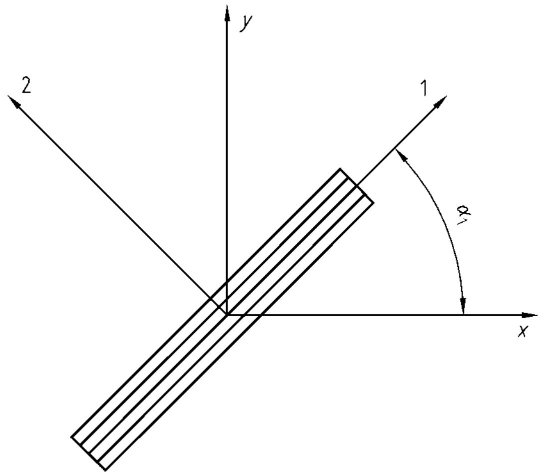



**Key**

1 Ply No. K
2 Upper surface
3 Lower surface
4 Core (zero stiffness)
5 Ply No. 1
6 Mid plane

**Figure B.1 — Conventions for laminates**

Ply numbering is from $z = -h/2$ to $z = h/2$, with ply number 1 at the bottom. Co-ordinate reference axis designation is illustrated in Figure B.2. On-axis refers to the principal orientation of the fibres of a lamina and is referenced as the 1-2 axis, 1 being parallel to the fibres, 2 being transverse to the fibres. Off-axis refers to the principal material axis and is referenced as the x-y axis. As referenced in this annex the x-axis is the vessel or nozzle longitudinal axis, and the y-axis is the hoop or circumferential axis.




**Key**
1, 2 are on-axis co-ordinates
x, y are laminate (off-axis) co-ordinates

**Figure B.2 — Coordinate reference axis**

## B.3 Basic assumptions

In the application of laminate theory as used in this annex, certain assumptions are made:

- interlaminar or transverse shear is not addressed;
- laminate stress resultants and moment resultants are taken as averages of ply stresses across the thickness of the laminate;
- ply stress is based on homogeneity within each ply where the fibre and the matrix are not recognised as distinct phases;
- laminate is assumed to consist of perfectly bonded lamina, i.e. displacements are continuous across laminate boundaries and no lamina slips relative to another;
- since the stress distribution across a multidirectional laminate is not constant due to the variation in ply modulus, the stress-strain relationship is defined in terms of average stress.

## B.4 Lamina (ply) properties

Laminate theory as applied in this annex requires four elastic constants and five strength constants are determined for orthotropic lamina. This should be determined by appropriate standards according to 6.4:

Elastic properties required are:

$E_1$ longitudinal tensile modulus;

$E_2$ transverse tensile modulus;

$G$ in-plane shear modulus;

$\nu$ Poisson's ratio.

Strength properties required are:

$X_t$ longitudinal tensile strength;

$X_c$ longitudinal compressive strength;

$Y_t$ transverse tensile strength;

$Y_c$ transverse compressive strength;

$S_s$ in-plane shear strength.

Physical properties are:

$t_k$ thickness of each lamina;

$z_k$ distance from the laminate mid-plane to the ply surface;

$h$ theoretical laminate thickness.

## B.5 Determination of the stiffness matrix

The stress-strain relationship for an orthotropic lamina can be written as follows:

$$\begin{Bmatrix}\sigma_{11}\\ \sigma_{22}\\ \sigma_{33}\\ \sigma_{23}\\ \sigma_{13}\\ \sigma_{12}\end{Bmatrix}=\begin{bmatrix}Q_{11} & Q_{12} & Q_{13} & 0 & 0 & 0\\ Q_{12} & Q_{22} & Q_{23} & 0 & 0 & 0\\ Q_{13} & Q_{23} & Q_{33} & 0 & 0 & 0\\ 0 & 0 & 0 & Q_{44} & 0 & 0\\ 0 & 0 & 0 & 0 & Q_{55} & 0\\ 0 & 0 & 0 & 0 & 0 & Q_{66}\end{bmatrix}\begin{Bmatrix}\varepsilon_{11}\\ \varepsilon_{22}\\ \varepsilon_{33}\\ 2\varepsilon_{23}\\ 2\varepsilon_{13}\\ 2\varepsilon_{12}\end{Bmatrix} \tag{B.1}$$

OR:

$$\begin{Bmatrix}\varepsilon_{11}\\ \varepsilon_{22}\\ \varepsilon_{33}\\ 2\varepsilon_{23}\\ 2\varepsilon_{13}\\ 2\varepsilon_{12}\end{Bmatrix}=\begin{bmatrix}S_{11} & S_{12} & S_{13} & 0 & 0 & 0\\ S_{12} & S_{22} & S_{23} & 0 & 0 & 0\\ S_{13} & S_{23} & S_{33} & 0 & 0 & 0\\ 0 & 0 & 0 & S_{44} & 0 & 0\\ 0 & 0 & 0 & 0 & S_{55} & 0\\ 0 & 0 & 0 & 0 & 0 & S_{66}\end{bmatrix}\begin{Bmatrix}\sigma_{11}\\ \sigma_{22}\\ \sigma_{33}\\ \sigma_{23}\\ \sigma_{13}\\ \sigma_{12}\end{Bmatrix} \tag{B.2}$$

The compliance matrix [S] is the reciprocal of modulus and is obtained from a matrix inversion of the stiffness matrix [Q]:

$$[S] = \begin{bmatrix} \frac{1}{E_{11}} & -\frac{\nu_{12}}{E_{22}} & -\frac{\nu_{13}}{E_{33}} & 0 & 0 & 0 \\ -\frac{\nu_{21}}{E_{11}} & \frac{1}{E_{22}} & -\frac{\nu_{23}}{E_{33}} & 0 & 0 & 0 \\ -\frac{\nu_{31}}{E_{11}} & -\frac{\nu_{32}}{E_{22}} & \frac{1}{E_{33}} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{G_{23}} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{G_{13}} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{G_{12}} \end{bmatrix} \tag{B.3}$$

where

$E_{11}$, $E_{22}$, $E_{33}$ are the tensile moduli along the 1,2,3-directions of the lamina;

$\nu_{23}$, $\nu_{13}$, $\nu_{12}$ are the Poisson's coefficients;

$G_{23}$, $G_{13}$, $G_{12}$ are the shear moduli in the 2-3, 1-3, 1-2 planes.

Lamina mostly can be considered as transversally isotropic:

$$E_{22} = E_{33} \ en \ G_{23} = \frac{E_{22}}{2\,(1+\nu_{23})} \tag{B.4}$$

Based on the orientation $\alpha_k$ of each ply, the transformed modulus components of each lamina can be calculated, using the transformation equations shown below (rotation round z-axis by – $\alpha_k$):

$$\begin{Bmatrix} \sigma_{11} \\ \sigma_{22} \\ \sigma_{33} \\ \sigma_{23} \\ \sigma_{13} \\ \sigma_{12} \end{Bmatrix} = [T] \begin{Bmatrix} \sigma_{xx} \\ \sigma_{yy} \\ \sigma_{zz} \\ \sigma_{yz} \\ \sigma_{xz} \\ \sigma_{xz} \end{Bmatrix} \text{ with } [T] = \begin{bmatrix} m^2 & n^2 & 0 & 0 & 0 & 2\,mn \\ n^2 & m^2 & 0 & 0 & 0 & -2\,mn \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & m & -n & 0 \\ 0 & 0 & 0 & n & m & 0 \\ -mn & mn & 0 & 0 & 0 & (m^2 - n^2) \end{bmatrix} \tag{B.5}$$

where

$m = \cos\alpha$ and $n = \sin\alpha$

Strains are transformed in a similar way:

$$\begin{Bmatrix} \varepsilon_{11} \\ \varepsilon_{22} \\ \varepsilon_{33} \\ 2\varepsilon_{23} \\ 2\varepsilon_{13} \\ 2\varepsilon_{12} \end{Bmatrix} = [R]\,[T]\,[R]^{-1} \begin{Bmatrix} \varepsilon_{xx} \\ \varepsilon_{yy} \\ \varepsilon_{zz} \\ 2\varepsilon_{yz} \\ 2\varepsilon_{xz} \\ 2\varepsilon_{xy} \end{Bmatrix} \text{ with } [R] \begin{bmatrix} 1\,0\,0\,0\,0\,0 \\ 0\,1\,0\,0\,0\,0 \\ 0\,0\,1\,0\,0\,0 \\ 0\,0\,0\,2\,0\,0 \\ 0\,0\,0\,0\,2\,0 \\ 0\,0\,0\,0\,0\,2 \end{bmatrix} \quad \text{(B.6)}$$

The transformed relationship B.1 is:

$$\begin{Bmatrix} \sigma_{xx} \\ \sigma_{yy} \\ \sigma_{zz} \\ \sigma_{yz} \\ \sigma_{xz} \\ \sigma_{xy} \end{Bmatrix} = \begin{bmatrix} Q_{11}^* & Q_{12}^* & Q_{13}^* & 0 & 0 & Q_{16}^* \\ Q_{12}^* & Q_{22}^* & Q_{23}^* & 0 & 0 & Q_{26}^* \\ Q_{13}^* & Q_{23}^* & Q_{33}^* & 0 & 0 & Q_{36}^* \\ 0 & 0 & 0 & Q_{44}^* & Q_{45}^* & 0 \\ 0 & 0 & 0 & Q_{45}^* & Q_{55}^* & 0 \\ Q_{16}^* & Q_{26}^* & Q_{36}^* & 0 & 0 & Q_{66}^* \end{bmatrix} \begin{Bmatrix} \varepsilon_{xx} \\ \varepsilon_{yy} \\ \varepsilon_{zz} \\ 2\varepsilon_{yz} \\ 2\varepsilon_{xz} \\ 2\varepsilon_{xy} \end{Bmatrix} \quad \text{(B.7)}$$

with:

$$\left[Q^*\right] = \left[T\,(\alpha)\right]^{-1}\,[Q]\left\{\left[T\,(\alpha)\right]^{\mathrm{T}}\right\}^{-1}$$

Constitutive laws of a laminate give the relationship between stress-resultants and deformations. For thin shells with distributed loads the following assumptions are made: the stress component $\sigma_{zz}$ is negligible and a normal plane to the mid-plane remains normal after deformation (= KIRCHHOFF's laws):

$$\begin{aligned} &\sigma_{zz} = 0 \\ &u\,(x, y, z) = u_0\,(x, y) - z\,\frac{\partial w_0}{\partial x} \\ &v\,(x, y, z) = v_0\,(x, y) - z\,\frac{\partial w_0}{\partial y} \\ &w\,(x, y, z) = w_0\,(x, y) \end{aligned} \quad \text{(B.8)}$$

where

$u$, $v$, $w$ are the displacements along the $x$, $y$ and $z$-axis, $u_0$, $v_0$ and $w_0$ are the displacements of the neutral plane.

Strains are written as follows:

$$\begin{aligned} &\varepsilon_{xx} = \frac{\partial u_0}{\partial x} - z\,\frac{\partial^2 w_0}{\partial x^2} = \varepsilon_{xx,0} + z\kappa_{xx} \\ &\varepsilon_{yy} = \frac{\partial v_0}{\partial y} - z\,\frac{\partial^2 w_0}{\partial y^2} = \varepsilon_{yy,0} + z\kappa_{yy} \\ &2\,\varepsilon_{xy} = \frac{\partial u_0}{\partial y} + \frac{\partial v_0}{\partial x} - 2z\,\frac{\partial^2 w_0}{\partial x \partial y} = \varepsilon_{xy,0} + z\kappa_{xy} \end{aligned} \quad \text{(B.9)}$$

Deformations of the mid-plane are obtained by putting z = 0 in previous formulas. By omitting $\sigma_{zz}, \sigma_{xz}, \sigma_{yz}, \varepsilon_{zz}, \varepsilon_{xz}, \varepsilon_{yz}$ in B.7 these formulas change to:

$$\begin{Bmatrix} \sigma_{x} \\ \sigma_{yy} \\ \sigma_{xy} \end{Bmatrix} = \begin{bmatrix} Q_{11}^{*} & Q_{12}^{*} & Q_{16}^{*} \\ Q_{12}^{*} & Q_{22}^{*} & Q_{26}^{*} \\ Q_{16}^{*} & Q_{26}^{*} & Q_{66}^{*} \end{bmatrix} \begin{Bmatrix} \varepsilon_{xx} \\ \varepsilon_{yy} \\ \varepsilon_{xy} \end{Bmatrix} \tag{B.10}$$

The matrix $[Q^{*}]$ of the reduced stiffness matrix $[Q']$:

$$[Q^{*}] = [T'(\alpha)]^{-1} [Q'] \{[T'(\alpha)]^{T}\}^{-1} \tag{B.11}$$

with:

$$E_{11} = E_{1};\ E_{22} = E_{2};\ \nu_{12} = \nu_{21} = \nu;\ G_{12} = G$$

The terms of $[Q']$ are:

$$Q'_{11} = \frac{E_{1}}{1 - \nu\,\nu} \quad Q'_{22} = \frac{E_{2}}{1 - \nu\,\nu} \tag{B.12}$$

$$Q'_{12} = Q'_{21} = \nu \frac{E_{1}}{1 - \nu\,\nu} \quad Q'_{66} = G$$

The stress resultants are, Figure B.1:

$$\{N_{x} \quad N_{y} \quad N_{xy}\} = \int_{-h/2}^{h/2} \{\sigma_{xx} \quad \sigma_{yy} \quad \sigma_{xy}\}\, dz$$

$$\{M_{x} \quad M_{y} \quad M_{xy}\} = \int_{-h/2}^{h/2} \{\sigma_{xx} \quad \sigma_{yy} \quad \sigma_{xy}\}\, z dz \tag{B.13}$$

The stress-strain relations are:

$$\begin{Bmatrix} N_{x} \\ N_{y} \\ N_{xy} \\ M_{x} \\ M_{y} \\ M_{xy} \end{Bmatrix} = \begin{bmatrix} A_{11} & A_{12} & A_{16} & B_{11} & B_{12} & B_{16} \\ A_{12} & A_{22} & A_{26} & B_{12} & B_{22} & B_{26} \\ A_{16} & A_{26} & A_{66} & B_{16} & B_{26} & B_{66} \\ B_{11} & B_{12} & B_{16} & D_{11} & D_{12} & D_{16} \\ B_{12} & B_{22} & B_{26} & D_{12} & D_{22} & D_{26} \\ B_{16} & B_{26} & B_{66} & D_{16} & D_{26} & D_{66} \end{bmatrix} \begin{Bmatrix} \varepsilon_{xx,0} \\ \varepsilon_{yy,0} \\ 2\varepsilon_{xy,0} \\ \kappa_{xx} \\ \kappa_{yy} \\ \kappa_{xy} \end{Bmatrix} \tag{B.14}$$

The "ABD"-matrix determines the stiffness of the laminate. Elements are calculated as follows:

$$A_{ij} = \sum_{k=1}^{n} \left(Q^{*}{}_{ij}\right)_{k} \left(z_{k} - z_{k-1}\right)$$

$$B_{ij} = \frac{1}{2} \sum_{k=1}^{n} \left(Q^{*}{}_{ij}\right)_{k} \left(z_{k}^{2} - z_{k-1}^{2}\right) \tag{B.15}$$

$$D_{ij} = \frac{1}{3} \sum_{k=1}^{n} \left(Q^{*}{}_{ij}\right)_{k} \left(z_{k}^{3} - z_{k-1}^{3}\right)$$

# Annex C
(normative)

# Extrapolation method for long term behaviour

## C.1 General

This annex describes an extrapolation method for the determination of the long term behaviour of filament wound GRP pressure vessels based on the results of long term tests in accordance with 7.2. These results can be extrapolated for a longer service life.

## C.2 Description of the method

A specified number of results will be determined in a specified number of periods. Based on the method of least squares the fitted straight line in log-log scale will be determined with the linear regression and the lower confidence line as the minimum curve will be calculated. In doing so it is only allowed to extrapolate 2,3 decades beyond the last measured value.

## C.3 Symbols

$t$ time in hours

$a$, $b$ coefficients of the regression line

$K_B$ measured value

$K_{B\ min}$ minimum of the measured value

$K_{BL}$ extrapolated long-term value

$K_{B\ min}$ minimum of the extrapolated long-term value

$x$ independent variable

$y$ dependent variable

$n$ number of measured values

## C.4 Evaluation of the regression characteristic

At least 18 values shall be measured. These values shall meet the following requirement regarding their distribution over the test periods:

**Table C.1 — Minimum number of measured values**

| test period [h] | number of measured values in the test period |
|---|---|
| 0,1 to 1 | minimum 4 |
| 1 to 10 | minimum 3 |
| 10 to 100 | minimum 2 |
| 100 to 1 000 | minimum 1 |

The general equation of a straight line shall be written according to Equation (C.1).

$$Y = a + b \times r \qquad \text{(C.1)}$$

The following statistical values shall be calculated:

$$\bar{x} = \sum x_\mathrm{i} / n$$

$$\bar{y} = \sum y_\mathrm{i} / n$$

$$Q_\mathrm{x} = \sum x_\mathrm{i}^2 - \left( \left( \sum x_\mathrm{i} \right)^2 / n \right) \qquad \text{(C.2)}$$

$$Q_\mathrm{y} = \sum y_\mathrm{i}^2 - \left( \left( \sum y_\mathrm{i} \right)^2 / n \right)$$

$$Q_\mathrm{xy} = \sum x_\mathrm{i} y_\mathrm{i} - \left( \left( \sum x_\mathrm{i} \right) - \left( \sum y_\mathrm{i} \right) / n \right)$$

$$S_\mathrm{R}^2 = \left( Q_\mathrm{y} - \left( Q_\mathrm{xy}^2 / Q_\mathrm{x} \right) \right) / (n - 2)$$

$$S_\mathrm{R} = \sqrt{\ } S_\mathrm{R}^2$$

$$r^2 = Q_\mathrm{xy}^2 / \left( Q_\mathrm{x} \times Q_\mathrm{y} \right)$$

$$r = \sqrt{\ } r^2$$

$$b = Q_\mathrm{xy} / Q_\mathrm{x}$$

$$a = \bar{y} - b \times \bar{x}$$

The regression line shall be determined by using the log values of the measured values. Results for test periods less than 0,1 h are not allowed to be used.

Where

$$y = \log K_B \tag{C.3}$$

$$x = \log t$$

Using the Equation (C.3) for the regression line, the results are written to Equation (C.4)

$$\log K_B = a + b \times \log t \tag{C.4}$$

After determination of the coefficients $a$ and $b$ the values for the square of the correlation coefficient $r^2$ and of the variance $S_R^2$ shall be calculated.

The measured values can only be considered as usable for a long term statement, if the following conditions are fulfilled:

— value $r^2$ has to be more than 0,65;

— value $S_R^2$ has to be less than 0,006 5.

If one of these conditions is not fulfilled, the regression analysis can not be used for the extrapolation. By having more measured values in the needed test periods the situation can be improved.

# Annex D
(informative)

# Calculation example

## D.1 Design parameters

Filament wound pressure vessel

| | |
|---|---|
| — Vessels content | water |
| — Protective layer material | PE |
| — Diameter | 1 600 mm |
| — End-dome | helical wound isotensoid |
| — Design pressure | 1,05 MPa |
| — Design temperature | 65 °C |
| — Material | Glass/Epoxy |
| — HDT | 100 °C |
| — Fibre content | 70 % by mass |
| — Winding pattern | Helical winding ± 18° |
| — Hoop winding | 90° |
| — Fibre-tie | 40 × 1 200 tex |

## D.2 Design of a filament wound pressure vessels

**Table D.1 — Design factor** $K$ = 4,00 (see 7.2)

| Factor | Value | Remarks |
|---|---|---|
| $A_1$ | 1,00 | In case of statistical evaluation, see to 7.2.2 |
| $A_2$ | 1,10 | EN 13121-2, see 7.2.3 |
| $A_3$ | 1,30 | see 7.2.4 |
| $A_5$ | 1,35 | see 7.2.5 |

The allowable strain (see 7.3) is: 0,60 %/$A_5$ = 0,44 %

## D.3 Design calculations

**Table D.2 — Elastic properties**

| | $E_1$ | $E_2$ |
|---|---|---|
| $\alpha_1$ = 18° | 35 000 N/mm² | 5 000 N/mm² |
| $\alpha_2$ = 90° | 35 000 N/mm² | 5 000 N/mm² |

**Table D.3 — Strength properties**

| | $X_t$ | $Y_t$ |
|---|---|---|
| $\alpha_1$ = 18° | 610 N/mm² | 30 N/mm² |
| $\alpha_2$ = 90° | 1 085 N/mm² | 30 N/mm² |

Laminate stress resultants (see 7.4)

For internal pressure is:

$$N_\phi = \frac{\text{PS}\ D}{4} = 420\ \text{N/mm} \qquad N_\theta = \frac{\text{PS}\ D}{2} = 840\ \text{N/mm}$$

Method A (see Clause 8)

Helical winding (with end-dome):

$$\sigma_{1,\,\text{h}} = \frac{N_\phi}{t_\text{h}\ \cos^2\ \alpha_{0,\,\text{h}}} \leq \frac{\sigma_\text{ULT}}{K} = 152\ \text{N/mm}^2$$

$$\varepsilon_{1,\,\text{h}} = \frac{\sigma_{1,\,\text{h}}}{E_1} \leq \frac{\varepsilon_\text{lim}}{A_4} = 0{,}44\ \%$$

The design is stress-limited: $t_\text{h}$ > 3,1 mm satisfies both conditions.

Hoop winding:

$$\sigma_{1,\,\text{c}} = \frac{N_\theta\left(1 - \dfrac{\tan^2\ \alpha_{0,\,\text{h}}}{2}\right)}{\text{t}_\text{c}} \leq \frac{\sigma_\text{ULT}}{K} = 271\ \text{N/mm}^2$$

$$\varepsilon_{1,\,\text{c}} = \frac{\sigma_{1,\,\text{c}}}{E_1} \leq \frac{\varepsilon_\text{lim}}{A_4} = 0{,}44\ \%$$

The design is strain-limited: $t_\text{c}$ > 5,17 mm satisfies both conditions. These calculation results shall be checked by prototype testing according to 8.3.

## D.4 Winding pattern calculation

Fibre-tie

| | | | |
|---|---|---|---|
| 40 rovings of 1 200 tex | = | 48,00 g/m | (70 % by mass) |
| Epoxy | = | 20,60 g/m | (30 % by mass) |
| Fibre-tie | = | 68,60 g/m | |
| density $\rho$ | = | 1 847 kg/m$^3$ | |
| section $B_s$ of the fibre-tie | = | 37,10 mm² | |

The laminate

Theoretical thickness according to method A

Helical

$$t_h = \frac{n_w \times 2 \times B_s}{\pi \times D \times \cos\theta} = \frac{228 \times 2 \times 37{,}1}{\pi \times 1\,600 \times \cos 18°} = 3{,}54 \text{ mm}$$

where

$n_w$ is the number of windings;

$B_s$ is the fibre-tie section;

$D$ is the diameter;

$\alpha$ is the winding angle 0.

Hoop

$$t_c = n_l \times \frac{B_s}{b} = 11 \times \frac{37{,}1}{78} = 5{,}23 \text{ mm}$$

where

$n_l$ is the number of hoop windings;

$B_s$ is the fibre-tie section;

$b$ is the width of the fibre-tie 0.

The following winding configuration fulfils all design restrictions:

**Table D.4 — Calculated winding pattern**

| Winding | Angle | Width | Number | Theoretical thickness |
|---|---|---|---|---|
| | ° | mm | Method A | Method A |
| Helical | ± 18 | 60 | 228 wind. | 3,54 |
| Hoop | 90 | 78 | 11 layers | 5,23 |

# Annex ZA
(informative)

## Relationship between this European Standard and the Essential Requirements of EU Directive 97/23/EC

This European Standard has been prepared under a mandate given to CEN by the European Commission to provide a means of conforming to Essential Requirements of the New Approach Directive 97/23/EC of the European Parliament.

Once this European Standard is cited in the Official Journal of the European Communities under that Directive and has been implemented as a national standard in at least one Member State, compliance with the clauses of this European Standard given in Table ZA.1 confers, within the limits of the scope of this European Standard, a presumption of conformity with the corresponding Essential Requirements of that Directive and associated EFTA regulations.

**Table ZA.1 — Correspondence between this European Standard and Directive 97/23/EC**

| Clause(s)/sub-clauses of this EN | Essential Requirements (ERs) of Directive 97/23/EC | Qualifying remarks/Notes |
|---|---|---|
| 8.1 | 2.2.2 | Design for adequate strength |
| 6.4, 7.2, 8, 9 | 2.2.3 | Design for adequate strength — calculation method |
| 11.1.2, 11.1.3 | 3.1.1 | Manufacturing – Preparation of the component parts |
| 11.1.4 | 3.1.4 | Manufacturing – Heat treatment |
| 12 | 3.2 | Final assessment |
| 6 | 4.1, 4.2 | Materials |
| 12.3 | 7.4 | Hydrostatic pressure test |

**WARNING:** Other requirements and other EU Directives may be applicable to the product(s) falling within the scope of this European Standard.

# Bibliography

[1] EN ISO 14125, *Fibre-reinforced plastic composites — Determination of flexural properties (ISO 14125:1998)*

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