



BSI Standards Publication

Design of tensioned membrane structures

National foreword

This Published Document is the UK implementation of CEN/TS 19102:2023.

The UK participation in its preparation was entrusted to Technical Committee B/525, Building and civil engineering structures.

A list of organizations represented on this committee can be obtained on request to its committee manager.

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English Version

Design of tensioned membrane structures

Conception et calcul des structures en membrane
tendue

Bemessung von vorgespannten Membrantragwerken

This Technical Specification (CEN/TS) was approved by CEN on 24 August 2023 for provisional application.

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COMITÉ EUROPÉEN DE NORMALISATION
EUROPÄISCHES KOMITEE FÜR NORMUNG

CEN-CENELEC Management Centre: Rue de la Science 23, B-1040 Brussels

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European foreword

This document (CEN/TS 19102:2023) has been prepared by Technical Committee CEN/TC 250 “Structural Eurocodes”, the secretariat of which is held by BSI. CEN/TC 250 is responsible for all Structural Eurocodes and has been assigned responsibility for structural and geotechnical design matters by CEN.

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. CEN shall not be held responsible for identifying any or all such patent rights.

This Technical Specification has been prepared under Mandate M/515 issued to CEN by the European Commission and the European Free Trade Association.

This Technical Specification has been drafted to be used in conjunction with relevant execution, material, product and test standards, and to identify requirements for execution, materials, products and testing that are relied upon by the Eurocodes.

Any feedback and questions on this document should be directed to the users’ national standards body. A complete listing of these bodies can be found on the CEN website.

According to the CEN-CENELEC Internal Regulations, the national standards organizations of the following countries are bound to announce this Technical Specification: Austria, Belgium, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Norway, Poland, Portugal, Republic of North Macedonia, Romania, Serbia, Slovakia, Slovenia, Spain, Sweden, Switzerland, Türkiye and the United Kingdom.

0 Introduction

0.1 Introduction to CEN/TS 19102

This document for the design of tensioned membrane structures, which was prepared in line with the Eurocodes, is intended for use by designers, clients, manufacturers, constructors, relevant authorities (in exercising their duties in accordance with national or international regulations), educators, software developers, and committees drafting standards for related product, testing and execution standards.

NOTE Some aspects of design are most appropriately specified by relevant authorities or, where not specified, can be agreed on a project-specific basis between relevant parties such as designers and clients. The Eurocodes identify such aspects making explicit reference to relevant authorities and relevant parties.

0.2 Verbal forms used in the Eurocodes

The verb “shall” expresses a requirement strictly to be followed and from which no deviation is permitted in order to comply with the Eurocodes.

The verb “should” expresses a highly recommended choice or course of action. Subject to national regulation and/or any relevant contractual provisions, alternative approaches could be used/adopted where technically justified.

The verb “may” expresses a course of action permissible within the limits of the Eurocodes.

The verb “can” expresses possibility and capability; it is used for statements of fact and clarification of concepts.

0.3 National Annex for CEN/TS 19102

This document gives values within notes indicating where national choices can be made. Therefore, a national document implementing CEN/TS 19102 can have a National Annex containing all Nationally Determined Parameters to be used for the assessment of buildings and civil engineering works in the relevant country.

When not given in the National Annex, the national choice shall be the default choice specified in the relevant Technical Specification.

The national choice can be specified by a relevant authority.

When no choice is given in the Technical Specification, in the National Annex, or by a relevant authority, the national choice can be agreed for a specific project by appropriate parties.

National choice is allowed in CEN/TS 19102 through the following clauses:

4.3.1.2(3)	4.4.3.2(1)	8.2.1(3)	8.3.1(3)
9.2.1(1)	9.6.1(3)	C.3	C.4
C.5	C.6		

National choice is allowed in CEN/TS 19102 on the application of the following informative annexes:

Annex A	Annex H
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The National Annex can contain, directly or by reference, non-contradictory complementary information for ease of implementation, provided it does not alter any provisions of the Eurocodes.

1 Scope

1.1 Scope of CEN/TS 19102

(1) This document applies to the design of buildings and structural works, made of structural membrane material. It provides guidance for the design of tensioned membrane structures, either mechanically or pneumatically tensioned at a defined prestress level.

NOTE 1 Membrane materials comprise structural fabrics, coated structural fabrics and foils.

NOTE 2 For elements of tensile surface structures not governed by this Technical Specification (for example made of steel, aluminium, wood or other structural materials), see relevant Eurocode parts.

(2) This document is concerned with the requirements for resistance, serviceability and durability of tensioned membrane structures, as given in EN 1990.

NOTE 1 The safety criteria follow EN 1990 and will consider specific limit states for tensioned membrane structures.

NOTE 2 Specific requirements concerning seismic design are not considered.

(3) Design and verification in this document is based on limit state design in conjunction with the partial factor method.

NOTE Special attention goes to the action of prestress, snow, wind and rain action on membrane structures and the combined effect of wind and rain or snow.

(4) This document covers analysis methodologies appropriate for tensioned membrane structures, from analytical to full numerical simulation methods.

(5) This document considers connections between membrane materials and between membrane materials and others.

(6) This document is applicable for hybrid membrane structures integrating different kinds of load bearing behaviour (tension, compression, bending, inflation...), in a way that the structural membrane shares loadbearing capacity with other structural elements made of different materials.

NOTE The term 'hybrid structure' refers to this combined structural behaviour or use of materials.

1.2 Assumptions

(1) The assumptions of EN 1990 apply to this document.

(2) This document is intended to be used in conjunction with EN 1990, the EN 1991 series, the EN 1993 series, the EN 1999 series, ENs, EADs and ETAs for construction products relevant to tensioned membrane structures.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

NOTE See the Bibliography for a list of other documents cited that are not normative references, including those referenced as recommendations (i.e. in 'should' clauses), permissions ('may' clauses), possibilities ('can' clauses), and in notes.

EN 1990:2023, *Eurocode — Basis of structural and geotechnical design*

EN 1991 (all parts), *Eurocode 1 — Actions on structures*

EN 1993 (all parts), *Eurocode 3 — Design of steel structures*

EN 1999 (all parts), *Eurocode 9 — Design of aluminium structures*

EN ISO 527-1:2019, *Plastics — Determination of tensile properties — Part 1: General principles (ISO 527-1:2019)*

EN ISO 527-3:2018, *Plastics — Determination of tensile properties — Part 3: Test conditions for films and sheets (ISO 527-3:2018)*

EN ISO 1421:2016, *Rubber- or plastics-coated fabrics — Determination of tensile strength and elongation at break (ISO 1421:2016)*

EN ISO 13934-1, *Textiles — Tensile properties of fabrics — Part 1: Determination of maximum force and elongation at maximum force using the strip method (ISO 13934-1)*

3 Terms, definitions and symbols

For the purposes of this document, the terms and definitions given in EN 1990 and the following apply.

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

- ISO Online browsing platform: available at <https://www.iso.org/obp>
- IEC Electropedia: available at <https://www.electropedia.org/>

3.1 Terms and definitions

3.1.1

anchor

device used to secure a membrane or cable to a support, usually buried in the ground, so installed as to provide a firm point of attachment for resisting uplift

3.1.2

biaxial

stress state with stress along two orthogonal axes simultaneously

3.1.3

boundary cable

cable at the edge or termination of the membrane

3.1.4

cable

flexible linear or curvilinear element acting in tension

Note 1 to entry: A cable can be a wire rope, strand or web.

3.1.5

cable fitting

any accessory used as an attachment to, or support for, a cable

3.1.6

cable pocket

method of wrapping the membrane around a cable at a boundary condition

3.1.7

clamped connection

connection made by a series of shaped, overlapping plates that are clamped together by bolting

3.1.8

coated fabric

fabric with an adherent layer of polymeric material on one or both sides, the coated product remaining flexible

[SOURCE: ISO 472:2013, 2.152]

3.1.9

compensation

reduction in size of a cutting pattern, so that during installation the panel elongates to achieve an initial nominal prestress

[SOURCE: EN 17117-2:2021, 3.2]

3.1.10

compensation value

amount by which the dimensions of the pattern geometry is reduced by compensation

Note 1 to entry: The compensation value is expressed as a percentage of length in the direction to be compensated.

[SOURCE: EN 17117-2:2021, 3.3]

3.1.11

connection

location at which two or more elements meet, e.g. two structural membrane panels or a structural membrane and the supporting structure; for design purposes, it is the assembly of the basic components required to represent the behaviour during the transfer of the relevant internal forces and moments at the connection

[SOURCE: EN 1993-1-8:—¹, 3.1.3, modified to clarify the possible contribution of the structural membrane]

¹ Under preparation. Stage at the time of publication: FprEN 1993-1-8:2023.

3.1.12**cutting pattern**

two-dimensional geometry developed from a pattern to be cut out of an individual piece of membrane

Note 1 to entry: The pattern refers to a seam layout-based subdivision of the three-dimensional surface.

[SOURCE: EN 17117-2:2021, 3.4, modified – “coated fabric” replaced by “membrane”]

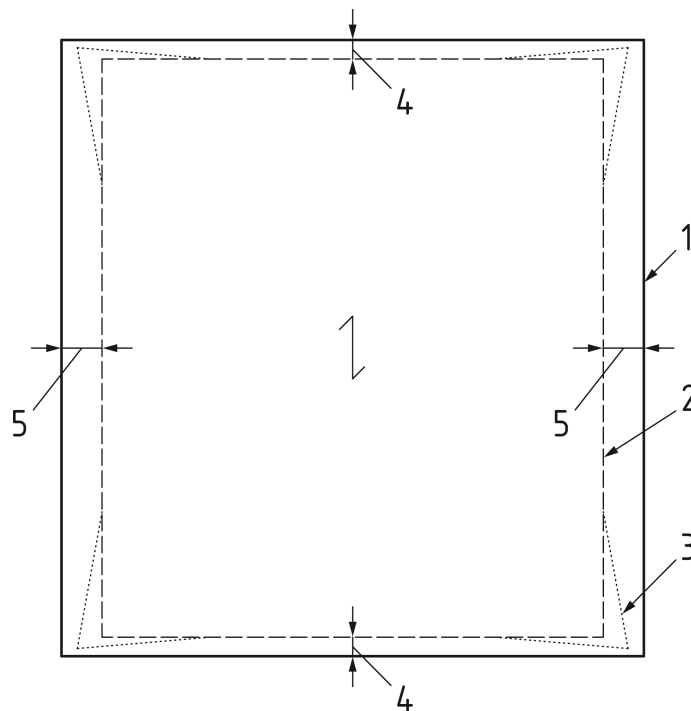
3.1.13**decompensation**

partial or complete reduction of compensation

Note 1 to entry: Decompensation may be applied to ease the installation process, typically in the vicinity of boundaries.

Note 2 to entry: Typical application of compensation and decompensation to a piece of membrane is depicted in Figure 3.1.

[SOURCE: EN 17117-2:2021, 3.5, modified – “coated fabric” replaced by “membrane” in Note 2 to entry]

**Key**

- 1 final geometry when stressed with nominal prestress
- 2 geometry compensated, unstressed
- 3 geometry decompensated, unstressed
- 4 half of the pattern compensation measure in warp
- 5 half of the pattern compensation measure in fill

Figure 3.1 — Typical application of compensation and decompensation to a piece of membrane

3.1.14

European Technical Product Specification

- European Product Standard (EN),
- or a European Technical Assessment (ETA) based on a European Assessment Document (EAD),
- or a transparent and reproducible assessment that complies with all requirements of the relevant EAD

3.1.15

eyelet

metal ring used to reinforce a small round hole in the membrane for threading a lace, string or rope through

3.1.16

external structure

structural elements of the construction, to which the membrane structure is connected, which carry vertical and horizontal loads from the membrane structure down to the foundations of the construction

Note 1 to entry: The external structure is out of the scope of this document.

3.1.17

extrusion direction

extrusion direction (or machine direction), abbreviated as “ED” (or “MD”), is the direction of extrusion of a foil, corresponding with the longitudinal direction of a rolled-up sheet

3.1.18

fabric

sheet material produced from yarn or roving by a weaving process

3.1.19

fill

weft

all wires running crosswise of the cloth as woven

[SOURCE: ISO 2395:1990, 3.2.22]

3.1.20

foil

film

unsupported film with uniform thickness

[SOURCE: CEN ISO/TS 80004-11:2020, 3.1.4]

Note 1 to entry: Strictly the term foil refers to a metallic membrane. However, it is now the most commonly used term for all isotropic structural plastic membranes including ETFE foils.

3.1.21

form found shape

equilibrium shape of the membrane depending on the geometry of the boundaries and the ratio of prestress in the main structural directions

3.1.22

hem

edge of a membrane panel folded and stitched or welded or both

3.1.23**high point**

commonly used expression for a radially patterned conical structure with elevated mid-ring

3.1.24**initial type testing**

initial tests performed to determine the strength of seams and edge connections that can be achieved

3.1.25**installation**

erecting the membrane structure on site

3.1.26**keder**

encased cable edge treatment for membrane surfaces, either used in conjunction with grooved profile extrusions or with plates, for connecting to rigid boundaries, corner plates and boundary cables

3.1.27**manufacture**

converting the membrane material into a panel ready to be installed

3.1.28**material production**

production of the membrane (base) material in the form of a roll

3.1.29**membrane material (base material)**

thin, sheet-like material to create tensile surface structures, comprising structural fabrics, coated structural fabrics and foils

3.1.30**nominal prestress**

input data of prestress prescribed during the form finding and structural analysis, and part of the structural design

[SOURCE: EN 17117-2:2021, 3.10]

3.1.31**numerical model**

numerical representation of a physical model

3.1.32

panel

final three-dimensional assembly of pieces of membrane, cut according to the cutting pattern, ready to be installed on site

[SOURCE: EN 17117-2:2021, 3.8, modified – “coated fabric” replaced by “membrane”]

Note 1 to entry: An architectural tensioned envelope may be made of more than one panel.

Note 2 to entry: A panel made of pieces of membrane is depicted in Figure 3.2.

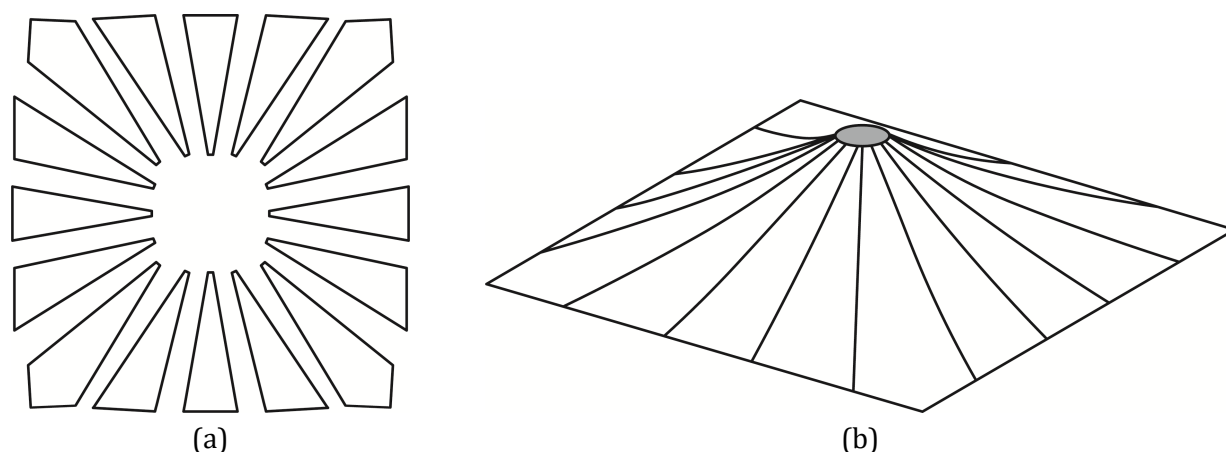


**Figure 3.2 — Example of a panel assembled of pieces of membrane:
(a) Pieces of membrane, cut according to the cutting pattern, (b) panel**

3.1.33

piece of membrane

two-dimensional piece cut from a roll of membrane

[SOURCE: EN 17117-2:2021, 3.9, modified – “coated fabric” replaced by “membrane”]

3.1.34

ponding

accumulation of water or snow in flat or reversed areas

3.1.35

prestress

effect of prestressing process, namely, internal forces in the sections and the deformation of the structure

[SOURCE: EN 1992-1-1:2023, 3.1.64]

3.1.36

primary structure

stable structural system conceived to hold up the structural membrane

Note 1 to entry: This term is only used in the context of stability.

3.1.37

seam

connection of two or more pieces of membrane material, typically welded, stitched or glued

3.1.38**seam layout**

definition of location and direction of seams over the surface of an architectural tensioned envelope

[SOURCE: EN 17117-2:2021, 3.12]

3.1.39**secondary structure**

is only stable if connected to a primary structure (or an adjacent building), it can consist of the following components: membrane, clamping profile, corner fittings, boundary cable/rope, ridge cable/rope, valley cable/rope, pendulum supports, pendulum rods, hinged masts, supporting cables/ropes, “air supports”, back cables/ropes, etc.

Note 1 to entry: Consider as example a four-point sail with four masts and back cables/ropes. All above-ground components form the secondary structure, while the foundations form the primary structure. But if the top points of the four masts are connected (e.g. with cables), only the membrane, the corner fittings and the boundary cables form the secondary structure, since the rest remains standing without these components and thus forms the primary structure.

Note 2 to entry: This term is only used in the context of stability.

3.1.40**structural membrane**

tensioned membrane

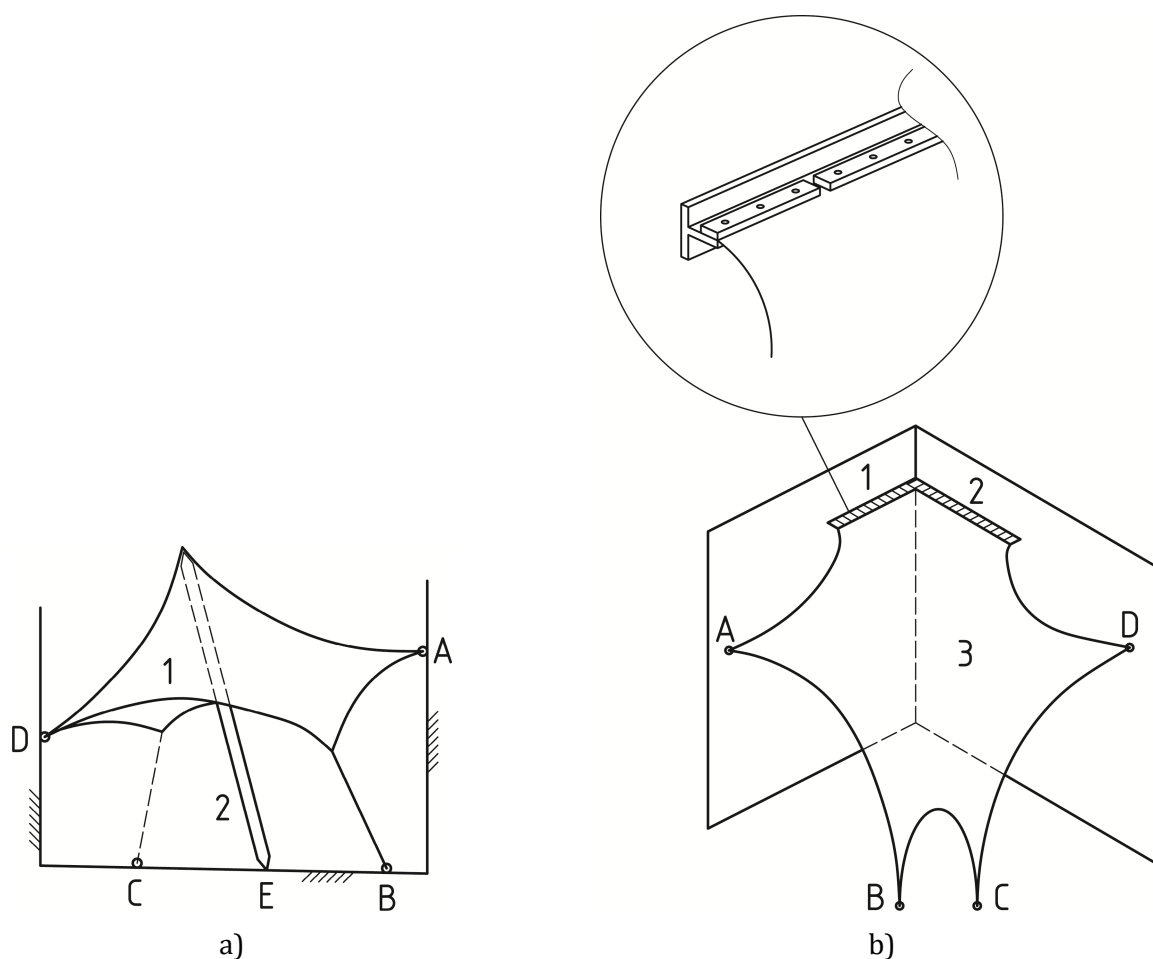
tensile membrane

surface structure, carrying the loads by in-plane tension, attached to the supporting structure

3.1.41**supporting structure**

membrane supporting structure

assembly of structural members (poles, cables, arches etc.), which carries the structural membrane and resist loads that this structure is subjected to

**Key**

A, B, C, D, E fixing points to the external structure
 1 structural membrane
 2 membrane supporting structure (pole)

Key

A, B, C, D fixing points to the external structure
 1, 2 supporting structure with fixing lines to the external structures
 3 structural membrane

Figure 3.3 — Examples of supporting structures: (a) Fixing points to the external structure, (b) Fixing lines to the external structure

Note 1 to entry: A membrane structure always ends at fixing points or fixing lines to foundations or to external structures (e.g. adjacent walls). Elements (e.g. beams, columns, etc.), which are not structurally needed for the membrane structure, are out of the scope of this document. Foreseeable deviations such as deflections, shortenings, or elongations of the elements of the external structure should be communicated to the designer of the membrane structure, so that these can be taken into account in the design.

3.1.42**tensioned membrane structure**

membrane structure

tensile surface structure

combination of the structural membrane and its supporting structure

3.1.43**textile**

woven fabric, knitted fabric, etc., formed by the interlocking of fibres and yarns having a certain cohesion

Note 1 to entry: Textiles often include certain types of non-woven fabrics.

[SOURCE: ISO 16373-3:2014, 2.1]

3.1.44**transversal direction**

direction transverse to the extrusion direction, abbreviated as “TD”, of a foil, corresponding with the width of a rolled-up sheet

3.1.45**turnbuckle**

device composed of a doubly threaded cylinder commonly used to provide length adjustment of a cable

3.1.46**uniaxial**

stress state with stress along one axis only

3.1.47**warp**

all wires running lengthwise in the cloth as woven

[SOURCE: ISO 9044:2016, 3.4]

3.1.48**welding**

means of connecting coated membrane or foil materials by a melting process like through hot air, hot edge, hot bar, High Frequency or Ultra Sonic technology

3.1.49**work hardening**

strengthening of a polymer, combined with plastic strain

Note 1 to entry: Within the scope of this document the strengthening of foil material like ETFE is meant, caused by a single or multiple loading.

3.1.50**wrinkle**

local buckling deformation of a membrane under compressive stresses

3.2 Symbols and abbreviations

3.2.1 Latin uppercase symbols

E	Young's modulus
P	Pressure
R_d	Design value of the resistance
R_k	Characteristic value of the resistance
T	Temperature
V	Volume
V_x	Coefficient of variation

3.2.2 Latin lowercase symbols

f_E	Characteristic foil stress in the considered direction in the framework of the SLS verification
f_{Ed}	Design membrane stress in the considered direction
f_{el23}	Characteristic (= 5 % fractile) elastic limit of a foil in the framework of the SLS verification determined from in a uniaxial short-term tensile test at $T = 23\text{ °C}$
f_{k23}	Characteristic (= 5 % fractile) tensile strength of a membrane or connection in a uniaxial short-term tensile test at $T = 23\text{ °C}$
f_{str23}	Stress limit of a foil in the framework of the SLS verification
f_R	Characteristic tensile strength of a foil or a foil connection in the framework of the SLS verification
f_{Rd}	Design tensile strength of a membrane or a membrane connection
$f_{R,mod}$	Characteristic tensile strength of a foil or a foil connection related to the specific SLS design situation
$f_{Rd,mod}$	Design tensile strength of a foil or a foil connection related to the specific design situation
f_{u23}	Characteristic (= 5 % fractile) tensile strength of a foil in a uniaxial short-term tensile test at $T = 23\text{ °C}$
f_{uw23}	Characteristic (= 5 % fractile) tensile strength of a foil connection in a uniaxial short-term tensile test at $T = 23\text{ °C}$
k	Modification factor taking into account separate specific effects influencing the membrane properties in specific design situations

3.2.3 Greek lowercase symbols

β	Reliability index
ε_{irr}	Irreversible strain
ε_{res}	residual strain after a relaxation time
ε_{sat}	strain when elongation has stopped in a creep test
γ	Shear angle
γ_m	Partial factor for a material property
γ_M	Partial factor for a material property, also accounting for model uncertainties and dimensional variations
γ_{M0}	Partial factor for material
γ_{M1}	Partial factor for connections
$\gamma_{M,ser}$	Partial factor for material in the SLS verification
γ_{Rd}	Partial factor associated with the uncertainty of the resistance model
ν	Poisson's ratio
φ	Spreading angle in a cable pocket

3.2.4 Abbreviations

CC	Consequence class
Cl.	Clause
D	Dimension
EXC	Execution class
EPDM	Ethylene propylene diene (monomer) rubber
ETFE	Ethylene-tetrafluoroethylene
FEP	Fluorinated Ethylene Propylene
PES	Polyester
PET	Polyethylene terephthalate
PFA	Tetrafluoroethylene perfluoroalkoxy vinyl ether copolymer
PP	Polypropylene
PTFE	Polytetrafluoroethylene
PVC	Polyvinylchloride
PVDF	Polyvinylidene fluoride
QL	Quality level
UV	Ultraviolet

4 Basis of design

4.1 General rules

4.1.1 Basic requirements

(1) The form of a structural membrane should be found as an equilibrium shape depending on the geometry of the boundaries and the ratio of prestress levels in the main structural directions. The obtained equilibrium shape is the form found shape.

(2) The structural membrane should be kept in equilibrium by supporting elements. The supporting structure consists of the elements assuring the prestress in the structural membrane.

NOTE 1 Structural membranes are prestressed, and the spatial shape is mostly doubly curved. Both characteristics ensure that the membrane can carry loads by activating only tensile stresses.

NOTE 2 The form can be anticlastic (in general mechanically prestressed like saddle shaped structures) or synclastic (in general pneumatically prestressed by air inflation) or even monoclastic or flat.

NOTE 3 Usually, membrane structures are mixed structures. The supporting structure for the structural membrane can be made of steel, timber or other material. The membrane itself is carrying the external loads to the supporting structure.

NOTE 4 The engineering of membrane structures consists of several design steps (see Table 4.1): form finding, structural analysis, cutting pattern design and construction engineering.

Table 4.1 — Design steps for the design of membrane structures

Form finding <	> Structural < analysis	> Cutting pattern < design	> Construction engineering
Form depending on the geometry of the boundaries and the prestress	Load assumptions for the spatial surface geometry Assumption of appropriate material stiffness properties Structural analysis	Division into single cutting patterns Determination of the plane unstressed patterns	Planning of the erection and prestressing procedure

NOTE 5 Interactions exist between the various design steps. The design is often an iterative process. For instance, the structural analysis has an impact on the choice of the prestress level and thus on the form finding.

NOTE 6 Maintenance and end of life scenarios can be integrated into the design.

(3) The cutting pattern design shall consist of the division into single cutting patterns, the “flattening” of the three-dimensional geometry onto a plane, and the compensation.

NOTE The compensation is a reduction in size of a cutting pattern so that during installation the panel elongates to achieve an initial prestress.

(4) Construction engineering should consider the erection and prestressing procedure.

(5) The design of membrane structures shall be in accordance with the rules given in EN 1990 and the supplementary provisions for membrane structures given in this document.

(6) The basic requirements of EN 1990 are deemed to be fulfilled for membrane structures when the following are applied together:

- limit state design in conjunction with the partial factor method in accordance with EN 1990;
- actions in accordance with the EN 1991 series, for prestress see 4.3.1.2;
- combination of actions in accordance with EN 1990;
- the principles and rules of application given in this document; and
- resistances, durability and serviceability in accordance with this document.

(7) The minimum design prestress should be maintained throughout the design service life.

(8) The design of the membrane structure shall ensure the compatibility of deformations between the supporting structure and the structural membrane

(9) The Execution Class should be proposed by the design team.

NOTE For the relevance of executions classes see informative Annex H.

4.1.2 Stability, security, redundancy

(1) The supporting structure should be stable without the structural membrane or membrane parts.

NOTE If the supporting structure is stable without the structural membrane or membrane parts, it is the primary structure, and then the structural membrane is the secondary structure.

(2) Complementary cables and redundant devices should be included to increase the safety at critical points, such as top masts, arches or frames, in order to prevent collapse.

NOTE The stability of the whole structure depends on the integrity of each component. A local failure (for instance due to fire) can easily cause a general collapse.

4.1.3 Structural reliability

(1) The rules for structural reliability given in EN 1990 shall be followed.

4.1.4 Robustness

(1) The rules for robustness given in EN 1990 shall be followed.

4.1.5 Design service life

(1) The rules for the design service life given in EN 1990 shall be followed, including the specification of the intended design service life of a temporary or a permanent building.

(2) A membrane structure may be designed for a design service life of 50 years. The membrane may be designed to be replaceable.

NOTE 1 The 50 years design service life is related to the definition of the loading in EN 1990.

NOTE 2 The life expectancy of the membrane can be different. Typically for coated fabrics and ETFE foils the service life is more than 25 years.

NOTE 3 For structural elements not designed for the total design service life of the building, see 4.1.6(6).

4.1.6 Durability

(1) Depending on the type of action affecting durability and the design service life (see EN 1990:2023, A.1.4) membrane structures should be:

- designed for degradation arising from environmental factors;
- designed for wearing; and
- designed for accidental actions (see EN 1991-1-7).

NOTE Fire can be regarded as an accidental action (see Annex F).

(2) Membrane structures design should consider easy inspection and maintenance.

(3) The rules for durability given in EN 1990 shall be followed.

(4) To ensure durability, buildings and their components should either be designed for environmental actions and fatigue if relevant or else protected from them.

(5) The effects of deterioration of material where relevant should be considered by appropriate choice of material (see Clause 6), and of connections (see Clause 10), or by structural redundancy.

(6) If a building includes components that need to be replaceable, the possibility of their safe replacement should be verified as a transient design situation.

(7) For structural design, deflation of inflated components should be considered as an accidental condition (e.g. water ponding).

4.2 Principles of limit state design

(1) Design conditions, Ultimate limit states and Serviceability limit states shall be analysed according to EN 1990.

4.3 Basic variables

4.3.1 Actions and environmental influences

4.3.1.1 General

(1) Actions for the design of membrane structures shall be taken according to the relevant parts of EN 1991 unless otherwise specified in this document.

NOTE 1 In case of hybrid structures the rules for the different materials are applied, even if the partial factors are different.

NOTE 2 There is a need to further develop climatic actions on membrane structures in EN 1991.

4.3.1.2 Prestress

(1) To ensure the biaxial loadbearing behaviour and to avoid slack areas as well as large deflections, membrane structures shall be prestressed biaxially.

NOTE The prestress considered in this document is applied mechanically by membrane compensation or pneumatically by inner pressure.

(2) The prestress level should be chosen in accordance with the structural analysis.

NOTE The selected prestress level, limitation of wrinkles and maintenance of prestress is considered as project specific. Minimum prestress levels can be defined in the National Annex.

(3) Additional requirements for the selected prestress level, limitation of wrinkles and maintenance of prestress should be as specified or, where not specified, agreed for a specific project by the relevant parties.

(4) Compensation values shall be considered according to the design, where appropriate determined from compensation tests. Compensation values may be determined according to EN 17117-2.

4.3.1.3 Wind

(1) For membrane structures, force coefficients as given in EN 1991-1-4:2005, 7.3 may be used. The force coefficients specify the overall effect of the wind on a structure as a whole.

NOTE EN 1991-1-4 rules are not always appropriate for complex three-dimensional curved shapes.

(2) If there is no acceptable approximation available for the considered double curved shape (accepted by involved parties or experts), experimental tests or numerical simulations (e.g. wind-tunnel testing, CFD-simulations) should be used.

(3) The effect of a perforation (like in mesh fabrics or in case of micro perforations) of the membrane may be considered.

4.3.1.4 Snow

(1) For membrane structures, actions due to snow given in EN 1991-1-3:2003/A1:2015 may be used.

NOTE EN 1991-1-3 rules are not always appropriate for complex three-dimensional curved shapes.

(2) If there is no acceptable approximation available for the considered double curved shape (accepted by involved parties or experts), experimental tests or numerical simulations should be used.

4.3.1.5 Effect of tolerances

(1) Tolerances in the supporting structure might affect the prestress level, therefore special consideration should be given to the sensitivity of membrane structures to these tolerances.

(2) The acceptable tolerances of the supporting structure to the interface to the structural membrane should be agreed in the design phase.

NOTE For further information on tolerances of the supporting structure, see informative Annex H, H.16.2.

4.3.2 Material and product properties

4.3.2.1 General

(1) The structural properties of membrane materials to be used for the design should be those specified in a European Technical Product Specification, unless otherwise indicated in Clause 5 in this document.

(2) For the design of membrane structures, characteristic values X_k or nominal values X_n of the material properties shall be used.

(3) For the structural design and analysis, nominal values of dimensions may be used.

4.3.2.2 Creep and relaxation

(1) The effect of creep or relaxation should generally be taken into account for the verification of serviceability limit states.

NOTE 1 Creep and relaxation are time-dependent properties of membrane materials that can affect the prestress or the geometry.

NOTE 2 As creep and relaxation can affect the prestress, corresponding behaviour is not fully covered by applying a modification factor to the strength.

4.3.3 Geometric data

(1) The rules for geometric data given in EN 1990:2023, 6.3 shall be followed.

(2) The geometry of the three-dimensional shape of a membrane structure should be considered together with the size tolerances at connection points where components from different materials are assembled.

4.4 Verification by the partial factor method

4.4.1 Design value for the membrane resistance

(1) The design value for a material or connection property shall be obtained by dividing its characteristic value by a relevant partial factor, γ_M .

(2) Modification factors k should be used to take into account separate specific effects influencing the membrane properties in specific design situations.

4.4.2 Design value of geometrical data

(1) Geometrical data for structural membranes may be taken from design drawings and treated as nominal values.

4.4.3 Design resistances

4.4.3.1 General

(1) The design resistance for a specific design situation shall be calculated based on Formula (8.18) of EN 1990:2023.

(2) For textile structures, the design value R_d of a resistance should be calculated from Formula (4.1)

$$R_d = \frac{1}{\gamma_M} R_k (k_{age}; k_{biax}; k_{dur,*}; k_{temp,*}; k_{size}; k_x) \quad (4.1)$$

where

R_k	is the characteristic value of the particular resistance determined with characteristic or nominal values for the material properties and dimensions;
γ_M	for simplicity, the partial factors γ_m and γ_{Rd} given in Formula (8.18) of EN 1990:2023 may be combined into a single partial material factor ($\gamma_M = \gamma_m \cdot \gamma_{Rd}$); for the value of γ_M , see Resistance of fabrics and their connections 8.2.1.
k_{age}	is the modification factor for environmental (ageing, deterioration) effects;
k_{biax}	is the modification factor for biaxial effects;
$k_{dur,*}$	is the modification factor for various load durations (permanent, long-term, medium-term and short-term);
$k_{temp,*}$	is the modification factor for temperature effects;
k_{size}	is the modification factor linked to the panel size, which takes into account the increasing risk of defects with a larger surface;
k_x	is a variable for a modification factor for not yet specified effects;

NOTE 1 Tear control is addressed in 9.5.

NOTE 2 For $k_{temp,*}$ a typical elevated testing temperature is 70 °C, the temperature to take into account depends on specific environmental conditions and material properties, like the energy absorption influenced by the colour.

(3) For foil structures, the design value R_d (ULS) or R (SLS) of a resistance should be calculated from Formula (4.2)

$$R_d \text{ (or } R) = \frac{1}{\gamma_M} R_k (k_{age}; k_{biax}; k_{dur,*}; k_{temp,*}; k_{single}; k_{QL}; k_x) \quad (4.2)$$

where

- R_k is the characteristic value of the particular resistance determined with characteristic or nominal values for the material properties and dimensions;
- γ_M for simplicity, the partial factors γ_m and γ_{Rd} given in Formula (8.18) of EN 1990:2023 may be combined into a single partial material factor ($\gamma_M = \gamma_m \cdot \gamma_{Rd}$);
- k_{age} is the modification factor for environmental (ageing, deterioration) effects;
- k_{biax} is the modification factor for biaxial effects;
- $k_{dur,*}$ is the modification factor for various load durations (permanent, long-term, medium-term, short-term);
- $k_{temp,*}$ is the modification factor for various temperature effects (0 °C, 40 °C or 50 °C);
- k_{single} is the modification factor for single layer ETFE structures, only applied in SLS
- k_{QL} is the modification factor considering the manufacturers quality level
- k_x is a variable for a modification factor for not yet specified effects;

NOTE The recommended partial factors for material properties γ_M are given in Clause 8.3.1 for the Ultimate Limit State (ULS) and in Clause 9.6.1 for the Serviceability Limit State (SLS).

(4) The values for the k-factors given in Annex C may be used.

4.4.3.2 Combination of actions

(1) The combination of actions for the Ultimate and Serviceability Limit States and the partial factors of actions shall be in accordance with EN 1990. The recommended lower and upper partial factor values for prestress are $\gamma_{Pinf} = 0,9$ and $\gamma_{PSup} = 1,25$ respectively.

NOTE Actions for particular regional or climatic or accidental situations, as the case of fire, can be given in the National Annex.

(2) Load combinations of external actions shall be applied on the equilibrium state of the structural membrane (see 4.1.1(1)) after formfinding under prestress, considering the prestress level which is the most unfavourable (*1, *0,9 or *1,25).

4.4.3.3 Application of partial safety factors to the action or to the effect of the action

(1) Membrane structures shall be analysed by a geometric nonlinear analysis, as the relationship between action and effect is not proportional.

(2) Uncertainties regarding the effects of the action due to uncertainties of the structural analysis model and the analysis type should be considered.

NOTE How to apply EN 1990 can be specified in the National Annex.

4.4.4 Verification of static equilibrium

(1) For the verification of static equilibrium, the design values of actions specified in Table A.1.2(A), Design values of actions (EQU) (Set A), in EN 1990:2023, Annex A, A.1 should be applied.

4.5 Design assisted by testing

NOTE For design assisted by testing this document refers to EN 1990:2023, Annex D.

5 Materials

5.1 General

(1) This document covers the design of tensioned membrane structures fabricated from fabrics, foils or other materials at least characterized according to the requirements provided in 5.2 and 5.3.

NOTE 1 Examples of materials covered in this clause include polyvinyl chloride (PVC)-coated polyethylene terephthalate (PET)-fabrics (short: PES-PVC), polytetrafluoroethylene (PTFE)-coated glass fibre fabrics (short: glass-PTFE) and foils made from ethylene-tetrafluoroethylene (ETFE). Other materials can be used.

NOTE 2 PET is generally called polyester, commonly abbreviated with PES. The abbreviation PES is used in this document.

(2) If other materials than the ones listed above are used, the characteristics shall be determined with suitable tests and procedures.

5.2 Fabrics

5.2.1 Strength

(1) Strength values shall be confirmed by experimental tests according to EN ISO 1421 for coated fabrics or EN ISO 13934-1 for uncoated fabrics, respectively. The calculation of the 5 % fractile should be based on a logarithmically normal distribution.

NOTE 1 EN 1990:2023, Annex D provides a method to determine the characteristic value.

NOTE 2 Test procedures are suggested in H.9 for quality control and in H.13.2 for inspection of incoming materials.

NOTE 3 Specimens are carefully prepared. A yarn on both sides is removed. The precise width of each specimen is measured and mentioned in the report.

(2) The required minimum tensile strength values shall be defined according to the statical analysis (see 8.2.1).

(3) Tear strength values should be determined according to EN 1875-3:2023, method B.

NOTE For more specific evaluation, tear tests on biaxially stressed wide panels can be executed and the results considered for the design.

(4) For coated fabrics, adhesion values should be determined according to EN ISO 2411. Test specimen preparation procedure 2 should be used and the materials should be welded.

(5) Besides conventional PES-PVC and glass-PTFE fabrics, other types of fabric and coated fabric, may be used. In any case, the required tensile strength values shall be defined by the structural engineers depending on the specific needs of the project.

NOTE As an orientation, Annex A provides tensile strength classifications for conventional PES-PVC and glass-PTFE fabrics as well as indicative tear and adhesion strength values for each tensile strength class.

5.2.2 Decreasing and increasing effects on the tensile strength

(1) Decreasing effects on the tensile strength shall be considered.

(2) Increasing effects on the tensile strength may be considered.

NOTE Decreasing effects on the tensile strength are for instance temperatures higher than the reference temperature $T = 23\text{ °C}$ or crease folds in glass-PTFE fabrics, increasing effects are for instance temperatures lower than the reference temperature $T = 23\text{ °C}$.

(3) Modification factors as stated in Clause 4.4.3.1 should be used to consider decreasing and increasing effects.

(4) Annex B, which provides the principle for the determination of the modification factors and the test procedures to determine them, should be used in the design.

NOTE For orientation and preliminary design, Annex C provides typical ranges of modification factor values for different coated fabrics.

(5) If not provided in this document, suitable test procedures to determine the modification factors should be developed and used.

(6) Unfavourable influences on the tensile strength shall be considered by performing tests on test specimens that are or were exposed to this influence.

(7) The effect of crease folds on the tensile strength in glass-PTFE fabrics should be considered in case that crease folds are observed during fabrication, packaging, transport or installation. The degrading effect may be expressed by a modification factor; in such a case the principle of Annex B, B.3 shall be followed.

5.2.3 Stiffness parameters

(1) The tensile stiffness of the material may be determined according to EN 17117-1.

(2) During the design it shall be checked that, for the project under consideration, the stress ratios and stress levels correspond to those used to achieve the stiffness values. If not, project specific evaluation procedures may be used.

(3) The shear stiffness of the material may be determined according to an appropriate experimental method, for example using the picture frame test, the bias extension test or the shear ramp in a biaxial test.

5.3 Foils

5.3.1 Strength

(1) Strength values shall be confirmed by experimental tests.

NOTE Procedures are suggested in H.9 for quality control and in H.13.2 for inspection of incoming materials.

(2) The tensile strength at 23 °C in extrusion and transversal direction shall be determined according to EN ISO 527-3. The provisions in Annex I shall be used for the test parameters for uniaxial tests. The required minimum values shall be defined according to the statical analysis (see 8.3.1).

NOTE EN 1990:2023, Annex D provides a method to determine the characteristic value.

(3) The tear propagation strength at 23 °C in extrusion and transversal direction should be determined with tear tests according to EN 17679.

NOTE The typical strength values for ETFE foils are given in Table A.5.

5.3.2 Decreasing and increasing effects on the tensile strength

(1) Decreasing effects on the tensile strength shall be considered.

(2) Increasing effects on the tensile strength may be considered.

NOTE Decreasing effects on the tensile strength are for instance temperatures higher than the reference temperature $T = 23\text{ }^{\circ}\text{C}$, increasing effects are for instance temperatures lower than the reference temperature $T = 23\text{ }^{\circ}\text{C}$ or work hardening of foils.

(3) Modification factors as stated in 4.4.3.1 should be used to consider decreasing and increasing effects or the test procedures according to Annex E should be used in which temperature, load duration and load cycling effects are implicitly considered.

(4) Annex B, which provides the principle for the determination of the modification factors and the test procedures to determine them, should be used in the design.

NOTE For orientation and preliminary design, Annex C provides typical ranges of modification factor values for ETFE foils for the ULS and SLS.

(5) If not provided in this document, suitable test procedures to determine the modification factors should be developed and used.

(6) Unfavourable influences on the tensile strength, shall be considered by performing tests on test specimens that are or were exposed to this influence. If the influence is reversible (e.g. in short-term tests at elevated temperature), it should be present during the test, otherwise (e.g. long-term loading) it should be introduced to the sample prior to the test.

5.3.3 Stiffness parameters

(1) Stiffness parameters should be determined by biaxial testing.

NOTE For more details, see 8.3.

(2) During the design it shall be checked that, for the project under consideration, the stress ratios and stress levels correspond to those used to achieve the stiffness values. If not, project specific evaluation procedures may be used.

(3) Stiffness parameters may be temperature dependent.

NOTE For ETFE foils the stiffness parameters are highly temperature dependent.

5.4 Connection devices

(1) Material properties for connection devices at seams or membrane edges like clamping or corner plates should be taken from the relevant material-specific Eurocodes.

5.5 Structural elements

(1) Material properties for rigid structural elements should be taken from the relevant material-specific Eurocodes.

(2) Material properties for cables should be taken from EN 1993-1-11 and the EN 12385 series.

(3) Material properties of belts made from synthetic fibres should be determined from experimental tests.

(4) Material properties of fibre ropes made from synthetic fibres should be taken from:

— EN ISO 1141, *Fibre ropes — Polyester — 3-, 4-, 8- and 12-strand ropes (ISO 1141)*;

- EN ISO 1346, *Fibre ropes — Polypropylene split film, monofilament and multifilament (PP2) and polypropylene high-tenacity multifilament (PP3) — 3-, 4-, 8- and 12-strand ropes (ISO 1346)*; and
- EN ISO 1969, *Fibre ropes — Polyethylene — 3- and 4-strand ropes (ISO 1969:2004)*.

NOTE For any other semi-finished or finished structural product used in the structural design of buildings, the required properties can be found in a European Technical Product Specification.

6 Durability

6.1 General

- (1) The effects of deterioration of material, e.g. due to environmental exposure or fatigue loads where relevant shall be taken into account.
- (2) To ensure durability of the structure due consideration should be given to:
 - a) detailing, such that the membrane that is in contact with the supporting structure (cables, clamped edges, etc.) is not damaged, even with cyclic loading and large movements of the membrane;
 - b) ensuring that the used materials for clamping and detailing are of sufficient durability considering the intended membrane service life;
 - c) inspection of all load bearing components according to an inspection plan established for each product; and
 - d) ensuring that no tearing occurs, especially in areas with stress concentration.
- (3) For elements that cannot be inspected, an appropriate deterioration allowance shall be included.
- (4) Parts susceptible to mechanical wear or fatigue should be designed such that inspection, maintenance and reconstruction can be carried out satisfactorily and access is available for in-service inspection and maintenance.
- (5) For pneumatic structures, adequate measures should be taken to ensure that the air pressure is maintained during the whole design service life and to ensure that the air humidity control is maintained during the whole design service life.

6.2 Fabrics

- (1) To ensure durability of the structural membrane due consideration should be given to:
 - a) tensile strength during the whole service life of the fabric, which may be measured according to EN ISO 1421 after natural weathering or accelerated weathering;
 - b) antifungal properties, to be assessed according to EN ISO 846:2019, method A, considering the expected climate on site;
 - c) sufficient lacquer adhesion in cases where lacquer is used;
 - d) sufficient anti-wicking properties;
 - e) sufficient strength or reinforcements to prevent tearing.

6.3 Foils

- (1) To ensure durability of the structural membrane due consideration should be given to:
- a) tensile strength during the whole service life of the foil, which may be measured according to EN ISO 527-3 after natural weathering or accelerated weathering; and
 - b) sufficient coating adhesion (e.g. printing, low-e) in cases where coating is used.
- (2) The durability of the coating for foils shall be proven under cyclic loading tests.

7 Structural Analysis

7.1 General

7.1.1 Structural modelling for analysis

- (1) The general rules for structural analysis given in EN 1990 shall apply.
- (2) The membrane surface shall be defined using a numerical or experimental form-finding procedure to reach an equilibrium state. The form found state shall result in acceptable levels of stress, strain, and geometry under design loads.

NOTE Numerical form-finding procedures are generally used.

- (3) Analysis shall be based on mathematical models of the membrane structure that are capable of predicting stresses, strains, and displacements to a sufficient level of accuracy and detail for the limit state under consideration.

NOTE The term “sufficient” relates to the complexity and capabilities of the mathematical models to describe the physics of the structure in the simulation.

- (4) The mathematical model and basic assumptions for the calculations should be capable of simulating the structural behaviour for the relevant limit state with appropriate accuracy and consistent with the anticipated behaviour of the materials and structural components, including the connections and other details.
- (5) For each relevant limit state verification, the calculation model of the structure shall be comprised of:
- a description of the membrane structure, the materials from which it is made, and the relevant environment of its location;
 - the behaviour of the whole or parts of the structure, related to the relevant limit states; and
 - the actions and how they are imposed.

- (6) The method used for the analysis shall be consistent with the design assumptions.

- (7) Analyses shall be carried out using idealisations of both the geometry and the behaviour of the structural details (e.g. connection rotation). The idealisations selected shall be appropriate to the structure being considered.

- (8) All load cases shall be applied to the form found model. Applied loads shall be determined according to the form found geometry. During iterative analysis, loads should be adjusted to the computed deformed geometry.

- (9) Partial factors for prestress shall be included as defined in Clause 4.4.3.2(1) and for loads as defined in EN 1990.