CEN/TC 250/WG 5 Membrane Structures
Scientific and Policy Report (SaP-Report)

~~Guideline~~ Background documentation for a European Structural Design of Tensile Membrane Structures Made from Fabrics and Foils

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Background documents in support to the implementation, harmonization and further development of the Eurocodes

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~~Guideline~~ Background document for a European Structural Design of Tensile Membrane Structures Made from Fabrics and Foils

European Commission
Joint Research Centre
Institute for Protection and Securoty of the Citizen

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To be done by JRC

Foreword

To be done …

Foreword 2nd page

Report Series "Support to the implementation, harmonization and further development of the Eurocodes"

In the light of the Commisssion Recommendation of 11 December 2003, DG JRC is collaborating with DG ENTR and CEN/TC250 "Structural Eurocodes", and is publishing the Report Series **"Support to the implementation, harmonization and further development of the Eurcodes"** as JRC Scientific and Policy Reports. This Report Series includes, at present, the following types of reports:

1. **Policy support documents**, resulting from the work of the JRC in cooperation with partners and stakeholders on "support to the implementation and further development of the Eurocodes and other standards for the building sector";
2. **Technical documents**, facilitating the implementation and use of the Eurocodes and containing information and practical examples (Worked Examples) on the use of the Eurocodes and covering the design of structures or its parts (e.g. the technical reports containing the practical examples presented in the Workshop on the Eurocodes with worked examples organized by the JRC);
3. **Pre-normative documents**, resulting from the works of the CEN/TC250 and containing background information and/or first draft of proposed normative parts. These documents can be then converted to CEN technical specifications;
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5. **Scientific/Technical information documents**, containing additional, non-contradictory information on current Eurocode part, which may facilitate its implementation and use, or preliminary results from pre-normative work and other studies, which may be used in future revisions and further developments of the standards. The authors are various stakeholders involved in Eurocodes process and the publication of these documents is authorized by relevant CEN/TC250 Sub-Committee or Working Group.

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The publication of these reports by the JRC serves the purpose of implementation, further harmonization and development of the Eurocodes. However, it is noted that neither the Commission nor CEN are obliged to follow or endorse any recommendation or result included in these reports in the European legislation or standardization processes.

The reports are available to download from the "Eurocodes: Building the future" website (http://eurocodes.jrc.ec.europa.eu).

Acknowledgements

This report has been prepared for the development of a future European design standard for membrane structures under the aegis of CEN/TC 250. Both CEN/TC 250 and JRC acknowledge the substantial contribution of the many international experts of CEN/TC 250/WG 5, CEN/TC 248/WG 4, COST Action TU1303 and others, who have supported the works by their essential input and reviews.

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Content

1 Introduction and general

1.1 Placement of a Eurocode on membrane structures

Membrane structures made from technical textiles or foils are increasingly present in the urban environment. They are all summarized in the term ‘Textile Architecture’. Whereas membrane structures were, decades ago, mainly built as highly curved roofs because they are able to economically and attractively span large distances (such as sports facilities), an evolution towards a much wider scope of applications is noticeable today. Textile architecture in the built environment can nowadays be found in a variety of structural skins, ranging from private housing to public buildings and spaces. This may be in the form of small scale canopies (to provide solar shading or protection against rain), in performance enhancing façades (such as dynamic solar shading, foils replacing glass elements and acting as substrates for solar energy harvesting systems), roof constructions (to protect archaeological sites, market places, bus stations …) and formwork for light shell structures, see exemplary Figure 1-1.

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Figure 1-1 Modern membrane structures

Tensioned membrane constructions have unique properties that other, more conventional, building elements often do not possess simultaneously, such as low self-weight, high flexibility, translucency and the capability of forming architecturally expressive shapes that enhance the urban environment. In addition, membrane structures are known to be ‘optimal’ since they are only loaded in tension and adapt their shape to the flow of forces. Hence, they use a minimal amount of material to cover a space. Typical shapes are synclastic and anticlastic forms, in some cases also flat structures are built like façades, which are presented in Figure 1-2. Generally, synclastic structures are pneumatically and flat and anticlastic structures are mechanically prestressed.

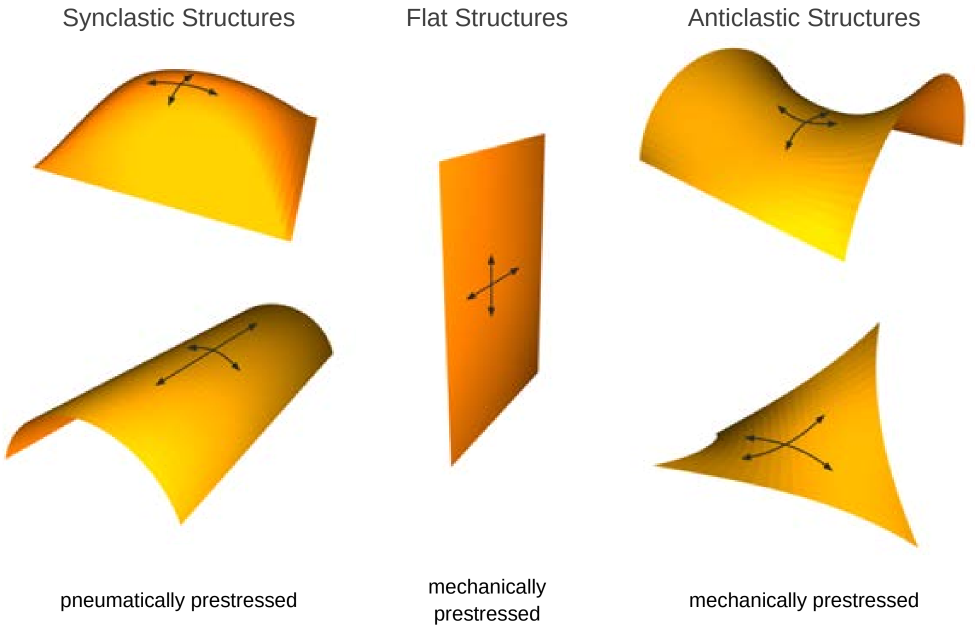


Figure 1-2 Typical shapes of membrane structures [US13a]

In most cases membrane structures consist of a primary and secondary structure. The primary structure is the supporting structure which is in most cases a steel structure but can also be made of aluminium, timber or concrete. The secondary structure is the textile membrane or foil structure. Only for air supporting halls or when inflatable beams are used, the primary and secondary structures may be both made of textile fabrics or foils. In cases of different materials for the primary and secondary structures the design of these structures has to be performed using design rules which are matched for different materials, e.g. steel-membrane or timber-membrane, to achieve the same safety level and reliability. This is one of the main reasons for which a harmonized European standard for the design of membrane structures is required which would rely on the principles of existing Eurocodes.

However, at present only few national design codes for several types of membrane structures, such as air halls, are available in some European countries, despite of a considerable amount of scientific knowledge of the structural behaviour. For this reason, the industry desired a comprehensive European design code in order to

- provide verification techniques representing the latest state of the art and recognized research,
- provide a common pool of design approaches and

- achieve a harmonized safety level.

For this reason, within CEN/TC 250 “Structural Eurocodes”, Working Group (WG) 5 on structural membranes was created that is commissioned to elaborate the corresponding design code. The specific purpose of these works for WG 5 is to develop structural design rules for membrane structures in a stepwise procedure that finally should result in a new Eurocode on the design of membrane structures, see Figure 1-3.

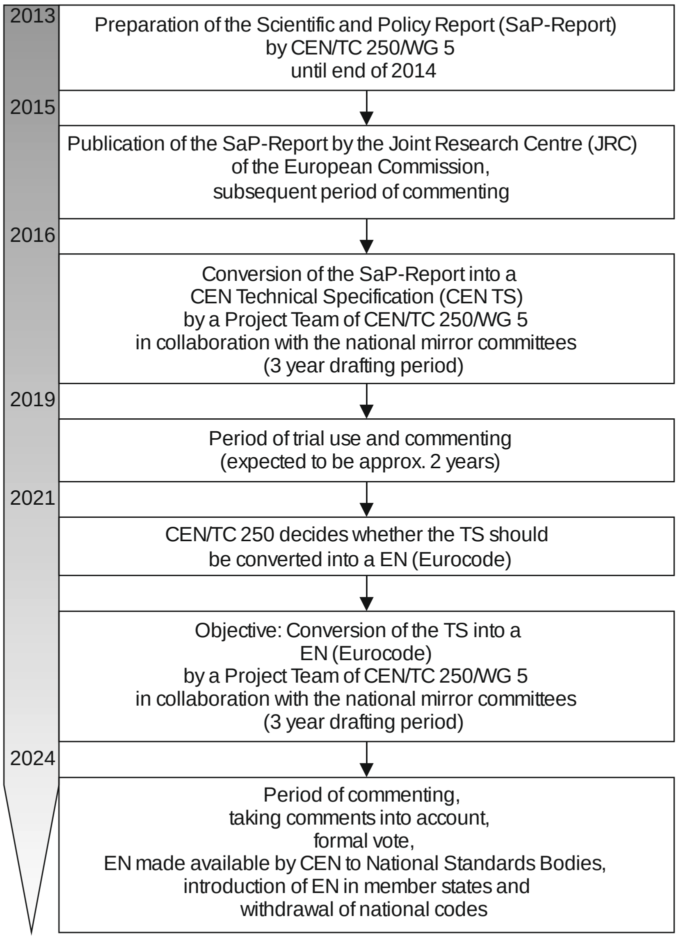


Figure 1-3 Steps to a Eurocode for Membrane Structures [SUMG14]

In view of this, in a first step, the present Scientific and Policy Report (SaP-Report) was to be prepared as a background documentation for a future Eurocode for membrane structures. This background document consists of three major parts:

(1) general explanations for the design of membrane structures with scientific and technical background,
(2) state-of-the-art overview on existing national and European rules and recommendations on the design of membrane structures,
(3) proposals for European harmonized rules for the design of membrane structures, which could be part of the future Eurocode for membrane structures.

Herewith, the SaP-report contains a presentation of the scientific and technical background. Furthermore, it gives a complete state-of-the-art overview related to the design of membrane components as a kind of review. It reflects and refers to the existing state of the art, existing national codes or rules and the latest scientific knowledge. Finally, the report includes proposals for European harmonized rules for the design of membrane structures or of what content future rules should be. These rules could be used - in a second step after agreement with the Commission and the CEN Member States – as a basis for standardisation that will indicate necessities of the code up to codelike formulations of selected items.

Figure 1-4 illustrates the European code environment for the preparation of the SaP-report for structural membranes with regard to the “three columns” of the European codification of structural issues:

- specifications of structural material and products,
- rules on structural design and
- execution rules.

Membrane structures require special execution rules for textile fabrics and foils. As no specific code is planned to be prepared, as exemplary EN 1090-2 [X132] for steel and aluminium structures exist, the specific execution rules for membrane structures are planned to be considered in a separate chapter of the structural design guide for membrane structures. Material specifications comprise both material- and testing standards and EOTA-Guidelines and ETA’s; they provide the product properties used in design. The reference from the design guideline to the supporting standards as material specifications and execution standards requires consistency that will be achieved by simultaneous working on these standards, for which cooperation is provided in early stages of the drafting between CEN/TC 250, CEN/TC 248 and EOTA.

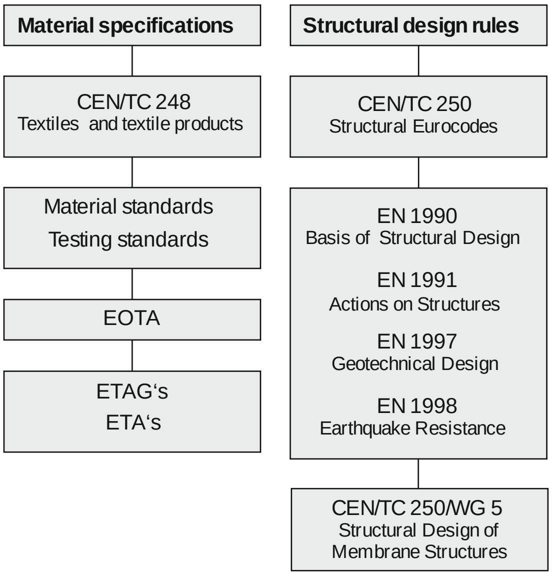


Figure 1-4 European code environment for the preparation of the Scientific and Policy Report for Structural Membranes

1.2 Eurocode rules applicable to membrane structures

Within the Eurocode family, a future standard (Eurocode) on the design of membrane structures has to fit to the principles of the structural design concept according to the existing Eurocodes in order to achieve a harmonized level of safety independent from the different construction materials. For this reason, firstly, the general specifications of Eurocode 0 (EN 1990 [X100]) “*Basis of Design*” have to be considered. Secondly, the loads specified in Eurocode 1 (EN 1991 [X101]) “*Action of Structures*” have to be applied. The combinations of actions are regulated in EN 1990. Looking at the wind and snow actions already defined in Eurocode 1, the question arises which of those already specified loads are applicable for membrane structures. Trying to answer this question it becomes obvious that up to now, no actions are specified in Eurocode 0 which complies with membrane structures. For this reason, this topic will be discussed within this SaP-report as well.

Thirdly, the design rules for membrane structures have to be applicable simultaneously with other material based design standards as there are Eurocode 2 to 9 (design rules for concrete structures, steel structures, composite structures, timber structures, masonry structures, geotechnical design, design in seismic regions, aluminum structures) as well as the future Eurocode on structural glass, see Figure 1-5.

An overview of other Eurocodes which are suitable for steel-membrane, timber-membrane, aluminium-membrane and concrete-membrane structures is given in Figure 1-6.

EN 1990
Eurocode 0: Basis of Design

EN 1991
Eurocode 1: Actions on Structures
1-1 Densities, self-weight etc.
1-2 Actions on structures exposed
to fire
1-3 Snow loads
1-4 Wind actions
1-5 Thermal actions
1-6 Actions during execution
1-7 Accidential actions
2 Traffic loads on bridges
3 Actions induced by cranes and
machinerys
4 Silos and tanks

EN 1992 to EN 1996
Eurocode 2: Concrete Structures
Eurocode 3: Steel Structures
Eurocode 4: Composite Structures
Eurocode 5: Timber Structures
Eurocode 6: Masonry Structures

EN 1997 and EN 1998
Eurocode 7: Geotechnical Design
Eurocode 8: Design in Seismic Areas

EN 1999 and EN xy
Eurocode 9: Aluminium Structures
Eurocode xy: Structural Glass

Figure 1-5 Survey of the existing and planned Eurocodes, missing: Eurocode on Structural Membranes

EN 1990 - Eurocode: Basis of Structural Design

EN 1991	**Actions on Structures**
Part 1-1	Densities, self-weight, imposed loads for buildings
Part 1-2	Actions on structures exposed to fire
Part 1-3	Snow loads
Part 1-4	Wind actions
Part 1-5	Thermal actions
Part 1-6	Actions during execution
Part 1-7	Accidental actions

EN 1992	**Design of Concrete Structures**
Part 1-1	General rules and rules for buildings
EN 1993	**Design of Steel Structures**
Part 1-1	General rules and rules for buildings
Part 1-4	Stainless steel
Part 1-8	Joints
Part 1-12	Structures with tension components
EN 1995	**Design of Timber Structures**
Part 1-1	General - Common rules and rules for buildings
EN 1999	**Design of Aluminium Structures**
Part 1-1	General structural rules

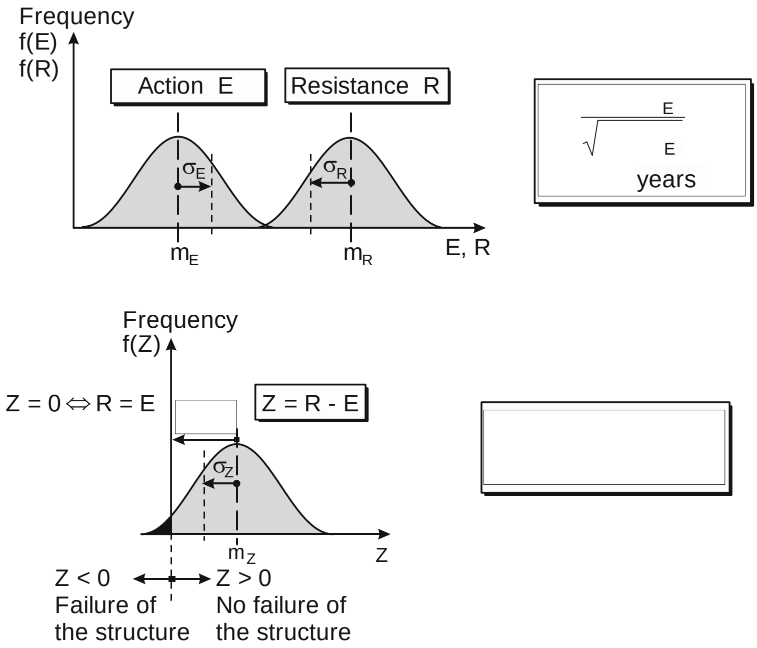
Figure 1-6 Other Eurocodes suitable for steel-membrane, timber-membrane, aluminum-membrane and concrete-membrane structures

EN 1990 specifies the general format of limit state verifications for the

- ultimate limit state including robustness,
- serviceability limit state and
- durability.

Furthermore, EN 1990 specifies failure consequences for the ultimate and serviceability limit states. Herein, the failure probability p_f ranges from 10^{-2} in the serviceability limit state up to $7 \cdot 10^{-5}$ in the ultimate limit state for normal failure consequences with reliability class 2 and a 50 year re-occurrence. In the latter case the reliability index β becomes the well-known value of $\beta = 3.8$.

The Eurocode design approach relies on the semiprobabilistic design concept in which the action effects E_d resulting from the applied actions are verified against the design resistance R_d of the structural elements. In most cases the action effect E_d must be smaller than the design resistance R_d in order to fulfill the requirements. For the normal reliability class, the design values of actions effects E_d and resistances R_d can be derived as a function of the statistical parameters of E and R and the reliability index $\beta = 3.8$ as given in Figures 1-7 and 1-8. The definition of E_d is expressed as the effect of a combination of actions with the permanent action G, the leading variable action Q_{k1} and the accompanying variable action $\gamma_{Q2} \cdot \psi_{0,2} \cdot Q_{k2}$, see Figure 1-8. R_d describes the design resistance of the structural member and is based on the statistical evaluation of tests. The resistance R of membrane structures depends not only on the strength of the material achieved from tensile tests (or biaxial tensile tests) as it is the case for other materials but also on other characteristics as the load duration, the accompanying temperature, the environmental conditions etc. They all influence the design resistance of membrane structures. Usually these influencing effects are not mentioned either in the standards for actions or in the standards for the determination of the resistance. The Eurocodes reveal the possibility to consider these effects on the resistance side by decreasing the resistance as it is already done in some national standards.



The failure probability p_f is defined as $p_F = \int_{-\infty}^{Z=0} f(Z)\,dZ$.

With $m_Z = m_R - m_E$ and $\sigma_Z = \sqrt{\sigma_R^2 + \sigma_E^2}$ it follows $m_Z = \beta \cdot \sigma_Z$ with

$$\Rightarrow \beta = \frac{m_Z}{\sigma_Z} = \frac{m_R - m_E}{\sqrt{\sigma_R^2 + \sigma_E^2}}.$$

Failure of a structure occurs if Z < 0 and $m_Z < \beta \cdot \sigma_Z$.

A structure is safe if $m_Z \geq \beta \cdot \sigma_Z$.

$$\Rightarrow m_R - m_E \geq \beta \cdot \sqrt{\sigma_R^2 + \sigma_E^2}$$

$$\Leftrightarrow m_R - m_E \geq \beta \cdot \frac{\sigma_R^2 + \sigma_E^2}{\sqrt{\sigma_R^2 + \sigma_E^2}}$$

$$\Leftrightarrow m_R - m_E \geq \beta \cdot \left(\underbrace{\frac{\sigma_R}{\sqrt{\sigma_R^2 + \sigma_E^2}}}_{\alpha_R = 0.8} \cdot \sigma_R + \underbrace{\frac{\sigma_E}{\sqrt{\sigma_R^2 + \sigma_E^2}}}_{\alpha_E = -0.7} \cdot \sigma_E \right)$$

$$\Leftrightarrow m_R - m_E \geq \beta \cdot \left(\alpha_R \cdot \sigma_R - \alpha_E \cdot \sigma_E \right) \quad ^{1)}$$

$$\Leftrightarrow m_R - \beta \cdot \alpha_R \cdot \sigma_R \geq m_E - \beta \cdot \alpha_E \cdot \sigma_E$$

$$\Leftrightarrow R_d \geq E_d$$

1) Due to the fact that α_E is defined to be negative a change of the algebraic sign has to be applied.

Figure 1-7 Statistical interpretation of design values

Action effects	$\leq$	Resistance
E_d	$\leq$	R_d
$E_d = \gamma_G G_k + \gamma_{Q1} Q_{k1} + \gamma_{Q2} \psi_{0,2} Q_{k2}$	$\leq$	$\frac{R_k}{\gamma_M}$

Figure 1-8 Use of design values in the ultimate limit state

Whereas steel, timber, aluminium and concrete structures show in structural analysis in most cases a linear behaviour, tensile membrane structures behave in a highly non-linear way. This means that the relationship between the action and the action effect is over- or underlinear, depending on the structure itself, see Figure 1-9 [USS14]. For this reason, it has strictly to be distinguished whether the partial factor is considered already on the action or only the action effect. EN 1990 gives some indications how to act in these cases. This topic will be discussed in detail in this report.

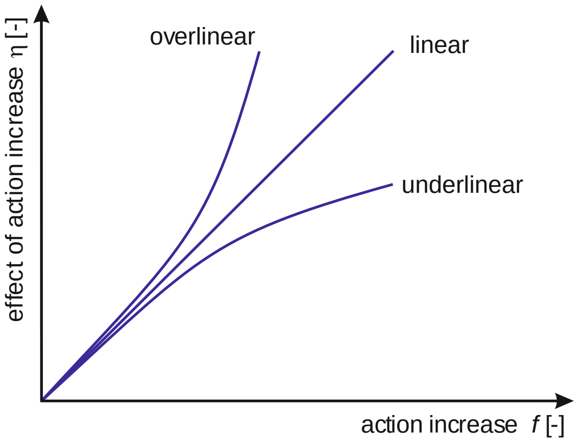


Figure 1-9 Linear and nonlinear behaviour of structures [USS14]

1.3 Structuring the Eurocode

A survey on the existing national and European codes for material testing and the structural design of membrane structures shows that although in some member states a considerable amount of codes exist, currently not all types of structures are covered in all member states. Particularly for foil structures no design codes currently exist at all in Europe.

It will be a main task of this Scientific and Policy Report to carve out, what specific design rules exist up to now in the different existing codes and to harmonize, transfer and extend them in a reasonable way as well as to structure them into a European guideline complying with the rules of CEN/TC 250 and the latest state of scientific and technical knowledge.

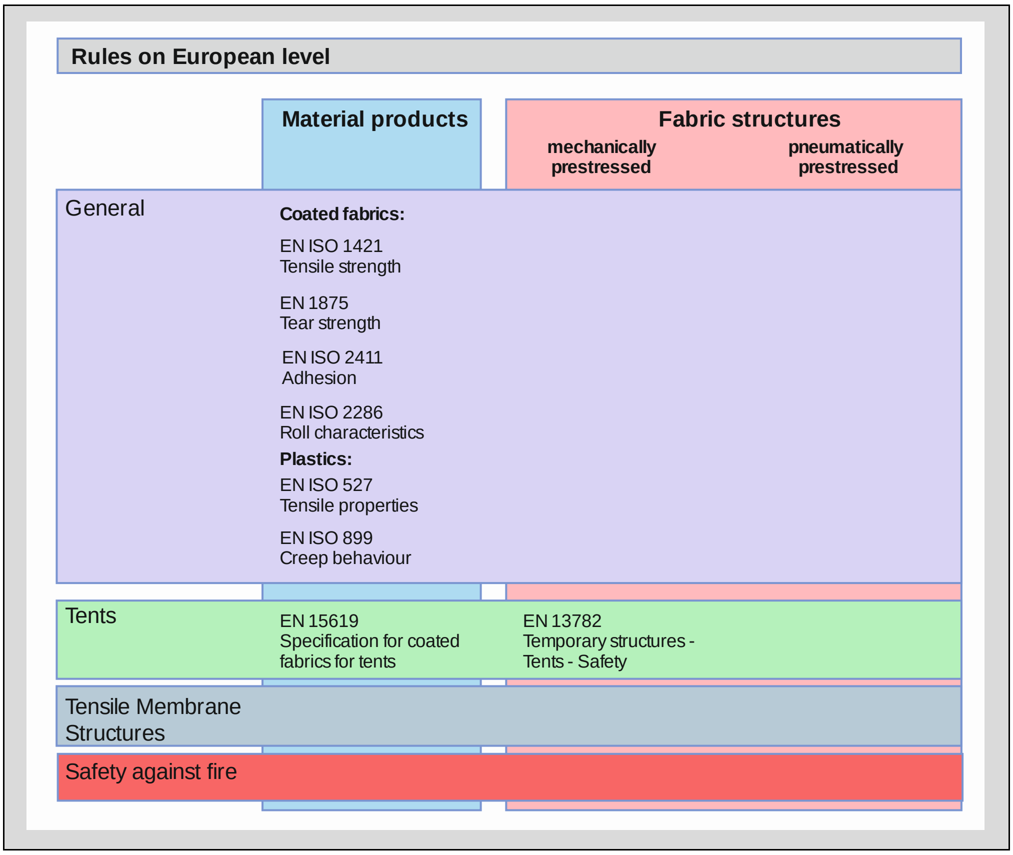
In the following a code review on existing standards and regulations is given, see Code Review No. 1. For this purpose, the following distinction between Tents and Tensile Membrane Structures in general is defined:

Tents are meant to be mobile room closure structures that are planned to be frequently dismantled and reconstructed anywhere else. They can be regularly prestressed – either mechanically or pneumatically – but they do not have to. They are primarily designed for temporary use and may be applied for different functions.

In contrast **Tensile Membrane Structures** is a more general term. Tensile Membrane Structures are meant to be engineered and regularly prestressed – either mechanically or pneumatically. They are in the majority stationary and permanent, but can be mobile and installed temporarily as well (e.g. air supported halls covering swimming pools in winter time or structures for event/theater areas). Tensile Membrane Structures comprise permanently mechanically fixed structures, inflatable and foldable structures as well as combinations of these. Actually, for the definition in this code review the term Tensile Membrane Structures contains all forms of tensile and prestressed structures made from structural membrane elements except tents.

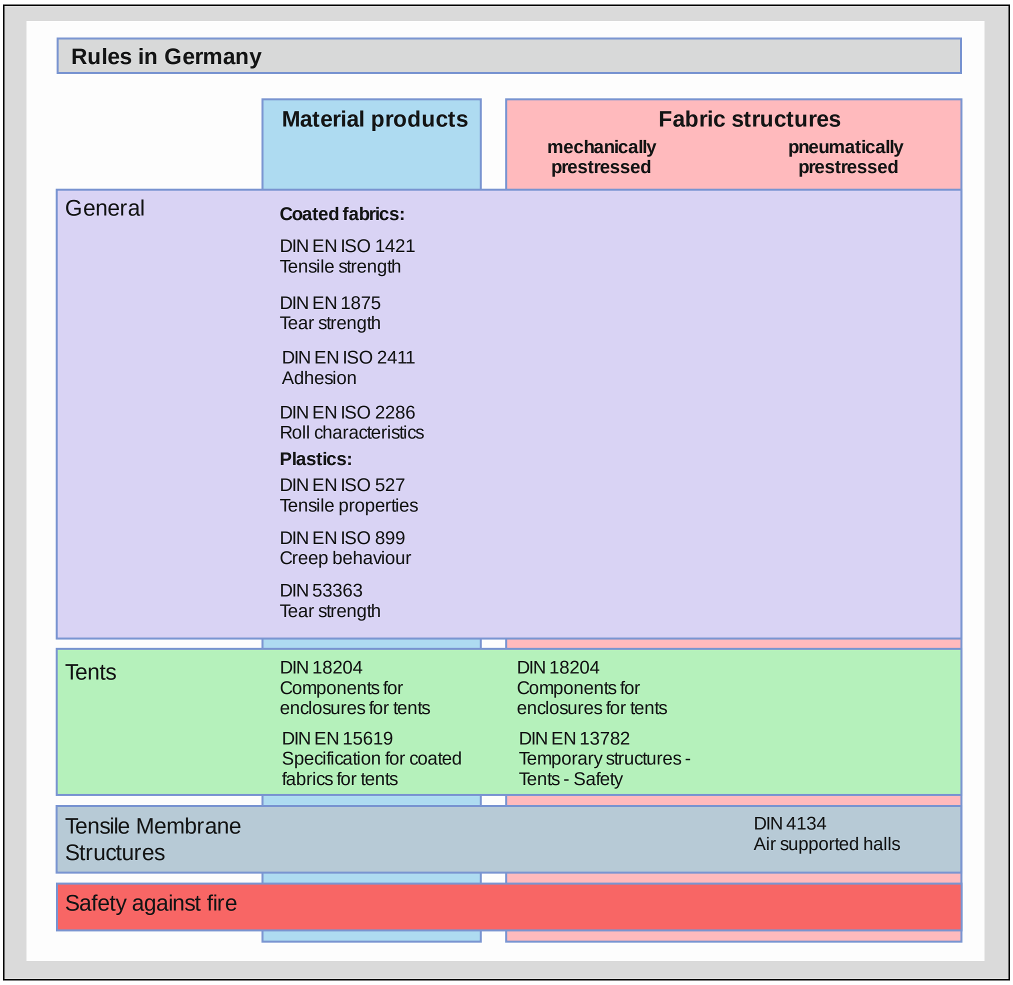
Code Review No. 1

The review on existing national codes and/or regulations for some member states (on European level, Germany, The Netherlands, Italy, France and Belgium) is shown in the following figures (making no claim to be complete). United Kingdom, Spain, Bulgaria and Russia have no specific standards for membrane structures.



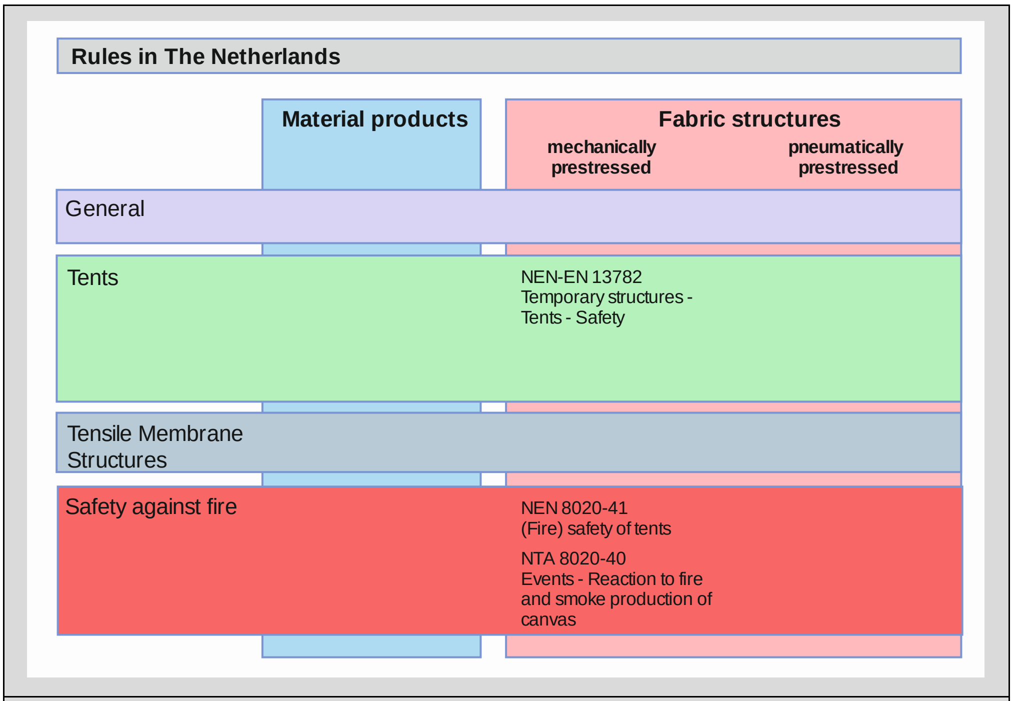
Rules on European level

	Material products	Fabric structures mechanically prestressed	 pneumatically prestressed
General	**Coated fabrics:** EN ISO 1421 Tensile strength EN 1875 Tear strength EN ISO 2411 Adhesion EN ISO 2286 Roll characteristics **Plastics:** EN ISO 527 Tensile properties EN ISO 899 Creep behaviour		
Tents	EN 15619 Specification for coated fabrics for tents	EN 13782 Temporary structures - Tents - Safety	
Tensile Membrane Structures			
Safety against fire			



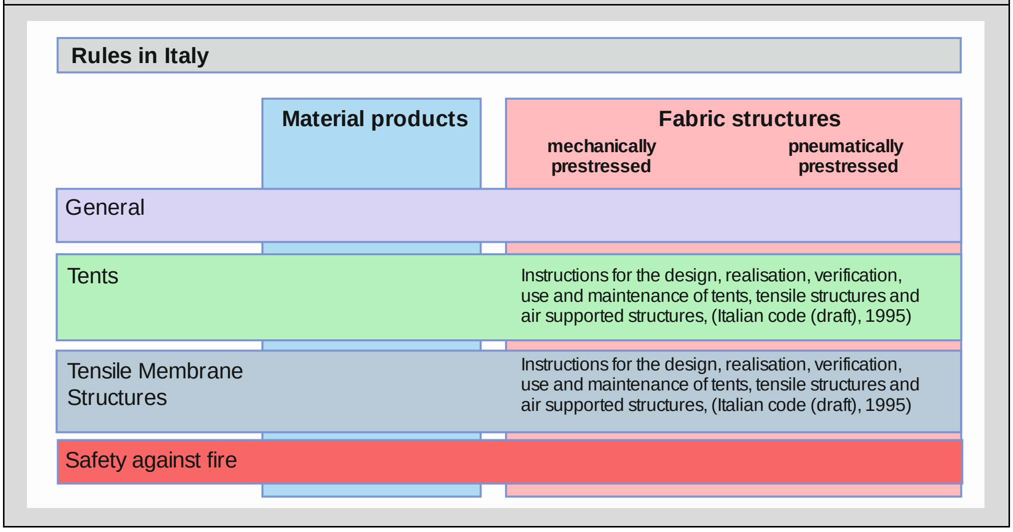
Rules in Germany

	Material products	**Fabric structures** **mechanically prestressed**	**Fabric structures** **pneumatically prestressed**
General	**Coated fabrics:** DIN EN ISO 1421 Tensile strength DIN EN 1875 Tear strength DIN EN ISO 2411 Adhesion DIN EN ISO 2286 Roll characteristics **Plastics:** DIN EN ISO 527 Tensile properties DIN EN ISO 899 Creep behaviour DIN 53363 Tear strength		
Tents	DIN 18204 Components for enclosures for tents DIN EN 15619 Specification for coated fabrics for tents	DIN 18204 Components for enclosures for tents DIN EN 13782 Temporary structures - Tents - Safety	
Tensile Membrane Structures			DIN 4134 Air supported halls
Safety against fire			



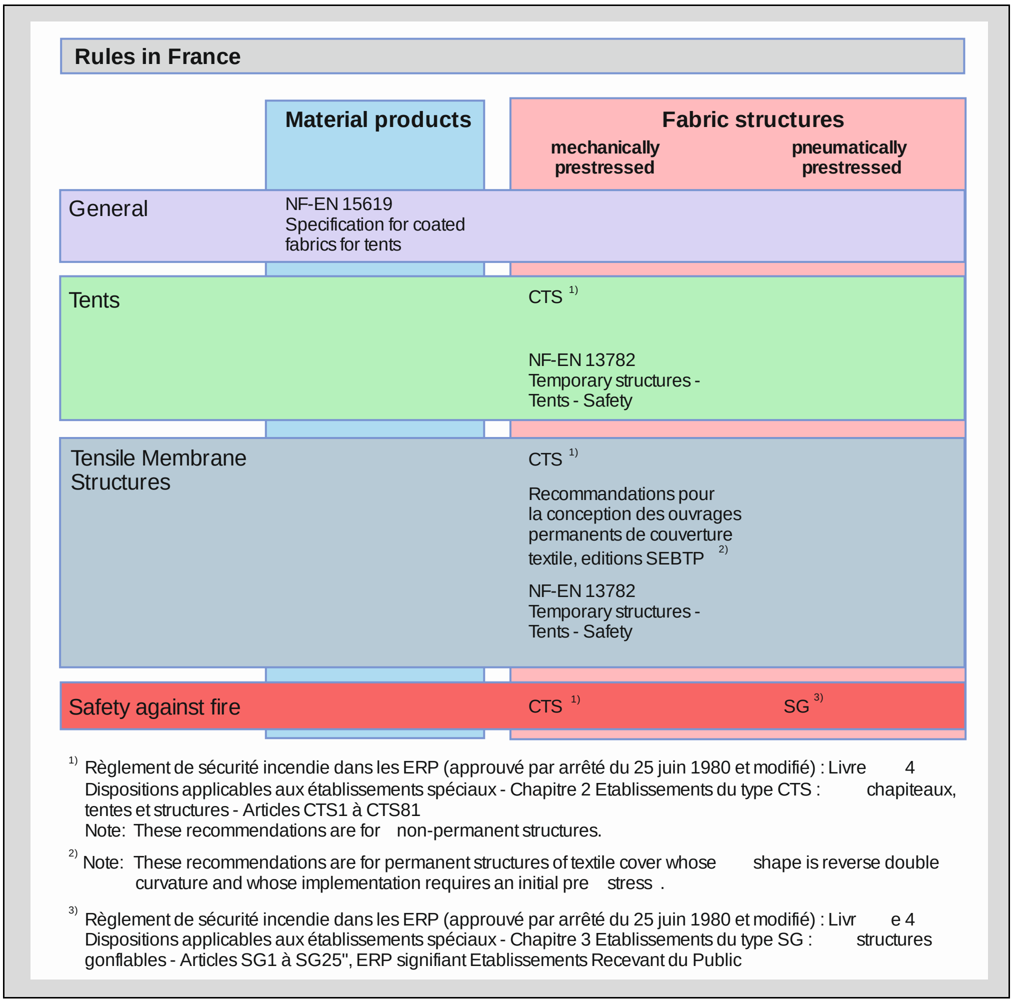
Rules in The Netherlands

	Material products	Fabric structures	
		mechanically prestressed	pneumatically prestressed
General			
Tents		NEN-EN 13782 Temporary structures - Tents - Safety	
Tensile Membrane Structures			
Safety against fire		NEN 8020-41 (Fire) safety of tents NTA 8020-40 Events - Reaction to fire and smoke production of canvas	



Rules in Italy

	Material products	Fabric structures	
		mechanically prestressed	pneumatically prestressed
General			
Tents		Instructions for the design, realisation, verification, use and maintenance of tents, tensile structures and air supported structures, (Italian code (draft), 1995)	
Tensile Membrane Structures		Instructions for the design, realisation, verification, use and maintenance of tents, tensile structures and air supported structures, (Italian code (draft), 1995)	
Safety against fire			



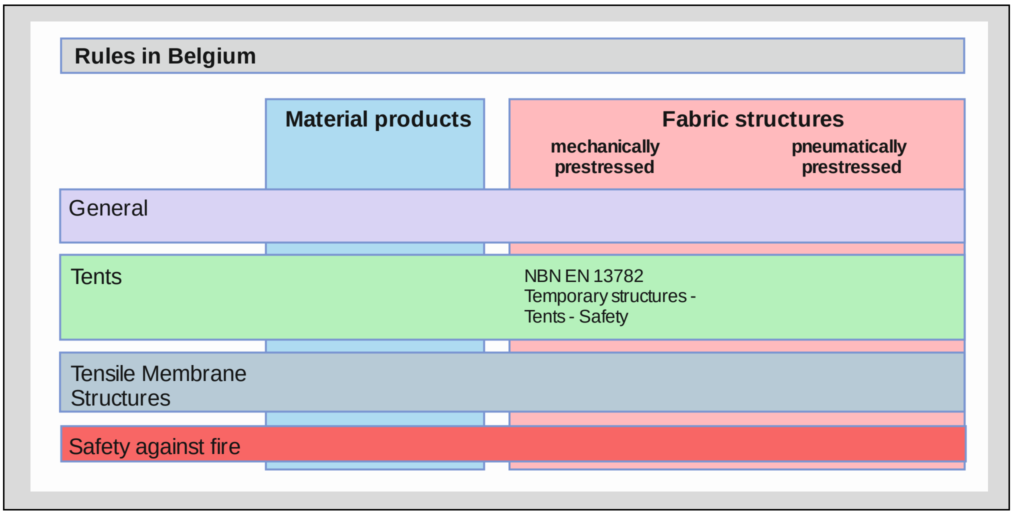
Rules in France

	Material products	**Fabric structures** **mechanically prestressed**	**Fabric structures** **pneumatically prestressed**
General	NF-EN 15619 Specification for coated fabrics for tents		
Tents		CTS [1)] NF-EN 13782 Temporary structures - Tents - Safety	
Tensile Membrane Structures		CTS [1)] Recommandations pour la conception des ouvrages permanents de couverture textile, editions SEBTP [2)] NF-EN 13782 Temporary structures - Tents - Safety	
Safety against fire		CTS [1)]	SG [3)]

[1)] Règlement de sécurité incendie dans les ERP (approuvé par arrêté du 25 juin 1980 et modifié) : Livre 4 Dispositions applicables aux établissements spéciaux - Chapitre 2 Etablissements du type CTS : chapiteaux, tentes et structures - Articles CTS1 à CTS81
Note: These recommendations are for non-permanent structures.

[2)] Note: These recommendations are for permanent structures of textile cover whose shape is reverse double curvature and whose implementation requires an initial prestress .

[3)] Règlement de sécurité incendie dans les ERP (approuvé par arrêté du 25 juin 1980 et modifié) : Livre 4 Dispositions applicables aux établissements spéciaux - Chapitre 3 Etablissements du type SG : structures gonflables - Articles SG1 à SG25", ERP signifiant Etablissements Recevant du Public



The future Eurocode for the design of structural membranes should have an appropriate structuring that complies with the European approach of a material related design codes in civil engineering and to the basic reference normative documents such as EN 1990 and EN 1991.

For this reason, three parts of the Eurocode should be implemented: the first part with all design related regulations, the second part regarding structural fire design and a third part dealing with rules for the execution of structural tensile membrane structures.

Eurocode Outlook No. 1

(1) The main structure may be as follows:
1st part: General rules and rules for buildings
2nd part: Structural fire design
3rd part: Execution of structural tensile membrane structures

Eurocode Outlook No. 2

(1) The frames of the Eurocode on structural membranes should comply with the CEN/TC 250 rules for a material specific design code. In combination with the particular necessities of structural membranes and foils the composition of the first part of the Eurocode may be as follows:

1 General
  1.1 Scope
    1.1.1 Scope of Eurocode xy
    1.1.2 Scope of Part 1 of Eurocode xy
  1.2 Normative references
    1.2.1 General reference standards
    1.2.2 Other reference standards
  1.3 Assumptions
  1.4 Distinction between principles and application rules
  1.5 Terms and definitions
    1.5.1 General
    1.5.2 Additional terms and definitions used in the present standard
  1.6 Symbols

- *2 Basis of design*
  - *2.1 Requirements*
    - *2.1.1 Basic requirements*
    - *2.1.2 Reliability management*
    - *2.1.3 Design working life, durability and robustness*
  - *2.2 Principles of limit state design*
  - *2.3 Basic variables*
    - *2.3.1 Actions and environmental influences*
    - *2.3.2 Definition and handling of prestress*
    - *2.3.3 Material and product properties*
    - *2.3.4 Deformations of membranes*
    - *2.3.5 Geometric Data*
  - *2.4 Verification by the partial factor method*
    - *2.4.1 General*
    - *2.4.2 Design value of material properties*
    - *2.4.3 Design value of geometric data*
    - *2.4.4 Design resistances*
    - *2.4.5 Combination of actions*
    - *2.4.6 Verification of static equilibrium (EQU)*
  - *2.5 Design assisted by testing*
- *3 Materials*
  - *3.1 General*
  - *3.2 Coated Fabrics*
    - *3.2.1 Range of Materials*
    - *3.2.2 Materials Properties*
    - *3.2.3 Dimensions, mass, tolerances*
    - *3.2.4 Design values of material constants*
  - *3.3 Uncoated Fabrics*
    - *3.3.1 Range of Materials*
    - *3.3.2 Materials Properties*
    - *3.3.3 Dimensions, mass, tolerances*
    - *3.3.4 Design values of material constants*
  - *3.4 Foils*
    - *3.4.1 Range of Materials*
    - *3.4.2 Materials Properties*
    - *3.4.3 Stress-strain behaviour*
    - *3.4.4 Dimensions, mass, tolerances*
    - *3.4.5 Design values of material constants*
    - *3.4.6 Plastic deformation*
    - *3.4.7 Creep*
    - *3.4.8 Seams*
    - *3.4.9 Connection details*
    - *3.4.10 Durability*
  - *3.5 Connection devices*
  - *3.6 Structural Elements*
- *4 Durability*
  - *4.1 General*
- *5 Basis of Structural analysis*
  - *5.1 General*
  - *5.2 Structural modelling for analysis*
    - *5.2.1 Structural modelling and basic assumptions*
    - *5.2.2 Form-finding*
    - *5.2.3 Modelling of the membrane*
    - *5.2.4 Modelling of seams*
    - *5.2.5 Modelling of connections*

    - *5.2.6 Modelling of cable/webbing*
    - *5.2.7 Application of applied loads*
    - *5.2.8 Patterning*
    - *5.2.9 Ground-structure interaction*
    - *5.2.10 Wind-structure interaction*
  - *5.3 Global analysis*
    - *5.3.1 Effects of deformed geometry of the structure*
    - *5.3.2 Structural stability of supporting structure*
    - *5.3.3 Integrated analysis*
  - *5.4 Imperfections*
  - *5.5 Methods of analysis*
    - *5.5.1 General*
    - *5.5.2 Elastic global analysis*
    - *5.5.3 Non-linear material global analysis*
- *6 Ultimate limit states (ULS)*
  - *6.1 General*
  - *6.2 Resistance of material and joints*
    - *6.2.1 General*
    - *6.2.2 Design Resistance Long Term Load*
    - *6.2.3 Design Resistance Short Term Load Cold Climate*
    - *6.2.4 Design Resistance Short Term Load Warm Climate*
    - *6.2.5 Membrane Stress Verification*
    - *6.2.6 Shear*
    - *6.2.7 Tear propagation*
  - *6.3 Connections*
  - *6.4 Design of ... subjected to*
- *7 Serviceability limit states (SLS)*
  - *7.1 General*
  - *7.2 Serviceability limit states for buildings*
    - *7.2.1 Vertical deflections*
    - *7.2.2 Horizontal deflections*
    - *7.2.3 Distance to other parts*
    - *7.2.4 Safeguards*
    - *7.2.5 Post tensioning*
    - *7.2.6 Ponding*
    - *7.2.7 Wrinkling*
  - *7.3 Tear control*
    - *7.3.1 General considerations*
    - *7.3.2 Minimum reinforcement areas*
    - *7.3.3 Control of tearing without direct calculation*
    - *7.3.4 Calculation of tear propagation*
- *8 Details/Connections*
  - *8.1 General*
  - *8.2 Membrane joints*
  - *8.3 Membrane edges*
  - *8.4 Membrane corners*
  - *8.5 Ridges and valleys*
  - *8.6 High and low points*
  - *8.7 Reinforcements*
  - *8.5 Stays, Ties*
  - *8.6 Base plates for masts and anchor*
  - *8.7 Anchors and foundations under tension*
- *9 Design Assisted by Testing*

(2) The structuring of the <u>second</u> part of the Eurocode on structural membranes may be as follows:

1 General - Structural fire design
  1.1 Scope
  …

(3) The structuring of the third part of the Eurocode on structural membranes may be as follows:

1 General – Execution of structural tensile membrane structures
  1.1 Scope
2 Manufacture/fabrication, handling, packing and installation
  2.1 General
  2.2 Cutting pattern determination, workshop drawings
  2.3 Acquisition of the membrane material
  2.4 Processing, cutting, welding
  2.5 Particulars in PTFE processing
  2.6 Inspection before packing
  2.7 Packaging and transportation
  2.8 Erection
3 Inspection and maintenance
  3.1 Cleaning
  3.2 Corrosion
  3.3 Water drainage and ponding
  3.4 Prestress and restress
  3.5 Repair
  3.6 Replacement

2 Materials and material properties

2.1 General

Membrane structures are made of fabrics or foils. The different kind of material properties are determined by special testing procedures especially developed for these kinds of materials. It has to be distinguished between those properties which are important in view of the load carrying capacity, the stiffness and the durability of structural membranes and further properties like e.g. light transmission values, insulation values which are assumed to be not relevant in regard to the Eurocode for the design of structural membranes.

Structural fire design is planned to be the content of Part 2 of the future Eurocode, see Eurocode Outlook No. 1. Fire safety of the ~~materials~~ of construction products (materials) may be classified by EN 13501-1 [X133].

Fabrics are mainly woven textiles and can be distinguished in uncoated fabrics for indoor applications and coated fabrics for outdoor and indoor applications, see Figure 2-1. Foils can be used in indoor and outdoor applications as well.

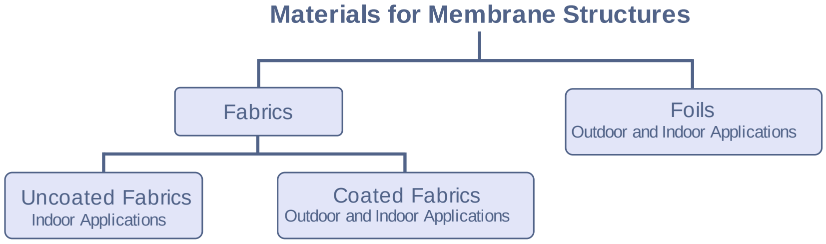


Figure 2-1 Materials for membrane structures

In the following, the different kind of products, fabrics and foils, will be presented combined with an explanation of the most relevant testing procedures for the determination of their material properties. For some typical products, material properties will be given.

2.2 Fabrics

2.2.1 Range of materials

For architectural fabrics, single yarns are mostly woven orthogonally to each other. The completed web is rolled up on rolls up to 5 m wide. Yarns in longitudinal direction of a roll are called warp yarns, the perpendicular ones weft or fill yarns. The most common weaving procedures for fabrics used in textile architecture are plain weave (1/1) and Panama weave (2/2), as shown in Figure 2-2. Because of the weaving procedure, fabrics show a highly non-linear stress-strain relationship and normally different material properties in warp and fill direction. Most fabrics are characterized by a greater stiffness in the warp than in the fill direction.

For indoor applications, the fabrics have not to be coated. Architectural fabrics for outdoor applications are coated and lacquered, see Figure 2-3, mainly for protection of the weave and to obtain desired physical properties (durability, fire performance etc.). Although the coating is ~~locally~~ also used to transmit shear forces (epspacially at weld seams), it has no significant influence on the load bearing behaviour of the coated fabric itself. The warp and fill yarns are the load-bearing elements of these composite materials. As they have no defined section height, membrane forces are referred to the length instead of the cross section area of a structural membrane. Nevertheless, the term “membrane stress” is used traditionally.

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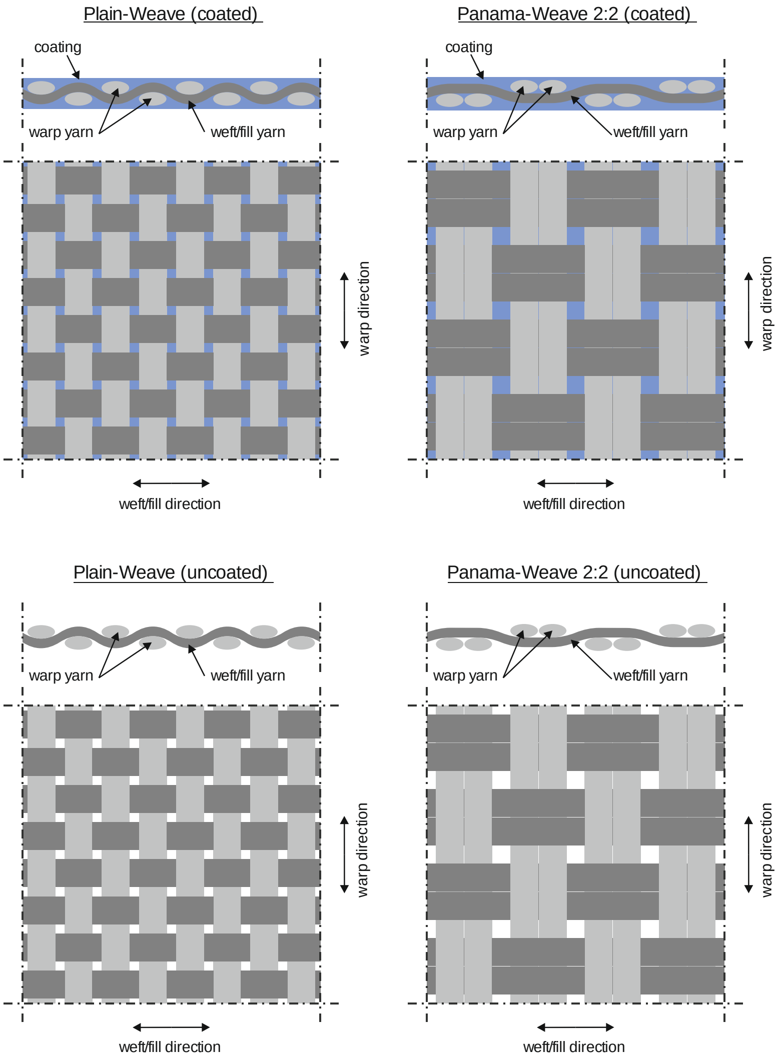


Figure 2-2 Most common weaving procedures for fabrics used in textile architecture [© ELLF]

Different materials and material combinations are used for the composites. Architectural fabrics are often woven from yarns made from Polyester (PES), Glass fibre or Polytetrafluorethylene (PTFE). Typical coating materials are Polyvinylchloride (PVC), Polytetrafluorethylene (PTFE) and silicone [SSU14]. The following material combinations are used in the majority, see Figure 2-3:

- PVC (Polyvinylchloride)-coated Polyester(PES) fabrics (PES/PVC-fabrics),
- PTFE (Polytetrafluorethylene)-coated Glass fabrics (Glass/PTFE-fabrics).

For some structures PTFE-fabrics are used, too. They are available with different coatings, e.g. silicone or PTFE. Usually they are used for foldable constructions.

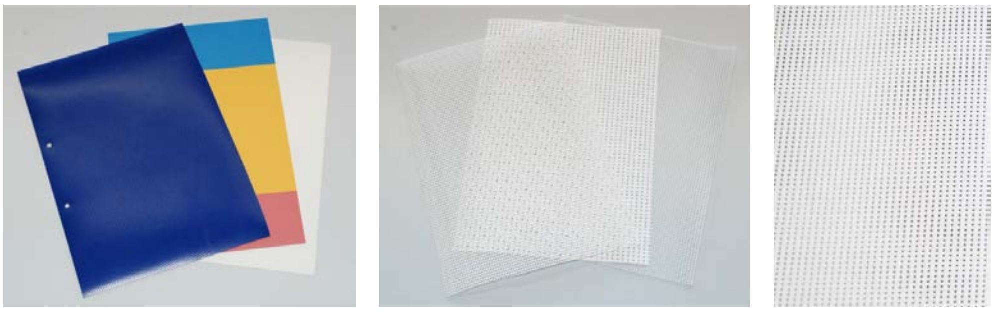
For these three mentioned composites the future Eurocode is intended to provide indications of design properties. Further materials and material combinations are less commonly used [Seid09].

Uncoated fabrics are usually made of

- Polytetrafluorethylene (PTFE) or
- Polyvinylidenfluorid (PVDF).

The future Eurocode will mainly deal with uncoated PTFE-fabrics.

PVC (Polyvinylchloride)-coated Polyester(PES) fabrics (PES/PVC-fabrics)



PTFE (Polytetrafluorethylene)-coated Glass fabrics (Glass/PTFE-fabrics)

Figure 2-3 Main fabrics used in textile architecture [© ELLF]

2.2.2 Material properties

2.2.2.1 General

Up to date, strength values for the design of structural membranes are taken from ~~experimental test series~~data sheets from the material suppliers or values derived from own experiences, both for the ~~basic~~ base material (e.g. tensile and tear strength) and connections (e.g. seam strength). Regarding major projects with e.g. modified material products and individual connection details, it is foreseeable, that this procedure will remain the same even when a design code or product standards exist. In order to give support for smaller projects the Eurocode is supposed to give simplified and conservative strength values for conventional materials, i.e. unmodified standard materials.

The most important strength values to be considered are the

- tensile strength,
- seam strength,
- tear strength and
- adhesion.

For glass fibre fabrics the

- tensile strength after crease fold

is an important measure as well as they are sensitive to folding.

Furthermore, the determination of

- stiffness parameters

is of main interest, too.

Regarding the strength values, a “two way procedure” is intended to be implemented in the Eurocode, which recommends to determine these values by experimental testing at first (first way). Only if the amount of experimental tests is aimed to be minimized in a project or aimed to be avoided at all, safe-sided strength values may be taken from tables, which are given in the Eurocode (second way). These tables standardize the typical classifications for structural fabrics. Stiffness parameters have always to be determined by experimental testing either by the material producer, in this case the relevant values are specified in the material certificates, or by testing laboratories based on the project needs.

Eurocode Outlook No. 3

(1) Strength values shall be taken from experimental tests.

(2) Tensile strength values shall be determined according to EN ISO 1421 and the characteristic value shall be determined according to EN 1990 Annex D.

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

(4) Adhesion values should be determined according to EN ISO 2411.

(5) In order to limit or avoid testing, conservative strength values for conventional material products may be directly taken from the respective tables given in the Eurocode .

NOTE 1: Beside conventional material products structural membranes are oftentimes modified or even specifically produced for single projects in order to adjust not only the structural but also physical properties (e.g. light transmission) to the specific project requirements. In these cases project specific strength values have to be determined by experimental tests.

NOTE 2: The strength tables in the Eurocode give strength values that are typically guaranteed by material producers for conventional material products.

2.2.2.2 Tensile Strength

The tensile strength is experimentally determined by the tensile (strength) test using the strip method. The aim of the tensile test is to determine the fundamental mechanical behaviour of uncoated and coated fabrics. They are commonly used for material quality control of the base material, joints as welding seams, edge details and other type of joints in tensioned membrane structures.

The principle of a tensile test is to load a test specimen uniaxially to failure. The load is applied in warp or weft direction or perpendicularly to joints as welding seams or edge details. Tensile tests are used to determine the maximum tensile strength and elongation. ~~If required the breaking force and the elongation at break can be determined, too.~~ The measurements of the strength ~~(respectively force)~~ and elongation are used to derive the mechanical properties of the fabric and of connections.

The tensile test is specified in European and national standards as EN ISO 1421 [X90], and EN ISO 13934-1 [X98] on European level, particularly in Germany DIN 53354 [X99-1] (although withdrawn) and the guideline of Deutsches Institut für Bautechnik (DIBt) for acceptance test of coated fabrics and their joints [X99-2] and on international level ASTM D 5035-95 [X99-3].

The test specimen is a raveled or cut strip in warp or weft direction or perpendicularly to joints such as welded seams or edge details. Cut strips are used e.g. for materials with special weave construction which cannot be raveled. The dimensions of the test specimen depends upon the relevant standard, the kind of test sample (base material, welding seam, edge detail etc.) and testing temperature (room temperature or temperature ≠ 23 °C). Exemplary dimensions of test specimens are summarized in Table 2-1.

Table 2-1 Dimensions of the test specimens and test speeds depending on the kind of specimen and temperature (values in brackets are possible variations)

Kind of specimen	Temp. [°C]	Gauge length [mm]	Width [mm]	Test speed [mm/min]	Specified in
Base material	23	200	50	100	EN ISO 1421 EN ISO 13934-1 DIN 53354
		(400)	(100)	(200)	in accordance with EN ISO 1421 EN ISO 13934-1 DIN 53354
	≠ 23	800	100 (50)	400	
Welding seam	23	400	100 (50)	200	
	≠ 23	800	100 (50)	400	
Edge detail	23	≥ 400	100 (50)	≥ 200	
	≠ 23	≥ 400	100 (50)	≥ 200	

The tests have to be performed with a CRE tensile testing machine according to EN ISO 1421. Exemplary, Figure 2-4 shows a tensile test specimen with a welded seam. It has to be taken care, that the clamps are at least as wide as the specimen.

A slippage of the specimen as well as a fracture at the clamp must be avoided. If slippage and fractures at the clamps cannot be avoided, other clamp types have to be used. For these reasons, preliminary tests might be necessary.

During testing the tensile test specimen is loaded either in warp or weft direction or perpendicularly to joints till break. For this reason, the mobile clamp has to be set in motion with a constant speed until the test specimen breaks. The test speed depends on the gauge length and behaviour of the

Figure 2-4 Tensile test specimen with welding seam in the testing machine before testing [© ELLF]

material. Depending on the mass per unit area and kind of specimen an initial stress has to be applied. If required tensile tests can be performed with wet specimens or under temperatures ≠ 23 °C. Typically, at least five specimens should be tested from each swatch of the laboratory sample. Typical force-elongation-curves for coated fabrics resulting from tensile tests are presented in Figure 2-5.

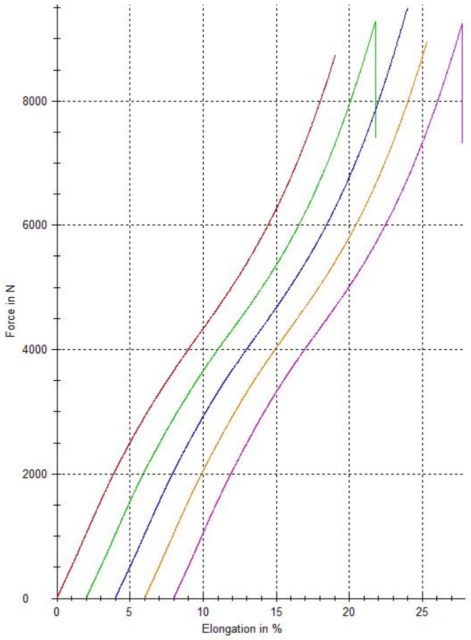


Figure 2-5 Typical results of tensile strength tests [© ELLF]

The test report shall include

- a reference to the applied standard,
- the applied test method (strip method),
- the number of specimens taken from each swatch of the laboratory sample,
- the width of each specimen,
- the conditioning and the condition of the specimens (wet or dry),
- the test temperature,
- the gauge length and the kind of clamping (with or without initial stress),
- the type and measuring range of the testing machine,
- the achieved tensile strength (and breaking load) for each test specimen as well as the mean value and the standard deviation of the tensile strength (and breaking load) in [N] and [kN/m] plus coefficient of variation,
- the values for elongation at tensile strength (and breaking load) for each test specimen as well as the mean value, the standard deviation of elongation of tensile strength (and breaking load) in [%] plus coefficient of variation,
- deviations from the considered test standards or special features and
- the date of the test.

2.2.2.3 Decreasing effects on the tensile strength (durablility?)

As described above, most of the materials used for coated fabrics are polymers. Polymers are known for decreasing strength due to long term loads, UV rays and high temperature. Furthermore, it has been discussed for a long time whether biaxial stress states lead to a strength decrease as well. Most of these influences have been investigated in detail by *Minte* [Min81]. In the future Eurocode, it is the aim to incorporate a design concept on the resistance side that takes account of these influences by strength reduction factors. Furthermore, it is supposed to give experimental test procedures in order to determine the strength reduction factors in an informative annex. The following explanations, particularly the specified values, refer to PES-PVC and Glass-PTFE materials.

Add a sentence that these factors affect the durability of the structure

Biaxial loading

Regarding a possible strength decrease due to biaxial loading, contradictory research results exist. *Meffert* [Meff78] had made tests on cylindrical test specimens of coated fabric, which were specifically produced for the tests. The test results showed up to 20% lower strength results compared to the strength measured in uniaxial tensile tests. These results have been incorporated in the work of *Minte* [Min81] and are still often used in Germany for conservative approaches. Ideally, the biaxial test would be performed using a cylindrical test specimen. The disadvantage of such a cylindrical specimen is that it has either to be especially woven or it has to be produced by placing a seam in longitudinal direction of the cylinder. Herewith the test specimen does not properly correspond to the material in the realized structure [Sax13]. On the other hand, *Reinhardt* [Rei76] reported on different test specimen forms for plane biaxial tests and pointed out, that for a cruciformtest specimen with long arms and slits in the arms a biaxial strength equal to the uniaxial strength could be reached, when barrel formed mountings are used. With these tests it could be shown, that biaxial loading does not have to decrease the strength. In order to determine strength reduction factors for the future code, it is recommended to further investigate this issue and prepare an improved test procedure.

Long term loading

Long lasting loads lead to a deterioration of strength. To investigate the amount of deterioration, experimental long-time load tests can be carried out, using a test procedure according to EN ISO 899-1 [X91]. The test specimens are loaded constantly over time and the time period until failure is measured. At least three load levels with constant loads with at least three test specimens per load level should be tested. The load levels should be chosen in such a way that a failure of the test specimens occurs within the planned maximum test duration. The test results can be illustrated in a “time to failure-load–diagram”, see Figure 2-6. A linear relationship between load level and time to failure can be obtained in a diagram with logarithmic axes. A regression line for the test results can be determined and extrapolated to the planned lifetime of the structure. The tensile strength at time t (lifetime of the structure) can be read out from the regression line. The strength decrease due to long-term loads does not differ much between base material and connections, but it strongly depends on the planed lifetime of the structure.

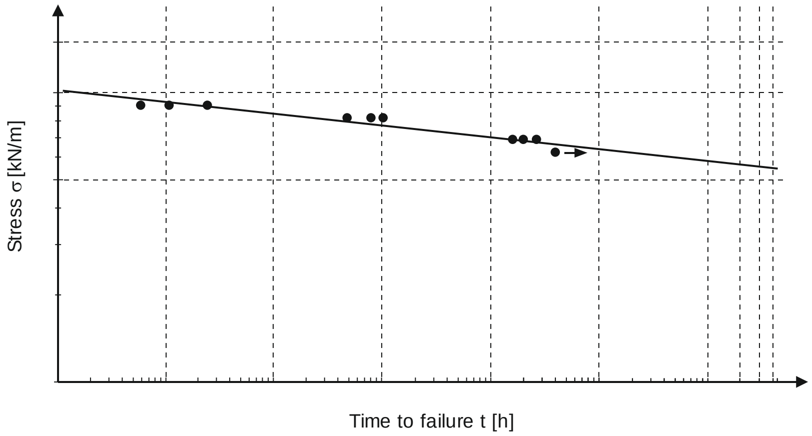


Figure 2-6 Time to failure-load–diagram [© ELLF]

Environmental impacts

The deterioration of strength of a material or connection due to exposure to environmental impacts and weather effects (UV-rays, raining etc.) is difficult to measure and the spectrum of the numerical amount found in literature is quite high. Values are given e.g. in [MIN81, Sclz87, Saal94]. Numerical values are mostly derived from material that was exposed to outdoor weathering, either in experimental tests or taken from dismantled structures. Artificial weathering is not generally used. Strength decrease is reported for base material between approximately 10% and 50%. For connections, where the coating is affected (e.g. by sewing) the deterioration depends very much on the coverage of the connection.

High temperature impacts

In order to determine high temperature impacts, uniaxial tensile tests have to be performed with an elevated temperature, usually 70 °C and the resulting tensile strength is compared to the tensile strength at room temperature, usually 23 °C. This particularly affects connections. A strength decrease of 10 % to 25 % is usual for the base material, at connections the strength can decrease in single cases to half of the strength at room temperature.

Crease folds

Regarding Glass fibre fabrics it has to be mentioned that crease folds may lead to cracks in single yarns and in the following to a strength decrease. In a loaded membrane these initial damages grow to so called “short cuts”. Typically short cuts are defined as cuts with a length of not more than 50 mm to 150 mm. “Short cuts” can be longer as well. A case to case assessment is necessary depending on the location in the structure etc. If the cut could be repaired with economical effort Detailed information is given in chapter 9. It shall be aimed during the manufacturing, packing and installation of a membrane to limit the number of short cuts by careful handling of the membrane aiming to avoid folds [Böhm12]. However, folds can never be avoided completely and thus a certain number of short cuts have to be accepted for Glass fibre fabrics. Once a short cut appears, tear propagation has to be avoided. Tear propagation is linked to the tear strength [FM04, Bid89, BlBö07]. Independently of that, short cuts should be repaired quickly, e.g. by welding patches on them. ~~Furthermore, regarding the acceptable length of short cuts, it has to be considered that the historical minimum factor of safety of 4 for membrane structures was based upon an initial tear of around 50 mm which should be the limit for a short cut. Longer short cuts may decrease the implied factor of safety.~~

Shorten here to the degradation effect. Put rest in chapter 9 (execution)

2.2.2.4 Tensile strength after crease fold

The tensile strength after crease fold is an important measure for glass fibre fabrics as they are sensitive to folding.

The aim of crease fold tests is to determine the resistance to creasing and folding by measuring the breaking force after repeated folding and force applications. Fabric sections are subjected to repeated folding and force applications to folds during packaging and fabrication (and transport and installation). This test method is primarily for use in coated and laminated fabrics as PTFE-coated glass fibre fabrics.

The principle of a crease fold test is that a strip of fabric is folded and the looped end rolled with a cylinder of specified mass. This folded test specimen is loaded uniaxial on a tensile testing machine till break. The load is applied in warp or weft direction.

The apparatus for creasing and folding the specimen is specified by ASTM D4851-07 [X97]. The preparation of the specimens and the measuring of the breaking force have to be performed according to EN ISO 1421 or in Germany according to DIN 53354 (withdrawn July 2007) or the guideline of Deutsches Institut für Bautechnik (DIBt) for acceptance test of coated fabrics and their joints.

The test specimen is a raveled strip in warp or weft direction. The test specimen has a gauge length of 200 mm and a width of approx. 50 mm.

The best possibility to determine the residual force after repeated folding and force applications is to compare the breaking force after a crease fold test to the breaking force after a tensile strength test without repeated folding and force applications. For this purpose, a double length raveled strip in warp or weft direction has to be prepared which has to be cut in half. Thereby two strips with the same system of yarns can be tested.

The apparatus for repeated folding and force applications is a cylindrical 4.5 kg mass with a diameter of approximately 90 mm and a length of 100 mm.

To perform a crease fold test each specimen has to be looped end to end and hold on a flat surface, see Figure 2-7. It is not allowed to flatten the loop by hand. “*Roll the specimen with the 4.5 kg cylindrical mass, unless otherwise specified, by placing the mass near the free ends and roll to and over the looped end. Do not push down on the mass, push horizontally and roll only in one direction, from open end to looped end. The mass must roll perpendicularly to the loop and pass over the fold so that all the mass is passed over the fold at the same instant. Roll the mass at a rate in which it will traverse the specimen in approximately 1 s. After rolling the mass over the loop of the specimen, pick up the mass and place it back near the end of the specimen. Repeat creasing of the fold nine additional times until a total of ten rolls have been applied. Unfold the specimens and lay on flat surface. Determine the breaking force after crease-fold of fabric specimens […] as directed in the breaking force procedure in the [description of a tensile strength test]. Position the crease-folded area approximately midway between the upper and lower clamps in the tensile testing machine.*” [X97]

At least five specimens have to be tested from each swatch in the laboratory sample.

Figure 2-7 Preparation of the looped specimen for the crease fold test acc. to ASTM D4851-07 [© ELLF]

The test report shall include

- a reference to the applied standard,
- the applied test method (breaking force after crease fold),
- the number of specimens taken from each swatch in the laboratory sample,
- the width of each specimen,
- the conditioning and the condition of specimens,
- the test temperature,
- the gauge length and the kind of clamping (with or without initial stress),
- the type and measuring range of the testing machine,
- the values for breaking force after crease fold for each test specimen as well as the mean value and the standard deviation of breaking force after crease fold in N and kN/m plus coefficient of variation,
- differences from standards or special features and
- the date of the test.

For some materials the aforementioned repeated folding and force application procedure according to ASTM D4851-07 is not sharp enough to simulate the repeated folding and force applications to folds during packaging and fabrication (and transport and installation). The reasons for this are first, the duration of application on the loop (fraction of 1 s) and second, the intensity of application on the loop (4.5 kg on 50 mm specimen).

For this reason two other test methods – the Essen method (Essener Verfahren) and an impact test on loop (Schlaufen-Schlag-Prüfung) - were developed at the Essen Laboratory for Lightweight Structures (ELLF) at University of Duisburg-Essen [Hom03], which are described in the following.

Essen method (Essener Verfahren)

The Essen method is a modification of the crease fold test according to ASTM D4851-07. The repeated folding and force application is not passed over the fold but on the fold. The principle of the Essen method is that a specimen of coated fabric is folded and the looped end is stressed with a specified mass. This folded test specimen is loaded uniaxially in a tensile testing machine until failure. The load is applied in warp or weft direction.

The preparation of specimens and the measuring of the breaking force are performed according to EN ISO 1421 (method 1), DIN 53354 (withdrawn July 2007) or the guideline of Deutsches Institut für Bautechnik (DIBt) for acceptance test of coated fabrics and their joints. The test specimen is identical to the ASTM-method.

For the Essen method the apparatus for the repeated folding and force application is a loading device with a mass of 5 kg. The apparatus consists of a cylinder made of steel with two handle bars and a plastic roll at the bottom side. If required the apparatus can be extended up to 20 kg, see Figure 2-8.

Figure 2-8 Left: loading device for the Essen method for repeated folding and force applications, right: rolling the load device on the looped end [© ELLF]

To perform the Essen method test each test specimen has to be looped end to end and held on a flat surface. It is not allowed to flatten the loop by hand. Place the loading device in the middle of the looped end and roll over forward and backward. Do not push down on the device, push horizontally. The device must roll exactly on the looped end. Roll the device at a rate in which it will traverse the looped end in approximately 1 s. After rolling the mass over the looped end forward roll it backward. Repeat creasing of the fold until a total of ten rolls (five times forward and five times backward) have been applied. Afterwards a tensile test has to be performed as already described for the ASTM-method.

Impact test on loop (Schlaufen-Schlag-Prüfung)

The Schlaufen-Schlag-Prüfung was developed on the basis of EN 1876-2 [X99-6]. The scope of this standard is a low temperature test to determine the brittle temperature of plastics-coated fabrics. The principle of the impact test on loop is that a specimen of coated fabric is folded and the looped end is stressed with a specified mass dropped from a specified height. Afterwards this folded test specimen is loaded uniaxially in a tensile testing machine until failure. The load is applied in warp or weft direction.

The preparation of the specimens and the measuring of the breaking force has to be carried out according to EN ISO 1421 (method 1), DIN 53354 (withdrawn July 2007) or the guideline of Deutsches Institut für Bautechnik (DIBt) for acceptance test of coated fabrics and their joints. The test specimen is identical to the ASTM-method.

The apparatus for folding and force application consists of two parts, see Figure 2-9. On the one hand it is a centering system consisting of four round steel bars with length of 1000 mm and a diameter of 18 mm, an upper holding ring with an inner diameter of 95 mm and base plate. On the other hand it is dumbbell-shaped drop weight made of aluminum with a mass of 667 g, height of 177 mm and an outer diameter of 95 mm.

To perform the test each test specimen has to be looped end to end and held on a flat surface. The loop cannot be flattened by hand. Place the looped test specimen in the middle of the centering system, see Figure 2-10. Do not position the looped end at the edge of the centering system but exactly in the middle. The dumbbell-shaped weight is dropped from a specified height onto the looped end (only once). The drop height of 200 mm, 400 mm or 800 mm has to be specified according to prior agreement. Do not push the drop weight downward and avoid slowing the fall. The test specimen has to be left in the centering system until the drop weight comes to rest. Afterwards a tensile test has to be performed as already described for the ASTM-method.

Figure 2-9 Left: loading device for the Essen method for repeated folding and force applications, right: rolling the load device on the looped end [© ELLF]

Figure 2-10 Impact test on loop, left: Positioning the specimen in the middle of the centering system, right: the drop weight dropped on the looped end [© ELLF]

Further test methods already used in practice

A test membrane will be produced and folded in the same way as it will be for the final membrane field. After unfolding, test samples will be cut out of the specific folded areas and tested as described before.

Experimental tests based on the Flexometer-Test can be performed. Herein, a test strip is folded in two directions at the same time. The folded test sample will be tested afterwards as described before.

2.2.2.5 Stiffness parameters

As structural membranes are generally loaded biaxially in the structure, tensile tests are performed biaxially in order to investigate the stress-strain-behaviour and to determine material stiffness properties. Usually, cruciform test specimens are used in plane biaxial tests for this purpose, see Figure 2-11, but other methods are under development as well, e.g. [NgTh13]. The arms of the cruciform are normally parallel to the orthogonal yarns.

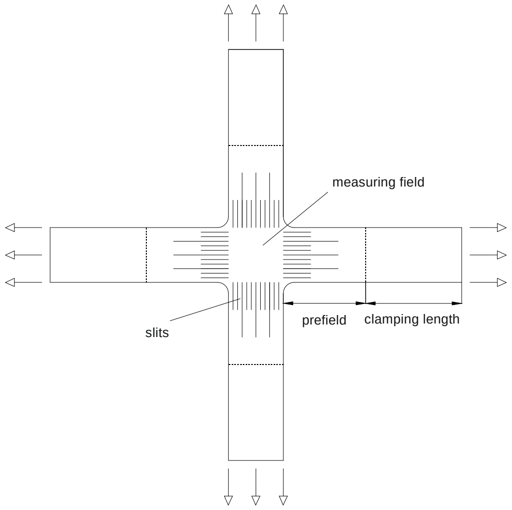


Figure 2-11 Example of a cruciform test specimen for biaxial testing [© ELLF]

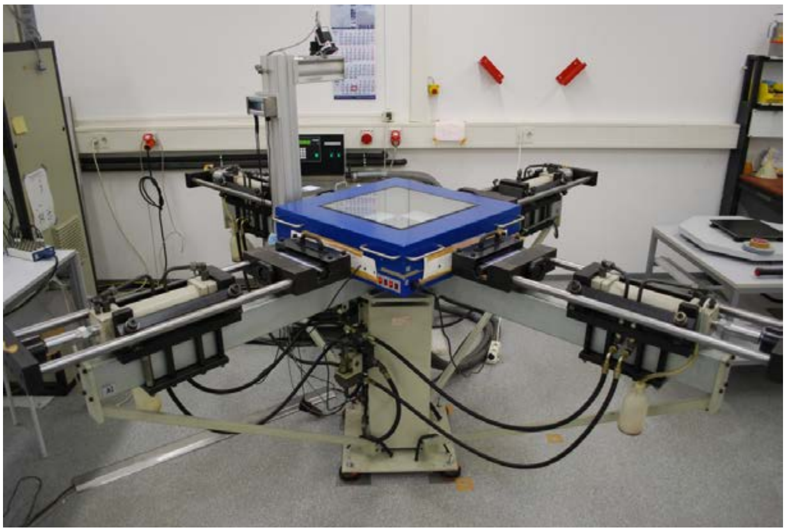


Figure 2-12 Biaxial testing machine with temperature chamber of the Essen Laboratory for Lightweight Structures at University of Duisburg-Essen, Germany [© ELLF]

The principle of a biaxial test is, that the cruciform test specimen is biaxially loaded in the plane of the fabric. Hereby, the warp and weft directions are loaded cyclically by stresses or strains simultaneously. The arms of the cruciform test specimen are slit in order to achieve a central measuring field of homogeneous strain and a well known stress state, see Figures 2-11 and 2-12.

Conducting biaxial tensile tests, fabrics show a highly nonlinear and anisotropic stress-strain-behaviour, which strongly depends on the load ratios warp/fill and the loading history. Furthermore, the stress-strain-behaviour is highly dependent on the crimp interchange of the yams that lay crimped within the coating matrix. The initial crimp value depends on the stress in the warp and weft direction that is applied during the weaving process. As the stresses in warp and weft direction frequently do not have the same values during the coating procedure, the fabric shrinks differently in both directions under load. This explains the orthogonal anisotropic stress-strain-behaviour. For the purpose of the structural design, this behaviour is usually modelled by an orthotropic linear-elastic constitutive law, using elastic constants in the main anisotropic directions of the fabric. Beside the geometrical stiffness, the material stiffness is of great importance for the structural analysis results [BrBi12, US13a, US13b].

Up to now, many different test protocols and evaluation procedures are established worldwide. Standardised procedures that are established or used in Europe are e.g. the Japanese standard MSAJ/M-02-1995 “Testing Method for Elastic Constants of Membrane Materials” [MSAJ95], the method described in the “European Design Guide for Tensile Surface Structures” [FM04] or the procedure according to the French Recommendations [ABT97], see Code Review No. 2. A typical load history diagram and typical load-strain-diagrams are given in Figures 2-13 and 2-14. The biaxial testing machine should allow symmetrical loading and elongation whereby movements of the center of the sample must be avoided. It should be possible, that both axes are activated independently. The tensile force can be applied by means of four servo-hydraulic actuators rigidly fixed at the extremities of a Greek cross shaped frame as shown in Figure 2-12. Both main directions should be equipped with at least one load cell. The elongation of the sample is to be measured in the central measuring field. This can be done by strain gauges or a video extensometer. It should be possible that the data can be recorded at different frequencies, see also [Bec11].

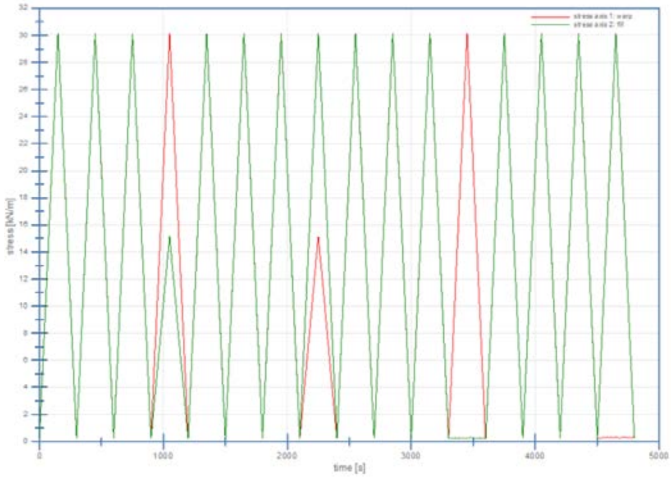


Figure 2-13 Typical load history diagram according to MSAJ/M-02-1995 [© ELLF]

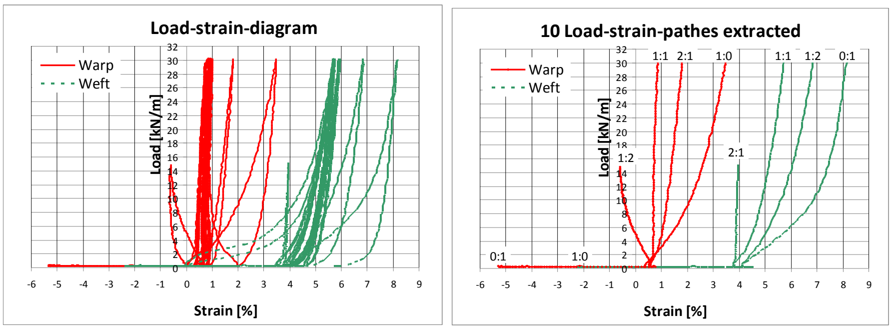


Figure 2-14 Left: Load-strain-diagram as a result of a biaxial test on Glass/PTFE material according to MSAJ/M-02-1995; right: Ten load-strain-paths (warp/weft at five load ratios), extracted from the diagram as the basis for the determination of elastic constants [US13b]

The strains and stresses are to be measured in warp and weft directions simultaneously with the applied loads. The strain measurement has to be carried out in the homogenous strain region in the center area of the test specimen, ideally without contact. If required a biaxial test should be performed under temperature ≠ 23 °C. For this reason a temperature chamber is needed, see Figure 2-12.

The test report shall include

- the date of the test, the project details,
- the identification of the material (batch number, etc.),
- the complete test profile - stress (kN/m) vs time (s),
- the strain (%) vs time (s) plot,
- the stress (kN/m) vs strain (%) plot,
- a listing of measured data,
- comments of abnormalities and if required
- detailed results summary (individual and mean values) of the tensile stiffness (elastic modulus) & Poisson's ratios.

Regarding the interpretation of test results and the determination of elastic constants, suggestions can be found e.g. in [BrGo10, USSS11, FM04]. Because of the complexity, usually the design offices use in-house procedures for the design of membrane structures which are adapted to the needs of specific projects.

Stiffness properties are needed for the structural analysis and can be useful when reviewing compensation values for the material. Separate biaxial tests are to be conducted to evaluate the specific properties. CEN/TC 248/WG 4 is preparing a new European standard that is intended to give standardized biaxial test methods as well as procedures for the evaluation of stiffness properties of coated fabrics which are needed for the structural design and the compensation. But due to the great variety of structural forms in the field of membrane structures, project specific procedures will maintain a high significance. Given the large variation in surface stresses for most projects, the normal approach is and will be to use a set of upper bound and lower bound stiffness values to verify the sensitivity of the design.

Eurocode Outlook No. 4

(1) The stiffness of the material may be determined according to the biaxial test standard which is prepared by CEN/TC 248/ WG4 or any other appropriate rule.

NOTE 1 Checks must be undertaken during the design if the stress ratios and stress levels used to achieve the stiffness values are applicable to the individual project. If not, project specific evaluation procedures may be used.

NOTE 2 Compensation values and tests shall be considered according to the design.

Code Review No. 2

French recommendations [ABT97]

3.1.1 Characteristics

- *type of the fabric (material)*
- *mass of the support and the total mass of the complex(g/m2) [ref. NF- EN 22286]*
- *nature of the coating of the inner and outer faces*
- *fabric weave [ref. NF- G 07155]*
- *instant average uniaxial strength (N/5cm) in the weft and the warp direction [ref. NF- G 37103]*
- *elastic moduli (see ANNEX A)*
- *biaxial elongation curves for the ratio 1/1, 1/2; 2/1 (see ANNEX A)*
- *Poisson's coefficient (see ANNEX A)*
- *Tear propagation resistance (N) (trapeze) in the warp and the weft direction [PR-EN 1875-3]*
- *adhesion (N/5cm) (NF G 37 107)*
- *resistance to welding at 65 ° (N/5cm)*
- *fire resistance (2 sides) (index) [NF P 92 507*

ANNEX A - MECHANICAL CHARACTERISTICS

Poisson's coefficient

In the absence of accurate measurement of the value of Poisson's ratios, we accept the following standard values:

warp / weft : ν=0.3

weft /warp: ν=0.5

Prestress

- *the test is performed with the pretension load ratio warp / weft 1/1*
- *it is composed of 5 loading cycles at a constant speed*
- *the nominal force applied per cycle is 0.25 kN/m*
- *the maximum force applied per cycle is equal to 5% of the tensile strength in warp and weft direction*

Moduli of elasticity

The warp and weft elasticity moduli are defined experimentally by a biaxial test series under cyclic loading.

- *Each test series consisted of three elongation tests carried out under the load ratios warp / weft 1/1, 1/2 and 2/1.*
- *Each elongation test consists of two series of five loading cycles (Figure A, rapport 2/1).*
- *The speed of loading and unloading is constant*
- *The minimum applied force per cycle is equal to 0.25 kN/m*
- *The highest force is equal to 10% of the tensile strength in the warp direction for the first five cycles, and 25% of the tensile strength in the warp direction for the next five cycles.*

The elasticity moduli to be used for design are secant moduli defined by the low starting point of the first cycle and the high point of the fifth cycle of the second series of five cycles of biaxial tests ratio of 1/2 and 2/1 (Figure B, ratio 2/1).

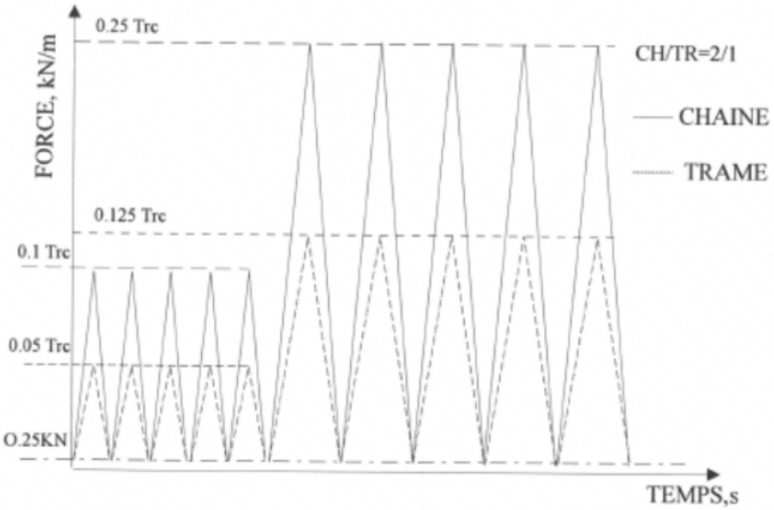


Figure A

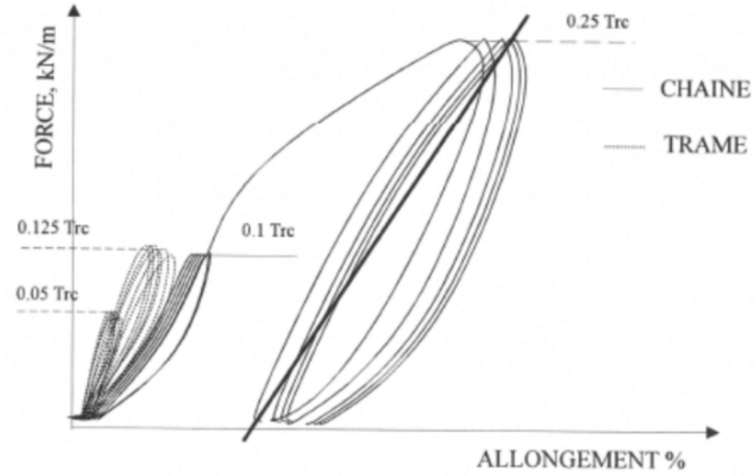


Figure B

2.2.2.6 Tear Strength

The tear strength is tested by means of the tear test. The principle of a tear test is to load the yarns or filaments of coated fabrics one after another until tear. The load is applied in warp or weft direction. Tear tests are used to determine the resistance of the yarns or filament to a load before tearing. They are specified in European and national standards as EN 1875-3 [X93] and DIN 53363 [X95]. Originally, DIN 53363 is applicable to foils only, but traditionally also applied to fabrics. Due to the fact that it is still the standard on which the fabricator rely on, it is mentioned in this chapter. In the context of the Eurocode development it is envisaged to focus on the European test standards only.

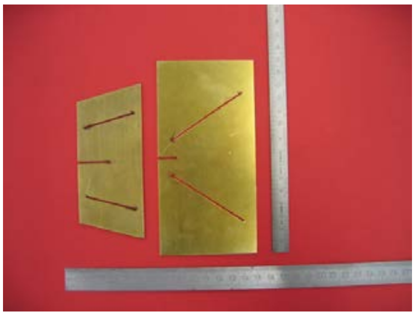


Figure 2-15 Templates for the application of the incision in the test specimens for the tear test [© ELLF)

The test specimen is a trapezoidal test specimen with an incision. As an example, the dimensions of the specimen are specified to 150 mm x 75 mm according to EN 1875-3. Ideally, the incision is applied using a template as presented in Figure 2-15.

The testing machine used for tear tests should fulfill the requirements as defined in chapter 2.2.2.2.

To perform a tear test the yarns or filaments of coated fabrics are loaded one after another till tear. Special care has to be given on the positioning of the test specimen in the upper and lower clamps: the lower edge of the upper clamp and the upper edge of the lower clamp has to be laid exactly on the marks of the test specimen. The test setup and exemplary results are presented in Figure 2-16.The applied load has to be constantly recorded while the mobile clamp is set in motion with a constant speed. The testing speed has to be set to 100 ± 10 mm/min. If required, the tear test has to be performed under temperature ≠ 23 °C. In total five specimens have to be tested at least from each swatch in warp and weft direction.

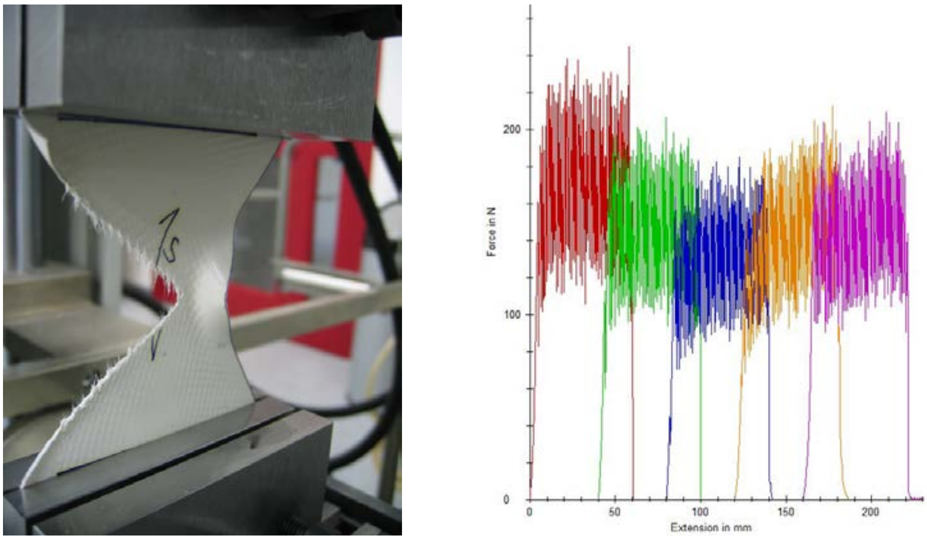


Figure 2-16 Test setup for the tear test (left) and typical results (right) [© ELLF]

The test report shall include

- a reference to the applied standard,
- the number of specimens taken from each swatch in the laboratory sample,
- the identification of the material and its thickness,
- the conditioning and the test temperature,

- the values for tear strength for each test specimen as well as the mean value and the standard deviation in [N] plus the coefficient of variation,
- all anomalies and differences from the standards or special features and
- the date of the test.

2.2.2.7 Adhesion

The aim of adhesion tests is to determine the mechanical behaviour of the adhesion of the coating to fabric. The principle of an adhesion test is to pull a specimen, which is welded by sealing two material strips face to back, until the separation of the bonded specimen occurs.

On European level, the adhesion test is required to be performed according to EN ISO 2411 [X94].

In Germany, a different test method is specified by the guideline of Deutsches Institut für Bautechnik (DIBt) for acceptance test of coated fabrics and their joints using the test evaluation of DIN 53357 [X99-4]. DIN 53357 is still applied in Germany although it is withdrawn. In the following the German test procedure is explained due to the fact that it is the common procedure even for international projects. Nonetheless, in the context of the Eurocode development it is envisaged to focus on the European test standards only. For this purpose further development and investigations have to be performed for the transformation and comparison of the different test procedures.

According to the guideline of the DIBt, the test specimen is a 20 mm by 150 mm strip, which is cut from the center of a sealed double-layer strip. For a distance of 50 mm the fabric has to be stripped from one layer down. To facilitate separation, at least one side of the double layer has not to be sealed, see Figure 2-17.

The testing machine used for adhesion tests should fulfill the requirements as defined in chapter 2.2.2.2.

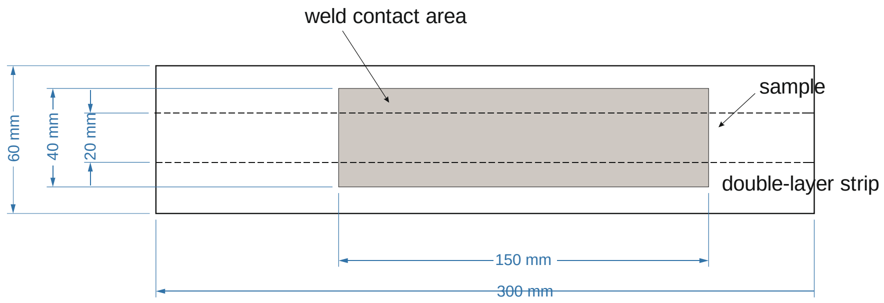


Figure 2-17 Sealed double-layer strip and position and dimension of the test specimen according to the German DIBt-Guideline for the acceptance test of coated fabrics and their joints [X99-2]

To perform an adhesion test, one end of the separated portion has to be clamped in the lower jaw of the testing machine and the other end of the specimen in the upper jaw. The test specimen has to be positioned in the clamps exactly parallel to direction of trajectory motion. The test setup and exemplary results are presented in Figure 2-18. The force as a function of the movement of the mobile clamp must be recorded while the mobile clamp has to be set in motion with a constant speed. The testing speed has to be set to 100 ± 10 mm/min. If required the adhesion test has to be performed under temperature $\neq 23$ °C.

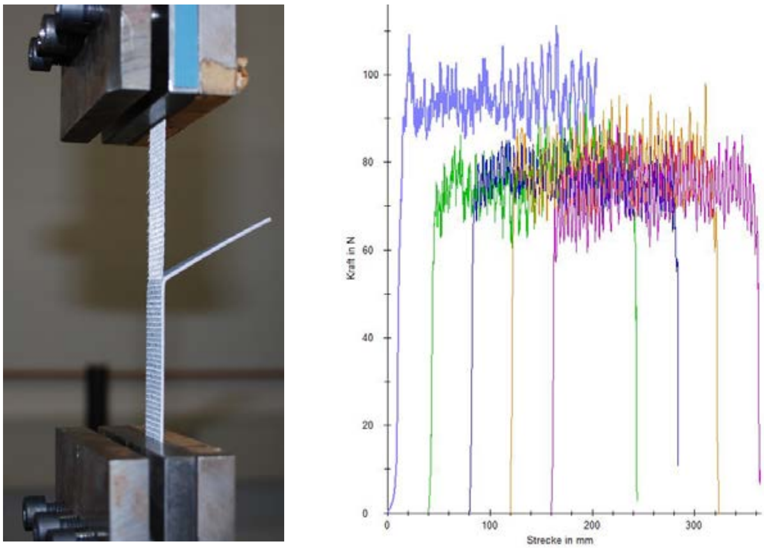


Figure 2-18 Test setup for an adhesion test (left) and typical results (right) [© ELLF]

The test evaluation can be performed according to DIN 53357 [X99-4] although this standard is withdrawn. Furthermore, at least five specimens have to be tested from each swatch.

The test report shall include

- a reference to the applied standards,
- the number of specimens taken from each swatch in the laboratory sample,
- the identification of the material and its welding,
- the conditioning and the test temperature,
- the values for adhesion of coating to fabric for each test specimen as well as
- the mean value and the standard deviation in N/cm plus coefficient of variation,
- all anomalies and differences from standards or special features and
- the date of the test.

2.2.3 Tabulated strength values for coated fabrics

2.2.3.1 General

In the following strength values for coated fabrics are summarized. For a future Eurocode it will be helpful to classify the materials as it is partially already done by the material producers and some national recommendations. Only those values are specified in the following which are of interest in the context of the design of a tensile membrane structure.

2.2.3.2 PVC-coated Polyester fabrics (PES/PVC-fabrics)

The following tables give strength values for conventional material products.

Up to now, the only standardized classification exists in the French recommendations, which is given in the following Code Review No. 3. The materials are classified mainly by the material weight.

Code Review No. 3

French recommendations

The following table is not a standard but a project master document.

Table 1: Typology of polyester fabrics with PVC coating

Type	***I***	***II***	***III***	***IV***
Weight in g/m²	*750/900*[1)]	*1050*	*1050/1250*[1)]	*1350/1850*[1)]
Tensile strength in warp and weft [3)] ***(N/5cm)*** ***(kN/m)***	*2800/2800* *56/56*	*4200/4000* *84/80*	*5600/5600* *112/112*	*8000/7000* *160/140*
Tear strength in warp and weft (N/5cm)[3)]	*300/280*	*550/500*	*800/650*	*1200/1100*
Ultimate elongation (%)	*15/20*	*15/20*	*15/25*	*15/25*
Minimum width of the welds (cm)	*3*	*4*	*4*	*4*
Light passing at 500nm, translucent white color	*13*	*9.5*	*8*	*5*
Reaction to fire	*M2*[2)]	*M2*[2)]	*M2*[2)]	*M2*[2)]

[1)] *The two values indicate an order of magnitude.*

[2)] *Classification according to French standards NF P92-503 and NF P92-507. Class M2 corresponds to class B-s2,d0 in EN 13501-1.*

[3)] *Strength values are given as mean values.*

The classification of material types for PES/PVC-fabrics that are used throughout Europe is currently being harmonized for the purpose of the Eurocode development. Eurocode Outlooks No. 5 and 6 display a coordinated classification harmonization. Although the weight and the tensile strength are normally closely linked to each other (one exception is fluorpolymer coated PTFE fabrics, the future Eurocode classification aims to classify by the tensile strength as this is the item directly linked to the structural verification.

Those strength values which are directly linked to the stress verification in the Ultimate Limit State (ULS) have to be taken into account in the design verification as characteristic values, i.e. 5%-fractile values. These are the tensile strength of the base material and the seam strength, see Eurocode Outlook No. 5. The values given in Eurocode Outlook 6 – the tear strength and adhesion – are important material properties for the structural behaviour, but are not supposed to be directly used for the design verification of the structural safety.

Eurocode Outlook No. 5

PES/PVC-fabrics

Strength values of PVC-coated polyester fabrics directly linked to the stress verification in the ULS

Parameter	*Standard*	*Value*	*Type I warp/weft*	*Type II warp/weft*	*Type III warp/weft*	*Type IV warp/weft*	*Type V warp/weft*
Tensile Strength [kN/m]	*EN ISO 1421*	*Mean value*	*55/55*	*80/80*	*110/100*	*150/130*	*185/160*
		5% fractile	*50/50*	*70/70*	*100/90*	*135/120*	*170/145*
Seam strength~~/ tensile strength~~ at 23°C	*EN ISO 1421*	*percentage of the respective tensile strength*	*>≥90%*	*>90%*	*>90%*	*>90%*	*>80%*$^{1)}$
Seam strength~~/ tensile strength~~ at 70°C	*EN ISO 1421*	*percentage of the respective tensile strength*	*>70%*	*>70%*	*>70%*	*>60%*	*>55%*

$^{1)}$ *Higher values might be possible, but maybe not economical.*

Eurocode Outlook No. 6

PES/PVC-fabrics

Strength values of PVC-coated polyester fabrics not directly linked to the stress verification in the ULS

Parameter	*Standard*	*Type I warp/weft*	*Type II warp/weft*	*Type III warp/weft*	*Type IV warp/weft*	*Type V warp/weft*
Tear Strength$^{1)}$ *[daN]*	*EN 1875-3 Method B (62°) 4)*$^{2)}$	*17/17*	*28/28*	*45/45*	*75/75*	*110/110*
Adhesion$^{1)}$ *[N/5cm]*	*EN ISO 2411*	*100*	*110*	*120*	*130*	*140*

$^{1)}$ *This values are given as mean values.*

$^{2)}$ *Accompanying the Eurocode development, a new biaxial test standard is currently under development in CEN/TC 248/ WG 4 which aims to substitute the method of EN 1875-3 in the future.*

2.2.3.3 PTFE-coated glass fibre fabrics (Glass/PTFE-fabrics)

The following tables give strength values for conventional PTFE-coated glass fibre material products (Glass/PTFE-fabrics).

Up to now, the only standardized classification exists in the French recommendation [X124], which is given in the following Code Review No. 4.

Code Review No. 4

French recommendations

The following table is not a standard but a project master document.

Table 2: Typology of glass fabrics with PTFE coating

Type	***I***	***II***	***III***	***IV***
Weight in g/m^2	*800*	*1050*	*1250*	*1500*
Tensile strength in warp and weft [2] ***(N/5cm)*** ***(kN/m)***	*3500/3000* *70/60*	*5000/4400* *100/88*	*6900/5900* *138/118*	*7300/6500* *146/130*
Tear strength in warp and weft (N/5cm) [2]	*300/300*	*300/300*	*400/400*	*500/500*
Ultimate elongation (%)	*3-12*	*3-12*	*3-12*	*3-12*
Light passing at 500nm, translucent white color	*12-18*	*12-18*	*10-16*	*10-16*
Reaction to fire	*M2*[1]	*M2*[1]	*M2*[1]	*M2*[1]

NOTE Packing has an important impact on the properties of the material.

[1] Classification according to French standards NF P92-503 and NF P92-507. Class M2 is correspondent to class B-s2,d0 in EN 13501-1.

[2] Strength values are given as mean values.

Eurocode Outlooks No. 7 and 8 give a proposal for a future classification. Comparable to PES/PVC-fabrics, see above, those strength values, which are directly linked to the stress verification in the Ultimate Limit State (ULS), have to be taken into account in the design verification as characteristic values, i.e. 5%-fractile values. These are the tensile strength of the base material and the seam strength, see Eurocode Outlook No. 7. Other values like tear strength, adhesion and tensile strength after crease fold are important material properties for the structural behaviour but are not supposed to be directly used for the verification of the structural safety.~~ Tensile strength after crease fold is an important measure for glass fibre fabrics as they are sensitive to folding~~. Bernd will send additional sentence regarding Nick

Nevertheless, for the purpose of this report all requirements linked to the specific material types are given as mean values.

Eurocode Outlook No. 7

Glass/PTFE-fabrics

Strength values of PTFE-coated glass fibre fabrics directly linked to the stress verification in the ULS

Parameter	*Standard*	*Value*	*Type I warp/weft*	*Type II warp/weft*	*Type III warp/weft*	*Type IV warp/weft*
Tensile Strength Data Sheet [kN/m]	*EN ISO 1421*	*Mean value*	*80/55*	*120/110*	*135/130*	*155/150*
		5%-fractile	*To be determined by experimental investigations*			
Seam Strength/ Material Strength at 23°C	*EN ISO 1421*	*percentage of the respective tensile strength*	*>80%/ >80%*	*>90%/ >90%*	*>90%/ >90%*	*>90%/ >90%*
Seam Strength/ Material Strength at 70°C	*EN ISO 1421*		*>60%/ >60%*	*>70%/ >70%*	*>70%/ >70%*	*%>70%/ >70%*

Eurocode Outlook No. 8

Strength values of PTFE-coated glass fibre fabrics not directly linked to the stress verification in the ULS

Parameter	*Standard*	*Type I warp/weft*	*Type II warp/weft*	*Type III warp/weft*	*Type IV warp/weft*	*Type V warp/weft*
Tensile Strength after Crease Fold Test 1) 3)	*ASTM D 4851 3)*	*>60%/ >60%*	*>70%/ >70%*	*>80%/ >80%*	*>90%/ >90%*	*>90%/ >90%*
Tear Strength [daN] 1)	*EN 1875-3 2)*	*15/15*	*20/25*	*30/30*	*40/40*	*50/50*
Adhesion [N/5 cm] 1)	*EN ISO 2411*	*35*	*50*	*80*	*100*	*120*

1) This values are given as mean values.

2) Accompanying the Eurocode development, a new biaxial test standard is currently under development in CEN/TC 248/ WG4 which aims to substitute the method of EN 1875-3 in the future.

3) The referred standard for the crease fold test is an ASTM-standard, which should not be used in a Eurocode design standard. Beside this, modified crease fold tests procedures exist, on which it could be relied on. In future, it has to be investigated, which crease fold test is the most reliable one. Furthermore, this test procedure should be standardized in a European standard.

2.2.3.4 Fluorpolymer-coated PTFE fabrics

Eurocode Outlooks No. 9 and 10 give a proposal for a future classification of fluorpolymer-coated PTFE-fabrics.

Eurocode Outlook No. 9

Fluorpolymer-coated PTFE fabrics

Typical strength values of fluorpolymer-coated PTFE fabrics directly linked to the stress verification in the ULS

Parameter	*Standard*	*Value*	*Type 0 warp/weft*	*Type I warp/weft*	*Type II warp/weft*
Tensile strength at 23°C in [kN/m] and [N/5cm]	*EN ISO 13934-1*	*5%-fractile*	*30/32 1500/1600*	*48/52 2400/2600*	*80/80 4000/4000*
Tensile strength at 50°C in [kN/m] and [N/5cm]	*EN ISO 13934-1*		*20/22 1000/1100*	*34/36 1700/1800*	*60/60 3000/3000*
Tensile strength at 70°C in [kN/m] and [N/5cm]	*EN ISO 13934-1*		*18/19 900/950*	*29/31 1450/1550*	*48/48 2400/2400*
Seam strength at 23°C	*EN ISO 13934-1*	*percentage of the respective tensile strength*	*>90%/ >90%*	*>90%/ >90%*	*>90%/ >90%*

Eurocode Outlook No. 10

Fluorpolymer-coated PTFE fabrics

Properties of fluorpolymer-coated PTFE fabrics not directly linked to the stress verification in the ULS

Parameter	*Standard*	*Type 0 warp/weft*	*Type I warp/weft*	*Type II warp/weft*
Weight [g/m^2]1)		*250*	*340*	*1100*
Tear strength 1) in [daN] and [N]	*DIN 53363 2)*	*39* *390*	*70* *700*	*100/100* *1000/1000*
Reaction to fire	*EN 13501-1*	*B-s1, d0*	*B-s1, d0*	*B-s1, d0*
Fabrication		*sewing*	*sewing*	*sewing/welding*

1) *The values for weight and tear strength are mean values.*

2) *Accompanying the Eurocode development, a new biaxial test standard is currently under development in CEN/TC248 WG4 which aims to substitute the method of DIN 53363 in the future.*

2.2.4 Tabulated strength values for uncoated fabrics

2.2.4.1 General

In the following strength values for uncoated fabrics are summarized. For a future Eurocode it will be helpful to classify the materials as it is partially already done by the material producers and some national recommendations. Only those values are specified in the following which are of interest in the context of the design of a tensile membrane structure. As already stated, uncoated fabrics in textile architecture are usually made of polytetrafluorethylene (PTFE) or polyvinylidenfluorid (PVDF). In the following values will be given for uncoated PTFE-fabrics only.

2.2.4.2 Uncoated PTFE-fabrics

Eurocode Outlooks No. 11 and 12 give a proposal for a future classification of uncoated fabrics made from PTFE-yarns. As uncoated fabrics are typically available with higher strength values only, the classification starts with type III.

Eurocode Outlook No. 11

Uncoated PTFE-fabrics

Typical strength values of uncoated PTFE-fabrics directly linked to the stress verification in the ULS

Parameter	*Standard*	*Value*	*Type III warp/weft*	*Type IV warp/weft*	*Type V warp/weft*
Tensile strength at 23°C in [kN/m] and [N/5cm]	*EN ISO 13934-1*	*5%-fractile*	*100/100* *5000/5000*	*150/150* *7500/7500*	*205/205* *10250/10250*
Tensile strength at 50°C in [kN/m] and [N/5cm]	*EN ISO 13934-1*		*70/70* *3500/3500*	*105/105* *5250/5250*	*144/144* *7200/7200*
Tensile strength at 70°C in [kN/m] and [N/5cm]	*EN ISO 13934-1*		*60/60* *3000/3000*	*90/90* *4500/4500*	*124/124* *6200/6200*
Seam strength at 23°C	*EN ISO 13934-1*	*percentage of the respective tensile strength*	*>50%/ >50%*	*>50%/ >50%*	*>50%/ >50%*

Eurocode Outlook No. 12

Uncoated PTFE-fabrics

Properties of uncoated PTFE-fabrics not directly linked to the stress verification in the ULS

Parameter	*Standard*	*Type III warp/weft*	*Type IV warp/weft*	*Type V warp/weft*
Weight [g/m²] [1)]		*930*	*990*	*1400*
Reaction to fire	*EN 13501-1*	*B-s1, d0*	*B-s1, d0*	*B-s1, d0*
Fabrication		*sewing*	*sewing*	*sewing*

[1)] *The values for weight are mean values.*

2.3 ETFE-Foils

2.3.1 General

The Eurocode is also intended to apply to ETFE-foils, short for Ethylen-Tetrafluoroethylene, which is a copolymer of ethylene (E) and tetrafluoroethylene (TFE). TFE is based on the natural mineral fluorospar. It forms a long linear molecular chain. The material is first polymerized and then extruded into pellet form.

Herewith, ETFE is a solid, semicrystalline, transparent and thermoplastic fluorinated copolymer, consisting of two individual monomeric. In pellet form the material can be mixed with pigments or modification additives and can be extruded into a foil.

For the production of an ETFE-foil, ETFE-pellets are heated to approximately 340 °C and forced through a machine under pressure to form foils. It can be distinguished between two different production methods, which results in foils with different properties. Foils produced by the blown film extrusion method can have a greater width. As a result the thickness of the foil is effectively limited up to 150 µm. But the material is less isotropic than the foils produced by the second method, which is explained hereafter. Foils can also be produced by extrusion through a slit-die. Then they can achieve thicknesses up to 3~~0~~50 µm. In principle, the foils are much more transparent and free of defects. After extrusion, the foils can be printed or surface treated, see Figure 2-19.

Figure 2-19 Exemplary plain and printed ETFE-foils [© ELLF]

ETFE-foils have a wide service temperature range and they are low flammable (270 °C; the material dissolves, but does not cause molten drips). They are resistant to solvents, chemicals and radiation, to outdoor weathering and to tear and stress cracking. In the visible and UV ranges the foil has a high light transmission, the permeability is very low and it has non-stick characteristics.

Within tolerable material limits these foils can be assumed to be linear and isotropic, which means their behaviour in both directions is approximately equal. Foils tend to flow with constant load or especially at higher temperatures because of their thermoplastic properties. The creep of ETFE-foils ranges between 1 - 2% additional strain under elastic load. Give reference; is usually less than 1%

The individual ETFE-foils are joined by contact welding~~ or bonded by adhesive~~. Afterwards they can be used as a single-layer foil stretched between framework or as multi-layered pneumatically pressurized pillows. The internal pressure typically ranges between 200 and ~~750 ~~500 Pa, but could be chosen higher depending on external conditions like wind or snow. [Sch09, Hou13, KCGM10, Koc04] "more for snow load in winter time"

2.3.2 Material properties

2.3.2.1 General

The mechanical properties of ETFE-foils depend on the load duration and the ambient temperature. In the typical thickness range (100 to 3~~0~~00 µm) the linear elastic range reaches up to 1~~0~~ % elongation. In this sector the foil shows the highest stiffness. The reached tensile strength can be calculated static. In dependence on the stress condition the values may change. At low temperature, -25 °C, the elongation will get back to the initial situation after several cycles. But at higher temperatures, +35 °C, the foil is creeping and a residual strain remains. [Sch09, Hou13, KCGM10, Koc04]

Foils typically exhibit high levels of strain with multiple yield points and a very high capacity for plastic deformation.

Foils used for membrane structures are characterized by:

- thickness (µm),
- weight (g/m^2),
- extrusion direction, perpendicular direction,
- roll width (mm),
- yield point (N/mm^2) ,
- tensile strength,
- Young's modulus,
- G-modulus and
- Poisson's ratio.

Typical strength values are the

- tensile strength,
- seam strength and
- tear strength.

2.3.2.2 Tensile strength

In principle, the tensile strength of foils is determined by tensile tests in the same way as already explained for fabrics in chapter 2.2.2.2. The tensile test for foils is specified in EN ISO 527, Part 1 (general properties) [X92] and Part 3 (test conditions for films and sheets) [X92-2]. Tests on welding seams, edge details and other type of joints are performed according to EN ISO 527; in Germany in combination with the guideline of Deutsches Institut für Bautechnik (DIBt) for acceptance test of coated fabrics and their joints [X99-2].

The test specimen is a cut strip in machine or transverse direction or perpendicularly to joints as welding seams or edge details. The dimensions of the specimen are specified in EN ISO 527-3. In certain cases the length of the specimen has to be adapted, e.g. testing an edge detail.

Figure 2-20 shows a tensile test specimen of an ETFE-foil as well as typical stress-strain-diagrams for ETFE-foils.

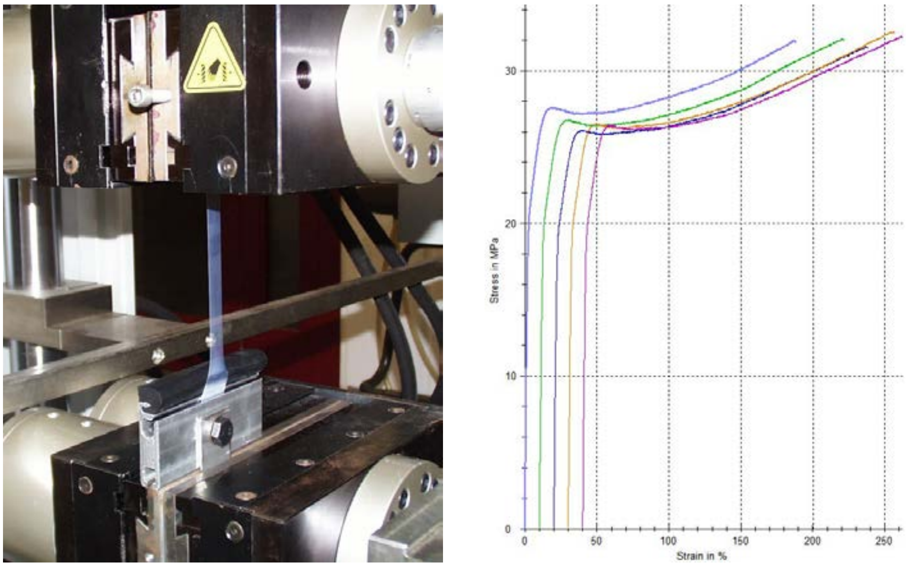


Figure 2-20 Tensile test specimen (here: ETFE-foil edge detail), left, and typical stress-strain-diagrams for ETFE-foils [© ELLF]

Eurocode Outlook No. 13

(1) *The tensile strength at 23 °C in extrusion and perpendicular direction has to be determined according to EN ISO 527-1.*

2.3.2.3 Tear strength

For foils no European standard exist up to now for the determination of the tear strength.

In Germany the tear test is specified in the national standard DIN 53363 [X95], see explanations for fabrics in chapter 2.2.2.5.

Typical force-extension-diagrams for ETFE-foils are presented in Figure 2-21.

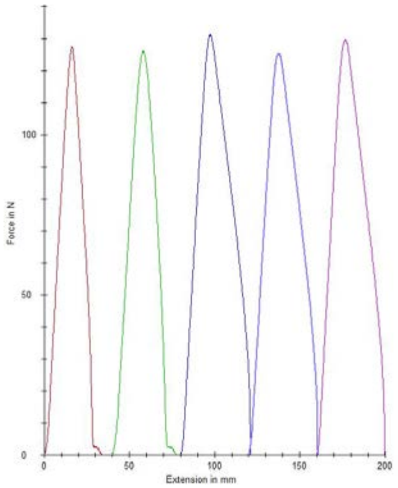


Figure 2-21 Typical force-extension-diagrams for ETFE-foils [© ELLF]

Eurocode Outlook No. 14

(1) The tear propagation strength at 23 °C in extrusion and perpendicular has to be determined with the tear test according to DIN 53363.

2.3.2.4 Stiffness parameters

In principle the stiffness parameters of foils are determined in the same way as for fabrics.

Eurocode Outlook No. 15

(1) For structures that experience high levels of stress in both extrusion and perpendicular directions simultaneously it is appropriate to carry out biaxial or multi-axial testing.

Up to now, for foils no standardized biaxial or multiaxial testing procedures exist. Currently, in CEN/TC 248/ WG4 a standard is under development for biaxial testing of fabrics. This standard might be adoptable for foils.

Eurocode Outlook No. 16

(1) If a foil material has been shown to be isotropic, then ~~uniaxial stress-strain data can be used to determine elastic moduli for design.~~elastic constants can be determined from different stress ratios than 1/1in a biaxial test.

2.3.2.5 Tabulated strength values for ETFE-foils

Eurocode Outlook No. 17 contains design values for ETFE-foils.

Eurocode Outlook No. 17

ETFE-foils

Parameter	*Standard*	*Value*	*Minimum value*
Tensile Strength [~~kN/m~~N/mm^2] at 23°C	*EN ISO 527-1*	~~*5%-fractile*~~mean value	*??*
Tear Strength [daN]	*DIN 53363*	*Mean value*	*??*
Seam Strength/~~Material Strength~~ at 23°C	*EN ISO 527-1*	*percentage of the respective tensile strength*	*??*
Seam Strength/~~Material Strength~~ at ~~7~~50°C 1)	*EN ISO 527-1*		*??*

~~1) *To obtain elastic constants: do 1 cycle 1/2 bi-axial test (values in the informative annex.)*~~

Formatiert: Hochgestellt

2.3.3 Durability

Eurocode Outlook No. 18

(1) To ensure durability of the structure due consideration should be given to:

- *(i) Detailing, such that the foil that is in contact with the supporting structure (cables, clamped edges, etc.) is not damaged, even with cyclic loading and large movements of the foil,*
- *(ii) Ensure that strain during the design life of the structure does not lead to excessive strength reduction of the foil,*
- *(iii) Ensure that the used materials for clamping and detailing are of the same durability as the foil,*
- *(iv) Ensure that the quality of air supply (in case of air supported foil) is given.*

2.4 Material laws in practice and their interconvertability

2.4.1 Different material laws in practice

The highly non-linear and non-elastic material behaviour of structural membranes is approached in practice by different formulations of a linear-elastic constitutive law in the plane stress state. The application of hyperelastic material models for tensile membrane structures is currently under research but might be finalized for use in the foreseeable future, e.g. [SBN14, Col14]. Further methods for the mathematical description of the stress-strain behaviour are under development, e.g. macro-mechanic methods (e.g. [Ball07, IBG13]).

To handle the typically rather high crimp interchange effect in membranes, many software packages dedicated to membranes today are using the “direct stiffness formulation of the plane stress model” with warp and weft stiffness and crimp interchange stiffness.

The better known corresponding “inverse stiffness formulation of the plane stress model” uses Young's Modulus E and Poisson’s Ratio ν, where typically the Poisson’s Ratio for isotropic solid materials cannot be equal or larger than 0.5. For anisotropic solid materials higher values may be feasible, see e.g. [Lem68]. This feature can be necessary for some membrane materials.

One formulation can be substituted by the other one, see the following section.

a. Direct stiffness formulation

$$\sigma_x = EA_x \cdot \varepsilon_x + EAP_y \cdot \varepsilon_y \tag{2.1}$$

$$\sigma_y = EA_Y \cdot \varepsilon_y + EAP_x \cdot \varepsilon_x \tag{2.2}$$

where EA_x, EA_y are the stiffness in warp and weft direction of a fabric and EAP_x, EAP_y are the crimp interchange stiffness in warp and weft direction.

b. Inverse stiffness formulation

$$\varepsilon_x = \frac{\sigma_x}{E_x} - \nu_{xy} \cdot \frac{\sigma_y}{E_y} \tag{2.3}$$

$$\varepsilon_y = \frac{\sigma_y}{E_y} - \nu_{yx} \cdot \frac{\sigma_x}{E_x} \tag{2.4}$$

where E_x, E_y are the stiffness in warp and weft direction of a fabric and ν_{xy}, ν_{yx} are the Poisson's Ratios in warp and weft direction.

Note: For easier readability, the mentioned values for σ and ε are the differential values, i.e. $\Delta\sigma$ and $\Delta\varepsilon$.

Both mathematical formulations are widely used in the field of membrane structure engineering and therefore particular care must be taken when stiffness parameters are specified or compared. In order to avoid mistakes, it can be recommended to always state the type of formulation – "direct stiffness formulation" or "inverse stiffness formulation" – when giving stiffness properties.

Often the software uses only one value for EAP or for ν while the other can be calculated internally based on the assumption of a symmetric stiffness matrix. Using the average value of the two can be an option, but the results need to be checked carefully.

2.4.2 Transformation between direct and inverse stiffness formulation

The equations above describe physically the same material, so that it is possible to transform Young's Modulus and Poisson's Ratio into direct stiffness and the other way around.

$$EA_x = \frac{E_x}{\left(1 - \nu_{xy} \cdot \nu_{yx}\right)} \tag{2.5}$$

$$EA_y = \frac{E_y}{\left(1 - \nu_{xy} \cdot \nu_{yx}\right)} \tag{2.6}$$

$$EAP_x = \nu_{xy} \cdot EA_x \tag{2.7}$$

$$EAP_y = \nu_{yx} \cdot EA_y \tag{2.8}$$

or

$$E_x = EA_x \cdot \left(1 - \nu_{xy} \cdot \nu_{yx}\right) \tag{2.9}$$

$$E_y = EA_y \cdot \left(1 - \nu_{xy} \cdot \nu_{yx}\right) \tag{2.10}$$

$$\nu_{xy} = \frac{EAP_x}{EA_x} \tag{2.11}$$

$$\nu_{xx} = \frac{EAP_y}{EA_y} \tag{2.12}$$

2.5 Connection devices

Material properties for connection devices at seams or membrane edges like clampings or corner plates should be taken from the respective Eurocodes, e.g. EN 1993 for steel and EN 1999 for aluminium.

2.6 Structural Elements

Material properties for beam elements should be taken from the respective Eurocodes.

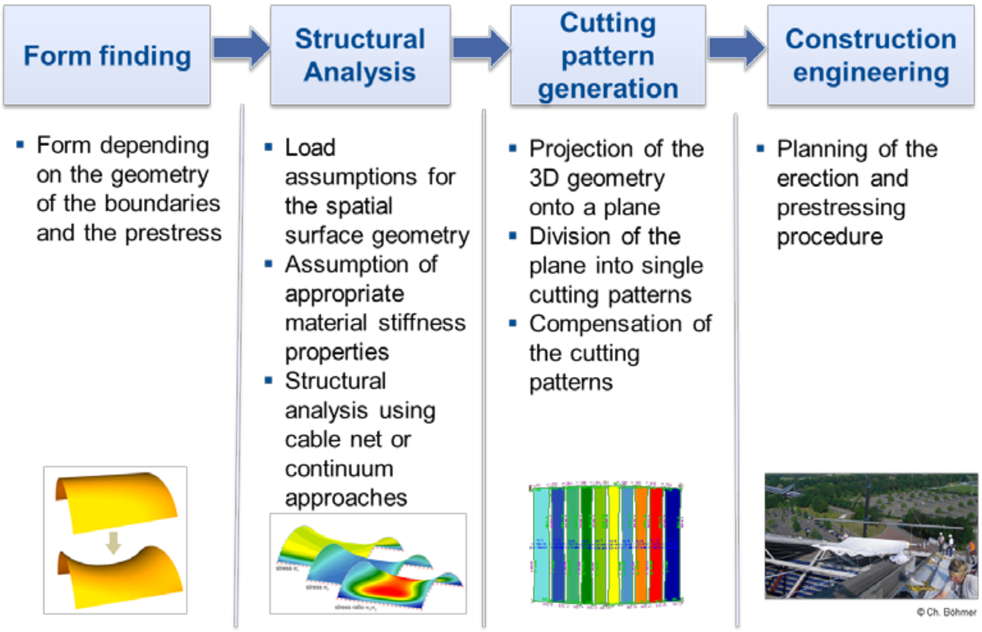
Material properties for cables can be taken from the respective European standard EN 12385 – Steel wire ropes-safety, particularly part 10: Spiral ropes for general structural applications [X126]. It is stated in that standard that in the majority spiral ropes for structural applications are produced customized for particular structural requirements. Nonetheless, typical strength values are displayed in Annex C of EN 12385-10.

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

3 Basis of design

3.1 General

The engineering of membrane structures consists of several design steps. In general these are form finding, structural analysis, cutting pattern generation and construction engineering, see Figure 3-1. Contrary to bending stiff structures the form of a tensile membrane has to be found in a first step as an equilibrium shape depending on the geometry of the boundaries and the prestress level – or rather the ratio of the prestress levels in the main structural directions. Different form finding approaches are in use up to date, see chapter 3.4. The cutting pattern generation consists of the ~~projection~~ “flattening” of the three-dimensional geometry onto a plane (the so called geometrical development), the division into single cutting patterns and the compensation. Compensation describes a reduction of the measures of the geometrically developed cutting patterns to such a value that it ensures the nominal prestress level in the membrane when it is elongated during the installation. Construction engineering has to consider possible sizes, the fabrication, transportation and erection. Cutting pattern generation and construction engineering have to ensure the predefined prestress level even at the end of the lifetime of the structure.



Form finding

- Form depending on the geometry of the boundaries and the prestress

Structural Analysis

- Load assumptions for the spatial surface geometry
- Assumption of appropriate material stiffness properties
- Structural analysis using cable net or continuum approaches

Cutting pattern generation

- Projection of the 3D geometry onto a plane
- Division of the plane into single cutting patterns
- Compensation of the cutting patterns

Construction engineering

- Planning of the erection and prestressing procedure

© Ch. Böhmer

Figure 3-1 Design steps for the design of membrane structures

The illustration of subsequent design steps in Figure 3-1 is a simplification. In fact, interactions exist between the various design steps. Because of these interactions the design procedure is actually an iterative process although frequently not performed in practice. For instance, the patterning and the compensation has an impact on the prestress level and thus on the form finding, the installation planning has in impact on the choice of the fabric direction in the structure and thus on the structural design and the cutting pattern generation, the results of the structural analysis have an impact on the choice of the prestress level and thus on the form finding etc.

The future design rules will be harmonized across Europe and will be in accordance with Eurocode rules, i.e. the general rules given in EN 1990, see Eurocode Outlooks No. 19 and 20. The following chapters discuss in detail how the basic requirements and the handling of the basic variables can be implemented in the surrounding of the Eurocode rules.

Eurocode Outlook No. 19

(1) The Eurocode should harmonize the different views on the safety concepts and residual load-bearing capacity among Europe in a consistent manner, e.g. using different classes.

Eurocode Outlook No. 20

(1*) The design of membrane structures shall be in accordance with the general rules given in EN 1990.*

3.2 Basic requirements

Tensile membranes require prestress and, moreover, the spatial shape of tensile membranes needs to be doubly curved. Both characteristics ensure that the membrane is able to carry gravitation loads as well as uplift loads (wind suction) by activating only tensile stresses while compression is avoided. The curvature can be synclastic (pneumatically prestressed by air inflation like cushions or inflated beams) or anticlastic (mechanically prestressed like saddle shaped four point sails), see Figure 1-2. The curvature radii are defined on the basis of architectural and structural requirements. The French Recommendations [X124] provide concrete proposals for a limitation of the curvature radii, see Code Review No. 5. The definition and handling of prestress is discussed in detail in chapter 3.3.

Usually, membrane structures are composed of a primary and a secondary structure. The primary structure is the supporting structure for the membrane which can be a steel, timber or concrete structure. The membrane itself is the secondary structure, carrying the external loads by tensile stresses to the primary structure.

Code Review No. 5

French recommendations [X124]: basic requirements

The shape of the textile covering membranes must be with double inverse curvature. The radii of the roofing membranes vary from one point to another, from one cutting plane to another. That is why the criterion is a global criterion.

The relationship between the chord and the deflection of the membrane, and the radius of curvature of the arc associated with the same chord and the same deflection between edges (see Figure 3-2) should be limited.

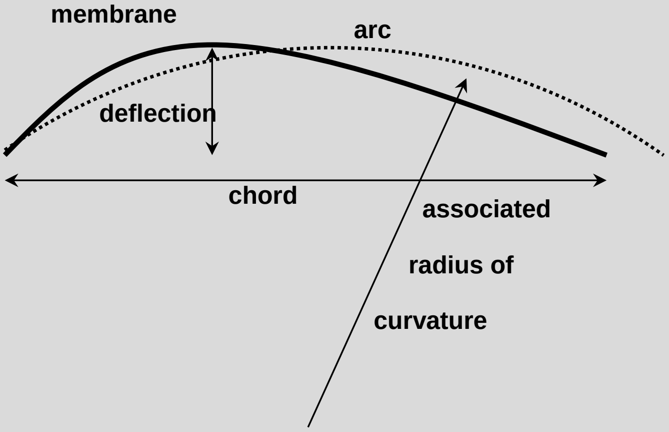


Figure 3-2 Membrane and associated arc

When there is pretensioning, the ratio between the chord and the sag of the covering membrane and the associated radius of curvature between the edges in the same plane must satisfy the following conditions:

$$\frac{c}{f} \leq 20 \text{ and } R \leq 70 \text{ m} \qquad (3.1)$$

where:		
	c	chord,
	f	sag
	R	associated radius of curvature.

Note: The first condition corresponds approximately to $R \leq 2.5c$ and $R \leq 50f$.

Form stabilizing devices such as valley cable, ridge cables or roof ridges can be used.

The use of type 1 polyester fabrics with PVC coating is allowed for covered areas less than 30 m^2, in planar projection.

The use of type 2, 3, 4 polyester fabrics with PVC coating is obligatory for covered areas greater than 30 m^2, in planar projection.

The radius of curvature of the boltropes must not exceed 25m.

The supporting structure must be stable in the absence of the covering membrane.

3.3 Actions and environmental influences

The majority of membrane structures are roofing structures and the only external actions on these structures are snow and wind loads as well as maintenance loads. For special structures like inflated beams or hybrid structures like tensairity girders or membrane restrained girders traffic loads may apply as well. The rules for actions and environmental influences are given in EN 1990, chapter 4.1. Actions to be used in design may be obtained from the relevant parts of EN 1991. For the combination of actions and partial factors of actions see Annex A to EN 1990.

The relevant parts of EN 1991 for use in design include:

- EN 1991-1-1: Densities, self-weight and imposed loads,
- EN 1991-1-2: Fire actions,
- EN 1991-1-3: Snow loads,
- EN 1991-1-4: Wind loads,
- EN 1991-1-5: Thermal actions,
- EN 1991-1-6: Actions during execution and
- EN 1991-1-7: Accidental actions.

The National Annexes may define actions for particular regional, climatic or accidental situations.

However, due to the great variety of forms for membrane structures, it is possible that loads may not accurately be defined using EN 1991. This is obvious for snow and wind loads.

Eurocode Outlook No. 21

NOTE: EN 1991-1-4 Wind loads is not appropriate for complex 3D curved shapes.

Regarding static wind loads, a basis of c_p-values for different typical structural forms can be found in the literature [FM04, Cook85, Cook90]. In [FM04] c_p-values are given for some typical structural membrane forms, e.g. for conical structures, ridge and valley structures, hypar and cantilevered canopy structures or stadia roofs.

Furthermore, Computational Fluid Dynamics (CFD) can be considered as well for accompanying analyses, e.g. for overall wind flow data. Although, the current state of research enables first applications for the design practice [Mich11, Mich14], the designer is not recommended to rely on CFD-analyses only. Another advantage of CFD is the possibility to consider dynamic amplification of the structural response to fluctuating wind loads. Particularly wide span membrane structures with small degrees of curvature and low prestress react with high vibration to a fluctuation of the wind speed. This vibration can be higher than the deformation due to the maximum static wind load.

Another well established possibility to determine static wind loads is wind tunnel testing. But the determination of the wind-induced motions of the membrane structures with small-scale wind tunnel tests is in general not possible [Mich11]. Furthermore, wind tunnel tests are generally only commercially viable for major projects.

It is planned to develop simplified general rules to incorporate in EN 1991 during the development of the Eurocode on Membrane Structures and to extend the basis of c_p-values mentioned above. Wind tunnel test are intended to be performed for that purpose. As a preliminary work for a wind tunnel test series a categorization of basic membrane forms has been conducted [Mich14] which is demonstrated in Figure 3-3.

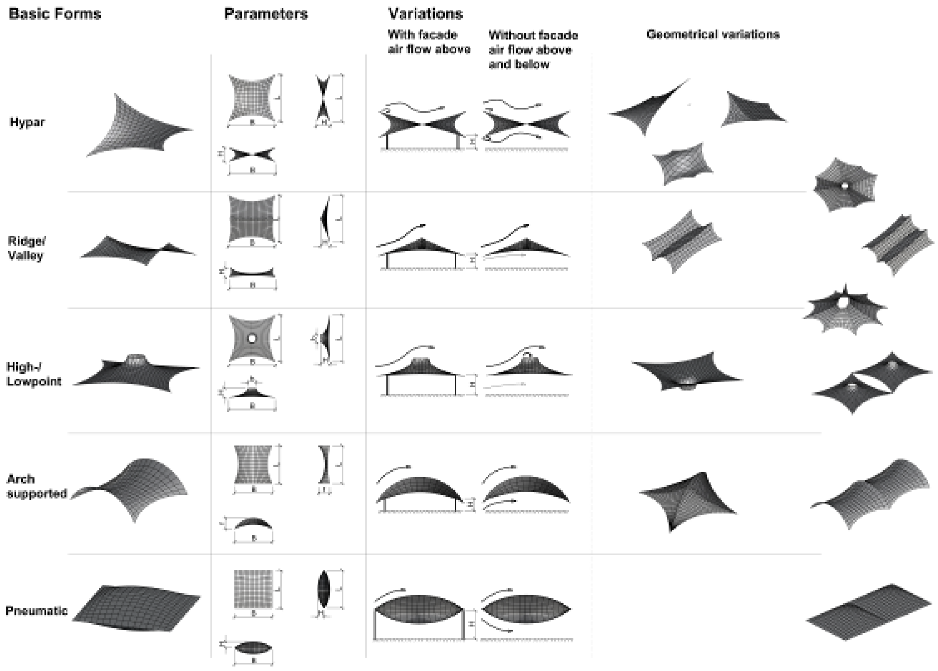


Figure 3-3 Categorization of basic membrane forms for the purpose of wind tunnel testing [Mich14]

3.4 Prestress

3.4.1 Definition and handling of prestress

The definition and handling of prestress in the design is under discussion in the CEN/TC 250/ WG5. Prestress stresses and stiffens a structural membrane at the same time. The question arises, whether prestress should be defined and handled as an action or as a stiffness property during the verification in the Ultimate Limit State (ULS) and the Serviceability Limit State (SLS). Two positions are discussed in the following. The difference of both positions is whether the handling of prestress as an action is appropriate or inappropriate in the frame of the verification of a membrane structure. Add a sentence that distinguishing between both positions is necessary because of partial safety factors

Position 1: Handling of prestress as an action is appropriate

For the purpose of the verification in the Ultimate Limit State (ULS), every impact on the structure that exposes it to a stress state is usually handled as an action. This action will be factorized with the correlated partial safety factor $\gamma_F > 1$ if an unfavourable deviation cannot be excluded for sure. For prestress this would be γ_p. In order to consider unfavourable deviations in the level of prestress after the installation of a membrane, setting $\gamma_p \geq 1$ seems to be recommendable in general. This is because a possible upwards deviation of the nominal prestress would normally lead to higher overall stresses than expected. This behaviour can be observed for mechanically as well as pneumatically prestressed structures.

The deviations might be different for different types of structures. For pneumatically prestressed structures, where normally a good control of the prestress level is enabled by pressure measurement and a changing prestress level might easily be adjusted over the whole lifetime of the structure, it might be justified to apply γ_p = 1.0. In mechanically prestressed structures usually the control of prestress is much more difficult. Also a controlled adjustment of the prestress level after the installation is difficult or completely impossible in many structures. As a result the initial prestress is frequently planned to be higher than the nominal prestress level, because the prestress is known to decrease with time due to creep, relaxation and a decline of the yarn crimp. In those cases, unfavourable upwards deviations of the prestress – and therefore the overall stress, too – could very easily be considered by setting $\gamma_p > 1.0$.

After all, in order to allow the design engineer to easily calculate the most unfavourable design stress level in the Ultimate Limit State (ULS), it seems to be appropriate to consider prestress as one more action – beside the external actions – and to handle it in the same stringent way.

The same procedure can be applied for the verification in the Serviceability Limit State (SLS), which is actually a verification of deflections in most cases. Here, an unfavourable deviation would be a downwards deviation of prestress or stiffness, respectively, leading to unfavourable greater deflections than for the nominal prestress level. Applying prestress as an action, this could be considered by applying $\gamma_p \leq 1.0$.

Independent of the verification – ULS or SLS – actual deviations of the prestress may also lead to actual deviations of the structural geometry. As a membrane form depends on the boundary geometry and the prestress level and distribution, deviations of the form would be automatically simulated during the form finding procedure when considering a possible unfavourable prestress deviation by γ_p . not true for anticlasrtic structures!!!!!

Position 2: Handling of prestress as an action is inappropriate

Applying prestress in a tensioned structure leads to an increase in the stiffness of the element, which is not the case for the more conventional materials such as concrete or steel. The effects of prestress cannot be compared in both cases.

In the following examples, the effect of prestress is presented in the cases of two colinear cables, two orthogonal cables (bi-cable), an inflatable beam, and a rectangular tensioned membrane.

Example 1: Effect of prestress on a system of two colinear cables [Lau92]

This example is voluntarily the simplest imaginable system, consisting of two identical aligned cables G_2K and KG_3, see Figure 3-4 (with the same length L, the same Young's Modulus E, and the same section area S). It is attached to the supports G_2 and G_3. Two cases are studied:

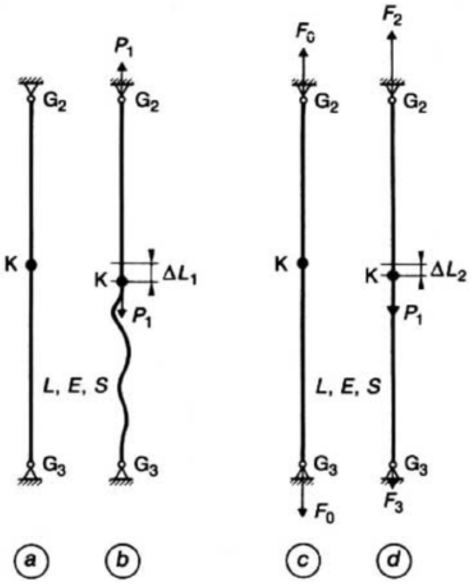


Figure 3-4 Model of the colinear cables [Lau92]

Without initial prestress

The initial tension is nil (Figure 3-4a), and a load P_1 is applied at the point K, following the direction $G_2{\cdot}G_3$. This leads to Figure 3-4b: a support action at the point $G_2{:}P_1$. The value of the tension in $G_2{\cdot}K$ is $F = P_1$. The tension in $K{\cdot}G_3$ is nil, which means that it is a totally relaxed state section (if such an element would be part of a framework, it would be likely to float or flap under the effect of a transverse stress, which is not conceivable).

The stress in G_2K is then $n = \frac{P_1}{S}$, and the elongation of G_2K (following Hooke's law):

$$\Delta L_1 = \frac{P_1 \cdot L}{E \cdot S} = \frac{P_1}{\frac{E \cdot S}{L}}, \tag{3.1}$$

where $\frac{E \cdot S}{L} = K_n$ represents what may be called the normal stiffness of the G_2K element.

With initial prestress

G_2G_3 is subjected to an initial tension F_0 (Figure 3-4c), and then the same force P_1 is applied at point K in the $G_2{\cdot}G_3$ direction. This leads to Figure3-4d: two new support actions F_2 and F_3, an elongation ΔL_2 of $G_2{\cdot}K$ and a shortening of the same value $G_2{\cdot}K$ of $K{\cdot}G_3$.

$G_2{\cdot}K$ and $K{\cdot}G_3$ are initially identical (this is valid after the application of F_0 and before the application of P_1). The increase of the tension in $G_2{\cdot}K$ equals in absolute value the reduction of the tension in $K{\cdot}G_3$ (Hooke's law), then:

$F_2 – F_0 = F_0 – F_3$ or $F_2 + F_3 = 2F_0$.

The static equilibrium leads in absolute value to $F_2 – F_3 = P_1$. It gives

$$F_2 = F_0 + \frac{P_1}{2} \text{ and } F_3 = F_0 - \frac{P_1}{2} \tag{3.2}$$

So, to ensure that $K{\cdot}G_3$ remains always in tension ($F_3 \geq 0$), despite its shortening ΔL_2, it is sufficient to have: $F_0 \geq \frac{P_1}{2}$.

If this strictly sufficient value is adopted for F, $F_0 = \frac{P_1}{2}$, one can obtain:

$F_2 = P_1$ (idem of case 1),

$F_3 = 0$ (idem of case 1).

Conclusion: The implementation of a judicious pretension in $G_2{\cdot}G_3$ in order to make it able to withstand the applied force P_1 at the point K, in the middle of $G_2{\cdot}G_3$, following the $G_2{\cdot}G_3$ direction, and avoiding the slackening of $K{\cdot}G_3$ therefore leads to, under the effect of P_1: the same reactions at G_2 and G_3 than without pretension. The elongation in K is reduced by half, because the increase of the tension in $G_2{\cdot}K$ $(P_1 - \frac{P_1}{2} = \frac{P_1}{2})$ gives:

$$\Delta L_2 = \frac{P_1}{2} \cdot \frac{L}{E \cdot S} = \frac{1}{2} \cdot \Delta L_1 \tag{3.3}$$

Note: The pretension which leads to a better use of the material than when lacking, gives the system an increased stiffness, and therefore, in principle, does not penalize dimensioning of the supports.

Example 2: Effect of prestress on a bi-cable modelling a membrane [ML93]

To illustrate the various aspects of the pretension, it is possible, with a simplified model, to study the equilibrium of a point on the surface. In the case of the negative double curvature, the model consists of two cables AB and CD respectively fixed in two "high" and two "low" points. The horizontal projection of the four points gives a quadrangle (see Figure 3-5).

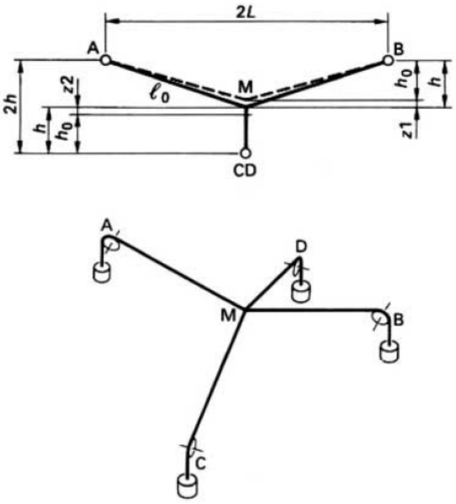


Figure 3-5 Model of the bi-cable [ML93]

For simplicity, let pose AB = CD = 2L. The length of the cables in their unstressed state is $2\ell_0$. The distance between the lines AB and CD is chosen greater than $2h_0$, where h_0 is the distance from the point M to the chord AB (or CD) corresponding to a zero tension in the cable AMB (or CMD). This same distance is $h_0 + z$ in the prestressed state, where z is the displacement of the point M. In this symmetric case, the preload consist to align the two points M of the cables halfway between the two horizontal planes: the corresponding deformation of the two cables is similar to applying a force T_2 to the upper cable and a force T_1 to the lower cable.

In both cases, it is possible to write the relation between the force applied to the node and the corresponding displacement relative to the unstressed state, which corresponds to the diagram Figure 3-6:

$$T = 2 \cdot EA \cdot \sin\alpha \frac{\sqrt{L^2 + (h_0 + z)} - \ell_0}{\ell_0} \tag{3.4}$$

where E is the Young's Modulus, A is the section area of the cable, and α is the angle between the cable and the horizontal.

This relationship introduces the terms of the second order with respect to the displacement, thus taking into account large displacements while remaining in small strains and linear elasticity.

This relationship between T and z is valid for both cables. The origin corresponds to the original undeformed geometry, where z = 0.

When no external action is applied, the static equilibrium leads of course to: $T_1 = T_2$. In this case, the displacement is z_1, which corresponds to the prestressed state (Figure 3-6).

When a vertically force F is applied downwardly, the point M common to both cables undergoes a displacement in the same direction. When the static equilibrium is reached again, the displacement of M being z_2, we have:

$$T'_1 + F = T'_2 \tag{3.5}$$

The displacement z_2 of the equilibrium point is such that the length KC on the diagram in Figure 3-6 is equal to F.

From point M representing the prestressed state ($z = z_1$), the released lower cable is represented by a symmetrical curve to the one of the upper tensioned cable relatively to a vertical line passing through M.

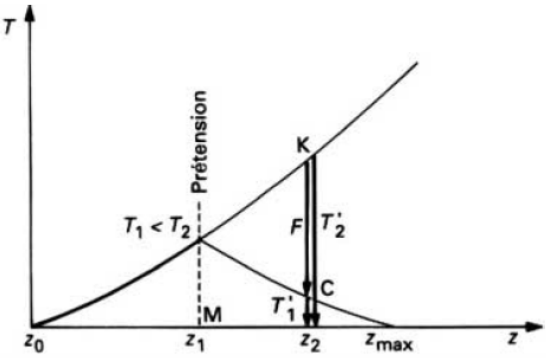


Figure 3-6 Operating diagram of the bi-cable [ML93]

As a result the equilibrium shows an increased force applied to the upper cable when the system is loaded, but the value T'_2 is lower than the sum $T_2 + F$ because T'_1 is smaller than $T_1(= T_2)$. There is therefore no addition of the effects of the pretensioned and applied loads, but combination.

The displacement of the crossing point M of the two cables is measured by the difference $z_2 – z_1$, which is less than in the abscissa z_1 when there is no pretension. The pretension therefore has a stiffening action on the membrane.

It is necessary in any case to ensure that the lower cable does not "Float", which corresponds to a tension equal to zero, so that z_2 is smaller than z_{max}, z_{max} being the abscissae of the intersection point of the curve with the z axis.

Regarding the level of pretension, a first analysis could lead to choose high values so that the displacement of the membrane is limited, regardless the climate actions characterized in our example by the force F.

But applying such a state of prestress to the membrane would stress the fabric excessively and therefore cause fatigue and premature aging of the fabric, and this only to support extreme values of actions that are seldom reached, and for a short period. It follows that the choice of the values of pretension is always a compromise between the displacements of the membrane considered as eligible, based on its shape and its use, and the fatigue imposed to the fabric. These values depend mainly on the climate action that may be applied to the membrane, but in practice values between 180 and 350 daN/m are considered.

Example 3: Effect of the prestress on inflatable beams [NTL12, LeWi05]

The point of departure to is the total Lagrangian formulation written in order to take into account the internal pressure which induces follower forces (they follow orthogonally the membrane, which is different to dead loads like the weight, which keeps the same direction). This means that the geometrical non linearity is taken into account.

Timoshenko's kinematic has to be used in the case of thin-walled structures.

After a final linearization, one obtains a set of linear equations which allows analytical formulations for the deflection. For a cantilever inflatable tubular beam:

$$\nu(x) = \frac{F}{\left(E_\ell + \frac{P}{S_0}\right) \cdot I_0} \left(\frac{\ell_0 \cdot x^2}{2} - \frac{x^3}{6} \right) + / - ?? \frac{F \cdot x}{\left(P + k \cdot G_{\ell t} \cdot S_0\right)} ?? \qquad (3.6)$$

where F is the force applied at the end of the cantilever, ℓ_0 is the length, E_l is the Young's Modulus in the longitudinal direction of the beam, I_0 is the second moment of area, S_0 is the surface of the section, G_{lt} is the shear coefficient, $P = p \cdot \pi \cdot r_0^2$ is the effect of the pressure p on the end surface of the beam (radius r_0).

In this formula, one can see that

- the relation between the load and the displacements is linear,
- the relation between the presstress effect and the displacement is non-linear and

- the effect $P = p \cdot \pi \cdot r_0^2$ of the inside pressure p of the beam reinforces explicitly the bending stiffness $\left(E_\ell + \frac{P}{S_0}\right) \cdot I_0$ and the shear stiffness $P + k \cdot G_{\ell t} \cdot S_0$.

Another interpretation is that the pressure p increases the material coefficients: E_ℓ is replaced by $E_\ell + \frac{p \cdot r_0}{2}$, and $G_{\ell t}$ is replaced by $G_{\ell t} + \frac{p \cdot r_0}{2k} = G_{\ell t} + p \cdot r_0$ because k = 0.5 in the case of a circular thin wall beam.

Example 4: Vibration of a rectangular tensioned membrane

In the case of a rectangular isotropic membrane, considering a uniform prestress, the analytical formulation for the eigenfrequency is [ch6]:

$$f = \frac{1}{2} \cdot \sqrt{\frac{T}{\rho}} \cdot \sqrt{\frac{m^2}{a^2} + \frac{n^2}{b^2}}\,, \tag{3.7}$$

where T is the linear tension, ρ is the masse/area, a and b are the width and length of the membrane, m and n are the numbering of the frequencies.

In comparison, the eigenfrequency of a beam is: $f\pi = \frac{\omega}{2\pi} = \frac{i^2}{2} \cdot \quad \cdot \sqrt{\frac{EI}{\rho \cdot S \cdot L^4}}$. (3.8)

Here also, the tension T has the same effect as the stiffness.

Conclusions

Prestress is a state of pretension before other external loads are applied, it is combined with the external loads, it reinforces the stiffnesses of the structures.

In regard of these facts, it seems inappropriate to consider the prestress in the same way as an external action.

3.4.2 Appropriate prestress levels

The prestress level is defined by the structural engineer in such a way that the structure meets the optical and structural requirements. The optical requirements are defined in cooperation with the architect and the building owner. Structural requirements are

- avoiding fluttering,
- avoiding slackening in all areas of the membrane under the design loads,
- meeting serviceability requirements such as possible deformation limits and
- avoiding of ponding.

Designers might appreciate concrete recommendations about the prestress level. Recommendations for minimum values are found in the French Recommendations [X124], see Code Review No. 6, or in the TensiNet European Design Guide for Tensile Surface Structures [FM04]. The last one proposes as a “rule of thumb” prestress levels not less than 1.3% of the short term tensile strength for PVC coated polyester fabrics and 2.5% for PTFE coated glass fibre fabrics, but not less than 2.0 kN/m for the last one. Moreover, concrete minimum values are given for PVC coated polyester fabrics depending on the material type:

- Type I: p > 0.70 kN/m,
- Type II: p > 0.90 kN/m,
- Type III: p > 1.30 kN/m,
- Type IV: p > 1.60 kN/m and

- Type V: p > 2.00 kN/m.

Code Review No. 6

French recommendations [X124]

4.1.2 Prestress

By construction, structural membranes must be submitted to an initial prestress of at least 1.5 kN/m.

Maximum prestress values are given in EN 13782 [X131] and the TensiNet European Design Guide for Tensile Surface Structures [FM04]. EN 13782 – which is intended for fabrics made of cotton and synthetic fibres – recommends for tents that the prestress should not exceed 5% of the short term tensile strength at the edge of the membrane unless tests proof the permissibility. For Glass/PTFE fabrics a maximum prestress of 6% of the short term tensile strength is recommended as a “rule of thumb” in [FM04].

The cited across-the-board proposals give rather an orientation than strict rules. There might be good reasons why lower or higher values would be used. Choosing an appropriate prestress level depends on the structure itself, whether it is permanent or temporary, strongly curved or not, whether it is restressable etc. Moreover, effects like creep, relaxation and loss of initial yarn crimp have to be considered when defining the initial prestress level in order to still ensure the nominal prestress level at the end of the structure’s lifetime.

3.5 Form finding and resulting geometric data

Basically, the form of a membrane structure is defined after completing the form finding procedure. The geometric data, i.e. the coordinates of surface nodes of the 3D equilibrium shape can be provided in a three-dimensional, spatial coordinate system. The equilibrium shape depends on the boundary conditions and the prestress state which is defined by the design engineer in order to satisfy structural safety and serviceability. The formfound geometry and the correlated prestress state are the basis for all subsequent structural analyses.

Form finding can be conducted by physical experiments and by analytical or numerical procedures. In most cases the resulting shape cannot be determined in an analytical way but using numerical methods like the force density method, dynamic relaxation or the “Updated Reference Strategy” which actually is a generalization of the force density method. Typically, numerical methods are based on variants of the finite element method. Additionally, the cutting pattern generation may influence the form finding process. [BlRa99, BLW09].

The handling of geometric data as characteristic or design values is defined in EN 1990. This chapter should be referenced in a future standard which adopts the partial factor method, see Eurocode Outlook No. 22.

Eurocode Outlook No. 22

(1) The rules for geometric data to be used for design are given in EN 1990, chapter 4.3. The geometry of the 3D shape of the membrane should also be considered, together with the size

tolerances at connection points with components from different materials.

3.6 Verification by the partial factor method

The future use of the semiprobabilistic concept using partial safety factors is envisaged. However, for nonlinear analyses – which are necessary for tensile structures due to their large deflections – the question arises whether to apply the partial factors of the action side γ_F to the action or to the effect of the action. This question is discussed in chapter 3.5.1. In fact, the decision depends on whether the structural behaviour is over- or underlinear. A sensitivity analysis – a method to check the structural behaviour – is proposed in chapter 3.5.2. If the partial safety factor of the action side γ_F is applied to the action – which means indeed that different partial factors can be applied to different actions – the designer needs orientation especially on the magnitude of the partial factor for prestress γ_p. EN 1990 delegates the definition of the magnitude of γ_p to the material Eurocodes. As a first step towards the definition, a review of partial factors for prestress for different prestressed structures is given in chapter 3.5.3.

3.6.1 Application of partial factors to the action or to the effect of the action

Performing a linear analysis, it does not matter whether the partial factors are applied to the actions (loads) or to the action effects (e.g. stresses) because superposition is applicable.

Due to the specific behaviour of membrane structures, a geometrically non-linear analysis is required. An increase of actions does not lead to a proportional increase of the action effects anymore as it is usually assumed for concrete, steel and timber structures. The nonlinear behaviour can be either underlinear or overlinear, see Fig. 3-7.

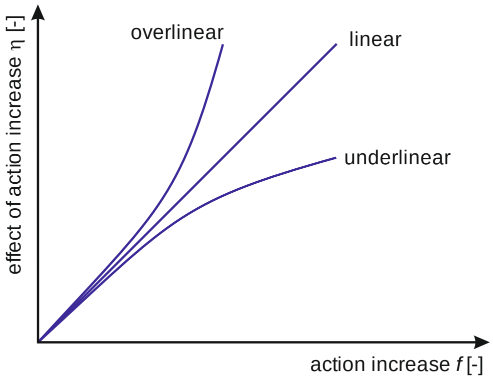


Figure 3-7 Linear as well as overlinear (category a) and underlinear (category b) behaviour of structures [USS14]

In EN 1990, 6.3.2(4) these two cases are described as given in the following Code Review No. 7.

Code Review No. 7

EN 1990:2010-12, chapter 6.3.2 (4) and (5)

For non-linear analysis (i.e. when the relationship between actions and their effects is not linear), the following simplified rules may be considered in the case of a single predominant action :

a) When the action effect increases more than the action, the partial factor γ_F should be *applied to the representative value of the action.*

b) When the action effect increases less than the action, the partial factor γ_F should be applied to the action effect of the representative value of the action.

In those cases where more refined methods are detailed in the relevant EN 1991 to EN 1999 (e.g. for prestressed structures), they should be used in preference to the above stated simplified rules.

Eventually, the simplified rules of EN 1990 mean, that

a) the several actions F in a load combination are multiplied with their corresponding partial safety factors γ_F (i.e. P,Q) before the calculation of the action effect (category (a)), or

b) the overall action effect resulting from a characteristic load (or load combination) is multiplied with one single partial factor γ_F afterwards (category (b)).

Herewith, in the category (b) procedure the possibility is lost to apply different partial safety factors for different actions. Further explanations are given in [USS14].

Other design codes state very similar rules, see Code Reviews No. 8 and 9.

Code Review No. 8

DIN 18800:, El. (725) [X122]

When structures are insensitive for load changes, e.g. soft cable structures, the partial factors on the action are decreased and the partial factors on the resistance side (that equals an application to the action effect) is increased compared to the recommended values for linear structures.

Code Review No. 9

EN 13782, chapter 7.5.1

In cases where nonlinear displacements can lead to favourable load bearing effects on specific elements, the partial factors are not to be applied to the actions but to the resistance (which equals an application to the action effects).

The application of partial factors is currently under discussion in CEN/TC250 WG5, see e.g. [PWB13, USS14]. In the following two positions are presented. Following position 1 it is recommended to generally apply the partial factor γ_F to the effect of an action (or to the effect of a combination of actions) in case the structural behaviour is underlinear. Position 2 recommends to apply the partial factor γ_F to the actions for nonlinear structural behaviour in the same way as for linear structural behaviour. Only in case the behaviour is underlinear *and* the structure is loaded with one single predominant action γ_F may be applied to the action effect following this position. The last mentioned case corresponds to the condition in chapter 6.3.2 (4) in EN 1990, see above.

Position 1: Apply partial factors γ_F to the action effect in case of underlinear structural behaviour

For underlinear structural behaviour (category b) the application of partial factors to the actions (prestress or external loads) would lead to only minor changes of the action effects (membrane stresses). To ensure a safe sided design approach, the partial factor is recommended by EN 1990 to directly be applied to the action effect.

Cable and membrane structures show in many cases an underlinear behaviour, i.e. they fit to category b. To ensure this for each individual structure, this should be checked for the locations of the relevant design stresses. This could be done by a sensitivity analysis [USS14].

For membrane structures the load carrying characteristics can change if the actions are factored rather than the effects of the action. Load sharing between warp and fill could change if the actions are factored [Gib13].

Furthermore, the stress state of the complete structure is closely correlated to the shape of the structural membrane [PWB13]. The impact of membrane deformation is high because the deformation of tensile membranes is comparably large. Factoring the loads has therefore a great impact on the deformation and shape of the membrane, which may have a great influence not only on the stress state of the membrane itself but also on the primary structure. In [PWB13] an example regarding the connection of a membrane to the primary structure is given, see Fig. 3-8. In the deformed state of the membrane the excentricity Δx, which strongly influences the moment $M_{steelworks}$, is significantly higher.

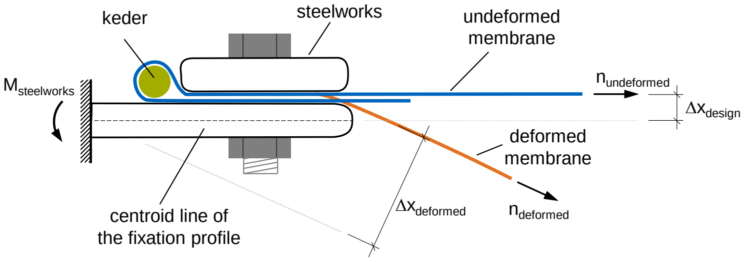


Figure 3-8 Example of the impact of membrane deformation on excentricities of the primary structure [PWB13]

For all these reasons, applying the partial factor to the action effect is a safe-sided and easy to handle approach that does not modify the load carrying characteristics of the model in an unfavourable way.

Position 2: Usually apply partial factors γ_F to the action in case of nonlinear structural behaviour, but in case of underlinear behaviour and one single predominant action one single partial factor γ_F may be applied to the action effect

French comment about the application of partial safety factors γ_F to the action effect:

- The application of the rule 6.3.2 b) of EN 1990 may lead to inconsistencies. It is possible to meet membranes which are intrinsically category b (EN 1990, 6.3.2 b), but which are supported by a deformable structure reporting to category a (EN 1990, 6.3.2 a). One has to study the case in an overall calculation and obviously under ULS combinations if one does not want to find oneself in insecurity.
- The clauses 6.3.2 (4) a) and b) of Eurocode 0 are explicitly simplified rules. As such, they cannot possibly emerge as unique rules in a particular Eurocode. The possibility of increasing the actions and not their effects must necessarily remain an open possibility (at least).
- The fact of increasing the effects of actions and not the actions themselves is obviously a conservative approach; but this practice equals to regress to a concept of Allowable Stresses. The obvious and demonstrated shortcomings of this concept are precisely at the origin of Limit States which gradually replaced the old practices since the 1970s in France with BAEL *(Béton Armé aux États Limites),* BPEL (*Béton Précontraint aux États-Limites)* and in Europe with the Eurocodes.
- From this point of view, the calculation 6.3.2 b) allowed in Eurocode 0 is against the current basic guidelines of Eurocodes: it is unacceptable to prescribe this calculation as a single solution.

The French position concerning the ‘Application of partial safety factors to the action or to the effect of the action’ is explained hereafter:

- Due to the specificity of the membrane, a non linear analysis shall be conducted.
- Refined rules: In accordance with EN1990 6.3.2(5), the partial factors γ_F have to be applied to the actions, and the non linear analysis has to be carried out.
- Simplified rules: In accordance with EN 1990 6.3.2 (4), simplified rules may be applied, considering category b, the partial factors γ_F should be applied to the action effects, in the case of a single predominant action.

Position 2 refers to stated rules in France. Code Review No. 10 gives reference to how non-linear membrane structures are handled referring to the French Recommendations [X124], chapter 5, particularly considering the application of partial factors and the combination of actions.

Code Review No. 10

French recommendations [X124]
5.1 Behaviour assumptions
This is the mechanical and geometrical non-linearity, and the displacement of the supporting structure.

5.1.1 Mechanical non-linearity
The strain and strength calculation is exempt from the consideration of the material non-linearity. Use is made of the elastic moduli defined according to Annex A.

The material non-linearity has to be taken into account for the derivation of the cutting patterns.

5.1.2 Geometrical non-linearity
The calculation must take into account the geometrical non-linearity of the membrane.

5.1.3 Displacements of the supporting structure
The displacements of the supporting structure can be neglected in the calculation of the membrane when they do not disturb the behaviour.
Otherwise, the displacement of the supporting structure should be included in the calculation.
(...)

5.4 Combinations of actions
Generally metal, wood and concrete structures have a linear behavior. For membranes it is required to take into account the geometric non-linear behaviour. To do this, combinations are to be performed on actions and not on the effects.

5.4.1 Initial shape
The initial shape of the membrane is given by the calculation of its state of equilibrium under pre-stress and self-weight.
Accordingly, the initial form of the membranes and the initial equilibrium state shall be calculated as the combination of the prestress and the self-weight, without coefficients.

5.4.2 Deformations
Combinations under normal and extreme loads applicable to the calculation of deformations of the membranes under the action of climatic overloads are not weighted.

5.4.3 Stresses
Combinations of actions for the calculation of the stresses in the membrane under the climatic loadings are given for the material-specific rule of the load-bearing structure, while adapting the weighting to the peculiarities for the calculation of the membranes.

The specific rules for different materials of load-bearing structures are stated in the "Document

Technique Unifié" (DTU) and give combinations of actions for structures made from different materials:

- *for steel structures: "Constructions Métalliques" (CM), published in 1966, sections 1.21 and 1.23 of CM 66 (DTU P 22701) rules,*
- *for aluminum structures: "Aluminium" (AL), published in 1976, sections 3.32 and 3.34 of AL 76 (DTU P 22702) rules,*
- *for timber structures: "Constructions Bois" (CB), published in 1971, sections 1.21 and 1.22 of CB 71 (DTU P 21701) rules.*

The sections 1.21 and 1.23 of the CM 66 cover the methods of justification on the principle of weighting load coefficients. Paragraph 1.21 gives the value of the weighting factors for the following cases:

- *work under SLS, taking into account the permanent loads, variable loads and effects of temperature (1.211),*
- *erection (1.212) and*
- *exceptional circumstances (1.213).*

Section 1.23 describes the verification methods.

In the AL 76 there are similar texts for aluminum to those for steel constructions. Paragraph 3.32 gives the values of the weighing factors, and paragraph 3.34 provides the methods of verification.

For wood, in the same spirit, 1.21 corresponds to the expressions of the total weighted stresses involved in the calculations, and 1.22 to the verification in the cases of permanent loads, operating loads and climate loads.

The latest version of the Recommendations has been released in 2007. Since then, Eurocodes have gradually replaced those documents. These texts are completely replaced today in France by the corresponding Eurocodes:

- *EN 1993 (Steel),*
- *EN 1999 (Aluminium) and*
- *EN 1995 (Timber)*

In the stated combinations for the stress verification the weighting factor to be applied for the self-weight of the membrane, the prestress, and the flat-rate minimum load is kept to 1. The provision of the "flat-rate minimum load" applies when no existing climate stress is defined (in the absence of a regulatory weight). The combination concerning the replacement of a membrane element must involve the prestress of the neighbouring elements and self-weight without weighting.

The clause of EN 1990 6.3.2(5) opens the possibility to use more refined rules when the simplified rules given in EN 1990 6.3.2(4) should not or cannot to be applied. Fortunately, the basic rules of EN 1990 are actually more refined rules. In fact, the partial safety factor γ_F is composed of the two components γ_f and γ_{Sd}: $\gamma_F = \gamma_f \cdot \gamma_{Sd}$. The factor γ_f accounts for an unfavourable deviation of the representative load, γ_{Sd} accounts for uncertainties in modelling the actions and effects of actions. Herewith, the design value of an action effect E_d can be written as (see EN 1990)

$$E_d = \gamma_{Sd} \cdot E\left\{\gamma_{f,i} \cdot \psi \cdot F_{k,i}; a_d\right\}. \tag{3.9}$$

where E is the effect of the actions and E_d is the design value of E, ψ a factor for the combination of actions, F is the action and a_d symbolizes the geometric measures on which the effect of the actions depend. Herewith, partial factors are partly applied to actions and partly to the effect of the action:

- the actions F are multiplied with γ_f before the structural analysis is conducted and
- the effect of the actions E is multiplied with γ_{Sd} after the structural analysis is conducted.

More detailed explanations can be found in [USS14]. It may be favourable to apply the more refined approach for nonlinear membrane structures but this will be decided by the ongoing discussion in CEN/TC250 WG5.

Eurocode Outlook No. 23

(1) *The Eurocode should give rules about the procedure of partial factor application for membrane structures.*

(2) *The Eurocode should define the partial factor levels for each of the procedures. In case that the partial factor is applied to the action effect, only one partial factor can be possibly applied to the overall action effect.*

3.6.2 Sensitivity analysis

To check, whether a specific structure or a certain part of a structure fits to category (a) or (b) – see chapter above –, a sensitivity analysis should be performed. One way for conducting a sensitivity analysis with minimal effort is to compare stress values calculated from the characteristic load with stress values calculated from loads factorized with an arbitrary load increase factor [Sti14a, USS14]. The arbitrary load increase factor may be symbolised by f. With the two stress results, a dimensionless stress increase factor η can be determined to

$$\eta = \frac{\sigma(f \cdot F_k)}{\sigma(F_k)} \tag{3.10}$$

where f is the arbitrary load increase factor,

F_k is a characteristic load or a characteristic load combination,

$\sigma(f \cdot F_k)$ is the stress at a specific location and direction of the membrane due to $f \cdot F_k$,

$\sigma(F_k)$ is the characteristic stress at a specific location and direction of the membrane due to F_k.

Repeating the structural analysis and concurrently altering the load increase factor f several times (at least three times) would enable to plot a f-η-graph as shown in Figure 3-7, from which the structural behaviour can be obtained. Of course, for a practical sensitivity analysis it is not necessary to alter the load increase factor and repeat the structural analysis. The structural behaviour can already be realized with a one step analysis.

To simplify the interpretation of the results, the stiffening factor e is introduced as follows:

$$e = \frac{\sigma(f \cdot F_k)}{f \cdot \sigma(F_k)} = \frac{\eta}{f} \tag{3.11}$$

Herewith, it can be easily seen, that if $e = 1$ the system behaves linear, if $e < 1$ the system behaves underlinear (category (b)) and if $e > 1$ the system behaves overlinear (category (a)), see Table 3-1.

Table 3-1 Verification of the structural behaviour

Stiffening factor e	Structural behaviour
1	linear
<1	underlinear
>1	overlinear

3.6.3 Partial factors for prestress

In case the partial factor for actions γ_F is applied directly to the several single actions, different partial factors for each action can be possibly used. As the partial factor for prestress γ_p is supposed to be defined in the material Eurocodes, it will be one task of the code development to define the partial factor level. The following review of codes that deal with prestressed structures gives summary considering the Ultimate Limit State verification for different construction materials.

Code Review No. 11

EN 1990:2010-12

Prestress is considered as a permanent action, caused by controlled loads and/or controlled deformations. The characteristic value of the prestress at a given moment may be an upper value or a lower value. For Ultimate Limit States, a mean value can be used. Values are considered to be given in the material Eurocodes EN 1992 to EN 1996 and EN 1999, see 4.1.2(6), 6.5.3(3) and Annex A2, EN 1990. Combinations of actions that include prestressing forces should be dealt with as detailed in EN 1992 to EN 1999, see annex A1, EN 1990 (application for buildings, A1.2.1(4)).

Annex A2, EN 1990 (Bridges) allows (A2.3.1), if in those Eurocodes no partial factors are given, that these factors may be established in the National Annex or for the individual project. They depend on the prestress type, the classification of the prestress as a direct or indirect action, the type of the structural analysis, the favourable or unfavourable influence of prestress and the leading or accompanying character of prestressing in the combination.

Code Review No. 12

DIN EN 1990/NA/A1:2012-08

In table NA.A2.1 of the German National Annex of EN 1990 (annex A2: bridges) numbers for the partial safety factors $\gamma_{P,unfav}$ *(unfavourable) und* $\gamma_{P,fav}$ *(favourable) are given for the ultimate limit state STR (design of structural members) of concrete structures. The factors differ depending on the use of linear proceeding with uncracked cross-sections (*$\gamma_P = 1.0$*) or non-linear proceeding (*$\gamma_{P,unfav} = 1.2$, $\gamma_{P,fav} = 0.8$ *). These partial safety factors are directly taken from DIN EN 1992-1-1 including DIN EN 1992-1-1/NA.*

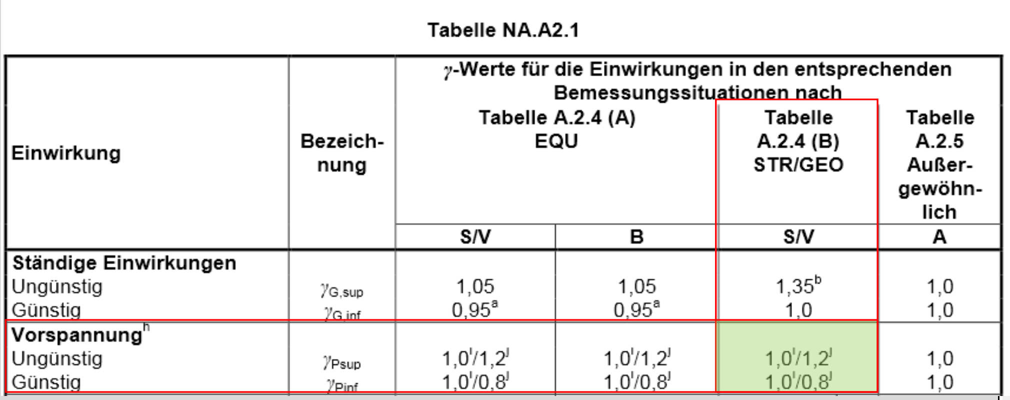


Tabelle NA.A2.1

Einwirkung	Bezeichnung	γ-Werte für die Einwirkungen in den entsprechenden Bemessungssituationen nach Tabelle A.2.4 (A) EQU		Tabelle A.2.4 (B) STR/GEO	Tabelle A.2.5 Außergewöhnlich
		S/V	B	S/V	A
Ständige Einwirkungen					
Ungünstig	$\gamma_{G,sup}$	1,05	1,05	1,35[b]	1,0
Günstig	$\gamma_{G,inf}$	0,95[a]	0,95[a]	1,0	1,0
Vorspannung[h]					
Ungünstig	γ_{Psup}	1,0[i]/1,2[j]	1,0[i]/1,2[j]	1,0[i]/1,2[j]	1,0
Günstig	γ_{Pinf}	1,0[i]/0,8[j]	1,0[i]/0,8[j]	1,0[i]/0,8[j]	1,0

Relevant design situations:

STR Internal failure or excessive deformation of the structure or structural members, where the strength of the construction materials of the structure governs

S/V persistent/transient design situations

Relevant notes:

i linear procedure with uncracked sections

j Nonlinear procedure

Figure 3-9: Extract from table NA.A2.1 from the German National Annex to EN 1990, the relevant values are marked by the red boxes.

Code Review No. 13

EN 1992-1-1:2011-01 and German National Annex DIN EN 1992-1-1/NA

In a prestressed concrete construction the prestress generally has a favourable effect. As a result the partial safety factor $\gamma_{P,fav}$ *should be used principally for the Ultimate Limit State. The recommended value is 1.0.*

For a nonlinear second order Ultimate Limit State verification of an externally prestressed member, where an increased prestress level may have unfavourable effects, normally $\gamma_{P,unfav}$ *has to be used. The recommended value is* $\gamma_{P,unfav} = 1.3$*. Differing from the EN-recommendation, the German National Annex gives* $\gamma_{P,unfav} = 1.2$ *and* $\gamma_{P,fav} = 0.83$*, demanding to apply the most unfavourable value of the both at a time.*

Code Review No. 14

DIN 18204-1:2007-05

In Chapter 9.3.1.2 the partial safety factor for prestress is given for a membrane under tension in warp or weft direction as $\gamma_F^P = 1.35$.

Code Review No. 15

DIN 4134:1983-02

In the German code for air halls single action effects are superposed in three different predefined load combinations. Every action effect has its own partial factor in each combination. Action effects from prestress are generally increased by partial factors greater than 1. In the "winter *storm"-load combination as well as for the "summer thunderstorm"-combination prestress is increased by 1.1 and for the "continuous load"-combination, which contains only the permanent actions dead load and prestress, the latter one is increased by 1.3.*

Code Review No. 16

<u>EN 1993-1-11:2010-12</u>

EN 1993-1-11 "Eurocode 3: Design of steel structures – Part 1-11: Design of structures with tension components" defines in chapter 2.2(2), that gravitation loads G and prestress P are to be applied as one single uniform action "G+P". The relevant partial safety factor γ_{Gi} *is given in chapter 5. Therefore the permanent influence "G+P" has to be multiplied for the Ultimate Limit State verification with* $\gamma_{G,sup}$*, if the action effect due to permanent or variable loads are both unfavourable. Does the permanent load "G+P" have favourable effects, as a rule it has to be multiplied by the factor* $\gamma_{G,inf}$*. The national annex may define to what extent a uniform partial safety factor* γ_G *may be applied to "G+P" outside the scope of EN 1993.*

EN 1990:2010-12 defines for the factors $\gamma_{G,sup} = 1.35$ *and* $\gamma_{G,inf} = 1.0$ *for the Ultimate Limit State STR (design of structural members).*

Furthermore, for structures with an underlinear structural response (this case is named category b in EN 1990, 6.3.2(4)) the partial factor for actions may be slipped to the resistance side of the verification equation. That means that several single actions cannot be handled differently anymore. In the given verification format for that case (7.2) $\gamma_F = 1.5$ *is implicitly applied to the overall action effect resulting from permanent and variable loads.*

Code Review No. 17

<u>DIN 18800 in combination with Application rule for DIN 18800</u>

The former German code for the design of steel structures DIN 18800 [X122] – which also incorporated rules for cable structures – proposed in conjunction with the Application Rules for this code [X123] a partial factor for the permanent load prestress of $\gamma_P = 1.35$ *– in case the considered action effect is unfavourably increased by the prestress [X122]. In case of a favourable impact on the considered action effect,* $\gamma_P = 1.0$ *should be considered.*

The partial factor $\gamma_P = 1.35$ *could be reduced by 0.9 in case of a controlled introduced prestress, which leads to* $\gamma_P = 1.215$*, which is typically rounded to* $\gamma_P = 1.25$ *[X123].*

Code Review No. 18

<u>DIN EN 13782</u>

In chapter 7.5.2 of DIN EN 13782 [X131] the prestress is defined as an action. In combination of actions the prestress shall be taken into account with an adequate partial safety factor. A certain partial safety factor is not given.

Basically EN 1990 specifies, that the partial safety factors γ_P are defined in the relevant material specific Eurocodes. In EN 1990 itself, no numbers for γ_P are given. Only the partial safety factors γ_G are given, numerical values for γ_P can be found in the national annexes. The numerical values given in Annex A2 (bridges) in the German National Annex of EN 1990 are directly taken from EN 1992-1-1 and DIN EN 1992-1-1/NA, respectively. Therefore, they only refer to prestress in prestressed concrete bridges. For those design situations where an increased prestress level has unfavourable effects an

$\gamma_{P,unfav}$ has to be used, with values for $\gamma_{P,unfav} > 1$: 1.2 in the German National Annex, 1.3 in EN 1992.

Values for γ_P for tensile and membrane structures are given in DIN 18204, DIN 4134 and EN 1993-1-11. DIN 18204 (tents) sets $\gamma_P = 1.35$. In the German air hall code DIN 4134 prestress is generally increased by partial factors in predefined load combinations between 1.1 and 1.3.

EN 1993-1-11 defines to summarize all permanent actions (dead load G and prestress P) together in one single action “G+P” and apply the partial factor γ_G to it. That means in effect, that EN 1993-1-11 indirectly prescribes $\gamma_P = \gamma_G = 1.35$ in case of unfavourable effects of prestress in the Ultimate Limit State.

EN 13782 also handles prestress as an action within a combination of actions, but gives no concrete value for γ_P.

In general, the code review reveals that for the use in the Ultimate Limit State verification all above investigated codes consider an unfavourable variation of the nominal prestress level by multiplying the prestress with a partial factor $\gamma_P > 1$.

In contrast the French Recommendations apply a partial factor $\gamma_P = 1$ for prestress in membrane structures, see Code Review No. 19.

Code Review No. 19

French Recommendation

5.4.3 Stresses
In these combinations, the weighting factor to be applied for the self-weight of the membrane, the pretension, and the flat-rate minimum load is kept to 1.

In the French design practice for membrane structures, prestress is not weighted and the nominal prestress level is introduced to the design model, see also below.

It is one of the main tasks of the work of CEN/TC250 WG5 to harmonize the different views on how to apply partial factors on nonlinear membrane structures and how to handle prestress within this procedure.

Eurocode Outlook No. 24

(1) *The Eurocode should harmonize the different views of existing codes related to membrane structures.*

(2) *As one possibility for the ULS: the unfavourable possibility of increased prestress compared to the nominal prestress state could be taken into account by a partial safety factor* $\gamma_p > 1$.

(3) *As one possibility for the SLS, where prestress can be interpreted as stiffness, the nominal prestress state or the unfavourable possibility of decreased prestress compared to the nominal prestress state could be taken into account by a partial safety factor* $\gamma_p \leq 1$.

3.6.4 Combinations of actions

The combination of actions will be adjusted to the basic rules on EN 1990. Due to the nonlinearity of membrane structures, preassigned load combinations have to be established and analyzed in order to identify the decisive ones for the verification of the structure. Regarding the application of partial safety factors within these combinations see the explanations in the chapters above.

Eurocode Outlook No. 25

(1) *Combinations of actions should consider the rules of EN 1990, i.e. differ between leading and accompanying actions. To identify the decisive combination within a nonlinear analysis, preassigned load combinations have to be established.*

(2) *The preassigned combinations of external actions should be applied to the initial equilibrium state of the membrane in the considered limit state.*

3.6.5 Design resistance

According to EN 1990 the design resistance R_d is derived from the characteristic resistance R_k by dividing these values by a partial safety factor for the resistance γ_M. The partial factor γ_M itself is derived by multiplication of the two factors γ_{Rd} and γ_m. These consider:

- γ_{Rd}: model uncertainty in structural resistance,
- γ_m: uncertainty in material properties.

This concept covers uncertainties that result directly from the engineering work: uncertainties resulting from material testing, idealization and modelling of structural properties. CEN/TC 250/ WG5 aims to adopt this concept for the future standard.

The resistance R should be given as characteristic values, which is a specified fractile. Usually, a 5% fractile is applied for the characteristic value of the resistance (EN 1990, chapter 4.2). This covers natural deviations of material properties which every material is subjected to.

Additional to this concept to cover uncertainties and natural deviations, structural membranes experience actual strength reductions due to environmental influences, long term loads, UV-rays etc. Moreover, statistical influences (the greater the membrane surface the greater the probability of a material weakness) and the quality of execution – especially at welds – may have an impact on the design strength. These influences could be considered separately by strength reduction factors. The concept of strength reduction factors is presented in detail in chapter 6.

4 Sustainability(Durability??)

4.1 General

The French recommendations "Recommandations françaises pour la conception, la confection et la mise en œuvre des ouvrages permanents de couverture textile aux éditions SEBTP2" [X124] consider sustainability aspects of PES/PVC-fabrics. These recommendations have been published 1997 and revised in 2007. Annex B of the French recommendations is entitled "Sustainability of Polyester PVC Textile Fabrics". Herewith, formulated recommendations are already given. Due to the fact that they are the only one which exist so far, they are presented in the following neither in a Code Review nor in a Eurocode Outlook. The future rules for sustainability will be derived on the basis of these French recommendations.

4.2 Notions of sustainability of textile fabrics

The concept of sustainability of fabrics is related to the appreciation of the evolution of their damage in service. Sustainability of textile coatings depends primarily on the nature and on the thickness of the coating.

The list of alteration agents, alone or in combination, affecting the evolution of features is as follows:

- humidity,
- UV radiation,
- the chemical aggressiveness of the surrounding environment,
- the state of tension,
- heat,
- etc.

Each of these alteration agents does not result in significant damages separately, but a fairly realistic assessment of the damages resulting from the combination of alteration agents can be obtained, for example:

- moisture under UV radiation and
- chemical attack combined with heat.

Furthermore, the sensitivity of the coating is increased by the presence of a constant or variable mechanical tension due to the following reasons:

- reduction of the thickness of the coating material in proportion of thickness above the yarns intersection,
- increase of vulnerability to chemical attack when the skin is stretched and
- stress gradient in the thickness of the coating in relation to the variations of the weaving relief.

4.3 Principles for conducting a sustainability analysis

4.3.1 General

In the frame of French investigations [X124], which are described by Annex B of the French recommendations [X124], some observations *in situ* were used to compare the loss of performance of fabrics which have been submitted to the same combinations of alteration agents under static and dynamic loads. The results of these comparisons were used to calibrate the estimation of the damage with degradations observed in known environments. A series of three adjustment coefficients was evaluated to correlate the test results with observed cases. In future, the accuracy of the adjustment coefficients has to be improved progressively with the consideration of additional real cases or tests.

4.3.2 Fields of application of the adjustment coefficients

The adjustment coefficients cover the following areas:

- unstressed fabric,
- fabric under different levels of prestress and
- fabrics with different areas of stresses,

the whole being submitted to the same groups of alteration agents by type of fabric.

4.3.3 Families of mechanical stresses

The damage of a fabric submitted to the effect of a combination of alteration agents is the addition of the damage when the fabric is submitted to a static tension and the damage when it is submitted to a dynamic tension.

The static tension corresponds to the state of pre-stress after crimp, and the dynamic tension is due to wind after filtering of the tension due to the prestress.

4.3.4 Mechanical stresses on the fabric

CECM 52 curve was used to describe wind fluctuations for a 50-years period. Starting from a ranking in number of cycles, this curve describes the decrement of extreme wind to no wind. These statistics were used to calculate decrements operating with the analysis of periods less than 50 years in respect of an occurrence of 2% per year in the case of a cinquantenal wind.

In the case of extreme wind, some parts of the fabric are submitted to their stronger tensions such that:

Maximal Tension = Minimum Strength Guaranteed / Safety Coefficient.

The maximal tension is the addition of:

- firstly the static tension or pretension,
- secondly, the extent of dynamic tension due to wind loads

The damage produced by the static tension takes into account adjustment coefficients covering the areas of zero tension and of the pretension.

The damage produced by the dynamic tension takes into account the weighting of its adjustment coefficient so to be exploitable when using Miner summation (sum of the partial fatigue damage associated with different areas of tension of the fabric in service).

4.3.5 Interpretation of the results of the estimation sustainability program

The example shown in Figure 1 relates to a Polyester/PVC-fabric. The coating thickness at the cross-point was 350 μ. There were no antifouling on the coating. The climate, humidity, UV radiation and heat reflect the average value on the metropolitan French territory.

The first case is shown by the diagram Po = 1.1. The pollution level is between "zero" and "weak."

The second case is represented by the diagram Po = 1.4. The scale of pollution is between 'strong' and 'severe'. These are automotive exhaust gas on a high traffic road.

The diagrams show that the sustainability of fabrics is governed by:

- the safety factor Cs related to fracture and
- the level of pretension.

It can be noted that the strong pretensions are harmful to sustainability, as well as pretensions less than 1% of the rupture. In this last case, the increase of safety coefficient brings no more improvement because the filter of the variations of the dynamic stresses is no longer ensured by the pretension.

In addition, destructive floating occurs under the effects of wind. The diagrams presented here do not take into account the phenomenon of floating.

When the level of pretension increases, an attenuation of the dynamic damage occurs. On the contrary, the static damage evolves much faster in the wrong direction.

In general, it can be found that diagrams Po = 1.1 and Po = 1.4 are each tangent to a curve. This curve defines an area within which all states of the fabric can be represented in the analysis of damage.

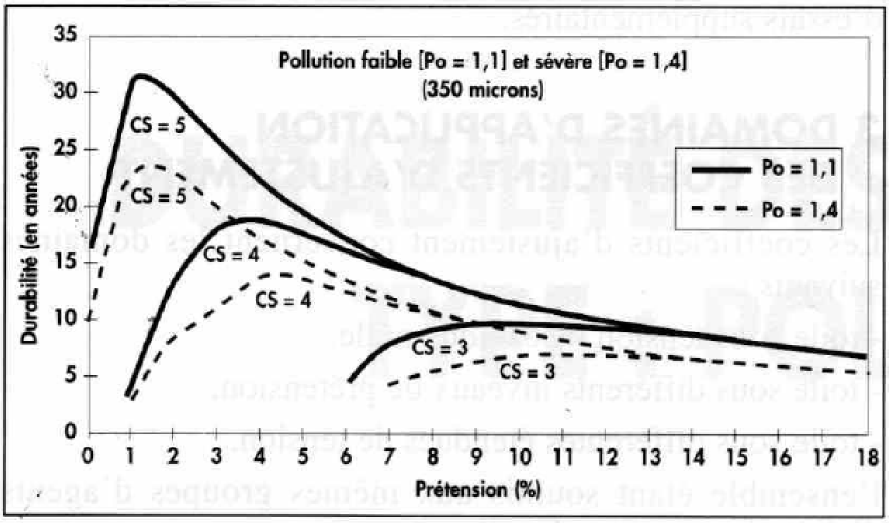


Figure 4-1 Sustainability-pretension-diagram considering low pollution (Po = 1.1) and severe pollution (Po = 1.4) for a PES/PVS-fabric [X124]

5 Basis of structural analysis

5.1 General

First of all, the preliminary step and the basis for all structural analysis in the field of tensile membrane structures is form finding. The equilibrium form depends on the defined prestress state and the boundary conditions. It can be found by physical experiments on the one hand or analytical or numerical methods on the other hand. Physical experiments have been the popular method in the beginning of engineering membrane structures before appropriate mathematical procedures have been established. They have been largely replaced by the latter ones today. Analytical methods are precise but only practical for comparable simple forms. Thus, the normal case in todays design practice is to apply numerical methods like the Force Density Method, Dynamic Relaxation or the Finite Element Method. These were described already in chapter 3.

The purpose of structural analysis is to establish the distribution of either internal forces and moments, or stresses, strains, and displacements, over the whole or part of the structure. Therefore, a structural model is established that sufficiently models the material behaviour and overall structural behaviour. Usually numerical methods are applied and the membrane is modelled as a 2-dimensional continuum or cable net within a 3-dimensional structural model. For further details see chapter 5.4. The supporting primary structure – stiff beam elements or cables – can be integrated in the model or idealised by appropriate bearings. Normally it is appropriate to model stiff beam elements as undisplaceable bearings. Comparable flexible boundaries can be modelled with elastic or spring elements. General requirements are specified in Eurocode Outlook No. 26.

Eurocode Outlook No. 26

(1)P The purpose of structural analysis is to establish the distribution of either internal forces and moments, or stresses, strains and, displacements, over the whole or part of the structure. Additional local analysis shall be carried out where necessary.

(2)P Analysis shall be based upon calculation models of the structure that are appropriate for the limit state under consideration.

NOTE "Appropriate" here means models of the structure that are capable of predicting stresses, strains, and displacements to a sufficient level of accuracy. The term "sufficient" relates to the mechanics and mathematics described in the calculation model and may require the use of a modelling partial factor.

(3)P For each relevant limit state verification, a calculation model of the structure shall be set up from:

- *an appropriate description of the structure, the materials from which it is made, and the relevant environment of its location;*
  NOTE: "Appropriate" here means a model of sufficient detail – see NOTE above for (2)P.
- *the behaviour of the whole or parts of the structure, related to the relevant limit states;*
- *the actions and how they are imposed.*

(4)P The general arrangement of the structure and the interaction and connection of its various parts shall be such as to ensure stability and robustness during construction and use.

(5)P The method used for the analysis shall be consistent with the design assumptions.

(6)P Analyses shall be carried out using idealisations of both the geometry and the behaviour of the structure. The idealisations selected shall be appropriate to the problem being considered.

NOTE "Appropriate" here means that the idealisation represents the geometry and behaviour of the structure – see NOTE above for (2)P.

(7)P The effect of geometry and properties of the structure on its behaviour at each stage of construction shall be considered in the design.

(8)P The model for the calculation of internal forces in the structure or in part of the structure shall take into account the displacements and rotations of the connections.

(9) The calculation model and basic assumptions should reflect the structural behaviour at the relevant limit state with appropriate accuracy and reflect the anticipated type of behaviour of the materials and connections. – see NOTE above for (2)P.

5.2 Structural modelling for analysis

The numerical membrane surface shall be form found using suitable form generation tools. This form shall be in equilibrium and can be verified with suitable analyses to confirm that both acceptable levels of stress and geometry exist.

Moreover, the structural model based on a suitable form found geometry should consider the following basic assumptions:

- The behaviour of a membrane structure is non-linear.
- The principal behaviour of a membrane structure is to resist loading through both changes in shape and material stresses.
- Changes in the shape of the membrane are normally significant and introduce geometric non-linearity (also known as stress-stiffening) into the physical behaviour of the structure.
- The materials normally used in the realisation of membrane structures have complex behaviour and may introduce material non-linearity into the physical behaviour of the structure.

In detail this means for the modelling of the membrane itself that the membrane should be modelled to cope with the physical requirements. That applies for example to the modelling of slack elements and anisotropic material properties considering individual material constants and the material orientation. Large strains may be necessary to be considered if the material may undergo large plastic deformations (foils).

Seam lines may be introduced to reflect the additional stiffness and strength that is generated in the fabric surface seams. The modelling of these seam lines shall reflect an acceptable patterning layout that will be used as the basis for the production of the final cutting patterns. The stiffness of these lines shall be determined from the proposed seam width and overall material properties.

Where the membrane connections provide significant additional stiffness or would have an impact upon the load carrying characteristics of the membrane surface, appropriate elements shall be included in the model. This should include all perimeter connection points as well as internal connections that might be required to transfer loads between membrane fields or into other structural elements. The support fixities should represent the intended connection designs and all relevant degrees of freedom restrained.

Supporting cables or webbing shall be included using appropriate elements. These elements shall allow differential tensions to be developed where full friction can be generated between the membrane and the element or to be frictionless where no friction exists. For intermediate cases where slip can occur, the worst case may be checked or the detail modelled as a slip surface with a suitable coefficient of friction. Friction and slip may appear in cable pockets which is one possibility to attach a membrane to an edge cable, see chapter 8.

Load assumptions are described in chapter 3.3. Because of the nonlinearity all load cases have to be applied to the structural model as predefined load combinations.

Eurocode Outlook No. 27

(1) *The numerical membrane surface shall be form found using suitable form generation tools to determine a shape of equilibirum. The form found state shall be verified with suitable analyses to confirm that acceptable levels of stress and geometry exist.*

(2) *Modelling of the structure should include all elements (membrane/seams/connection/cables) that have a significant effect upon the membrane surface.*

(3) *All loadcases are to be applied to the form found model to accurately reflect the determined loads.*

All load combinations should be applied as separate loadcases.

For all ponding analyses the additional load of any resulting pond should be added to the basic applied load. This process should be continued until a stable loading regime has been generated.

5.3 Global analysis

The effects of the deformed geometry of the primary (supporting) structure should be included by either inclusion of the support structure within the analyses or imposing support deflections within the analyses, as mentioned above. This leads to more accurate analysis results. The deformation of the supporting structure may be disregarded under special circumstances. For instance, as a safe sided approach a flexible frame of a plane membrane façade element may reasonably be disregarded for the verification in the Ultimate Limit State, because the flexibility of the frame results in smaller membrane stresses compared with an infinite stiff frame. In opposite, the deformation of the supporting structure shall be included in those cases where the deformation of the supporting structure significantly leads to an increase of the membrane stresses.

The stiffness of the membrane and the stiffness of the supporting structure may affect each other and the membrane can have a stabilizing effect on the supporting structure, e.g. an arch can be laterally stabilized by the adjacent membrane. This may be taken into account but it has to be ensured that in cases where the membrane might be removed or in case of collapse of the membrane the stability of the supporting structure is guaranteed.

Eurocode Outlook No. 28

(1) *Effects of deformed geometry of the structure*

The effects of the deformed geometry of the supporting structure shall be considered if they increase the action effects significantly or modify significantly the structural behaviour.

(2) *Integrated analyses*

When the supporting structure is integrated in the analysis, the membrane might have a stabilising effect on the supporting structure. This effect can be taken into account. When the membrane may be removed the integrity of the remaining structures must be ensured.

5.4 Methods of analysis

A continuum approach enables to consider not only tensile stiffness (i.e. “Young’s moduli” in the main anisotropic directions) but also transverse strains by using a stiffness parameter equivalent to Poisson’s ratio. This is not (directly) possible by modelling the membrane as a cable net. The same applies for shear stiffness which cannot be modelled in a conventional cable net model. However, specialized cable net software may be able to model Poisson’s ratio and shear modulus. In this case the cable net model is appropriate for every structural membrane analysis. If the shear modulus and/or transverse strain behaviour of the membrane material is negligible small, a simple cable net model can be applied neglecting shear and/or transverse strain effects.

Because great deflections are a main characteristic of tensile structures like membranes and cables, geometrical nonlinear analysis is required for these types of structures. In contrast, up to now, material nonlinearity is considered in such a way that the material models in the structural analysis take into account only the tension stiffness. Furthermore, the models consider that the material has no compression stiffness. The material model can be described by a bilinear stress-strain-diagram, see Figure 5-1.

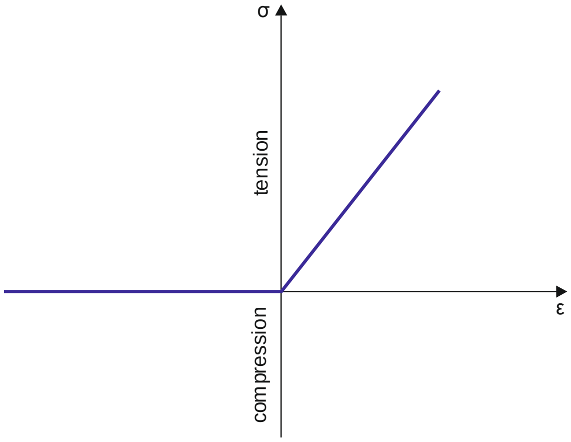


Figure 5-1 Bilinear material behaviour usually considered by up-to-date software that uses continuous membrane elements

Up to date, the actual inelastic and highly nonlinear material behaviour of membrane materials as described in chapter 2 is simplified as linear elastic material under tension loads. But a simple nonlinear material description has been developed in the recent past [GaLu09] which has already been implemented in commercial software. This model considers a changing tensile stiffness for changing load ratios warp:weft, see also explanations in chapter 2. Furthermore, sophisticated material descriptions are currently under development, e.g. hyperelastic constitutive laws [SBN14, Col14], macro-mechanical approaches [Ball07, IBG13] or neural networks [BGB13].

Eurocode Outlook No. 29

(1) The analysis of membrane structures shall reflect all relevant mechanical effects in the real structure. Normally it should be based on a continuum mechanical approach.

(2) Geometric non-linearity shall be included in the structural model.

(3) Material non-linearity may be included in the structural model.

Consideration must be given to the effect of membrane and pure tension elements, which *"go slack" when attaining a state of zero tension. The consequences for the structural and material integrity must be considered.*

(4) Elastic global analysis

Elastic analysis should be based upon the assumption that the stress-strain behaviour of the material is linear (small strains), whatever the stress level is.

Internal forces and moments may be calculated according to elastic global analysis even if the resistance of a cross section is based upon its plastic resistance.

Elastic global analysis shall be used for cross sections for which the resistance is limited by local buckling.

(5) Non-linear material global analysis

A non-linear material may be used for a more detailed modelling of non-elastic materials.

5.5 Pneumatic structures

5.5.1 General

This chapter gives an overview on special issues for pneumatic structures. Three types of pneumatic structures are widely known and used:

- air halls which have been popular throughout the last decades,
- cushions which are widely used today with ETFE-structures and
- inflatable beams which are used for temporary buildings like buildings after disaster, temporary bridges, temporary social events or storage units. [TSC13]

Moreover "tensairity" beams can be mentioned here but could be categorized as a type of inflatable beams. "Tensairity" combines an inflatable tube with attached cables at the outer surface where the function of the tube is to stabilize the cables and the latter ones are the actual structural elements.

Low pressure and high pressure structures can be distinguished. Air halls and cushions are pressurized with approximately 0.1 kN/m^2 to 1.0 kN/m^2, whereas inflatable beams need high pressures of about 20 kN/m^2 up to 700 kN/m^2. Figure 5-2 shows examples of low pressure pneumatic structures and Figure 5-3 shows examples of high pressure pneumatic structures using inflatable beams.

Air hall, The Netherlands   Botanic Garden, Aarhus, Denmark

Figure 5-2 Low pressure pneumatic structures [© CENO Membrane Technology GmbH]

(a) Inflatable frames (b) Inflatable buildings

(c) Inflatable mast during testing

Figure 5-3 High pressure pneumatic structures using inflatable beams [© J.-C. Thomas]

Air halls are well covered by the German standard DIN 4134 [X120] and are therefore not further examined here. In the following chapters basics for the structural analysis of cushions and inflatable beams are exposed. The latter chapter summarizes some of the research being undertaken at the laboratory GeM, Faculty of Science and Technology at the University of Nantes, France.

5.5.2 The analysis of cushions

5.5.2.1 General

The upper and lower layer of a cushion is prestessed due to the inner pressure of the cushion, see Figure 5-4. Under short term loading, the supporting air system cannot react that fast. For this reason the inner pressure is increasing if the volume becomes smaller and is decreasing if the volume becomes bigger. The superposing of full inner pressure with the wind load would lead to unrealistic high membrane stresses. To analyse this effect, the ideal gas law has to be applied:

$$p \cdot V = n \cdot R_m \cdot T \qquad (5.1)$$

with

p	absolute pressure,
V	volume,
T	temperature in [°K],
n	amount of substances,
R_m	gas constant.

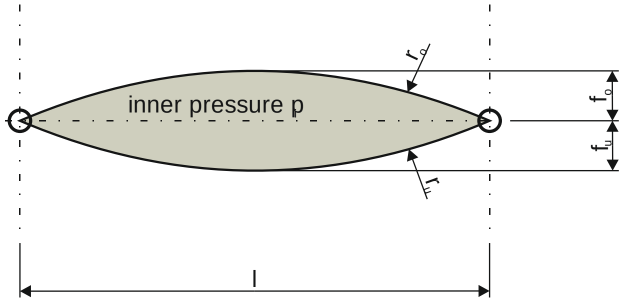


Figure 5-4 Section of a two layer cushion with inner pressure p_i

If the amount of substances is kept constant one gets the following law:

$$\frac{p \cdot V}{T} = \text{constant} \; .$$

If the temperature and the amount of substances is kept constant, one gets the Boyle-Marriot law:

$$p \cdot V = \text{constant} \; .$$

Under short term loading and reduction of the volume, the inner pressure is increasing. If the volume is extended, the inner pressure is decreasing. Consequently the Boyle-Marriot law is to be applied in the analysis. In an iterative process the inner pressure needs to be recalculated with the actual volume:

$$p_2 = p_1 \cdot \frac{V_1}{V_2} = \text{constant} \; .$$

This is illustrated in Figure 5-5 where the initial volume of a pneumatic body under inner pressure is deformed by an external load F.

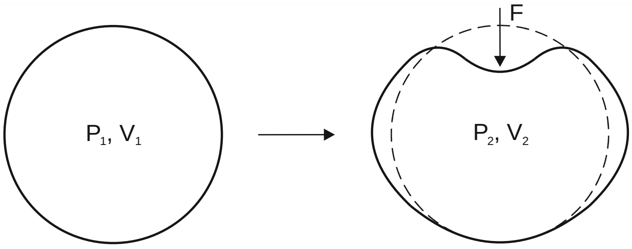


Figure 5-5 Initial configuration of a pneumatic body under inner pressure and deformed configuration due to the load F

5.5.2.2 Simplified method

Oftentimes the external (short term) loads – wind suction and wind pressure – are more than twice as great as the inner pressure of the cushion. In these cases a simplified method can be applied avoiding the iterative loading. The evidence of properness of the simplified method is shown in the next chapter by means of a numerical example.

Wind suction is pulling the upper layer of a cushion to the outside and tends to increase the volume. As the air cannot be pumped in as quickly by the air supporting system, the inner pressure (relative value) is reduced to zero. The upper layer is then carrying the wind suction only, and the lower layer is completely slack, see Figure 5-6.

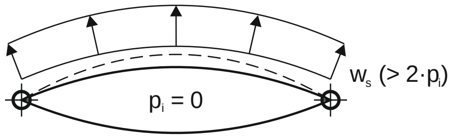


Figure 5-6 Two layer cushion under wind suction

Wind pressure is pressing the upper layer of a cushion to the inside until an equilibrium of wind pressure and inner pressure is reached. As soon as the prestress of the upper layer is fully compensated, the inner pressure is equal to the wind pressure. The lower layer is then carrying the wind pressure only, and the upper layer is completely slack, see Figure 5-7.

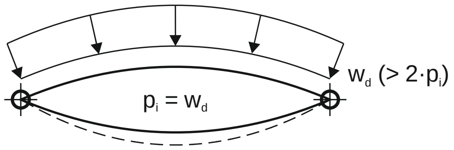


Figure 5-7 Two layer cushion under wind pressure

Under **snow load** the load increase is very slow, and the air can exhaust from the cushion. Therefore in case of snow, the inner pressure needs to be set to a value higher than the snow load. This loading situation is illustrated in Figure 5-8.

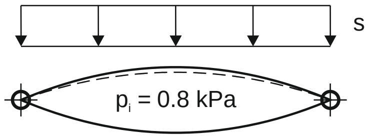


Figure 5-8 Two layer cushion under snow load

5.5.2.3 Validation analysis

The following numerical example demonstrates that the simplified method may be applied in usual cases specified above. A comparing analysis is performed on a simple two layer cushion, see Figure 5-9. The cushion is 7.5 m long, 4 m wide and has a sag of 80 cm on either side. The nominal inner pressure is pi = 400 Pa. Wind is applied in increments of 0.05 kN/m^2 up to a final load of 1.3 kN/m^2 within 26 load steps (load cases).

Three cases are analysed:

- case 1: the nominal inner pressure is kept unchanged while the wind load is applied stepwise,
- case 2: the inner pressure is set to zero when the wind load is applied (as explained above under “Simplified method”),

- case 3: the inner pressure is iteratively adjusted according to Boyle-Marriot's law (as explained above under "General").

The analyses are carried out for the loading situations "wind suction" and "wind pressure".

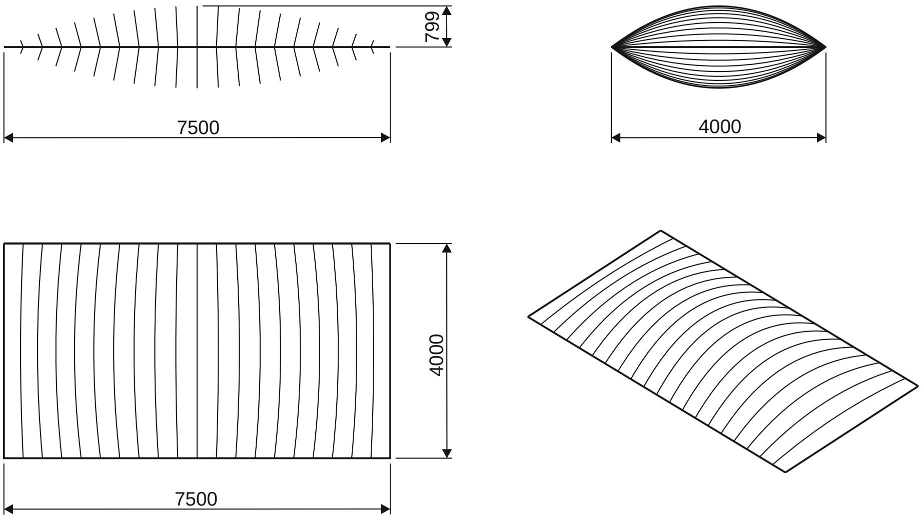


Figure 5-9 Numerical model of the exemplary two layer cushion for the numerical example

The results for the loading situation "wind suction" are illustrated in Figure 5-10. The diagram shows the resulting membrane stress Sx in the upper layer for all 26 incremental load cases. The thin red line marks the increasing wind load during these load steps. The thick red line illustrates the membrane stress for case 1 where the inner pressure of pi = 400 Pa is kept constants throughout the iteration. As explained at the beginning this assumption leads to unrealistic high membrane stresses – due to the inertia of the air supporting system. Case two (thick blue path) where the inner pressure is simplified assumed to be (approximately) zero leads to a considerable smaller membrane stress. This result can be validated with the "precise" model (case three, green path) where the inner pressure is iteratively adjusted during the loading procedure according to Boyle-Marriot's law. The comparison shows that for the analysis taking into account the law of Boyle-Marriot, the inner pressure is reduced under wind suction (purple path) and that the inner pressure becomes (approximately) zero for a wind suction that is twice the initial inner pressure. This happens in load case 16. From load case 18 on both models – simplified and "precise" – behave the same. As the design wind load is often more than twice the inner pressure, it is appropriate to apply in these cases the simplified method.

Figure 5-11 gives the results for the loading situation "wind pressure". Here only case 3 is examined, i.e. the application of Boyle-Marriot's law. The analysis shows that the inner pressure (purple path) is increasing with the wind pressure (red path – now negative because of the changed direction compared to the wind suction). Once the wind pressure has reached a value of twice the inner pressure the inner pressure equals the wind pressure: $p_i = w_d$. From this point on, the increase of the inner pressure is similar to the increase of the wind pressure so that the equality $p_i = w_d$ remains finally the same. As mentioned before, the design wind load is often more than twice the inner pressure, so it is appropriate to apply in these cases the simplified method.

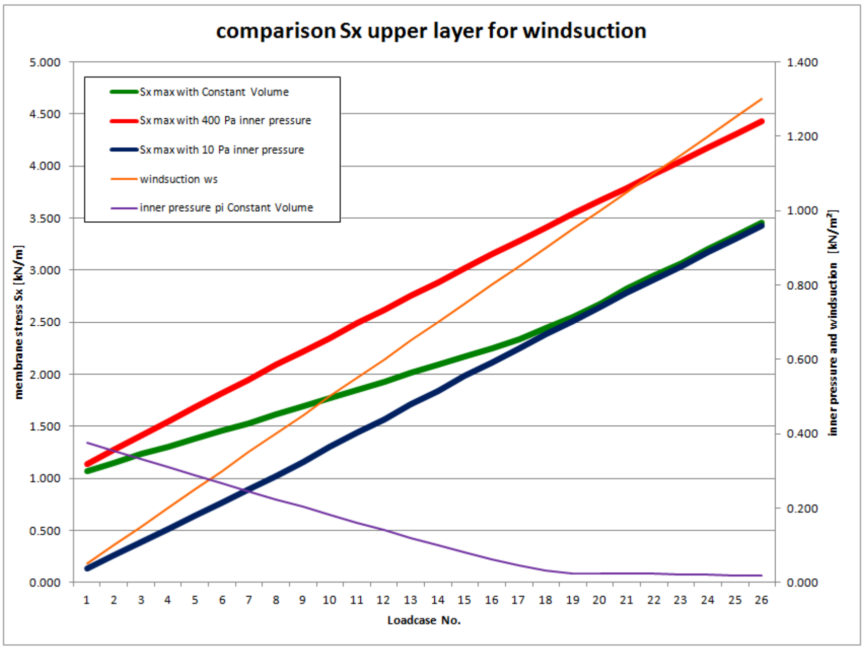


Figure 5-10 Resulting membrane stress S_x in the upper layer under wind suction for the three examined cases

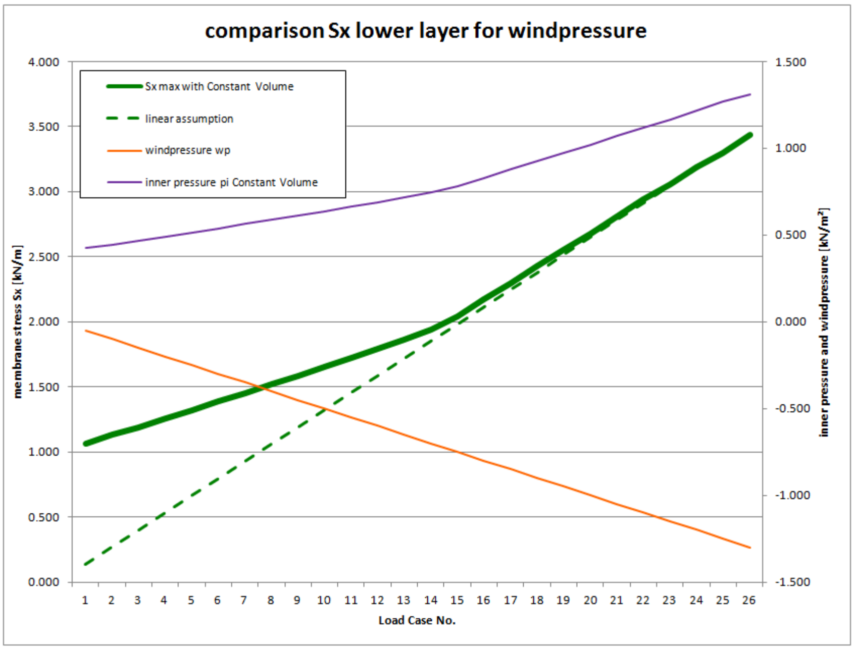
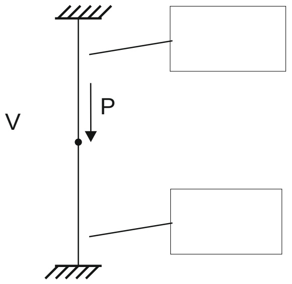


Figure 5-11 Resulting membrane stress S_x in the lower layer under wind pressure

The effect that one structural element goes slack and the other element carries all the load can be shown with a cable analogy as well, see Figure 5-12 and also Figure 3-4. A cable with two elements is prestressed with V and loaded in the middle, i.e. between the two elements, with a single force P. When the force equals 2P the full load is carried by the upper half of the cable while in the lower half the prestress is decreased to zero. The inflated cushion behaves the same like a prestressed cable where the applied force is transmitted to both structural elements (layers) up to the moment when the prestress on one of the elements becomes zero.



$P = V \longrightarrow S_1 = 1.5 \cdot V \qquad S_2 = 0.5 \cdot V$

$P = 2 \cdot V \longrightarrow S_1 = 2 \cdot V \qquad S_2 = 0$

Figure 5-12 A cable structure with two elements and a single force applied in the middle

5.5.2.4 Non-uniform loading

If non uniform wind loads are applied to a cushion, the area with the higher wind load is deflecting more, see Figure 5-13. The resulting deformations lead to only small changes of the volume and hence the wind load has low impact on the inner pressure. It could be seen from Figure 5-10 that a configuration with unchanged inner pressure results in high membrane stress. This situation of only small changes of the volume is even worse if there are areas with wind pressure and areas with wind suction at the same time.

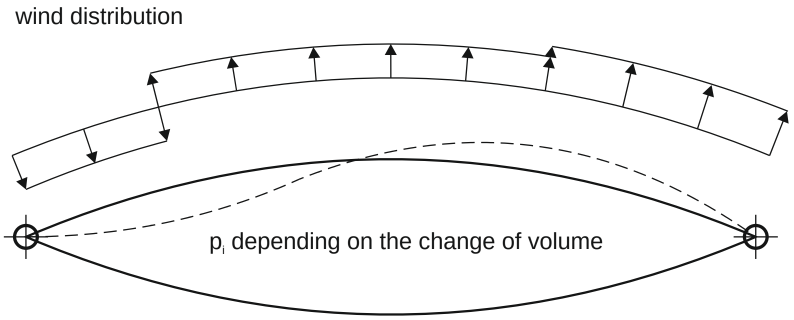


Figure 5-13 A two layer cushion with a non-uniform wind load distribution

The behaviour of large cushions – where a non-uniform load distribution has probably to be considered in the analysis – can be improved with chambers in the cushion. In the analysis these chambers need to be taken as separate volumes with the condition $p_i \cdot V_i$ = constant. A simplified approach as shown in Figure 5-14 might be possible under certain conditions, but it is recommended to analyse this configuration with the law of Boyle-Marriot.

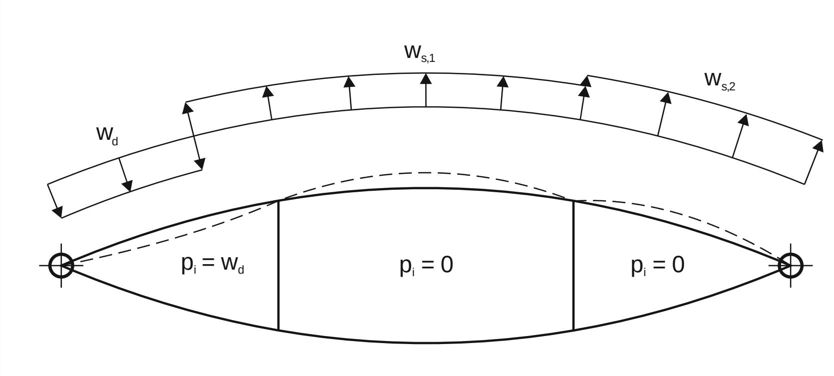


Figure 5-14 Separation of the cushion into three chambers in order to improve the behaviour under a non-uniform wind load distribution

5.5.3 The analysis of inflatable beams

5.5.3.1 General

Three states of an inflated beam are clearly identified in Figure 5-15. The natural state corresponds to the beam with an internal pressure near zero. The initial state corresponds to the simply pressurized beam, and the actual state occurs after the application of external loadings. The initial radius R and the initial length L are used in order to calculate the bending behaviour between the initial state and the actual state with strength of material formulae. The formulas presented here are valid for the bending of inflatable beams, so for the transition between the initial state and the actual state.

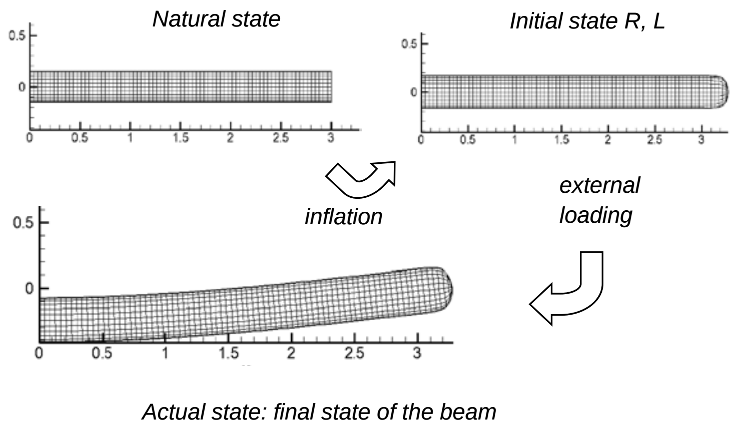


Figure 5-15 The three states for an inflated beam

In the case of inflatable beams, the usual deformation Navier-Bernoulli assumptions used in "classic" strength of materials for the study of solid beams in flexure are not valid. The thickness of the wall is thin and the beam is sensitive to shear. Furthermore, it is necessary to write the static equilibrium in the deformed configuration to properly account the effect of the pressure on the walls which generates follower forces. Then, use is made of the total Lagrangian formulation, following the hypothesis of Timoshenko for the kinematics of the beam since the straight section does not remain orthogonal to the neutral fibre, see Figure 5-16.

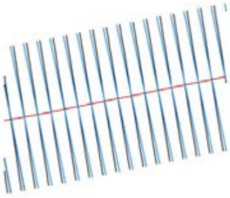


Figure 5-16 Timoshenko's kinematic: straight section and neutral fiber of a beam

After a final linearization, one obtains a set of linear equations which allow to get analytical formulations for the deflections. Initially, the theory was written for isotropic materials [LeWi05]. The formulas presented here are their adaptation to orthotropic materials [NTL12, Ngu13].

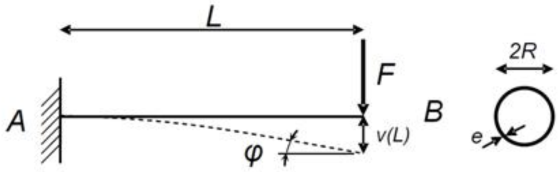
The specific behavior of the coated fabrics is particularly complex to model. This approach takes into account the orthotropic behavior of the fabrics (one remains in the linear elastic range). It limits the modeling of materials with Young's and shear modules, omitting the sensitivities to other parameters. It makes possible for engineers to model the structure by choosing the most influential parameters: the follower force due to the pressure, the external load, the material properties and the geometrical dimensions.

By definition, the inflatable tubes have a three-dimensional cylindrical shape. The tubes are made from strips of fabric. The main directions of the fabric correspond to the axes of symmetry of the tube, see Figure 5-17. Here l is the longitudinal direction, and t is the transversal direction.

Figure 5-17 Schematic sectional view of an inflatable tube

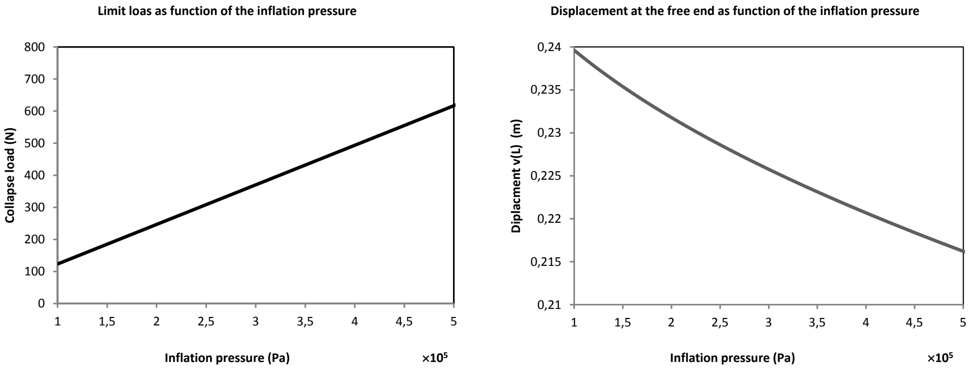
Behaviour of an inflatable tube

In the following a cantilever inflatable beam like illustrated in Figure 5-18 is analyzed. In the results, the pressure appears explicitly. It is then possible to design the structures taking into account the fact that the maximum loads beared by the beams (collapse loads) are proportional to the pressure (see Figure 5-19(a)) and that the deflection under flexural loading decreases nonlinearly with the inflation pressure (Figure 5-19(b)).



R = 0.1 m, L = 2 m, E_ℓ = 300,000 Pam, $G_{\ell t}$ = 20,000 Pam, k = 0.5, F = 80 N

Figure 5-18 A cantilever inflated beam



(a) (b)

Figure 5-19 Limit loads and displacements at the free end of a cantilever as functions of the inflation pressure

Eigenfrequencies

The dynamic analysis of inflatables tubes allows to get the eigenfrequencies of the tube [TJW06]. They also depend on the pressure.

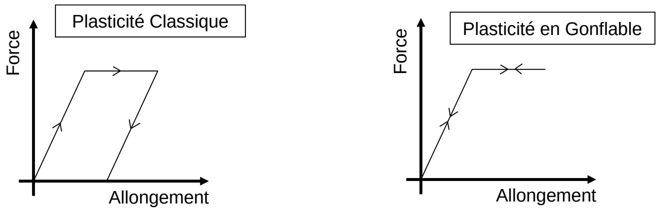
Limit loads

The limit load is achieved when the structure is no more resistant to the load. For this value, the isostatic or hyperstatic structure becomes a mechanism, and no longer resists. The estimate of the limit loads of the structures is based on an analogy with the limit analysis in plasticity [TCW08]. The limit momentum for the tubes is

$$M_{limit} = \frac{p \cdot \pi^2 \cdot R^3}{4} . \qquad (5.2)$$

Note: Inflatable structures are unique in that under certain circumstances they are able to refind their original form after a load greater than the limit load.

"When an inflatable tube or panel is loaded in bending under an increasing load, there is a deformation of the structure and appearance of a wrinkle, propagation of this wrinkle on the walls, and finally collapse of the structure. If there is a discharge following the same path, the structure returns closely to its original configuration, depending on the effects of the deferred deformation. Thus, it is possible to fabricate structures that withstand loads under specified conditions of use provided in the design, which will admit a ruin in exceptional conditions of stress, and gets back to its initial shape when return to normal operating conditions", see Figure 5-20 [Tho02].



(a) (b)

Figure 5-20 Diagrams showing the difference of the force-elongation-behavior of “classical plasticity”

(a) and the plasticity behaviour of inflatables (b)

In the following sections formulas are presented for the analysis of inflated tubular beams. Therefore, notation is used as given hereafter:

e	Fabric thickness [m],
E_ℓ	Longitudinal Modulus of longitudinal elasticity [Pa,m],
f	Line force [N/m],
F	Point force [N],
F_ℓ	Limit load [N],
E_t	Modulus of transverse elasticity [Pa,m],
$G_{\ell t}$	Shear modulus of the membrane [Pa,m],
I	Second moment [m^4],
k	Shear coefficient of shear force (k = 0.5 for a thick tube),
L	Characteristic lengths of the beam [m],
p	Inflation pressure [Pa],
$\theta(x)$	Rotation of the cross section [rad],
$\varphi(x)$	Slope [rad],
R	Radius of the inflatable tube [m],
S	Area of the straight section [m^2],
$v(x)$	Deflection of the beam [m].

In the case of a circular tube, the second moment is $I = \frac{\pi}{4}\left(R^4 - (R-e)^4\right) \approx \pi \cdot R^3 \cdot e$ and the surface of the section is $S = 2 \cdot \pi \cdot R \cdot e$. Since these terms are multiplied by E_ℓ and $G_{\ell t}$ in the stiffness, this gives: $EI = \pi \cdot R^3 \cdot E \cdot e$ and $GS = 2 \cdot \pi \cdot R \cdot G \cdot e$. In the case of fabric, the moduli are in fact products of the moduli with the thickness. So, to be coherent, the second moment and the surface of the section are

$$I = \pi \cdot R^3 \text{ and} \tag{5.3}$$

$$S = 2 \cdot \pi \cdot R\,. \tag{5.4}$$

In the following, all the formulations are given for the cantilever beam. The main formulas for sizing structures are given for other configurations: deflection, slope and limit load. They also are valuable in the case of an isotropic material. One has just to replace E_ℓ by the Young's modulus E, and $G_{\ell t}$ by the shear coefficient G.

5.5.3.2 Cantilever beam

Cantilever beam, point load

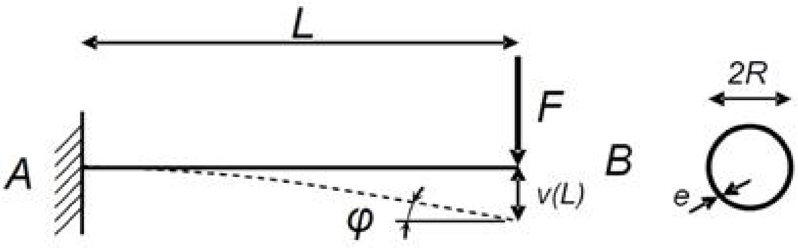


Figure 5-21 A cantilever inflated beam with a point load at the free end

Deflection and maximum displacement at the cantilever free end:

$$
\begin{aligned}
v(x) &= -\frac{F}{\left(E_\ell I + \frac{pI}{S}\right)}\left(\frac{Lx^2}{2} - \frac{x^3}{6}\right) - \frac{F}{p + kG_{\ell t}S}x \\
&= -\frac{F}{\left(E_\ell + \frac{pR}{2}\right)I}\left(\frac{Lx^2}{2} - \frac{x^3}{6}\right) - \frac{F}{\pi R\left(pR + 2kG_{\ell t}\right)}x
\end{aligned}
\tag{5.5}
$$

$$
v(L) = -\frac{F}{3\left(E_\ell + \frac{pR}{2}\right)I}L^3 - \frac{F}{\pi R\left(pR + 2kG_{\ell t}\right)}L \tag{5.6}
$$

Rotation of the section at x and at the free end:

$$
\theta(x) = -\frac{F}{\left(E_\ell + \frac{pR}{2}\right)I}\left(\frac{x^2}{2} - Lx\right) \tag{5.7}
$$

$$
\theta(L) = -\frac{F}{2\left(E_\ell + \frac{pR}{2}\right)I}L^2 \tag{5.8}
$$

Slope at x and slope at the free end:

$$
\varphi(x) = \frac{dv(x)}{dx} = \frac{F}{\left(E_\ell + \frac{pR}{2}\right)I}\left(\frac{x^2}{2} - Lx\right) - \frac{F}{\pi R\left(pR + 2kG_{\ell t}\right)} \tag{5.9}
$$

$$
\varphi(L) = -\frac{F}{2\left(E_\ell + \frac{pR}{2}\right)I}L^2 - \frac{F}{\pi R\left(pR + 2kG_{\ell t}\right)} \tag{5.10}
$$

Collapse load:

$$
F_\ell = \frac{p\pi^2 R^3}{4L} \tag{5.11}
$$

Notes:

- The inside pressure appears in the shear stiffness $P + kGS = \pi R(pR + 2kG)$ and in the bending stiffness $\left(E_\ell + \frac{pR}{2}\right)I$ via $P = p\pi R^2$ (p: pressure). This prestress comes from the pressure that acts on the walls. The prestress explicitly reinforces the stiffness of the beam.
- The rotations of the sections are different to the slope. This is due to the shear behaviour.

Cantilever beam, distributed load

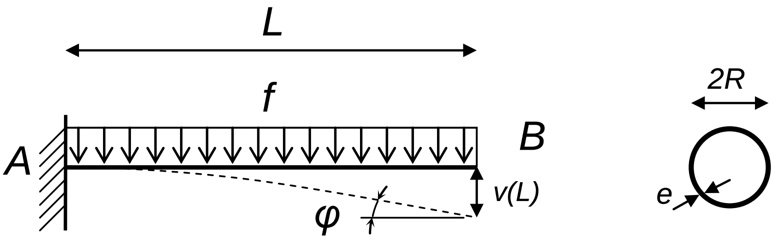


Figure 5-22 A cantilever inflated beam with a distributed load

Maximum displacement and slope at the free end, collapse load:

$$v(L) = -\frac{f}{8\left(E_\ell + \frac{pR}{2}\right)I} L^4 - \frac{f}{2\pi R\left(pR + 2kG_{\ell t}\right)} L^2 \tag{5.12}$$

$$\varphi(L) = -\frac{f}{6\left(E_\ell + \frac{pR}{2}\right)I} L^3 \tag{5.13}$$

$$F_\ell = \frac{p\pi^2 R^3}{4L} \tag{5.14}$$

5.5.3.3 Simply supported beam

Simply supported beam, point load

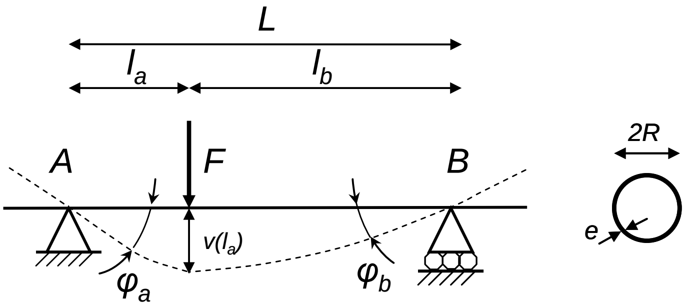


Figure 5-23 A simply supported beam with a single point load

Maximum displacement and slope, collapse load:

$$v(\ell_a) = -\frac{F\ell_a\ell_b}{L}\left(\frac{\ell_a\ell_b\pi R\left(pR + 2kG_{\ell t}\right) + 3\left(E_\ell + \frac{pR}{2}\right)I}{3\pi R\left(pR + 2kG_{\ell t}\right)\left(E_\ell + \frac{pR}{2}\right)I}\right) \tag{5.15}$$

$$\varphi(0)=\varphi_a=-\frac{F\ell_b}{L}\left(\frac{L+\ell_b}{6\left(E_\ell+\frac{pR}{2}\right)I}+\frac{1}{\pi R\left(pR+2kG_{\ell t}\right)}\right) \tag{5.16}$$

$$\varphi(L)=\varphi_b=-\frac{F\ell_a}{L}\left(\frac{L+\ell_a}{6\left(E_\ell+\frac{pR}{2}\right)I}+\frac{1}{\pi R\left(pR+2kG_{\ell t}\right)}\right) \tag{5.17}$$

$$F_\ell=\frac{p\pi^2R^3}{4}\frac{L}{\ell_a\ell_b} \tag{5.18}$$

Particular case $\ell_a=\ell_b=\frac{L}{2}$:

$$v\left(\frac{L}{2}\right)=-\frac{FL^3}{48\left(E_\ell+\frac{pR}{2}\right)I}-\frac{FL}{\pi R\left(pR+2kG_{\ell t}\right)} \tag{5.19}$$

$$\varphi(0)=\varphi_a=-\frac{FL^2}{16\left(E_\ell+\frac{pR}{2}\right)I}-\frac{F}{\pi R\left(pR+2kG_{\ell t}\right)} \tag{5.20}$$

$$F_\ell=\frac{p\pi^2R^3}{L} \tag{5.21}$$

Eigenfrequencies:

$$f_n=\sqrt{\frac{n^4\pi^4}{\rho_0\pi R^2\ell^2\left(\frac{\ell^2}{\left(E_\ell+\frac{pR}{2}\right)I}+\frac{n^2\pi^2}{\pi R\left(pR+2kG_{\ell t}\right)}\right)}} \tag{5.22}$$

Simply supported beam, distributed load

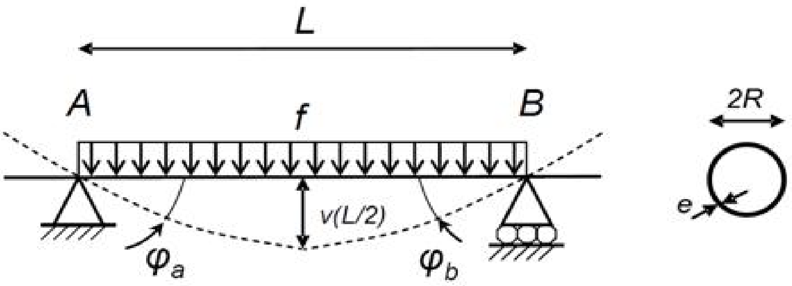


Figure 5-24 A simply supported beam with a ditsributed load

Maximum displacement and slope, collapse load:

$$v\left(\frac{L}{2}\right)=-\frac{fL^2\left(5\pi R\left(pR+2kG_{\ell t}\right)L^2+48\left(E_\ell+\frac{pR}{2}\right)I\right)}{384\pi R\left(E_\ell+\frac{pR}{2}\right)I\left(pR+2kG_{\ell t}\right)} \tag{5.23}$$

$$\varphi(0)=\varphi_a=-\varphi_b=-\varphi(L)=-\frac{fL}{24}\frac{\left(\pi R\left(pR+2kG_{\ell t}\right)L^2+12\left(E_\ell+\frac{pR}{2}\right)I\right)}{\pi R\left(pR+2kG_{\ell t}\right)\left(E_\ell+\frac{pR}{2}\right)I} \tag{5.24}$$

$$F_\ell=2\frac{p\pi^2R^3}{L} \tag{5.25}$$

5.5.3.4 Propped cantilever beam

Propped cantilever beam, point load

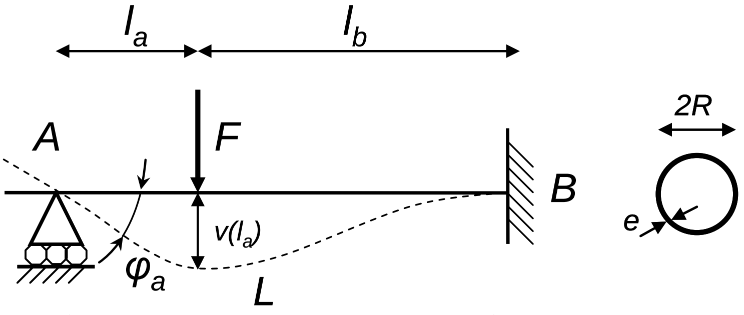


Figure 5-25 Propped cantilever beam with a single point load

Maximum displacement and slope, collapse load:

$$v\left(\ell_a\right)=F\ell_a\ell_b\left(\frac{\pi^2R^2\left(pR+2kG_{\ell t}\right)^2\left(3L^3\ell_a-5L^2\ell_a^2+L\ell_a^3+\ell_a^4\right)}{12L\pi R\left(pR+2kG_{\ell t}\right)\left(E_\ell+\frac{pR}{2}\right)I\left(\pi R\left(pR+2kG_{\ell t}\right)L^2+3\left(E_\ell+\frac{pR}{2}\right)I\right)}+\frac{12\pi R\left(pR+2kG_{\ell t}\right)\left(E_\ell+\frac{pR}{2}\right)I\left(L^2+L\ell_a-\ell_a^2\right)+36\left(E_\ell+\frac{pR}{2}\right)^2I^2}{12L\pi R\left(pR+2kG_{\ell t}\right)\left(E_\ell+\frac{pR}{2}\right)I\left(\pi R\left(pR+2kG_{\ell t}\right)L^2+3\left(E_\ell+\frac{pR}{2}\right)I\right)}\right) \tag{5.26}$$

$$\varphi(0)=\varphi_a=-\frac{F}{4L\left(\left(E_\ell+\frac{pR}{2}\right)I\pi R\left(pR+2kG_{\ell t}\right)\left(\pi R\left(pR+2kG_{\ell t}\right)L^2+3\left(E_\ell+\frac{pR}{2}\right)I\right)\right)}\cdot\left(\begin{array}{l}\pi^2R^2\left(pR+2kG_{\ell t}\right)^2\ell_aL^2\left(L-\ell_a\right)^2+\\ \left(E_\ell+\frac{pR}{2}\right)I\pi R\left(pR+2kG_{\ell t}\right)\left(4L^3-6L\ell_a^2+2\ell_a^3\right)+\\ 12\left(E_\ell+\frac{pR}{2}\right)^2I^2\left(L-\ell_a\right)\end{array}\right) \tag{5.27}$$

$$F_\ell=\frac{p\pi^2R^3}{4}\frac{\left(L+\ell_a\right)}{\ell_a\left(L-\ell_a\right)} \tag{5.28}$$

Particular case $\ell_a=\ell_b=\frac{L}{2}$:

$$v\left(\frac{L}{2}\right)=-\frac{FL}{768}\frac{7\pi^2R^2\left(pR+2kG_{\ell t}\right)L^4+240\left(E_\ell+\frac{pR}{2}\right)I\pi R\left(pR+2kG_{\ell t}\right)L^2+576\left(E_\ell+\frac{pR}{2}\right)^2I^2}{\left(E_\ell+\frac{pR}{2}\right)I\pi R\left(pR+2kG_{\ell t}\right)\left(\pi R\left(pR+2kG_{\ell t}\right)L^2+3\left(E_\ell+\frac{pR}{2}\right)I\right)} \tag{5.29}$$

$$\varphi(0)=\varphi_a=-\frac{F}{32}\frac{\pi^2R^2\left(pR+2kG_{\ell t}\right)^2L^4+22\left(E_\ell+\frac{pR}{2}\right)I\pi R\left(pR+2kG_{\ell t}\right)L^2+48\left(E_\ell+\frac{pR}{2}\right)^2I^2}{\left(E_\ell+\frac{pR}{2}\right)I\pi R\left(pR+2kG_{\ell t}\right)\left(\pi R\left(pR+2kG_{\ell t}\right)L^2+3\left(E_\ell+\frac{pR}{2}\right)I\right)} \tag{5.30}$$

$$F_\ell=\frac{3p\pi^2R^3}{L} \tag{5.31}$$

Propped cantilever beam, distributed load

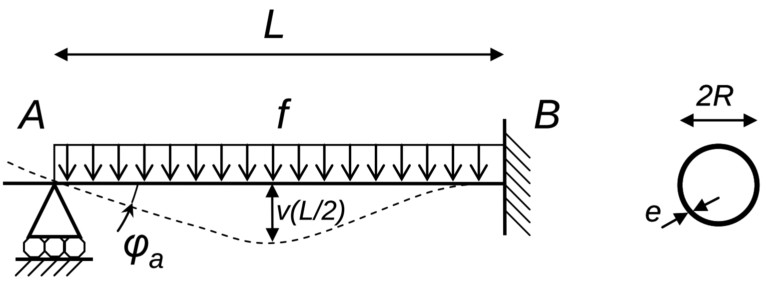


Figure 5-26 Propped cantilever beam with a distributed load

Maximum displacement and slope, collapse load:

$$v\left(\frac{L}{2}\right) = -fL^2 \frac{\left(2L^4\pi^2R^2\left(pR+2kG_{\ell t}\right)^2 + 63\pi R\left(pR+2kG_{\ell t}\right)\left(E_\ell + \frac{pR}{2}\right)IL^2 + 144\left(E_\ell + \frac{pR}{2}\right)^2 I^2\right)}{384\left(3\left(E_\ell + \frac{pR}{2}\right)I + \pi R\left(pR+2kG_{\ell t}\right)L^2\right)\pi R\left(pR+2kG_{\ell t}\right)\left(E_\ell + \frac{pR}{2}\right)I} \tag{5.32}$$

$$\varphi(0) = \varphi_a = -fL \frac{\left(L^4\pi^2R^2\left(pR+2kG_{\ell t}\right)^2 + 30\pi R\left(pR+2kG_{\ell t}\right)\left(E_\ell + \frac{pR}{2}\right)IL^2 + 72\left(E_\ell + \frac{pR}{2}\right)^2 I^2\right)}{48\left(3\left(E_\ell + \frac{pR}{2}\right)I + \pi R\left(pR+2kG_{\ell t}\right)L^2\right)\pi R\left(pR+2kG_{\ell t}\right)\left(E_\ell + \frac{pR}{2}\right)I} \tag{5.33}$$

$$F_\ell = 3\frac{p\pi^2R^3}{L} \tag{5.34}$$

5.5.3.5 Bi-clamped beam

Bi-clamped beam, point load

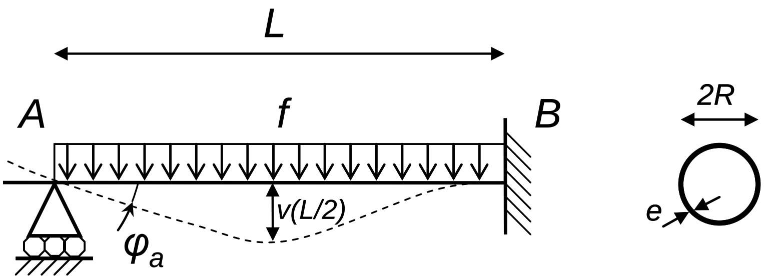


Figure 5-27 Bi-clamped beam with a single point load

Maximum displacement, collapse load:

$$v\left(\ell_a\right) = -F\ell_a\ell_b \frac{\left(\begin{array}{l}\pi^2R^2\left(pR+2kG_{\ell t}\right)^2 \ell_a^2\ell_b^2 + \\ 3\pi R\left(pR+2kG_{\ell t}\right)\left(E_\ell + \frac{pR}{2}\right)I\left(L^2 + L\ell_a - \ell_a^2\right) + 36\left(E_\ell + \frac{pR}{2}\right)^2 I^2\end{array}\right)}{3L\pi R\left(pR+2kG_{\ell t}\right)\left(E_\ell + \frac{pR}{2}\right)I\left(\pi R\left(pR+2kG_{\ell t}\right)L^2 + 12\left(E_\ell + \frac{pR}{2}\right)I\right)} \tag{5.35}$$

$$F_\ell = \frac{p\pi^2R^3L}{2\ell_a\ell_b} \tag{5.36}$$

Particular case $\ell_a = \ell_b = \frac{L}{2}$:

$$v\left(\frac{L}{2}\right) = -FL\frac{\pi R\left(pR+2kG_{\ell t}\right)L^4 + 48\left(E_\ell + \frac{pR}{2}\right)I}{192\pi R\left(pR+2kG_{\ell t}\right)\left(E_\ell + \frac{pR}{2}\right)I} \tag{5.37}$$

$$F_{\ell} = \frac{2p\pi^2R^3}{L} \tag{5.38}$$

Bi-clamped beam, distributed load

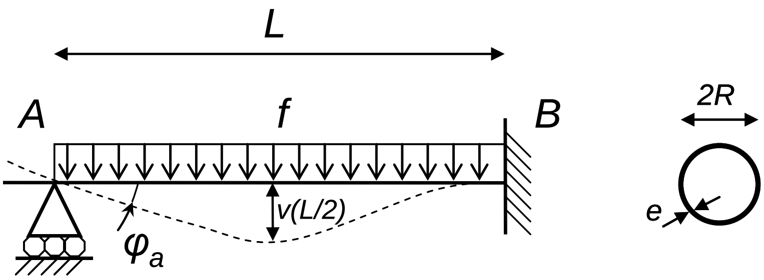


Figure 5-28 Bi-clamped beam with a distributed load

Maximum displacement, collapse load:

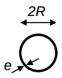
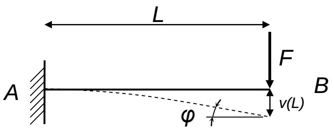
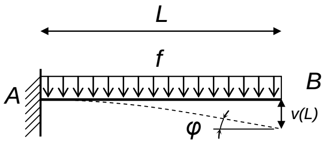
$$v\left(\frac{L}{2}\right) = -\frac{f}{384\left(E_{\ell} + \frac{pR}{2}\right)I}L^4 - \frac{f}{8\pi R\left(pR + 2kG_{\ell t}\right)}L^2 \tag{5.39}$$

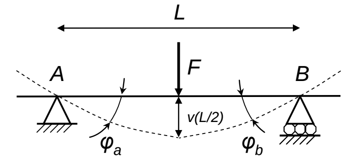
$$F_{\ell} = \frac{4p\pi^2R^3}{L} \tag{5.40}$$

5.5.3.6 Numerical examples

Table 5-1 presents numerical examples for all structural configurations for which sizing formulas were given in the previous sections.

Table 5-1 Numerical examples for the presented structural configurations of inflatable tubular beams

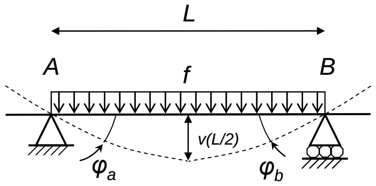
Numerical applications for the examined inflatable tubular beams		
	R = 0.10 m p = 200 kPa $G_{\ell t}$ = 20000 Pam	L = 2 m E_{ℓ} = 30000 Pam f = F/L
Configurations	**Displacement**	**Collapse load**
	For F = 160 N v(L) = 46 cm	F_{ℓ} = 246 N
	For F = 160 N v(L) = 17.7 cm	F_{ℓ} = 493 N



For F = 500 N

v(L/2) = 10.6 cm

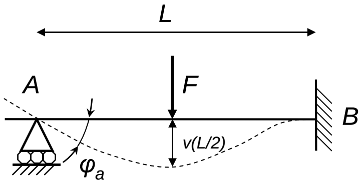
F_ℓ = 937 N



For F = 500 N

v(L/2) = 6.3 cm

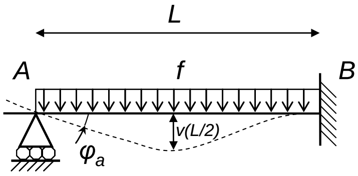
F_ℓ = 1973 N



For F = 800 N

v(L/2) = 9.6 cm

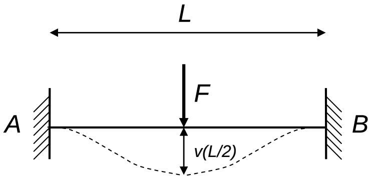
F_ℓ = 1480 N



For F = 800 N

v(L/2) = 5.3 cm

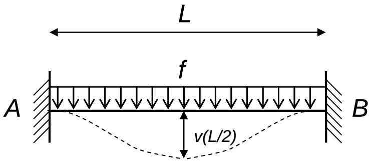
F_ℓ = 2960 N



For F = 1200 N

v(L/2) = 9.9 cm

F_ℓ = 1973 N



For F = 1200 N

v(L/2) = 4.9 cm

F_ℓ = 3947 N

6 Ultimate limit states (ULS)

6.1 General

The aim of the Ultimate Limit State (ULS) verification is to proof the safety of a structure. In general, EN 1990 defines the following Ultimate Limit States:

- EQU: Loss of static equilibrium of the structure or any part of it considered as a rigid body,
- STR: Internal failure or excessive deformation of the structure or structural members, including footings, piles, basement walls, etc., where the strength of construction materials of the structure governs,
- GEO: Failure or excessive deformation of the ground where the strengths of soil or rock are significant in providing resistance and
- FAT: Fatigue failure of the structure or structural members.

The Ultimate Limit State EQU is only applicable for rigid bodies which exludes structural membranes per definition and GEO is only a geotechnical Limit State. Fatigue was up to now never a topic of research in the field of structural membranes because typical membrane structures are not exposed to numerously repeated loads. Thus, FAT is not an eligible Limit State for structural membranes. For the verification of membrane structures only the Ultimate Limit State STR is considered here.

In the verification of the Ultimate Limit State STR it has to be proofed that the governing membrane stresses at any location of the structure are smaller than the tensile strength of the membrane material or connection. This has to consider safety factors according to EN 1990 as explained in chapter 1. Furthermore, any physical reality that leads to a reduction of the tensile strength in the investigated design situation has to be taken into consideration. From a material point of view the latter aspect is particularly important because the mainly polymeric membrane materials (fabrics and foils) are known to be sensitive to environmental impacts, long term loads, high temperature etc. as stated in chapters 2 and 4. These impacts can be measured in experimental tests and strength reduction factors can be derived from the test results. A further aspect to be considered can be a statistical degradation of the strength related to the size of the membrane: the risk of a critical defect increases with increasing panel size. This is of course no material related correlation but applies generally. The last aspect is the quality of the membrane material itself and the connections (weld seams etc.). Up to now, the last aspect is considered in the design practice by means of experimental tests accompanying the fabrication of the membrane panels. These aspects are incorporated in the existing national design standards in quite different manners. The different approaches are reflected in detail in the next chapter. Based on that survey a harmonized view on the ULS verification is layed out in chapter 6.3.

6.2 Resistance of material and joints – existing approaches

Existing standards or guidelines consider the above mentioned impacts, see the national documents DIN 4134 [X120], DIN 18204 [X121], French Recommendations [X124] and the European standard for the design of tents EN 13782 [X127]. However, the consideration appears to be quite different. First, not all mentioned impacts are considered in all standards. Second, the strength reduction impacts are partly clearly separated from the safety factor [X120, X124] and partly merged to a combined factor that includes safety aspects and real physical strength reduction [X121, X127], usually known as “stress factor”. This is reflected by the Code Reviews 20 and 21 which demonstrate the concepts of the German design standard for air halls DIN 4134 [X120] and the French Recommendations [X124]. In the German practice the so-called A-factor concept is oftentimes used for the stress verification. The A-factors are strength reduction factors that describe the strength reduction due to a single impact compared to a basic value of the tensile strength. This basic value is the short term tensile strength under room temperature, e.g. according to the test standard EN ISO 1421, see chapter 2.

Code Review No. 20

DIN 4134 and the PhD-Thesis of Minte "Mechanical behaviour of connections of coated fabrics"

The German practice combines DIN 4134 "Tragluftbauten" [X120] and the PhD-thesis of Minte [MIN81]. The latter derives strength reduction factors – called A-factors – based on numerous tests.

In Germany non-regulated materials such as coated fabrics need to be approved. This can be done either as a general approval by the Institute for Building Technology (DIBT), or as an approval in a single case by the highest building authority of the federal state where the application is.

The scope of testing is at the discretion of the engineer, and the authority needs to agree on this. It is usually dependent on the size and importance of the structure, and whether similar materials and details have been employed on previous projects.

However, where the design engineer relies on the experience of previous projects it is necessary for fabricators to validate the membrane material's strength. Historically the stress verification in DIN 4134 (Ultimate Limit State) is based on a load factoring approach using the following predefined design load combinations for different design situations:

- *Load combination A („winter storm"):* $1.0 \cdot n_g + 1.1 \cdot n_p + 1.6 \cdot n_w \leq zul\ n_0$
- *Load combination B („Summer storm"):* $1{,}0 \cdot n_g + 1{,}1 \cdot n_p + 0{,}7 \cdot n_w \leq zul\ n_\theta$
- *Load combination C („Permanent"):* $1{,}0 \cdot n_g + 1{,}3 \cdot n_p \leq zul\ n_t$

where

n_g	*membrane stress from dead load of the membrane (which is usually negligible),*
n_p	*membrane stress from prestress,*
n_w	*membrane stress from wind loads,*
$zul\ n_0$	*admissible short term resistance at T = 20 °C,*
$zul\ n_\vartheta$	*admissible short term resistance at T = 70 °C,*
$zul\ n_t$	*admissible long term resistance at T = 20 °C.*

DIN 4134 does not provide a load combination for the design situation "snow" on air halls. According to the PhD-thesis of Minte snow load shall be treated as a permanent load. Some engineers have a different approach, as for example:

- *Load combination D („Maximum snow"):* $1.0 \cdot n_g + 1.1 \cdot n_p + 1.5 \cdot n_s \leq zul\ n_t$

where

n_s	*membrane stress from snow load.*

The approach of the load combination B "summer storm" takes into account the fact that seam strength decreases with increasing temperatures (verification against zul n_ϑ*) and, moreover, that in hot conditions the wind speeds are naturally lower (load factor of 0.7 for summer wind). The fact that the verification has to be done against zul* n_ϑ *may not seem particularly logical since* *strong winds will always cool a membrane surface. But it cannot be assumed that all welds, including clamped details, will cool off rapidly to a test temperature of 23 °C.*

In the current design practice in Germany this procedure has been modified to a stress factor approach applying unfactored loads in the structural analysis (unless dealing with stability checks). This revised approach does however incorporate a load factor depending on the current design situation. But this load factor is introduced as a reduction factor on material strength (compare section 3.6.1). The allowable stresses are defined (similar to Minte) as follows:

$f_d = f_{tk} / (\gamma_f \cdot \gamma_M \cdot A_i)$

where f_d *= allowable design stress,*

f_{tk} *= tensile strength defined as 5%-fractile of at least 5 strips 10cm wide, tested at 23 °C (codes: DIN 53 354, ISO 1421). (Alternatively, from Minte, 0.868 x mean tensile strength for the fabric or 0.802 x mean strength for / near the seams),*

γ_f *= load factor, see explanations below,*

γ_M *= material safety coefficient for all approved materials:* $\gamma_M = 1.4$ *within the fabric surface,* $\gamma_M = 1.5$ *for connections,*

A_i *= individual strength reduction factors to be applied depending on the design situation, see explanations below.*

The various individual reduction factors differ depending on whether a main fabric area or a seam / detail is being considered.

Since it is neither possible nor realistic to combine in a linear way the various types of loading (permanent, wind or snow) the following combinations have been proposed so as to comply with codified practice when accounting for load effects applied to the results of non-linear analyses based on unfactored loads:

Permanent: $\gamma_f = 1.5$,

Winter storm: $\gamma_f = 1.6$,

Maximum Snow: $\gamma_f = 1.5$.

In the above, the "summer storm" factor has been excluded. This is partly because for permanent or semi-permanent membranes it will rarely be the governing case for membrane stresses or details. Also for the design of structures temporarily deployed in the summer only it is recommended to use the appropriate / approved seasonal loadings.

The individual "A"-factors take into account single material related strength reducing impacts. They are the result of many tests which have been done in the last 20 – 30 years. Four factors are typically in current use for the membrane surface. These are stated in the following together with typical numerical ranges. The values given in brackets are appropriate for connections, with the ranges depending on the connection type (e.g.: welded, clamped etc.) and the seam width.

$A_0 = 1.0 – 1.2\ (1.2)$	*Strength reduction factor for biaxial loading, taking into account that the small width strip tensile test produces a higher value than the biaxial strength.* *(The lower value of 1.0 is appropriate if the loading produces dominant stress in one direction of the weave).*
$A_1 = 1.6 – 1.7\ (1.5 – 3.4)$	*Strength reduction factor for long-term loads, with the connection factors very dependent on seam widths (excluding stitched seams).*
$A_2 = 1.1 – 1.2\ (1.2)$	*Strength reduction factor for pollution and degradation (again excluding stitched seams).*

$A_3 = 1.1 – 1.25$ (1.4 – 1.95) Strength reduction factor for high temperature load cases (i.e. design situation "summer storm & excluding wind cooling").

Appropriate seam widths are assumed in the above – particularly for the connection factors for A_1 and A_3 – with typical minimum values of 40mm for PVC-PES type I and 80 mm for PVC-PES type IV).

To summarise the above the following ranges of global reduction factors (including safety factors and strength reduction factors) for the different design situations can be obtained:

For the Material

Permanent: $\gamma \cdot A_{res} = \gamma_f \cdot \gamma_M \cdot A_0 \cdot A_1 \cdot A_2 \cdot A_3 = 4.9 – 6.4$

Winter storm: $\gamma \cdot A_{res} = \gamma_f \cdot \gamma_M \cdot A_0 \cdot A_2 = 2.9 – 3.2$

Maximum snow: $\gamma \cdot A_{res} = \gamma_f \cdot \gamma_M \cdot A_0 \cdot A_1 \cdot A_2 = 4.4 – 5.1$

For Connections (only welded seams with appropriate widths for fabric type)

Permanent: $\gamma \cdot A_{res} = \gamma_f \cdot \gamma_M \cdot A_0 \cdot A_1 \cdot A_2 \cdot A_3 = 6.7 – 9.5$

Winter storm: $\gamma \cdot A_{res} = \gamma_f \cdot \gamma_M \cdot A_0 \cdot A_2 = 3.5$

Maximum snow: $\gamma \cdot A_{res} = \gamma_f \cdot \gamma_M \cdot A_0 \cdot A_1 \cdot A_2 = 4.9$

The global strength reductions for long term loads and snow loads are comparable with other international guidelines. The German approach provides a very low global reduction for short-term wind loads generally around 3.0 which may seem surprising. But being the only code using the strong short-term behaviour of composite plastics this may seem reasonable.

However, this approach neglects the potential tear propagation due to pre-existing flaws and is commonly treated in this design strategy as a failure load case.

It can be observed from Code Review No. 20 that in the A-factor concept the different single strength reduction factors are applied in a manner that fits to the different design situations. A-factors and the safety factors – here γ_f and γ_M – are clearly separated.

The French Recommendations use also a strength reduction factor that considers a degradation due to environmental impact (pollution). In contrast to the German concept no further material related factors are introduced. Instead of this, two factors are defined which consider possible strength reductions due to the size of the membrane and a not ideal quality during the manufacture. These impacts are disregarded by the German approach. The quantities of the factors are explicitly defined. In a direct comparison it can be recognized as an advantage of this concept that no extensive experimental tests are required to enable the design engineer to perform the stress verification. This is a necessity in the A-factor concept – unless safe sided values are used.

Code Review No. 21

French recommendations [X124]

For covering structures more than 250 m^2, or more than 20 m of radius of curvature

- *the absence of inversion of curvature must be checked for the combination:*
  prestress + own weight + normal snow,
- *inversions of curvature may be admitted, provided that the repetition does not affect fatigue, durability of the membrane and their connections for the combination:*
  prestress + own weight + normal wind
- *the absence of pockets that can collect and store water must be checked for the combination:*

prestress + own weight + extreme snow.

For each combination of predominant action thus defined, the following design relationship should be checked:

$$T_C \leq T_D = \frac{k_q \cdot k_e \cdot T_{rm}}{\gamma_t} \quad (1)$$

with:

T_C: *membrane stress under the respective load combination, assuming characteristic values for the actions,*
T_D: *design strength of the membrane, in the warp or weft direction,*
T_{rm}: *medium uniaxial tensile strength, in warp or weft,*
k_q: *quality factor of the membrane,*
k_e: *scale factor depending on the surface of the coverage element,*
γ_t: *safety factor, taking into account environmental degradation.*

The quality factor of the membrane is obtained with:

$$k_q = min(k_t, k_s) \quad (2)$$

with

k_t: *quality factor of the fabric,*
k_s: *quality factor of the welds.*

The quality factor of the fabric is 1 if its mechanical properties are subject to self-controlling of manufacture validated by an outside laboratory, or if the manufacture is ISO 9001 certified. It is equal to 0.8 otherwise.

The quality factor of the welds is 1 if its mechanical properties are subject to self-controlling of manufacture validated by an outside laboratory, or if manufacture is ISO 9001 certified. It is equal to 0.8 otherwise.

The scale factor depends of the surface S [m^2] of the element of textile coverage and is given by (3a) and (3b), or in simplified form in Table 6-1:

$$k_e = 1 \text{ for } S \leq 50\, m^2 \quad (3a)$$

$$k_e = \left(\frac{50}{S}\right)^{\frac{1}{15}} \text{ for } S > 50\, m^2 \quad (3b)$$

Table 6-1 Scale factors k_e for different surface sizes

S [m^2]	***from 0 to 50***	***from 50 to 200***	***from 250 to 500***
k_e	*1*	*0.9*	*0.86*
The scale factor takes into account the flat rate increase with the surface of the risk of the presence of a critical defect			

The safety factor γ_t is given in Table 6-2, according to the exposure conditions of the structure to pollution, and the nature of the armature.

Table 6-2 Safety factors γ_f

Exposure conditions	***Medium pollution***	***Heavy pollution***
Polyester fiber fabric	*4*	*4.5*
Glass fiber fabric	*4*	*4.5*

The design stress of the attachment areas (borders, point field etc.) is calculated with:

$$T_D = \frac{k_q \cdot n_{eff} \cdot T_{rm}}{\gamma_{tloc}} \qquad (4)$$

with:

k_q: *quality factor of the membrane previously defined,*
n_{eff}: *effective number of layers in case of reinforcements, taken equal to 1 in the absence of reinforcement,*
T_{rm}: *medium uniaxial tensile strength, in warp or weft,*
γ_{tloc}: *local safety factor, equal to 5.*

For the verification of edges the following rules are to be applied:

- *The strength of the edges must be justified experimentally.*
- *The number of samples shall be at least three.*
- *The tensile strength to consider is the smallest of the series of tests.*
- *The safety factor with respect to tensile strength must at least equal 2.5.*

For the verification of connections the following rules are to be applied:

The strength of the constituent elements of the connections (ropes, tensioner, points fields etc.) must be justified with reference to experimental failure loads guaranteed by the manufacturers of these components. In case of absence of specific regulations, the safety factor for the tensile strength, to take into account the justification of the components under the effect of weighted loads is "γ" _"a" =2 for cables and "γ" _"a" =2.5other parts.

The steel anchoring points must be justified according to the rules applicable to structural steel components.

For both concepts “stress factors” can be carved out as the product of the strength reduction factors and the safety factors. A comparison of the stress factors is undertaken in [PWB13]. Regarding only the strength of the basic material it reveals for the German concept stress factors of approximately 2.9 – 6.4 and for the French concept of approximately 4.0 – 7.0. This result shows that using A-factors enables – under certain circumstances – a sharper verification. The flip side is the requirement for extensive experimental testing for each project – whereas the French approach provides the designer a fast and cost-saving method for the verification.

6.3 Harmonized view of the ULS verification of structural membranes

In order to clarify the safety margin of a structure it is recommendable to sharply distinguish between safety factors and strength reduction factors [USS14a]. Only this enables the designer to clearly identify the safety of the designed structure in every design situation. The aim of safety factors according to EN 1990 is to consider

- uncertainties in representative values of actions (γ_f),
- model uncertainties in actions and action effects (γ_{Sd}),
- model uncertainties in structural resistance (γ_{Rd}) and
- uncertainties in material properties (γ_m).

The aim of the strength reduction factors is to ensure the structural safety in a critical design situation, i.e. for instance at the end of the lifetime (which usually includes long term loading and environmental impacts) and under elevated temperature. Even at that critical design situation the safety margin which is introduced by the safety factors should be secured in order to cover the above mentioned uncertainties.

A harmonized approach for the verification of structural membranes is demonstrated in the Eurocode Outlooks No. 30 and 31. In a first step, this concept only considers woven fabric membranes so far. Strength reduction factors are introduced that cover single independent impacts on the material or connection strength. Based on the above presented Code Reviews five factors are identified:

- k_{age}: considers environmental impacts (pollution, UV-rays, rain, abrasive blast etc.),
- k_{biax}: considers a potentially reduced strength due to a biaxial stress state,
- k_{ong}: considers the effect of long term loads,
- k_{temp}: considers the effect of elevated temperature and
- k_{size}: considers a potentially increased risk of strength reduction linked to increased sizes of membrane panels.

The Eurocode is supposed to provide clearly defined test procedures to determine the material related strength reduction factors k_{age}, k_{biax}, k_{long} and k_{temp}, see Eurocode Outlook No. 32. Furthermore, a “wild card” for one or more additional factors is introduced – k_x – that enables to consider further impacts. For instance, a widely used practice is that a factor is introduced to take into account a clearly measurable reduced strength of a connection detail compared to the strength of the base material.

In order to enable designers also a fast and cost-saving engineering for smaller structures it is envisaged to provide safe-sided values for the k-factors in the Eurocode. This is in line with the “two way procedure” presented in chapter 2.2.2.1. The objective of this procedure is to enable an economic design by basing the design strength and the determination of the material related strength reduction factors on individual experimental testing results on the one hand (“first way”). This practice is required especially for innovative new materials and for materials that are modified project orientated by the material producer – which is both characteristic for the field of textile architecture – but can be used for a better utilization of the typical materials, too. On the other hand the aim is to enable a safe-sided design for those projects where the amount of experimental testing is aimed to be minimized, either for determination of the material strength and the material related strength reduction factors. This procedure copes with the needs of innovative and major projects as well with those of smaller projects using typical materials at the same time.

A topic for future research should be to investigate into the effect of combined impacts. This is partly already done for the combination of long term load with high temperature effects [MIN81].

Eurocode Outlook No. 30

(1) The design value of an action effect in the material shall not exceed the corresponding design resistance and if several action effects act simultaneously the combined effect shall not exceed the resistance for that combination.

(2) Due to the geometrical nonlinear behavior it is not appropriate to combine action effects, that is why the effect of combined actions needs to be determined.

(i) The following expression shall be satisfied at every location of the membrane:

$$n_d \leq f_d$$

where

n_d *is the design membrane stress in the considered direction and*

f_d *is the design tensile strength of the membrane or the joint related to the specific design situation.*

NOTE For fabrics the different properties in warp and fill direction should be considered.

(ii) The general term for the design tensile strength of the membrane material or the joint is given by

$f_d = f_{k,23} / (\gamma_{M.}\cdot \{ k_{age}; k_{biax}; k_{long}; k_{temp}; k_{size}; k_x \})$ *with* $k_i \geq 1$.

(iii) Instead of applying the individual reduction factors k_{age}, k_{biax}, k_{long}, k_{temp} *according to (ii), a combined reduction factor* k_{comb} *may be applied which is obtained from experimental tests. These tests must consider the different influencing parameters as there are biaxial effects, long term load effects, aging effects due to environmental exposure and or high temperature effects. If one or more of these effects are not considered in the experimental test, these effects have to be taken into account by multiplying* k_{comb} *with the reduction factors given in section (ii):*

$f_d = f_{k,23} / \gamma_{M.}\cdot (k_{comb}.\ k_{size})$

The safety factor γ_M is clearly separated from the strength reduction factors. Two safety factors are introduced: one for the resistance of the basic materials (γ_{M0}) and one for the resistance of joints (γ_{M2}), each to be applied in the particular design situation. This approach reflects the potentially higher uncertainties linked to joints and their fabrication and modelling. Both factors are to be derived from a reliability analysis with the objective to ensure a reliability index of $\beta = 3.8$, see chapter 1.2.

The basic characteristic strength value $f_{k,23}$ is the 5% fractile of the short term tensile strength under room temperature (23°C) from at least 5 test sepcimens measured accoding to EN ISO 1421. To enable a cost-saving design it is envisaged to give safe-sided values for $f_{k,23}$ for typical materials in the Eurocode, see the statements on the two way procedure above (see also Eurocode Outlook No. 3). These values are tabulated in the Eurocode Outlooks No. 5, 7, 9 and 11.

Eurocode Outlook No 31

(1) The partial factors γ_M *should be applied to the various characteristic values of resistance in this chapter as follows:*

- *resistance of material* γ_{M0} *and*
- *resistance of joints* γ_{M2}.

(3) The reduction factors k_{age}, k_{biax}, k_{long}, k_{temp}, k_{size} *and* k_x *can be determined with project specific tests. Recommended values can safely be applied if no tests are made.*

(4) The characteristic tensile strength $f_{k,23}$ *is the short term tensile strength of the material or the joint at T=23°C.* $f_{k,23}$ *is derived from uniaxial material or joint tests. It is the 5% fractile result of a testing with at least 5 specimens.*

Eurocode Outlook No. 32

The Eurocode should give clearly defined test procedures to determine the material related *strength reduction factors k_{age}, k_{biax}, k_{long} and k_{temp}.*

The determination of the 5%-fractile according to EN 1990 can be obtained by equation (6-1).

$$f_{k,23} = m_x \left(1 - k_n V_x\right) \tag{6-1}$$

with m_x mean value of the test results for n tests [kN/m], assuming a normal distribution,

k_n characteristic fractile factor given in table D.1 of EN 1990, annex D depending on the numbers of tests and whether the coefficient of variation is known or unknown [-],

V_x Coefficient of variation [-].

The characteristic tensile strength can be estimated from mean values using confirmed values for the coefficient of variation. Hosser reported for the basic material of PVC-coated fabrics type II and III a maximum coefficient of variation of $V_x \leq 8\%$ ([Hos79], cited in [Min81]). Minte's test experience showed for coated fabric materials in general a maximum coefficient of variation of $V_x = 0.06$ and for joints of $V_x = 0.12$ [Min81]. Todays laboratory experience confirms these values as upper limits. The characteristic fractile factor k_n can then be picked for the number of underlying tests and "V_x known".

Regarding the application of the k-factors three specific design situations are identified:

- Long term loading, combined with both warm and cold climates, including snow loads,
- Short term loading combined with a cold climate and
- Short term loading combined with a warm climate.

Snow is assumed to be a long term load. Thus, "short term loading combined with cold climate" is considered for the verifications of load combinations including wind ("winter storm") or potential other traffic loads. "Short term loading combined with warm climate" considers the same load combinations but additionally takes into account the high temperature impact on the design strength. For these three design situations the determination of the specific design strengths is given in the Eurocode Outlooks No. 33-35.

Eurocode Outlook No. 33

Design Resistance Long Term Load

The design tensile strength for material and joints $f_{LT,d}$ is calculated with the following equations:

$f_{LT,d} = f_{k,23} / (\gamma_M \cdot k_{age} \cdot k_{biax} \cdot k_{long} \cdot k_{temp} \cdot k_{size})$.

NOTE Snow load is assumed to be a long term load.

Eurocode Outlook No. 34

Design Resistance Short Term Load Cold Climate

The design tensile strength for material and joints $f_{STC,d}$ is calculated with the following equations:

$f_{STC,d} = f_{k,23} / (\gamma_M \cdot k_{age} \cdot k_{biax} \cdot k_{size})$

Eurocode Outlook No. 35

Design Resistance Short Term Load Warm Climate

The design tensile strength for material and joints $f_{STW,d}$ *is calculated with the following equations:*

$f_{STW,d} = f_{k,23} / (\gamma_M \cdot k_{age} \cdot k_{biax} \cdot k_{temp} \cdot k_{size})$

NOTE Areas with warm climate are regions without snow load.

6.4 Membrane reinforcement

In case that one layer of the membrane material does not provide appropriate strength for the structure considered – or parts of it – the membrane can be reinforced by additional layers. Usually only the highly stressed parts of a structure are reinforced. In this case the “basic” membrane layer runs continuously from one edge of the membrane panel to the other. The additional layer(s) are attached only to a part of the basic layer, usually between one edge of the membrane panel and a location in the field, see Figure 6-1. The additional layer is attached to the basic layer by seams along the edges of the additional layer. It can be imagined that the stress distribution between both layers is not uniform due to a comparable lower stiffness alongside the attachment seams. It would be even more differential if the basic materials of the layers themselves would have different stiffnesses. In a concrete example of a basic layer reinforced with one additional layer that means that not both layers carry half of the stress. With other words: the strength of the membrane is not doubled by the second layer. There are clearly a number of issues that affect the possible strength, e.g. the extent and location of seams together with the possible fabrication tolerances that could create an imbalance in the load sharing characteristics of the final fabricated membrane. These all impact upon how the load from one layer is transferred into the second layer.

Figure 6-1 Membrane partly reinforced with a second layer at the low point and membrane corners [© Ceno Membrane Technology GmbH]

Only the French recommendations give guidance for reinforcement factors up to now, see Code Review No. 22. The recommendations are based on the strict demand that the reinforcement is arranged in a way that allows for uniform stress distribution as good as possible. On this basis, a reinforcement factor n_{eff} is given, for instance for a double layer membrane as 1.9.

Code Review No. 22

French recommendations [X124]

Efficiency of reinforcements:

The reinforcement must be made with the base fabric.

Only one single reinforcement is admitted for fiber glass fabrics.

The increase of the resistance to the strength due to the reinforcements must be assessed as follows:

Strength (fabric + 1 reinforcement): $n_{eff} = 1.9$
Strength (fabric + 2 reinforcements): $n_{eff} = 2.6$
Strength (fabric + 3 reinforcements): $n_{eff} = 3.1$

The arrangement of the reinforcements must permit a uniform distribution of the stresses in the various layers.

As mentioned above the stress distribution und thus the strength increase depends on many factors which may have a greater deviation in a wider economic area for that the Eurocode would apply. Because of that a more safe-sided approach as in the French recommendations is discussed currently in CEN/TC 250 WG5. A clearly safe-sided factor for many different configurations is agreed upon as 1.5. Future research may confirm higher factors. The Eurocode should give the possibility to proof a higher strength by means of project orientated experimental testing anyway. This is reflected in the Eurocode Outlook No. 36.

Eurocode Outlook No. 36

(2) If parts of the membrane surface are reinforced with an additional layer of membrane, the design resistance is increased by 50% unless a more precise evaluation by tests has been performed.

NOTE For more than 2 layers tests have to be performed with the 3 or 4 layer detail.

7 Serviceability limit states (~~U~~SLS)

7.1 General

The aim of the verification in the Serviceability Limit States is to ensure the serviceability of the structural membranes and the structure as a whole. In principle, Serviceability Limit States that apply for membrane structures are

- limitation of deflections,
- limitation of vibration due to wind actions in order to ensure the functioning of the structure or its structural members (e.g. cracks in partitions, damage to the membrane or the connections),
- limitation of wrinkles and therefore avoidance or limitation of stressless areas within the membrane surface,
- maintenance of the prestress and
- definition of allowable tear widths and tear propagation control.

Special attention should be paid to the distinction between reversible and irreversible limit states. Long term deformations due to relaxation or creep should be considered where relevant, see also EN 1990 Annex A. This requirement is also directly linked to the maintenance of the prestress which may decrease during the lifetime due to relaxation and creep as well as – in case of fabrics – due to the (only partly reversible) decrease of the yarn crimp under cyclic loading.

It is assumed in the verification of the Serviceability Limit States that all partial safety factors are equal to 1.

All of the above listed requirements cannot be quantified generally. They should be defined project orientated and agreed upon with the client, see Eurocode Outlook No. 37.

Eurocode Outlook No. 37

(1) Any serviceability limit state and the associated loading and analysis model should be specified for a project.

As a general safeguard the supporting structure shall remain stable if the membrane is removed or in case of a collapse of the membrane. This is reflected in Eurocode Outlook No. 38, compare also Eurocode Outlook No. 28.

Eurocode Outlook No. 38

(1) In case of collapse of the membrane all load bearing components shall remain stable.

(2) In so far as rigid load bearing components (e.g. masts, supports, etc.) are restraint solely by membrane, the overturning of such components in the event of a one-sided removal of the membrane shall be prevented by additional measures, and the degree of freedom of movement in the operation condition shall remain intact.

7.2 Deflections

7.2.1 General

Deflection limits cannot be generally given and thus existing standards do not state quantitative limits. The French recommendations contain the qualitative demand that a snap through (inversion of curvature) has to be avoided for structures of a certain size, see Code Review No. 23, unless it is proofed that the repetitive snap through does not have a negative effect to the membrane or their connections.

Structural membranes are typically subject to considerable deflections, but in principle, as long as a structural membrane maintains its serviceability “unlimited” deflections are permissible. Therefore, potential limits (e.g. due to aesthetical reasons) should be agreed with the client or the National authority. Deflection limits may also be specified in the National Annexes of the Eurocode, see Eurocode Outlook No. 39.

Code Review No. 23

French recommendations

For covering structures more than 250 m^2, or more than 20 m of radius of curvature

- *the absence of inversion of curvature must be checked for the combination:*
  prestress + own weight + normal snow
- *inversions of curvature may be admitted, provided that the repetition does not affect fatigue or durability of the membrane and their connections for the combination:*
  prestress + own weight + normal wind

Eurocode Outlook No. 39

(1) With reference to EN 1990 – Annex A1.4 limits for vertical and horizontal deflections should be specified for each project and agreed with the client.

NOTE: The National Annex may specify the limits.

7.2.2 Distance to other parts

In order to ensure the serviceability of the membrane two aspects linked to deflections have to be particularly considered by the design engineer. First, the distance to other parts of the building and second, the appearance of snow or water ponds. The latter aspect is investigated in detail in chapter 7.2.2.

The deformed membrane must not hit the primary structure or any other objects. This may damage the membrane – instantly or after a number of contacts – and can finally lead to a collapse. If this risk exists appropriate deflection limits should be defined by the engineer in order to ensure a suitable distance of the deformed membrane to other parts. If it is not possible to avoid contact this should be considered in the analysis. Provisions could be taken to protect the membrane or to proof experimentally that the membrane resists the repetitive contact, compare also Eurocode Outlook No. 18. Local reinforcements could improve the resistance. This aspects are summarized in the demand of Eurocode Outlook No. 40. In any case special attention has to be paid to proper material stiffness parameters in order to enable a suitable accuracy of the deformation analysis.

Eurocode Outlook No. 40

(1) Because a load bearing membrane can be subject to considerable deflections, care shall be taken to ensure that no structural or other parts may hinder the deformation, if this has not been taken into account in the analysis.

7.2.3 Ponding

The particular risk to membrane structures of snow or water ponds requires special notice. Ponds can appear in all kinds of membranes – anticlastic, synclastic, plane – when the structural membrane or a part of it exhibits a synclastic curvature with a low point in “midfield” so that it has the form of a basin. The typical ponding mechanism is that a basin forms out under a snow load. This is because the snow load does not vanish instantly in contrast to liquid water that immediately flows off the membrane edges when no initial basin exists. Once a basin has formed out and the snow melts the melting water cannot flow off. In this case the water could only evaporate unless manual action is taken like lifting of the low point. During that time the risk exists that due to further snowfall or rainfall the load in the pond increases. This results in an increase of the pond until a certain load level is reached where an equilibrium exists between the deformation of the membrane and the pond load. Further water would overflow the edge of the pond then. In a critical case the tensile strength of the membrane can be exceeded before this equilibrium is reached. This means the failure of the membrane of course. Other ponding mechanisms linked to individual structures may occur as well. Figure 7-1 shows an example of a water pond at the corner of a conic structure caused by rain load in combination with rotating of the pylons. The rotation of the pylons enabled an initial pond which grew subsequently during the filling with water that ran down from the high point.

Figure 7-1 Ponding at the corner of conic structures caused by rain load in combination with rotating of the pylons (kinematics displacement) of the supporting structure [© V. Tanev]

The French recommendations are the only guidance that demands a ponding check today, see Code Review No. 24.

Code Review No. 24

French recommendations

For covering structures more than 250 m^2, or more than 20 m of radius of curvature

- *Ponding must be checked for the combination:*
  prestress + own weight + extreme snow

It is recommendable to firstly attempt to avoid ponding completely. But in some cases it cannot be avoided. In the current design practice ponds are frequently permitted – particularly for ETFE-foil structures. It can be permitted to some extend when it is ensured that the water or snow accumulation is limited. Such a limitation can be achieved or supported by construction, e.g. by providing additional cables under the foil. Considering this, a future regulation of ponding should be dependent on the technical background. Three cases are identified:

- If ponding is planned to be permitted and the limitation is proofed in the analysis or the pond is limited by structural elements the verification of the stresses in the membrane and the supporting elements resulting from the allowed pond should be performed in the ULS.
- If ponding is planned to be avoided, it should be ensured that actually no pond appears by checking the form in the SLS.
- The membrane stress caused by ponds that could possibly appear by accident (e.g. ponding caused by rotating of a pylon or caused by a loss of prestress in general in combination with rain load, see Figure X200) should be verified in the ULS using combination of actions for accidental design situations.

Predicting the ponding is not an easy task. As mentioned above the application of proper material stiffness parameters is decisive. Moreover, the shape of the roof could alter the snow distribution. The question arises whether to calculate the ponding with uniformly distributed snow load or with possible snow accumulation. The latter approach could require a previous extensive survey on potential “snowslides”.

Besides the checks on the main membrane (which are usually done by using the global structural model) special attention should be paid to potential local ponds at connection details. This is especially the case for cover flaps that can compromise the natural drainage path from the membrane surface, see Figure 7-2.

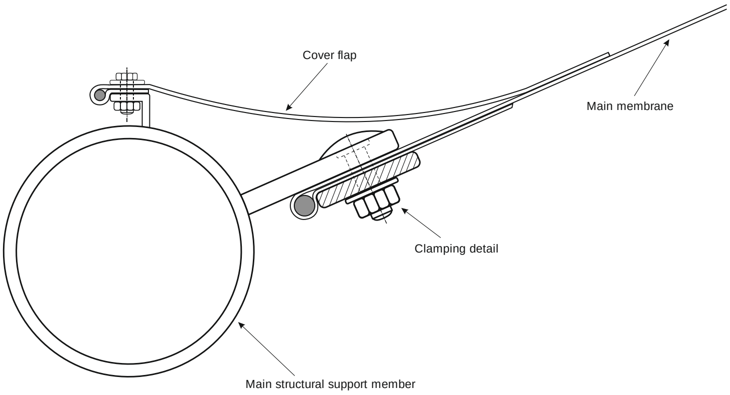


Figure 7-2 Attention to local ponding at a cover flap which a check on the main membrane in the structural model may not reveal

Eurocode Outlook No. 41 summarizes the main demands that were developed in this chapter.

Eurocode Outlook No. 41

(1) Under snow and rain actions ponding should be avoided in membrane structures.

(2) If ponding cannot be avoided in all parts of a membrane structure, a detailed analysis with realistic snow, ice and water accumulation needs to be carried out, to verify the serviceability as well as the structural integrity.

(3) For ponding analyses the lower limits for the elastic constants may be used.

Comment: In addition to reduced elastic constants a reduction in prestress should be used.

7.3 Maintenance of the prestress and post tensioning

The loss of prestress as explained above – due to relaxation, creep and the decrease of yarn crimp – can theoretically be considered during the compensation planning. This would mean that as the initial prestress level a level higher than the nominal prestress level would be aimed at. That would lead to higher compensation values compared with those that aim to reach the nominal prestress level right after the installation. After the processes of creep and relaxation are finished and after a certain amount of load cycles the nominal prestress level would then be approached. If this procedure is disregarded it should be ensured by constructive details that the structural membranes can be restressed, see exemplary Figure 8-4.

Eurocode Outlook No. 42

(1) If not taken into account during the design, design measures which enable post tensioning should be incorporated to compensate creep of the membrane.

Prestress can also decrease or vanish due to an irreversible deformation of the primary structure. It shall be understood that the primary structure shall remain elastic. Plastic deformations of beams or other structural parts are to be avoided. If slip in bolted connections can lead to a considerable irreversible loss of prestress measures should be taken to limit or avoid the slip. An example where a small slip in a bolted connection leads to large irreversible deformation of the supporting structure is illustrated in Figure 7-3. A membrane is attached to the tip of a cantilever and the cantilever is attached to a supporting element by a bolted connection which contains hole play. Under unfortunate circumstances it may be the case that the slip in the bolt holes is not activated under prestress due to friction but that the friction is overcome under the working stress of the membrane due to the occurrence of external loads. Depending on the length of the cantilever a small rotation in the bolted connection can lead to a large displacement of the cantilever tip. When the external load removes the friction in the connection still exists. From that follows that the cantilever displacement will not be reset. That means that this mechanism is followed by a decrease of prestress in the membrane.

The general demand derived from this conclusion is stated in Eurocode Outlook No. 43.

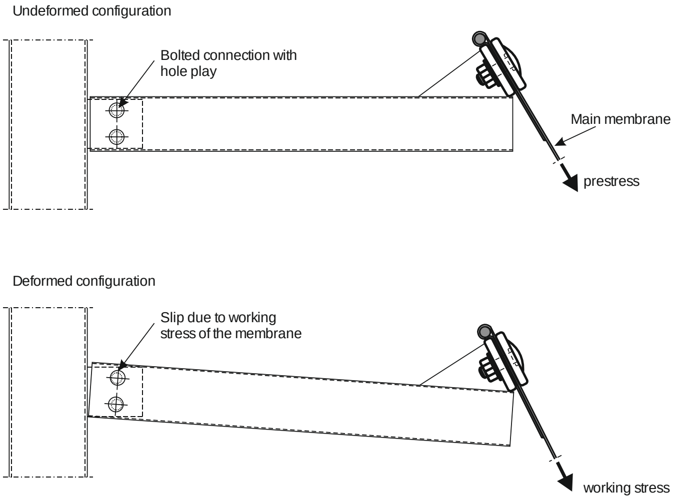


Figure 7-3 Large irreversible displacement at the cantilever tip due to a small rotation at the cantilever support

Eurocode Outlook No. 43

(1) Irreversible deformation of the primary structure which results in a considerable decrease of prestress shall be avoided.

7.4 Wrinkling

Wrinkles do not mean a damage to the membrane – unless they occur repeated – but for optical reasons the aim should be to avoid wrinkles. However, a complete avoidance is unrealistic for most membranes. A limitation of wrinkles should be envisaged. Figure 7-4 shows slight wrinkles at one edge of a membrane near a corner detail. Wrinkles appear when the membrane is stressless in one direction or in areas where the stress ratio is very high. High shear leads to wrinkles as well. Wrinkles in a membrane structure should be evaluated project orientated. The shape of the structure, its stiffness and the prestress have to be taken into account. Unbalanced tension in the membrane has to be avoided. Deviations shall not occur in statically relevant areas.

Wrinkles cannot be simulated with the Finite Element analysis when membrane elements are used or the structure is modelled with a cable net. They may be observed in the result plots but appear randomly. The use of shell elements might enable the simulation of wrinkles. This is a topic of current mechanical research [SBS11].

Figure 7-4 Slight wrinkles in a corner detail [© R. Koenen]

Wrinkles may also result from the material inhomogeneity or due to the manufacturing process. Due to the finite length of the processed strands in a textile, the diversify behaviour of strands/strands charges and variations in the coating a textile can be called an inhomogeneous material. As for the clothing industry disturbance cannot be excluded during manufacturing; especially for heavier textiles (PVC coated polyester fabric, PTFE coated glass fiber fabric etc.). In the final membrane structure these disturbances can appear as optical inhomogeneity or also in little wrinkles. These kinds of deviations are state of the art and for textile architecture unavoidable.

Wrinkles along the edge- or seam- details as well as within the area cannot be excluded because of the inhomogeneous material behaviour and also because of unavoidable tolerances during the welding process (also by thoroughly exposure with the known parameter).

As mentioned above wrinkles in a lightweight structure are state of the art because of the material behaviour and its further processing (also for ETFE- projects) and they have to be assessed project orientated. A possible future guidance regarding wrinkles is summarized in Eurocode Outlook No. 44.

Eurocode Outlook No. 44

(1) *The objective of the design should be the limitation of wrinkles to a minimum.*

(2) *High differential membrane stress (i.e. means high stress ratios) should be avoided in the prestress state as well as under external loading. Deviations should be limited to areas that are not statical relevant.*

(3) *Areas with high shear should be limited.*

7.5 Tear control

There are different reasons for cuts in membrane fabrics, e.g. production inhomogeneity, knots, little cracks or similar in the fabric itself; points of sharp folding (especially for Glass/PTFE-fabrics), pre-damages caused by handling during production, fabrication or installation or also through third parties etc. Quite often several facts are coming together.

Because of the fabric behaviour, tolerances in the membrane and/or the substructure cuts, damages etc. can occur in membranes during their installation. These failures cannot be excluded in general and it is also not possible to give an overall rule regarding this topic. It should be aimed to limit the appearance of tears.

Main important regarding failures is how they will be handled and how they will be repaired. Project orientated it is necessary to gauge them, i. e. to assess where they are placed (statically high stressed area…), what size they have, what kind of repair can be considered, whether a repair is optical passable and in which relation this failure stands against the whole membrane area. Based on this evaluation possible repairing work can be worked out. Repairing works on site must always be carried out by expert staff.

The same obtains for necessary membrane adaptations which can be caused by tolerances in the membrane surface and/or the substructure and also for later caused damages by other parties.

As already mentioned, tears cannot be completely avoided particularly in glass fibre fabrics. The reason for tears in glass fibre fabrics is oftentimes a previous crease fold which leads to a local crack of the glass fibres, see also chapter 2.2.2.3.

Tears cannot be completely avoided, particularly not in glass fibre fabrics. But the aim should be to limit the appearance of tears. Tears which result from previous folds are sometimes called “short cuts”. A short cut is shown in Figure 7-5. Therefore glass fibre fabrics should be handeld during the manufacturing and installation with utmost care in order to avoid folds. Typical rules to ensure this are: workers should not walk over the membrane with heavy shoes during the fabrication; during the installation it should be avoided to pull the membrane over a sharp edge; the packing should be planned accuaretly with the aim to avoid crease folds. See chapter 2 and particularly chapter 9 for more details. But even if these rules are followed it is unavoidable to induce some folds to the membrane, particularly in panels with very complex geometry and a high degree of curvature. The appearance of short cuts at the locations of the previous folds after a certain amount of time is the consequence. The short cuts may appear years after the installation.

Figure 7-5 “Short cut” in a glass fibre fabric due to previous crease fold [© K. Saxe]

A tear does not grow unless the membrane stress near the tear exceeds the tear resistance (compare chapter 2). Thus, the tear resistance is a first measure to assess the risk of an existing tear. When tears are detected during an inspection a rapid reaction should be initiated. First, it should be assessed whether a repair on site is possible. This is for instance the case for short cuts. A patch can be welded over the short cut on both sides of the membrane. For safety reasons this should be done promptly. In case of big tears the membrane panels may have to changed.

The calculation of tear propagation using the methods of fracture mechanics may help to define allowable tear widths and to asses how urgent a repair has to be conducted. This is currently a topic of research (see e.g. [BlBö07]).

The allowable number of tears per area or at all can not be given in a standard. This is recommended to be agreed with the client. For some projects a maximum number of failures is given in the contract. These numbers/descriptions given for one project cannot be transferred to another project. It is always necessary to handle this criterion project-related.

8 Details and connections

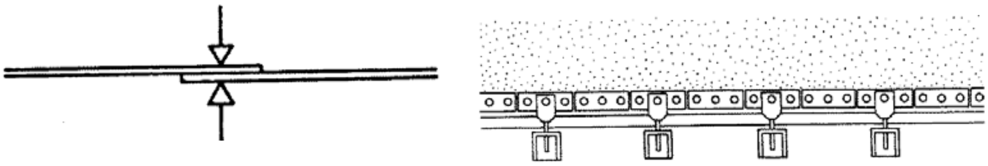
8.1 General

Details and connections in membrane structures can be distinguished in the following parts according to Bubner [Bub 97], see also Figure 8-1:

- membrane joints,
- membrane edges,
- membrane corners,
- ridges and valleys and
- high and low points.

(a) Welded membrane joint

(b) Rigid membrane edge with fitting and tension elements



(c) Membrane corner with belt (membrane strip) and clamp as fastening for the membrane in the spandrel

(d) Ridge cable arranged in loops

(e) High point
rosette-shaped construction of a mast head

(f) Low point
with leaf-like building members which are staggered on top of each other in the shape of a laminated spring

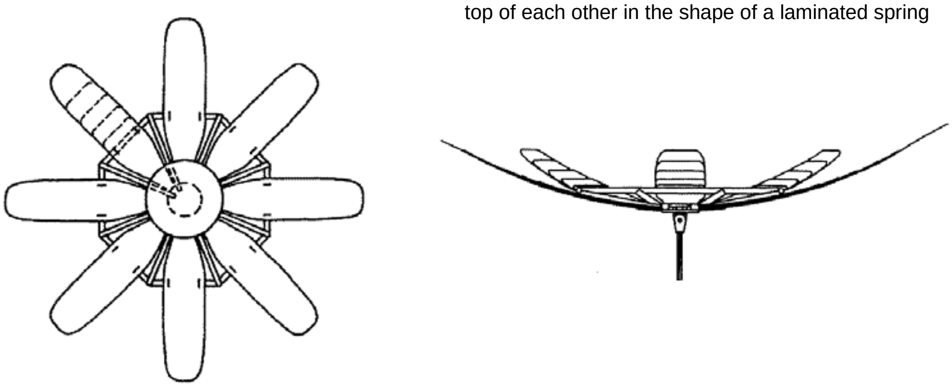


Figure 8-1 Typical exemplary details and connections in membrane structures [Bub97]

For the design of details and connections, the following objectives should be considered:

- consistency with the model of the structure (geometrical, physical and numerical),
- appearance,
- strength,
- flexibility,
- adjustability and re-tensioning,
- security and redundancy,
- protection of the membrane,
- water tightness,
- fire resistance,
- buildability,
- durability over the service life and
- maintenance and accessibility.

Consistency with the model of the structure (geometrical, physical and numerical)

Detail elements shall be able to respect the load path geometry whenever external loading conditions change. They shall be fluently integrated into the geometry of the system. Space enough shall be provided. Details and connection points shall follow exactly the system line geometry of the suspension points. Eccentricities shall be avoided in order to guarantee the correct shape of the total system.

Appearance

A general view of the whole design is needed so as to decide on the legibility of the structure, to determine the visual quality of all the elements. Membrane structure details shall be simple, flexible, of minimal configuration and expressing their own textile characteristics that are different to other building technologies. Details shall also be coordinated in scale with the structure and in coherence with the material used.

Strength

The transfer of internal forces and applied loads through the membrane field and to the supporting structure accommodating resistance and geometry should be guaranteed. Eccentricities in the connection details are not desirable but shall be considered. Loads may be static, dynamic, repeated or sustained. Resistance to failure of cables and fittings elements must be guaranteed by the manufacturers. The minimum value of the breaking strength should be clearly indicated.

Flexibility

The connections shall consider the requirements allowing large displacements, rotations and long-term effects of the membrane for elongation and flexure in the direction of the joint.

Adjustability and re-tensioning

Due to membrane creeping effects, it is essential to give a sufficient scope to re-tensioning and prestress preservation during the service life of the structure.

Security and redundancy

Membrane skins are liable to vandalism. The design shall be carried out in such a way that in the event of failure of one or more membrane fields within a roof, the supporting system does not collapse, and heavy elements such as masts are retained from falling down by a safety rigging.

Potential failure should not result in disproportionate damages. Security elements may need to be added into the structural system.

Protection of the membrane

Damage to the membrane shall be avoided. All care should be taken during detailing in such a way that membranes in contact with the structure and fittings (edge ropes, stays, clamp plates etc.) shall not be damaged, even under cyclic loading and large movements of the membrane. The supporting elements shall be free of rough spots, sharp edges, droplets following hot dip galvanization drying process or other defects that may injure the membrane material.

Buildability

During installation, particular movements and rotations can be required at the connection points.

Flexible connections are needed to provide enough degrees of freedom during installation because the membrane is not in its final position and before hoisting, is at a position determined by gravity. This can, for instance, cause a 180° rotation of a corner during lifting of the fabric.

Durability over the service life of the structure

Details should function satisfactorily throughout their lifetime. Sub-elements shall be designed to withstand the effects of long term loading, accounting for the creep and fatigue characteristics of the membrane and other structural materials. It has to be ensured that the prescribed and definitely chosen materials for clamping and detailing are of the same durability as the fabric or foil and provide coherent weather resistance, rustproof protection.

8.2 Membrane joints

According to Bubner [bub97] a membrane joint is defined as a connection which ties together either single membrane sheets or membrane fields composed of several sheets. Joints can be divided into those which fix membranes permanently to each other, as in sewed or welded joints, and joints that can be separated again, e. g. site joints.

Up to now neither regulations nor standards exist for the design of membrane joints. Since membrane joints are of decisive significance for the load bearing capacity and consequently for the durability of the entire membrane structure [bub97], design rules have to be developed for implementation in the future Eurocode on membrane structures.

The joint between two membranes is carried out by seams. The term “seam” has been derived from tent-building tradition and is still commonly used disregarding how this connection is actually carried [bub97]. For this reason this term will also be used in this background document.

Seams make an important contribution to the final configuration of the whole structure. The material is translucent and the joints are viewed against the light. Properly planned, these enhance the clarity that stems from the flow of forces, main slopes and spatial trends.

Membrane joints should be designed and fabricated so that they meet at least the strength requirements specified in chapter 2. Furthermore, project related seam strength requirements can be defined.

The following three different kinds of membrane joints are the most common seam types in practice:

- welding,
- sewing and
- clamping.

Additionally, glued joints as well as laced joints and joints with zip-fasteners are possible methods. Due to the fact that they are not widely used, they are not planned to be considered in the future Eurocode for membrane structures.

Seams between textile fabrics can be executed by welding or sewing or – more rarely – by a combination of both.

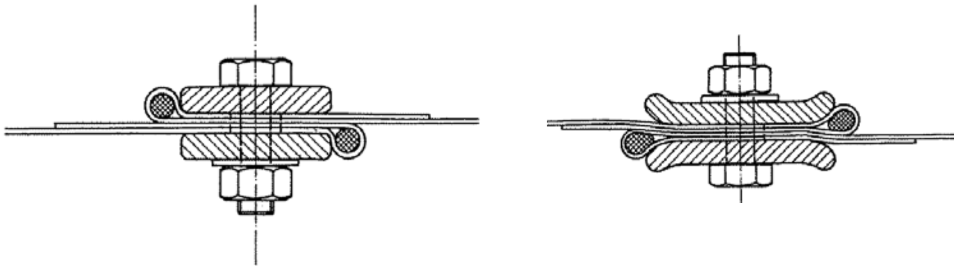
Seams between foils can be executed by welding.

Furthermore, clamped connections can be carried out for textile fabrics and foils. This type of connection is installed on site, has a strong visual appearance and is used to join large prefabricated membrane panels together. It can be made out of materials capable of taking the load e.g. wood, steel, aluminium or plastic.

Different kinds of solutions for bolted membrane joints, so called site joints, are exemplary given in Figure 8-2. Furthermore, Bubner [bub97], Seidel [Seid09] and the TensiNet Design Guide [FM04] give further examples and explanations also for welded, sewed, glued and laced joints as well as for joints with zip-fasteners.

(a) Site joint of a conventional construction

(b) Metal plate with folded peripheral ends



(c) Metal plate with bending, bolt rope inside and ring-like spacer

(d) For thick membranes: fixing by means of a separate membrane strip

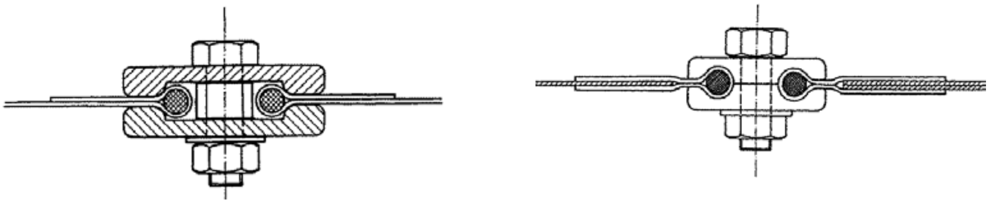


Figure 8-2 Typical exemplary clamped (bolted) membrane joints with metal plates, bolt ropes and bolts according to [Bub97]

The width of a welded seam should be determined by uniaxial short time tensile (strength) tests using calibrated testing equipment according to chapter 2.2.2.2. The tests shall be performed at testing temperatures of 23 °C and 70 °C.

The tests should be applied in weft and warp in accordance with specified standards and referring to the existing project details. The strength requirements for the seams result from the design calculations. Usually a percentage relating to the tensile strength of the material used is selected as a basis, see chapters 2.2.3 for coated fabrics, 2.2.4 for uncoated fabrics and 2.3.2.5 for ETFE-foils.

The strength of a welding seam depends substantially on the adhesion of the coating onto the weave, the welding parameters and the seam width. Seam tensile (strength) tests are therefore required for each processed material lot.

In the following typical exemplary widths for welded seams are given for a simple overlap weld for the standard range of PES/PVC-fabrics based on an evaluation of existing test results for both 23° and 70° C. However, the width of the welding seam may be reduced if verified by sufficient test results or may have to be increased if the results signify this. Typical exemplary widths of welded seams for PES/PVC fabrics are (only for orientation):

- Type I: 30 - 40 mm,
- Type II: 40 - 60 mm,
- Type III: 40 - 80 mm,
- Type IV: 40 - 80 mm and
- Type V: 80 - 100 mm.

Actually, the design of the constructive elements of clamped seams, e. g. metal plates and bolt assemblies, is carried out taking into account the relevant standards for them, as for example EN 1993-1-8, EN 1993-1-11, EN 1999-1-1 etc. Procedure tests, in which the whole membrane joint is tested experimentally, might become necessary. As already explained, tensile tests are performed for welded and sewed seams, in which the seams have to show that they have a load bearing capacity of at least a specified percentage related to the tensile strength of the material used.

Eurocode Outlook No. 45

(1) Membrane joints considered in this standard are welded seams, sewed seams and clamped seams or combinations of them.

Note: Other types of membrane joints, e. g. glued seams, are possible as well. The design resistance of them has to be determined by means of procedure tests.

(2) The design resistance of welded, sewed and combined welded and sewed seams has to be determined experimentally by tensile tests. It has to be calculated as the 5% fractile of the experimental test results. The minimum seam strength values are specified in chapters 2.2.3 for coated fabrics, 2.2.4 for uncoated fabrics and 2.3.2.5 for ETFE-foils.

(3) The determination of the design resistance of clamped joints has to be carried out taking into account the relevant standards for the constructive elements, e. g. steel or aluminium plates and bolt assemblies, as for example EN 1993-1-8, EN 1993-1-11, EN 1999-1-1 etc. The load-bearing capacity of clamped joints including the membrane material might be determined experimentally by a procedure test.

8.3 Membrane edges

8.3.1 General

At a membrane edge, a membrane field is fastened at its exterior border [Bub97]. It has to carry all loads in the membrane field and transmit them to other building parts, as supports, walls, foundations etc. Membrane edges are distinguished in flexible and rigid edges, see Figures 8-3 and 8-4 as well as [FOM04, Bub97, Seid 09].

Up to now neither regulations nor standards exist for the design of membrane edges.

"*When developing edge details, the biaxial behavior of tension and elongation has especially taken into consideration*" [Bub97]. "*Every movement which might occur in the membrane under stress must not lead to increased, excessive stresses in its edge zone.*

This is basically the same with forces running parallel to the edge, the … tangential forces.”

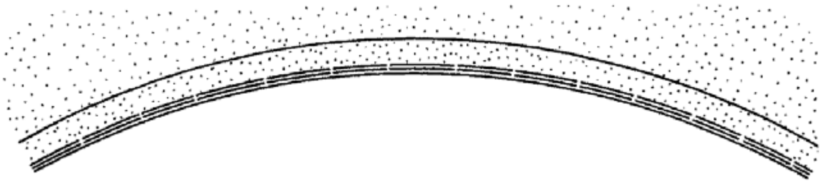


Figure 8-3 Typical flexible membrane edge - reinforcement with cable or belt according to [Bub97]

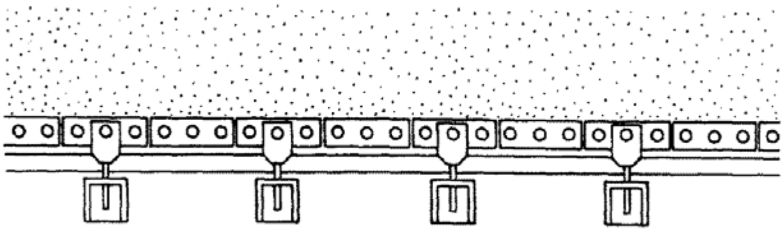


Figure 8-4 Typical rigid membrane edge with fitting and tension elements according to [Bub97]

Eurocode Outlook No. 46

(1) *Membrane edges are distinguished in flexible and rigid edges.*

(2) *The design of membrane edges has to be carried out taking into account the relevant standards for the constructive elements, e. g. steel or synthetic cables, steel or aluminium plates and bolt assemblies, as for example EN 1993-1-8, EN 1993-1-11, EN 1999-1-1 etc. The load-bearing capacity of the clamped joint including the membrane material might be to be determined experimentally by a procedure test.*

8.3.2 Flexible membrane edges

Flexible membrane edges show in the plan a course, which is composed of curved, wreath-like segments. They are typically made of cables or belts. Typical flexible edges are presented in Figure 8-5.

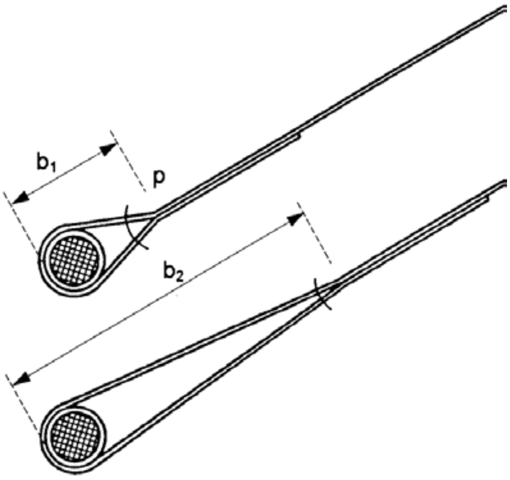
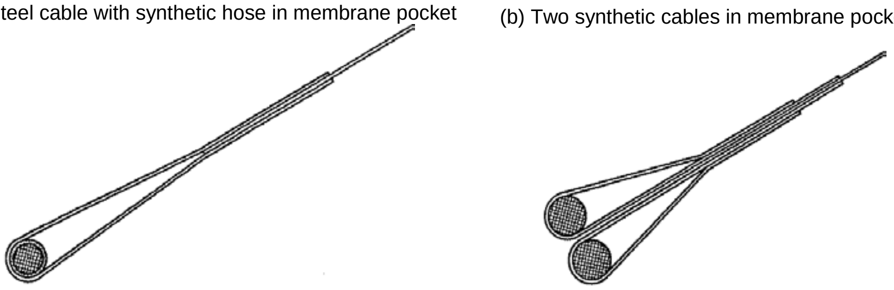
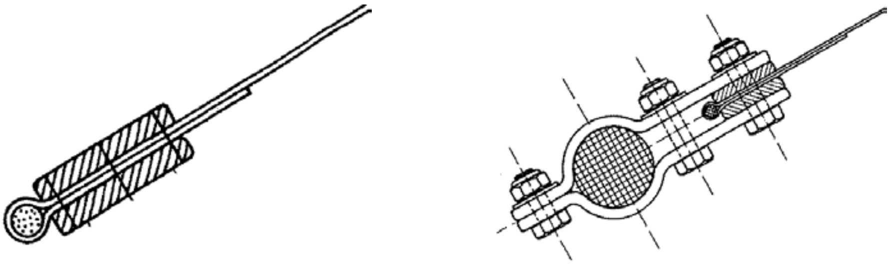


Figure 8-6 Different widths of membrane pockets [Bub97]

As presented in Figure 8-5(a) and (b) one possibility to carry out a flexible edge is to put cables (made of steel or synthetic ones) in a membrane pocket. According to the TensiNet Design Guide [FOM04] an important parameter for the strength of the membrane pocket is the angle between the upper and lower surfaces of the pocket, see Figure 8-6. This value depends on the width of the pocket in relation to the diameter of the cable. This must be large enough to avoid large peeling forces along the line where he pocket is welded to the membrane, i. e. where the upper and lower surfaces of the pocket diverge from another.



(a) Steel cable with synthetic hose in membrane pocket (b) Two synthetic cables in membrane pockets



(c) Sewed double belt (d) Two-piece fitting with clamp bolt

Figure 8-5 Typical exemplary flexible membrane edges according to [Bub97]

According to Bubner [Bub97] the width of a membrane pocket (b1 and b2 in Figure 8-6) cannot be determined by a generally applicable measure. The width depends on the tensile strength which occurs right-angled to the membrane edge. The higher the tension, the greater is the force which stresses the welded or sewed seam at point p, figure 8-6. The smaller the angle at point p is, the lower is the shear force which might tear the seam.

Movements of the fabric along the cable in the tangential direction have to be prevented to avoid abrasion damage. In some cases belts are used to carry the tangential membrane forces directly into the corners [FOM04].

Eurocode Outlook No. 47

(1) The width of a membrane pocket has to be designed taking into

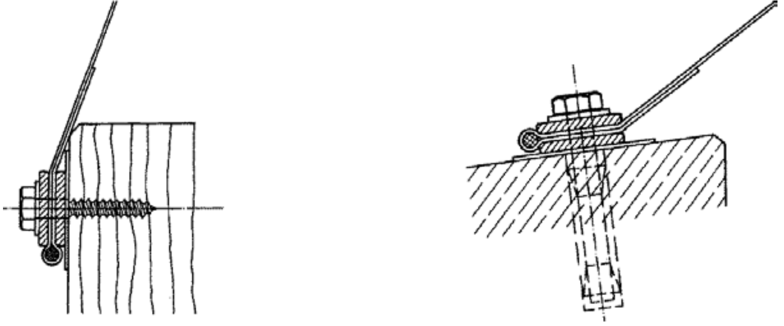
- *the angle between the upper and lower surfaces of the pocket and*
- *the tensile strength which occurs right-angled to the membrane edge.*

(2) Tangential forces along the membrane pocket have to be considered in the design process in order to prevent deformations between the cable and the membrane.

8.3.3 Rigid membrane edges

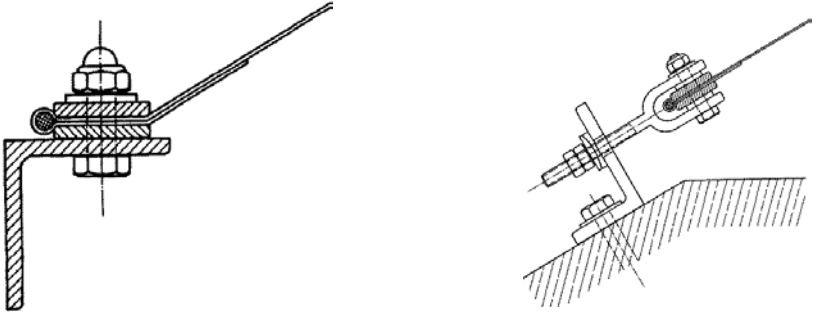
At rigid edges the membrane is held continuously by a supporting structure which has a much higher stiffness than the membrane itself. Typically, rigid connections are made of steel, concrete or timber. At these edges the membrane is often connected by means of stretchable elements [Bub97]. Typical constructive possibilities for rigid edges are presented in Figures 8-7.

Figure 8-8 presents a principle of an edge element made of rotating metal fitting and tension bolt which allows flexible fastening parallel to the edge by a movable anchor track [Bub97]. The fitting adjusts to the membrane's slope by means if the rotating bolt fastening. High tangential forces cannot be resolved by the fitting.



(a) Vertical fastening on timber with screws

(b) Fastening with dowel on concrete



(c) Horizontal fastening on a steel profile

(d) Edge element made of steel angle and tension bolt

Figure 8-7 Typical exemplary rigid membrane edges according to [Bub97]

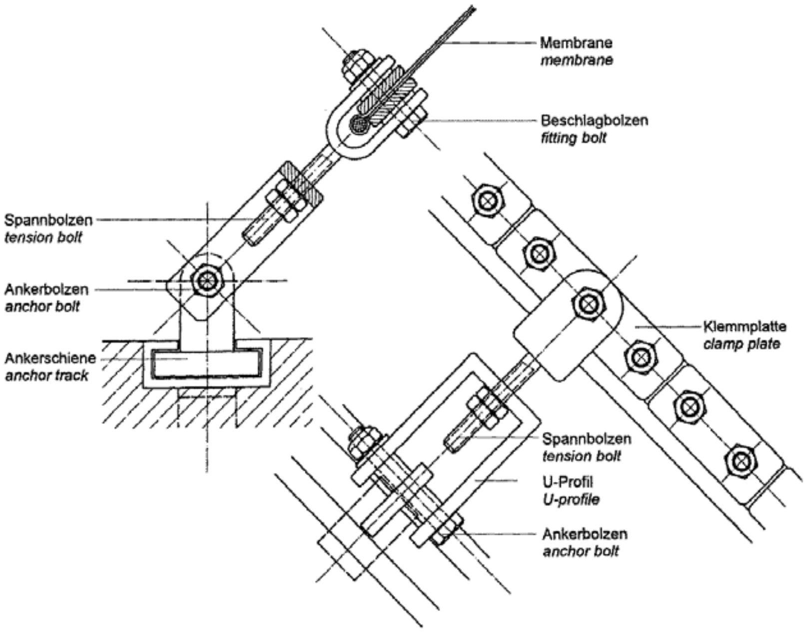


Figure 8-8 Edge element made of rotating metal fitting and tension bolt according to [Bub97]

8.4 Membrane corners

A membrane corner describes the junction of two membrane edges [bub97]. It has to be distinguished between membrane corners for flexible or rigid membrane edges [bub97, FOM04]. The forces in the membrane flow into the boundary elements which transmit them to the corners. Doubly curved membranes have stresses in both warp and fill directions. Stresses perpendicular to an edge are transferred into the edge element. The stresses in the other direction run along the edge and need to be collected at each end, e. g. the corners [FOM04].

Problems concerning the fastening of a membrane field in such a corner are mainly dependent upon three facts [Bub97]:

- upon the geometrical plan of the corner, i. e. the angle between both edges,
- upon the construction of the edge, whether it is flexible or rigid; with rigid edges, whether it has tension elements or nor and
- upon the magnitude of the tangential force.

Membrane corners of flexible edges

Corners of flexible edges are created by using a spandrel. The spandrel region is very critical to overstresses since the short distance between the edges neither allow an elongation of the membrane nor an angular displacement of the fabric in order to reduce overstresses [Bub97]. In addition to that, the membrane has the tendency to glide off the spandrel when under pretension and this overload the membrane, see Figure 8-9. However, looking at the tension in a membrane spandrel between two flexible edges, it cannot be assumed that the membrane overstresses in the region are compensated by the “flexibility” of the edges. Edge cable, edge fitting and corner support or foundation together form a relatively stiff building member in this region. Here the term “flexible” is not an appropriate description when compared with the flexibility of the membrane [Bub97]. Further explanations are given in [Seid09].

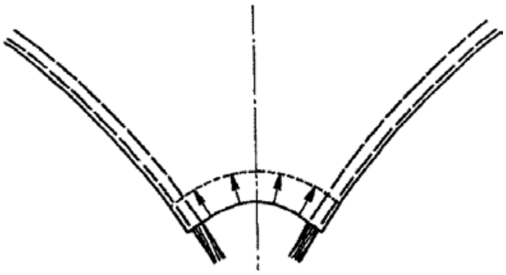
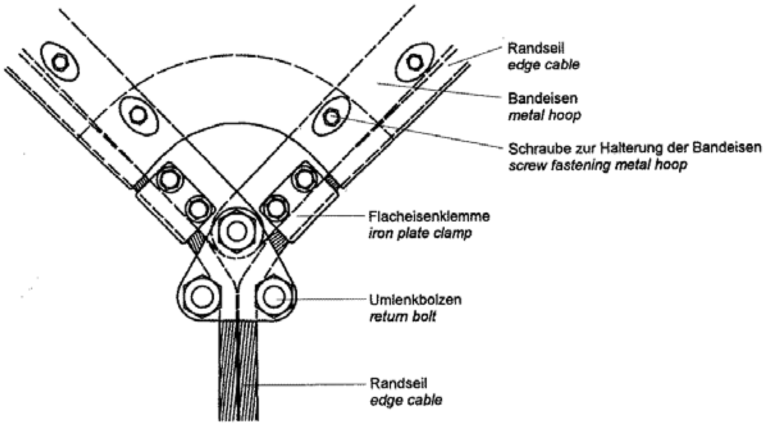


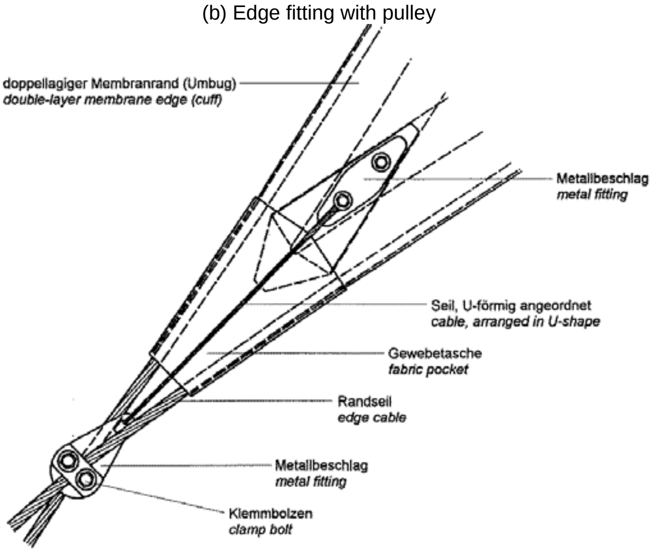
Figure 8-9 Gliding of the membrane in the corner of flexible edges due to tangential forces according to [Bub97]

Some typical solutions for membrane corners of flexible edges are exemplary presented in Figure 8-10. Of course, several other solutions are possible as well, see [FOM04, Seid09, Bub97].

(a) Corner fitting with three bolts



(b) Edge fitting with pulley



(b) Corner fitting at continuous cable connected to main suspension cable

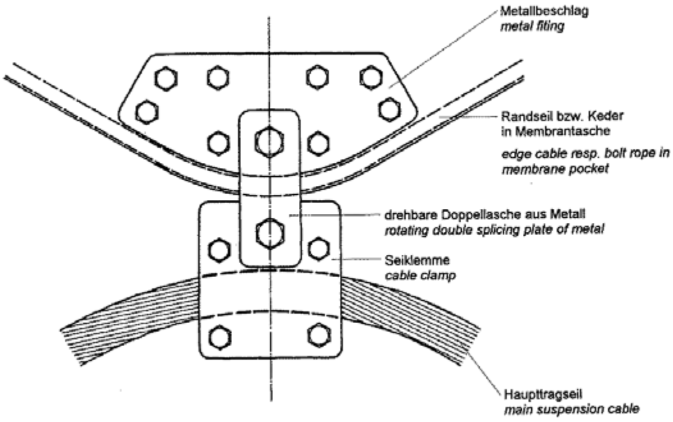


Figure 8-10 Typical exemplary membrane corners of flexible edges according to [Bub97]

Membrane corners of rigid edges

Optimally, membrane corners of rigid edges should avoid corners at all, using curved or oval edges [Bub97]. The smaller becomes the angle of the corner, the more difficult it is to introduce the pretension in the membrane without the formation of folds. One exemplary solution for an obtuse-angled corner with tensioning elements is presented in figure 8-11.

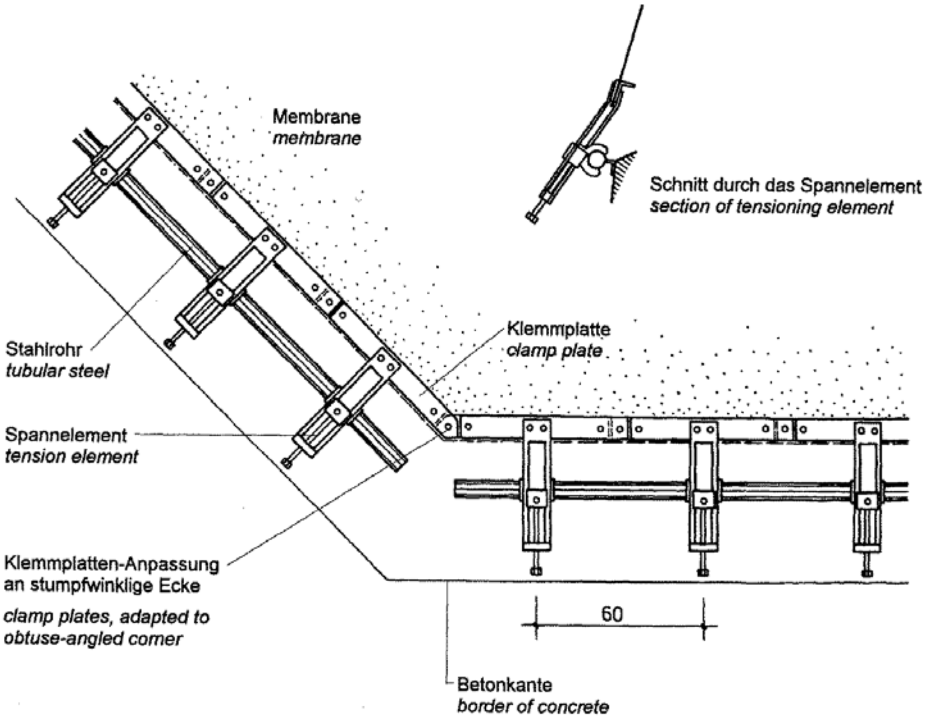


Figure 8-11 Exemplary obtuse-angled corner with tensioning elements of a rigid membrane edge according to [Bub97]

Eurocode Outlook No. 48

(1) In principle, two different kind of membrane corners have to be distinguished.

- *membrane corners of flexible edges and*
- *membrane corners of rigid edges.*

(2) The design of membrane corners has to be carried out taking into account the relevant standards for the constructive elements, e. g. steel or synthetic cables, steel or aluminium plates and bolt assemblies, as for example EN 1993-1-8, EN 1993-1-11, EN 1999-1-1 etc. The load-bearing capacity of the corner might be determined experimentally by a procedure test.

8.5 Ridges and valleys

Ridges and valleys are of similar construction. They differentiate primarily through the fact that ridges form the border at the highest point and valley form the border at the lowest point of two membrane fields. The angles which are formed by abutting membrane fields at ridges and valley range from obtuse- to acute-angled [Bub97].

The supporting constructing elements of ridges and valleys may be carried out with flexible (cables, belts) or rigid (beams, trusses) material [Bub97].

Ridges and valleys are similar in construction of the edges of membrane structures, in some cases even identical [Bub97]. Further explanations are given in [Bub97].

8.6 High and low points

According to [Bub97] the expressions “high point” and “low point” describe a form of construction which only occurs when constructing with flexible elements. The high point is the highest point in a membrane surface. The low point is located inside the membrane field.

High and low points are required to obtain sufficient curvature on the flexible membrane surface which is subject to tensile forces. Their position and frequency of use is predominantly determined by this purpose [Bub97].

Thus, high and low points describe boundary supports for the membrane. The forces developing within the surface ultimately become focused at these boundary supports [FOM04].

Further explanations are given in [Bub97, FOM04, Seid09].

8.7 Reinforcements

In all areas where stress concentrations can occur, e. g. edges, ridges, valleys, corners, high and low points, the membrane shall be reinforced as required with additional fabric/foil or belts. When reinforcing of the membrane or membrane liner is required, it shall consist of either membrane, metallic or non-metallic cables or non-metallic reinforcing. Such materials shall be of uniform quality and shall have properties for the intended usage.

8.8 Base plates for masts and anchors

Base plates for masts and anchors made of steel, concrete, timber etc. shall be designed according to the relevant standards. They have to be able to allow the anticipated rotations and shall have enough adjustability to maintain proper tension forces. Furthermore, deformations due to long-term effects and eccentricities have to be taken into account.

8.9 Anchors and foundations under tension

The anchorage system shall be designed to distribute individual anchor loads uniformly to the membrane in such a way that excessive stress concentrations in the membrane are avoided. Movements and rotations of the membrane and/or the membrane structure under loading and the changes in the direction of the reaction or load application shall be considered in the design of all anchorages.

9 Execution of membrane structures

9.1 General

The execution of membrane structures requires special attention. The membrane reacts very sensitive to overstresses and misleading detailing. Furthermore, the primary and secondary structures, which are made of different materials and have different stiffness, behave different and require different execution rules. The execution rules for the primary structure made of steel, aluminium, concrete or timber are specified in their related execution standards, as for example EN 1090-2 for steel structures.

EN 1090-2 specifies the component specification, which consists of the documents provided by the manufacturer and/or purchaser giving all necessary information and technical requirements for manufacturing the structural components. Herein workshop drawings are covered.

Due to the fact that specific standards or recommendations do not exist for membrane structures, execution rules have to be specified for the future Eurocode for membrane structures. As a first step towards such rules, the recommendations already given in the TensiNet Design guide [FOM04] have been reviewed and improved. In the following these improved execution rules are presented.

9.2 Cutting pattern determination, workshop drawings

Cutting patterns and workshop drawings shall be prepared with utmost care meeting the tolerances given in the project specifications.

Biaxial tests based on the loads resulting from the engineer’s structural analysis should be used in determining the “compensation values” to be applied to the cutting patterns. The process requires utmost care as well.

To assist in making a “fault-free” production the cutting patterns and workshop drawings should be furnished with all the information required for each work piece. The drawings should include cross-references to all components to be connected to each panel such as ropes, cables, steelwork etc.

The component specifications (drawings etc.) are to be provided with caution notes and control measures and tolerances necessary for quality monitoring. In preparing these drawings it must be checked that each pattern can be cut from the roll as a complete piece. Division into sub-pieces within a single pattern must not be permitted.

In particular, the following detail information should be included in the component specification:

(a) Layout plans including the numbering system of the individual parts and fabric panel distribution. It has to be ensured that the correct direction of the seam overlap is indicated with reference to the direction of the rainwater flow.

(b) Drawings of the individual panels including relevant co-ordinates, definition of the warp and weft direction, seams and seam widths.

(c) The welding process to be used.

(d) All necessary details such as doublings, reinforcements, edge cable pockets and any other elements to be added, including the corresponding details on the welding seam, as well as belt reinforcements with an indication of the belt’s connection to the seam.

(e) The setting-out of all holes and the required radii, including reference to drawings of corresponding hardware, clamping plates, etc.

(f) Detailed information for all elements (such as clamping plates, corner fittings, cables to be pulled through, etc.) those are to be connected to the membrane during the shop-phase.

Parallel with the cutting patterns, workshop drawings need to be prepared for ancillary fixation accessories which are the link between the membrane and supporting structure. These should include the following:

a) All hardware components including information on the materials to be used and their surface treatment, the connection elements and their positioning and fastening.

b) Dimensions that have to be checked for conformity with the supporting framework drawings and the cutting patterns prior to release.

c) Cable types including fittings, quality standards and corrosion protection thereof, unstrained system lengths after “pre-stretching” of each cable, and the required production markings.

Prior to the start of production it should be ensured that all relevant component specifications (drawings etc.) contain the approval of the responsible engineer. All drawings and / or the corresponding data files should be stored at least for the warranty period of the project

9.3 Acquisition of the membrane material

The membrane material has to be ordered in accordance with the contractually agreed engineering design specification. Quality assurance has to be agreed with the material manufacturer in such a way that the material conforms in full with the specified properties and quality requirements. Corresponding test certificates, approvals, etc. have to be obtained.

The membrane quantity to be ordered should be determined in such a way that the complete project, or at least the panels related to a single prefabricated membrane field, can be manufactured from a single production lot. When using multiple production lots, it needs to be ensured that biaxial tests are run for each lot so that any differences in [%] compensation values can be taken into account.

Marking rules and other specifications such as minimum roll length, type of packaging, etc. should be included in the order. An error log should be given upon delivery.

Supplied material should be checked for quality conformance, quantity and surface appearance immediately upon receipt of the goods.

A 3.1 certificate according to EN 10204 [X99-7] from the membrane supplier should be available for each supplied material. If no 3.1 certificates are preservable, the following tests have to be carried out for each lot to check the conformance with the technical data:

- Tensile strength tests in weft and warp at 23°C and adhesion tests (suitably calibrated test machines should be used).
- If required, it can be checked as to what extent a given deviation is admissible for the project, based on the engineering calculations.
- Translucent material shall be passed over a light table to determine any additional flaws (fabric damage, colour inconsistencies, etc.). Fabric pieces that have coating defects, which could lead to strength and life impairment at a future date, are to be excluded from processing.

- In addition, a visual inspection for “bow” and “skew” of the warp and weft yarns has to be carried out. In case of significant deviations, the opinion of the responsible engineer has to be obtained before processing can commence.

9.4 Processing, cutting and welding

Only previously approved material shall be used for processing.

Individual pieces can be cut out by hand using templates, or by a cutting head directed automatically via electronic data files, see Figure 9-1. It has to be documented which material is used in which membrane field / part.

Before further manufacturing a random measuring check of the cuttings should take place.

During cutting, the material’s surface has to be checked for defective areas. Such defective areas have to be discarded.

The individual pieces should be marked in accordance with the panel layout so that correct placing within the completed panel is ensured. Markings must be removed promptly after completion of panel fabrication unless located in a covered seam area.

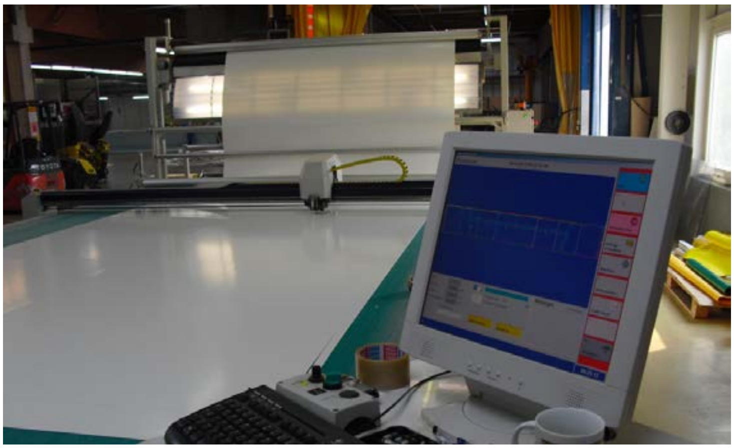


Figure 9-1 Automatically cutting of membrane material via electronic data files [© CENO Membrane Technology GmbH]

For PVDF-coated material, the surface of the seam area has to be ground prior to welding. When doing so, it has to be ensured that PVDF particles are removed completely as otherwise there is a risk that the required seam strengths may not be achieved. At the same time, it has to be ensured that the remaining coating sufficiently covers the crowns of the fabric’s yarns and that the yarns themselves are not damaged. If damage occurs, the corresponding panel should no longer be used.

Appropriate to each task, the welding electrode, heating bars or similar have to be prepared. The welding seam parameters as well as the performance parameters of the welding equipment have to be considered. Electrodes, heating bars, etc. should be produced with rounded corners. The equipment must be checked for operative readiness, accurate adjustment and cleanliness. In particular, the intimate and continuous contact between the electrode heating bar and the welding table has to be ensured.

The settings of the welding parameters for each machine have to be defined using seam tests. During manufacturing the present welding parameters have to be checked by a manual test (e.g. manual tearing test to view the welding seam) beginning of each working shift. All welding parameters for these tests must be documented. A typical welding situation can be seen from Figure 9-2.

Figure 9-2 Typical welding situation [© CENO Membrane Technology GmbH]

For middle and larger projects (??? Specification needed??) uniaxial tension test must be carried out in addition. These tests should be done weekly for each main membrane detail. The results of the tests and the parameters have to be recorded and included in the project documentation.

In case of project or material changes, new tests have to be carried out.

In case welding shrinkage may occur, the seams have to be stretched to a defined load by an appropriate technique during the welding process.

By appropriate means at the welding machine, it also has to be ensured for primary seams that the required welding parameters (welding time, capacity, pressure, cooling time, cooling temperature etc.), are controlled during the whole processing time.

Welded seams have to be visually inspected by the machine operator and periodic checks may be fulfilled by the welding expert. Particular attention has to be paid to areas with doublings, seam crossing, etc..

For any imperfection it is necessary to check these once with the responsible welding expert or / and project engineer before further production.

The edge weldments, such as reinforcements, belts, rope pockets, rainwater deflectors, etc. are added afterwards on the basis of the drawings and specifications. The corresponding welding parameters for these elements *should* be checked and recorded. A final dimensional protocol with control dimensions has to be prepared and included with the documentation.

It is important that edge rope pockets, edge reinforcements or similar are cut to fit the “form found” shape of the membrane fields to which they are to be attached. During the patterning of these components, the same standard has to be applied for the direction of the warp and weft yarns as for the definition of the main panel. For sewn or welded-on belts, the difference in their strain behaviour with that of the membrane panel has to be taken into account to ensure structural compatibility.

The structural capacity of corner edge reinforced areas should be proved during the detail design process.

For holes which will be punched into the membrane during fabrication (e.g. holes for high point clamping) the compensation values have to be taken into account. The specifications given on the drawings have to be complied exactly.

Where clamp plates have been installed and edge ropes pulled through following the final inspection / acceptance of the finished membrane, it is important that any sharp-edged or heavy components are suitably wrapped to prevent damage to the membrane by chafing during packing and transport.

9.5 Particulars in PTFE glass fibre processing

During in-house movement, processing and packaging, the high sensitivity of PTFE coated glass fibre to folding has to be taken into account. In particular it is essential to avoid sharp-edged buckling and folding. Where folding is required for handling and transportation reasons, the insertion of intermediate layers of foam rubber cushioning or similar is of paramount importance.

The importance of the preparation and adjustment of parameters and their safeguarding over the whole manufacturing operation applied in the processing of PVC-coated fabrics equally applies to the processing of PTFE coated glass albeit adapted to different welding equipment.

During welding usually a PFA or FEP film between the layers is used as a welding-aid:

a) FEP (Fluorinated Ethylene Propylene) is a fluor chemical product that is very similar to PTFE and ETFE. It is typically used for the top coating of PTFE coated glass fibre fabrics. It is available as foil and is used as a “bonding agent” to provide a higher strength of the welding seam.

b) PFA (Tetrafluoroethylene perfluoroalkoxy vinyl ether copolymer) is a fluor chemical with very similar characteristics to PTFE and FEP which is, among other forms, also available as foil.

Both films are very similar, the only difference is the melting behaviour (a PFA film melts at about 10-24°C higher than FEP film).

When pre-fixing the film, it is important to make sure that the selected process will not damage the filaments.

Adequate measures should be taken to minimize welding shrinkage during welding procedure.

9.6 Inspection before packing

Before packaging a final inspection has to be done and documented. Together with the results of all material tests, tensile tests (e.g. seams, other details) and all notes made during production this final inspection report has to be included in the overall documentation of the project. These documents shall be retained at least for the duration of the warranty period.

Panel dimensions such as seam lengths, edge lengths and opening clearance control dimensions need to be checked. In addition, control dimensions that were specified during preparation of the panels and workshop planning have to be checked.

Project-related membrane tolerances must be defined. If none are given the following should be followed:

Surface seams edges: 0.5 - 1 % depending on the overall length

Clamping edges: 0.25 – 0,5 % depending on the overall length

Edge cable pockets: max. 0.5 % depending on the overall length.

A visual inspection before packaging ensures that the membrane is free from all forms of mechanical damage, the surface is clean, tailored steel plates or similar are packed and that all reinforcements and seams are properly welded.

9.7 Packaging and transportation

The individual membrane elements are to be packed in accordance with the packaging instructions (folding plan, marking specifications, type of packaging, planned transportation) in such a way that any damage in transit is excluded and that identification of discrete items at the site is possible.

In order to prevent any damage by chafing during transportation, each individual membrane element has to be wrapped in a protective covering.

The packaging has to be chosen so as to ensure damage-free loading and unloading.

When packing PTFE coated glass material, every precaution has to be taken with respect to its susceptibility to fold damage. Appropriate packaging materials are various foamed materials, jacketed PVC tubes, “bubble wrap”. Crosswise folds should be avoided. The folded and packaged membrane must not be walked on or put under load at any stage by depositing other components on it. For truck or container transport separate precautions may have to be taken, such as the use of intermediate floors.

9.8 Erection

As several different types of membrane structures exist, like e. g. highpoint-, arch- or free spanned areas, structures with fixed borders or cable pockets, membranes made out of coated or uncoated polyester, glass fibre material or ETFE-foils, a lot of different ways of installation are possible, which always depends on the structure.

For membranes which are designed on a fixed geometry, the focus has to be laid on other points as for adjustable surfaces. Even for one and the same project different installation methods might be needed because of roof and façade areas. Consequently, for every membrane structure a project related method statement has to be worked out including a detailed risk analysis.

Furthermore, due to the uncommon material behaviour of fabrics and ETFE-foils their installation should always be carried out by skilled and trained labors.

During the erection phase, stresses initially tend to flow mainly through the membrane rather than through the edge ropes which remain slack until the membrane reaches its tensioned position. Thus, the weight of the fabric is carried solely by its connection to the corner.

Corners themselves have a particular mass that shall be taken into account during the installation procedure. Temporary support may be needed to hold the corner in place and properly direct it to its rough final angle.

Installation devices are needed to enable the lifting, stretching and pre-stressing of the membrane. The corners shall be provided with means of attachment such as spare holes, for instance.

10 Concluding Remarks

To be done

11 References

Test Standards

[X90] EN ISO 1421:1998, Rubber- or plastics-coated fabrics – Determination of tensile strength and elongation at break

[X91] EN ISO 899-1:2003, Plastics – Determination of creep behavior, Part 1: Tensile creep

[X92] EN ISO 527-1:2012, Plastics – Determination of tensile properties, Part 1: General principles

[X92-2] EN ISO 527-3:1995+AC:1998+AC:2002, Plastics - Determination of tensile properties, Part 3: Text conditions for films and sheets

[X93] EN 1875-3:1997, Rubber- or plastics-coated fabrics – Determination of tear strength – Part 3: Trapezoidal method

[X94] EN ISO 2411:2000, Rubber- or plastics-coated fabrics – Determination coating adhesion

[X95] DIN 53363:2003-10, Prüfung von Kunststoff-Folien – Weitereißversuch an trapezförmigen Proben mit Einschnitt

[X96] EN ISO 2286:1998, Rubber- or plastics-coated fabrics – Determination of roll characteristics

[X97] ASTM D 4851-07, Standard Test Methods for Coated and Laminated Fabrics for Architectural Use

[X98] EN ISO 13934-1:2013, Textiles – Tensile properties of fabrics – Part 1: Determination of maximum force and elongation at maximum force using the strip method (ISO 13934-1:2013)

[X99-1] DIN 53354:1981-02, Prüfung von Kunstleder; Zugversuch (withdrawn July 2007)

[X99-2] Draft DIBt-Richtlinie: Richtlinien für die Zulassungsprüfung beschichteter Gewebe und deren Verbindungen, October 1983 (DIBt - Deutsches Institut für Bautechnik, Berlin, Germany – Draft DIBT-Guideline for the acceptance test of coated fabrics and their joints)

[X99-3] ASTM D 5035-95, Standard Test Method for Breaking Force and Elongation of Textile Fabrics (Strip Method)

[X99-4] DIN 53357:1982-10, Prüfung von Kunststoffbahnen und -folien; Trennversuch der Schichten (withdrawn)

[X99-5] EN ISO 7500-1:2004, Metallic materials , Verification of static uniaxial testing machines , Part 1: Tension/compression testing machines , Verification and calibration of the force-measuring system

[X99-6] EN 1876-2:1997, Rubber- or plastics-coated fabrics - Low temperature tests, Part 2: Impact test on loop

[X99-7] EN10204:2004, Metallic products , Types of inspection documents

Design Standards / Technical Recommendations

[X100] EN 1990:2002 + A1:2005 + A1:2005/AC:2010, Eurocode 0 – Basis of structural design

[X101] EN 1991, Eurocode 1 – Actions on structures

[X102] EN 1992, Eurocode 2 – Design of concrete structures

[X104] EN 1993-1-1: 2005 + AC:2009, Eurocode 3: Design of steel structures, Part 1-1: General rules and rules for buildings.

[X105] EN 1993-1-11: 2006 + AC:2009, Eurocode 3: Design of steel structures, Part 1-11: Design of structures with tension components

[X120] DIN 4134:1983-02, Tragluftbauten – Berechnung, Ausführung und Betrieb

[X121] DIN 18204-1:2007-05, Raumabschließende Bauteile aus textilen Flächengebilden und Folien (Zeltplanen) für Hallen und Zelte, Teil 1: PVC-beschichtetes Polyestergewebe

[X122] DIN 18800-1:2008-11, Stahlbauten – Bemessung und Kontsruktion

[X123] Mitteilungen Deutsches Institut für Bautechnik, 29. Jahrgang Sonderheft Nr. 11/2, 3. Auflage, Anpassungrichtlinie Stahlbau, Herstellungsrichtlinie Stahlbau. Dezember 1998, Ernst & Sohn, 1998

[X124] Recommandations pour la conception, la confection et la mise en œuvre des ouvrages permanents de couverture textile aux éditions SEBTP, ISBN 978-2-35917-003-0

[X125] EN 15619:2014, Rubber or plastic coated fabrics - Safety of temporary structures (tents) - Specification for coated fabrics intended for tents and related structures

[X126] EN 12385-10:2003+A1:2008, Steel wire ropes – Safety – Part 10: Spiral ropes for general structural applications

[X127] EN 13782: Temporary structures – Tents – Safety

[X128] ASCE SEI 55-10:2010, Tensile Membrane Structures

[X129] Règlement de sécurité incendie dans les ERP (approuvé par arrêté du 25 juin 1980 et modifié) : Livre 4 Dispositions applicables aux établissements spéciaux - Chapitre 2 Etablissements du type CTS : chapiteaux, tentes et structures - Articles CTS1 à CTS81

[X130] Règlement de sécurité incendie dans les ERP (approuvé par arrêté du 25 juin 1980 et modifié) : Livre 4 Dispositions applicables aux établissements spéciaux - Chapitre 3 Etablissements du type SG : structures onflables - Articles SG1 à SG25", ERP signifiant Etablissements Recevant du Public

[X131] EN 13782:2005: Temporary Structures – Tents – Safety

[X132] EN 1090-2:2008+A1:2011, Execution of steel structures and aluminium structures – Part 2: Technical requirements for steel structures

[X133] EN 13501-1:2007+A1:2009, Fire classification of construction products and building elements, Part 1: Classification using data from reaction to fire tests

Technical Approvals

[T100] Allgemeine bauliche Zulassung (abZ) Nr. Z-10.5-18: Membranhülle, Nolte

[T101] Allgemeine bauliche Zulassung (abZ) Nr. Z-10.5-26: Traglufthalle, Brinckenkamp

[T102] Allgemeine bauliche Zulassung (abZ) Nr. Z-10.5-27: Traglufthalle, Güteüberweisung

[T103] Allgemeine bauliche Zulassung (abZ) Nr. Z-10.5-32: Membranhülle, Sarna

[T104] Allgemeine bauliche Zulassung (abZ) Nr. Z-10.5-35: Traglufthalle, Struckmeyer

[T105] Allgemeine bauliche Zulassung (abZ) Nr. Z-10.5-36: Silo, Krause

[T106] Allgemeine bauliche Zulassung (abZ) Nr. Z-10.5-54: Gewebe, Wülfing+Hauck

[T107] Allgemeine bauliche Zulassung (abZ) Nr. Z-10.5-59: Gewebe, KIB

[T108] Allgemeine bauliche Zulassung (abZ) Nr. Z-10.5-60: Gewebe, Nolte

[T109] Allgemeine bauliche Zulassung (abZ) Nr. Z-10.5-72: Traglufthalle, Strohmeyer

[T110] Allgemeine bauliche Zulassung (abZ) Nr. Z-10.5-91: Folienkissen, Foiltec

[T111] Allgemeine bauliche Zulassung (abZ) Nr. Z-10.5-188: Gewebe, Verseidag

[T112] Allgemeine bauliche Zulassung (abZ) Nr. Z-10.5-191: Seilnetzhalle, Wülfing + Hauck

[T113] Allgemeine bauliche Zulassung (abZ) Nr. Z-10.5-206: Gewebe Typ 609, Sattler

[T114] Allgemeine bauliche Zulassung (abZ) Nr. Z-10.5-207: gewebe Typ 648, Sattler

[T115] Allgemeine bauliche Zulassung (abZ) Nr. Z-10.5-224: Gewebe, Best-Hall

Journal Papers, Research References and Background Documents

[ABT97] Annals Du Batiment Travaux, Recommendation pour la conception des ouvrages permanents de Couverture Textile, 1997.

[Ball07] Ballhause, D., Diskrete Modellierung des Verformungs- und Versagens-verhaltens von Gewebemembranen, PhD-Thesis, University of Stuttgart, 2007.

[BGB13] Bartle, N. J., Gosling, P. D., Bridgens, B. N., A neural network material model for the analysis of fabric structures, Proceedings of the TensiNet Symposium, Istanbul, pp. 33- 42, 2013.

[BD04] Balz, M., Dencher, M., Design loading conditions, in: Forster, B., Mollaert, M. (eds.), European Design Guide for Tensile Surface Structures, TensiNet Association, 2004.

[Bec11] Beccarelli, P., Bridgens, B.N., Galliot, C., Gosling, P.D., Stimpfle, B., Zanelli, A., Round-robin biaxial tensile testing of architectural coated fabrics, in: Proceedings of the IABSE-IASS Symposium, 2011

[Bid89] Bidmon, B., Zum Weiterreißen von beschichteten Geweben, PhD-Thesis, Universität Stuttgart, 1989.

[BlBö07] Bögner, H., Blum, R., Crack propagation and the dimensioning for PTFE-coated Glass-Fibre-Fabrics, TensiNet Symposium, Milano, 2007.

[Böhm12] Böhmer, C., Transport und Montage von Membrankonstruktionen – Lehren aus der Praxis, in: Proceedings of the Essener Membranbau Symposium 2012, Saxe, K., Stranghöner, N., (eds.), Shaker Verlag, Aachen, 2012.

[BrBi12] Bridgens, B.N., Birchall, M., Form and function: The significance of material properties in the design of tensile fabric structures, Engineering Structures, Vol. 44, pp. 1-12, 2012.

[BrGo10] Bridgens, B.N., Gosling, P.D., Interpretation of results from the MSAJ “Testing Method for Elastic Constants of Membrane Materials”, Proceedings of the TensiNet Symposium, Sofia, 2010, pp. 49-57.

[Bub97] Bubner, E.: Membranskonstruktionen – Verbindungstechniken, edition 1997, Druckerei Wehlmann GmbH, Essen, ISBN 3-9805790-7-7.

[CEN13] CEN/TC 250, Towards a second generation of EN Eurocodes, Response to mandate M/515, May 2013.

[ch6] http://www.mcise.uri.edu/sadd/mce565/Ch6.pdf

[Col14] Colasante, G., Presentation on CEN/TC 250 WG5 meeting, September 2014, Paris (unpublished)

[Cook85] Cook, N .J., The designer´s guide to wind loading of building structures, Part 1: Background, damage survey, wind data and structural classification, Butterworths, 1985.

[Cook90] Cook, N. J., The designer´s guide to wind loading of building structures, Part 2: Static structures, Butterworths, 1990.

[FM04] Forster, B., Mollaert, M. (eds.), European Design Guide for Tensile Surface Structures, TensiNet, 2004.

[FrMG13] French Mirror Group, Membrane struct FrMG position partial safety factors, working document for CEN/TC250 WG 5, 2013 (unpublished).

[GaLu09] Galliot, C., Luchsinger, R., A simple model describing the non-linear biaxial tensile behaviour of PVC-coated polyester fabrics for use in finite element analysis, Composite Structures, Vol. 90, No. 4, pp. 438-447, 2009.

[GCH12] Gulvanessian, H., Calgaro, J.-A., Holicky, M., Designers' Guide to Eurocode: Basis of structural design, EN 1990, Second Edition, Thomas Telford, London, 2012.

[Gib13] Gibson, N.D., CEN TC 250 – Review of partial factors in membrane analysis, working document for CEN/TC250 WG 5, 2013 (unpublished).

[Gos13] Gosling, P. et al., Analysis and design of membrane structures: Results of a round robin exercise, Engineering Structures, Vol. 48, pp. 313-328, 2013.

[Hom03] Homm, Th., Vergleichende Untersuchungen zur Schädigungswirkung von Knickbeanspruchungen an PTFE-beschichteten Glasfasergeweben, Diploma Thesis, University of Duisburg-Essen, 2003.

[Hos79] Hosser, D., Erläuterungen zum Bemessungskonzept für Tragluftbauten, Frankfurt, 1979 (unpublished).

[Hou13] Houtman, R. (ed.), TensiNet European Design Guide for Tensile Structures Appendix5: Design recommendations for ETFE foil structures, TensiNet, 2013.

[IBG13] Iliffe, C.N., Bridgens, B.N., Gosling, P.D., A predictive model for the design of functional textiles, in: Proceedings of the Structural Membranes 2013, pp. 395-406, Bletzinger, K.-U., Kröplin, B., Oñate, E. (eds), Munich, Germany, 2013.

[KCGM10] Knippers, J., Cremers, J., Gabler, M., Lienhard, J., Atlas Kunststoffe + Membranen – Werkstoffe und Halbzeuge, Formfindung und Konstruktion; Institut für Internationale Architektur-Dokumentation, München, 2010.

[KM12a] Kathage, K., Misiek, T., Bemessung und Konstruktion von Zuggliedern nach DIN EN 1993-1-11, Stahlbau, Vol. 81, No. 4, pp. 324-331, 2012.

[KM12b] Kathage, K., Misiek, T., Bemessung von Zuggliedern nach DIN EN 1993-1-11 – Grenzzustände der Gebrauchstauglichkeit, Stahlbau, Vol. 81, No. 8, pp. 621-623, 2012.

[Lau92] Laute, J.-P., Structures à câbles, Techniques de l'Ingénieur, C2580, 10 February 1992.

[Lem68] Lempriere, B. M., Poisson's ratio in orthotropic materials, AIAA Journal, Vol. 6, No. 11, pp. 2226–2227, 1968.

[Koc04] Koch, K.-M., Bauen mit Membranen – Der innovative Werkstoff in der Architektur; Prestel-Verlag, 2004.

[ML93] Malinowsky, M., Lyonnet, Ch., Structures textiles, Techniques de l'Ingénieur, C2470, 10 August 1993.

[Meff78] Meffert, B., Mechanische Eigenschaften PVC-beschichteter Polyestergewebe, PhD-Thesis, RWTH Aachen University, 1978.

[Mich11] Michalski, A., Haug, E., Wüchner, R., Bletzinger, K.-U., Validierung eines numerischen Simulationskonzepts zur Strukturanalyse windbelasteter Membrantragwerke, Bauingenieur, Vol. 86, No. 3, pp. 129-141, 2011.

[Mich14] Michalski, A., Membrantragwerke im Wind – Berechnungsmethoden und Herausforderungen, in: Proceedings of the 2. Essener Membranbau Symposium 2014, Stranghöner, N., Saxe, K., Uhlemann, J. (eds), Shaker-Verlag, Aachen, 2014.

[Min81] Minte, J., Das mechanische Verhalten von Verbindungen beschichteter Chemiefasergewebe, PhD-Thesis, RWTH Aachen University, 1981.

[MSAJ95] Membrane Structures Association of Japan, “MSAJ/M-02-1995 – Testing Method for Elastic Constants of Membrane Materials”, (1995).

[Ngu13] Nguyen Q., T., Contribution à l'étude du gonflage, de la flexion et du flambement de tubes membranaires orthotropes, PhD-Thesis, LUNAM University, Nantes, 2013.

[NgTh13] Nguyen, Q. T., Thomas, J.-C., Van, A. L., An exact solution to calculate the length and radius of an orthotropic inflatable beam – a theoretical application to the determination of the material coefficients, Proceedings of the TensiNet Symposium, Istanbul, 2013, pp. 333-342.

[Peil00] Peil, U., Bauen mit Seilen, in: Kuhlmann, U. [ed.], Stahlbau-Kalender 2000, pp. 690-755, Berlin, Ernst & Sohn, 2000.

[PWB13] Philipp, B., Wüchner, R., Bletzinger, K.-U., Conception and design of membrane structures considering their non-linear behaviour, Proceedings of the Structural Membranes, Munich, 2013.

[Rei76] Reinhardt, H.-W., Zweiachisge Prüfung und Festigkeit von textilen Baustoffen, Bautechnik, Vol. 53, No. 4, pp. 138-141, 1976.

[Saal94] Saal, H., Bucak, O., Schulz, U., Der Einfluss von Temperatur und Freibewitterung auf das Langzeitververhalten von Membranwerkstoffen und ihren Verbindungen, in: Saal, H., Neue Entwicklung im konstruktiven Ingenieurbau, Universität Karlsruhe, Versuchsanstalt für Stahl, Holz und Steine, Karlsruhe, pp. 87-109, 1994.

[Sax12] Saxe, K., Zur Berechnung und Bemessung von ETFE-Folientragwerken, , in: Proceedings of the Essener Membranbau Symposium 2012, Saxe, K., Stranghöner, N. (eds), Shaker-Verlag, Aachen, 2012.

[Sax13] Saxe, K., Membrantragwerke und ihre Prüfmethoden – Biaxialprüfung der Festigkeit textiler Baustoffe, *Bautechnik Spezial 2013*, pp. 68-73, 2013.

[SBN14] Schröder, J., Balzani, D., Nisters, C., Zur Modellierung dünner Schalen mit hyperelastisch isotropem und anisotropem Materialverhalten, , in: Proceedings of the 2. Essener Membranbau Symposium 2014, Stranghöner, N., Saxe, K., Uhlemann, J. (eds), Shaker-Verlag, Aachen, 2014.

[SBS11] Schröder, J., Balzani, D., Stranghöner, N., Uhlemann, J., Gruttmann, F., Saxe, K., Membranstrukturen mit nicht-linearem anisotropem Materialverhalten - Aspekte der Materialprüfung und der numerischen Simulation, Bauingenieur, Vol. 86, No. 9, pp. 381-389, 2011.

[Sch09] Schmid, G., Neues Bauen mit ETFE-Folien, Entwerfen und Konstruieren mit dem Hightech-Werkstoff (Teil 1), Planung – Bäderbau; AB Archiv des Badewesens 04/2009

[Sclz87] Schulz, U., Einfluss der Freibewitterung bei Membranwerkstoffen und ihren Verbindungen, Berichte der Versuchsanstalt für Stahl, Holz und Steine, 4. Folge, Heft 17, Karlsruhe, 1987[ABT97] Annals Du Batiment Travaux, Recommendation pour la conception des ouvrages permanents de Couverture Textile, 1997.

[Seid09] Seidel, M., Tensile Surface Structures – A Practical Guide to Cable and Membrane Construction, Ernst & Sohn, Berlin, 2009.

[Sof12] Sofistik 2012, handbook.

[SSU14] Saxe, K., Stranghöner, N., Uhlemann, J., Membranwerkstoffe: Zusammenhang zwischen Bauaufgabe und Materialauswahl, in: Proceedings of the 2. Essener Membranbau Symposium 2014, Stranghöner, N., Saxe, K., Uhlemann, J. (eds), Shaker-Verlag, Aachen, 2014 (including presentation held at the symposium at 28 September 2014).

[Sti14a] Stimpfle, B., Proposal sensitivity analysis, working document for CEN/TC250 WG 5, 2014 (unpublished).

[Sti14b] Stimpfle, B., ETFE Design concept with partial safety factors, working document for CEN/TC250 WG 5, 2014 (unpublished).

[Sti14c] Stimpfle, B., *Data abz*, working document for CEN/TC250 WG 5, 2014 (unpublished).

[SU13] Stranghöner, N., Uhlemann, J., Study regarding the partial safety factors on the action side, working document for CEN/TC250 WG 5, 2013 (unpublished).

[SU14] Stranghöner, N., Uhlemann, J., Determination of 5%-fractiles according to EN 1990, working document for CEN/TC250 WG 5, 2014 (unpublished).

[SUMG14] Stranghöner, N., Uhlemann, J., Mollaert, M., Gosling, P., The Development of a Eurocode “Tensile Membrane Structures”, Proceedings of the 37th IABSE International Symposium, Madrid, Spain, September 3-5, 2014, p. 1572-1578.

[TEC12] The European Commission, Mandate M/515 EN – Mandate for amending existing Eurocodes and extending the scope of Structural Eurocodes, Brussels, 12th December 2012.

[Tho02] Thomas, J.-C., Etude expérimentale et modélisations analytiques et numériques de poutres gonflables à haute pression, PhD-Thesis, University of Nantes, 2002.

[TCW08] Thomas, J.-C , Chevreuil, M., Wielgosz, C., Limit analysis of inflatable beams, Proceedings of the ninth international conference on computational structures technology, Athens, Greece, 2008.

[TJW06] Thomas, J.-C., Jiang, Z., Wielgosz, C., Continuous and finite element methods for the vibrations of inflatable beam, International Journal of Space Structures, Vol. 21, pp.197-222, 2006.

[TSC13] Thomas, J.-C., Schoefs, F., Caprani, C., Rocher, B., An application of reliability analysis to inflatable structures, Proceedings of the TensiNet Symposium, Istanbul, pp. 323- 331, 2013.

[USSS11] Uhlemann, J., Stranghöner, N., Schmidt, H., Saxe, K., Effects on Elastic Constants of Technical Membranes Applying the Evaluation Methods of MSAJ/M-02-1995, Proceedings of the International Conference on Textile Composites and Inflatable Structures, STRUCTURAL MEMBRANES 2011, Barcelona, 2011.

[US13a] Uhlemann, J., Stranghöner, N., Einfluss fiktiver elastischer Konstanten von textilen Gewebemembranen in der Tragwerksanalyse von Membranstrukturen, Stahlbau, Vol. 82, No. 9, pp. 643-651, 2013.

[US13b] Uhlemann, J., Stranghöner, N., Spectra of computed fabric stress and deformation values due to a range of fictitious elastic constants obtained from different established determination procedures, Proceedings of the International Conference on Textile Composites and Inflatable Structures, STRUCTURAL MEMBRANES 2013, Munich, 2013.

[USS14] Uhlemann, J., Stimpfle, B., Stranghöner, N., Application of the semiprobabilistic safety concept of EN 1990 in the design of prestressed membrane structures, Proceedings of the Eurosteel, Naples, 2014.

[USS14a] Uhlemann, J., Saxe, K., Stranghöner, N., Aktuelle Sicherheitsansätze in der Bemessung von Membrankonstruktionen, in: Stranghöner, Saxe, Uhlemann (eds.), Essener Membranbau Symposium 2014, Shaker Verlag, Aachen, 2014.

[wCOS] http://www.cost.eu/domains_actions/tud/Actions/TU1303

[wECO] www.eurocodes-online.com