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Prospect for European Guidance for the Structural design of Tensile Membrane Structures

Support to the implementation, harmonisation and further development of the Eurocodes

Stranghöner, N., Uhlemann, J., Bilginoglu, F., Bletzinger, K.-U., Bögner-Baltz H., Corne, E., Gibson, N., Gosling, P., Houtman, R., Llorens, J., Malinowsky, M., Marion, J.-M., Mollaert, M., Nieger, M., Novati, G., Sahnoune, F., Siemens, P., Sousa, M. L., Stimpfle, B., Tanev, V., Thomas, J.-C.

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FOREWORD[1]

The construction ecosystem is of strategic importance to the European Union (EU), as it delivers the buildings and infrastructures needed by the rest of the economy and society, having a direct impact on the safety of persons and the quality of citizens' life. The construction ecosystem[2] includes activities carried out during the whole lifecycle of buildings and infrastructures, namely the design, construction, maintenance, refurbishment and demolition of buildings and infrastructure. The industrial construction ecosystem employs approximately 24.9 million people in the EU and provides an added value of EUR 1 158 billion (9.6% of the EU total).

The construction ecosystem is a key element for the implementation of the European Single Market and for many other important EU strategies and initiatives. Ensuring more sustainable and climate resilient buildings and infrastructure, i.e., adapting the construction ecosystem to inevitable impacts of the changing climate is one of the central priorities of the European Green Deal (COM(2019) 640)[3]. The European Green Deal aims to achieve climate neutrality for Europe by 2050, and relies on numerous initiatives, noteworthy:

1. the **New Circular Economy Action Plan** (COM(2020) 98 final)[4] and the **New Industrial Strategy for Europe** (COM(2020) 102 final)[5] intending to accelerate the transition of the EU industry to a sustainable model based on the principles of circular economy;

2. the **Renovation Wave for Europe** (COM(2020) 662 final)[6] addressing the twin challenge of energy efficiency and energy affordability and aiming to double, at least, the annual renovation rates of the building stock (currently around 1%) and launching the **New European Bauhaus** (COM(2021) 573 final)[7] that is a creative and interdisciplinary initiative that connects the European Green Deal to our living spaces and experience;

3. the **review** (COM(2022) 144) [8] of the **Construction Products Regulation** (Regulation (EU) No 305/2011)[9] and the proposal for the **revision of the Energy Performance of Buildings Directive** (COM(2021) 802 final)[10] to ensure that the design of new and renovated buildings at all stages is in line with the needs of the circular economy, and lead to increased digitalisation and climate-proofing of the building stock.

4. the **new EU Climate Adaptation Strategy** (COM(2021) 82 final)[11] that sets out how the EU can adapt to the unavoidable impacts of climate change and become climate resilient by 2050. The Strategy has four principle objectives: to make

[1] Since this is a re-edition of the 2016 report, the foreword has been edited to account for updated information.
[2] https://ec.europa.eu/docsroom/documents/47996
[3] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2019%3A640%3AFIN
[4] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2020%3A98%3AFIN
[5] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52020DC0102
[6] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52020DC0662
[7] https://europa.eu/new-european-bauhaus/index_en
[8] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52022PC0144
[9] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A32011R0305
[10] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52021PC0802&qid=1641802763889
[11] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM:2021:82:FIN

adaptation smarter, swifter and more systemic, and to step up international action on adaptation to climate change.

Recognizing that the EU's ambition towards a climate neutral, resilient and circular economy cannot be delivered without leveraging the European standardisation system, the European Commission presented a new **Standardisation Strategy** (COM(2022) 31 final)[12], to enable global leadership of EU standards in promoting values and a resilient, Green and Digital Single Market. The Strategy spots standards as "*the silent foundation of the EU Single Market and global competitiveness*", since they are "*invisible but a fundamental part of our daily life*". European standards are embedded in the EU policy objectives and have a key role to achieve a climate-neutral, resilient and circular economy.

The EU has already put in place a number of policy and regulatory instruments for the construction sector, including related European Standards (EN). Within this framework, the Eurocodes are a series of 10 European Standards, EN 1990 to EN 1999, comprising 59 parts and providing common technical rules for the design of buildings and other civil engineering works. They cover in a comprehensive manner the basis of structural design, actions on structures, the design of structures of the principal construction materials such as concrete, steel, composite steel-concrete, timber, masonry and aluminium, and the geotechnical, seismic and structural fire design as well.

Tensioned Membrane Structures have unique properties compared to the more conventional built environment. Besides their low self-weight and high flexibility these structures are known to be 'optimally' constructed, as they are only loaded in tension. It results in shapes adapted to the flow of forces and a minimum of material needed to realise the span. Despite a considerable amount of scientific knowledge exists, only few design codes are available. A common standardised approach as well as a comprehensive European design standard is needed in order to provide verification techniques, a common pool of design approaches and to achieve a harmonized safety level.

Within CEN/TC 250/WG 5, CEN/TC 248/WG 4, the TensiNet Association and COST Action TU1303, an international team of researchers, engineers, architects, material producers and manufacturers has been working on this report, which provides background information in support to the implementation and development of a future Eurocode for the structural design of tensile membrane structures. The final aim is to develop a Eurocode for the Structural Design of Tensile Membrane Structures which will help to design and implement these lightweight structures. The Eurocode will not only assist and support the industry and engineering offices but will also encourage potential clients to choose these sustainable applications.

This pre-normative document is published as a part of the JRC Report Series "Support to the implementation, harmonization and further development of the Eurocodes" with the aim to provide basis for debate on a harmonized European approach to the structural design of tensile membrane structures. It consists of three major parts:

a) general explanations giving scientific and technical background for the design of membrane structures,

[12] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52022DC0031

b) state-of-the-art overview on existing national and European rules and recommendations on the design of membrane structures, and

c) proposals for European harmonized design rules, which could be part of the future Eurocode for Tensile Membrane Structures.

The editors and authors have sought to present useful and consistent information in this report. However, users of information contained in this report must satisfy themselves of its suitability for the purpose for which they intend to use it.

The report is available to download from the “Eurocodes: Building the future” website (http://eurocodes.jrc.ec.europa.eu).

Ispra, January 2023

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The contribution of Maria Luisa Sousa (formerly JRC Scientific Project Officer) and Francesca Sciarretta (JRC Scientific Project Officer) in the present re-edition of the report is gratefully acknowledged.

REPORT SERIES "SUPPORT TO THE IMPLEMENTATION, HARMONIZATION AND FURTHER DEVELOPMENT OF THE EUROCODES"

In the light of the Commission 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 Eurocodes"** as JRC Science 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, promotion 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;

4. **Background documents**, providing approved background information on current Eurocode part. The publication of the document is at the request of the relevant CEN/TC250 Sub-Committee;

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.

Editorial work for this Report Series is **performed by the JRC** together with partners and stakeholders, when appropriate. The publication of the reports type 3, 4 and 5 is made after approval for publication by CEN/TC250, or the relevant Sub-Committee or Working Group.

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 standardisation processes.

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

ACKNOWLEDGEMENTS

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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 facades (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.

Trichterschirm Montabaur, Germany, source and ©: formTL ingenieure für tragwerk und leichtbau GmbH

Zénith de Strasbourg, France, source and ©: formTL ingenieure für tragwerk und leichtbau GmbH

Campus Luigi Einaudi Turin, Italy, source: formTL ingenieure für tragwerk und leichtbau GmbH, © Michele D'Ottavio

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, deformability, 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 facades, which are presented in Figure 1-2. Generally, synclastic structures are pneumatically and flat and anticlastic structures are mechanically prestressed.

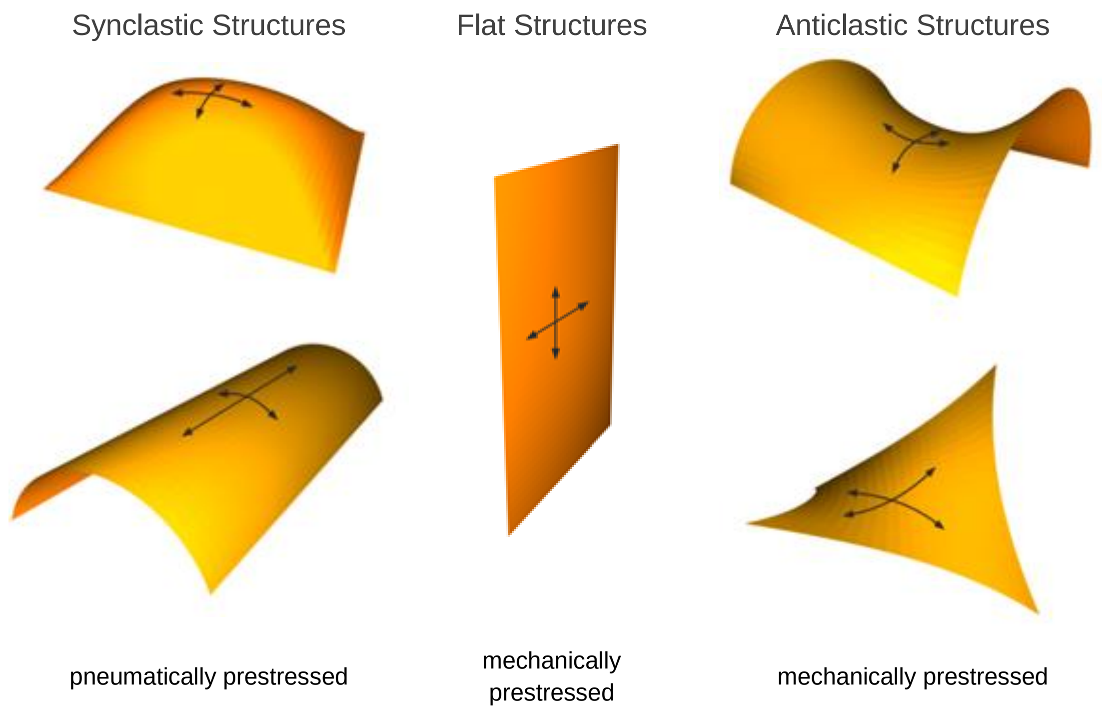


Figure 1-2 Typical shapes of membrane structures [US13a]

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 possibly reinforced by cables or belts. 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 specific 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. The preparation of it already started within the TensiNet WG Specifications Eurocode in 2008.

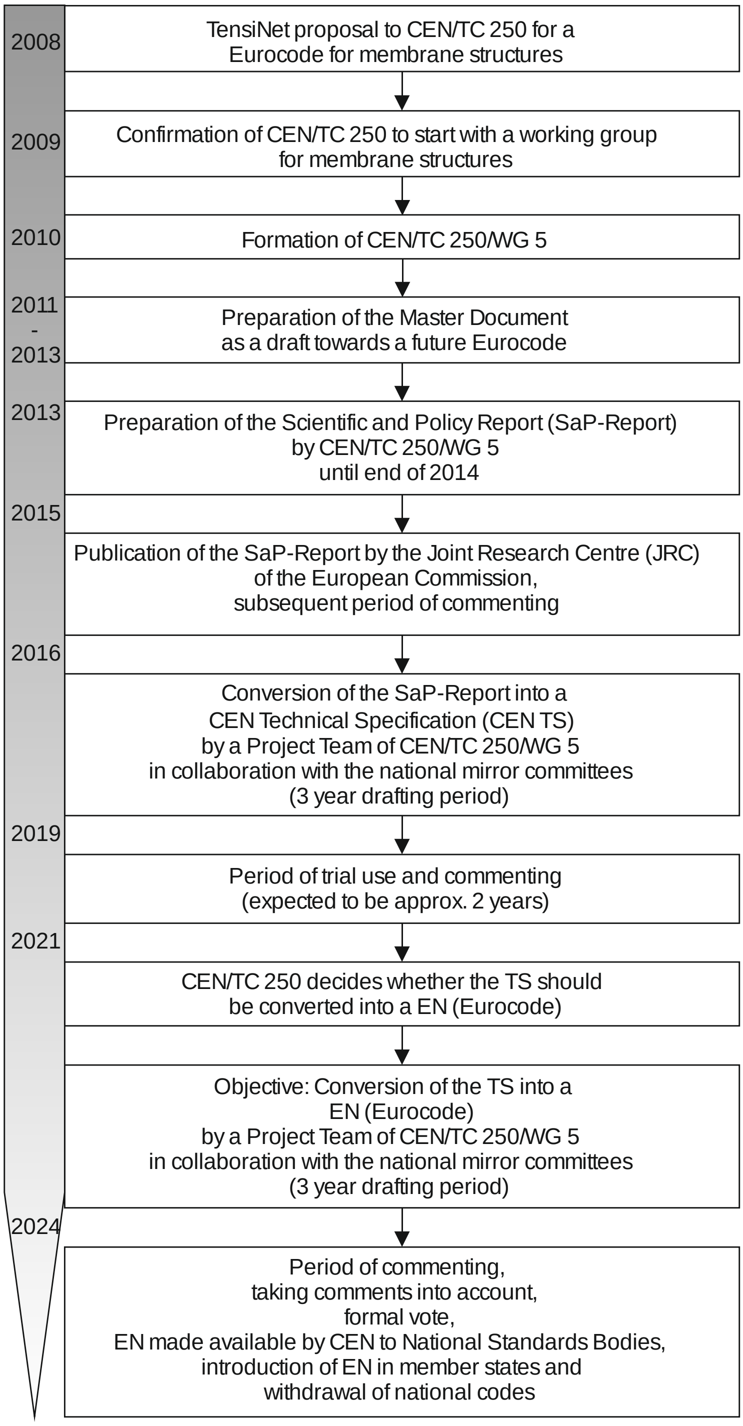


Figure 1-3 Steps to a Eurocode for Membrane Structures [SUMG14]

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 an up-to-date 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.

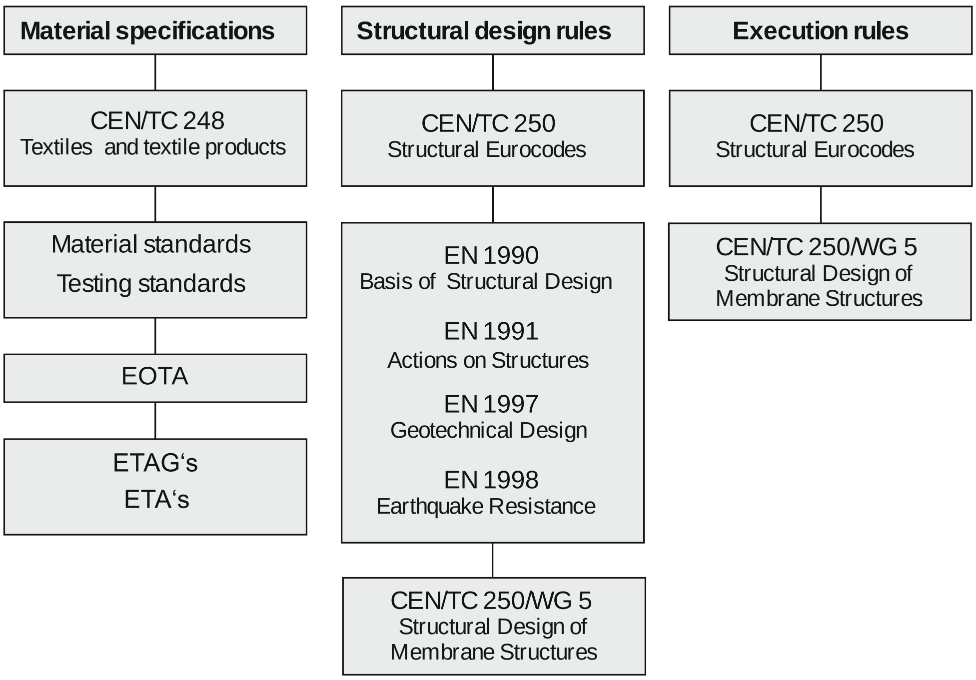


Figure 1-4 European code environment for the preparation of the Scientific and Policy Report for Structural Membranes

Membrane structures require special execution rules for the use of structural fabrics and foils. As no specific code is planned to be prepared, as exemplary EN 1090-2 [S36] 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, the Eurocode 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.

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 [S20]) "*Basis of Design*" have to be considered. Secondly, the loads specified in Eurocode 1 (EN 1991 [S21]) "*Actions on 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.

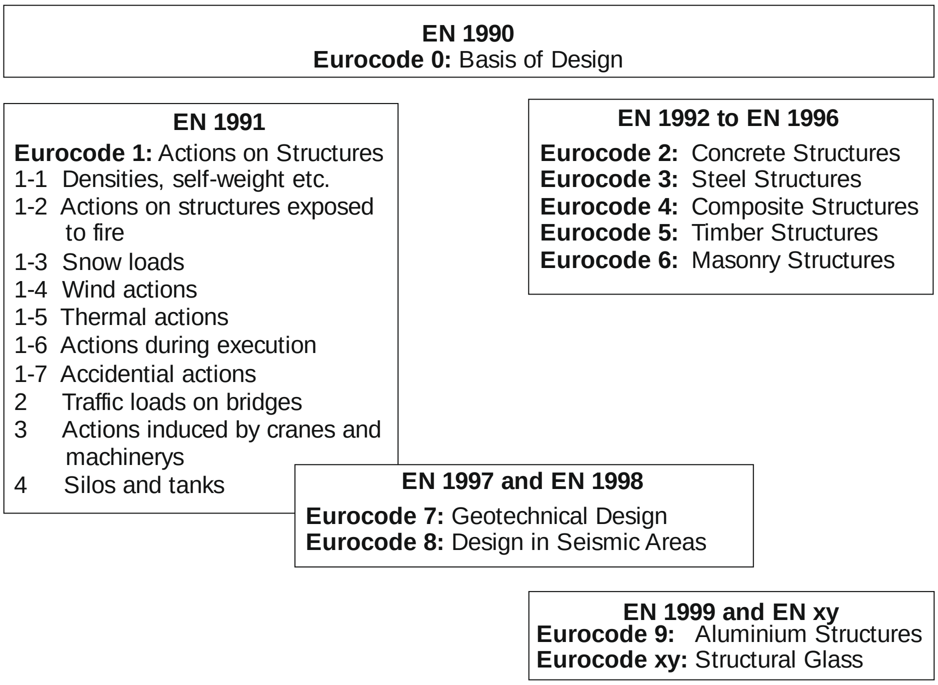


Figure 1-5 Survey of the existing and planned Eurocodes, missing: Eurocode for Structural Membranes

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: Basis of Structural Design

EN 1991	**Actions on Structures**	**EN 1992**	**Design of Concrete Structures**
Part 1-1	Densities, self-weight, imposed loads for buildings	Part 1-1	General rules and rules for buildings
Part 1-2	Actions on structures exposed to fire	**EN 1993**	**Design of Steel Structures**
Part 1-3	Snow loads	Part 1-1	General rules and rules for buildings
Part 1-4	Wind actions	Part 1-4	Stainless steel
Part 1-5	Thermal actions	Part 1-8	Joints
Part 1-6	Actions during execution	Part 1-11	Structures with tension components
Part 1-7	Accidental actions		
		EN 1994	**Design of Composite Steel and Concrete Structures**
		Part 1-1	General rules and rules for buildings
		EN 1995	**Design of Timber Structures**
		Part 1-1	General - Common rules and rules for buildings

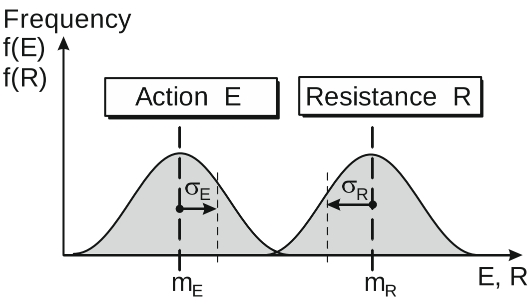
Figure 1-6 Other Eurocodes suitable for steel-membrane, timber-membrane, aluminum-membrane and concrete-membrane structures

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

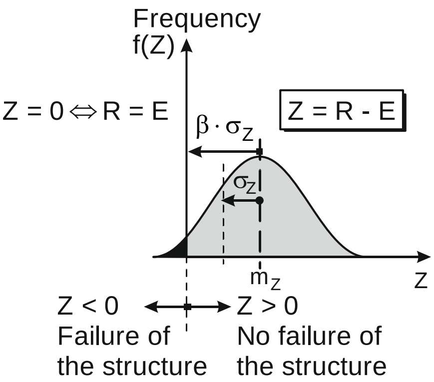
- ultimate limit state including robustness,
- serviceability limit state and
- durability.

Furthermore, EN 1990 specifies for conventional structures 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 $\beta = 3.8$ (Figure 1.7).

For structural membranes the 50 years life expectancy is not achieved, but the overall structure could be made for 50 years and after a certain time (for example 20 or 25 years) the structural membrane could be replaced. Since the reliability index β is linked to the reference period, β could be adjusted if a structural membrane is designed for a shorter lifetime.



$$\beta = \frac{m_R - m_E}{\sqrt{\sigma_R^2 + \sigma_E^2}} \geq 3{,}8$$
$$T_{ref} = 50 \text{ years}$$



$$p_F = p(Z < 0) = 7 \cdot 10^{-5}$$
$$\Rightarrow \beta = 3{,}8$$

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 $m_Z \geq \beta \cdot \sigma_Z$.

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

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

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

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

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

$$\Leftrightarrow R_d \geq E_d$$

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 [©ELLF]

The Eurocode design approach relies on the semiprobabilistic design concept in which the action effect E_d resulting from the applied actions is 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 fulfil the requirements. For the normal reliability class, the design values of action effect E_d and resistance 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 (uni- 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.

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 [USS14b]. For this reason, it has strictly to be distinguished whether the partial factor is considered already on the action or only on the action effect. EN 1990 gives some indications how to act in these cases. This topic will be discussed in detail in this report.

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

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

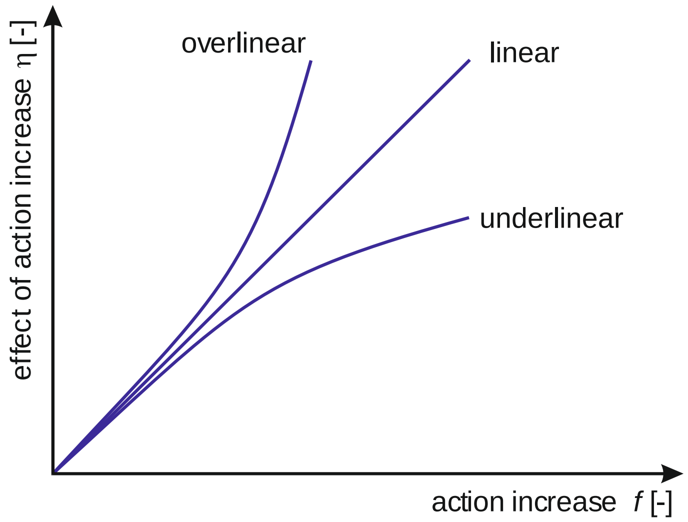


Figure 1-9 Linear and nonlinear behaviour of structures [USS14b]

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.

The listing in Code Review No. 1 disregards standards like EN 14716 for stretched ceilings or EN 13561 for exterior blinds. These are structures containing cognate tensile elements and thus these standards may be consulted for single aspects during the design of tensile membrane structures. However, the mentioned structures have clearly different requirements than tensile membrane structures.

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, Belgium and Spain) is shown in the following figures (making no claim to be complete). United Kingdom, Bulgaria and Russia have no specific standards for membrane structures.*

Rules on European level

	Material products	Fabric structures: mechanically prestressed	Fabric structures: pneumatically prestressed
Not specific	**Coated fabrics:** EN ISO 1421 Tensile strength EN 1875 Tear strength EN ISO 2411 Adhesion EN ISO 2286 Roll characteristics **Uncoated fabrics:** EN ISO 13934 Tensile properties **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	EN 13501 Fire classification		

Rules in Germany

	Material products	Fabric structures mechanically prestressed	 pneumatically prestressed
Not specific	**Coated fabrics:** DIN EN ISO 1421 Tensile strength DIN EN 1875 Tear strength DIN EN ISO 2411 Adhesion DIN EN ISO 2286 Roll characteristics **Uncoated fabrics:** DIN EN ISO 13934 Tensile properties **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	DIN EN 13501 Fire classification DIN 4102 Fire beheviour of building materials		

Rules in The Netherlands

	Material products	Fabric structures: mechanically prestressed	Fabric structures: 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	Fabric structures: 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

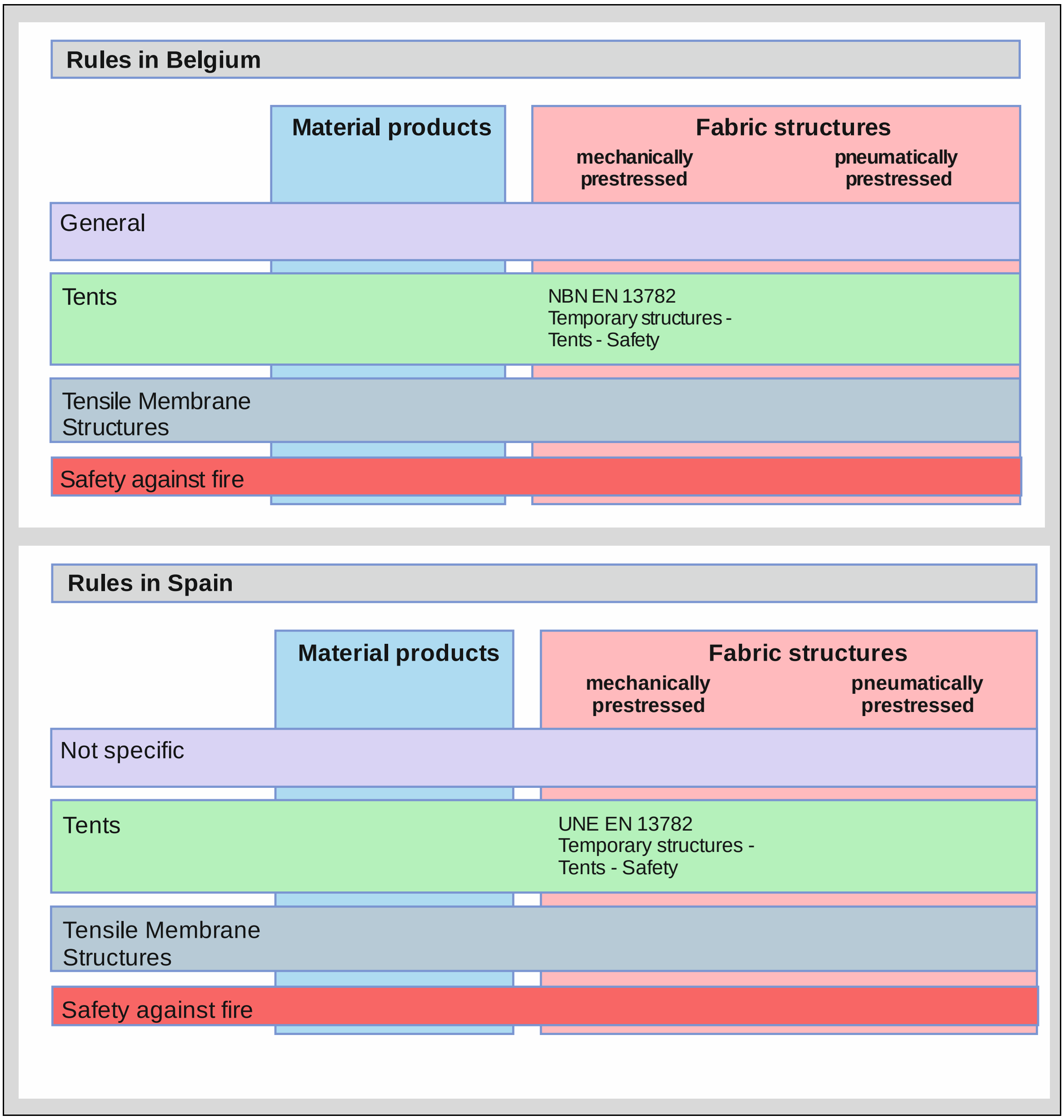
	Material products	Fabric structures – mechanically prestressed	Fabric structures – pneumatically prestressed
General	NF-EN 15619 Specification for coated fabrics for tents		
Tents		CTS [1)] NF-EN 13782 Temporary structures - Tents - Safety	
Tensile Membrane Structures		CTS [1)] Recommandations pour la conception des ouvrages permanents de couverture textile, editions SEBTP [2)] NF-EN 13782 Temporary structures - Tents - Safety CRAST [4)]	
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

[4)] CRAST 1984: Cashier de Règles de l'Art de Structures Textiles, distribué par le Club de la Structure Textile



The future Eurocode for the design of structural membranes should have an appropriate structuring that complies with the European approach of material related design codes in civil engineering and 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 tensile membrane structures. Eurocode Outlook No. 1 gives an overview on the global structure and Eurocode Outlook No. 2 provides an outlook on the future detail structure.

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 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

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 <u>third</u> part of the Eurocode on structural membranes may be as follows:

1 General – Execution of 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

1.4 What are membrane structures? Introduction to ‘engineering membrane structures’

1.4.1 General

It is worthwhile to outline the nature and characteristics of membrane structures and to describe the primary issues that designers and engineers have to consider. From an engineering point of view fabric structures are thin membranes which by virtue of their surface shape and inherent large deflection behaviour are able to support imposed loads. They are modestly prestressed to enhance their stiffness.

So called “saddle” shaped roofs started to be built commencing with the Raleigh Livestock Arena in North Carolina, USA, designed by engineer Fred Severud and architect Matthew Nowicki and completed in 1952, see Figure 1-10. In essence the roof consists of a 2-way network of cables spanning 95 m between a pair of arches inclined away from one another at 20° to the horizontal.

Figure 1-10 © Dorton Arena West Side by Leah Rucker, licensed under CC BY-SA 3.0, via Wikimedia Commons - https://upload.wikimedia.org/wikipedia/commons/a/a2/Dorton_Arena_West_Side.JPG

The building displays two primary features of the modern tension structure: the arch boundaries act together to “contain” the forces coming out of the cable network whilst the configuration of the arches enables the roof surface to be doubly curved.

In the 10 years following Raleigh the German architect Frei Otto developed his knowledge of tent design through a fruitful collaboration with the tent maker Peter Stromeyer. Between 1955 and 1965 many doubly curved tents were designed and made for Federal Garden Shows and other national exhibitions such as Lausanne in 1964 [IL76].

His first major cable net, designed with fellow architect Rolf Gutbrod, was the German Pavilion for the Montreal Expo in 1967. Both architecturally and structurally it was a radical departure in a number of ways. It had a very free-form plan, and as a result, the net was hung from masts of varying heights and inclinations, with the concentration of forces at mast tops cleverly intercepted and carried by loop cables lying within the net surface. Ten thousand square metres of PVC coated polyester textile were suspended from the cable net and tensioned to form the enclosing skins. The engineering design of the Pavilion was led by the office of Leonhardt and Andrä, who continued on with Günter Behnisch and Frei Otto to realise the astonishing cable net roofs for the 1972 Olympic Games in Munich.

Materials currently used in fabric structures consist of a woven textile encapsulated in a polymeric coating. There are different constructions of weave, weaving techniques and coatings that all lead to variations in the characteristics of the materials. These variations need to be understood and considered in the design process.

1.4.2 Form and behaviour of fabric structures

1.4.2.1 General

The form and physical behaviour of fabric structures are very different to those of conventionally stiff “linear-elastic” framed structures used in most buildings.

Designers of fabric structures concern themselves with three primary structural factors: choice of surface shape, levels of prestress and surface deformability.

1.4.2.2 Surface shape

Most contemporary fabric structures have as their basis an “anticlastic” surface geometry. This is one in which a set of “arching” tensile elements act in opposition to a similar set of “hanging” elements, see Figure 1-11. Physically the two groups of elements represent the two directions of the textile yarns (warp and weft) within the membrane.

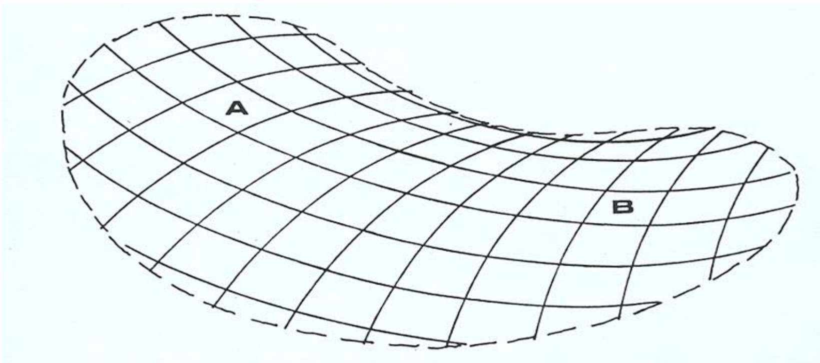


Figure 1-11 Anti-clastic surface [© M. R. Barnes]

This configuration has a valuable property in that the surface as a whole is prestressable without significant change occurring to its overall shape.

It also possesses clear and separate “load-paths” for inward and outward pressure. Downward pressure from snow is carried by the yarns in the “hanging” curvature and outward suction from wind flow is carried by the yarns in the “arching” curvature.

There are four generic types of anticlastic surface in common use: the “cone”, the arched “saddle”, the “hypar” and “ridge and valley”. The shapes that are possible for fabric structures aren’t simply limited to the 4 generic shapes. Indeed hybrid versions and combinations thereof increase the choice of forms considerably.

Furthermore, the geometry of a membrane’s surface is not defined by imposing on it a mathematically based surface of revolution as in the case of shells, rather it needs to be defined by its “internal equilibrium of prestress” within a predetermined boundary system of support. The physical analogy of the soap film is useful here in that a film can only form within a boundary system whose geometry permits tensile equilibrium to exist between the film’s molecules. Therefore in terms of designing fabric structures the designer is essentially involved in choosing a set of “boundary conditions” in the process of defining the membrane’s shape. Boundary conditions are in effect the disposition of all elements that contact and provide support to the membrane, for instance, ridge and edge cables, masts, arches, beams etc.

The process of determining the form of the structure is commonly referred to as “form finding”. It is an iterative process where changes and adjustments are made to the disposition of supporting elements such as edge and ridge cables and the relative heights of masts etc. The surface shape is the outcome of both the choice of boundary conditions and the choice of prestress ratios within those boundaries.

1.4.2.3 Prestress

Prestress contributes significantly to a membrane’s stiffness due to its opposing curvature components interacting to constrain what would otherwise be severe deformations typical of flat or singly curved surfaces. For example in Figure 1-11 the deformation of the “hanging” curvature due to loading in zone A is constrained by the “arching” tensions in zone B. Actual values of prestress used in practice generally represent a small proportion of a membrane’s ultimate strength.

The chosen level of prestress will normally be a compromise – low enough to reduce the work done during installation – whilst sufficiently high to maintain a sufficient prestress after losses due to “creep” of the membrane material over time.

The final level of prestress will also be dependent upon the material to be used – each material has its own range of preferred prestress.

The choice of the initial boundary conditions for an anticlastic surface can often be guided by the use of the relationship T = p x R where T = membrane tension, p = pressure applied normal to the surface, and R = radius of one curvature of the surface, see Figure 1-12. Thus by knowing what the applied pressures are likely to be as well as what the membrane tensions should be limited to, then the radius/radii or curvature can easily be found. This can then be fed back into the initial assumptions made about the geometry of the boundary conditions.

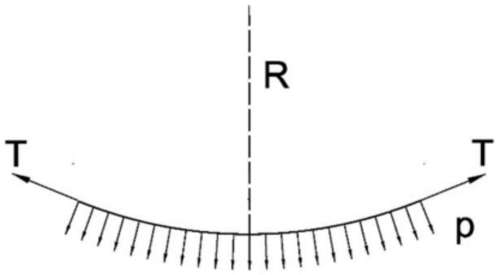


Figure 1-12 T = p x R [© M. Mollaert]

Where geometric constraints are placed upon a design – such as to require the use of flatter and therefore larger radii of curvature – then larger values of prestress will be required to control the size of the membrane’s deflections. There are practical limits to what can be safely applied and remain in the long term. In the limit where the surface becomes flat (radius = ∞) then prestress and the material’s stiffness (EA) are the only parameters controlling deflection.

For many structures the same quantity of prestress is applied to both directions of the textile’s weave. However in cases where the magnitude of the inward and outward applied loads are markedly different to one another then it can be economically advantageous to determine the membrane’s shape such that a smaller (tighter) radius of curvature is subjected to the higher external pressure and vice-versa a larger (flatter) radius of curvature carries the lower external pressure. In this way the resulting maximum membrane tensions will be of a similar size.

1.4.2.4 Deformability

Unlike in more conventional forms of building construction deformability is seen as a useful and important characteristic of a fabric structure. Indeed due to its relatively low surface stiffness (both in-plane and out-of-plane), changes in geometry/surface shape are a fabric structure's primary response to externally applied load coupled with changes in stress distribution throughout its surface [Lid94]. In addition the strains developing within membrane material are several orders of magnitude larger than those in steel for instance. Consequently fabric structures exhibit very much larger deflections and geometric changes under load than orthodox framed construction. Flexibility in the supports of a membrane also adds to its deformability providing of course that overall stability is assured [Wag07].

All this has the beneficial effect of stresses not rising linearly with applied loads due to the geometric changes that occur in the surface as a whole.

For instance wind flowing around a conical membrane causes a "pin-ended" mast to lean into the wind allowing changes to surface curvature on the windward face to attenuate the rise in membrane stresses in that zone, but also with membrane curvatures on the leeward side acting to stabilise the mast.

Encouraging deformation of the membrane's surface is beneficial provided that the deformed surface under load remains with positive inclinations throughout. The inherent danger of shallow gradients is that an accumulation of snow/ice can cause a depression into which meltwater and rain can collect ("ponding") with the surface geometry having changed from "anticlastic" to "synclastic", see Figure 1-13. This in turn can increase the depth of the depression allowing more water to pond and hence creating a larger depression and so on. It may remain as water or convert to ice according to weather conditions. The effect however is for snow loads to progressively increase far beyond those applicable to a more rigid structure. The objective must be the achievement of a form which as it deflects maintains positive gradients under the effect of the worst credible loading conditions.

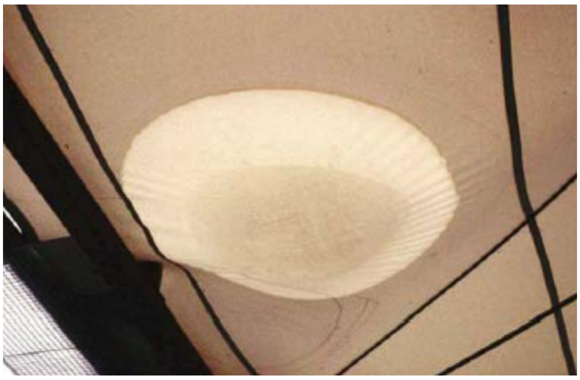


Figure 1-13 Ponding [© J. Llorens]

The deformation of each structure under snow loading must therefore be investigated and tested carefully in the design stage. The choices made for boundary geometry are high influential as well as the realistic assessment of the flexibility (i.e. spring stiffness) of all supporting elements in the system.

In ridge and valley structures the loads are carried by the deflected curvature of the ridge and valley cables with the membrane panel acting as a prestressed web spanning between them. The panels are slightly warped but because of their length to width aspect ratio the applied pressures of snow and wind will both largely be carried in the short direction of the panel as a result of "form inversion", regardless of whether it is pressure or suction loading. An example is the Cargolifter Airship Hangar in Germany, shown in Figure 1-14.

Figure 1-14 Cargolifter Airship Hangar [© formTL]

The deformability of the surfaces comes into play where snow builds up but “ponding” of rainwater and melting snow is avoided by the deflected membrane surfaces remaining positive in inclination due in effect to the initial choice of boundary support stiffness and geometry.

1.4.2.5 Conceptual development

If a fabric structure is to form part of the enclosing skin of a building the opportunity may exist to geometrically integrate the two so that, like the Raleigh Arena and others such as the Saga building, the membrane’s tensile forces are largely and economically absorbed within the building’s framework (as opposed to heavy ground anchorages) and sealing between wall and roof is relative simple.

Geographical location has a very direct bearing on the type and magnitude of loading which a fixed non-retractable roof must support. Design values for wind and snow have to be derived from the Eurocode (and National Annexes) and where necessary through wind tunnel model testing. As the doubly curved shapes are not covered by the code, model testing is often required - especially for structures of significant size.

Membrane materials are easy to cut with a sharp knife and are therefore susceptible to accidental damage from vandalism and flying objects. As with conventional structures the accidental removal of individual members or membrane panels needs investigation to demonstrate the inherent damage limitation of the whole system.

A fabric structure is composed entirely of prefabricated elements which once assembled forms a prestressed system with its own particular geometry and prestress distribution. The fabric and cable elements therefore have to be made to smaller dimensions than those finally intended so as to allow for the development of appropriate strains during the process of assembling the whole structure.

Generally, elements are loosely assembled on a suitably level plane. A set of displacements are then required to draw the membrane towards its various points of support to induce the desired prestress. The designer needs to anticipate this and must ensure that throughout the design’s development there are embodied within it practical and effective means by which the desired prestress configuration can be achieved.

In some cases this may require discrete elements to be included in the design whose lengths can be changed significantly during the stressing process but remain in the system as permanent elements, such as masts that are jacked, and aerial ties that are shortened as in Figure 1-15. The designer also needs to anticipate the scale and direction of displacements and rotations that are likely during installation, as well as thereafter in service so that appropriate articulation is provided between elements and at support points. The design process can therefore involve a number of “feedback loops” which may require revision to element lengths, topology and coordinates.

Figure 1-15 Shortening of aerial ties [© M. Mollaert]

1.4.2.6 Detailed design

The detailed design process involves several stages, and, in order to provide an efficient design, is invariably based around the use of geometrically non-linear analysis software [Day78]. This process can be summarised in the following two steps:

(a) Developing the design concept

This involves defining a physical configuration of elements, defining materials and their strength and stiffness properties, element sizes; defining the connections between all elements. An “equilibrium form” needs to be established using zero-stiffness finite elements representing the membrane and cables each of which have specified tensions. By changing the relative values of tensions and the relative geometry of the supports, different surface geometries result. This can be advantageous in accommodating, for instance, the dominance of a particular service load, and in improving areas that may be prone to ponding or inversion.

In the structural analysis that follows the form finding stage, cable and membrane elements with real stiffness values are used; particular elements whose tensions go to zero are automatically switched out during the analysis to simulate a slack cable or buckled membrane. The element meshes used in the computer model are aligned with the directions of weave and anticipate the position and direction of the seams between the individual panels of fabric that will make up the whole surface.

It is important to note that the positioning and direction of seams over the membrane’s surface is never arbitrary or merely a matter of taste, except in the most lightly loaded structures.

The seams are an indication of the direction of the warp yarns. Since in most cloths the warp direction is stronger than the weft, the warp would be placed to follow the higher stresses for reasons of economy.

In regions of significant snow loading the warp would generally be chosen to follow the sagging curvature so that its greater stiffness can limit snow load deflections in the medium to long term. Where wind loads are significantly higher than snow loads then it can make sense to place the seams in the arching direction.

Some PTFE coated glass materials are woven with a high crimp in the weft direction and consequently with fairly straight warp yarns. This allows the introduction of a biaxial prestress by simply extending the weft yarns whilst holding the warp steady.

The membrane's stiffness properties used in the above analysis need to be determined via biaxial testing of the material to be employed on the project.

Appropriate pressure distributions representing wind and snow loads are applied to the surface of the analysis model in appropriate directions. Load vectors are applied to the element surface geometry in its deformed state. The deformed surface under self-weight and snow loading needs to be examined for the possibility of ponding and load accumulation. In this respect a rigorous examination of potential loading patterns and intensities must be undertaken.

(b) Determining how it is to be built

This involves developing a sequence of assembly and the step by step means of obtaining the desired prestress distribution in advance of fabrication. The purpose of this is to confirm the viability of a particular sequence and, where necessary, to determine individual component forces and movements during the construction process. Such information must feed into the detailing of connections etc. It can also assist in establishing the best "starting position" of the primary elements. This can be simulated numerically by modelling step by step the removal of prestress from the structure [For98]. It involves presupposing a series of discrete steps which should of course be practicable. The chosen strategy and techniques for installing the appropriate prestress on site need of course to be as insensitive as possible to fabrication and construction tolerances.

1.4.2.7 Fabrication information

Accurate fabrication dimensions are essential to the successful construction of fabric structures. This requires membrane cutting patterns to be taken out of the "at prestress" model of the structure. Seam lines between panels of cloth are defined by geodesic lines for efficiency in material use. Patterns have to be "compensated", that is shrunk by percentage values in both warp and weft directions so as to allow for the development of strains necessary to give prestress. Batch testing of the fabric to be used in the work has to be carried out to determine these values. Local adjustments to edge lengths ("decompensation") are often made at some boundaries, e.g. continuous beam edges, to facilitate safe installation.

In addition to the fabric related items, schedules will also be required for accurately dimensioning cables, taking into account stretch compensations and adjustment details. The shop drawings for metalwork items including membrane plates and support masts and frames have to be developed, and these should take into account final form geometry and angles.

Accuracy in both the dimensioning and the cutting out of individual fabric panels is important since gross errors will prevent the development of the intended strains and therefore the required prestress. In addition the membrane's finished appearance may be impaired by the formation of folds and wrinkles. Accuracy is important as it is generally not possible to correct errors on site.

1.4.2.8 Pneumatic structures

These form a specialist group of tensile structures as they are almost always composed of synclastic surfaces rather than anticlastic surfaces. Prestress and stiffness are introduced via inflation of the structures. Examples of these are: air halls, cushions (frequently inflated ETFE) and air beams (primarily used for temporary structures where speed of installation is important) (Figure 1-16).

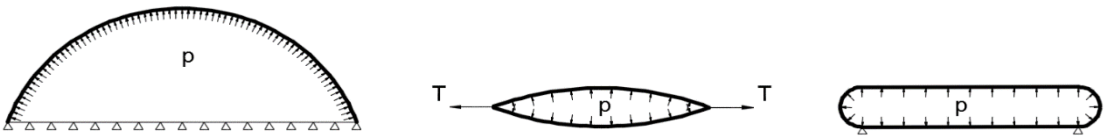


Figure 1-16 Air halls (left), cushion (middle) and air beam (right) [© M. Mollaert]

These structures offer minimal rigid support structure and therefore lend themselves to temporary structures and those that need to be installed in numerous locations. These are designed to keep weight down and may require limitations on the wind speed or snow load that they are required to resist.

The material used would typically be PVC-coated polyester which is both light and strong. It can also cope with being frequently folded and stored for future use.

Inflated cushions using ETFE provides a transparent barrier in the same way as glass but much lighter. This allows for longer spans to be used and for associated support structure to be reduced. The thermal characteristics can be enhanced using multiple layers within the cushion and also a variety of fritting (printed) patterns to be used on the surface.

The cushions can be used in combination of other roofing systems. Cushions provide a much more flexible solution to glass as they cope with large deflections of the supporting structure without leading to failure. They can also be formed into quite challenging 3D shapes providing much greater freedom in developing the geometry of the roof.

Air beams require high pressures to generate their required stiffness and strength. These structures resist loads as both axial and bending elements. The high pressures ensure that there is sufficient surface tension to prevent the material from going slack under compression.

These are frequently used in applications where rapid deployment is required. This could be for example in disaster relief where infrastructure has been destroyed or does not exist – in remote areas. The structures can be quickly deployed to provide shelter and act as field hospitals.

Acknowledgement

Chapter 1.4 is partly based on Chapter 2 ‘Engineering membrane structures’ of the TensiNet Design Guide [FM04]. The authors acknowledge that this chapter could be reprocessed for inclusion in the SaP-report.

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 or insulation values which are assumed to be not relevant in regard to the Eurocode for the design of membrane structures.

Structural fire design is planned to be the content of Part 2 of the future Eurocode, see Eurocode Outlook No. 1. Fire safety of construction products (materials) may be classified by EN 13501-1 [S37].

Fabrics are mainly woven textiles and can be distinguished in uncoated fabrics mainly used 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.

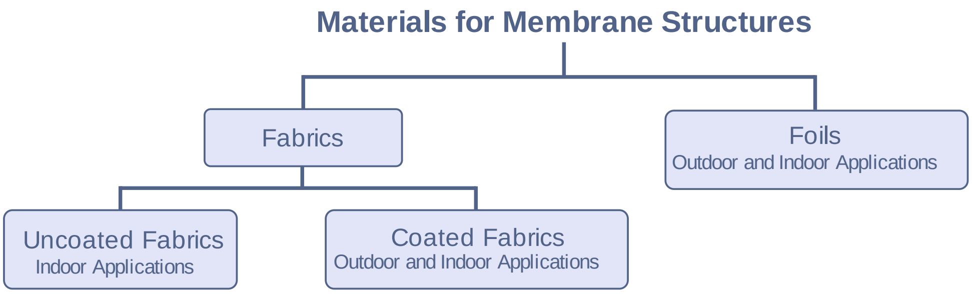


Figure 2-1 Materials for membrane structures [© ELLF]

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 structural 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 weft direction. Most fabrics are characterized by a greater stiffness in the warp than in the weft direction.

For indoor applications, the fabrics have not to be coated. Architectural fabrics for outdoor applications are usually 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 also used to transmit shear forces (especially at weld seams), it has no significant influence on the load bearing behaviour of the coated fabric itself. The warp and weft yarns are the load-bearing elements of these composite materials. As they have no defined section height, membrane forces are referred to the width instead of the cross section area of a structural membrane. Nevertheless, the term “membrane stress” is used traditionally.

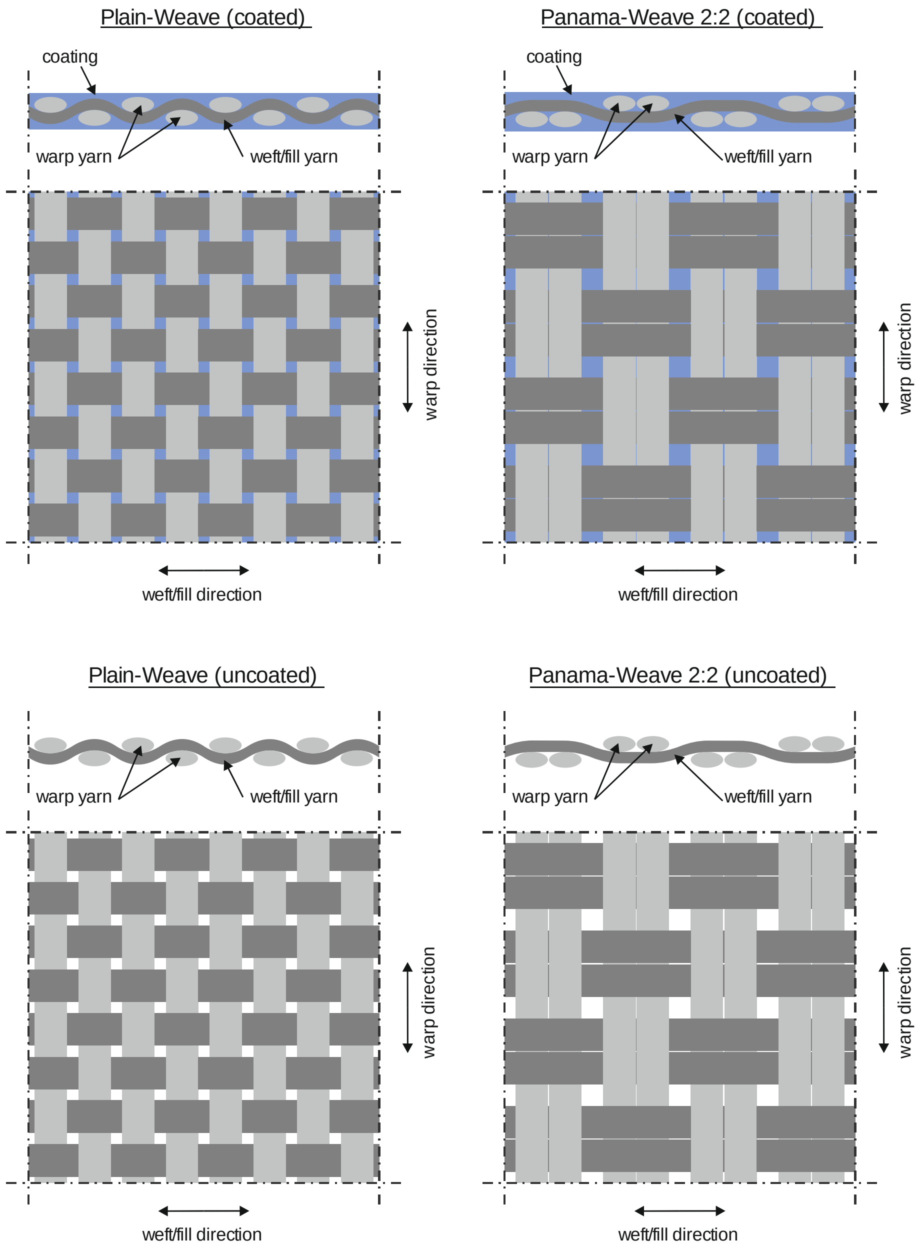


Figure 2-2 Most common weaving constructions for fabrics used in textile architecture [© ELLF]

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 [KCGL10, 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], just as other constructions of the textiles such as non-wovens or knitted fabrics [SoSp93].

Uncoated fabrics are usually made of

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

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

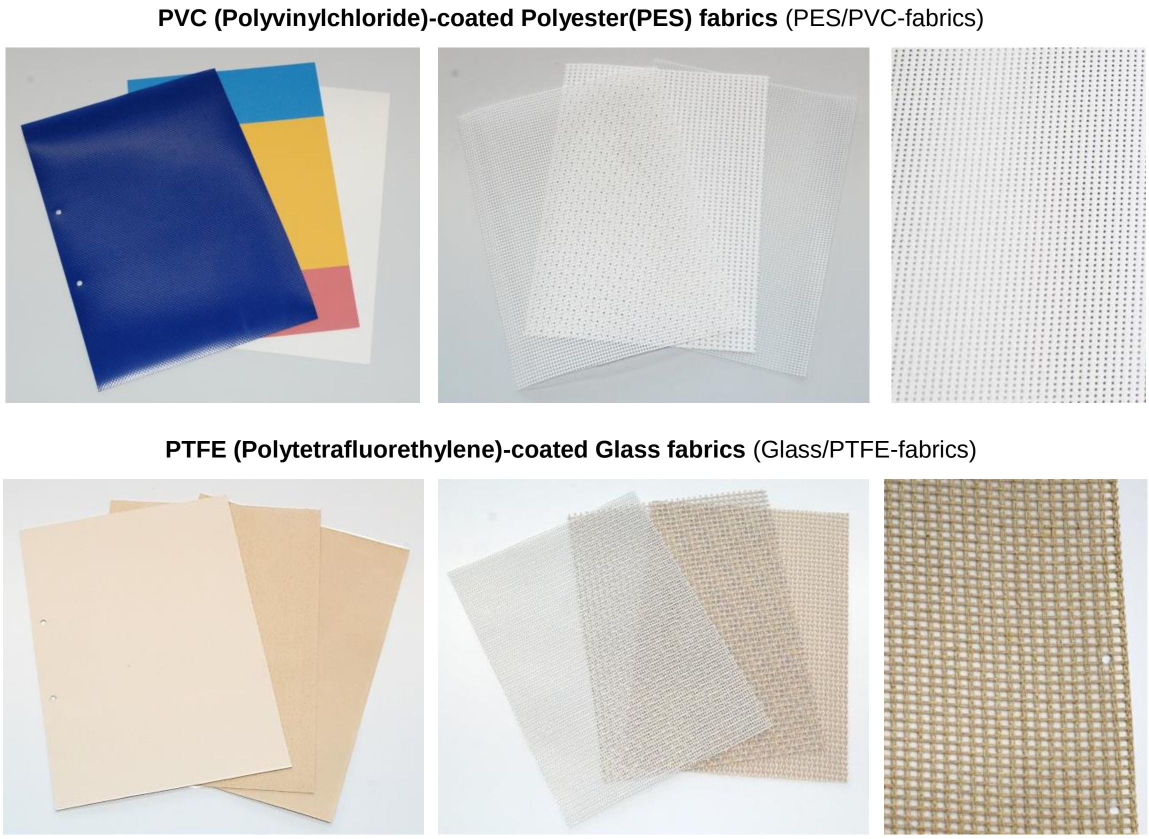


Figure 2-3 Main fabrics used in textile architecture [© ELLF]

2.2.2 Material properties

2.2.2.1 General

Up to date, base material tensile strength values for the design of structural membranes are taken from data sheets from the material suppliers or values derived from own experiences. For base materials and particularly for connections (e.g. seam strength), strength values are oftentimes to be confirmed in experimental tests prior to the installation. Regarding major projects with e.g. special 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 which 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. The measurements of the strength and elongation are used to derive the mechanical properties of the fabric and of connections. The typical load-elongation behaviour of fabrics can be seen in Figure 2-4.

The tensile test is specified in European and national standards as EN ISO 1421 [S1], and EN ISO 13934-1 [S10] on European level, particularly in Germany DIN 53354 [S11] (although withdrawn) and the guideline of Deutsches Institut für Bautechnik (DIBt) for acceptance test of coated fabrics and their joints [S12] and on international level ASTM D 5035-95 [S13]. The procedure of the tensile test is described in Annex B1.

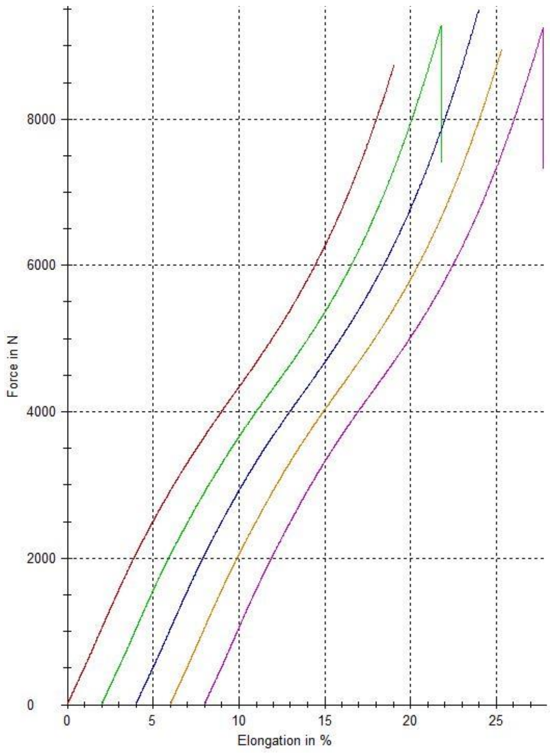


Figure 2-4 Typical results of tensile strength tests [© ELLF]

2.2.2.3 Decreasing effects on the tensile strength

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. Some of these influences affect also the durability of the structure. It is supposed to give experimental test procedures in order to determine the strength reduction factors in an informative annex. The following explanations refer to PES-PVC and Glass-PTFE materials. Test procedures for the determination of strength reduction factors for fabrics are described in Annex C.

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, see Annex C2. 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 cruciform test 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, see Annex C3.

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, SBS94]. 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. Annex C4 describes a determination procedure for the respective strength reduction factor.

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. Annex C5 describes a determination procedure for the respective strength reduction factor.

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 can grow to small tears, see chapter 7.7 for further information on tears and tear control and chapter 9 for detailed information on the handling on site. Annex B2 presents various test procedures aiming to enable an assessment of the sensitivity of a specific glass fibre fabric to crease fold by means of comparing materials in their sensitivity.

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.

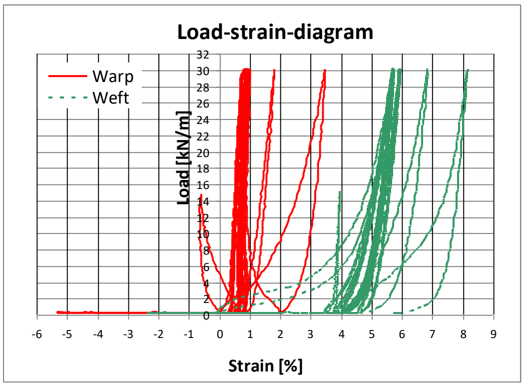
The aim of crease fold tests is to determine the resistance to creasing and folding by measuring the breaking force after repeated folding and force applications. Fabric sections are subjected to repeated folding and force applications to folds during packaging and fabrication (and transport and installation). This test method is primarily for use in coated and laminated fabrics as PTFE-coated glass fibre fabrics. Several test procedures exist which are described in Annex B2.

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, but other methods are under development as well, e.g. [NgTh13].

The arms of the cruciform are normally parallel to the orthogonal yarns. Procedures of biaxial tensile tests are described in Annex B3.1.

Conducting biaxial tensile tests, fabrics show a highly nonlinear and anisotropic stress-strain-behaviour, which strongly depends on the load ratios warp/weft and the loading history as shown exemplary in Figure 2-5.



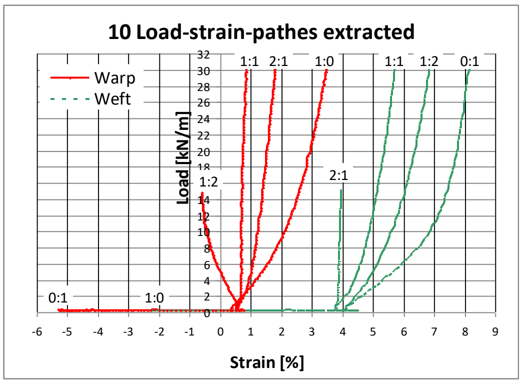


Figure 2-5 Left: Load-strain-diagram as a result of a biaxial test on Glass/PTFE material according to MSAJ/M-02-1995; right: Ten load-strain-paths (warp/weft at five load ratios), extracted from the diagram as the basis for the determination of elastic constants [US13b]

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” [BBN04b] or the procedure according to the French Recommendations [ABT97], see Code Review No. 2.

Regarding the interpretation of test results and the determination of elastic constants, suggestions can be found e.g. in [BrGo10, USSS11, BBN04b]. 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.

One possibility to determine the stiffness parameters of coated fabrics using a structural model developed by Blum/Bögner is presented in Annex D.

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 2286]*
- *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).

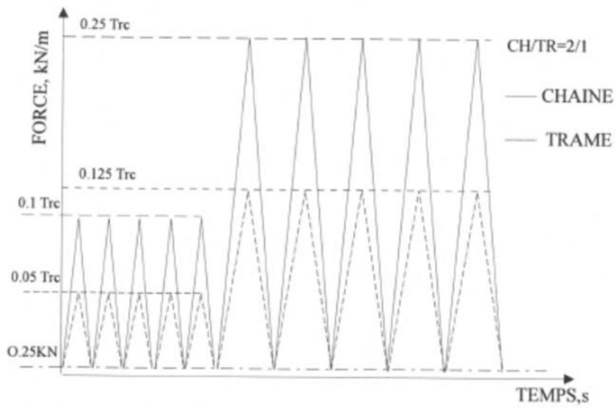


Figure A

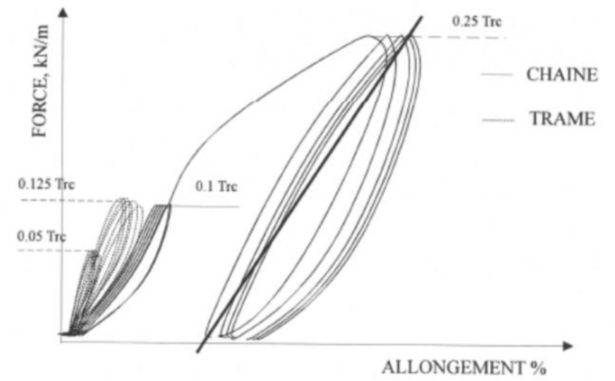


Figure B

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 [S5] and DIN 53363 [S7]. 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. Another possibility is to perform a wide panel tear test [BBN04b]. In the context of the Eurocode development it is envisaged to focus on the European test standards only. Procedures of tear tests are described in Annex B4.

Exemplary results of a tear test are presented in Figure 2-6.

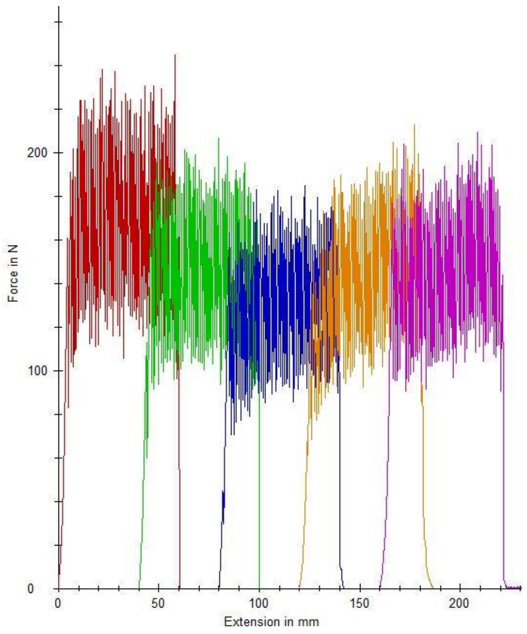


Figure 2-6 Typical results of a tear test [© ELLF]

2.2.2.7 Shear behaviour of fabrics

The shear behaviour should also be considered for coated fabrics. Indeed the shear is not important for the stress state in the field far away from any corners and edges. But near the edges and gussets the shear stiffness is extremely important for the stress distribution especially if the mean axes of anisotropy are not perpendicular to the edge. It can be shown by means of discussing the symmetry group of orthotropic materials that the shear behaviour is not coupled with the behaviour in the directions of warp and weft.

The determination of the shear modulus can be performed in a biaxial shear test. The biaxial shear test is presented in Annex B5. The typical shear stress-strain-behaviour is shown in Figure 2-7.

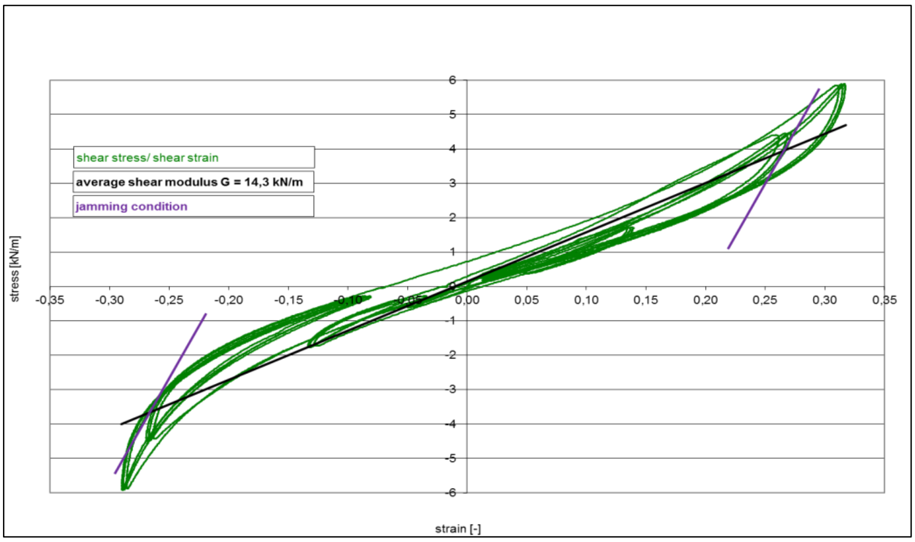


Figure 2-7 Shear stress in dependence of shear strain and average shear modulus G [© DEKRA/Labor Blum]

2.2.2.8 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 [S6]. 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 [S14]. DIN 53357 is still applied in Germany although it is withdrawn. In Annex B6 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.

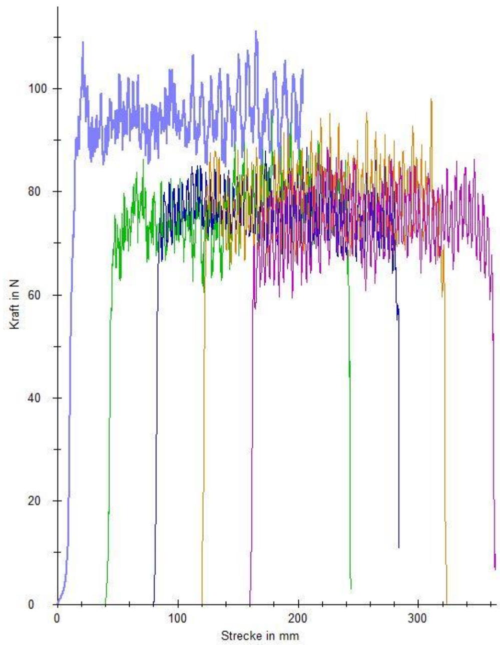


Figure 2-8 Typical results of an adhesion test [© ELLF]

Typical results of an adhesion test are presented in Figure 2-8.

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)] in (N/5cm) and (kN/m)	*2800/2800 56/56*	*4200/4000 84/80*	*5600/5600 112/112*	*8000/7000 160/140*
Tear strength in warp and weft in (N/5cm)[3)] and (kN/m)	*300/280 6/5,6*	*550/500 11/10*	*800/650 16/13*	*1200/1100 24/22*
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 fabric), 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 No. 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 [N/5cm] [kN/m]	*EN ISO 1421*	*Mean value*	*2750/2750 55/55*	*4000/4000 80/80*	*5500/5000 110/100*	*7500/6500 150/130*	*9250/8000 185/160*
		5% fractile	*2500/2500 50/50*	*3500/3500 70/70*	*5000/4500 100/90*	*6750/6000 135/120*	*8500/7250 170/145*
Seam strength at 23°C	*EN ISO 1421*	*percentage of the respective tensile strength*	*≥90%*	*≥90%*	*≥90%*	*≥90%*	*≥80%[1)]*
Seam 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)] [N]	*EN 1875-3 Method B (62°) 4)[2)]*	*170/170*	*280/280*	*450/450*	*750/750*	*1100/1100*
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 [S29], 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/m²	*800*	*1050*	*1250*	*1500*
Tensile strength in warp and weft ²⁾ in (N/5cm) and (kN/m)	*3500/3000* *70/60*	*5000/4400* *100/88*	*6900/5900* *138/118*	*7300/6500* *146/130*
Tear strength in warp and weft in (N/5cm) ²⁾ and (kN/m)	*300/300* *6/6*	*300/300* *6/6*	*400/400* *8/8*	*500/500* *10/10*
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	*M2¹⁾*	*M2¹⁾*	*M2¹⁾*	*M2¹⁾*

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. Tear strength and tensile strength after crease fold are subjective criteria which allow to compare materials in their sensitivity during fabrication, handling and installation. For further information see chapter 7.7 or annex B2.

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 [N/5cm] [kN/m]	*EN ISO 1421*	*Mean value*	*3500/2500* *70/50*	*4250/4000* *85/80*	*7000/6000* *140/120*	*8000/7000* *160/140*
		5%-fractile	*To be determined by experimental investigations*			
Seam Strength at 23°C	*EN ISO 1421*	*percentage of the respective tensile strength*	*≥80%*	*≥90%*	*≥90%*	*≥90%*
Seam Strength at 70°C	*EN ISO 1421*		*≥60%*	*≥70%*	*≥70%*	*≥70%*

Eurocode Outlook No. 8

Glass/PTFE-fabrics

Strength values of PTFE-coated glass fibre fabrics <u>not</u> 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***
Tear Strength [N][1)]	*EN 1875-3[2)]*	*150/150*	*200/250*	*300/300*	*400/400*
Adhesion [N/5 cm][1)]	*EN ISO 2411*	*35*	*50*	*80*	*100*

[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.

2.2.3.4 Silicone-coated glass fibre fabrics (Glass/silicone-fabrics)

Silicone-glass is a glass fibre fabric impregnated and coated with silicone elastomer. There is no emission of toxic fumes at high temperatures. Silicone coated fabrics are very flexible at a temperature range from –50°C to 200°C. The material is treated to resist wicking along the fibres for prolonged outdoor use and has a surface coating which improves soil resistance and handle during manufacture. The silicone coating can be translucent or pigmented to either reduce the translucency or to get coloured fabric. UV-B and UV-C radiation is blocked by the silicone while the UV-A radiation is passing.

The seams are stitched or glued. Currently material with a tensile strength up 10000 N/5cm is available.

Eurocode Outlooks No. 9 and 10 give a proposal for a future classification of conventional silicone-coated glass fibre fabrics. 5%-fractile values for the tensile strength have still to be determined.

Regarding further information on strength after crease fold see chapter 7.7 or annex B2.

Eurocode Outlook No. 9

Glass/silicone-fabrics

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

Parameter	***Stan-dard***	***Value***	***Type I- warp/weft***	***Type I+ warp/weft***	***Type III warp/weft***	***Type III+ warp/weft***	***Type V warp/weft***
Tensile Strength [N/5cm] [kN/m]	*EN ISO 1421*	*Mean Value*	*2600/2000* *52/40*	*4000/3900* *80/78*	*6000/5600* *120/112*	*7500/7500* *150/150*	*10000/9900* *200/198*
Seam Strength at 23°C	*EN ISO 1421*	*percentage of the respective tensile strength*	*70 %*	*70 %*	*70 %*	*70 %*	*70 %*
Seam Strength at 70°C	*EN ISO 1421*		*70 %*	*70 %*	*70 %*	*70 %*	*70 %*

Eurocode Outlook No. 10

Glass/silicone-fabrics

Strength values of silicone-coated glass fibre fabrics <u>not</u> directly linked to the stress verification in the ULS

Parameter	***Standard***	***Type I- warp/weft***	***Type I+ warp/weft***	***Type III warp/weft***	***Type III+ warp/weft***	***Type V warp/weft***
Tensile Strength after Crease Fold Test[1) 3)]	*ASTM D 4851[3)]*	*82.5%*	*>92%*	*to be determined*	*>99%*	*>99%*
Tear Strength [N][1)]	*EN 1875-3[2)]*	*176/133*	*190/190*	*400/400*	*550/550*	*900/850*
Peel [N/5 cm][1)]	*EN ISO 2411*	*>150*	*>150*	*>150*	*>150*	*>150*

[1)] This values are given as mean values.
[2)] Accompanying the Eurocode development, a new biaxial test standard is currently under development in CEN/TC248 W 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.

2.2.3.5 Fluorpolymer-coated PTFE fabrics

Eurocode Outlooks No. 11 and 12 give a proposal for a future classification of fluorpolymer-coated PTFE-fabrics.

Eurocode Outlook No. 11

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

Eurocode Outlook No. 12

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)] [N]	*DIN 53363 [2)]*	*390*	*700*	*1000/1000*
Reaction to fire	*EN 13501-1*	*B-s1, d0*	*B-s1, d0*	*B-s1, d0*
Fabrication		*sewing*	*sewing*	*sewing/welding*

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. 13 and 14 give a proposal for a future classification of uncoated fabrics made from PTFE-yarns. As uncoated PTFE fabrics are typically available with higher strength values only, the classification starts with type III.

Eurocode Outlook No. 13

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

Eurocode Outlook No. 14

Uncoated PTFE-fabrics

Properties of uncoated PTFE-fabrics <u>not</u> 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 350 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 2-9.

Figure 2-9 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 is up to 1% for usual stress ranges of up to approximately 9 N/mm^2, but can yield up to 2% for higher stress levels up to 13 N/mm^2 [Sax12].

The individual ETFE-foils are joined by contact welding. 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 500 Pa, but can be chosen higher depending on external conditions like wind or snow [Sch09, Hou13, KCGL10, Koc04].

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 300 µm) the linear elastic range reaches up to 1 % 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, KCGL10, 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 strength [N/mm^2],
- tensile strength [N/mm^2],
- Young's modulus [N/mm^2],
- shear modulus [N/mm^2] and
- Poisson's ratio [-].

Typical strength values are the

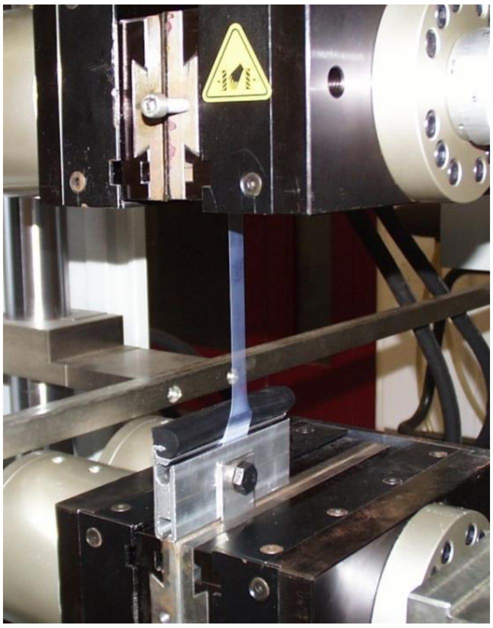
- yield and tensile strength,
- seam strength and
- tear strength.

2.3.2.2 Yield and tensile strength

In principle, the yield and 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) [S3] and Part 3 (test conditions for films and sheets) [S4]. 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 [S12].

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 2-10 shows a tensile test specimen of an ETFE-foil as well as typical stress-strain-diagrams for ETFE-foils.



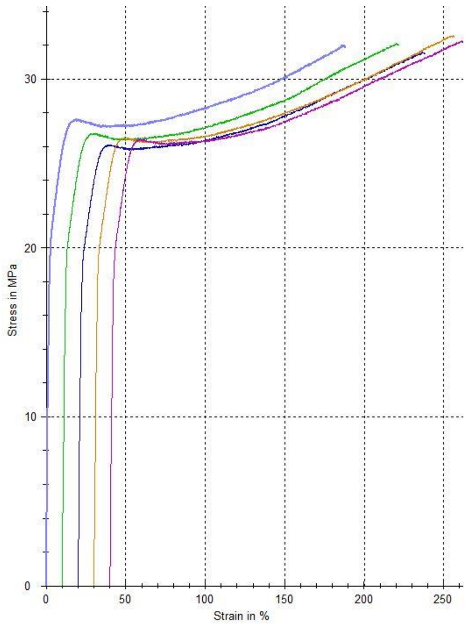


Figure 2-10 Tensile test specimen (here: ETFE-foil edge detail), left, and typical stress-strain-diagrams for ETFE-foils [© ELLF]

Eurocode Outlook No. 15

(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 [S7], see explanations for fabrics in chapter 2.2.2.5.

Typical force-extension-diagrams for ETFE-foils are presented in Figure 2-11.

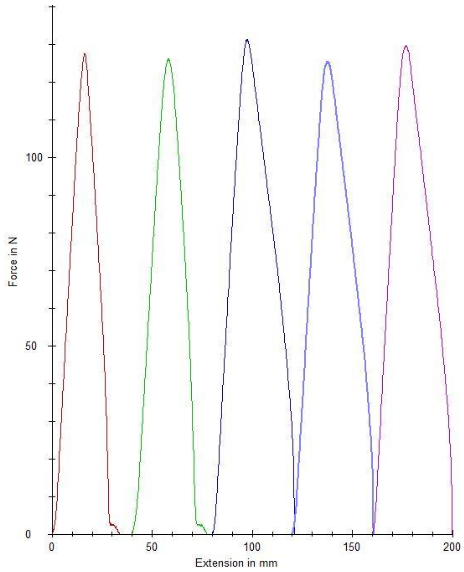


Figure 2-11 Typical force-extension-diagrams for ETFE-foils [© ELLF]

Eurocode Outlook No. 16

(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, see Annex B3.1. An additional test procedure is presented in Annex B3.2.

Eurocode Outlook No. 17

(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. 18

(1)	*If a foil material has been shown to be isotropic, then elastic constants can be determined from different stress ratios than 1/1 in a biaxial test.*

2.3.2.5 Tabulated strength values for ETFE-foils

Eurocode Outlook No. 19 contains design values for ETFE-foils.

Eurocode Outlook No. 19

ETFE-foils

Parameter	*Standard*	*Value*	*Minimum value*
Tensile Strength at 23°C [N/mm²]	*EN ISO 527-1*	*Mean value*	*50*
Tear Strength [N/mm]	*DIN 53363*	*Mean value*	*450*
Seam Strength at 23°C [N/mm²]	*EN ISO 527-1*	*percentage of the respective tensile strength*	*30*
Seam Strength at 50°C [N/mm²]	*EN ISO 527-1*		*24*

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]), see also Annex D of this document.

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

$$\sigma_x = E_x^d \cdot \varepsilon_x + E_{xy}^d \cdot \varepsilon_y \tag{2.1}$$

$$\sigma_y = E_y^d \cdot \varepsilon_y + E_{yx}^d \cdot \varepsilon_x \tag{2.2}$$

where σ_x, σ_y are the membrane stress in warp and weft direction in [kN/m], ε_x, ε_y are the strain in warp and weft direction in [-], E_x^d, E_y^d are the direct stiffness in warp and weft direction of a fabric in [kN/m] and E_{xy}^d, E_{yx}^d are the crimp interchange stiffness in warp and weft direction in [kN/m].

b. Inverse stiffness formulation

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

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

where σ_x, σ_y are the membrane stress in warp and weft direction in [kN/m], ε_x, ε_y are the strain in warp and weft direction in [-], E_x^i, E_y^i are the stiffness in warp and weft direction of a fabric in [kN/m] – synonymously to the Young's modulus – and ν_{xy}, ν_{yx} are the Poisson's Ratios in warp and weft direction in [-].

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 equivalent and can be transformed from one to the other. The transformation is presented in chapter 2.4.2. They are both widely used in the field of membrane structure engineering and therefore particular care must be taken when stiffness parameters are specified or compared. In the usual case where the crimp interchange stiffness or the Poisson's Ratio are unequal to zero, direct stiffness E_x^d, E_y^d and inverse stiffness E_x^i, E_y^i do not exhibit the same values. This fact is accommodated by the superscripts "d" for "direct stiffness" and "i" for "inverse stiffness". In order to avoid mistakes, it can be recommended to always use the superscripts or state the type of formulation – "direct stiffness formulation" or "inverse stiffness formulation" – when giving stiffness properties.

Often the software uses only one value for the crimp interchange stiffness or for the Poisson's Ratio, respectively, while the other can be calculated internally based on the assumption of a symmetric stiffness matrix. Using the average value of the two values within one of the formulations – crimp interchange stiffness or Poisson's Ratio, respectively – 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 the inverse stiffness values Young's Modulus and Poisson's Ratio into direct stiffness and the other way around:

$$E_x^d = \frac{E_x^i}{\left(1 - \nu_{xy} \cdot \nu_{yx}\right)}, \tag{2.5}$$

$$E_y^d = \frac{E_y^i}{\left(1 - \nu_{xy} \cdot \nu_{yx}\right)}, \tag{2.6}$$

$$E_{xy}^d = \nu_{xy} \cdot E_x^d, \tag{2.7}$$

$$E_{yx}^d = \nu_{yx} \cdot E_y^d \tag{2.8}$$

or

$$E_x^i = E_x^d \cdot \left(1 - \nu_{xy} \cdot \nu_{yx}\right), \qquad (2.9)$$

$$E_y^i = E_y^d \cdot \left(1 - \nu_{xy} \cdot \nu_{yx}\right), \qquad (2.10)$$

$$\nu_{xy} = \frac{E_{xy}^d}{E_x^d}, \qquad (2.11)$$

$$\nu_{yx} = \frac{E_{yx}^d}{E_y^d}. \qquad (2.12)$$

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” [S31]. 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 3.5. The cutting pattern generation consists of the division into single cutting patterns, the “flattening” of the three-dimensional geometry onto a plane (the so called geometrical development) 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 or after an elongation due to external loading, respectively. The goal of the cutting pattern determination is to assure the final shape with the desired level of prestress. There are various established approaches for the cutting pattern determination, ranging from the application of compensation values to the definition of continuum-mechanical based optimization problems, see e.g. [DWB12, GMS00, KL02, LWB08, MM99, TT07]. Construction engineering has to consider possible sizes, the fabrication, transportation and erection.

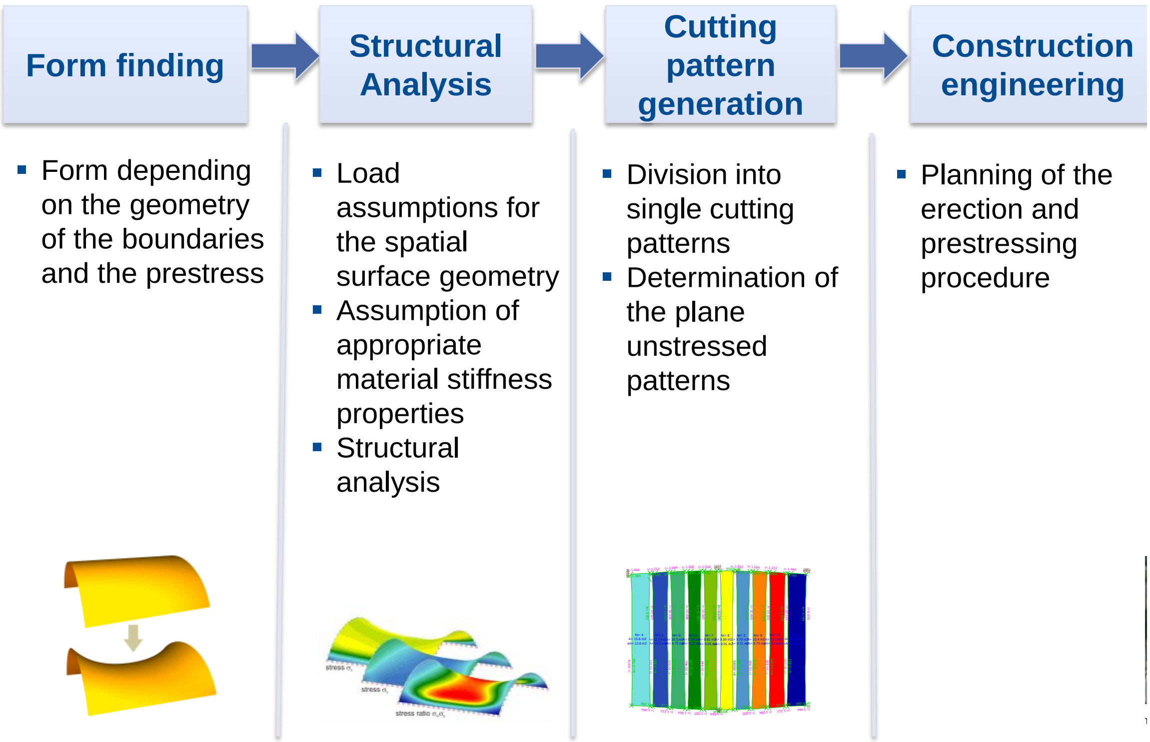


Figure 3-1 Design steps for the design of membrane structures [Figures: © ELLF]

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 when conducted by experienced engineers. For instance, the patterning and the compensation has an impact on the prestress level and thus on the form finding, the installation planning has an 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. Moreover, detailing may have significant influence on stresses [Syn08].

The future design rules for all the mentioned design steps 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. 20 and 21. 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. 20

(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. 21

(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 all loads by activating only tensile stresses. The curvature can be anticlastic (mechanically prestressed like saddle shaped structures) or synclastic (pneumatically prestressed by air inflation like cushions or inflated beams), see Figure 1-2. The curvature radii are defined on the basis of architectural and structural requirements. The French Recommendations [S29] 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

<u>French recommendations [S29]: basic requirements</u>

The shape of the 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 ratio of the chord to the sag, and the radius of curvature of the arc associated with the same chord and the same sag (see Figure 3-2) should be limited.

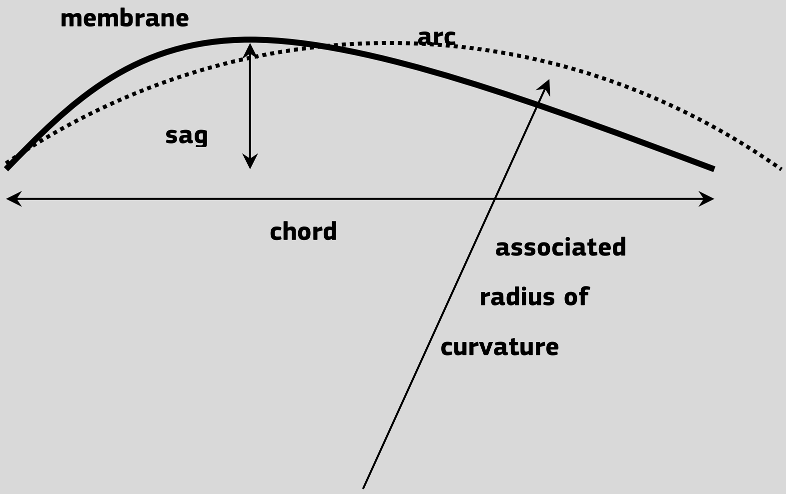


Figure 3-2 Membrane and associated arc

When there is pretension, the ratio of the chord to the sag, 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 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 (see 5.5.1) 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. 22

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 amplitudes 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 tests 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.

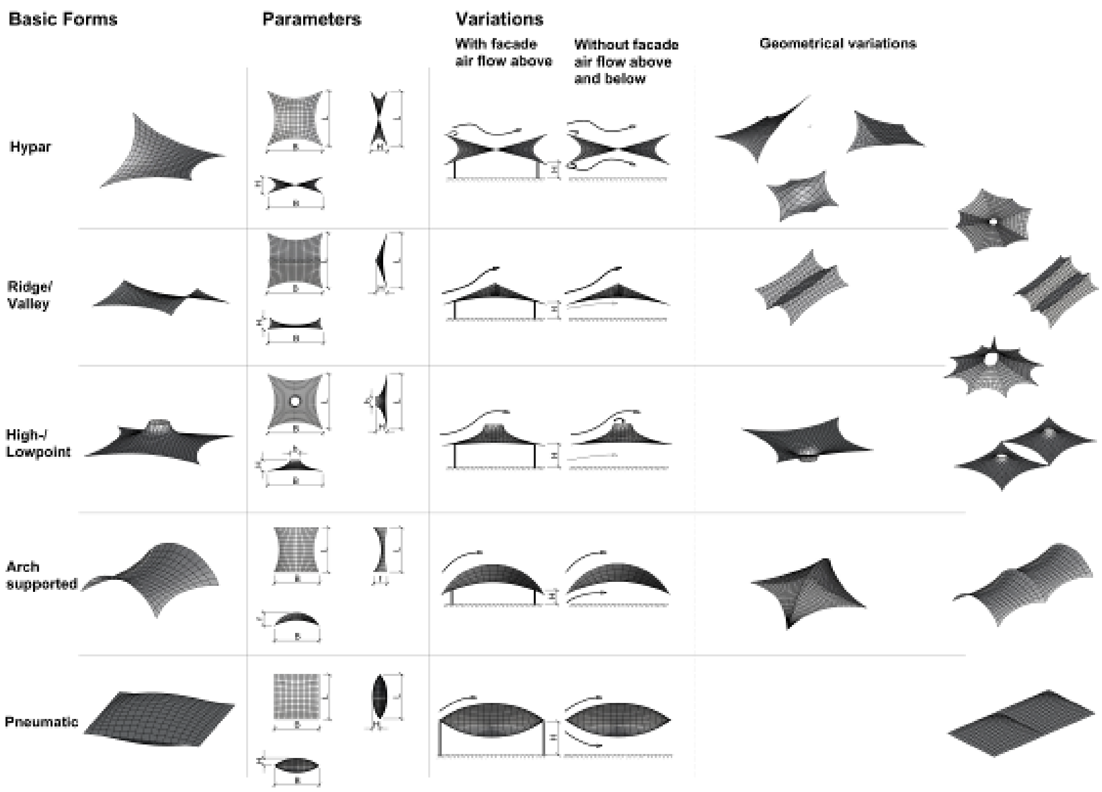


Figure 3-3 Categorization of basic membrane forms for the purpose of wind tunnel testing [© Alexander Michalski] [Mich14]

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 stiffens and stresses 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). The distinction has impact on the application of partial factors. Two positions are discussed in the following – unaffected of the discussion of the application of partial factors in general in chapter 3.6. 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. The different positions lead to a different handling 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 $\gamma_p = 1.0$. 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 $\gamma_p \leq 1.0$.

Position 2: Handling of prestress as an action is inappropriate

Membranes structures present a quite particular specialty which distinguishes it from more usual structures: no prestress – no structure.

Applying prestress in a tensioned structure leads to an increase in the structural geometric stiffness, which is not the case for the more conventional structures such as built from 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. The behaviour of the material is supposed linear, which does not change the comprehensiveness of the conclusions about the influence of the prestress on the stiffness.

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:

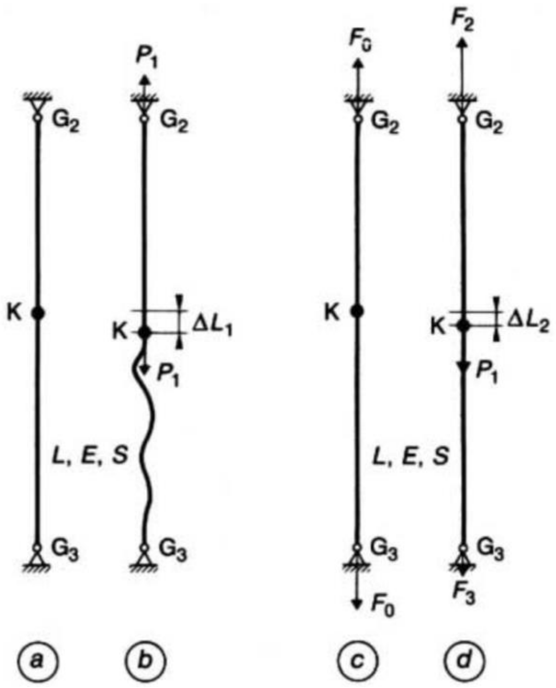


Figure 3-4 Model of the colinear cables [Lau92]

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 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]

Mechanical specifications

From the mechanical point of view and in relation to traditional rigid structures, tensioned textile structures have a very particular nature marked in particular by:

- an initial state of **prestress** required to increase the stiffness of the structure,
- the imperative need to have at any point a state of **tensile stresses in the weft and warp directions**, and a double reverse curvature,
- the existence of **large displacements**, and sometimes **large deformations** which induce a geometric nonlinearity,
- the **anisotropy of the material** used, and sometimes the need to take into account the structural non-linearity in the elastic field,
- the **low value of the own weight** compared to the climatic and prestressing forces,
- the **technological manufacturing constraints** that impose to cut out the rough surfaces under different initially plane constrained size limited elements,
- the existence of **substantial support reactions**, comprising particular vertical lifting components and strong horizontal components.

All of these constraints result in a very strong interrelation between form, forces and materials. The initial kinetic uncertainty and the necessity of determining the geometry of cutting demand to adopt a particular design methodology for this type of structures. The non-linear calculations also require the use of iterative and/or incremental calculation methods and a visualization graph of the deformed shape that allows manual corrections (to avoid the appearance of wrinkles or pockets for example, or to increase the curvature).

Need for double curvature

The local equilibrium at a point of tensioned membranes is characterized by the values of the principal tensions T_1 and T_2 (see Figure 3-5).

The principal curvature radii which correspond to the tensions are respectively R_1 and R_2.

The local balance equation is:

$$\frac{T_1}{R_1} + \frac{T_2}{R_2} = p$$
.

p represents a surface density of external actions. Two cases can be considered:

- the surface has double negative or inverse curvature: balance is possible with a p value of zero (the values of R_1 and R_2 being assigned an opposite sign). This is the case of linearly or concentrated tensioned textile structures;
- the surface has double positive curvature, in which case R_1 and R_2 being of the same sign, the balance can exist only by adding a third permanent term p_i correspondent in practice to a uniform internal pressure applied to the membrane. This is the case of inflatable structures.

In both cases, the external actions by a pressure must not cancel the principal tensions, which would result in the appearance of wrinkles in the membrane.

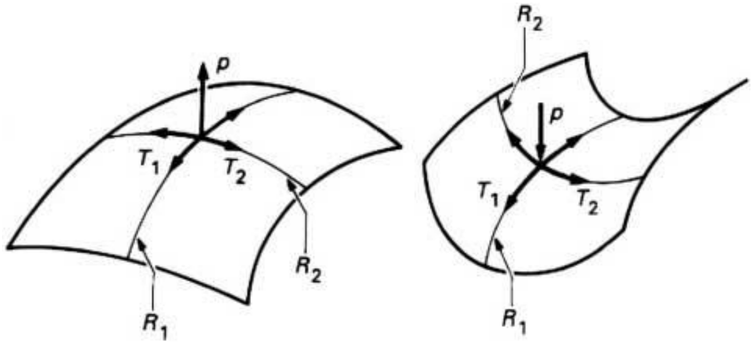


Figure 3-5 Local Equilibrium of a tensioned membrane

Role of pretension

The need for double curvature is established, the stability of the membrane is achieved by pretensioning, that is to say by introducing a prestress. The pretension is to induct traction in each of the two yarn families (in warp and weft) to limit the displacements of membrane subjected to external actions.

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 3-6).

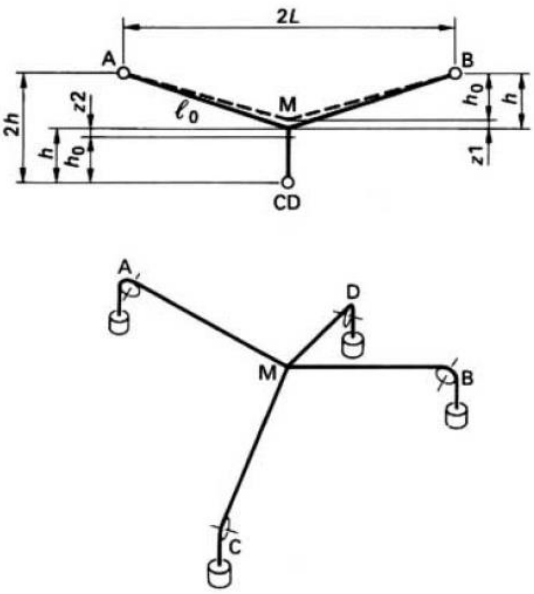


Figure 3-6 Model of the bi-cable [ML93]

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 points M of the two 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 3-7:

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

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 3-7).

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 3-7 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.

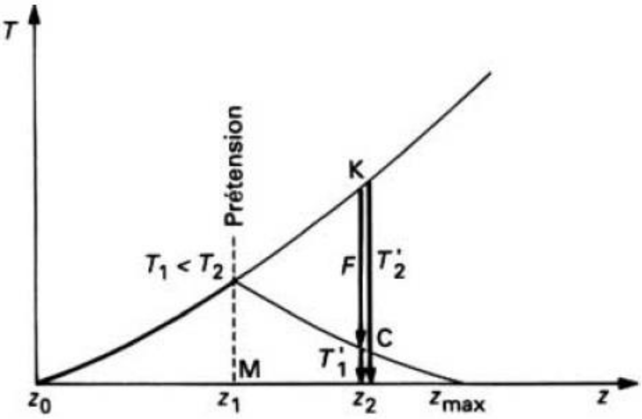


Figure 3-7 Operating diagram of the bi-cable [ML93]

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 smaller 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 (1.8 kN/m and 3.5 kN/m) are considered.

Example 3: Effect of the prestress on inflatable beams [NTL12, LeWi05, Ngu13]

For the following explanations a cantilever beam of length L is considered submitted to a force F, see Figure 3-8. The classical formulation for the deflection of a cantilever beam made of an isotropic material is given by the strength of materials theory. If the shear deformations are not neglected, this deflection is

$$v(x) = -\frac{F}{EI}\left(\frac{Lx^2}{2} - \frac{x^3}{6}\right) - \frac{Fx}{GS} \tag{3.6}$$

where I is the second moment of area, S is the surface of the straight section, E the Young's modulus and G the shear modulus.

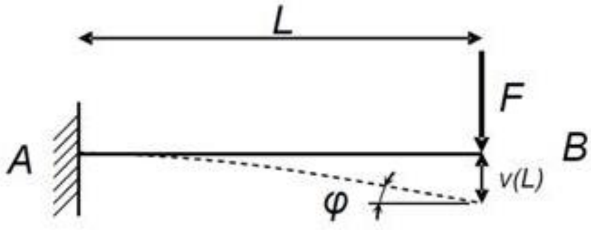


Figure 3-8 Cantilever beam with single point load at the tip

The strength of material theory dedicated to inflatable beams can be found in [LeWi05, NTL12, Ngu13]. More explanations can be found in 5.5.3. In the case of an orthotropic membrane for which the orthotropy directions are aligned with the principal directions of the tube, the deflection is given by (with Figure 3-9)

$$v(x) = -\frac{F}{\left(E_\ell I + \frac{PI}{S}\right)}\left(\frac{Lx^2}{2} - \frac{x^3}{6}\right) - \frac{Fx}{(P + kG_{\ell t}S)} \tag{3.7}$$

Here, E_ℓ is the Young's modulus in the longitudinal direction, $G_{\ell t}$ is the shear modulus, and k is a shear coefficient. In this formula, $P = p \cdot \pi \cdot R^2$ is the effect of the pressure p on the end surface of the beam (radius R), and corresponds to the prestress.

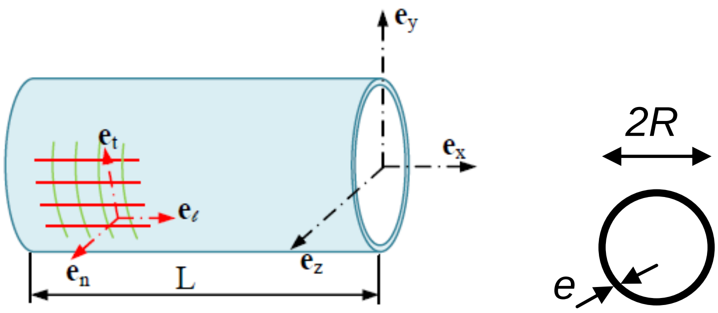


Figure 3-9 Tube coordinates and section details

In the case of inflatable beams, this leads to the following conclusions:

- the relation between the load and the displacements is linear,
- the relation between the presstress and the displacement is non-linear and
- the effect $P = p \cdot \pi \cdot R^2$ of the inside pressure p of the beam reinforces explicitly the bending stiffness $\left(E_\ell + \frac{P}{S}\right) \cdot I$ and the shear stiffness $P + k \cdot G_{\ell t} \cdot S$.

In the case of an inflated tubular beam of radius R, another interpretation is that the pressure p increases the material coefficients: E_ℓ is replaced by $E_\ell + \frac{p \cdot R}{2}$, and $G_{\ell t}$ is replaced by $G_{\ell t} + \frac{p \cdot R}{2k} = G_{\ell t} + p \cdot R$ 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]:

$$f = \frac{1}{2} \cdot \sqrt{\frac{T}{\rho}} \cdot \sqrt{\frac{m^2}{a^2} + \frac{n^2}{b^2}}, \tag{3.8}$$

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: $f = \frac{\omega}{2\pi} = \frac{i^2}{2} \cdot \pi \cdot \sqrt{\frac{EI}{\rho \cdot S \cdot L^4}}$. (3.9)

Here also, the tension T (which can be considered as the prestress) has the same effect as the stiffness.

General conclusions for the prestress

Prestress is a state of pretension before other external loads are applied, it is combined with the external loads, it reinforces the stiffness 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 aesthetic and structural requirements. The aesthetic 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 [S29], 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 with regard to the type of fabric that is applied:

- for PVC coated polyester fabrics not less than 1.3% of the short term tensile strength and
- for PTFE coated glass fibre fabrics not less than 2.5% of the short term tensile strength, but not less than 2.0 kN/m.

Code Review No. 6

French recommendations [S29]
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 [S32] 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. The engineer's choice of 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

Form finding is a procedure to determine the shape of equilibrium of the desired prestress state and the boundary conditions. The shape of equilibrium is usually described by its surface coordinates. The prestress state and the boundary conditions are defined to satisfy structural, aesthetic and serviceability requirements. 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 [Sob94]. In most cases the resulting shape cannot be determined in an analytical way but using numerical methods like the force density method [Lin99], dynamic relaxation [Bar99, Wak99] or the "Updated Reference Strategy" [BlRa99] 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 interacts with 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. 23.

Eurocode Outlook No. 23

(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. Different proposals are under discussion in

CEN/TC250 WG5. This is reflected in chapter 3.6.1. One of them is based on whether the structural behaviour is over- or underlinear

A sensitivity analysis – a method to check the structural behaviour – is proposed in chapter 3.6.2. 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 3.6.3.

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 Figure 3-10. Numerical examples are presented in Annex E for five different typical membrane shapes.

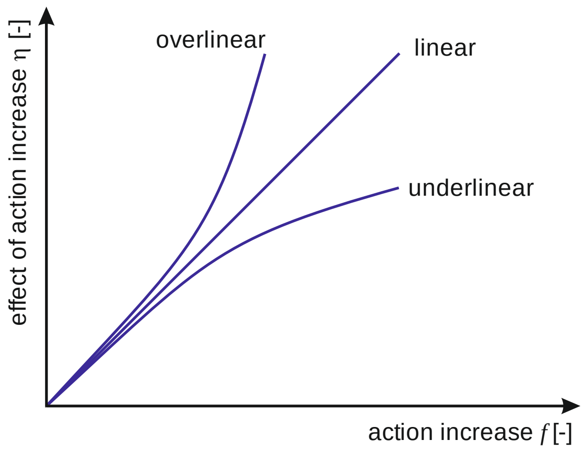


Figure 3-10 Linear as well as overlinear (category a) and underlinear (category b) behaviour of structures [USS14b]

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 “Design values of the effects of actions”

(1) For a specific load case the design values of the effects of actions (E_d) can be expressed in general terms as :

$$E_d = \gamma_{Sd} E\left(\gamma_{f,i} F_{rep,i} ; a_d\right) i \geq 1 \qquad (6.2)$$

where:

a_d is the design values of the geometrical data (see 6.3.4);

γ_{Sd} is a partial factor taking account of uncertainties:

- in modelling the effects of actions;

- in some cases, in modelling the actions.

NOTE In a more general case the effects of actions depend on material properties.

(2) In most cases, the following simplification can be made:

$$E_d = E\left(\gamma_{F,i} F_{rep,i}; a_d\right) i \geq 1 \qquad (6.2a)$$

with $\gamma_{F,I} = \gamma_{Sd} \cdot \gamma_f$, *(6.2b)*

NOTE When relevant, e.g. where geotechnical actions are involved, partial factors $\gamma_{F,i}$ *can be applied to the effects of individual actions or only one particular factor* γ_F *can be globally applied to the effect of the combination of actions with appropriate partial factors.*

(3)P Where a distinction has to be made between favourable and unfavourable effects of permanent actions, two different partial factors shall be used ($\gamma_{G,inf}$ *and* $\gamma_{G,sup}$*).*

(4) 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.*

NOTE Except for rope, cable and membrane structures, most structures or structural elements are in category a).

(5) 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, 6.3.2(4) 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 [USS14b].

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

Code Review No. 8

DIN 18800:, El. (725) [S27]

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, USS14b]. 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. A simplified procedure may be applied only in case of a single predominant action: γ_F may then 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 [USS14b].

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 weft 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 Figure 3-11. In the deformed state of the membrane the eccentricity Δx, which strongly influences the moment $M_{steelworks}$, is significantly higher.

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.

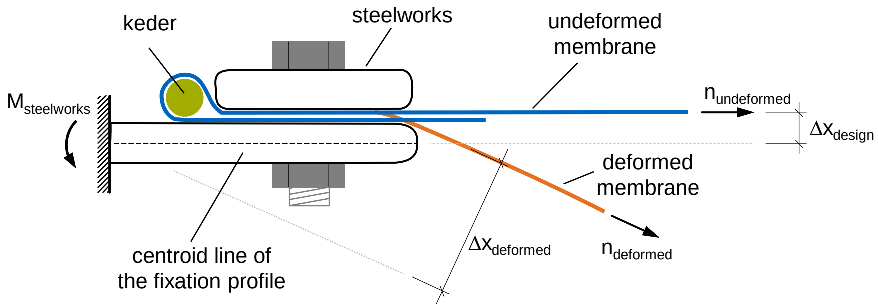


Figure 3-11 Example of the impact of membrane deformation on eccentricities of the primary structure [PWB13]

Position 2: For tensile membrane structures, generally apply the fundamental expression (6.2) of EN 1990; in particular cases where there is only one single predominant action, the γ_F factor specified for this action may be applied to the action effects, as a simplified procedure

In the general framework of the Eurocodes, the design of tensile membrane structures has to be developed according to the semi-probabilistic concept using partial safety factors, as defined in Eurocode 0. In this respect, the general expression of the design effects of actions is given by expression (6.2) in EN 1990 (see Code review No. 7):

$$E_d = \gamma_{Sd} E\left(\gamma_{f,i} F_{rep,i}; a_d\right) i \geq 1 \tag{3.10}$$

Structures using common materials as concrete, steel or wood, present a linear or over-linear behaviour: the effects of actions increase proportionally to the increase of actions (linear behaviour) or, in cases of large slenderness and high gravity loads, more than proportionally (over-linear behaviour). For these structures, expression (6.2) may be simplified, on the safe side, according to expressions (6.2a) and (6.2b) in EN 1990:

$$E_d = E\left(\gamma_{F,i} F_{rep,i}; a_d\right) i \geq 1 \tag{3.11}$$

with $\gamma_{F,i} = \gamma_{Sd} \cdot \gamma_{f,i}$.

Tensile membrane structures behave quite differently. As fabrics, foils and cables offer no flexural stiffness at all, rigidity and equilibrium are obtained through initial preloading and through increase of tension forces generated by large deflections under the external loadings. Thus, the behaviour is under-linear and needs to be investigated through non-linear analysis and the basic reference for the design should remain expression (6.2).

In this context, it is important to describe, through non-linear analysis, the realistic deformed position of the membrane under factored actions, consistently with the Ultimate Limit States concept and according to expression (6.2) of EN 1990.

The application of a unique partial factor on the effects of actions would lead to under-evaluation of the global and local deflections and to undue increase of the effects of the preloading.

Under-evaluation of deflections could also lead to unsafe design of the connections of the membrane with the supporting structure as unfavourable consequences of deformation of the membrane are omitted.

In addition, if the supporting structure presents an over-linear behaviour, global non-linear analysis of the whole system (membrane+supporting structure) under unfactored actions would also lead to unsafe design. The same adverse situation could also be encountered if the design of some elements of the supporting structure is governed by combined efforts, especially with material non-linearity.

For all these reasons, the design approach of tensile membrane structures should be conducted as follows:

- Deflections and stresses in the membrane are calculated through non-linear analysis, under different combinations of actions including regular γ_F factors, as defined in Eurocode 0 – according to expression (6.2) of EN 1990, these values could be divided by the γ_{Sd} factor but it is easier and safe-sided to use directly γ_F factors. In the combinations, the γ_P factor applied to the pretension is taken as 1.0.
- γ_M values used on the resistance side are significantly higher for membranes than those defined for common structural materials, and thus they cover the part of γ_{Sd} omitted in the effects of actions obtained from non-linear analysis under common factored combinations of actions.

This design approach has been observed in France since the beginning of the development of use of tensile membrane structures in buildings. It is also in line with the recommendation of DIN 18800 quoted in Code Review No. 8.

According to clause 6.3.2(4)b of EN 1990, when one single action is predominant for the design, it is acceptable to use a simplified procedure: the non-linear analysis is carried out under the characteristic value of the action, and the results are then factored by γ_F value applicable to this action. In this procedure, the supporting structure of the membrane has to be rigid enough so that it does not affect the behaviour of the membrane and that it is not itself subject to non-linear effects. Special attention should also be paid to the connections between the membrane and the supporting structure to ensure that no adverse effects on their resistance are generated by any amplification of the deflections of the membrane. It is worth mentioning that, if the preloading level of the membrane is rather high, this simplified procedure could lead to uneconomic design.

Notes:

1) Increasing the effects of actions instead of increasing the actions themselves is obviously a conservative approach in evaluating the stresses in the membrane; but this practice is equivalent to regress to a concept of Allowable Stresses. The obvious and demonstrated shortcomings of this concept are precisely at the origin of the concept 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.
2) 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 [S29], chapter 5, particularly considering the application of partial factors and the combination of actions.

Code Review No. 10

French recommendations [S29]
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 behaviour. 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 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 already given by eq. (3.10) (see EN 1990)

$$E_d = \gamma_{Sd} \cdot E\left\{\gamma_{f,i} \cdot \psi \cdot F_{k,i}; a_d\right\}. \tag{3.10}$$

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 an 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 actions:

- 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 [USS14b]. 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. 24

- *(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, USS14b]. 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

$$\eta = \frac{\sigma(f \cdot F_k)}{\sigma(F_k)} \tag{3.12}$$

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 3-10, 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:

$$e = \frac{\sigma\left(f \cdot F_k\right)}{f \cdot \sigma\left(F_k\right)} = \frac{\eta}{f} \qquad (3.13)$$

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

<u>DIN EN 1990/NA/A1:2012-08</u>

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 (γ_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	Bezeich-nung	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 Außer-gewöhnlich
		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 3-12 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

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

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

EN 1993-1-11:2010-12

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

DIN 18800 in combination with Application rule for DIN 18800

The former German code for the design of steel structures DIN 18800 [S27] – which also incorporated rules for cable structures – proposed in conjunction with the Application Rules for this code [S28] 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 [S27]. 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* $\gamma_P = 1.25$ *[S28].*

Code Review No. 18

> *DIN EN 13782*
>
> *In chapter 7.5.2 of DIN EN 13782 [S32] 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. 25

> *(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. 26

(1) Combinations of actions should consider the rules of EN 1990, i.e. distinguish 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 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" [S29] consider durability aspects of PES/PVC-fabrics. These recommendations have been published 1997 and revised in 2007. Annex B of the French recommendations is entitled "Durability 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 durability will be derived on the basis of these French recommendations and merged with the German A-factor concept, see chapter 6.

The durability of foils is considered by some designers by means of an adjusted German A-factor concept or by means of an introduced k_{mod}-factor. Both concepts are still under discussion, see chapters 6 and 7.

4.2 Textile fabrics

4.2.1 Notions of durability of textile fabrics

The concept of durability of fabrics is related to the appreciation of the evolution of their damage in service. Durability 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.

4.2.2 Principles for conducting an analysis of durability

4.2.2.1 General

In the frame of French investigations which are described by Annex B of the French recommendations [S29], 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.

4.2.2.2 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.

4.2.2.3 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.

4.2.2.4 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 fifty-year 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).

4.2.2.5 Interpretation of the results of the estimation durability program

The example shown in Figure 4-1 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 durability 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 durability, as well as pre-tensions 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.

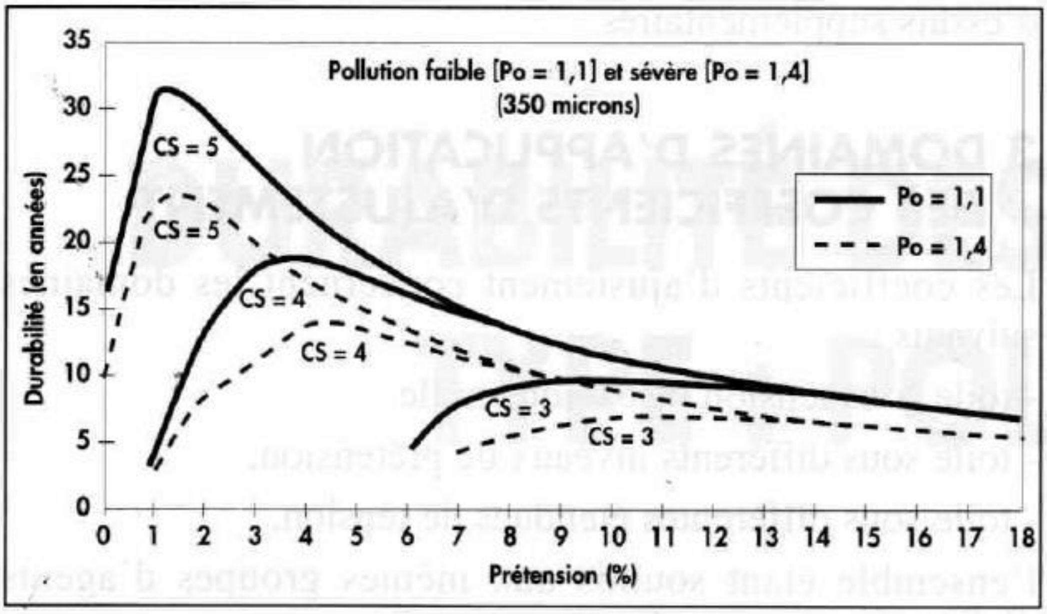


Figure 4-1 Durability-pretension-diagram considering low pollution (Po = 1.1) and severe pollution (Po = 1.4) for a PES/PVS-fabric [S29]

4.3 Foils

Eurocode Outlook No. 27

(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.

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 today's design practice is to apply numerical methods like the Force Density Method, Dynamic Relaxation or other methods eventually based on 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 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 struts, beam elements or cables – can be integrated in the model or idealised by appropriate bearings. Often it is appropriate to model stiff struts and beam elements as undisplaceable bearings. Otherwise, when the beams are flexible, e.g. in increasingly realized bending-active hybrid structures, they should be integrated in the formfinding and the structural analysis, see e.g. [LAG13, PB13, Lie14, PDW15]. General requirements are specified in Eurocode Outlook No. 28.

Eurocode Outlook No. 28

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

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

(8) 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 must 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 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 that the membrane should be modelled to cope with the physical requirements. That applies for example to the modelling of slack elements, shear deformation of elements and anisotropic material properties considering individual material constants and the material orientation. Large strain may be necessary to be considered if the material may undergo large plastic deformations (e.g. 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 modelling assumptions, e.g. appropriate elements in a finite element context. 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. 29

(1) *The numerical membrane surface shall be form found using suitable form generation tools to determine a shape of equilibrium. 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/connections/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 shall 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, like mentioned above for hybrid structures, or imposing support deflections within the analyses. This leads to more accurate analysis results and may be necessary to appropriately assess the overall safety of the primary and secondary structure. The deformation of the supporting structure may be disregarded under special circumstances. For instance, as a safe sided approach for the purpose of the membrane verification in the Ultimate Limit State a flexible frame of a plane membrane facade element may reasonably be substituted by undisplaceable bearings: 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 or where it significantly modifies the structural behaviour.

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 integrity of the supporting structure is guaranteed.

Eurocode Outlook No. 30

(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

The material properties of a structural membrane are characterized by tensile and shear stiffness through parameters such as the “Young’s moduli” in the main anisotropic directions and shear moduli, respectively. For typical (i.e. anisotropic) membrane materials, the shear modulus may not be equivalent to Poisson’s ratio, as it is the case in isotropic elastic continua. If the shear modulus and/or tangential shear strain behaviour of the membrane material is negligible small, a simple cable net model can be applied neglecting shear stress and/or shear strain effects. Specialized cable net software may be enhanced to model Poisson’s ratio and shear modulus. For many cases the enhanced cable net model is appropriate for structural membrane analysis.

Because great deflections are a main characteristic of tensile structures like membranes and cables, geometrical nonlinear analysis is required for these types of structures. Material nonlinearity is considered to model the loss of compression stiffness, e.g. in the case of wrinkling. In general material nonlinearity must be considered regarding safety. A typical material model considered by up-to-date software can be described by a bilinear stress-strain-diagram, see Figure 5-1.

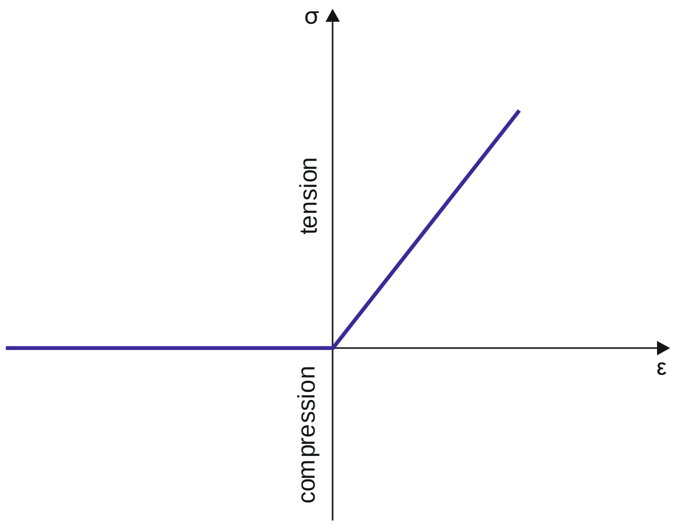


Figure 5-1 Bilinear material behaviour usually considered by up-to-date software that uses continuous membrane elements

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. 31

(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 may be based upon the assumption that the stress-strain behaviour of the material is linear in the stress interval of interest.
	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 compression struts and cables at the outer surface where the function of the tube is to stabilize the struts and the cables and the latter ones are the actual structural elements.

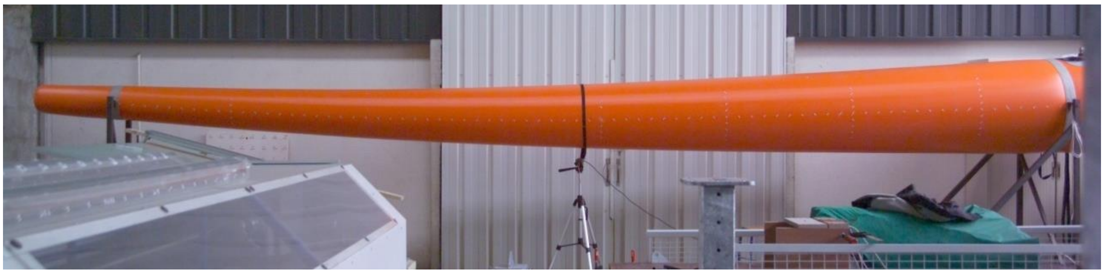
Low pressure and high pressure structures can be distinguished. Air halls and cushions are pressurized with approximately 0.1 kN/m^2 to 1.0 kN/m^2, whereas inflatable beams frequently need high pressures of about 20 kN/m^2 up to 700 kN/m^2. Nonetheless, low pressure inflated arches can be realized, too.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

Audi Sphere

Botanic Garden, Aarhus, Denmark

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

(a) Inflatable buildings



(b) Inflatable mast during testing

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

Air halls are well covered, e.g. by [Otto82] or the German standard DIN 4134 [S25], and are therefore not further examined here – though the rules have to be updated for a future Eurocode. In the following chapters basics for the structural analysis of cushions and inflatable beams are exposed which are less frequently a topic of technical literature and particularly standards. The latter chapter on inflatable beams summarizes some of the recent 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 prestressed 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:

$$p \cdot V = n \cdot R_m \cdot T \tag{5.1}$$

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

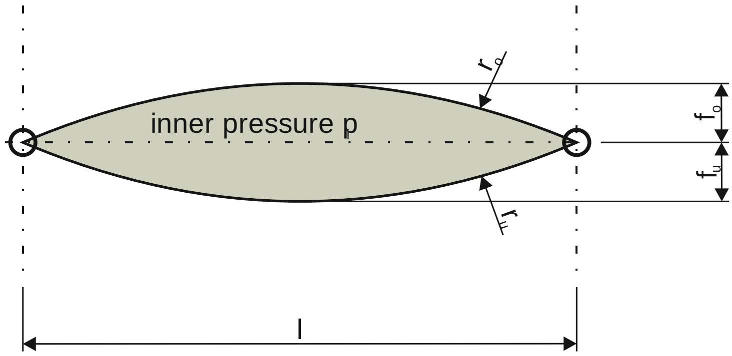


Figure 5-4 Section of a two layer cushion with inner pressure pi [source and ©: formTL ingenieure für tragwerk und leichtbau GmbH]

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-Mariotte law:

P·V = 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- Mariotte 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.

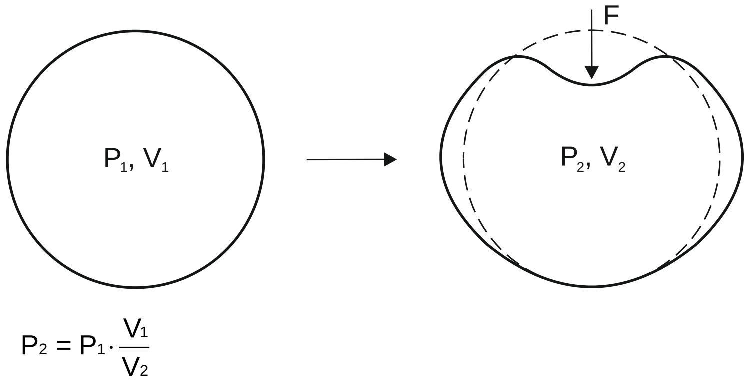


Figure 5-5 Initial configuration of a pneumatic body under inner pressure and deformed configuration due to the load F [source and ©: formTL ingenieure für tragwerk und leichtbau GmbH]

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.

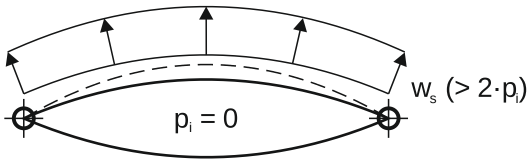


Figure 5-6 Two layer cushion under wind suction [source and ©: formTL ingenieure für tragwerk und leichtbau GmbH]

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.

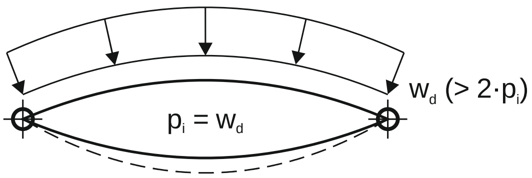


Figure 5-7 Two layer cushion under wind pressure [source and ©: formTL ingenieure für tragwerk und leichtbau GmbH]

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. The choice of this inner pressure is up to the engineer. Typically values for p_i are for example $p_i = 1.1 \cdot S_{max}$ or $p_i = S_{max} + 100$ Pa. Depending on the conditions of the projects, also $p_i < S_{max}$, but $p_i > S_{average}$ are possible.

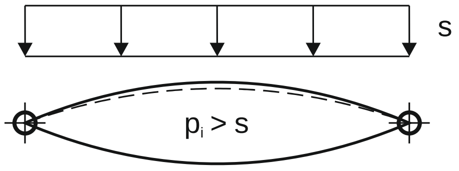


Figure 5-8 Two layer cushion under snow load [source and ©: formTL ingenieure für tragwerk und leichtbau GmbH]

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 $p_i = 400$ Pa = 0.40 kN/m². Wind is applied in increments of 0.05 kN/m² up to a final load of 1.3 kN/m² within 26 load steps.

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-Mariotte’s law (as explained above under “General”).

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

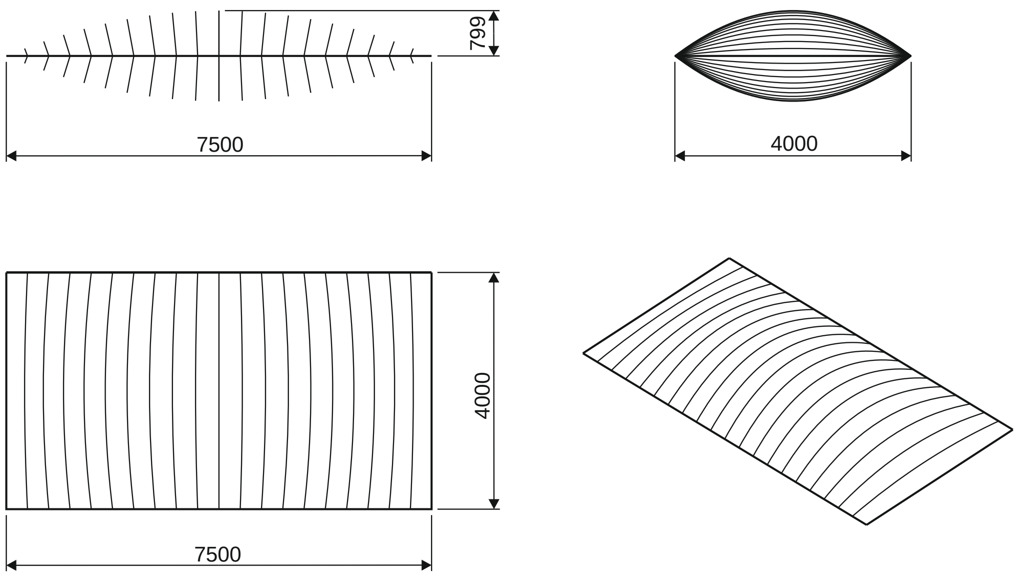


Figure 5-9 Numerical model of the exemplary two layer cushion for the numerical example [source and ©: formTL ingenieure für tragwerk und leichtbau GmbH]

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 steps. The thin red line marks the increasing wind load during these load steps. The thick red line illustrates the membrane stress for case one where the inner pressure of p_i = 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-Mariotte’s law. The comparison shows that for the analysis taking into account the law of Boyle-Mariotte, 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 step 16. From load step 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-Mariotte’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.

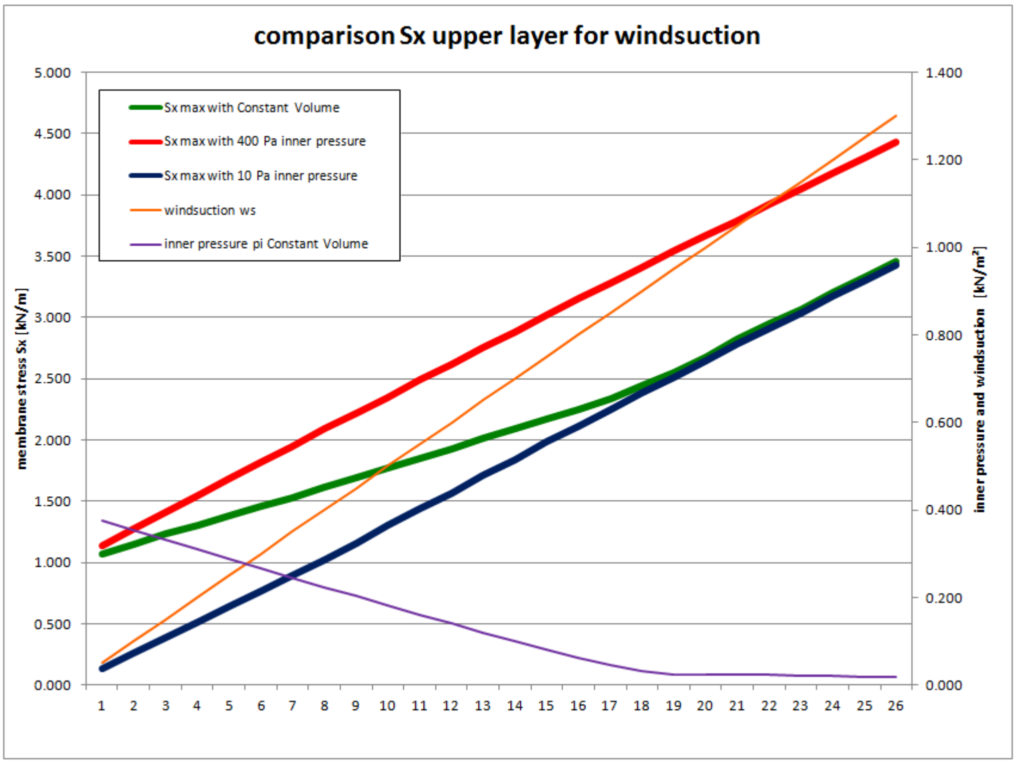


Figure 5-10 Resulting membrane stress Sx in the upper layer under wind suction for the three examined cases [source and ©: formTL ingenieure für tragwerk und leichtbau GmbH]

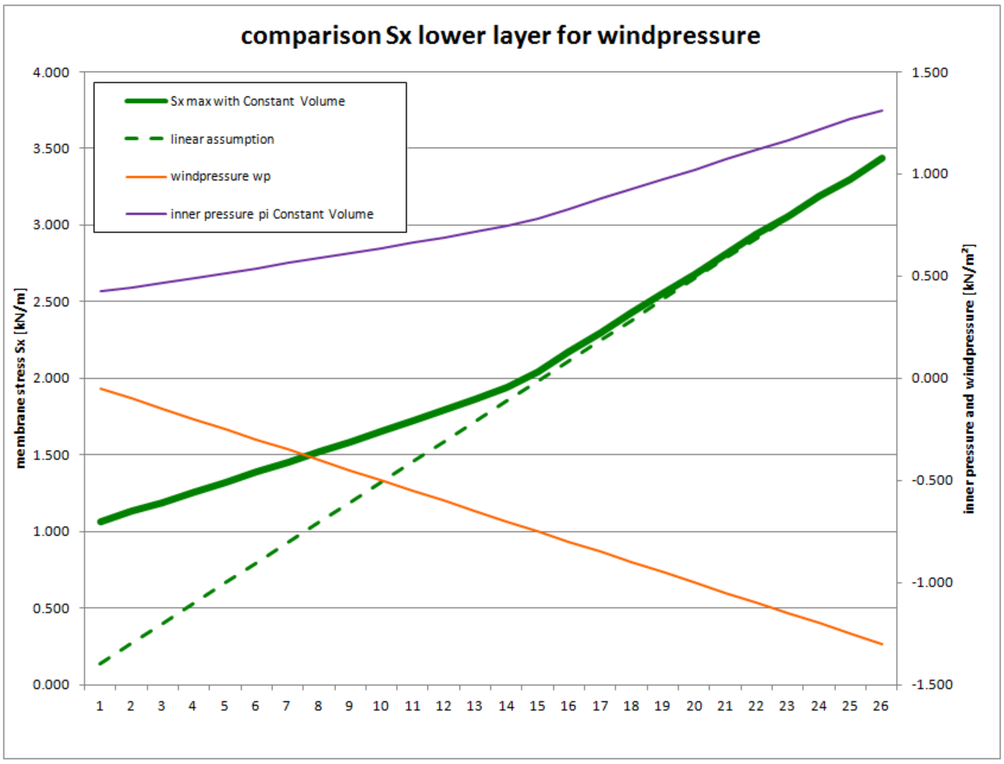


Figure 5-11 Resulting membrane stress Sx in the lower layer under wind pressure [source and ©: formTL ingenieure für tragwerk und leichtbau GmbH]

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 3-4. A cable with two elements is prestressed with F_0 and loaded in the middle, i.e. between the two elements, with a single force P_1. When the force equals $2F_0$ the full load is carried by the upper half of the cable while in the lower half the prestress is decreased to zero, see eq. (3.2). 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.

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 5-12. 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 pronounced if there are areas with wind pressure and areas with wind suction at the same time.

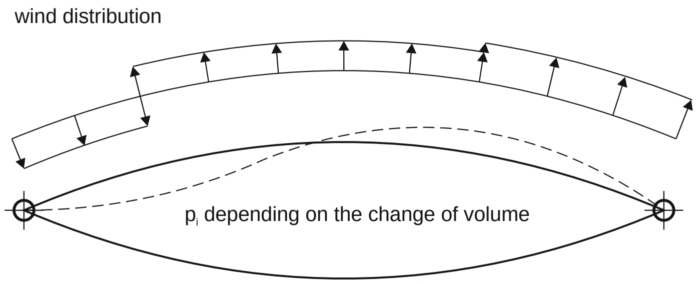


Figure 5-12 A two layer cushion with a non-uniform wind load distribution [source and ©: formTL ingenieure für tragwerk und leichtbau GmbH]

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 5-13 might be possible under certain conditions, but it is recommended to analyse this configuration with the law of Boyle-Mariotte.

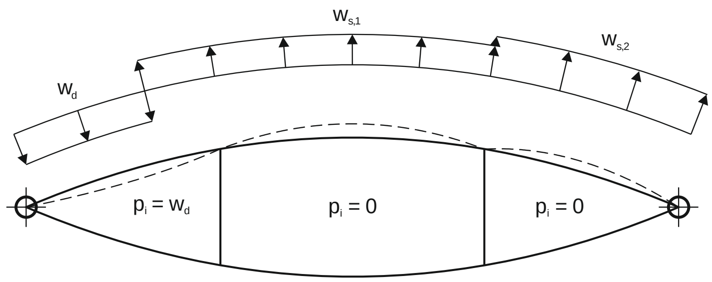


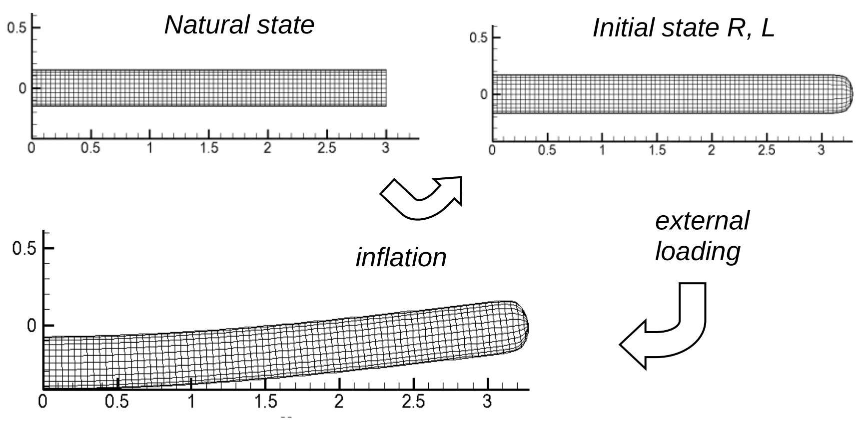
Figure 5-13 Separation of the cushion into three chambers in order to improve the behaviour under a non-uniform wind load distribution [source and ©: formTL ingenieure für tragwerk und leichtbau GmbH]

5.5.3 The analysis of inflatable beams

5.5.3.1 General

The following sections provide background on the analysis of inflatable beams. A summary of formulas for the analysis of basic structural systems and numerical examples are presented in Annex F.

Three states of an inflated beam are clearly identified in Figure 5-14. 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 formulas. The formulas presented here are valid for the bending of inflatable beams, so for the transition between the initial state and the actual state.



Actual state: final state of the beam

Figure 5-14 The three states for an inflated beam (source and ©: J.-C. Thomas)

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 bending 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 5-15.

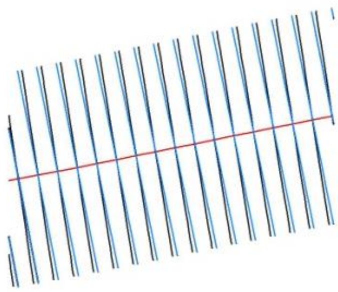


Figure 5-15 Timoshenko's kinematic: straight section and neutral fibre of a beam (source and ©: J.-C. Thomas)

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 behaviour of the coated fabrics is particularly complex to model. This approach takes into account the orthotropic behaviour of the fabrics (one remains in the linear elastic range). It limits the modeling of materials with Young's and shear modulus, omitting the sensitivities to other parameters. It makes it 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 5-16. Here l is the longitudinal direction, and t is the transversal direction.

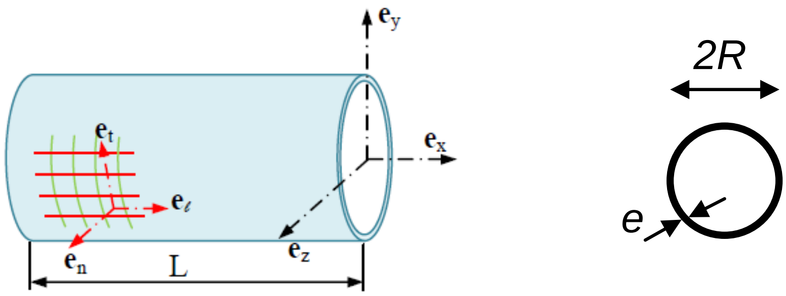
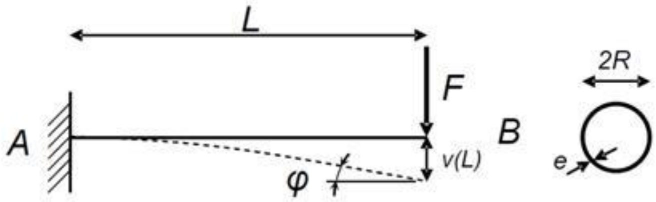


Figure 5-16 Schematic sectional view of an inflatable tube (source and ©: J.-C. Thomas)

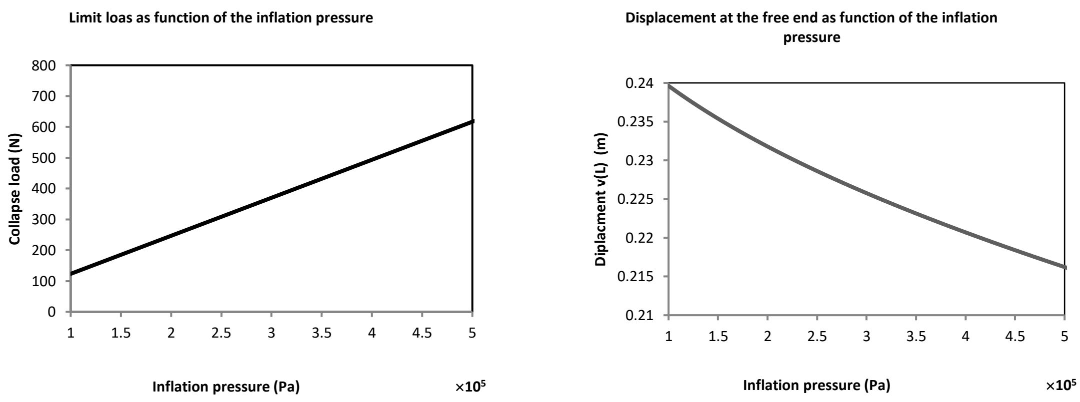
5.5.3.2 Behaviour of an inflatable tube

In the following a cantilever inflatable beam like illustrated in Figure 5-17 is analysed. In the results, the pressure appears explicitly. It is then possible to design the structures taking into account the fact that the maximum loads beard by the beams (collapse loads) are proportional to the pressure (see Figure 5-18(a)) and that the deflection under flexural loading decreases nonlinearly with the inflation pressure (Figure 5-18(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 5-17 A cantilever inflated beam (source and ©: J.-C. Thomas)



(a) (b)

Figure 5-18 Limit loads and displacements at the free end of a cantilever as functions of the inflation pressure (source and ©: J.-C. Thomas)

5.5.3.3 Eigenfrequencies

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

5.5.3.4 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

$$M_{limit} = \frac{p \cdot \pi^2 \cdot R^3}{4} \quad . \tag{5.2}$$

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 5-19 [Tho02].

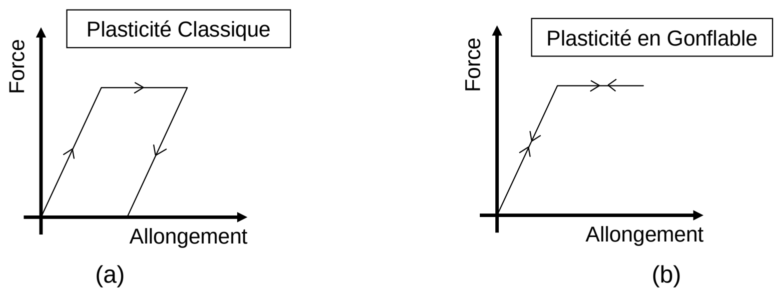


Figure 5-19 Diagrams showing the difference of the force-elongation-behaviour of "classical plasticity" (a) and the plasticity behaviour of inflatables (b) (source and ©: J.-C. Thomas)

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 Annex F, 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.

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 excludes structural membranes per definition and GEO is only a geotechnical Limit State. Fatigue – an additional aspect of durability to those discussed in chapter 4 – is linked to the failure of a structural membrane due to numerously repeated loads or wind-induced vibrations. The first can appear where the membrane experiences considerable bending deformation. This can happen in retractable structures, in surface areas where wrinkles repeatedly occur or where the angle between the undeformed and deformed membrane is considerable high, e.g. at clamped edge details, see Figure 3-11. If required for a particular structure, this has to be figured out from case to case – usually by appropriate experimental tests taking into account the particular loading situation. Hence, for the verification of membrane structures only the Ultimate Limit State STR is considered in the frame of this report.

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 on the durability 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 [S25], DIN 18204 [S26], French Recommendations [S29] and the European standard for the design of tents EN 13782 [S32]. 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 [S25, S29] and partly merged to a combined factor that includes safety aspects and real physical strength reduction [S26, S32], 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 [S25] and the French Recommendations [S29]. 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" [S25] 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), see e.g. [T1-T16] 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:

$f_d = f_{k,23} / (\gamma_f \cdot \gamma_M \cdot A_i)$

where f_d *= allowable design stress,*

$f_{k,23}$ *= tensile strength defined as 5%-fractile of at least 5 strips, tested at T = 23 °C (codes: DIN 53354, 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 – here A_0 to A_3 – and the safety factors – here γ_f and γ_M – are clearly separated.

The French Recommendations use also a strength reduction factor that considers degradation due to environmental impact (pollution). That means in both concepts durability aspects are considered. 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

<u>French recommendations [S29]</u>

For covering structures more than 250 m², 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 ponds 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:

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

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:

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

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 [m²] of the element of textile coverage and is given by (3a) and (3b), or in simplified form in Table 6-1:

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

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

Table 6-1 Scale factors k_e for different surface sizes

S [m²]	*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 fibre fabric	*4*	*4.5*
Glass fibre fabric	*4*	*4.5*

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

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

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 =2.5 other 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 that this might require additional experimental testing for single projects with particular demands – 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 fabrics

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 made from fabrics is demonstrated in the Eurocode Outlooks No. 32 and 33. 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. 34. 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 general, time-dependent factors (k_{age} and k_{long}) shall be determined for the specified design working life of the structural membrane.

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. 32

(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 behaviour 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 weft 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* $k_i \geq 1.0$.

(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):*

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

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 β = 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 specimens measured according 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, 11 and 13.

Eurocode Outlook No 33

(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} will be given as safe-sided values. They may also be determined with project specific experimental tests. In this case the test procedures specified in this code should be followed..

(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. 34

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, frequently termed n_{23} in the context of membrane structures

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 $V_x = 6\%$ and for joints of $V_x = 12\%$ [Min81]. Today's 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. 35-37.

Eurocode Outlook No. 35

Design Resistance Long Term Load

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

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

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

Eurocode Outlook No. 36

Design Resistance Short Term Load Cold Climate

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

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

Eurocode Outlook No. 37

Design Resistance Short Term Load Warm Climate

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

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

6.4 Proposals for the ULS verification of ETFE foils

6.4.1 General

No standard for the design of structural ETFE components exists worldwide. Different design approaches are used in practice and several proposals for a design concept for ETFE foils are published and discussed at the current stage. A summarized description of proposed concepts is given in the TensiNet European Design Guide for Tensile Surface Structures, Appendix A5 “Design recommendations for ETFE foil structures” [Hou13]. In order to provide an overview on the state of the art, this summary is – slightly modified and updated – given hereafter. The summary includes recommendations for the Ultimate Limit State (ULS), given below, as well as for the Serviceability Limit State (SLS), see chapter 7.3. Normally the SLS and not the ULS is the decisive limit state for ETFE foils which is due to their enormous breaking strain beyond the yield strength: usually the tensile strength cannot be reached before a SLS is reached. Partly, the A-factor concept, originally composed for fabrics (see Code Review No. 20), is adopted.

6.4.2 ETFE foil design concept developed by Karsten Moritz (seele)

The philosophy of Moritz is to follow the approach of the Eurocode as far as possible. His safety concept includes separated safety factors on resistance side and on action side. He differentiates the equations in Serviceability Limit State (SLS), see chapter 7.3.4, and Ultimate Limit State (ULS). The limit in the ULS refers to the tensile strength in welded specimens. Therefore the quality of the project-specific production of the weld influences the ULS-equations.

His concept includes reduction factors according to the A-factors originally investigated by Minte (A_0...A_4). The values are based upon a lot of mono-axial and biaxial tests on ETFE-foils and weldings carried out during his research at the TU Munich [Mor07]. An additional reduction factor A_S considers the reduction in tensile strength of welded seams compared to the base ETFE-material. This factor depends on the quality in the welding-process of the specific manufacturer.

Lars Schiemann tied his work [Scm09] to the work of Moritz (both at the TU Munich). Schiemann used bursting tests to examine the reduction factor A_0 for biaxial exposure in detail ($A_{0,Moritz} = 1.2$, $A_{0,Schiemann} = 1.15$). This results in slightly higher values in the Ultimate Limit States (ULS).

The concept of Moritz can be applied in all climatic zones by adjustment of the thermal reduction factor A_3 to the local conditions. The given relationship of mono-axial and biaxial parameters in SLS and ULS allows a project specific quality control basing on mono-axial tests at 23°C mostly. Biaxial tests have to be done only if special requirements exist or irregularities occur.

At first, the characteristic value of the resistance of the foil is determined:

R_k = characteristic value of the resistance = $R_{k,\,0.05} / A_{mod}$

with

$R_{k,0.05}$ = 5% fractile of the short term tensile strength at T = 23°C,

$A_{mod} = A_0 \cdot A_1 \cdot A_2 \cdot A_3 \cdot A_4 \cdot A_S$.

Table 6-3 A-factor description

A_0	The reduction factor is meant to take into account reduction of the mono-axial strength caused by biaxial (multi-axial) plane stress conditions. Both for the tensile strength and yield stress at T = + 23°C.
A_1	The reduction factor is meant to take into account the reduction of the strength of the mono-axially determined strength values caused by long-term and permanent load.
A_2	The reduction factor is meant to take into account the reduction of the strength of the mono-axially determined strength values caused by influences like UV-light, moisture etc. It is dependent on the expected situation at the building location and the reference period.
A_3	The reduction factor is meant to take into account the reduction of the strength of mono-axially determined strength values caused by temperature. change.
A_4	The reduction factor is meant to take into account the reduction of the strength of mono-axially determined strength values caused by production inaccuracies.
A_S	The reduction factor is meant to take into account the reduction of the strength of mono-axially determined strength values caused by welding.

Moritz has carried out extensive research on the following reduction factors. For the full explanation of this the reader is referred to the theses from Moritz [Mor07] and Schiemann [Scm09]. As a result, values as given in Table 6-4 are defined.

Also a number of mono-axial tests were carried out to determine the characteristic values (5%-fractile-values) of breaking strength for basic ETFE-materials (AGC, NOWOFOL) and the welded seams as well. They are given in Tables 6-5 and 6-6.

Table 6-4 A-factor values for ULS verification

	Reduction of strengths caused by	ULS, $f_{u,k,SN,0.05}$
A_0	Multi-axial stress	1.2 (1.15*)
A_1	Short term / long term / permanent loading	1.0 / 1.3 / 1.8
A_2	Environmental influences	1.1
A_3	Temperature change (T = +40°C)**	1.2
A_4	Production inaccuracies	1.0
A_S	Base material/weld	1.57 ***

* according to [Scm09]
** The reduction factor depends on the maximum temperature of the considered layer. The maximum temperature depends on the local ambient conditions at the specific load case. A diagram of the temperature-dependency of A_3 is given by Figure 2.27 in [Mor07].
*** dependent on the tensile strength of the weld

Table 6-5 5%-fractile values of mono-axial strengths of ETFE foil at T = 23°C [Mor07]

	5%-fractile values of mono-axial strength of ETFE-Foil at T = 23°C
mono-axial tensile strength of material	$f_{u,k,0.05,+23°C}$ = 47 N /mm^2
mono-axial tensile strength of weld	$f_{u,k,SN,0.05,+23°C}$ = 30 N /mm^2*

* example dependent on the tensile strength of the weld

Table 6-6 5%-fractile values of mono-axial strengths of ETFE foil at T = 3°C [Mor07]

	5%-fractile values of mono-axial strength of ETFE-Foil at T = 3°C
mono-axial tensile strength of material	$f_{u,k,0.05,+3°C}$ = 50 N /mm^2
mono-axial tensile strength of weld	$f_{u,k,SN,0.05,+3°C}$ = 33 N /mm^2*

* example dependent on the tensile strength of the weld

The above mentioned values are characteristic values. To arrive at design values, also a partial safety factor on resistance side γ_m needs to be determined: $R_d = R_k / \gamma_m$. The value for γ_m for ULS verification is given in Table 6-7.

Table 6-7 γ_m for ULS verification

	$\gamma_{m,\,ULS}$
basic and exceptional combinations, geometrical imperfections	1.1

These values result in a set of conditional equations for the design resistance of ETFE-foils including welds in the Ultimate Limit State as given hereafter:

$$R_{d,SN,ULS,w_S} = \frac{f_{u,k,F,0.05,+23°C}}{\gamma_m \cdot A_0 \cdot A_1 \cdot A_2 \cdot A_3 \cdot A_4 \cdot A_S} = \frac{47}{1.1 \cdot 1.2 \cdot 1.0 \cdot 1.1 \cdot 1.0 \cdot 1.0 \cdot 1.57} = 20.62\ \text{N/mm}^2$$

$$R_{d,SN,ULS,S} = \frac{f_{u,k,F,0.05,+3°C}}{\gamma_m \cdot A_0 \cdot A_1 \cdot A_2 \cdot A_3 \cdot A_4 \cdot A_S} = \frac{50}{1.1 \cdot 1.2 \cdot 1.3 \cdot 1.1 \cdot 1.0 \cdot 1.0 \cdot 1.57} = 16.87\ \text{N/mm}^2$$

$$R_{d,SN,ULS,p_{nom}} = \frac{f_{u,k,F,0.05,+23°C}}{\gamma_m \cdot A_0 \cdot A_1 \cdot A_2 \cdot A_3 \cdot A_4 \cdot A_S} = \frac{47}{1.1 \cdot 1.2 \cdot 1.8 \cdot 1.1 \cdot 1.2 \cdot 1.0 \cdot 1.57} = 9.54\ \text{N/mm}^2$$

with

w_S wind suction,

S snow,

p_{nom} inner pressure.

The resistances R_d shall be compared and be larger than the design load F_d: $R_d > F_d$.

The author points out that the design concept is applied only if the material properties of the used ETFE-foil comply with this concept and if the qualities of material and welded seams are ensured by an adequate quality assurance.

6.4.3 ETFE foil design concept developed by Klaus Saxe (ELLF – University of Duisburg-Essen)

A ULS verification is stated by Saxe, although he emphasizes that it has only low relevance compared to SLS [Sax12]. Because of the large strain every structure has lost its serviceability long before it reaches the Ultimate Limit State. From his point of view, a ULS verification is only suitable for the controlling of manufacturing quality of details. It is stated that the breaking strength of connections is critical compared to the base foil. The capacity of e.g. welds or connections should be tested monoaxially for each project at different temperature levels. The 5% fractile value of these test results ($X_{5\%}$) should be compared with the effect of the action.

On the basis of EN 1990, the following relations have to be verified in the ULS:

$$E_{d(T)} \leq R_{d(T)}$$

with

$$E_{d(T)} = \Sigma\gamma_{G,i} \cdot G_{k,i} \oplus \gamma_{Q,1} \cdot Q_{k,1} \oplus \Sigma\gamma_{Q,i} \cdot \psi \cdot Q_{k,i},$$

$$R_{d(T)} = \frac{R_k}{\gamma_M} = \frac{X_{5\%}}{\gamma_M},$$

$\oplus$: in combination with,

$E_{d(T)}$: temperature-dependent design value of the effect of the action,

$R_{d(T)}$: temperature-dependent design value of the resistance,

γ_G, γ_Q: partial factors for the actions G and Q,

$G_{k,i}$: characteristic value of a permanent action,

$Q_{k,1}$: characteristic value of the leading variable action,

$Q_{k,i}$: characteristic value of the accompanying variable action i,

$X_{5\%}$: 5% fractile value of monoaxially tested tensile strength at different temperature levels,

γ_M: partial factor for a material property.

With this set of formulas it is possible to determine the required capacity $X_{5\%,req.}$ for membrane joints and edge details.

Alternatively it is also possible to derive the required capacity by means of comparison with the characteristic effect of the action $E_{k(T)}$ instead of the design value $E_{d(T)}$ as stated above. This is because the interaction of partial load factors γ_G and γ_Q often leads to a kind of average value of $\gamma = 1.4$. Combined with the partial safety factor γ_M which is usually set to $\gamma_M = 1.5$ the product of these values leads to a global factor $\gamma_{Global} = 2.1$:

$X_{5\%,req.} \geq \gamma_{Global} \cdot \max E_{k(T)}$.

It proved to be suitable for pneumatic structures to reduce the value $\gamma_{Global} = 2.1$ down to 1.9 to 2.0. This is justified for ETFE cushions because stresses in the cushion reduce when the curvature in the cushion increases due to strain.

6.5 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 a different stiffness. 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 Membranes partly reinforced with a second layer: at the high point (left) and at the low point and membrane corners (right)
[© 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 [S29]

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.

Common values for reinforcements in Germany are as follows (state of the art even though not standardised):

- one reinforcement layer calculated with 75%: n_{eff} = 1.75,
- second reinforcement layer calculated with 50%: n_{eff} = 1.75·1.5 = 2.6.

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 n_{eff} = 1.5 for a two layer composition (base fabric + 1 reinforcement). 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. 38.

Eurocode Outlook No. 38

(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 1 reinforcement layer tests have to be performed.

7 Serviceability limit states (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. 39.

Eurocode Outlook No. 39

(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. 40, compare also Eurocode Outlook No. 30.

Eurocode Outlook No. 40

(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. 41.

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. 41

(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 7.2.3.

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. 27. Local reinforcements could improve the resistance. These aspects are summarized in the demand of Eurocode Outlook No. 42. 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. 42

(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 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, Central Railway Station Square, Sofia [© V. Tanev]

The French recommendations are the only guidance that demands a ponding check today, see Code Review No. 24.

Code Review No. 24

<u>*French recommendations*</u>

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 7-1) 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 "snow slides".

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.

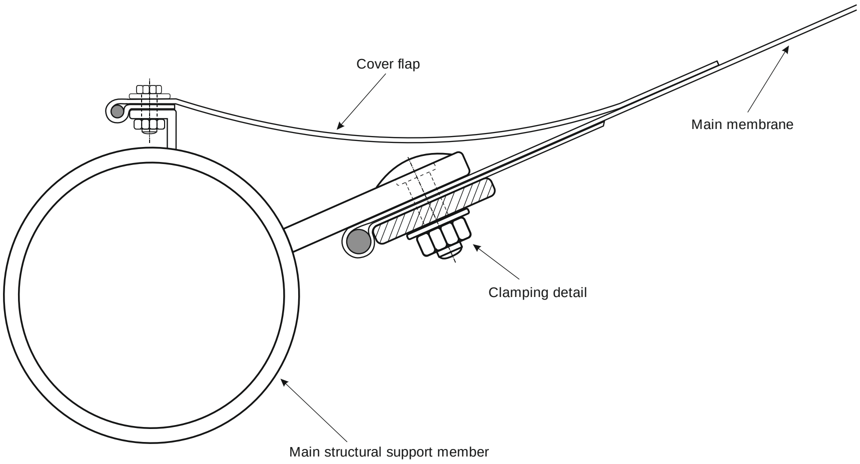


Figure 7-2 Attention to local ponding at a cover flap which a check on the main membrane in the structural model may not reveal [©ELLF]

Eurocode Outlook No. 43 summarizes the main demands that were developed in this chapter.

Eurocode Outlook No. 43

(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 can be used.

Comment: In addition to reduced elastic constants a reduction in prestress should be used.

7.3 Proposals for the SLS verification of ETFE cushions

7.3.1 General

Regarding ETFE foil structures the harmonization of design concepts is on an early stage. This chapter presents several proposals for design concepts for the Serviceability Limit State (SLS) – which is normally the decisive one due to the enormous breaking strain, see chapter 6.4. A summarized description of proposed concepts is given in the TensiNet European Design Guide for Tensile Surface Structures, Appendix A5 "Design recommendations for ETFE foil structures" [Hou13]. In order to provide an overview on the state of the art, this summary is – slightly modified and updated – given hereafter.

The concepts are presented as concepts for a SLS verification. This is mainly owed to the classification made by the proposing experts themselves in [Hou13]. All presented concepts are based on a verification against the yield strength. As classified as SLS verifications, all proofs are based upon characteristic stresses and characteristic strength values. However, the current discussion shows that many experts today suggest a verification against the yield strength with design stress, i.e. to interpret the presented concepts as ULS verifications.

7.3.2 Recommendations J.W.J. de Vries (TU Delft)

Jos de Vries has investigated mono-axial and biaxial properties of ETFE foil with the aim to define a design concept based on the "Limit State" approach. An important issue has been the determination of a yield point and creep limit. As the material behaves in a non-linear manner, a long- and short-term load is defined.

Reduction factors in Serviceability Limit State (SLS):

$\sigma_d = \sigma_{rep} / \gamma_m \cdot k_{mod}$,

σ_d = Design stress for ETFE foil,

σ_{rep} = representative stress for ETFE foil, to be determined (approximate values for 1:1; 12 N/mm^2, for 1:2 / 2:1; 15 N/mm^2),

γ_m = safety factor for material uncertainties, γ_m = 1.0,

k_{mod} = modification factor for temperature and creep, see Table 7-1.

Table 7-1 Reduction factor k_{mod} depending on temperature and load duration

Deformation criteria	Load duration	Temperature (°C)	k_{mod}
Adjusted for limited permanent deformation (< 5% strain)	Less than 15 min	t < 20	1.00
		20 < t < 30	0.91
		30 < t < 50	0.71
	More than 15 min	t < 20	0.84
		20 < t < 30	0.77
		30 < t < 50	0.60

The focus of the research was on the Serviceability Limit State. It is assumed that the Ultimate Limit State is not the restrictive state. Therefore no recommendations are mentioned for the ULS.

Important issues addressed here are the temperature-dependency of the creep level and strength of the foil.

7.3.3 ETFE Foil design concept developed by formTL

The design office formTL has developed an approach that focuses on the remaining strain of the foil, as this is a very important issue for ETFE foil structures. This also can be seen as a method addressing the Serviceability Limit State. formTL formulates their approach as follows: ETFE foil is an isotropic material. Due to the production method, there are slight differences in properties in the extrusion direction and perpendicular to the extrusion direction, but these differences are negligible for construction purposes. Unlike coated fabric, the foil suffers from large strains. Hence, the foil structure undergoes large deofrmation. The stress is reduced due to this deformation to some extent. Due to this behaviour for foil a different design concept must be applied. The most important criterion is the remaining strain in the foil (SLS). Due to the very high breaking strain, the breaking point of the foil cannot be reached in a structure under normal conditions (ULS).

Stress-strain diagrams of Nowofol done with the 200µm foil at 23°C show a 10% strain-stress of 21 N/mm², see Figure 7-3. Furthermore the foil shows linear elastic behaviour up to a stress of 15 N/mm².

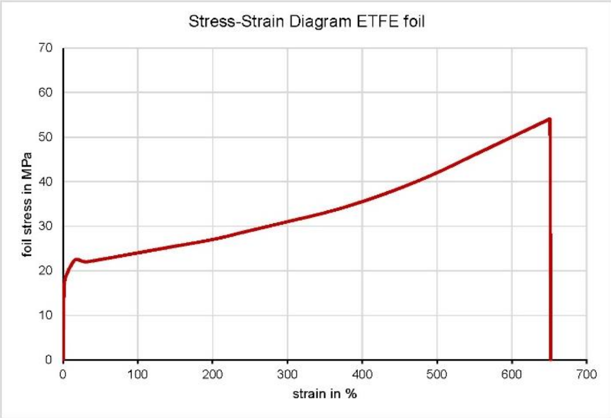


Figure 7-3 Typical stress strain diagram for an ETFE foil [source and ©: formTL ingenieure für tragwerk und leichtbau GmbH]

To minimize the remaining strain in the foil, a safety factor η_{10} is determined with 21 / 15 = 1.4 rounded up to η_{10} = 1.5.

For different projects formTL has conducted short-term tests for 100µm, 150µm and 200µm thick foils where the 10%-strain-stress, the yield strength and the breaking strength have been determined (Figure 7-4).

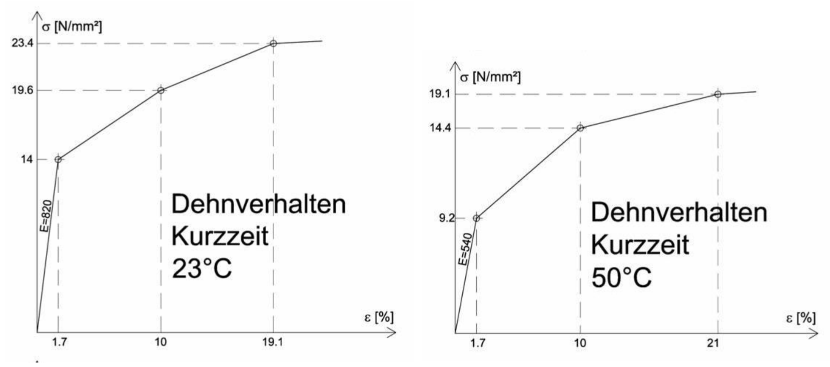


Figure 7-4 Simplified stress-strain diagrams for a uni-axial strip under short-term load and temperatures of 23°C and 50°C [source and ©: formTL ingenieure für tragwerk und leichtbau GmbH]

In all these projects the 5% fractile of the 10%-strain-stress has been used, as shown below:

23°C: $\sigma_{10;\ 23°C;\ 5\%}$ = 19 N/mm²,

50°C: $\sigma_{10;\ 50°C;\ 5\%}$ = 16 N/mm².

Furthermore, formTL has introduced a reduction factor A_2 for environmental conditions. This factor has been determined in one of their projects with A_2 = 1.05. This leads to the following design concept for ETFE foil:

$\eta = \sigma_{10;xx°C;5\%} / (\sigma * A_2) \geq 1.5$.

Based on this values the admissible stress is been determined as given in Table 7-2.

Table 7-2 Admissible stress [kN/m] for different foil thicknesses

thickness temperature	100µm	150µm	200µm	250µm	300µm
23 °C	1.2	1.8	2.4	3.0	3.6
50 °C	1.0	1.5	2.0	2.5	3.05

As the foil can be heated up, depending on the different load cases and the possible elevated temperature, the appropriate reference value must be used. Due to its behaviour, the ETFE cannot heat up more than 50°C due to solar radiation. With numerical simulations formTL has determined under worst conditions a maximum temperature of 48.5°C.

Biaxial tests show a much stiffer behaviour, but the remaining strain is approximately at the same stress level, therefore the previously mentioned values are reasonable for the dimensioning of the foil (Figure 7-5).

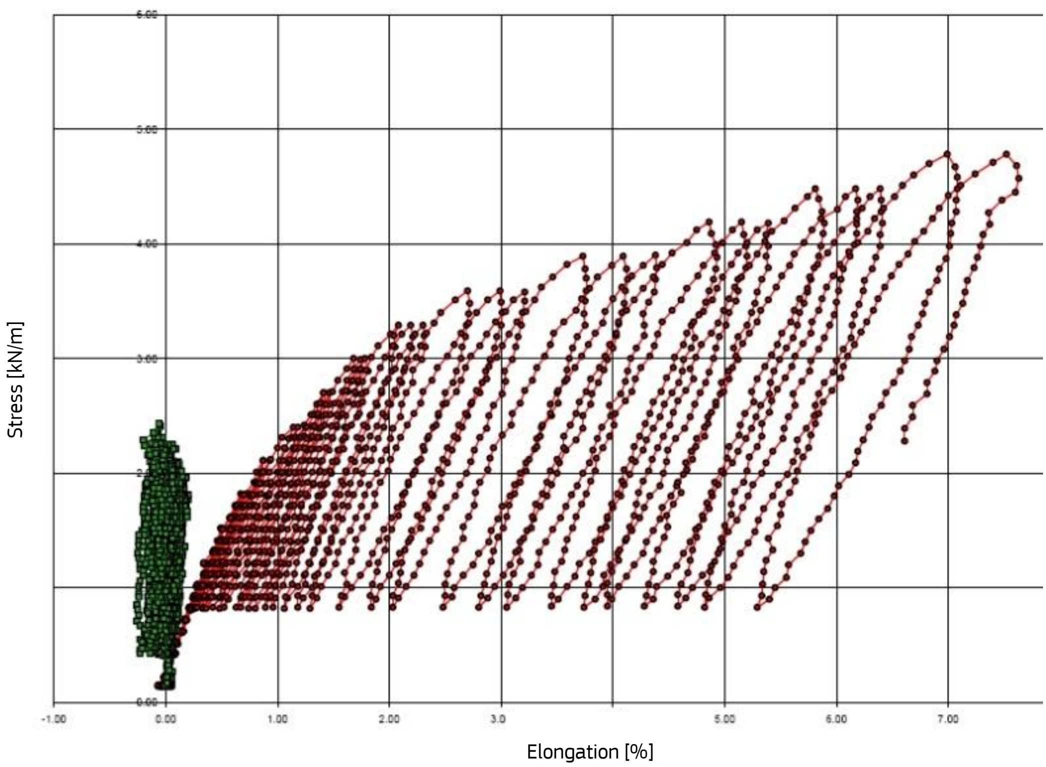


Figure 7-5 Biaxial stress-strain behaviour of a ETFE foil (tests made at ELLF).

7.3.4 ETFE foil design concept developed by Karsten Moritz (seele)

The limit in the SLS refers to the stress at yield. Limits refer to the stresses or strengths in welded specimen (in SLS yield-stress is identical for specimens with and without welding).

The concept of Moritz includes reduction factors as stated in chapter 6.4.2. As a result, values as given in Table 7-3 are defined.

Table 7-3 A-factor values for the SLS verification

	Reduction of strengths caused by	SLS, $f_{y,k,0.05}$
A_0	Multi-axial stress	1.4
A_1	Short term / long term / permanent loading	1.0 / 1.3 / 1.8
A_2	Environmental influences	1.0
A_3	Temperature change (T = +40°C)*	1.2
A_4	Production inaccuracies	1.0
A_S	Base material/weld	1.0

* The reduction factor depends on the maximum temperature of the considered layer. The maximum temperature depends on the local ambient conditions at the specific load case. A diagram of the temperature-dependency of A_3 is given by Figure 2.27 in [Mor07].

Also a number of mono-axial tests were carried out to determine the characteristic values (5%-fractile-values) of yield strengths for basic ETFE-materials (AGC, NOWOFOL) and the welded seams as well. Moritz distinguishes between a first and a second yield point, with the second yield point lying slightly higher than the first one. The yield strength at the second yield point is given in Table 7-4 for two temperatures. This allows permanent strains to a certain amount.

Table 7-4 5%-fractile values of mono-axial yield strengths of ETFE foil (material and weld) at T = 23°C and T = 3°C [Mor07]

Temperature / Vlaue	5%-fractile values of mono-axial yield strength (2. yieldpoint) of ETFE-Foil
T=23°C	$f_{y,k,0.05,+23°C}$ = 21 N /mm^2
T=3°C	$f_{y,k,0.05,+3°C}$ = 25 N /mm^2

The above mentioned values are characteristic values. To arrive at design values, also a partial safety factor on resistance side γ_m needs to be determined: $R_d = R_k / \gamma_m$. The value for γ_m in the SLS verification is given in Table 7-5.

Table 7-5 γm for SLS verification

	$\gamma_{m, SLS}$
basic and exceptional combinations, geometrical imperfections	1.0

These values result in a set of conditional equations for the design resistance of ETFE-foils including welds in the Serviceability Limit State as given hereafter:

$$R_{d,SN,SLS,W_S} = \frac{f_{y,k,F,0.05,+23°C}}{\gamma_m \cdot A_0 \cdot A_1 \cdot A_2 \cdot A_3 \cdot A_4 \cdot A_S} = \frac{21}{1.0 \cdot 1.4 \cdot 1.0 \cdot 1.0 \cdot 1.0 \cdot 1.0 \cdot 1.0} = 15.00 \text{ N/mm}^2$$

$$R_{d,SN,SLS,S} = \frac{f_{y,k,F,0.05,+3°C}}{\gamma_m \cdot A_0 \cdot A_1 \cdot A_2 \cdot A_3 \cdot A_4 \cdot A_S} = \frac{25}{1.0 \cdot 1.4 \cdot 1.3 \cdot 1.0 \cdot 1.0 \cdot 1.0 \cdot 1.0} = 13.73 \text{ N/mm}^2$$

$$R_{d,SN,SLS,p_{nom}} = \frac{f_{y,k,F,0.05,+23°C}}{\gamma_m \cdot A_0 \cdot A_1 \cdot A_2 \cdot A_3 \cdot A_4 \cdot A_S} = \frac{21}{1.0 \cdot 1.4 \cdot 1.8 \cdot 1.0 \cdot 1.2 \cdot 1.0 \cdot 1.0} = 6.94 \text{ N/mm}^2$$

with

w_S wind suction,

S snow,

p_{nom} inner pressure.

The resistances R_d shall be compared and be larger than the design load F_d: $R_d > F_d$.

The above is taken from the thesis of Karsten Moritz [Mor07]. The author points out that the design concept is applied only if the material properties of the used ETFE-foil comply with this concept and if the qualities of material and welded seams are ensured by an adequate quality assurance.

7.3.5 ETFE foil design concept developed by Klaus Saxe (ELLF – University of Duisburg-Essen)

Klaus Saxe has carried out extensive research on the properties of ETFE foils. Below a summary of the publication [Sax12] is presented. The design concept is based on the capacity check in the Ultimate Limit State, see chapter 6.4.3, and in the Serviceability Limit

State. The basis of the approach of Saxe is that of the Eurocode 0, with which he emphasizes the future design concept should correspond. He distinguishes between SLS and ULS. In the design concept both ETFE cushions and single-layer ETFE are incorporated.

Mechanical properties

Monoxial tests show less stiff behaviour than biaxial tests. Therefore, and because most ETFE foil structures are stressed biaxially, the research presented in [Sax12] is based mainly on biaxial tests. The influence of the temperature on the mechanical properties is considerable. Four temperature levels are taken into account for most of the presented tests: -25°C, 0°C, 23°C, 35°C.

Repeated loading with different loading sequences and a subsequent 24h recovery time after each loading sequence is investigated at T = 0°C and T = 35°C. The results show considerable permanent strain for T = 35°C whereas the permanent strain for T = 0°C after every loading sequence is less than 0.1% strain. Creep is investigated biaxially at different load levels. At higher load levels, the strain tends to an asymptote. To investigate these asymptotes further, relaxation tests are carried out. Starting with a temperature of -25°C and ending at 35°C, 50% of the tension is relaxed for each load level.

Established and regularly used limit stresses – given as yield strength values at typical temperatures: $\sigma_{lim}(0°C) = 15\ N/mm^2$, $\sigma_{lim}(23°C) = 12\ N/mm^2$, $\sigma_{lim}(35°C) = 10\ N/mm^2$ – are reviewed by means of experimental testing under various temperatures and stress ratios. They reveal to be conservative at T = 0°C, but are recommended to be reduced dependent on the stress ratio.

Furthermore, the loading velocity impact on plastic strain is investigated. High loading velocity leads to less plastic strain. With other words: In order to hold a specific strain limit higher stress limits are possible in case of high loading velocity. For a loading velocity that refers to a typical wind gust stress limits are experimentally determined such that the permanent strain is ensured to be smaller than 0.25%. This is conducted for different temperature levels.

First tests show that materials from different producers behave quite similar. That is to prove in any case.

Serviceability Limit State verification

The main requirements for the limitation of deformations are:

- pneumatically prestressed structures: compliance with the planned shape,
- mechanically prestressed structures: avoidance of loss of prestress due to creep and relaxation at high stress levels.

An appropriate Young's modulus is the basis for an accurate determination of the deformation. The Young's modulus of ETFE is dependent on the temperature and the biaxial stress ratio.

To enable a suitable calculation of the amount of creep and relaxation the stress (or load) duration is important to know – besides the stress level. Three load duration classes can reasonably be applied to structural ETFE elements: long-term, mid-term and short-term.

The formulation of the SLS concept is based on the concept for timber structures (EN 1995) which introduces a factor k_{mod} for consideration of moisture and load duration. For ETFE structures this approach has to be slightly modified:

- substitution of moisture with temperature and biaxial stress ratio,

- additional consideration of loading velocity to the class of load duration.

These are the four relevant impacts that govern the resistance. The loading velocity distinguishes a slow loading velocity as in the load case “snow” and a high loading velocity as in the load case “wind” which is featured by a typical wind gust duration of ten seconds. It can be understood that actually the loading velocity is linked to the load duration: high loading velocity is linked to short-term loading (wind) and slow loading velocity is linked to long-term loading (snow).

The verification can be conducted as follows:

$E_{d(T)} \leq C_{d(T)}$

where it can be set

$E_{d(T)} = E_{k(T)}$ because partial factors are set to $\gamma = 1.0$ in the SLS verification and

$C_{d(T)} = R_{k(T)} \cdot k_{mod}$.

Herein it is

$E_{d(T)}$: temperature-dependent design value of effect of actions,

$E_{k(T)}$: temperature-dependent characteristic value of effect of actions,

$C_{d(T)}$: temperature-dependent limit value of deformations,

$R_{k(T)}$: temperature-dependent characteristic value of the resistance,

k_{mod}: modification value, considering biaxial stress ratios, temperature, load duration and loading velocity.

$R_{k(T)}$ is used as the yield strength in the higher stressed direction under biaxial stressing. The following values are well-established and proved to be suitable in many projects:

$R_{k(0°C)} = 15.0$ N/mm^2,

$R_{k(23°C)} = 12.0$ N/mm^2,

$R_{k(35°C)} = 10.0$ N/mm^2.

As this resistance values represent the yield strength, their utilization in the verification ensures that the structure remains largely elastic. The temperature-dependent values for $R_{k(T)}$ are given for better clarity at this stage. It is possible to incorporate the temperature-dependency completey in k_{mod} in a future draft. Limit values for k_{mod} are given as follows:

Upper limit for short term load/high loading velocity: $k_{mod} = 1.8$,

Lower limit for long term load/low loading velocity: $k_{mod} = 0.5$.

This high values enclose the very high variation of resistance values that could be reasonably used in different design situations. The demonstrated limit values are directly derived from the test results presented in [Sax12]. For instance, the upper value $k_{mod} = 1.8$ is calibrated to admissible stress in case of high loading velocity such that it ensures a strain limit of 0.25% strain. This strain limit is an arbitrarily chosen limit value but it is considered to state a suitable limitation of permanent strain. Such defined admissible stress can be read from Figure 7-6. For instance, for a temperature of 20°C admissible stress of approximately 21 MPa can be read out, see the marked exemplary reading in Figure 7-6. In relation to the “basic” resistance $R_{k(23°C)} = 12.0$ MPa the modification factor yields as $k_{mod} = 21/12.0 = 1.75 \approx 1.8$.

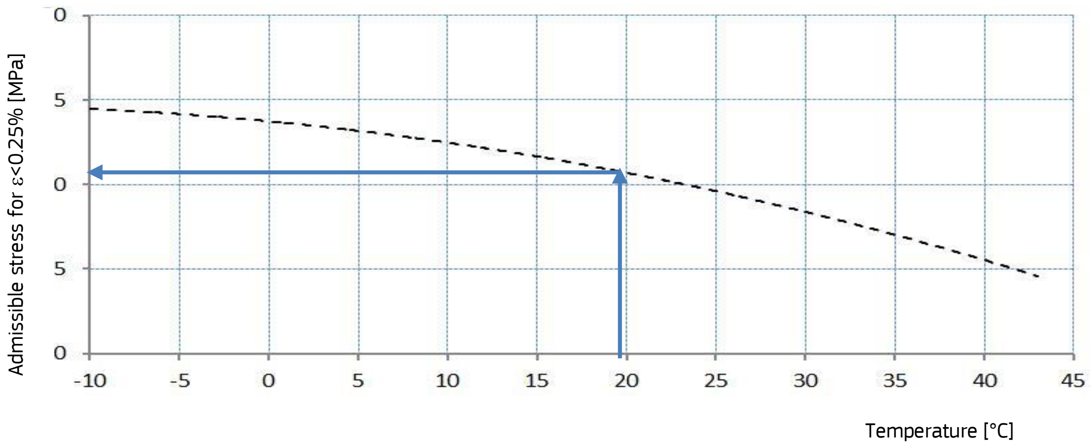


Figure 7-6 Admissible stress in case of high loading velocity ensuring a strain limit of 0.25% for different temperature levels [Sax12]

As the presented test results are complete, intermediate values for k_{mod} could be derived from case to case. A comprehensive formulation for the determination of k_{mod} for any possible design situation is still pending.

7.3.6 Statements by Vector Foiltec

Comments of Vector Foiltec are based on a 32 year history of analysing ETFE material behaviour and designing and building cladding systems throughout the world using the material ETFE. More than 1000 buildings have been realised by now in locations between the equator in hot and moist climates as much as in desert like high temperature climates and in the harshest locations in Siberia with extreme high wind and snow loads as much as extreme low temperatures.

Comments on the current documentation, see e.g. [Hou13, Sax12] are aiming at not to limit the application of ETFE foil systems by applying a non-comprehensive understanding of the ETFE material and systems using ETFE materials and to guarantee safe buildings.

This current understanding of the material derives from the fact that most of the published engineering culture has been developed using concepts which have been developed for more or less static building elements, i.e. the fabric industry for instance. These concepts work for fabrics but the same concepts do only in part reflect the ability of ETFE foils, in part they will limit the application of ETFE foils.

[Hou13] splits the many specific features of ETFE foils into advantages and disadvantages (page 7). In contrast, it can be rather preferred to describe the specific features of ETFE and not value them as advantages or disadvantages. Whether a feature is good or bad for a problem depends on the definition of the problem and not on a predefined mind set.

It can be suggested very strongly to take advantage of the extensive research and data base partly published in [Sax12], developing data for biaxial load configuration. Proposals that claim that uniaxial loads and biaxial loads give similar results when measuring the behaviour of ETFE foil material have to be rejected. It would be helpful to develop an understanding of the failure stress and failure mode for biaxial load scenarios which currently does not exist.

When applied in pneumatic cushions, ETFE foils need a much more comprehensive theoretical analysis than single layer ETFE systems. For single layer systems plastic deformation is not acceptable to most systems because the foil will get slack in critical load scenarios. This comprises the potential of being destroyed or permanently damaged due to flogging of the material. Only with technical systems that allow the introduction of additional prestress after the initial installation process this can be overcome. For detailed information about single layer foil verification see chapter 7.4.

Pneumatically stabilized cushion systems behave completely different. Elastic as well as plastic deformations whether due to creep under small loads or due to high load scenarios are potentially a favourable feature. The change of geometry of a cushion will influence the stresses in the foil considerably. Saxe accepts the fact and introduces a reduction of a global factor γ_{global} down to 2.0 or 1.9 [Sax12]. The suggested factors do not necessarily reflect the structural engineering truth. Instead of using a factor it should be suggested to actually calculate the change of geometry within a cushion related to a specific load scenario which can be achieved by an iterative calculation method. Some of the existing programs actually already enable the engineer to execute such iterations via an automatic numeric process. The foil-stress σ_{n+1} for load n+1 will be reduced after the first load n has caused a plastic deformation. This effect is even bigger for initially more flat cushion geometries. Thus it appears that a significant additional reliability compared with building materials without plastic deformation can be stated. This effect has to be analysed in detail.

General comment on the introduction of general factors to describe the behaviour of foils

It seems to be a commonly accepted fact that ETFE foil engineering has to consider a wide variety of factors to describe the behaviour of the foil. These factors consider

- multi axial stress,
- temperature,
- time dependent stress/load duration: long term loads, short term loads, permanent loads (long and short need a clear definition),
- environmental influences,
- production inaccuracies,
- base material/welding quality.

The current way of introducing these factors claims that the factors are totally independent of each other. Is this what reflects ETFE characteristics in reality? To take advantage of the foil material a three- or even more-dimensional factor table would probably be required which also takes into account the different E-moduli depending on where on the stress-strain curve one considers to be.

Test procedures

When comparing different labs and test methods for tensile tests it can be observed that results differ significantly. Not only sample preparation, sample size, sample shape but also test speed and temperature are not harmonized between labs. Measurement of elongation by optical devices cannot be compared directly with measurements performed by using mechanical sensors.

Monoaxial vs biaxial material evaluation

In the theoretical analysis as well as in the practical world uniaxial loads and biaxial load scenarios need different treatments using different material characteristic numbers.

The evaluation of a system needs to take on board geometrical specifics of a building and some issues need special considerations.

Variable pressure depending on load scenarios

A structural analysis concept suggested by formTL presumes constant volume in a cushion, see [Hou13] page 29/30. This leads to variable pressure depending on the different load scenarios. Any of these concepts rely on the assumption that all cushions of a system that are linked to one air supply and one pressure sensor experience the same load scenario. As is commonly known, large roof areas and even within relatively small cushions (not necessarily very large) the load distribution concerning snow- and wind loads can be rather different. Therefore rising the air pressure to a certain pressure level to cope with snow loads will most likely generate critical load cases in other areas of the system. The suggestion to have different air pressures by compartmentalizing one cushion and introducing different air pressures with several independent pressure measuring devices within one cushion is not realistic from a manufacturing perspective as from a measuring perspective.

Concerning the constant volume concept it can be agreed that under certain constraints this concept can be introduced especially for short term analysis of a cushion. But for some other long term evaluations this concept should be revised.

Water ponding/snow ponding analysis that not only analyses the cushion but also the structure that is holding the cushion in its place, need to be executed to achieve a safe building.

Introduction of the air supply system as an integral part of the structural engineering for the safe operations of a building

Using technical systems such as air supply systems as a structurally relevant component of a building is considered critical by Vector Foiltec. The failures of air supported structures throughout the world prove this approach to be critical. Especially in catastrophic scenarios buildings should potentially be fool proof. It could be argued that the air pressure generation and air pressure supply system when these systems are part of the structural safety of a cladding system should have a totally independent back up system including a rigorous service program. The backup covers not only the power requirements but also the pressure generation and airflow distribution.

7.3.7 Developments at Dekra / Labor Blum

The ideas that are formulating the basis of the plasticity theory [BBK13] are explained in a simplified manner: using a linear approximation instead of the 3-dimensional description. For the later use it will be necessary to be more precise. It can be stated that linear approximation will here be sufficient since elongations under biaxial loading do not exceed 6 - 7 %, although they reach higher values in the case of uniaxial loading.

The yielding behaviour with hardening effect in a uniaxial tensile test shall be explained descriptively: an idealised stress-strain diagram is shown in Figure 7-7. Idealising in this case means that all time-dependent viscous effects are neglected.

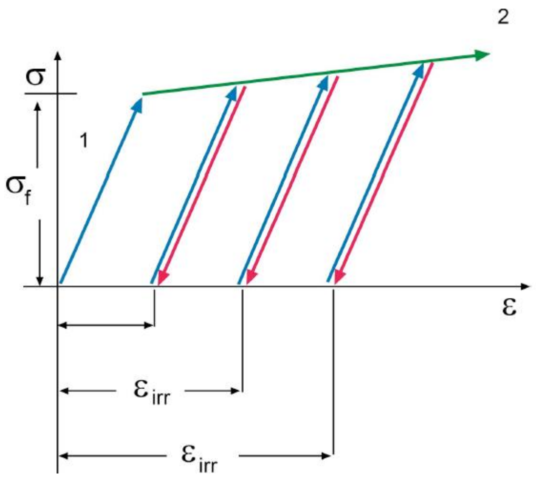


Figure 7-7 Idealised stress-strain curve [© DEKRA/Labor Blum]

First the stress increases proportionally to the elongations like in an ideal elastic material (first blue line). After a certain stress value - the yield stress σ_f - the gradient becomes smaller, the increase of the stress decreases (green line). This part of the stress-strain curve is called the plastic branch. Unloading in this part results in a decrease of the stress parallel to the first increasing part (red lines). On reduction of the stress close to zero, an irreversible part of the strain ε_{irr} remains. Repeated loading will lead to an increase parallel to the first loading branch (blue lines). After having reached the plastic branch (green line) it will follow this one with the smaller gradient. Repeated unloading and loading leads to the same behaviour again and again. It seems that the actual yield stress increases after having exceeded the first yield stress. It can thus not be considered to be a material constant. This effect is called hardening. This behaviour can be described mathematically, and extended to the biaxial stress strain relation.

The yielding depends on the ratio of the two mean stresses. The theory of hardening may be developed from these simple considerations by assuming a non-constant quality k. The two-dimensional plasticity theory with hardening is actually being formulated. Not all test results have been analysed yet. A circular shaped sample of the biaxial testing machine of Dekra DII is shown in Figure 7-8. The test machine has been converted to perform these tests. The stress field of this sample is more homogenous than the one of cruciform samples. The results are as such easier to interpret (Figure 7-9).

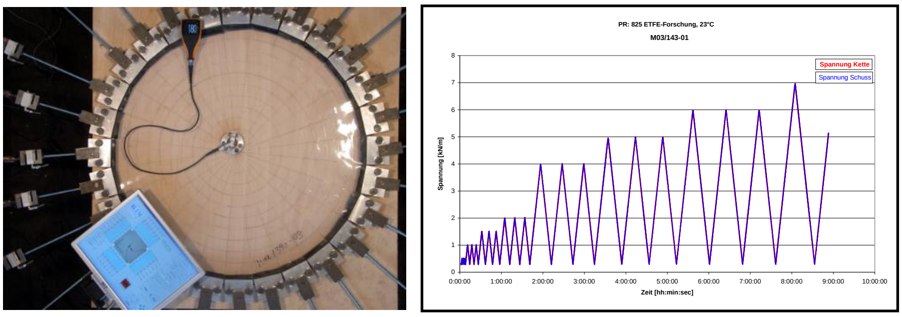


Figure 7-8 Left: multi-axial test on ETFE using a circular sample. In the middle one may see the installation to measure the thickness; right: load history for the first tests performed with the circular sample [© DEKRA/Labor Blum]

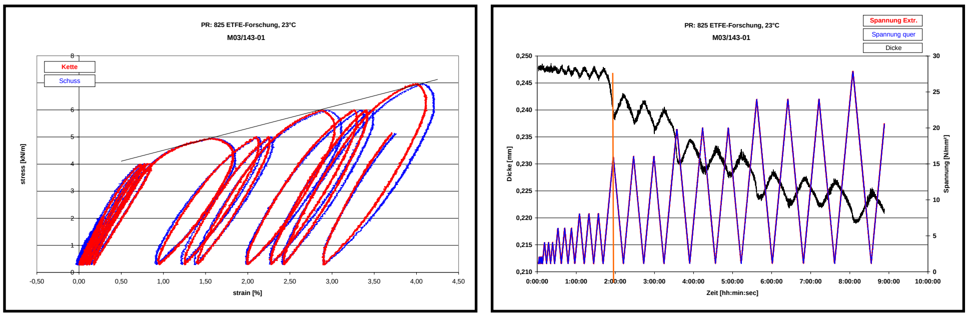


Figure 7-9 Left: deformation in direction of roll and perpendicular to roll direction. The interpretation of these results cannot be given here due to the lack of time. But it should be mentioned that the results conform to the von-Mises theory with hardening. It is to note that a viscous flow is superposed to the plastic behaviour. The yield point is not well defined; right: the behaviour of the thickness for this test. Here one can define clearly the yield point because of the step in thickness behaviour. This is marked with the orange line. [© DEKRA/Labor Blum]

From these considerations the following points shall be taken into account for the design of ETFE structures:

1. The yield point is not a material constant. It depends on the load history. Thus it shall not be used for the design.
2. The yield point can be detected clearly if the change is measured during testing.
3. The first yield point depends using the yield criterion of von-Mises on the stress ratio of the two mean stresses. The yield point in the hardening branch depends on the ratio of the two mean stresses and the direction of the two axes of mean stress. Thus the mechanical behaviour after having reached the yield point in a uniaxial test is different from the behaviour in a biaxial test. As such the uniaxial failure criterion shall not be used for the biaxial failure. This behaviour can easily be explained: yielding under uniaxial tensile loading leads to an orientation of the molecular chains in the direction of stress. The negative elongation in the direction perpendicular is large. This can be described as yielding in the surface. In biaxial stress states the orientation cannot take place. As such yielding occurs in the third direction with a reduction in thickness.
4. After having reached the maximum stress and the loading is reduced, the yield area will be left, the material behaviour is elastic as long as the previous yield stress is not exceeded again.
5. After having exceeded the yield point, thus after hardening and unloading the elongation will not come back to zero. A residual strain will stay which is corresponding to the plastic part of the deformation. To this plastic deformation a viscous part is superposed which can be formulated by extending the plasticity theory with hardening effect by a viscous part.
6. The part, which is at the moment missing, is the biaxial criterion of failure. The common tests – biaxial tests in cruciform or circle shape fail at the edges and not on the centre of the sample. First results at Dekra/Labor Blum show that a biaxial failure criterion will be found. Respective tests are not finished yet. Therefore a new testing installation has been built in which the failure happens in the centre. Edge effects have not occurred.
7. The statical analysis of ETFE is expected to become clearer and easier using the presented method.
8. Recommending design procedures for ETFE at the moment means that they represent the actual state of knowledge and will be preliminary. A final recommendation for statical analysis and design can be defined after having evaluated all results and included into the material laws.

7.3.8 Conclusions and outlook

Although all concepts aim at the yield strength in order to limit the residual strains the approaches are quite different. However, the yield point or the yield points, respectively, are not interpreted in the same way. Temperature, load duration and biaxial stress ratio are identified as influences on the yield strength by all authors. Additionally, formTL introduces a factor considering environmental impacts and Saxe introduces the loading velocity as fourth impact. The last aspect allows a comparable high resistance for short term loads with high loading velocity (wind load). A comparison of resulting design resistance values of all presented concepts is given in Table 7-6. Additionally to the above listed diversity of deterioration factors, differences in the resistance values are due to diverse definitions of strain limits for the SLS.

Table 7-6 Comparison of design resistance values for proposed SLS concepts

SLS	De Vries R_d [N/mm^2]	form TL R_d [N/mm^2]	Moritz R_d [N/mm^2]	Saxe R_d [N/mm^2]
Permanent load 35°C/40°C	7.2	7.0	6.9	6.0
Long-term load 0°C/3°C	10.8	15.5	13.7	9.0
Long-term load 23°C	9.2	10.0	11.5	8.0
Short-term load 23°C	12.0	12.5	15.0	21.6

A main task of the development of the Eurocode will be the harmonization of the views on ETFE verification. A first draft is given in Eurocode Outlook No. 44. The harmonization work also comprises the harmonization of test procedures to ensure an equal base whereupon the structural concepts and analyses are based.

Eurocode Outlook No. 44

1 ETFE foil - design concept with partial safety factors

1.1 General

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

– resistance of material and joints γ_M

NOTE Partial factors γ_M may be defined in the National Annex. The recommended value for foil structures is γ_M= 1.1

(2) The reduction factors k should be applied to the various characteristic values of resistance.

(3) The reduction factors k_{age}, k_{long}, k_{perm}, k_{temp*} can be determined with project specific tests. If compliant tests from other projects are available, these values can be used. The following recommended values can safely be applied if no tests are made.

NOTE Recommended values for the reduction factors in ETFE are as follows:

- Reduction factor for environmental effects k_{age} = 1.05,

- Reduction factor for long term effects: k_{long} = 1.2,

- Reduction factor for permanent long term effects k_{perm} = 1.8,

- In case of single layer foil with no regulation in the attachment details the reduction factor for permanent long term effects (prestress) should be set to k_{perm} = 3.5,

- Reduction factor for temperature effects 0°C k_{temp0} = 0.7,

- Reduction factor for temperature effects 50°C $k_{temp50} = 1.2$,

- Reduction factor for temperature effects 70°C $k_{temp70} = 1.7$.

(4) The characteristic elastic limit $f_{y10\%,23}$ is the average value of the 10 % strain stress at 23°C, determined in project specific uniaxial strip tests. If results from other projects are available, these can be used. The following recommended value can safely be applied if no tests are made.

NOTE The recommended values for the elastic limit is $f_{y10\%,23} = 21$ N/mm².

NOTE For post hardened foil higher values for the 10% strain stress can be applied. In this case $f_{y10\%,23}$ needs to be determined in appropriate biaxial tests.

1.2 Resistance of material and joints

1.2.1 General

(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 behaviour 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 foil:

$$n_d \leq f_d$$

where: n_d is the design foil stress in the considered direction, f_d is the design tensile strength of the foil or the joint related to the specific design situation.

1.2.2 Design Resistance Permanent Load

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

$$f_{PM,d} = f_{y10\%,23} / (\gamma_M \cdot k_{age} \cdot k_{perm})$$

1.2.3 Design Resistance Long Term Load at Low Temperature (0°C)

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

$$f_{LTL,d} = f_{y10\%,23} / (\gamma_M \cdot k_{age} \cdot k_{long} \cdot k_{temp0})$$

1.2.4 Design Resistance Long Term Load at Room Temperature (23°C)

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

$$f_{LTR,d} = f_{y10\%,23} / (\gamma_M \cdot kage \cdot klong)$$

1.2.5 Design Resistance Short Term Load

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

$$f_{ST,d} = f_{y10\%,23} / (\gamma_M \cdot k_{age})$$

1.2.6 Design Resistance Short Term Load at High temperature (50°C)

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

$$f_{STH,d} = f_{y10\%,23} / (\gamma_M \cdot k_{age} \cdot k_{temp50})$$

1.3 Foil Stress Verification

(1) The design value of the foil stress n_d in each area of the material shall satisfy: $n_d / f_d \leq 1.0$.

For **Permanent Load** the above mentioned equation leads to $f_{PM,d}$ = 21 / (1.1 · 1.05 · 1.8) = 10.1 N/mm² or an admissible characteristic stress of σ_{adm}= 10.1 / 1.35 = 7.5 N/mm². For single layer structures with no regulation or adjusting possibilities it yields $f_{PM,d}$ = 21 / (1.1 · 1.05 · 3.5) = 5.2 N/mm² or σ_{adm}= 5.2 / 1.35 = 3.8 N/mm².

For **Long Term Load at Low Temperature (0°C)** the above mentioned equation leads to $f_{LTL,d}$ = 21 / (1.1 · 1.05 · 1.2 · 0.7) = 21.6 N/mm² or an admissible characteristic stress of σ_{adm} = 21.6 / 1.5 = 14.4 N/mm².

For **Long Term Load at Room Temperature (23°C)** the above mentioned equation leads to $f_{LTR,d}$ = 21 / (1.1 · 1.05 · 1.2) = 15.2 N/mm² or an admissible characteristic stress of σ_{adm} = 15.2 / 1.5 = 10.1 N/mm².

For **Short Term Load** the above mentioned equation leads to $f_{LTR,d}$ = 21 / (1.1 · 1.05) = 18.2 N/mm² or an admissible characteristic stress of σ_{adm} = 18.2 / 1.5 = 12.1 N/mm².

For **Short Term Load at High Temperature (50°C)** the above mentioned equation leads to $f_{LTR,d}$ = 21 / (1.1 · 1.05 · 1.2) = 15.2 N/mm² or an admissible characteristic stress of σ_{adm} = 15.2 / 1.5 = 10.1 N/mm².

7.4 Proposals for the SLS verification of single layer ETFE

7.4.1 General

A summarized description of proposed concepts for single layer ETFE structures according to the compilation in the TensiNet European Design Guide for Tensile Surface Structures, Appendix A5 “Design recommendations for ETFE foil structures” [Hou13] is given. For further explanation see chapter 6.4 and 7.3. The above described concept of Saxe, see chapter 7.3.5, can be applied to single layer ETFE structures as well.

7.4.2 Recommendations formTL on single layer ETFE foil

Single layer ETFE structures cannot compensate for the effects of creep, temperature and tolerances by a slight geometry change, as cushions do. Therefore, these effects must be taken into account during the design process.

Effect of the temperature (change in length)

The thermal expansion coefficient of ETFE is approximately $10 \cdot 10^{-5}$/K. The supplier Asahi Glass specifies for their material $9.4 \cdot 10^{-5}$/K, so more or less the same.

In central Europe the air temperature typically varies within a range between -20°C and +40°C. Assuming an installation temperature of 10°C this leads to a variation of +/-30 K, which results in a strain variation of $+/-30 \cdot 10 \cdot 10^{-5}$= 0.3%.

Creep effect

Under constant load, the ETFE foil creeps. The magnitude of the creep depends on the level of stress.

In a uniaxial test, the material behaves as shown in the following graph, Figure 7-10 (Asahi Glass).

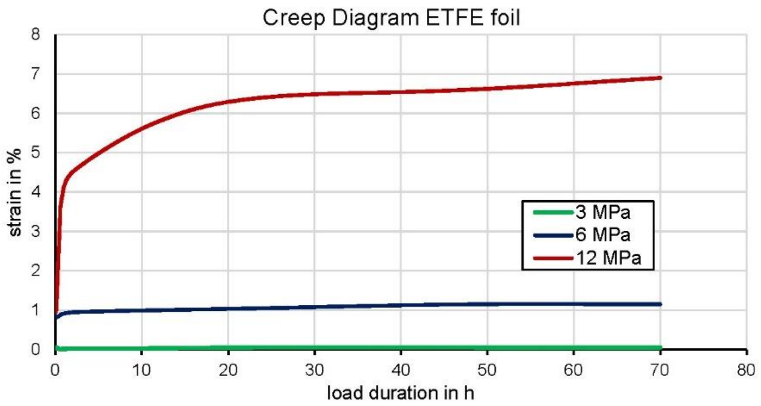


Figure 7-10 Typical creep diagram for an ETFE foil [source and ©: formTL ingenieure für tragwerk und leichtbau GmbH]

This means that up to a stress of 3 N/mm² the impact of creep is negligible, and for a stress of 6 N/mm² it stabilises at approximately 1%. With a permanent stress of 12 N/mm² the material creeps uni-axially towards a value of 7 to 8% after 70 hours, but has still not stabilised.

In biaxial tests it has been found that the biaxial strain is reduced to approximately 25% of the strain in uni-axial tests, so it is assumed that the permanent strain at 6 N/mm² will stabilise itself at a level of approximately 0.3 %, and at 12 N/mm² it will be approximately 2% after 70 hours.

This means ideally that the pretension in single layer ETFE foil structures should not exceed 3 N/mm² (e.g. 0.6 kN/m for 200 µ foil), and permanent high load like snow should be avoided.

The frequency and intensity of wind can only be determined statistically. In the following excerpt and graphs the wind speed in Germany is given in correlation with its probability. As an example this distribution is applied in 5 steps, and the resulting intensity is determined relative to the design wind speed. For the yearly occurring wind the intensity is approximately 60% of the design wind pressure

Table 7-7 Statistical frequency and intensity of German wind speed

Wind [m/s]	Wind per year	R (acc. to Caspar)	Windload [kN/m²]	Intensity [%]
45.5	0.03	30	1.3	100
40	0.2	5	1.0	77
35	1	1	0.8	59
30	5	0.2	0.6	43
25	29	0.035	0.4	30

Based on this intensity the stress level is determined for a 200 µm foil in a recently realized example. Relevant for the strain in the foil is the stress acting in larger areas. Stress peaks are not taken into account for this.

Table 7-8 Stress level of ETFE based on intensity level of Table 7-7

200 µm foil	Tension in N/mm²				
Pretension	2.0				
Max. tension under wind load	12.5				
	100%	77%	59%	43%	30%
Global tension under wind load	10.00	7.73	5.92	4.35	3.02

For the yearly wind the stress is approximately 6 N/mm², and under design load the stress can increase up to 12.5 N/mm².

For the biaxial tests appropriate load scenarios should be applied in order to determine a realistic compensation factor which takes into account a reasonable part of the permanent strain over the years.

Application

Once the short term compensation has been determined, these values must be corrected (if required) to comply with the strain variation due to temperature and due to long-term creep.

In some cases it will be necessary to insert means for re-tensioning in the details, as shown in Figure 7-11, for example.

Compensation factors for ETFE are in the range of 0.2 to 0.6%. These low values do not allow for high tolerances, therefore it is highly recommended to apply adjustable details along the border. These details can be used as well for re-tensioning after some years.

Figure 7-11 Unilever Building, Hamburg [source and ©: formTL ingenieure für tragwerk und leichtbau GmbH]

7.4.3 Recommendations J.W.J. de Vries (TU Delft) on single layer ETFE foil

Jos de Vries has investigated mono-axial and biaxial properties of ETFE foil with the aim to define a design concept based on the “Limit State” approach. An important issue has been the determination of a yield point and creep limit. As the material behaves in a non-linear manner, a long- and short-term load is defined.

Reduction factors in Serviceability Limit State (SLS):

$\sigma_d = \sigma_{rep} / \gamma_m \cdot k_{mod}$,

σ_d = Design stress for ETFE foil,

σ_{rep} = representative stress for ETFE foil, to be determined (approximate values for 1:1; 12 N/mm^2, for 1:2 / 2:1; 15 N/mm^2),

γ_m = safety factor for material uncertainties, γ_m = 1.0,

k_{mod} = modification factor for temperature and creep, see Table 7-9.

Table 7-9 Reduction factor kmod depending on temperature and load duration, no permanent deformation

Deformation criteria	Load duration	Temperature (°C)	k_{mod}
No permanent deformation	Less than 15 min	t < 20	0.84
		20 < t < 30	0.77
		30 < t < 50	0.60
	More than 15 min	t < 20	0.50
		20 < t < 30	0.46
		30 < t < 50	0.36

The focus of the research was on the Serviceability Limit State. It is assumed that the Ultimate limit State is not the restrictive state. Therefore no recommendations are mentioned for the ULS.

Important issues addressed here are the temperature dependence of the creep level and strength of the foil.

The maximum prestress level assumed at a temperature between 20°C and 30°C is

$\sigma_d = \sigma_{rep} / \gamma_m \cdot k_{mod} = 12 / 1.0 \cdot 0.46 = 5.5$ N/mm^2.

As the foil will get warmer than 30°C in summer, stresses should stay below to prevent creep.

$\sigma_d = \sigma_{rep} / \gamma_m \cdot k_{mod} = 12 / 1.0 \cdot 0.36 = 4.3$ N/mm^2.

7.4.4 Conclusions

To determine the appropriate values for the pretension level, different approaches can be taken: an approach not to allow for any creep or an approach for a controlled creep. It is anyway sure that the pretension level should be low compared to the possible pretension level of an ETFE cushion. The pretension level should range from 3 to 6 N/mm^2 depending on the anticipated elongation due to creep and the available adjustment possibilities. This is up to the judgement of the engineer.

For a Eurocode Outlook regarding single layer ETFE verification see chapter 7.3.7.

7.5 Maintenance of the prestress and post tensioning

The loss of prestress as explained above – due to relaxation, creep and the decrease of yarn crimp – has to be considered in the compensation planning. Due to this the specification for the biaxial test must include all important load cases. Based on this test the compensation values have to be defined with an eye on the relaxation of the material and the necessary prestress during installation. The compensation values have to be determined in such a way that the structure will preserve its necessary prestress during lifetime. Basically, this means that the initial prestress level after installation is higher than the nominal prestress level considered in the design. It is envisaged to establish a European standardized procedure for the determination of compensation values in CEN/TC 248/ WG4.

If this procedure is disregarded it should be ensured by constructive details that the structural membranes can be restressed, e.g. by a mast which can be tensioned back, valley ropes, adjustable border details etc. In practice, this is rather the exception than the normal case.

Eurocode Outlook No. 45

(1)	*Compensation values may be determined according to the biaxial test standard which is prepared by CEN/TC 248/ WG4 or any other appropriate rule.*
(2)	*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 7-12. 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 linked to a permanent decrease of prestress in the membrane.

The general demand derived from this conclusion is stated in Eurocode Outlook No. 46.

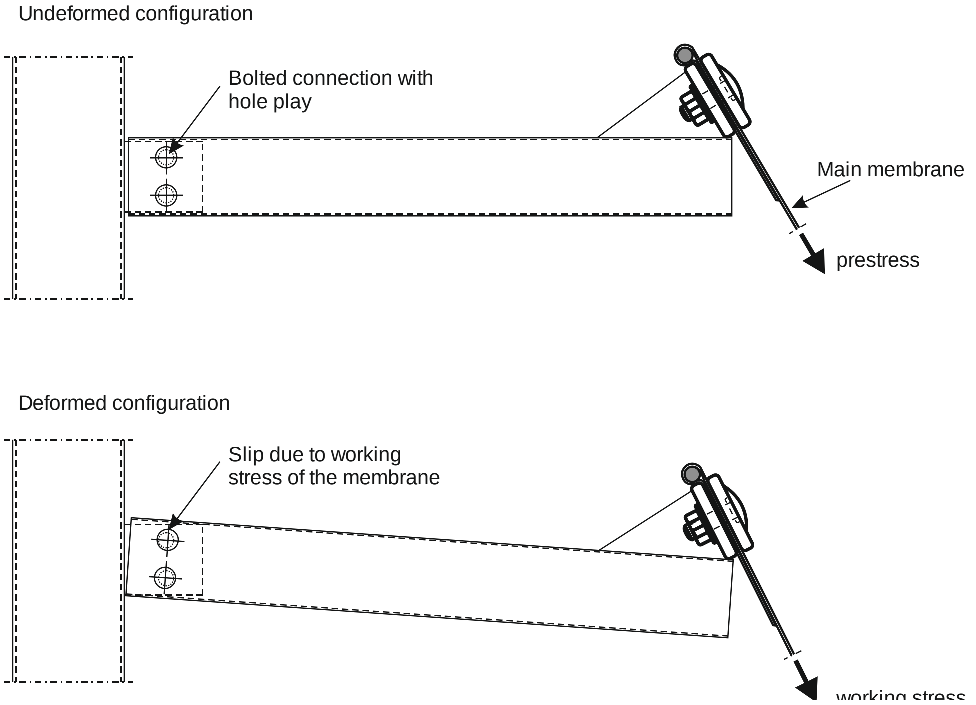


Figure 7-12 Large irreversible displacement at the cantilever tip due to a small rotation at the cantilever support [© ELLF]

Eurocode Outlook No. 46

(1)	*Irreversible deformation of the primary structure which results in a considerable permanent decrease of prestress shall be avoided.*

7.6 Wrinkling

Wrinkles do not mean damage to the membrane – unless they occur repeatedly – but for aesthetic reasons the aim should be to avoid wrinkles. However, a complete avoidance is unrealistic for most membranes. A limitation of wrinkles should be envisaged.

The smaller one of the principal stresses (σ_2) is the appropriate indicator for wrinkles: they appear when σ_2 approaches zero or the principal stress ratio σ_1/σ_2 is high in general. This and the relation to shear stress can be depicted with Mohr's circle, see Figure 7-13. It shows the relation between the principal stresses σ_1 and σ_2 on the one hand and the stresses σ_x, σ_y and τ_{xy} in a specific x,y-coordinate system on the other hand. For woven fabrics the x- and y-directions are usually aligned with the main fabric directions warp and weft. The mean stress $\sigma_m = ½(\sigma_x + \sigma_y)$ determines the centre of the circle and the radius is derived from the deviatoric stress $\sigma_d = ½(\sigma_x – \sigma_y)$ and the shear stress τ_{xy}:

$$r = \sqrt{\sigma_d^2 + \tau_{xy}^2} \; .$$

It can be seen from this equation that if the shear stress would increase within a stress state in a specific x,y-coordinate system the radius of Mohr's circle would increase as well and simultaneously the smaller one of the principal stresses σ_2 would decrease. In general, this means that increasing shear stress is linked to a rising risk of wrinkles. However, it is not necessarily the height of the shear stress but – as mentioned above – the value of the smaller principal stress which is the appropriate indicator for the risk of wrinkles.

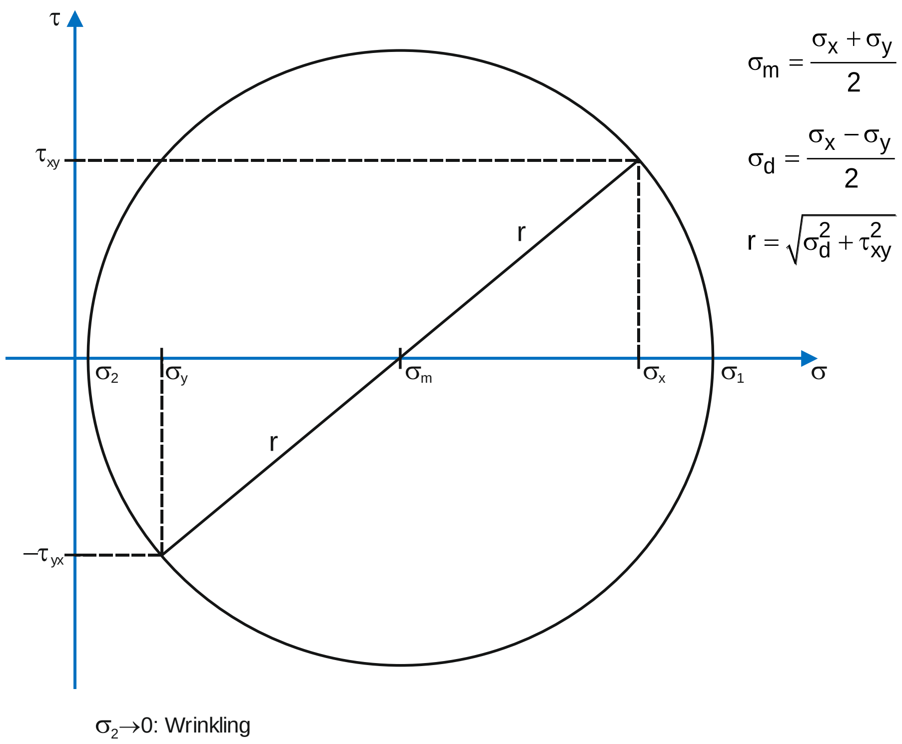


Figure 7-13 Mohr's circle with the relation between the principle stresses and stresses in a specific x,y-coordinate system [© ELLF]

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, i.e. a high principal stress ratio σ_1/σ_2, has to be avoided. Deviations shall not occur in statically relevant areas.

As it is a phenomenon of instability the proper simulation of wrinkles needs additional considerations of the remaining (but eventually small) bending stiffness. There exists an exhausting amount of literature on the analysis of wrinkles based on the membrane theory and the tension field theory, as well as to enhance finite element analysis using membrane elements. Alternatively, wrinkles may be simulated using shell models and directly consider the bending stiffness. Still, there is ongoing mechanical research in that regard.

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 diverse behaviour of strands/strands charges and variations in the coating a textile can be called an inhomogeneous material. Disturbance cannot be excluded during manufacturing; especially for heavier textiles (PVC coated polyester fabric, PTFE coated glass fibre 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 unavoidable for textile architecture.

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 thorough 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. 47.

Eurocode Outlook No. 47

(1) The objective of the design should be the limitation of wrinkles to a minimum.

(2) High differential membrane stress (i.e. high principal stress ratios) should be avoided in the prestress state as well as under external loading. Deviations should be limited to areas that are not statically relevant.

(3) Wrinkles in a membrane structure should be evaluated project orientated.

7.7 Tear control

Tears cannot always be completely avoided in membrane structures. There are different reasons for tears in structural membranes, e.g. production inhomogeneities, knots, little cracks or similar in the fabric itself, points of sharp folding, pre-damages caused by handling during production, fabrication or installation. Moreover, tears can be induced through third parties. Quite often tears do not occur unless several impacts act together.

Because of specific fabric characteristics and tolerances in the membrane and/or the substructure damages can occur in membranes during their installation. Of main importance regarding failures is how they will be handled and how they will be repaired. Basically, it is necessary to gauge them according to the demands of a specific project, i. e. to assess whether they are located in a statically high stressed area within the membrane surface, what size they have absolutely and in relation to the whole membrane surface, what kind of repair is possible and whether a repair is aesthetically passable. Based on this evaluation possible repairing work can be planned. Repairing works must always be carried out by expert staff.

The same applies 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.

In case of previous folding, glass fibre fabrics are more prone to tears than other materials. But if basic handling rules are realized glass fibre fabrics have an unrestricted excellent suitability as structural membranes and can prove their advantages in relation to other materials as there are long durability, fire safety etc.

Small tears in glass fibre fabrics that result from previous folds are referred to as “short cuts” by some expert witnesses – a term introduced in the context of investigations of damages. Experiences show that the vast majority of short cuts is actually found to not exceed a length of 50 mm. This observation matchs with the fact that short cuts oftentimes result from double folding, see Figure B2-5. In exceptional cases greater tears due to crease fold can occur, e.g. when a load of greater measures is accidentially applied on the membrane during one of the fabrication or installation steps.

In order to minimize the occurrence of tears glass fibre fabrics should be handled during the manufacturing and installation with utmost care in order to avoid crease 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 accurately with the aim to avoid crease folds etc. See chapter 9 for more details on handling rules. 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 tears at the locations of the previous folds after a certain load duration is the consequence. They may appear years after the installation. If they are professionally repaired they do not affect the Ultimate or Serviceability Limit States.

A tear does not grow unless the membrane stress near the tear exceeds the tear resistance. Thus, the tear resistance is a first measure to assess the risk of an existing tear [FM04, Bid89, BöBl07]. Once a tear appears, tear propagation has to be avoided in order to prevent a significant strength degradation of the membrane panel.

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. Usually, tears with a length of up to approximately 150 mm can be repaired easily, see chapter 9 (what basically does not mean that longer tears cannot be repaired or only with considerable effort). A patch can be welded over the tear. For safety reasons this should be done promptly, particularly for materials with low tear resistance. The way of welding should be decided project-orientated. If a crease fold is diagnosed to be the reason of a tear and the fold is recognized to be longer than the detected tear the patch should cover not only the tear but the whole fold in order to prevent future appearnce of a new tear due to this fold. In case of big tears the membrane panels may have to be replaced.

The calculation of tear propagation using the methods of fracture mechanics may help to define allowable tear widths and to assess how urgent a repair has to be conducted. This is currently a topic of research (see e.g. [BöBl07]).

As already mentioned, tears cannot be completely avoided. Basically, the aim should be to limit the appearance of tears. The allowable number of tears per area or at all cannot be given in a standard. This is recommended to be agreed with the client under consideration of the complexity of the specific structure. For some projects a maximum number of failures is given in the contract. Numbers or failure 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

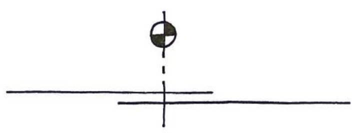
8.1 General

In the following, principle membrane details for coated and uncoated fabrics are described, whereby the focus is laid on coated membranes (PES/PVC and glass/PTFE).

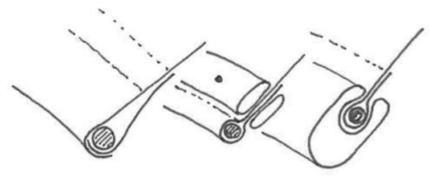
Details and connections in membrane structures can be distinguished in five main groups, see also Figure 8-1:

- membrane joints,
- membrane edges,
- membrane corners,
- ridges and valleys and
- high and low points (inside a fabric area).

(a) Welded membrane joint

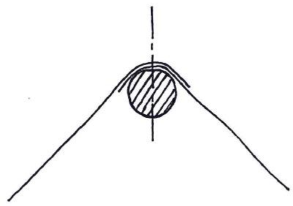


(b) Rigid membrane edge with fitting and tension elements



(c) Membrane corner with membrane strip (left) and with belts (right)

(d) Ridge cable arranged in loops



(e) High point

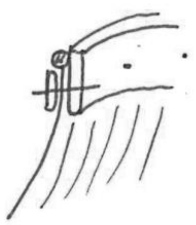


Figure 8-1 Typical exemplary details and connections in membrane structures [© M. Nieger]

For the design of details and connections, the following objectives should be considered:

- consistency with the model of the structure (geometrical, physical and numerical),
- strength,
- protection of the membrane,
- flexibility,
- buildability,
- security and redundancy,
- appearance,
- adjustability and re-tensioning,

- water tightness,
- fire resistance,
- 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 carry or transmit loads whenever external loading conditions change. Details and connection points shall follow exactly the system line geometry of the suspension points. They shall be fluently integrated into the geometry of the system. Space enough has to be provided. Eccentricities shall be avoided in order to guarantee the correct shape of the total system.

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. The minimum value of the breaking strength should be clearly indicated.

Protection of the membrane

Damages to the membrane must 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, clamping plates etc.) shall not be damaged, even under cyclic loading and large movements of the membrane. For execution, the supporting elements shall be free of rough spots, sharp edges, droplets following hot-dip galvanizing drying process or other defects that may injure the membrane material.

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.

Buildability

For the design of the supporting structure the way of installation has to be taken into account. The designer has to consider fixation points for working tools etc. in his structural design.

Furthermore, particular movements and rotations might be required at connection points during the membrane installation.

Flexible connections should be designed to provide enough degrees of freedom during installation because the membrane is not in its final position and before hoisting, it has a position determined by gravity. This can, for instance, cause a 180° rotation of a corner during lifting of the fabric.

Moreover, tolerances of the supporting structure and the membrane must be considered during the detail design.

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.

Appearance

A general view of the whole design is needed. Each single detail should fit into the design of the whole membrane and should 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.

Adjustability and re-tensioning

Because of the typical expansion behaviour of the membrane material, this effect has to be considered during the design process. As described before the compensation is one main important value.

Additionally, it is preferable for a membrane to introduce a sufficient scope to re-tensioning and prestress preservation for the installation and the service life of the structure. For some structures this is even essential (classical membrane – cable structures).

Tolerances of the membrane and the supported structure must be handled (see above).

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.

Maintenance and accessibility

When the design includes details which have to be maintained regularly, the accessibility must be secured, for example by removable flaps, a possible access from the inside, etc.

8.2 Membrane joints

According to Bubner [Bub97] a membrane joint is defined as a connection which ties together either single membrane layers or membrane fields composed of several layers. Joints can be divided into those which fix membranes permanently to each other, as in welded joints (for some materials also sewed joints), and joints that can be separated again, e. g. site joints.

Currently a lot of state of the art details exist, but they are not regulated or standardized so far. 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 for 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].

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 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 two different kinds of membrane joints are the most common seam types in practice for coated membranes:

- welding and
- clamping.

For uncoated fabrics, membrane joints are sewed.

Additionally, 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.

In textile architecture seams between coated fabrics are executed by welding. For uncoated fabrics they are sewed as already mentioned. For other textile fields like industrial, environmental etc. sometimes also sewing or – more rarely – a combination of both (welding and sewing) is used.

Seams between foils can be executed by welding.

Exemplary welded seams of coated fabrics and foils are illustrated in Figure 8-2.

Furthermore, clamped connections can be carried out for textile fabrics and – seldom – for 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 of materials capable of taking the load. Commonly, the plates are made of steel or aluminium. In some special cases wood or plastic are used

Different kinds of solutions for bolted membrane joints, so called site joints, are exemplary given in Figure 8-3. Furthermore, the TensiNet Design Guide [FM04], Seidel [Seid09] and Bubner [Bub97] give further examples and explanations also for welded, sewed and laced joints as well as for joints with zip-fasteners.

The width of a welded seam should be determined by uniaxial short term tensile (strength) tests using calibrated testing equipment. The tests shall be performed at testing temperatures of 23 °C and/or 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.

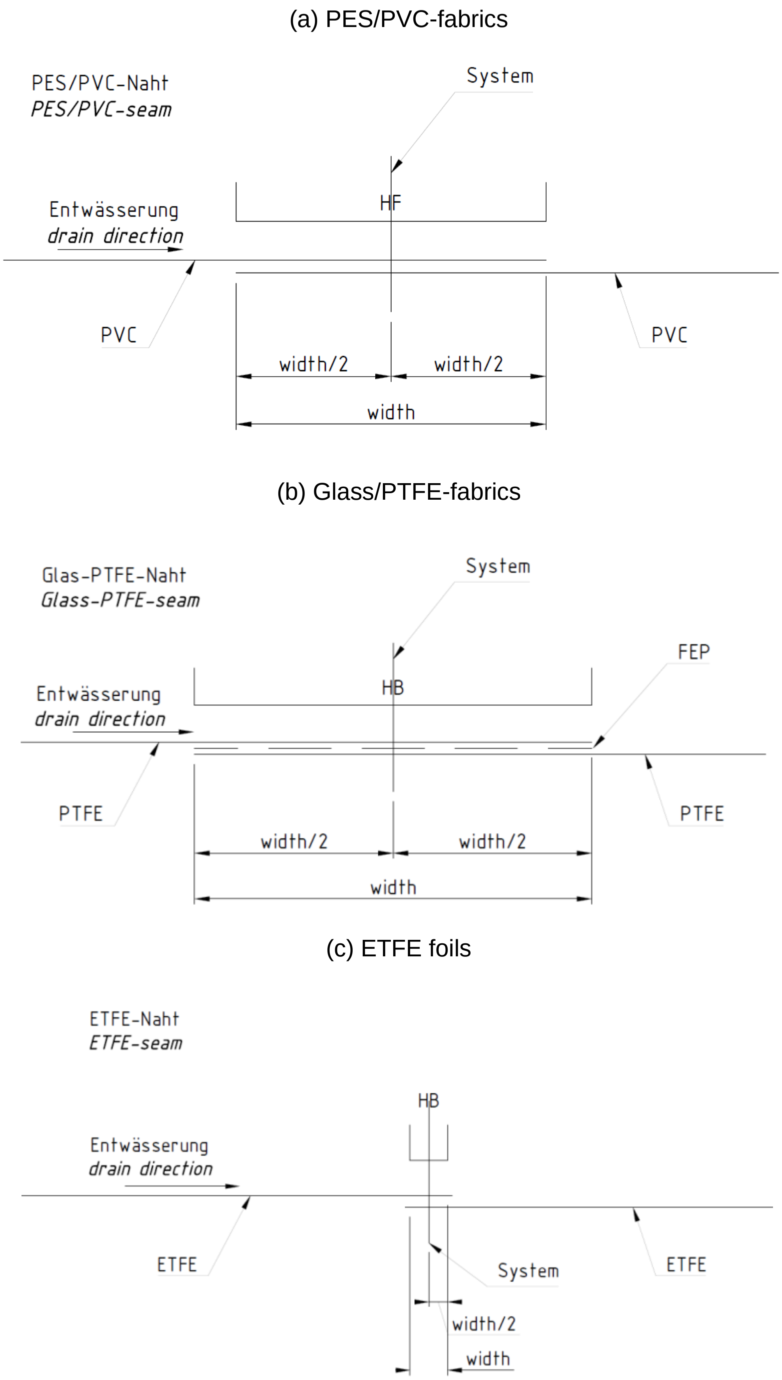


Figure 8-2 Typical exemplary welded seams of coated fabrics and foils [source and ©: formTL ingenieure für tragwerk und leichtbau GmbH]

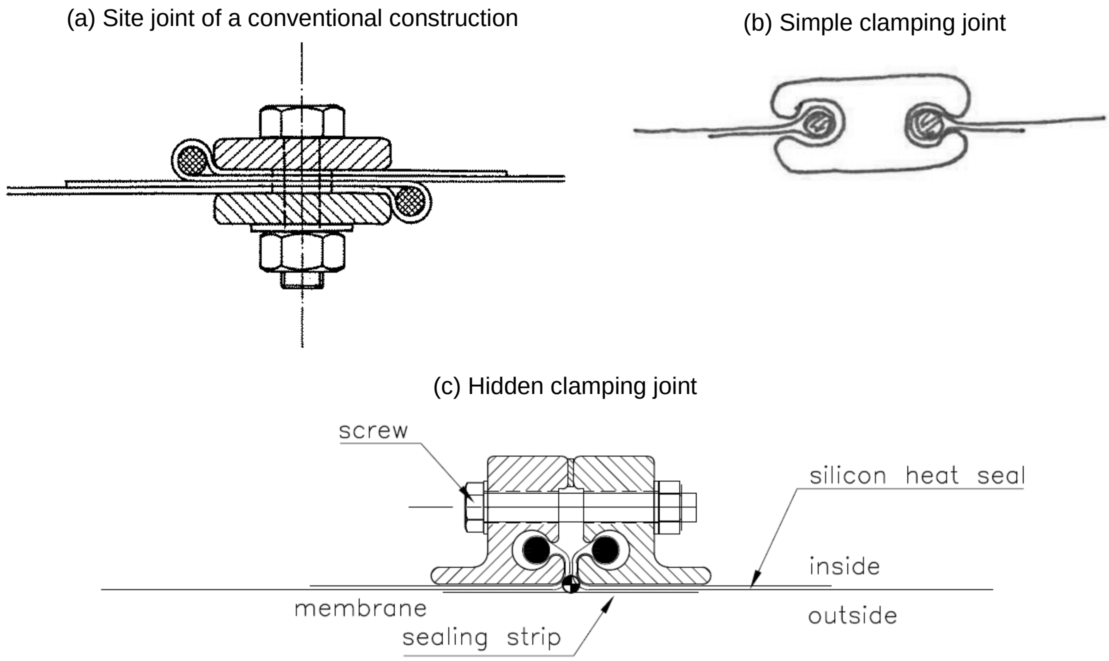


Figure 8-3 Typical exemplary clamped (bolted) membrane joints with metal plates, bolt ropes and bolts according to [1st row, left: Bub97, 1st row right: © M. Nieger, 2nd row © formTL]

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°C 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. These tests are performed until the failure of one part of the joint. That means that possibly a force according to membrane stress which is usually 4 to 5 times higher than the design membrane stress is applied, correspondent to a typical stress factor of 4 to 5. For this high loads it might be possible that the metallic parts yield or break prior to the breaking of the membrane. If the aim of the test is the determination of the breaking force of the membrane in a specific joint configuration this should be avoided by a reinforcement of the metallic parts.

Eurocode Outlook No. 48

(1) Membrane joints considered in this standard are welded seams and clamped details for coated fabrics and sewed seams for uncoated fabrics. Sewed seams or a combination of sewing and welding are not so common in the textile architecture but might be used in other textile structures.

Note: Other types of membrane joints, e. g. laced joints and zip-fasteners, are possible as well. The design resistance of them has to be determined by means of procedure tests.

(2) The design resistance of 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.

NOTE In case that the load bearing capacity of the membrane in the membrane joint detail shall be determined experimentally, due to the different safety levels against breaking of the membrane and aluminium or steel parts, it is typically necessary to reinforce the metallic parts in the test in order to avoid a failure of the metallic parts prior to a failure of the membrane.

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 8-4 and 8-5. Further details are given in [FM04, Seid09, Bub97 and Lor15].

As already mentioned, currently a lot of state of the art details exist, but they are not regulated or standardized so far. The design of membrane edges has to be carried out taking into account the relevant standards for the constructive elements.

For the design of a membrane edge, special attention has to be given to
- the movement of the fabric under different load cases,
- the forces running along an edge - especially for beveled edges (tangential forces) and
- the direction of the forces towards the membrane edge (warp and weft direction).

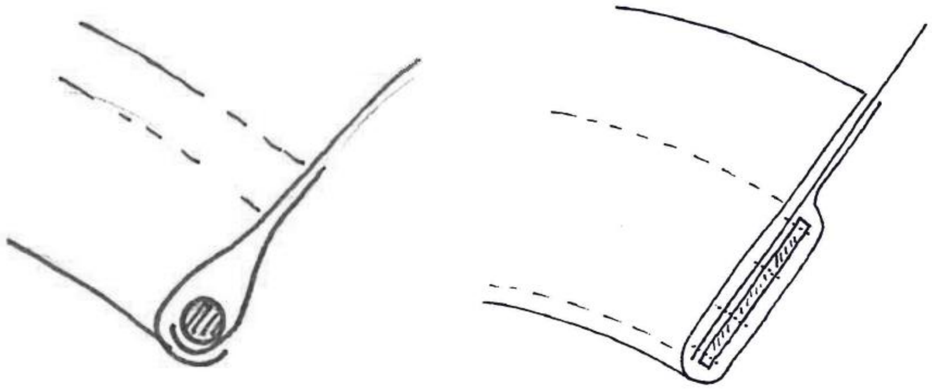


Figure 8-4 Typical flexible membrane edges with cable or belt [© M. Nieger]

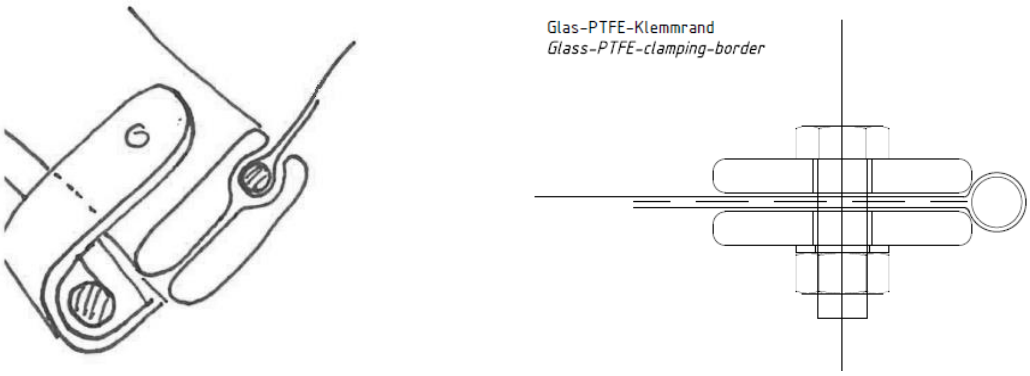


Figure 8-5 Typical rigid membrane edge [left: © M. Nieger, right: © formTL]

Eurocode Outlook No. 49

(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. In some cases it might be necessary to determine the load-bearing capacity of the whole membrane detail experimentally by a procedure test.*

NOTE In case that the load bearing capacity of the membrane in the membrane edge detail shall be determined experimentally, due to the different safety levels against breaking of the membrane and aluminium or steel parts, it is typically necessary to reinforce the metallic parts in the test in order to avoid a failure of the metallic parts prior to a failure of the membrane.

8.3.2 Flexible membrane edges

Flexible membrane edges show in the plan a curve. They are typically made of cables or segmented clamping plates fixed towards a cable. Sometimes flexible membrane edges are prepared with belts, especially for movable or temporary structures. Typical flexible edges are presented in Figure 8-4.

As presented in Figure 8-6 one possibility to carry out a flexible edge is to put a cable (made of steel (common version) or synthetic ones (smaller or temporary projects)) in a membrane pocket.

PES/PVC border pocket

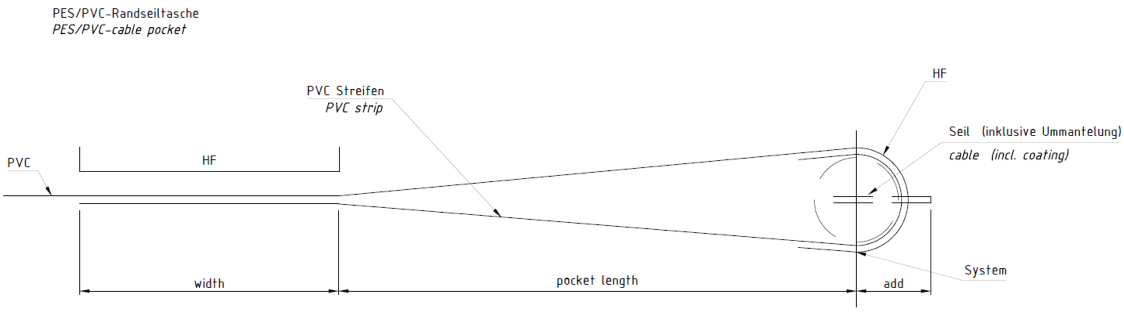


Figure 8-6 Typical exemplary PES/PVC border pocket [source and ©: formTL ingenieure für tragwerk und leichtbau GmbH]

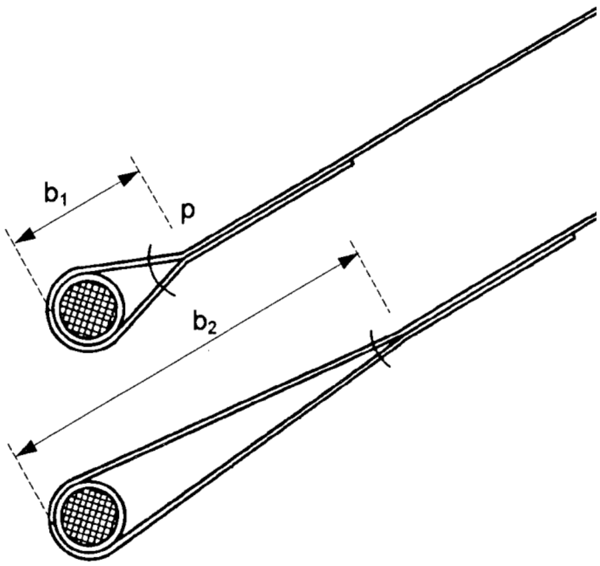


Figure 8-7 Different widths of membrane pockets [Bub97]

According to the TensiNet Design Guide [FM04] an important parameter for the strength of the membrane pocket is the angle between the upper and lower surfaces of the pocket, see Figure 8-7. 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 the pocket is welded to the membrane, i. e. where the upper and lower surfaces of the pocket diverge from another. According to Bubner [Bub97] the width of a membrane pocket (b1 and b2 in Figure 8-7) 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 8-7. The smaller the angle at point p is, the lower is the shear force which might tear the seam.

Furthermore, it has to be considered that the size of the cable pocket is dependent on the size of the cable fitting, as the cable has to be pulled through this during installation.

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 [FM04]. This is a main aspect especially during the installation process, when the membrane has not reached its final position.

Eurocode Outlook No. 50

(1) The width of a membrane pocket has to be designed taking into account

- *the angle between the upper and lower surfaces of the pocket,*
- *the tensile strength which occurs right-angled to the membrane edge and*
- *the size of the cable fittings.*

(2) Tangential forces along the membrane pocket have to be considered in the design process in order to prevent movement 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 or aluminum fixed towards a steel structure, foundation (concrete) or timber base. One typical constructive possibility for rigid edges is presented in Figure 8-8.

Figure 8-9 presents a principle of an edge element made of a movable anchor plate and tension bolt [Bub97]. The fitting adjusts to the membrane’s slope by means of the rotating bolt fastening. High tangential forces cannot be resolved by this detail.

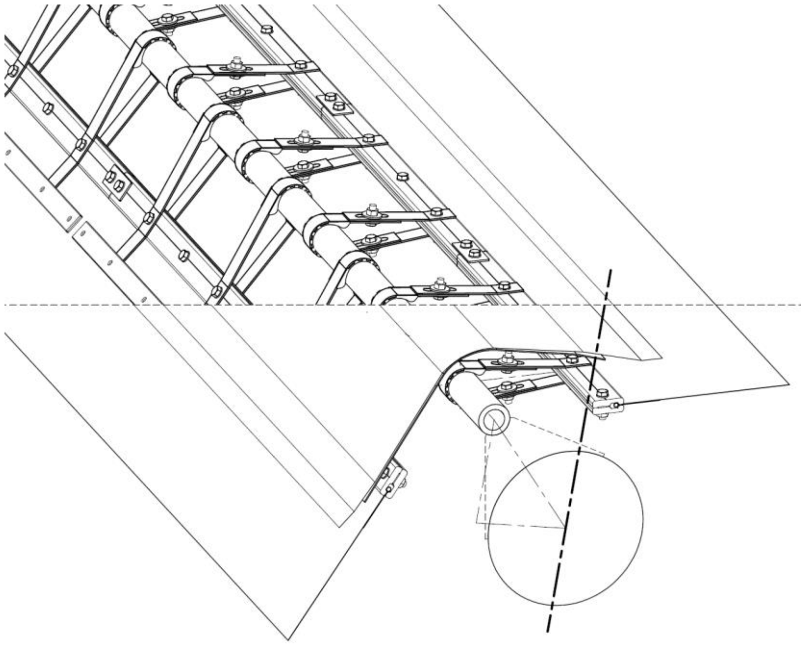


Figure 8-8 Rigid membrane edge: Glass/PTFE railing connection detail [formTL ingenieure für tragwerk und leichtbau GmbH]

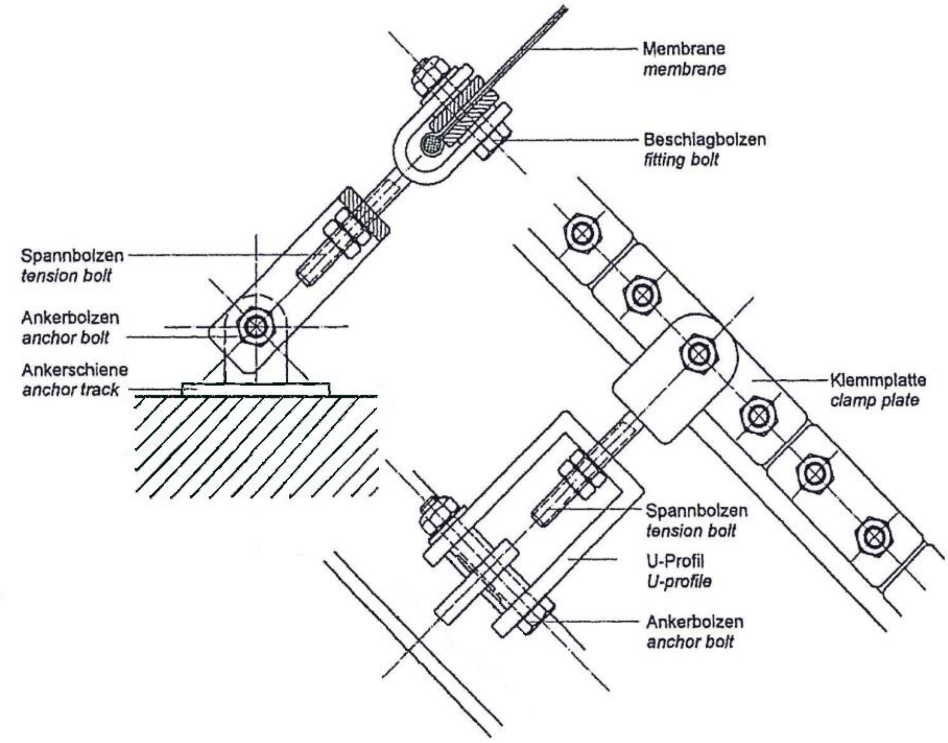


Figure 8-9 Edge element made of rotating metal fitting and tension bolt modified according to [Bub97]

The membrane can also be connected to rigid edges by eyelets and lacing. The French Recommendations provide specifications for this type of connection – amongst many others. This is exemplary documented in Code Review No. 25.

Code Review No. 25

French recommendations [S29]

Note: The requirements provided here concern mainly PVC coated polyester membranes

Eyeleted edges

Eyelets are installed at the edge of the polyester canvas, see Figure 8-10.

Figure 8-10 Eyeleted borders

They allow the connection between the membrane and a supporting rigid edge, typically a RHS, using a double lacing with halyard and a bungee cord. They must be designed in order to support the linking efforts given by the design documents. The use of eyelets on glass fabric is not allowed.

1. *Manufacturing of the eyeleted borders*

   The eyeleted edges consist of a hem around an edge halyard or similar. The eyelets are regularly spaced, see Figure 8-11. The minimum width of the hem should be 40 mm. The spacing of the eyelets must be given by the design note. The usual value is 150 mm

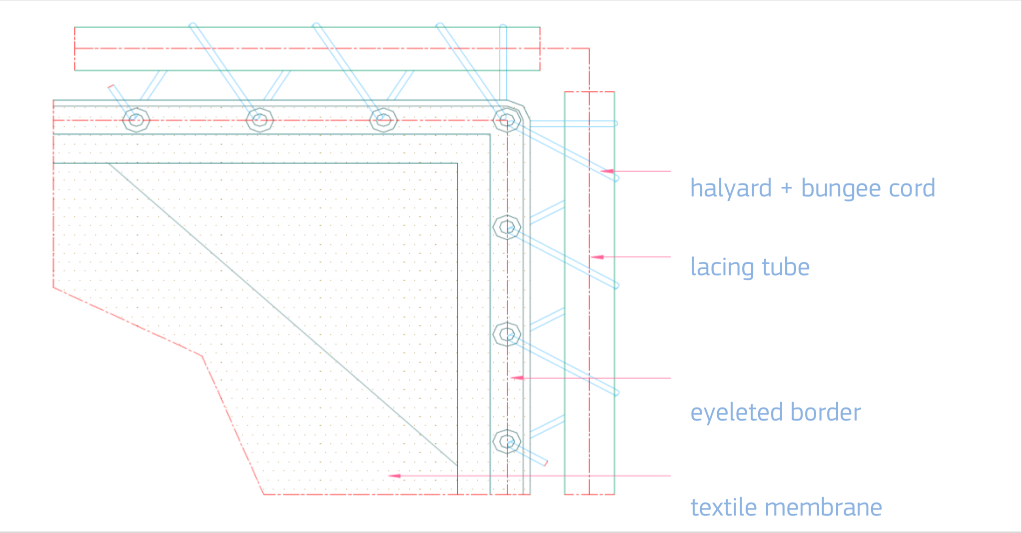


Figure 8-11 Fixing of eyeleted borders

The triple hem consists of a folded fabric strip welded to the main device canvas, see Figure 8-12.

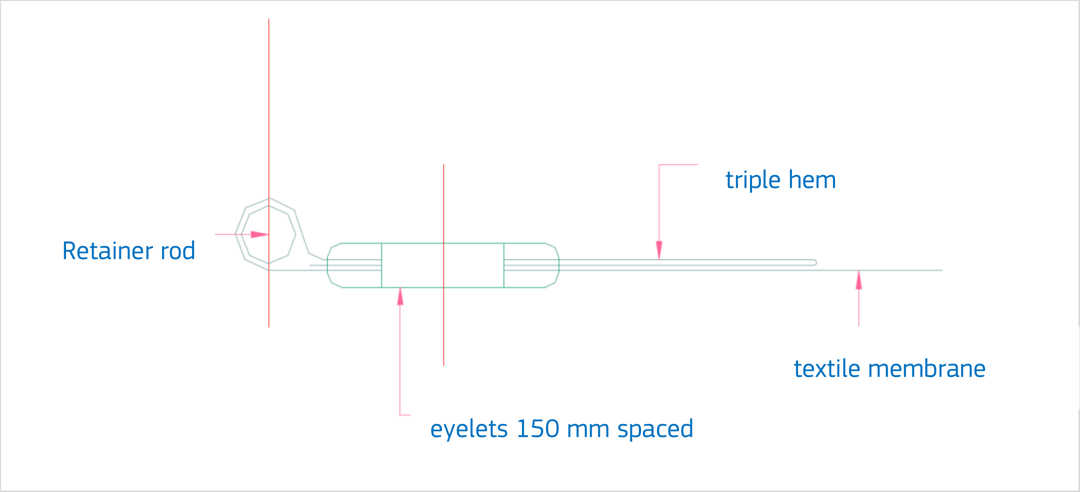


Figure 8-12 Cross section of the hem

The keder must be constituted either by a polyester halyard, PVC rod or steel wire, for which the minimum diameter must be 7mm. The eyelets must be made of brass or stainless steel with claws.

Their minimum internal diameter must be 18 mm so to admit a double lacing, rope with double and bungee. They must be installed without clearance abutment against the ring.

The minimum size of the bungee cords must be 9 mm. The minimum diameter of the polyester rope with a double braid must be 10 mm.

2. *Resistance of the eyeleted borders*

   The resistance of the eyeleted borders over connecting forces must be justified by experiment. It must be documented by a laboratory test minute no older than five years.

   The samples submitted for testing shall have been produced by the production unit concerned.

   The spacing of the eyelets must cover their range of use. The minimum number of samples is three. Each sample must have at least three eyelets. In cases the stability of the test pieces is uncertain, it is recommended to increase the number of eyelets, with the same spacing.

   The experimental ultimate resistance to consider is the smallest of the maximal breaking loads given by the load-displacement curves. Relatively to the breaking load, the safety factor to be considered is 2.5.

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 [FM04, Bub97]. 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 weft 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 [FM04].

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 not and
- upon the magnitude of the tangential force.

Membrane corners of flexible edges

Corners of flexible edges are created by 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 under pretension which might lead to an overloading of the membrane, see Figure 8-13. 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] and numerous examples can be found in [Lor15].

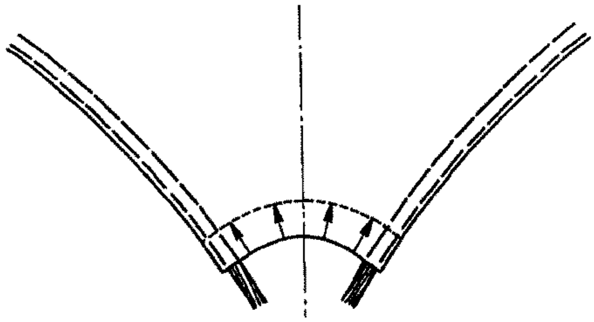


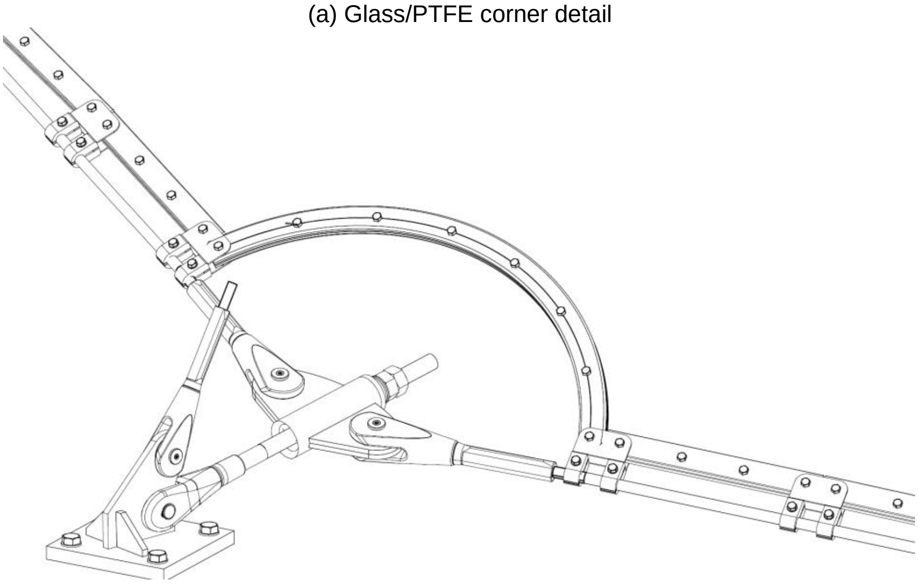
Figure 8-13 Gliding of the membrane in the corner of flexible edges due to tangential forces according to [Bub97]

Some typical solutions for membrane corners of flexible edges are exemplary presented in Figure 8-14. Of course, several other solutions are possible as well, see [FM04, Seid09, Bub97].

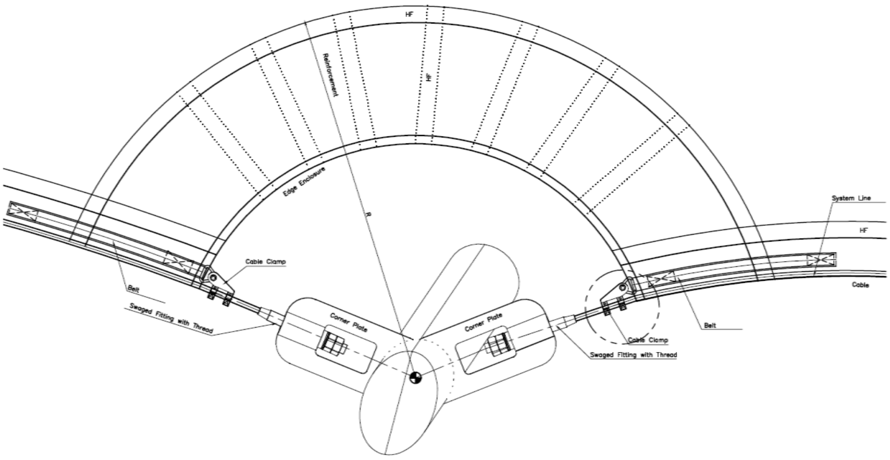
Membrane corners of rigid edges

Membrane corners of rigid edges should be reinforced by a double layer of membrane. In some cases the final part of the corner should be cut out (curved cut). It has to be taken into account that 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, expensive and for this reason not common solution for an obtuse-angled corner with tensioning elements is presented in figure 8-15.

(a) Glass/PTFE corner detail



(b) PES/PVC cut out detail



(c) Corner fitting at continuous cable connected to main suspension cable

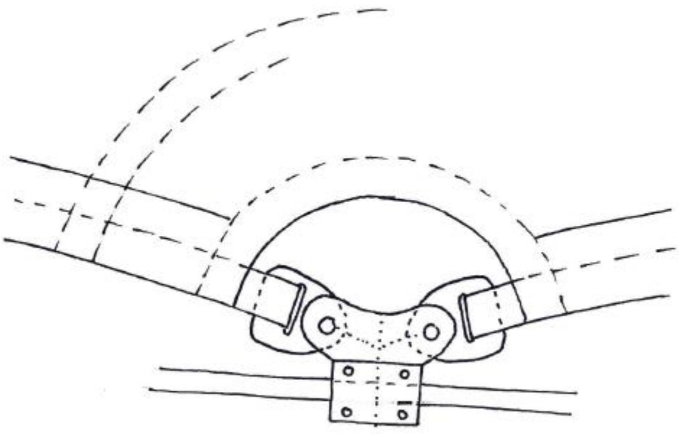
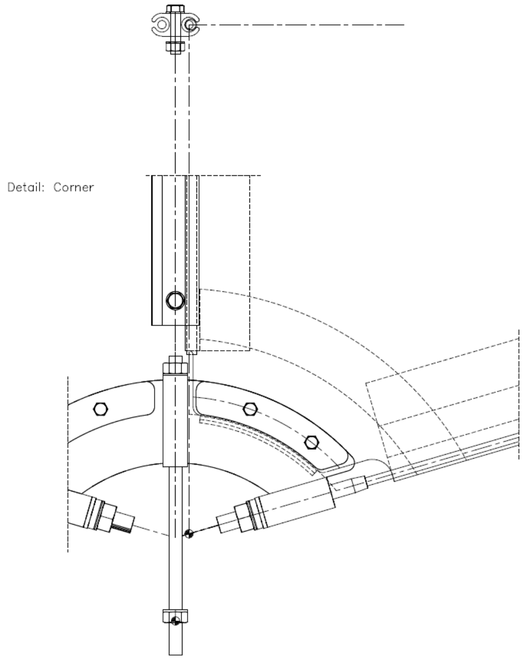


Figure 8-14 Typical exemplary membrane corners of flexible edges [(a) and (b): © formTL, (c): © M. Nieger]

(a) Glass/Silicone tip- and cut-out detail



(b) Obtuse-angled corner with tensioning elements of a rigid membrane edge

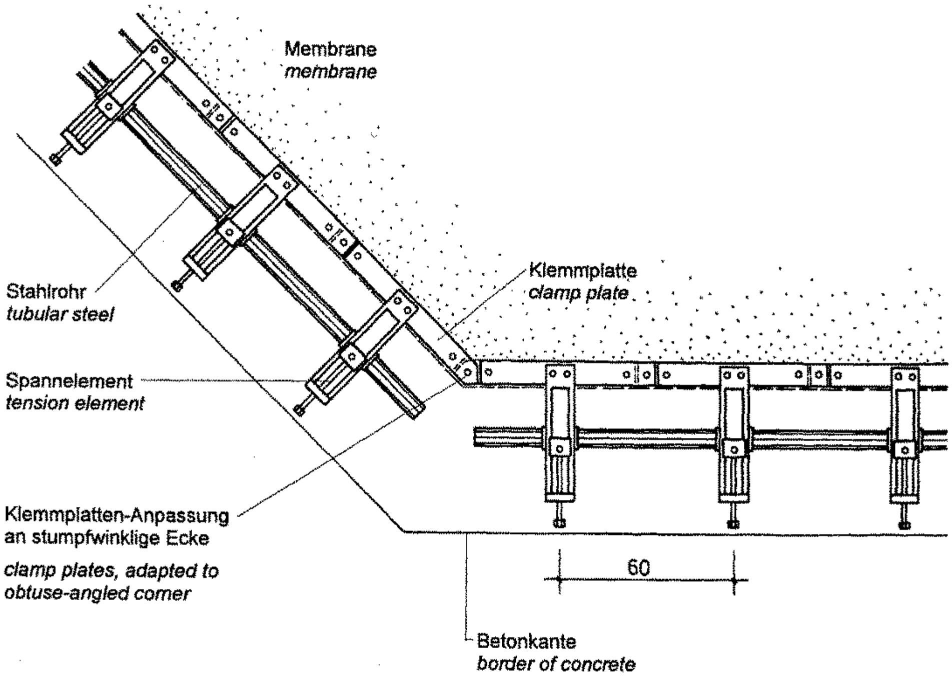


Figure 8-15 Exemplary rigid membrane edges [(a): © formTL, (b): Bub97]

Eurocode Outlook No. 51

(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. In some cases it might be necessary to determine the load-bearing capacity of the whole membrane detail 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. Further explanations are given in [Bub97].

An exemplary flexible valley detail is shown in Figure 8-16.

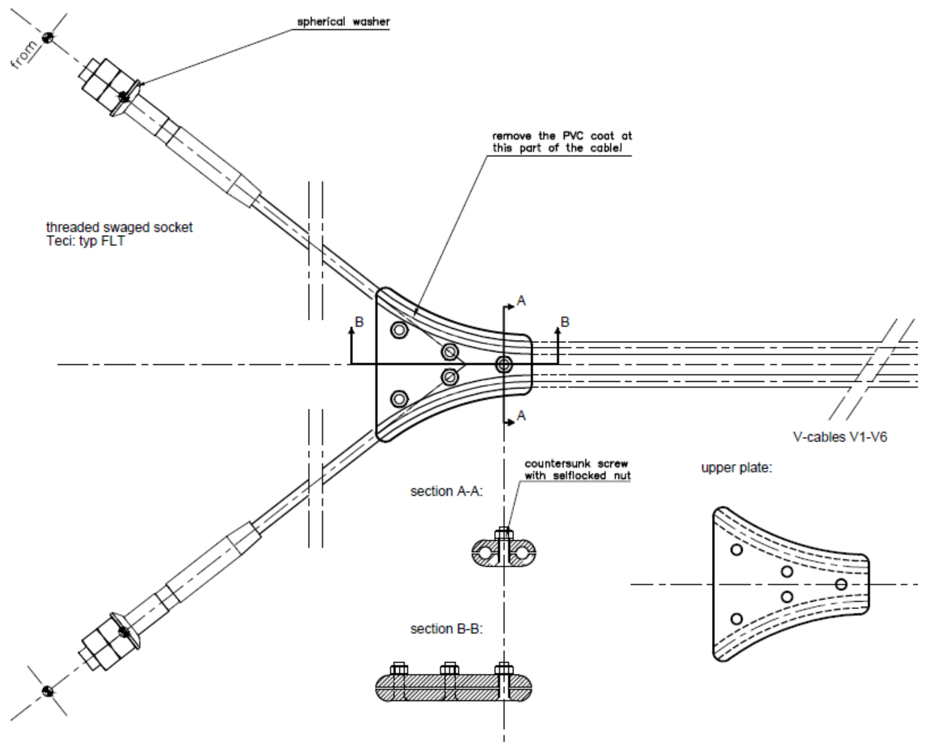


Figure 8-16 Exemplary flexible valley cable splitting detail [© formTL ingenieure für tragwerk und leichtbau GmbH]

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 [FM04].

Further explanations and examples are given in [FM04, Seid09, Bub97, StSc15].

Outer boundary points can also be called high or low point in membrane structures. Their definition depends on the supporting position and height (for example a classical 4-point-membrane has two high and two low points).

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 [S36] 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 [GCL04] have been reviewed and improved. In the following these improved execution rules are presented.

9.2 Cutting pattern determination, workshop drawings

Cutting patterns have significant influence on the structural behaviour, see chapter 3.1. Thus, 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:

g) All hardware components including information on the materials to be used and their surface treatment, the connection elements and their positioning and fastening.

h) Dimensions that have to be checked for conformity with the supporting framework drawings and the cutting patterns prior to release.

i) 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 [S17] 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.

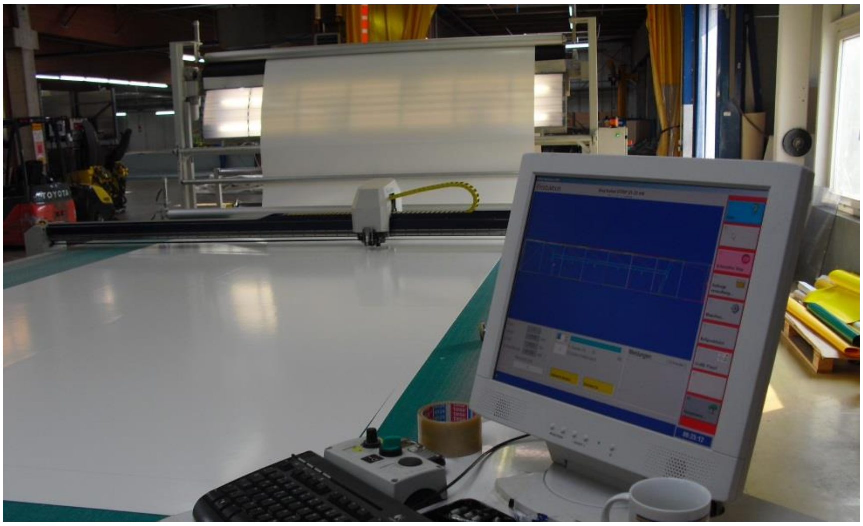


Figure 9-1 Automatically cutting of membrane material via electronic data files [© CENO Membrane Technology GmbH]

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 uniaxial tension tests 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.

The seam strength increases with increasing seam widths up to an optimized seam width where no further seam strength is achieved, see Figure 9-3. By performing seam strength tests under consideration of different welding parameters etc., an optimized seam width can be determined.

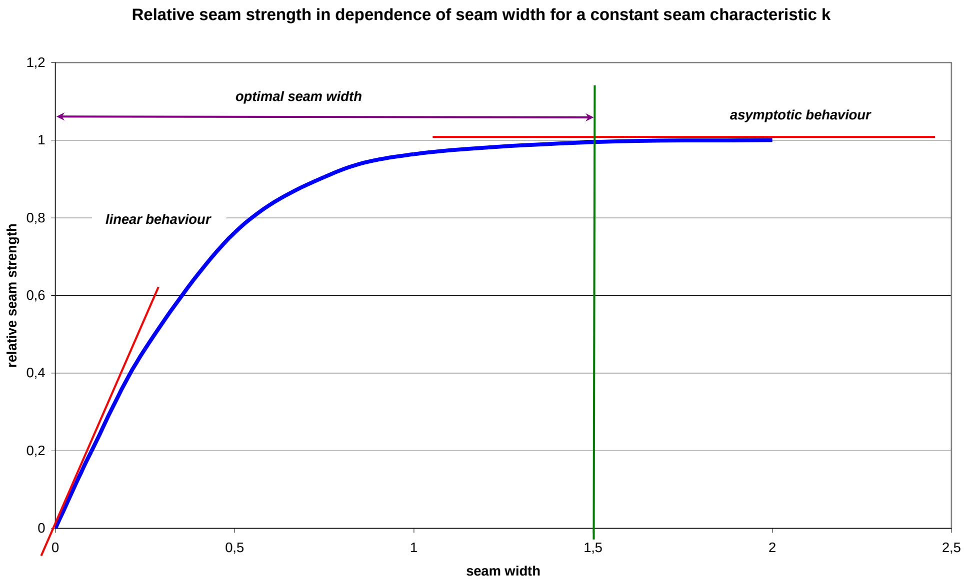


Figure 9-3 Optimum seam width, seam strength is increasing up to a maximum value, afterwards the strength does not increase any more [© DEKRA/Labor Blum]

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 and /or 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 glass/PTFE 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 fibres 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). These films can also be used to fix damages in the surface of PTFE-coated fabrics.

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 fibre 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 facade 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

Tensile membrane structures made from technical textiles or foils reflect the requirements of modern architecture in a particular manner. They are increasingly employed in the build environment because of their architectural attractivity due to spatial curvature and great variety of forms, sustainability, effectivity due to uniform utilization of the cross section etc. Due to their low self weight large column-free spans are easy to realize. Actually, the scope of structural skins is widened today and membranes are increasingly used – also with exceptional low curvature compared to traditional membrane structure design – in performance enhancing facades, roof structures or formwork. Their two dimensional measure can beneficially be combined for instance with solar shading and/or solar energy harvesting. The increasing relevance of membrane structures and the industry standing behind requires a comprehensive standardization. This is currently missing in Europe despite of a considerable amount of scientific knowledge of the structural behaviour and decades of experience with building membrane structures in numerous varieties.

The process of developing a new European standard – initiated by the TensiNet Association – was launched by CEN aiming at a future Technical Specification in a first step and should finally result in a new Eurocode part dealing with the structural design of membrane structures. The present report prepared by CEN/TC 250/WG 5 “Membrane Structures” serves as a pre-normative document and provides background information for the development of harmonized European design rules.

The report gives a state of the art overview on structural design rules across Europe by means of Code Reviews on existing national standards or recommendations. These reviews together with the latest scientific knowledge are the fundament for the harmonization work which has already begun in CEN/TC 250/ WG5 and will be carried on in the coming years together with the national mirror committees. The report reflects on how far this mission has already been conducted and it points out where further efforts are needed. It also documents current discussions in CEN/TC 250/WG 5 on specific apsects of the structural design basing on the design concept of the existing Eurocode surrounding. Eurocode Outlooks present the possible structure of the future code and numerous draft design rules for those topics where discussions are on an advanced stage. The content of the report covers the full range of aspects of the future code. Furthermore, concrete information on important items of the design of structural membranes together with background information on underlying test methods is provided. The establishment of harmonized design rules requires the simultaneous establishment of harmonized test methods which is performed by CEN/TC 248/WG 4. The present report merges these single aspects and therefore is a strong fundament for the upcoming standardization work.

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Annex A

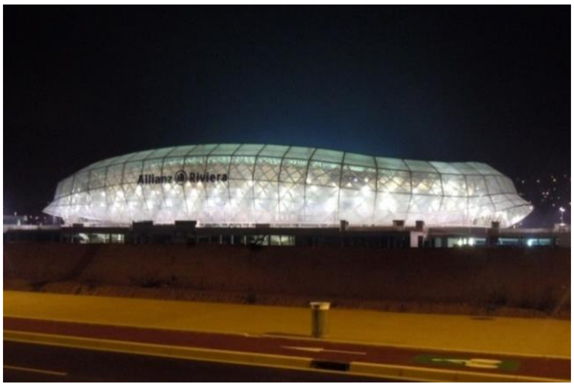
Reference tensile surface projects recently built in Europe


[© Canobbio]

Segece / Carrefour Property

Large inflated cushions for shopping mall. A 150m long and 12m wide textile roof cushion built with multilayer fabric. Two intermediate layers serve to reduce the air movement inside.
Another 13 cushions are located outside the building near the main entrance.

Location address: Claira (Perpignan), **France**
Year of construction: 2012
Client: Segece / Carrefour Property
Architects: DGLa Sud / Abaca, Montpellier
Engineering design: Abaca - Nicolas Pauli, Montpellier, France
Engineering WorkShop drawings: Asteo, France
Manufacturing: Canobbio SpA, Italy
Area: total 4200m^2
Fabric: PVC, ECTFE, Silicone
Type: Extension of shopping mall


[© IASO, S.A.]

Stade Allianz Riviera à Nice

The project includes a 35000 seat multi-purpose stadium, the National Museum of Sport, 29000m^2 of fully integrated retail space, an underground car park with 1300 spaces and landscaped grounds covering 2 hectares. The stadium is clad in a three-dimensional mixed wood and metal structure covered with PVC and ETFE canvas and a photovoltaic system.
This is a flagship project for sustainable development and technical performance: mass use of wood, geothermal energy for producing hot and cold air, natural ventilation, water recovery for watering the lawn and supplying the toilets, and implementation of a photovoltaic power system with a surface area of 8500m^2, making this an eco-positive stadium.

Location address: Nice, **France**
Year of construction: 2013
Client: Nice Eco Stadium
Promotor: ADIM Côte d'Azur
Architect: Wilmotte & Associés SA
Construction: Vinci Construction France
Membrane Précontraint® 1202 S2, Serge Ferrari: 12000m^2 for the roof + 1600m^2
Membrane fabrication & installation: ACS Production
General and environmental engineering: Egis
ETFE facade engineering, manufacturing and installation: IASO, S.A.


[© Groupe Alto]

Morocco Contemporary Exhibition Temporary Hall

A seemingly anachronic 500m^2 removable tensile exhibition Berber hall entirely designed and mounted within less than 2 months.

Main challenges where:

- Form finding with 8 randomly distributed inner masts reaching 9m high and exhibiting dramatic slopes and valleys;
- Settlement on a parking concrete slab with no anchorage possibility against wind uplift;
- Fixation of an outer custom-made dismountable skin made of camel and goat canvas strips;
- Complete parametric design with a merged Rhino & Grasshoper & Kangaroo application.

Location address: Paris, **France**
Year of construction: 2014
Client: Arabic World Institute, Paris
Architects: KILO Architectures
Structural Engineers, design, development, erection survey: Groupe Alto, Paris
Main contractor: Normandie Structures, Etrépagny
Supplier of the PS/PVC membrane: Serge Ferrari, La Tour du Pin
Surface project: 500m²
Total cost: €400.000 (excl. VAT)


[© Normandie Stuctures]

Three court covered tennis hall

Tensile architecture with slanted arches over the roof and facades, giving a non-standard vision from outside as well as from inside.

To be noticed:

- Huge 8 x 3,5m light sliding doors manually openable by a single operator;
- Mix of plain and open mesh fabrics;
- Water drainage entirely integrated in steel framework as well as all eyelet and rope edges tensioning.

Location address: Mourenx, **France**
Year of construction: 2012
Client: Mourenx Town Hall
Architect: Gilles Bouchez, Paris
Structural Engineers, design and development: Groupe Alto, Paris
Steel frame supplier: Nestadour, Mourenx
PES/PVC membrane supplier: Normandie Structures, Etrépagny
Surface project: 2.500m² (Club-house included)
Total cost: M€1.300 (excl. VAT)

[© Groupe Alto]

Covered abbey cloister

A real amazing and successful architectural integration between a patrimonial XVIIIth century abbey courtyard and its transparent coverture due to merely 9 air inflated ETFE cushions on a 550m^2 area.

Meeting with innovation:

- three foils cushions with variable silk prints to match with non-equally distributed sun exposition;
- integrated air inlet and monitoring into the stainless steel mono-tubular framework;
- use of high grade Duplex stainless steel (450MPa yield) so as to cope with a 28m diagonal free span;
- four bended crossing arches giving a medieval signage to this original roofing yet far ahead from the four sloped planes of a traditional pyramidal greenhouse.

Location address: Les Sables d'Olonne, **France**
Year of construction: 2013
Client: Sables d'Olonne Town Hall
Architects: SABA Architectes
Structural Engineers: Groupe Alto, Paris Main Contractor: AROC, La Rochelle
Supplier of the membrane: IASO, Llerida
Surface project: 550m²
Total cost: k€9.000 (excl. VAT)

[© Groupe Alto]

Skatepark canopy Jules Noël

Truly original tensile canopy supported by only 5 Jawerth-type beams of 28m span. Thus resulting in an inner vision of a single 1200m^2 continuous surface, free of any support. Complete 316L grade of stainless steel for the cable beams.

Location address: Paris, **France**
Year of construction: 2008
Client: Paris Town Hall, Sports and Youth Direction Designers: Groupe Alto (structural Engineers, design and development), Manuel Guislain (architecte)
Main contractor: Couverdure, Paris
Surface project: 1.300m²
Total cost: k€650 (excl. VAT)


[© formTL]

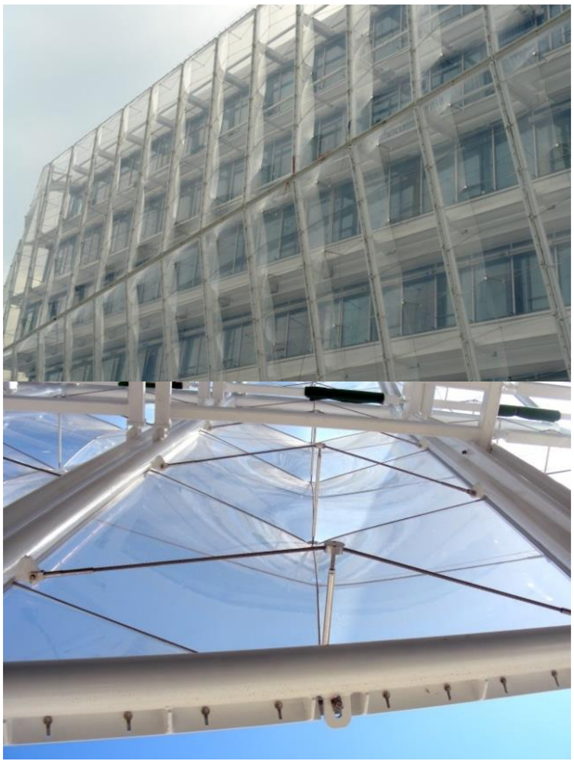
Parkbad Velbert

In the course of local cost-cutting measures the old indoor swimming pool was closed and the existing open air bath got a membrane roof and became an all-seasons bath.

The new roof of theall seasons bath consists of two mechanically prestressed membranes of 997 und 861m² and nine shaping cone tops which are pretensioned against the 53° inclined pylon.

The 2-layer membrane roof with 240mm PES thermal insulation material has a U-value of 0,16W/m²K.

Location address: Velbert, **Germany**
Year of construction: 2002
General design contractor: Dr. Krieger
Design membrane roof: IPL
Size: 2.630m²
Material: outer membrane: PES/PVC Type IV with PVDF-finish; Ferrari Précontraint 1302 product line 8000; B1 according DIN 4102
inner membrane: PES/PVC Type II with PVDF- finish; Ferrari Précontraint 1002 product line 8000; B1 according DIN 4102


[© formTL]

Foil facade Unilever Building

Unilever has moved its Headquarter for Germany, Austria and Switzerland to Hamburg's HafenCity.

The office building fulfills the Gold Standard for sustainable buildings. The polygonal transparent curtain wall facade can already be seen from far away. It prevents the building from unwanted solar energy. The, in this way, protected shading louvers can be used even with strong wind and sunshine.

The curtain-wall facade consists of 224 panels. Each single panel forms an independent unit. Basis is a rigid frame of hollow sections which is covered by a cable-supported ETFE-foil. In total 6.200m² ETFE-film and 10km inox-cables are installed.

Location address: Hamburg, **Germany**
Year of construction: 2009
Owner and General Contractor: Hochtief Projektentwicklung
Architect: Behnisch Architekten
Design, structural analysis curtain wall facade and foil patterning: formTL
Foil manufacturing: Vector Foiltec
Material: ETFE foil, 250µm and 300µm


[© CENO Membrane Technology GmbH]

Tropical Islands (former CargoLifter Airship Hangar)

The worldwide biggest hangar with 5.2 million m³ has modified into an indoor leisure park with tropical plants.

Size: 360m x 220m x 107m; 20,000m² of the altogether 40,000m² of the 2x2-layer membrane covering was replaced by 3-layer ETFE cushions with an U-value of 2.0W/m²K.
The formTL suggestion has offered 4 advantages: The solution is economic, compatible with the existing steel structure, realisable within short time, and: the inside development could continue weather protected also in the construction phase.
The advantage of the foil covering is the transmission of UV A and UV B radiation and high light transmission (>90%). This has a favourable effect on the plant growth.
Cushion construction: 200µm, 100µm, 20µm, on both sides with a forming cable net with 14 and 16mm aluminium coated steel cables.

Location address: Briesen Brand, **Germany**
Year of completion: 2005
General design contractor: CL Map
Manufacturing of the cushions: Ceno Tec, Greven
Structural design and workshop drawings of the cushion Facade: formTL

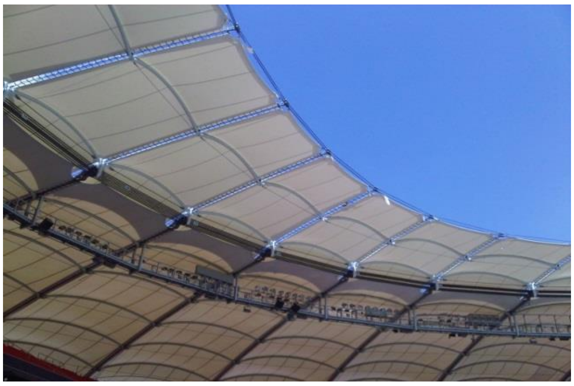

[© formTL]

Allianz Arena Munich

The by coloured light illuminated ETFE foil cushions for facade and roof are on a rhomboid steel substructure.

Size of the facade and roof: 60,000m² of foil cushions, 39km or 5664 steel beams, 2784 cushions
Cushion material: ETFE 200/200µm and 250/250µm, transparent inside, white outside in the facade
Roof completely transparent

Location address: Munich, **Germany**
Year of construction: 2002-04
Architect: Herzog & de Meuron
Structural design primary steel: SSP
Concrete structure: Arup
Facade design: R. Fuchs
Façade structure and cushions: structural analysis + calculation of situations under construction: IPL


[© schlaich bergermann partner]

Mercedes-Benz Arena
(former Gottlieb Daimler Stadium)

The Gottlieb-Daimler-Stadium was modernized for the track and field athletic world championship 1993. Within the extremely short planning and construction period (2 years), during continuous soccer league operations, Europe's largest membrane structure was built. It consists of an inner tension ring that is connected to the roof's two outer compression rings with 40 radial cables. The cables and consequently the roof consistently span 58m. The undulating roof form was created out of the intended expansion alternatives of the stadium. A PVC-coated polyester-membrane covers the roof. The covers double curvature is maintained by a secondary structure. The spoked-wheel-type construction principle chosen for this structure proved to be exceptionally economical especially with the existing foundation problems.
The roof was expanded inwards to cover the new seats, which lie more closely to the playing field. Flying masts were affixed to the existing ring cable nodes and braced through radial cables to the existing upper compression ring. Along with the new ring cable the flying masts mount the cable girders of the roof expansion.

Location address: Stuttgart, **Germany**
Completed: 1993; 2011
Owner: Landeshauptstadt Stuttgart
Conceptual design, construction design, site supervision, erection analysis, technical spots check: schlaich bergermann und partner
Architect: Planungsgemeinschaft Neckarstadion; schlaich bergermann und partner; Weidleplan; Siegel & Partner; asp architekten, Stuttgart
Type of structure: membrane roof on prestressed cable structure
Membrane / roof area: 34,000m² + 6,000m² roof expansion
Roof width: 58m; Max. girder length: 48m
Membrane PES-PVC
Steel: 3,000t
Steel cables and cast steel elements: 420t
Seats: 55,000

[© M. d´Ottavio]

[© Canobbio]

Turin University

The new headquarters of the faculty of law of the Turin University is located along the river Dora in the site of the ex Italgas area. Synergy among firms and design studios has been able to reinterpret the distribution of the pavilions: connections and passages have been added with the use of a highly characterizing element as the unique PTFE roof and the wavy facade.

The general concept of the architectural design has been developed by Architect Sir Norman Foster together with a pool of architects and engineers.

Location address: University Luigi Einaudi Turin, **Italy**
Year of construction: 2012
Main Contractor: Sinergie, Italy
Membrane Design: formTL, Germany
Area: 16.000m^2
Fabric: PTFE fiberglass
Type: membrane roof


[© Canobbio]

Verona Forum

A multipurpose covering has been built for the Crowne Plaza Hotel in Verona. The ETFE cushions are 4 layer cushions. The upper and lower layer have a thickness of 250µm each. The inner layers have a 100µm thickness. The nominal pressure in the cushion system is 300Pa. In winter time this will be increased to 600Pa and in case of reasonable snow fall up to 800Pa. A minimized attachment detail has been developed for the ETFE cushions. Small steel plates are placed perpendicular to the surface to which on either side the cushion is attached with a small extrusion profile. Integrated in this connection detail is a soft gutter that is guiding condensation towards the lower ends where it is guided in the drainage system. The structure consists of 7 transversal timber arches, which are connected to concrete foundations. The arches have different shape to generate the volume of a soft curved structure. At one side of the structure there is a cubical technical building.

Location address: Verona, **Italy**
Year of construction: 2012
Client: Verona Forum
Consulting engineer for Membrane: FormTL
Multidisciplinary Engineering: Canobbio SpA, Politecnico di Milano
Architects: Mario Bellini, Italy
Area: 650m^2
Fabric: ETFE foil
Type: Multipurpose covering


[© formTL]

Hagar Qim & Mnajdra

Two big roofs were built to protect the 5000 years old megalithic ruins of the Hagar Qim und Mnajdra temples from environmental influences. Three important preconditions had to be taken into account: the roofs needed to be removable without visible effects, their design had to follow the astronomical alignment of the temples and they should offer an effective weather protection. The structure of the roofs consists of two centre positioned, slightly inclined steel arches. Between the arches and the border cables a cable net with membrane is spanned. The biaxial cable nets allow realising the arches without any additional stabilization cables.

Location address: **Malta**
Year of construction: 2009
Client: Department of Contracts
Design: Arch. W. Hunziker and Arch. M. Kiefer (architectonic), formTL (membrane structure and details)
Area: 4.820m^2
Fabric: PTFE Fiberglass
Type: membrane roof for archeological area

[© Tentech]

Condensate Loading Tent, Gas Storage Bergermeer

Gas Storage Bergermeer is an independent gas storage facility located near Alkmaar in the Netherlands. It is developed by TAQA Energy and provides Northwest Europe of seasonal storage capacity.

The Loading Tent at Bergermeer is located near the entrance of the facility. Its function is twofold: it protects the underlying Condensate Loading Station and forms the architectural frontline of the storage area.

The architectural design was made by Jinx Architects together with Tentech. It is a 650m² Ferrari 1502 fabric with a TX30 coating. The fabric is supported by two main masts and four corner masts. Guy cables varying from Ø24mm to Ø40mm are used on all 6 masts. The main masts have a height of 18m. Due to the location of the structure above a gas condensate station, the risk of a fire or an explosion were taken into account and alternate load paths are incorporated in the design.

Location address: Alkmaar, **Netherlands**
Year of construction: 2014-2015
Client: TAQA Energy BV
Engineering: Tentech
Engineering design: 2009-2014
Architecture: Jinx architects & Tentech
Contractor membrane: Buitink Technology BV
Dimension: 650m²

[© Joaquim Rabassa]

Pneumatic wall with zero footprint

The “ORONA Ideo Innovation City” is situated in Hernani (Spain). The structure consists of a main front wall of about 100m long and a height from 0m to 11m and to 0m again. At the rear there is a similar wall (with less height) which forms a polyline and a small roof of about 80m². The structure is inflated at a pressure of 800Pa. The central part of the main wall (11m height) is the most challenging element. The section of this wall shows a straight line at windward side and an arch at the leeward side, in this way withstanding much better the wind forces. Details at the top and bottom of the wall allowed certain movements of the whole and prevented others, adapting the reactions to the building resistance.

Location address: Hernani, **Spain**
Client: ORONA S.Coop
Year of construction: 2014 (removable solution)
Engineering: R. Sastre, Àrea Cúbica, LKS Ingeniería SC
Engineering design: 2013
Architect: Xavier Barrutieta, LKS Ingeniería SC
Dimensions: 5160m² textile
Total Budget: 350.000€ VAT excl.


[© IASO, SA]

Expo Zaragoza 2008 Textile Shade Covers

Shade cover over an area of 400m of length and 24m of width in the Expo street

Location address: Zaragoza, **Spain**
Year of completion: 2008
Client: EXPO ZARAGOZA 2008
Architect: Félix Escrig / José Sánchez
Graphic Design: Isidro Ferrer
Structural engineer: IASO, S.A.
Design of patterning: IASO, S.A.
Erection planning: IASO, S.A.
Concept and Structural engineer: Félix Escrig / José Sánchez
Steel erection: IASO, S.A.
Wire ropes: REDAELLI
Erection of wire rope: IASO, S.A.
Membrane fabrication: IASO, S.A.
Membrane erection: IASO, S.A.
Roofed area: 5.000m^2
Membrane material type: PES/PVC Open mesh


[© IASO, SA]

Santa Lucia Hospital

'The hospital's south facade is clad with 9,000m² of Soltis FT beige 381-3123. Soltis FT 381 lines the main artery through the hospital, ensuring a similarly natural transition between the building's exterior and its interior. The Serge Ferrari openwork material is installed on an apparently anarchic metal frame, which in fact embodies an inverted pyramid structure. This unique aspect is achieved by a perfectly designed assembly of more than 200 tonnes of tubes and plates, to which the Soltis FT 381 is fixed. Light and flexible, the material hugs the intricate details of the structure without overloading it.[http://en.sergeferrari.com]

Location address: Cartagena, **Spain**
Year of completion: 2012
Client: MURCIA SALUD
Architect: Francesc Pernas. Casa Consultors i Arquitectes, S.L.
Structural engineer: IASO, S.A.
Design of patterning: ASO, S.A.
Erection planning: IASO, S.A
Concept and Structural engineer: IASO, S.A.
Steel erection: HORFASA
Membrane fabrication: IASO, S.A.
Membrane erection: IASO, S.A.
Roofed Area: 9.000m²
Membrane material type: PES/PVC Open mesh


[© IASO, SA]

New Iguzzini Headquarters

The IGUZZINI headquarters is an impressive textile facade project. The 1600m^2 shell designed by MIAS Architects aims at providing shade in the inside of the building. The translucency and different colours of the material make the specificity of the cover that change depending on the angle you look at it.

Location address: Sant Cugat del Vallès, **Spain**
Year of completion: 2012
Client: Iguzzini Illuminazione Iberica SA
Architect: Miàs Arquitectes
General Contractor: OHL
Structural engineer: LANIK, S.A.
Design of patterning: IASO, S.A.
Erection planning: IASO, S.A.
Concept and Structural engineer: LANIK, S.A.
Steel erection: LANIK, S.A.
Membrane fabrication: IASO, S.A.
Membrane erection: IASO, S.A.
Roofed area: 1600m^2
Membrane material type: PES/PVC Open mesh


[© IASO, SA]

Imaginalia Shopping Centre

Double arch structure that covers the Food Court of the shopping centre. The transparent ETFE film, placed on metallic arches, transmits a greater brightness to the interior of the building.

Location address: Albacete, **Spain**
Year f completion: 2005
Client: PROCOMSA
Architect: L35 Architecs
Project management: Bovis Lend Lease
Structural engineer: IASO, S.A.
Design of patterning: IASO, S.A.
Erection planning: IASO, S.A.
Concept and Structural engineer: TYPSA
Steel Erection: IASO, S.A.
Wire ropes: PFEIFER
Erection of wire rope: IASO, S.A.
Membrane fabrication: IASO, S.A.
Membrane erection: IASO, S.A.
Roofed area: 2.000m^2
Membrane material type: PES/PVC fabric, ETFE foil (transparent areas)


[© formTL]

Splash & Spa

The aim of the project was to build a spectacular water park dedicated to leisure, action, relaxation and well-being through water activities and Spa treatments.
3 pneumatic cupolas cover the swimming pools and wellness center with a 3 layer system.
The good climatic control is assured by reducing the heat transmission and keeping the material translucent. The client has charged Airlight Engineering to investigate a special Low Emissivity material to be used as inner layer in combination with PTFE and Silicon Glass fabric in order to achieve the highest emissivity value and the maximum transparency in the visible range. The result obtained was U = 0,77W/m^{2}K.

Location address: Rivera Monteceneri, **Switzerland**
Year of construction: 2013
Client: Splash & Spa
General Contractor: Garzoni SA for Credit Suisse
Engineering: formTL, Radolfzell – Airlight, Biasca
Area: 6.200m^2
Fabric: PTFE-glass outside, Silicone-glass inside, IR film in-between
Typology: Pneumatic


[© Niklaus Spoerri]


[© formTL]

Bus Terminal Aarau

A steel table and a large cushion wrapped by an arbitrary net of steel cables do not only form a bus terminal but a functional art piece in the urban space. A borderless pattern of bubbles has been printed on the blue upper and the transparent lower ETFE-foil. The world's largest inflated cushion has been built very airtight and energy efficient.
Integrated building services: All pipes for roof drainage and air, as well as wiring and control and feedback systems are invisibly integrated into the steel structure. Hence, the roof is clean and at the same time visually complex and readable: Bottommost are the bus lane and the pillars, followed by the cable network and the clear membrane. Behind these are the table structure, the upper blue skin, and finally the upper wire ropes.

Location address: Aarau, **Switzerland**
Year of construction 2012/13
Architect: vehovar & jauslin, Zürich; General design contractor and concrete structure: suisseplan Ingenieure AG Aarau; light design: Atelier Derrer Zürich; wind tunnel: Wacker Ingenieure Birkenfeld, print design Stefan Jauslin + Paolo Monaco
Realisation: Arge Foliendach RUCH AG (CH) + Vector Foiltec,
printing: Reisewitz; air support: Elnic
Cables+Nodes: Top-Line
Structural design, workshop design steel, foil and cables, quality control and site control: formTL
Length /width /height: 41/39/9m
1.070m² covered, 1.810m³ air capacity


[© Architen Landrell]

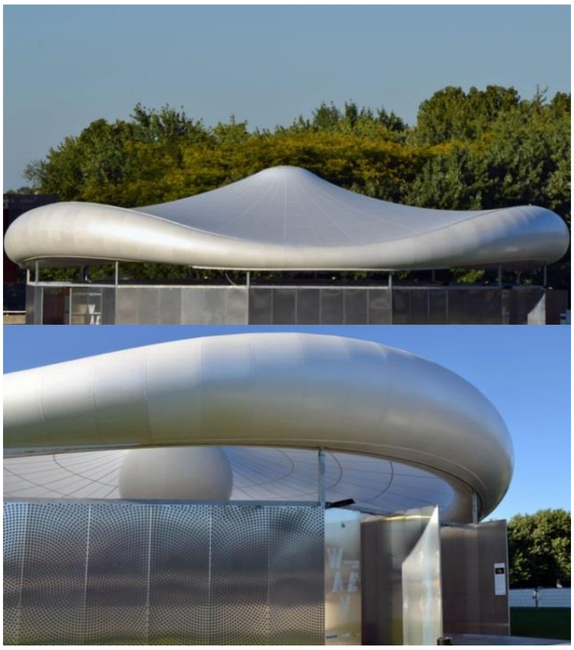
Kingly Court

Designed by MRP Architects for their property owning clients, the intent for the canopy is to provide short term temporary cover for events such as fashion shows within the courtyard.

The brief at Kingly Court was for a stylish structure which would provide the perfect backdrop for events, and yet provide shelter from the changeable British weather. This meant that not only was there a real need to quickly install and remove the canopies at short notice, it was also vital to ensure as much of the canopy and ancillary structural components as possible could be removed to comply with stringent Planning Office requirements.

The stunning structure, made of Gore Tenara, comprises three inverted cones, protecting the courtyard below from the weather.

Location address: Kingly Court, Carnabystreet, London, **United Kingdom**
Material: Tenara
Architects: MRP architects
Contractors: Architen Landrell Associates Ltd.


[© Tentech]

Inno-wave-tion

The roof structure is part of the main pavilion for exposition WAVE, organized by BNP Paribas, starting in Parc de la Villette, Paris, and now traveling through France and the world.

The roof structure has a UFO-like appearance. It consists of a 24m torus-shaped outer ring, a 4m sphere dominating the central area in the pavilion and a roof membrane attached to the outer ring and levitated by the central sphere creating the distinctive design. The structural system works as a combination of a tensile compression ring with Tensairity. The donut spreads the roof membrane and the central sphere's pressure controls its tension. The tension forces of the membrane are transferred into a steel ring inside the torus. A second steel ring transfers the forces to the columns below. The air pressure in the inflated tube is structurally twofold: it does not only support the upper steel ring, it also increases its buckling resistance.

Site: Around the world traveling pavilion
Year of construction: 2014
Engineering: Tentech
Engineering design: 2014
Architecture: Silvain Dubuisson Architecte
Client: BNP Paribas
Contractor: High Point Structures & Buitink Technology
Dimensions: $490 m^2$
Fabric Roof: Ferrari 402
Fabric Sphere & Torus: Ferrari 1202


[© formTL]

Modern Teahouse for the Museum für Angewandte Kunst

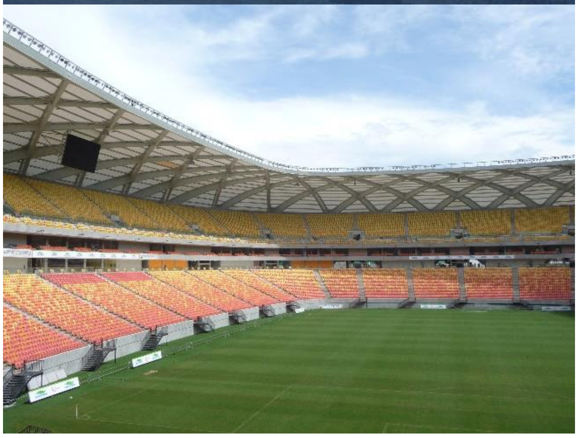
The Teahouse was a present for the city of Frankfurt/Main by Japanese companies. It can be placed in the entrance hall or on a little hill in the garden of the museum. When it is not used, it is waiting packed on a dolly.

The Teahouse got the working title “Peanut”, because of its shape. A bigger cover encloses a smaller inner one. The two are welded airtight and are blown up like an inflatable mattress. Instead of bars both covers are connected with 306 cables which create a golf ball like surface.

When an inner pressure of 1.000Pa is reached, the “Peanut” stands, with 1.500Pa, the “smooth shell” is stable enough to resist a storm.

The size of the contact area and the inner pressure determine significantly the stability.

Site: Mobile
Material: Membrane: Gore Tenara 3T40 (630 gr/m² PTFE-fabric with laminated fluoric foil) and 38% translucency
Architect: Kengo Kuma (J)
Blowers: Nolting
Membrane manufacturing: Canobbio (I)
Construction: 2007
Consulting, design, structural design, tender documents, workshop design membrane: formTL
Weight: 150kg
Dimensions: 9m long, 4,6m wide, 3,4m high



[© CENO Membrane Technology GmbH]

Arena da Amazonia Manaus

The stadium with 43.500 seats consists of a complex steel structure, which is covered with 252 textile roof membrane elements made of glass/PTFE. The designer set out by examining the tropical forms and colors of the region.
The textile roof membrane surface is approx. 31.000m². Due to the complex design of the details approx. 52.000m² material was processed.

Location address: Manaus, **Brasil**
Year of construction: 2013 - 2014
General Contractor: Andrade Gutierrez
Architect: gmp Architekten
Engineering Design: schlaich bergermann und partner
Implementation/Fabrication:
CENO Membrane Technology GmbH
Steel Construction: Martifer Group
Material: glass/PTFE B18039
Covered Area: ~31.000m²

[© CENO Membrane Technology GmbH]

"Residenzschloss" of Dresden

The "Kleiner Schlosshof" is the central meeting place within the castle complex in Dresden. The load-bearing structure is a double-vaulted lattice shell of welded quadratic steel profile construction. Some of these profiles are also used to supply the cushions with compressed air.
The lattice shell – which hovers over 30m above the courtyard – was filled one-by-one with a total of 265 ETFE cushions. Both the load-bearing structure and the cushions take the form of a rhombus with 4.10 x 2.80m diagonals.

Location address: Dresden, **Germany**
Year of construction: 2008
Client: Staatsbetrieb Sächs. Immobilien- und Baumanagement
Architect: Peter Kulka Architektur Dresden GmbH
Implementation/Fabrication: CENO Membrane Technology GmbH
Structural Design: form TL GmbH
Material: ETFE-foil 150µm / 250µm
Covered Area: 1.420m²

[© CENO Membrane Technology GmbH]

Botanical Garden Aarhus

The transparent ETFE dome at the botanical gardens in Aarhus with an oval plan view supplements the existing glass house from 1969.
A particularity of this ETFE structure is that it offers greatest possible volume with smallest possible surface and thereby a high energy efficiency.
In longitudinal and transverse axis the structure consists of 10 steel arches which form a net of different sized squares. Mainly the covering consists of two-layer cushions which are fixed with biaxial bended profiles. On the south side the cushions have been designed with three layers, two of them are printed. The position of the two printed layers to each other can be varied by changing the pressure. This reduces or increases the translucency of the ETFE cushions and thereby the light and heat input into the building.

Location address: Aarhus, **Denmark**
Year of construction: 2012
Client: University Aarhus
Architect: C.F. Moller
Engineering Design: Søren Jensen
Implementation/Fabrication:
CENO Membrane Technology GmbH
Design ETFE-cushions: form TL GmbH
Material: ETFE-foil 150µm / 250µm
Covered/Surface area: 1.145m² / 1.800m²


[© CENO Membrane Technology GmbH]

Audi "Sphere"

The Audi "Sphere" was built for Audi's crossover event in Copenhagen 2012.

A spectacular formation of three walkable, interconnected spherical bodies sends a strong signal at the Christiansborg Castle Square in Copenhagen. The three balls are made of a light membrane and embody not only the theme of lightweight but are a walk-in exhibition at the same time. The diameter of the air-inflated balls is ~11,50m.

The assembly and installation is done in two parts, the separation of the balls takes place along an slanting axis in equator nearness.

Location address: Copenhagen, **Denmark**
Year of construction: 2012
Client: Audi
Architect: Schmidhuber und Partner
Implementation/Fabrication:
CENO Membrane Technology GmbH
Material: PES/PVC - outside: silver, inside: white

The authors acknowledge for their contribution:

Stefania Lombardi (Canobbio), Rogier Houtman (Tentech), Ramon Sastre (UPC), Bernd Stimpfle (formTL), Feike Reitsma (IASO), Jean-Christophe Thomas (Université de Nantes), Amy Wilson (Architen), Markus Balz (sbp), Yannick Faurant (ACS-production), Etienne Cailleau (AFNOR), Marc Malinowsky (Groupe Alto), Meike Nieger (Ceno Membrane Technology).

Annex B
Testing methods

B1 Tensile test for fabrics

Tensile tests that aim to determine tensile strength properties of the base material or the seams are basic tests required for almost all projects. The tensile test is specified in European and national standards as EN ISO 1421 [S1] and EN ISO 13934-1 [S10] on European level, particularly in Germany DIN 53354 [S11] (although withdrawn) and the guideline of Deutsches Institut für Bautechnik (DIBt) for acceptance test of coated fabrics and their joints [S12] and on international level ASTM D 5035-95 [S13].

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 depend 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). The dimensions of test specimen for the base material are clearly specified in the EN ISO 1421, EN ISO 13934-1 and DIN 53354 for tests at room temperature and summarized in Table B1-1. The geometrical dimensions of the test specimens for tensile tests of the base material at temperatures ≠ 23 °C, of welding seams and edge details are mostly defined by the different laboratories on the basis of the mentioned standards in dependence of the testing equipment.

Table B1-1 Dimensions of the test specimens and test speeds depending on the kind of specimen and temperature (value in brackets is a possible variation)

Kind of specimen	Temp. [°C]	Gauge length [mm]	Width [mm]	Test speed [mm/min]	Specified in
Base material	23	200 (100)	50	100	EN ISO 1421 EN ISO 13934-1 DIN 53354

The tests have to be performed with a CRE tensile testing machine according to EN ISO 1421. Exemplary, Figure B1-1 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 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 B1-2.

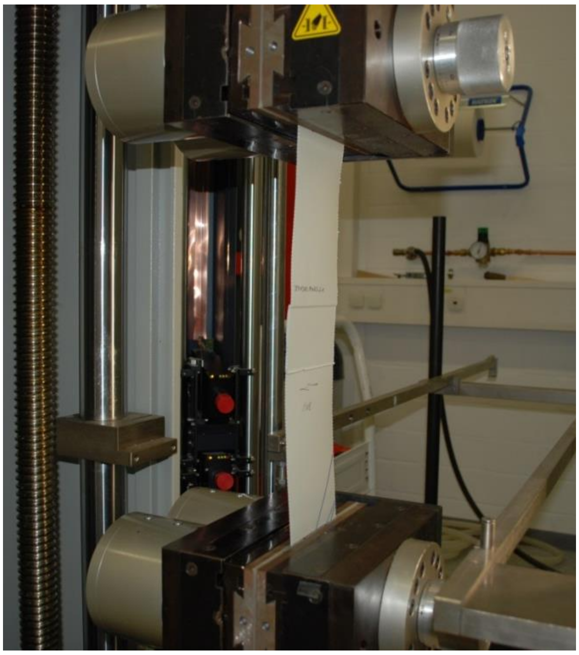


Figure B1-1 Tensile test specimen with welding seam in the testing machine before testing [© ELLF]

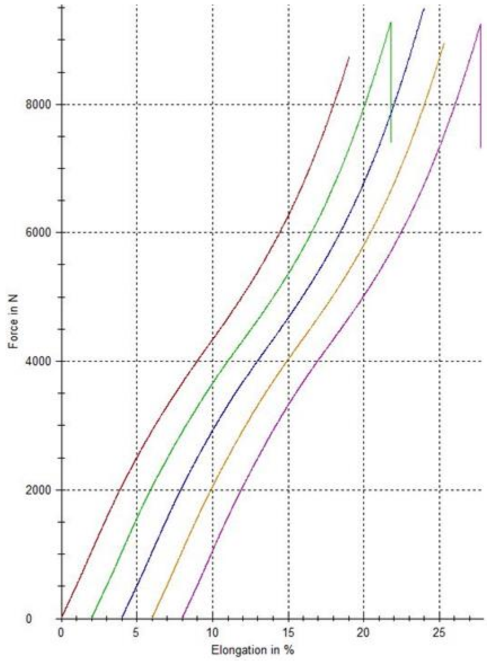


Figure B1-2 Typical results of tensile strength tests [© ELLF]

B2 Crease fold tests for fabrics

B2.1 General

Knowledge about the sensitivity of a specific glass fibre fabric to crease fold may help to define the required carefulness during manufacturing, packaging, transportation and installation. Basically, the determination of the tensile strength after crease fold for glass fibre fabrics is not an essential test procedure for every glass fabric project. Furthermore, the tensile strength after crease fold is not a required material property for the structural design. Hence, crease fold tests are conducted rather infrequently.

In Europe, no harmonized test procedure for the determination of the tensile strength after crease fold exists. Due to this lack, the American standard ASTM D4851-07 [S9] is used beside several procedures developed by testing laboratories, manufcaturers or engieering offices. In the follwing some of these methodes are described.

B2.2 ASTM D4851-07 [S9]

The principle of the 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. The preparation of the specimens and the measuring of the breaking force can 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 in 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 B2-1. 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.*" [S9]

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

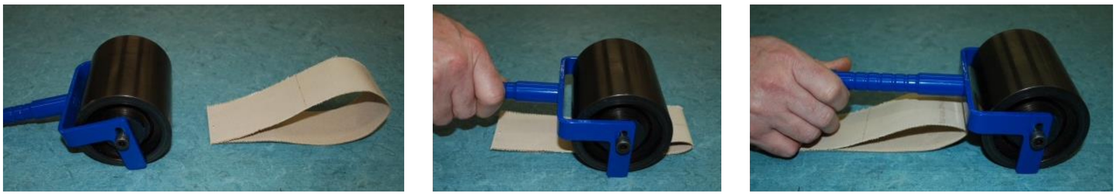


Figure B2-1 Preparation of the looped specimen for the crease fold test acc. to ASTM D4851-07 [© ELLF]

B2.3 Essen method and impact test on loop

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).

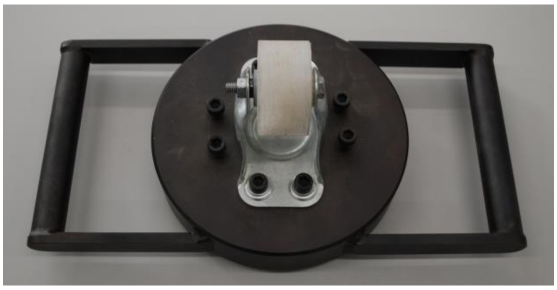
For this reason two other test methods – the Essen method (Essener Verfahren) and an impact test on loop (Schlaufen-Schlag-Prüfung) – were developed at the Essen Laboratory for Lightweight Structures (ELLF) at University of Duisburg-Essen [Hom03], which are described in the following.

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 depending on the tested material, see Figure B2-2.



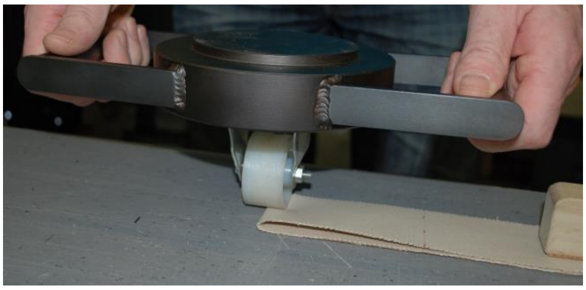


Figure B2-2 Left: loading device for the Essen method for repeated folding and force applications, right: rolling the load device on the looped end [© ELLF]

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 impact test on loop (Schlaufen-Schlag-Prüfung) was developed on the basis of EN 1876-2 [S16]. 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 B2-3. 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 B2-4. 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 B2-3 Left: loading device for the Essen method for repeated folding and force applications, right: rolling the load device on the looped end [© ELLF]

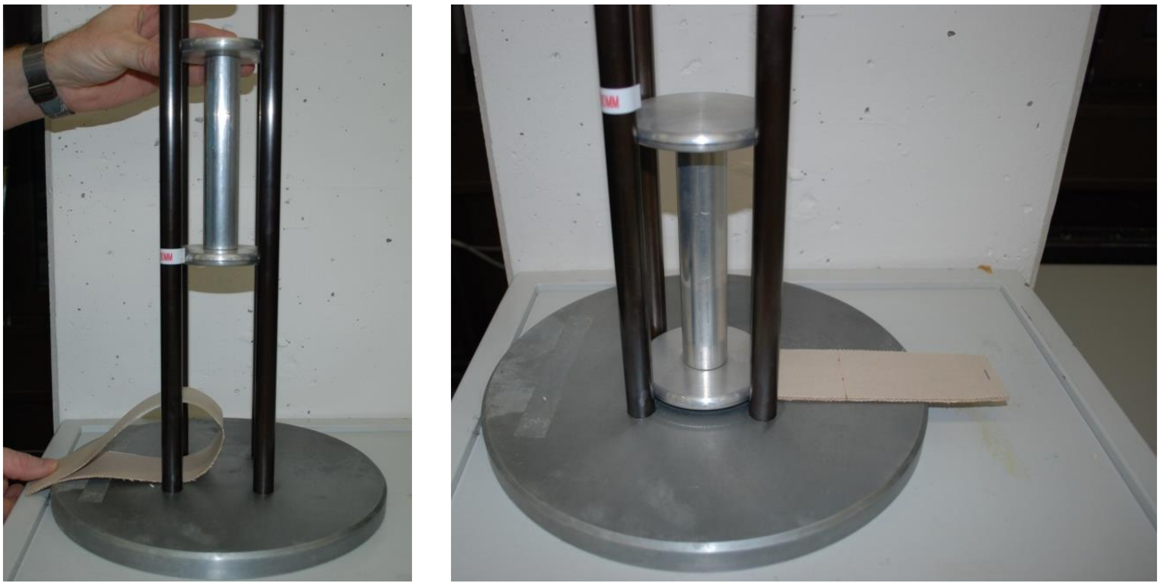


Figure B2-4 Impact test on loop, left: Positioning the specimen in the middle of the centering system, right: the drop weight dropped on the looped end [© ELLF]

B2.4 Folding tests “Running Crease” according to Labor Blum method

This method, see Figures B2-5 and B2-6, has been invented at Labor Blum to simulate severe damages, which have been detected in numerous projects during manufacturing and packing. Comparative tests between damages taken from production and the simulated creases have shown very good compliance.

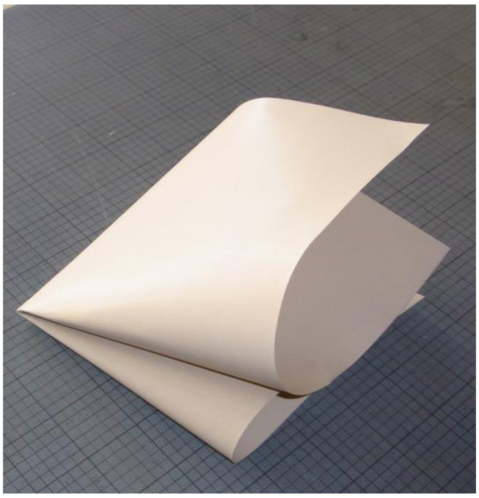


Figure B2-5 Procedure to create a running crease, specimen folded twice [© DEKRA/Labor Blum]

Figure B2-6 Procedure to create a running crease, lower part will be extracted by using a straight edge with a defined diameter [© DEKRA/Labor Blum]

The tests are executed as follows: a piece of fabric is folded in the middle axis parallel to the threads. Then a second fold perpendicular to the first one in the centre of the sample is added. The edges of the folds are not pushed down sharply. Then pulling the inner part from the corner in direction to the outer edge will generate a running crease.

Subsequently strip specimen will be cut with a visible damage in the centre of the specimen. A number of at least 5 specimens per weave direction shall be tested according to tensile test standard EN ISO 1421 [S1] or EN ISO 13934-1 [S10].

Alternatively a wide panel tear test may be executed, see Annex B5.

B2.5 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 conventional tensile tests are performed.

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.

B3 Folding tests for fabrics scheduled to be folded

B3.1 Folding test for materials intended to be used in retractable structures (DIN 53359) – Flex cracking test

The dimension of specimens should be 100 mm in width and 1200 mm in length which is not in accordance with the standard DIN 53359 [S18], but necessary to measure the residual strength after folding according to EN ISO 1421.

The test should be performed at +23°C, +70°C and -10 °C (or even lower temperatures if expected at the location of the structure). Specimens shall be tested in warp, weft and in some cases in diagonal direction, 5 specimens each.

The number of cycles should be chosen at least to the expected number of foldings of the roof structure.

Two different types of folding can be achieved according to DIN 53359. Single folds are achieved by folding the specimens in the lateral direction. Double foldings are done by a longitudinal and a lateral fold, see Figure B3-1 and B3-2.

After folding the specimens are tested according to EN ISO 1421. Parallel neighbouring specimens taken from the same laboratory sample shall be tested without folding to measure the initial strength under the respective temperatures. Also 5 samples shall be tested.

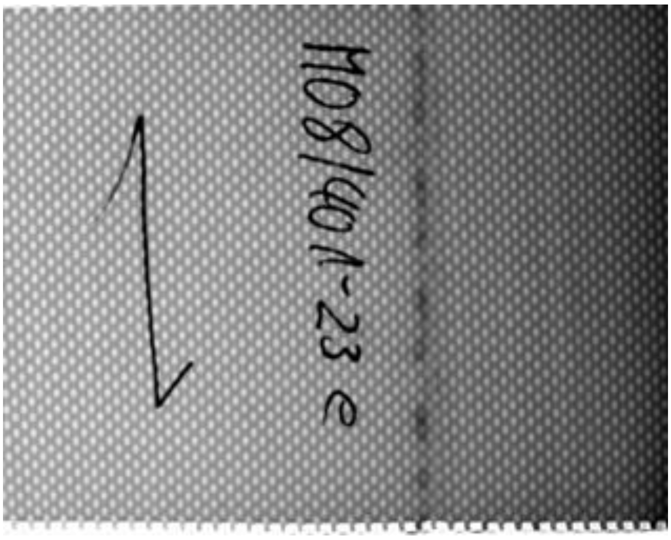
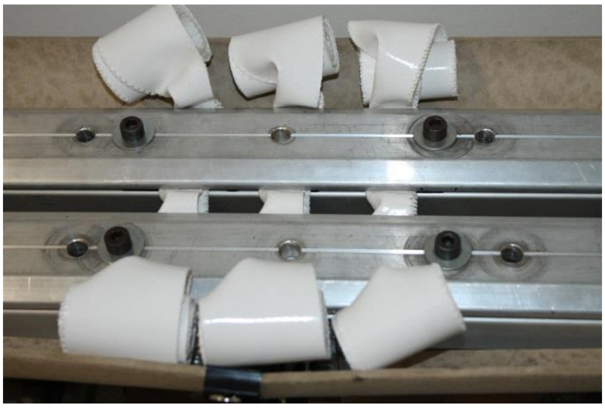


Figure B3-1 Folding figure single fold [© DEKRA/Labor Blum]

(a) Specimens in the test rig



(b) Folding figure double fold

(c) Folding figure double fold after folding

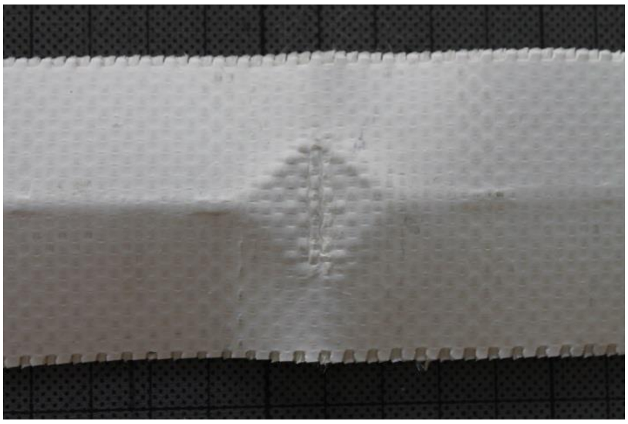


Figure B3-2 Specimens being tested with a double fold [© DEKRA/Labor Blum]

B3.2 Flex Fold Endurance Test

For foldable structures the durability of the material needs to be checked. One procedure to do this is with the flex endurance test. This test is a modification based on the ASTM D2176 (for paper) [S19], modified to suit for membranes.

A preloaded sample is folded quickly back and forth until the fabric breaks. The number of cycles until failure are recorded in the test report.

B4 Biaxial tensile test

B4.1 Biaxial tests for fabrics

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 or compensation values. Therefore, biaxial tests are essential for almost all projects. Moreover, they should be conducted for every material batch used in a project.

Usually, cruciform test specimens are used in plane biaxial tests for this purpose, see Figure B4-1 and also B6-1, but other methods are under development as well, e.g. [NgTh13]. The arms of the cruciform are normally parallel to the orthogonal yarns.

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. Different cruciform specimen geometries are used in different laboratories, see e.g. Figures 4-1 and 6-1, but a common characteristic is that 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 B4-1, B4-2 and B4-3. Despite the differences in geometry very similar test results are achieved, documentated in a round robin test conducted by Beccarelli [BBG11, Bec15].

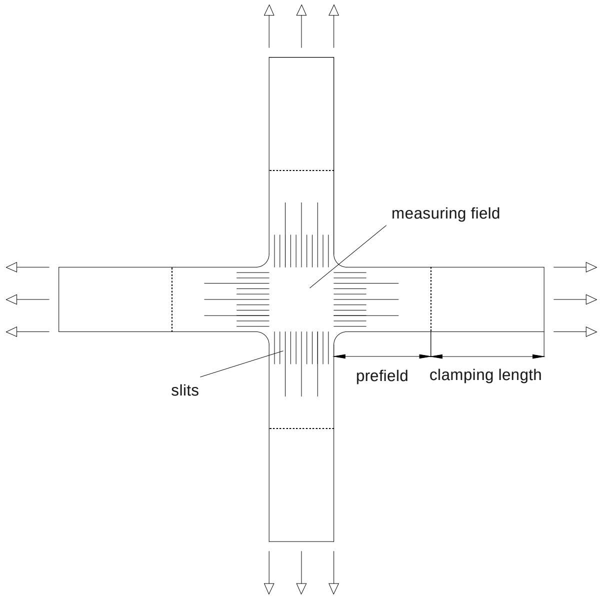


Figure B4-1 Example of a cruciform test specimen for biaxial testing [© ELLF]

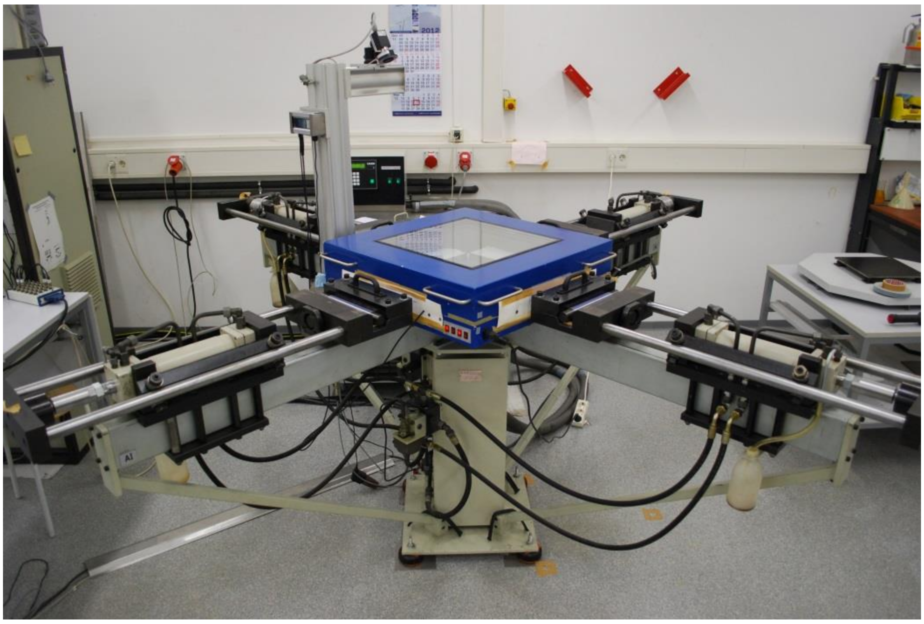


Figure B4-2 Biaxial testing machine with temperature chamber of the Essen Laboratory for Lightweight Structures at University of Duisburg-Essen, Germany [© ELLF]

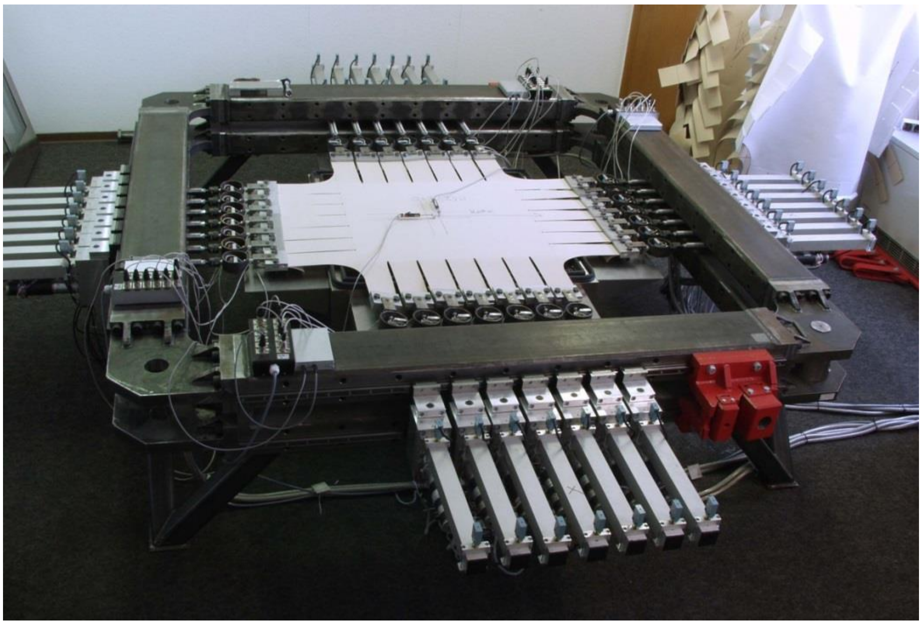


Figure B4-3 Biaxial Testing Machine with 7 servomotors and force gauges on every side [© DEKRA/Labor Blum]

Conducting biaxial tensile tests, fabrics show a highly nonlinear and anisotropic stress-strain-behaviour, which strongly depends on the load ratios warp/weft 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” [BBN04b] 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 B4-4 and B4-5. 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 servo-hydraulic actuators rigidly fixed at the extremities of a Greek cross shaped frame as exemplary shown in Figures B4-2 and B4-3. 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 [Bec15].

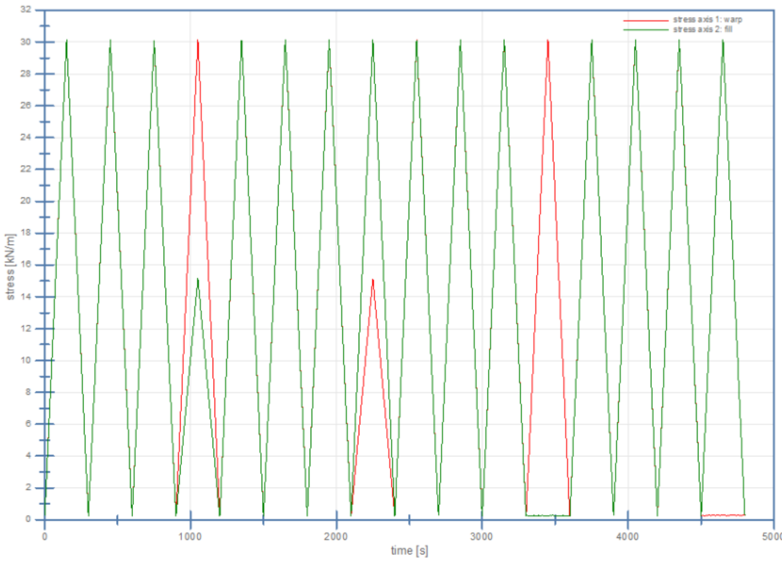


Figure B4-4 Typical load history diagram according to MSAJ/M-02-1995 [© ELLF]

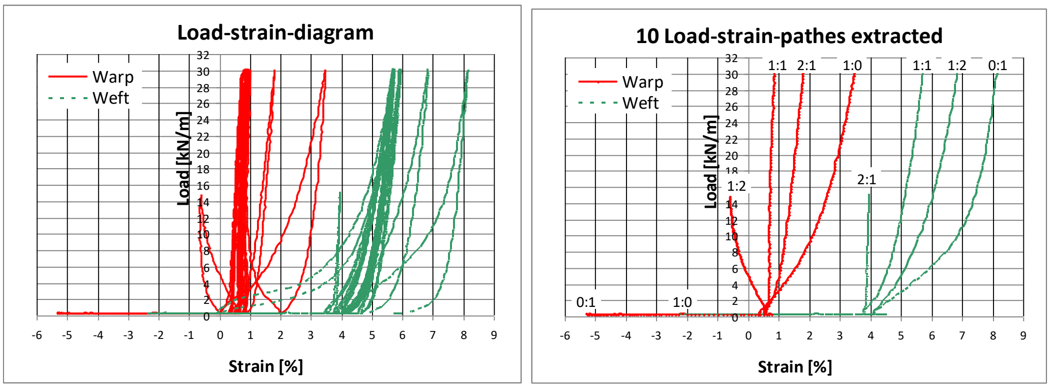


Figure B4-5 Left: Load-strain-diagram as a result of a biaxial test on Glass/PTFE material according to MSAJ/M-02-1995; right: Ten load-strain-paths (warp/weft at five load ratios), extracted from the diagram as the basis for the determination of elastic constants [US13b]

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 B4-2.

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.

MSAJ-Biaxial test modified to comply with real projects (formTL)

The biaxial test according to the Japanese standard MSAJ/M-02-1995 is a simple procedure that can be applied to determine elastic constants of the membrane.

The disadvantage of this test is that it runs 5 different stress ratios, while in reality a project has typically only few of these load histories at the same time. Therefore the results are highly influenced by load histories that never occur and so the determined stiffness values cannot be correct. Furthermore, real projects run between a certain prestress level and the maximum load in warp and weft. The Japanese test starts at zero prestress and goes up to 1/4 of the tensile strength. This leads in general to results which are much stiffer than under real load conditions.

Therefore, the design office formTL developed a modified version of this test, where formTL start after 5 prestress cycles from this prestress level, and then only up to the maximum stress in warp and in weft of the project. The numbers of cycles have been increased to 5 for each load regime – in contrast to the original MSAJ-procedure where only one load cycle is applied except for the 1:1 cycles which are repeated three times.

The following graph in Figure B4-6 shows the load scenario for such a modified test.

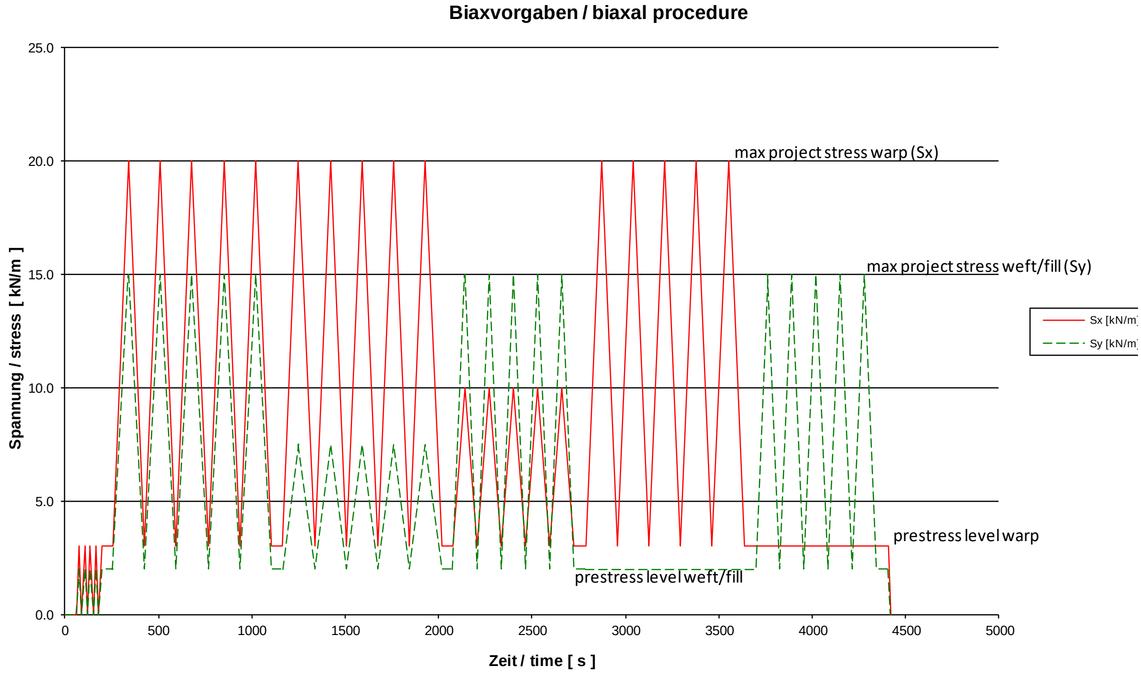


Figure B4-6 Load scenario for a modified biaxial test according to formTL [© formTL]

Even with this modified approach the sample is stressed with the full range of load histories, which will not happen in the real project. One idea to improve this, is to reorder the load history so that first those load regimes are tested which are realistic in a project, and then the less realistic.

For the evaluation of the stiffness, only the realistic cycles should be used.

Description of a standardized biaxial testing procedure (formTL)

For the initial structural design it is helpful to get standardized biaxial test results provided from membrane suppliers. In order to achieve comparable results formTL proposes to perform tests according to the procedure described in the following.

General

Three tests shall be performed in the stress ratios 1:1, 2:1 and 1:2.

The load range is determined based on the tensile strength of the material.

The initial stress (PRE) or prestress level is set to 2% of the minimum tensile stress in warp or weft.

The maximum stress (MAX) or service load is set to 15% of the minimum tensile stress in warp or weft.

The loading speed is set to 0.2 (kN/m)/s. In case of unequal stress, the higher value is taken as a reference.

Load Scenario 1:1

a. The initial tensioning is repeated 5 times with warp and weft (fill) loaded up to the same values PRE.

b. Then warp is loaded 5 times up to the value MAX, while the weft (fill) is kept at the value PRE.
c. Then weft (fill) is loaded 5 times up to the value MAX, while the warp is kept at the value PRE.
d. Then warp and weft are loaded 5 times up to the value MAX.

An example graphic for a material with a tensile strength of 80 kN/m are given in Figure B4-7.

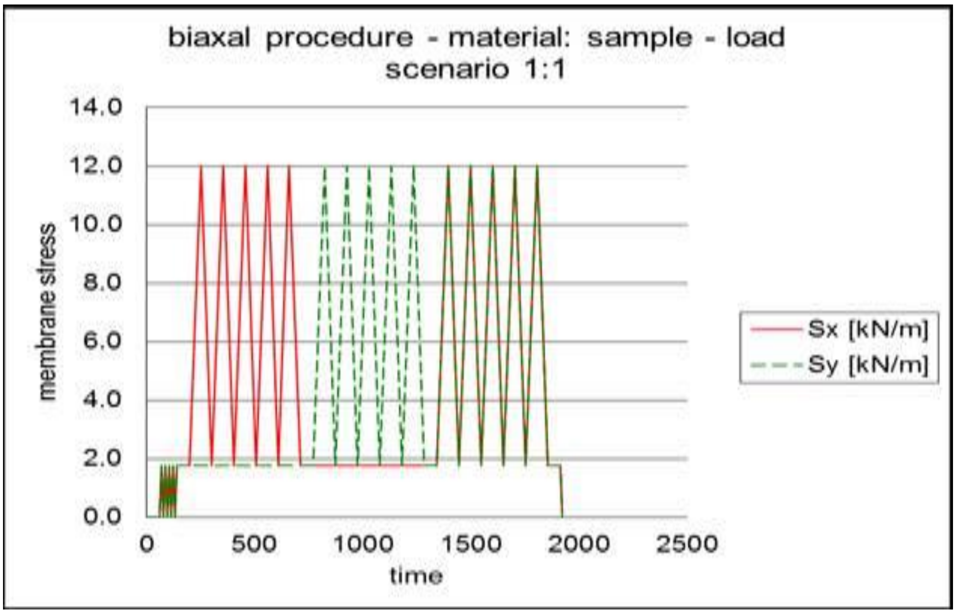


Figure B4-7 Biaxial load scenario 1:1 [© formTL]

<u>Load Scenario 2:1</u>

a. The initial tensioning is repeated 5 times with warp and weft (fill) loaded up to the same values PRE.
b. Then warp is loaded 5 times up to the value MAX, while the weft (fill) is kept at the value PRE.
c. Then weft (fill) is loaded 5 times up to the value MAX/2, while the warp is kept at the value PRE.
d. Then warp and weft (fill) are loaded 5 times up to the values MAX (warp) and MAX/2 (weft).

An example graphic for a material with a tensile strength of 80 kN/m are given in Figure B4-8.

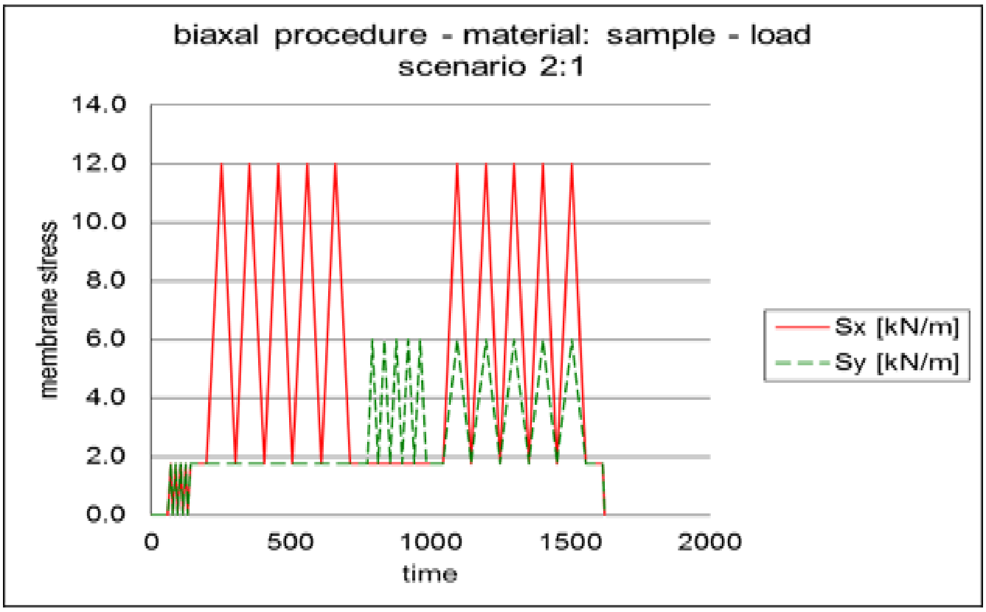


Figure B4-8 Biaxial load scenario 2:1 [© formTL]

Load Scenario 1:2

a. The initial tensioning is repeated 5 times with warp and weft (fill) loaded up to the same values PRE.
b. Then warp is loaded 5 times up to the value MAX/2, while the weft (fill) is kept at the value PRE.
c. Then weft (fill) is loaded 5 times up to the value MAX, while the warp is kept at the value PRE.
d. Then warp and weft (fill) are loaded 5 times up to the values MAX/2 (warp) and MAX (weft).

An example graphic for a material with a tensile strength of 80 kN/m are given in Figure B4-9.

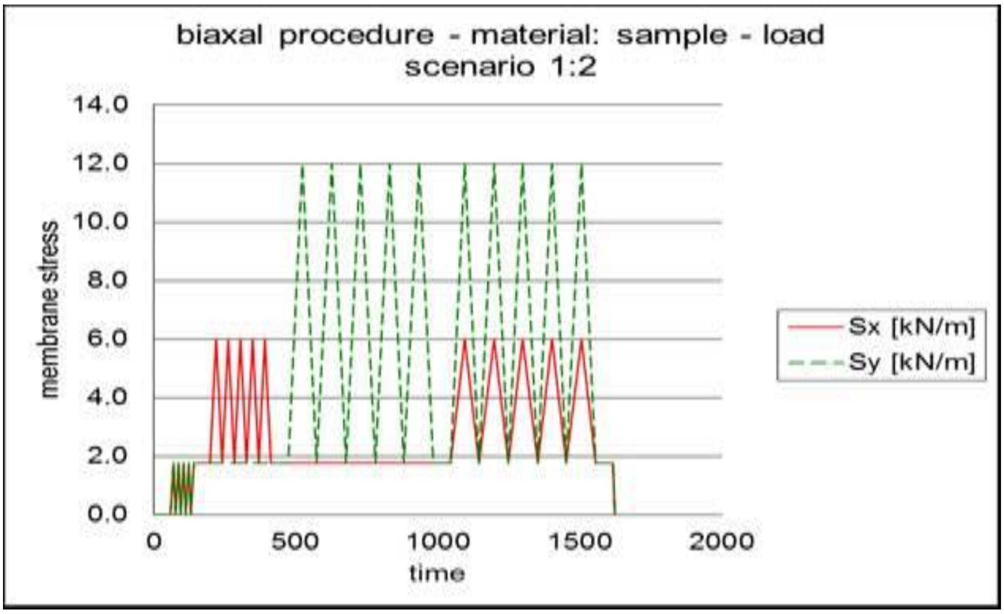


Figure B4-9 Biaxial load scenario 1:2 [© formTL]

B4.2 Biaxial tests for foils

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.

It has to be proved that the stress distribution in the field of measurements in a biaxial machine used for this purpose has to be homogeneous. For materials with a small Poisson's ratio such as some fabrics, the homogeneity of the stress state does not depend on the way of introducing the force into the test sample. But if the Poisson's ratio is high as it is for ETFE-films, the homogeneity depends widely on the homogeneity of the introduction of the forces into the sample. This can be avoided by controlling the force introduction into the sample by force controlling at single straps.

For very high deformations in an isotropic material as it is needed for ETFE-films to measure the biaxial yield behaviour, it may be recommended to take circular samples as it is shown in Figures B4-10 and B4-11. Here the homogeneity of the stress and deformation state is proved.

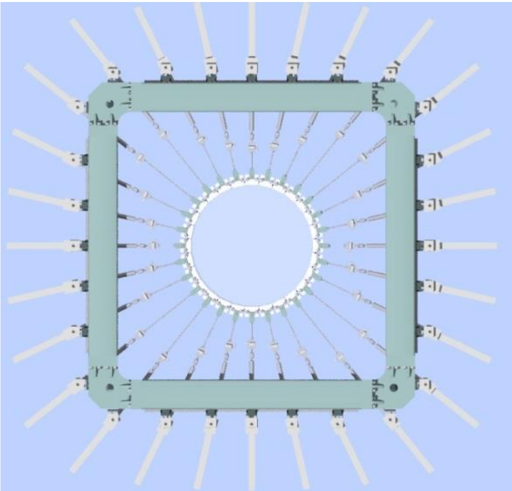


Figure B4-10 Circular Sample, principle, drawing [© DEKRA/Labor Blum]

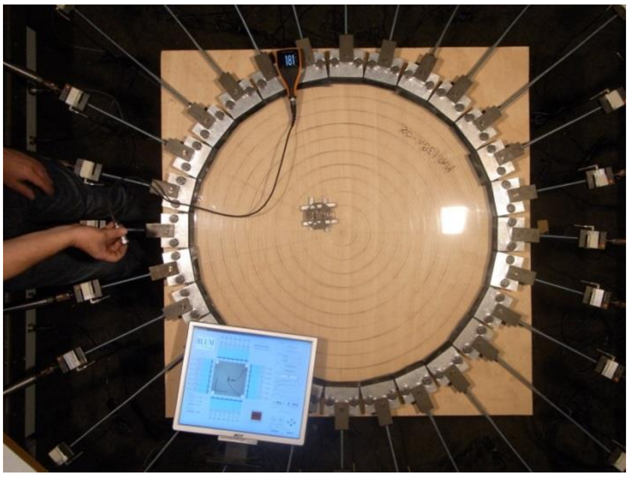


Figure B4-11 Circular sample in biaxial testing machine [© DEKRA/Labor Blum]

It is further to mention that the strength of the ETFE-foil measured in a biaxial test, e.g. using cylindrical specimens as shown in Figure B4-12, is different from the one measured in a uniaxial test. The reason is that in a uniaxial test one has orientation processes in the direction of loading. In biaxial loading, the orientation processes do not occur. Considering this the uniaxial behaviour cannot be compared with the one under biaxial loading.

One should remark that the proposals here are still under development.

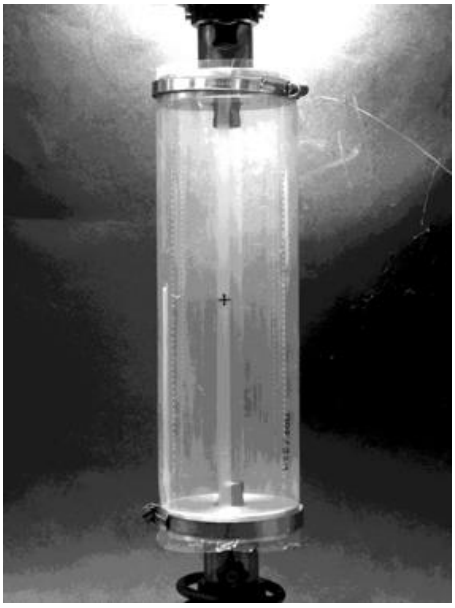


Figure B4-12 Cylindrical sample for the measurement of strength under biaxial stresses [© DEKRA/ Labor Blum]

B5 Tear test for fabrics

The tear strength is not a basic material property for the structural design but may be a useful engineering tool for specific projects. 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 [S5] and DIN 53363 [S7]. 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.

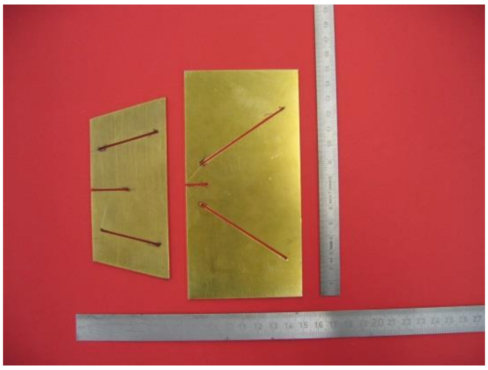


Figure B5-1 Templates for the application of the incision in the test specimens for the tear test [© ELLF]

The tear test according to EN 1875-3 is a uniaxial tensile test using 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 B5-1.

The testing machine used for tear tests should fulfill the requirements as defined for the tensile test.

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

B5-2. 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.

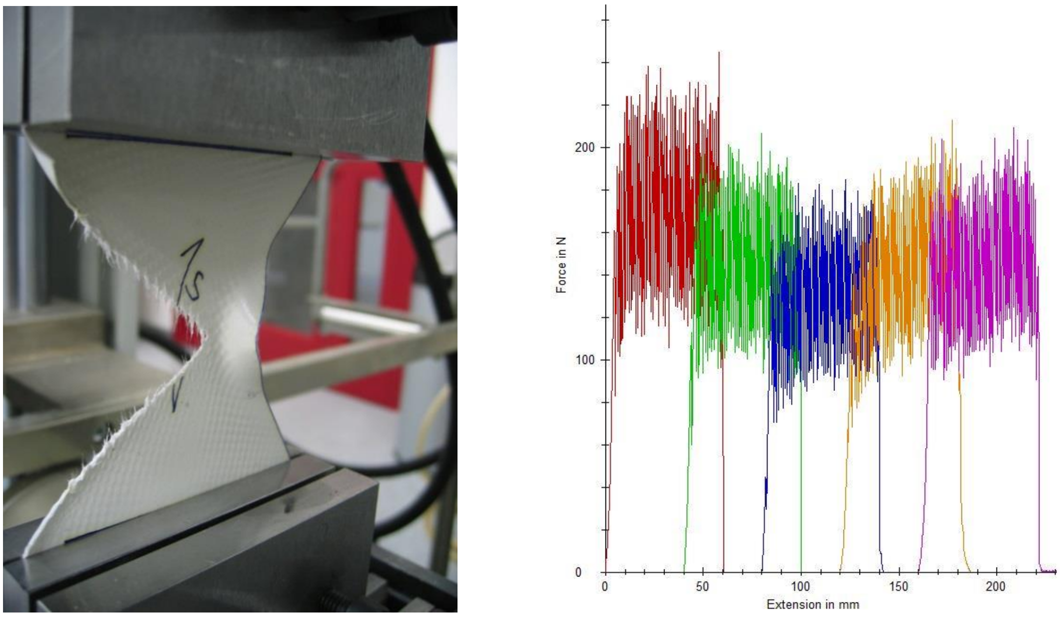


Figure B5-2 Test setup for the tear test (left) and typical results (right) [© ELLF]

Another possibilty for the determination of the tear strength is the “wide panel tear test” according to Bidmon, see Figures B5-3 to B5-5 and [BBN04b]. This is a biaxial tensile test with a tear placed in the centre of the measurement field. For tear propagation, three different tear lengths (of 5, 10 and 15 cm using 70 cm wide samples) in warp and weft direction shall be tested in order to evaluate the K_{IC}-factor of the material under the respective prestress in direction orthogonal to the tear. Slit lengths for different sample sizes shall be defined accordingly.

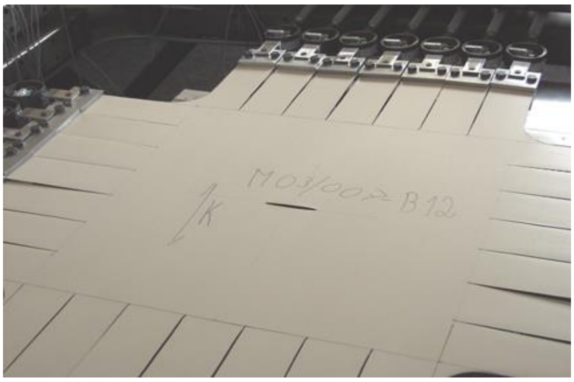


Figure B5-3 Biaxial test with a tear of defined length in the centre of the sample [© DEKRA/Labor Blum]

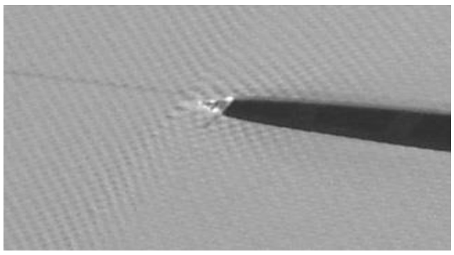


Figure B5-4 Stress concentration at the tip of a tear: the start of the propagating can well be seen [© DEKRA/Labor Blum]

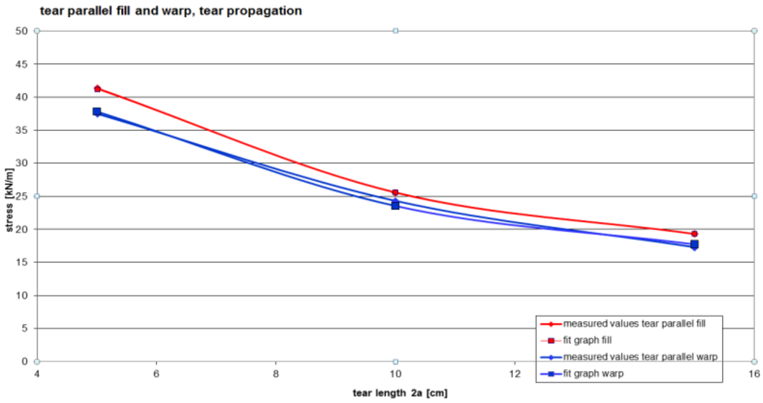


Figure B5-5 Stress concentration factor in dependence of tear length [© DEKRA/Labor Blum]

B6 Biaxial shear test for fabrics

The shear behaviour should also be considered for coated fabrics. Indeed the shear is not important for the stress state in the field far away from any corners and edges. But near the edges and gussets the shear stiffness is extremely important for the stress distribution especially if the mean axes of anisotropy are not perpendicular to the edge. It can be shown by means of discussing the symmetry group of orthotropic materials that the shear behaviour is not coupled with the behaviour in the directions of warp and weft.

The determination of the shear modulus can be performed in a biaxial shear test. A sample which can be used is shown in Figure B6-1. An exemplary load history is given in Figure B6-2 and the resulting typical shear stress-strain-behaviour is presented in Figure B6-3.

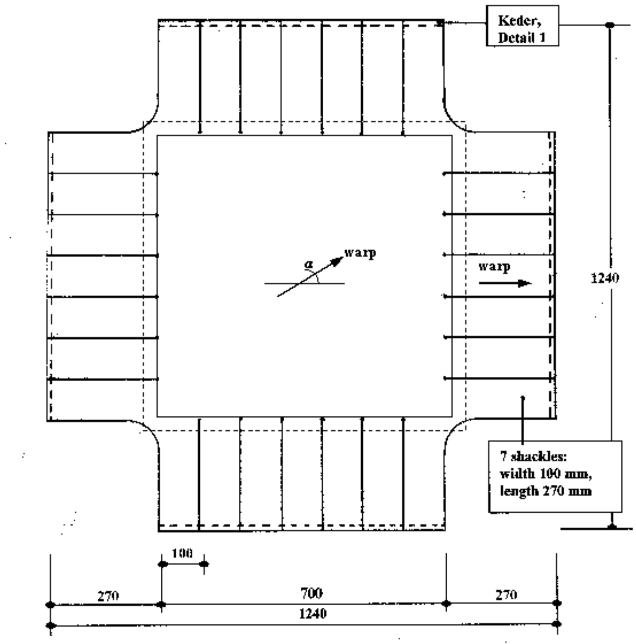


Figure B6-1 Sample shape for the determination of the shear behaviour [© DEKRA/Labor Blum]

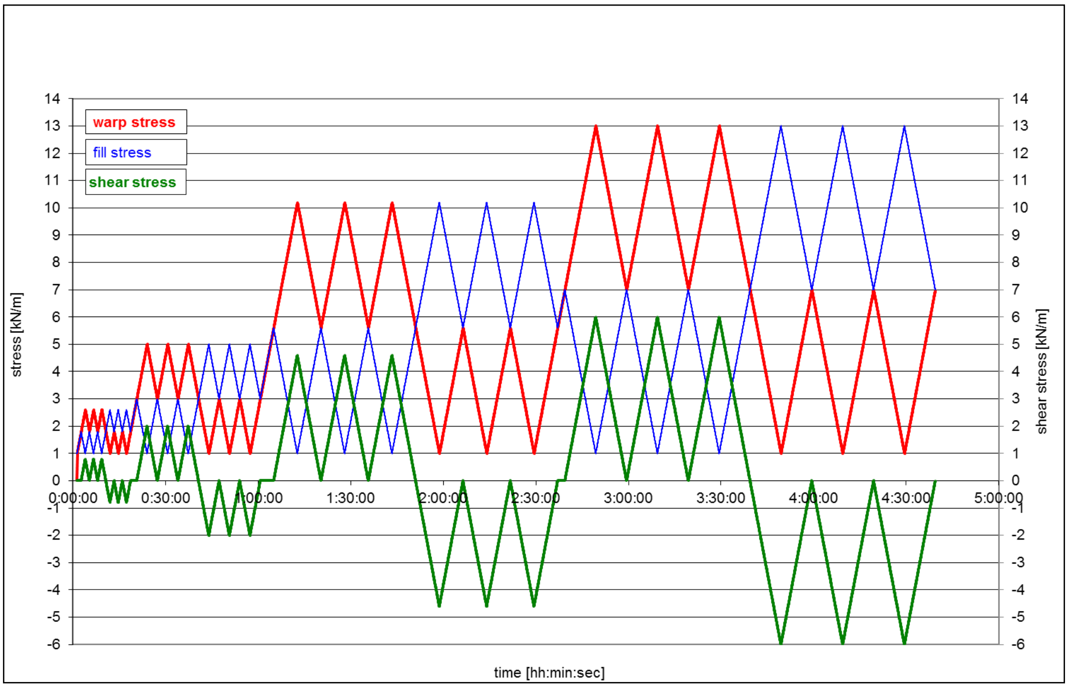


Figure B6-2 Exemplary load history of a shear test [© DEKRA/Labor Blum]

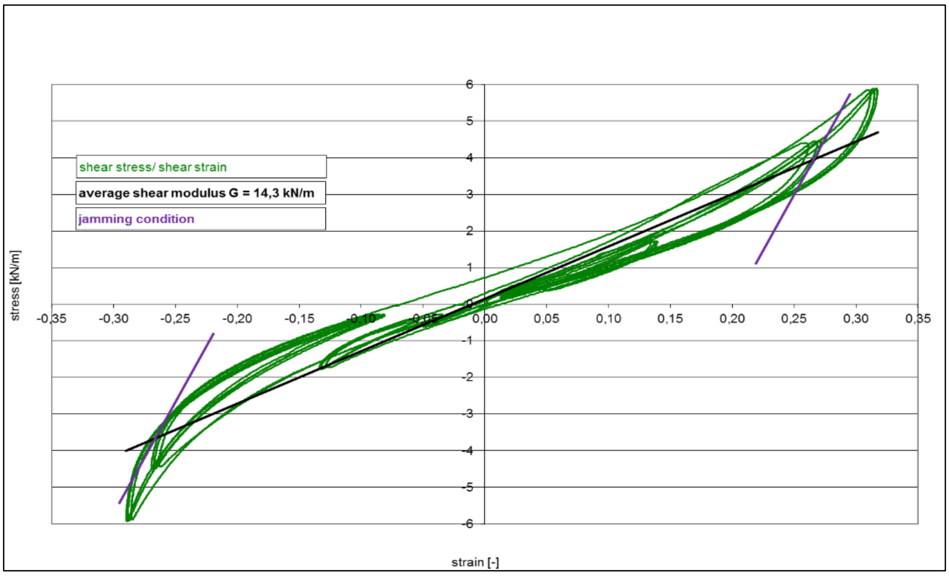


Figure B6-3 Shear stress in dependence of shear strain and average shear modulus G [© DEKRA/Labor Blum]

B7 Adhesion test for coated fabrics

The aim of the adhesion test is to measure the coating adhesion to the fabric, an important item for the strength of welded joints. On European level, the adhesion test is required to be performed according to EN ISO 2411 [S6]. 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 [S14]. 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 B7-1. The testing machine used for adhesion tests should fulfill the requirements as defined for tensile tests.

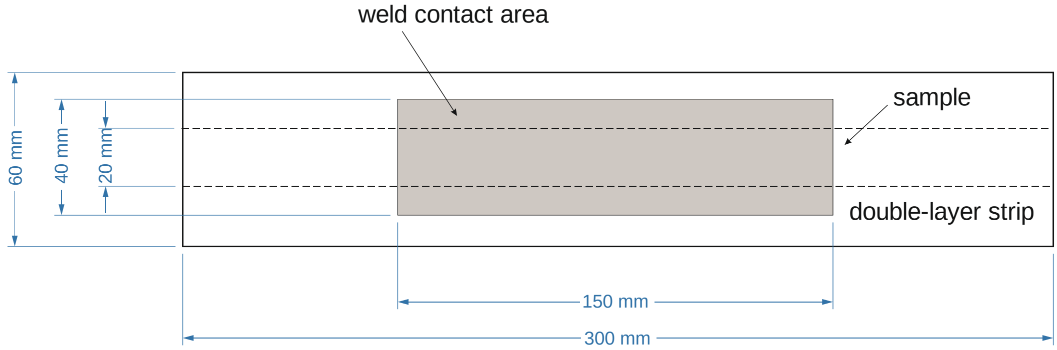
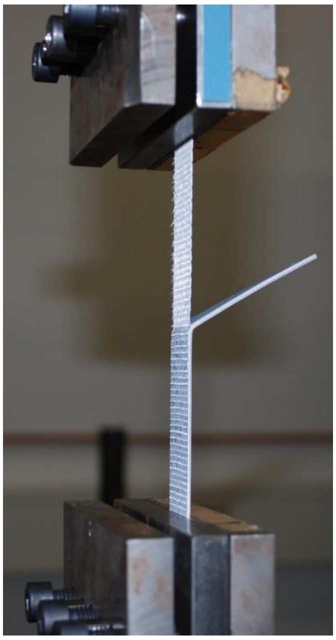


Figure B7-1 Sealed double-layer strip and position and dimension of the test specimen according to the German DIBt-Guideline for the acceptance test of coated fabrics and their joints [S12]

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 B7-2. 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 ≠ 23 °C.



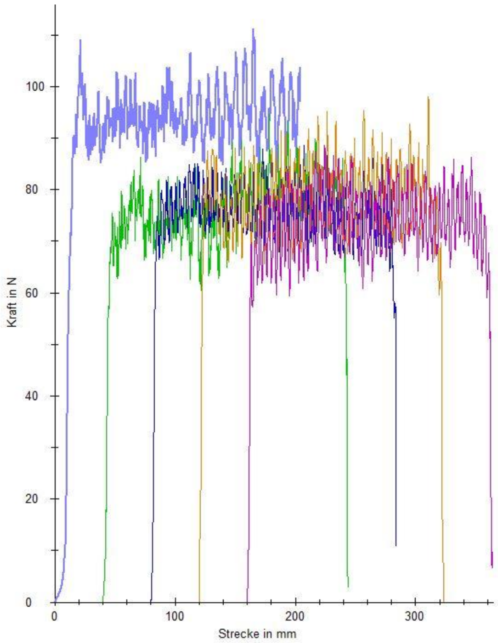


Figure B7-2 Test setup for an adhesion test (left) and typical results (right) [© ELLF]

The test evaluation can be performed according to DIN 53357 [S14] although this standard is withdrawn. Furthermore, at least five specimens have to be tested from each swatch.

B8 Test report

The test report has to include all relevant information which are:

- a reference to the applied standard,
- the applied test method,
- the number of specimens taken from each swatch of the laboratory sample,
- the geometrical dimensions 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 tested data including mean value, standard deviation and coefficient of variation,
- deviations from the considered test standards or special features and
- the date of the test.

Annex C

Determination of strength reduction factors for fabrics

C1 General

The A-factor concept was developed to consider strength reduction and duration aspects in the design of fabric structures, see Code Review No. 20, chapter 6.2. The A-factors are strength reduction factors taking into account for different strength reducing influences on the material or joint strength, mainly: biaxial stress states, high temperature and the time-dependent influences long term loads and environmental impact. Numbers for the A-factors are based on numerous experimental tests originally presented – amongst others – by Meffert [Meff78] and Minte [Min81]. Annex C provides background on the test procedures with which these factors were determined. This can be the fundament for future dicussion on the determination of the k-factors as proposed in chapter 6.3. Furthermore, latest suggestions are presented and discussion on the procedures is provided.

C2 A_0: reduction factor considering biaxial stress states

A possible reduction of the tensile strength due to a biaxial stress state in a fabric was investigated by Meffert with an inflated hose [Meff78], see Figure C2-1.

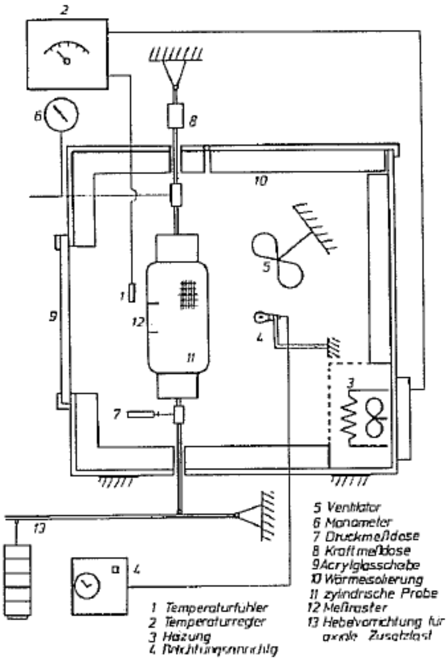


Figure C2-1 Test equipment for biaxial loads (principle sketch) [Meff78]

A special, custom-made cylindrical fabric specimen form without a seam was used. Coating was applied in a dipping bath and warp yarn stressing during the coating was simulated. With this experimental setup Meffert determined the reduction factor A_0 which he defined as:

$$A_0 = \frac{n_{23,uniax}}{n_{23,biax}} \tag{C1}$$

where $n_{23,uniax}$ is the short term tensile strength at T = 23°C under uniaxial stress state,

$n_{23,biax}$ is the short term tensile strength at T = 23°C under biaxial stress state.

Meffert measured a deterioration of approximately 15% and found a good agreement with bursting pressure tests which showed a deterioration of about 10%. The deterioration was shown to be largely independent of the stress ratio and the type of fabric. With a deterioration of 15% for the base material the strength reduction factor becomes $A_0 = 1.18$ which was rounded to $A_0 = 1.2$. It applies for biaxial stress with stress ratios warp:weft between 2:1 and 1:2. For the seams he discovered that the results under biaxial load can also become better than in the uniaxial test, as the combing out of the fibres effect is hindered by the orthogonal stress.

On the other hand it was reported in [Rei76] that for plane cruciform test specimens with specific geometry and a biaxial stress state in the centre field no strength reduction was detected. The base material for these tests was a usual commercial coated fabric. In this light, the findings in [Meff78] might be considered as a safe-sided approach.

C3 A_1: reduction factor considering long term load

Long lasting loads lead to a deterioration of strength for typical structural membnranes. In order to determine the long term reduction factor A_1 originally time to failure tests were established. Under different load levels the time to failure is recorded. In a double logarithmic scale this can typically be approximated by a straight line, so that the failure load for a desired life time can be extrapolated, see Figure C3-1. This is typically done for a $t = 10^5$ h (11.4 years) – as was done originally by Minte [Min81] – or $t = 2*10^5$ h (22.8 years) life time.

The reduction factor A_1 is defined by Minte as:

$$A_1 = 1.1 \cdot \frac{n_{23}}{n_{t,23}} \tag{C2}$$

where n_{23} is the short term tensile strength at T = 23°C,

$n_{t,23}$ is the tensile strength at T = 23°C after long term loading with time t.

The “extrapolation factor” of 1.1 introduced by Minte aimed to cover uncertainties of the extrapolation for the time between $t = 10^3$ h und $t = 10^5$ h because only few test experience existed for this period of time.

A test procedure according to EN ISO 899-1 [S2] can be utilized. 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. 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.

If the long term tests are performed at T = 23°C the factor A_1 can be derived as described above. If the tests are conducted with T = 70°C the combined effect of long term loading and high temperature $A_1 \cdot A_3$ can be determined.

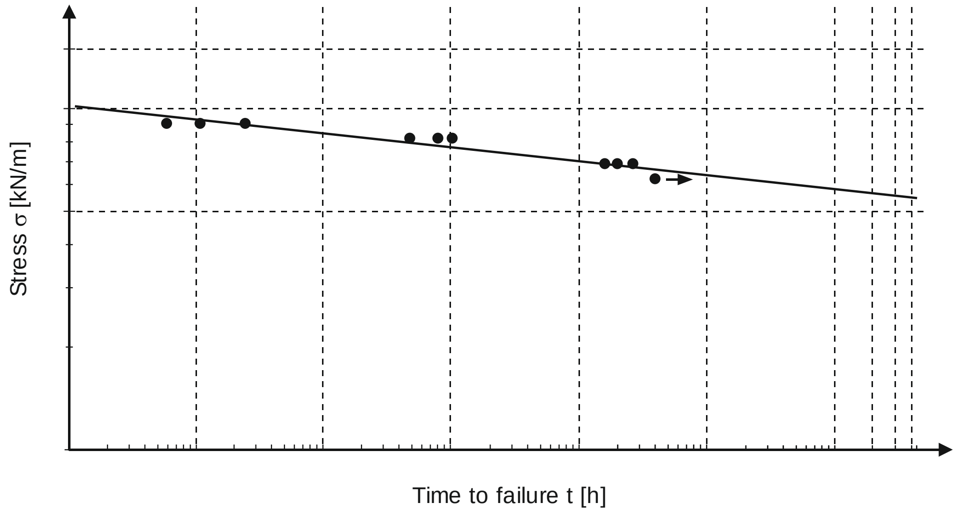


Figure C3-1 Time to failure-load–diagram [© ELLF]

Long-term loading – Blum/Bögner/Köhnlein approach

Another proposal for the determination of the analogous k-factor to A_1 – k_{long} – was developed by Blum/Bögner/Köhnlein and is presented in the following.

The reduction factors are initially based on the DIN 4134 [S25] for air-inflated structures and the dissertation of Minte [Min81, p.25].

All existing factors currently being used are related to the Minte thesis of 1981 and the PVC coated Polyester materials fabricated at that time.

Minte [Min81] proposed for the influence of long-term lasting loads to execute tests with duration of 1000 h under constant load. The loads have been chosen in such a manner that ruptures over the duration of the tests would happen. The loads have been normalised to the short term breaking loads (depending on the kind of detail approximately between 60 and 95%).

On a logarithmic scale (log n = f (log t)) the results are linearly approximated and then extrapolated to a typical life time of a membrane construction of $t = 10^5$ h = 11.5 years (assumed in 1981).

Thus the loads were chosen in such a high level which would typically not being expected to happen taking into account a safety factor of typically between 4 and 5 (thus 20 to 25% of the tensile strength).

Since then it has never been proved that the same damaging processes occur for the loading close to the short term strength as for the loads typically applied for the design of membrane structures.

Thus a new procedure is necessary. Long term tests of at least 1000 h at the following load levels could be executed:

n_p – prestress

$n_{0,5w}$ – 50% of working stress/ $n_{0,5w}$

n_w – working stress

The definition of these values shall be made according to the biaxial test standard.

The initial strength n_{23} shall be tested at 23 °C.

The initial strength is measured in tensile tests on neighbouring strips from the same laboratory sample without previous loading at 23 °C and 70°C respectively the appropriate elevated temperature (Figure C3-2).

Then 9 samples should be loaded at each level n_p, $n_{0,5w}$, n_w, three shall be taken out after 10 hrs., three after 100 hrs. and 3 after 1000 hrs. Then the residual strength shall be tested at 23°C according to tensile test standard EN ISO 1421 [S1] or EN ISO 13934-1 [S10]. Parallel the strain over time may be measured to find the uniaxial creep behaviour.

The same procedure should be executed at elevated temperature, 70°C for PVC coated materials, 50°C for ETFE or PTFE materials and the respective maximum temperatures for new materials and coatings.

The results shall be illustrated using a double logarithmic scale and a fitted straight line shall be found and extrapolated to 10^6 hours. The reduction factor should be found for an expectable lifetime of the structure of 30 years: $k_{long}=n_Z/n_{23}$.

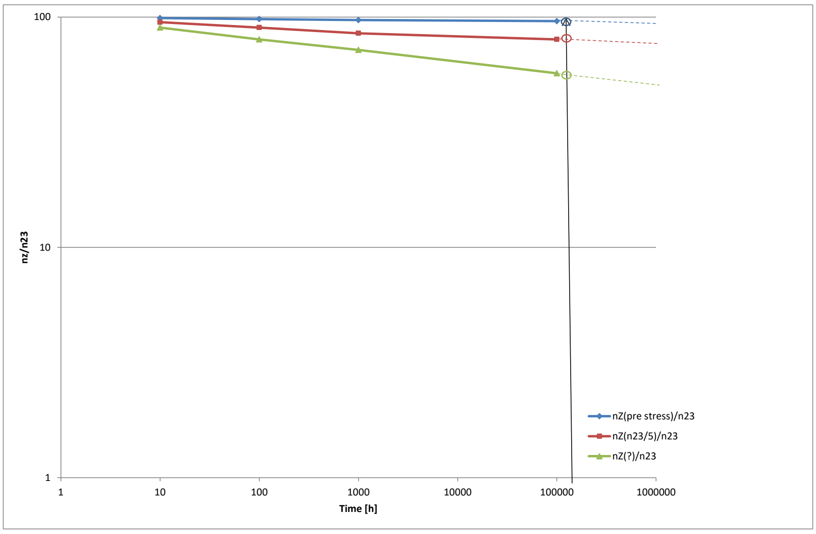


Figure C3-2 Residual strength of strips under constant load (3 load levels) over time (at 23°C and 70°C), logarithmic scale [© DEKRA]

C4 A_2: reduction factor considering environmental impact

In general, environmental impacts can be investigated with two procedures: natural (outdoor) or artificial weathering. Minte [Min81] evaluated weathering tests and conducted tests with dismantled material. With the results he confirmed the usually applied reduction factor of $A_2 = 1.1$ for material and welded seams. For stitched seams he determined $A_2 = 1.4$.

This way or the other, the test results show high variation. Some materials that were removed from structures and tested showed almost no deterioration after a life time of 20 years or more (even though with that method the influences of long term load actually covered by the factor A_1 are implicitly contained in the test results).

The reduction factor A_2 is defined by

$$A_2 = \frac{n_{23}}{n_{w,23}} \qquad \text{(C3)}$$

where n_{23} is the short term tensile strength at T = 23°C,

$n_{w,23}$ is the tensile strength at T = 23°C for a weathered test specimen.

The method and duration of weathering is not defined in [Min81]. Successive researchers employed various procedures. For instance, in [SBS94] test specimens were exposed to natural outdoor weathering for maximum eight years. Afterwards, the results were extrapolated for 11.5 years.

C5 A_3: reduction factor considering increased temperature

The reduction factor considering elevated temperature is determined with tensile tests at 70°C and at room temperature. It is defined by the following equation:

$$A_3 = \frac{n_{23}}{n_{70}} \tag{C4}$$

where n_{23} is the short term tensile strength at T = 23°C,

n_{70} is the short term tensile strength at T = 70°C.

Annex D

Stiffness parameters of coated fabrics using a microstructural model

An approach developed by Blum/Bögner gives the whole response surface for the elastic modulus taking into account the stiffness of the threads and the yarn geometry in the fabric. The evaluation is based on a structural model [Meff78, BB87, Blu85], which has been extended by Bögner [Bög04] by introducing springs between the thread knots to simulate the elasticity of the coating and a spring in the knot to take into account a change of thickness of the coated fabric (Figure D1).

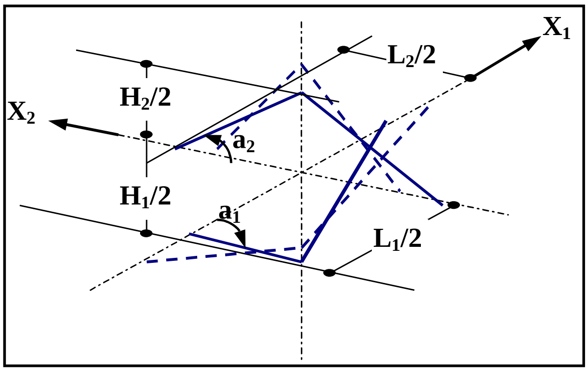


Figure D-1 Triangular model [Bög04]

The geometry of the yarns in the deformed state of the triangular model and the forces in the yarns can be calculated from

1. the equation of equilibrium in the direction normal to the fabric plane,
2. the relation between yarn deformation and fabric deformation in assuming a triangular model,
3. the force deformation behaviour of the yarns which may be different in warp and weft threads.

Projecting the yarn forces F into the plane the macroscopic Lagrange stresses n_{11} in warp dirction and n_{22} in weft direction can be calculated by division through the yarn distance in the deformed state:

$$n_{11} = F_1 / l_2 \cos\phi_1 \tag{D1}$$

$$n_{22} = F_2 / l_1 \cos\phi_2 \tag{D2}$$

The coating can be taken into consideration by an additive member. The elastic moduli $E_{\alpha\beta\gamma\delta}$ can be calculated by:

$$E_{\alpha\beta\gamma\delta} = \frac{\partial n_{\alpha\beta}}{\partial \varepsilon_{\alpha\beta}} \tag{D3}$$

One can prove that these moduli show hyperelastic structure if the yarn behaviour is elastic, the coating influence is elastic too and the geometry of the yarns in the fabric is triangular. Then the tensor of the moduli can be given by

$$E_{\alpha\beta\gamma\delta} = \begin{bmatrix} E_{1111} & E_{1122} & 0 \\ E_{1122} & E_{2222} & 0 \\ 0 & 0 & E_{1212} \end{bmatrix} \tag{D4}$$

All other components are equal to zero. These moduli cannot be assumed to be constant, they are principally a function of the deformations ε. Nevertheless, in linear approximation one may assume them to be constant.

The influence of coating between the knots can be calculated by adding springs, Euler stresses:

$$n_{11}^{*} = \frac{F_1}{L_1} \cos\phi_1 + P_1 \tag{D5}$$

$$n_{22}^{*} = \frac{F_2}{L_2} \cos\phi_2 + P_2 \tag{D6}$$

Influence of changement in thickness by using springs in the knots (Figure D2):

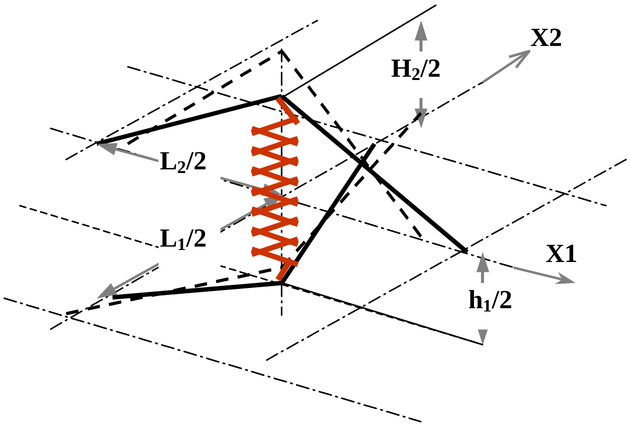


Figure D-2 Triangular model with a spring in the knot [Bög04]

The Lagrange stresses are then:

$$L_{11} = \frac{1}{L_2\left(F_1\left(\bar{\varepsilon}_1\right)c_1\left(k_1\right) + P_1\left(\mu_1\right)\right)} \tag{D7}$$

$$L_{22} = \frac{1}{L_1\left(F_2\left(\bar{\varepsilon}_2\right)c_2\left(k_2\right) + P_2\left(\mu_2\right)\right)} \tag{D8}$$

An example is shown in Figure D4.

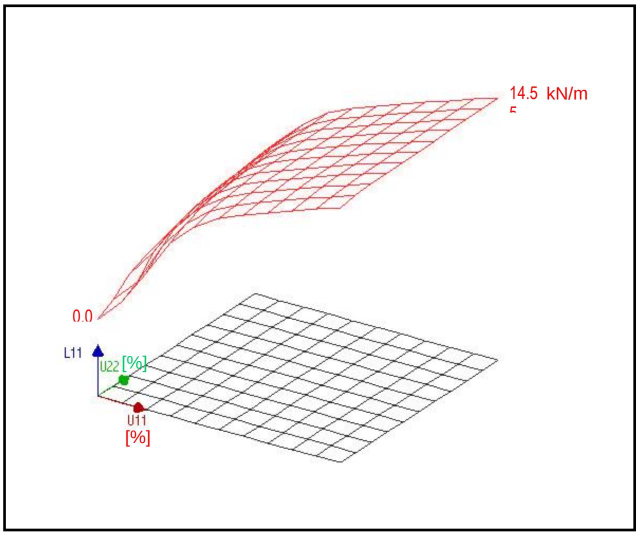


Figure D-3 Example for a stress surface n11 [kN/m] in dependence of the strains in warp ε_{11} and weft direction ε_{22} [© Bögner]

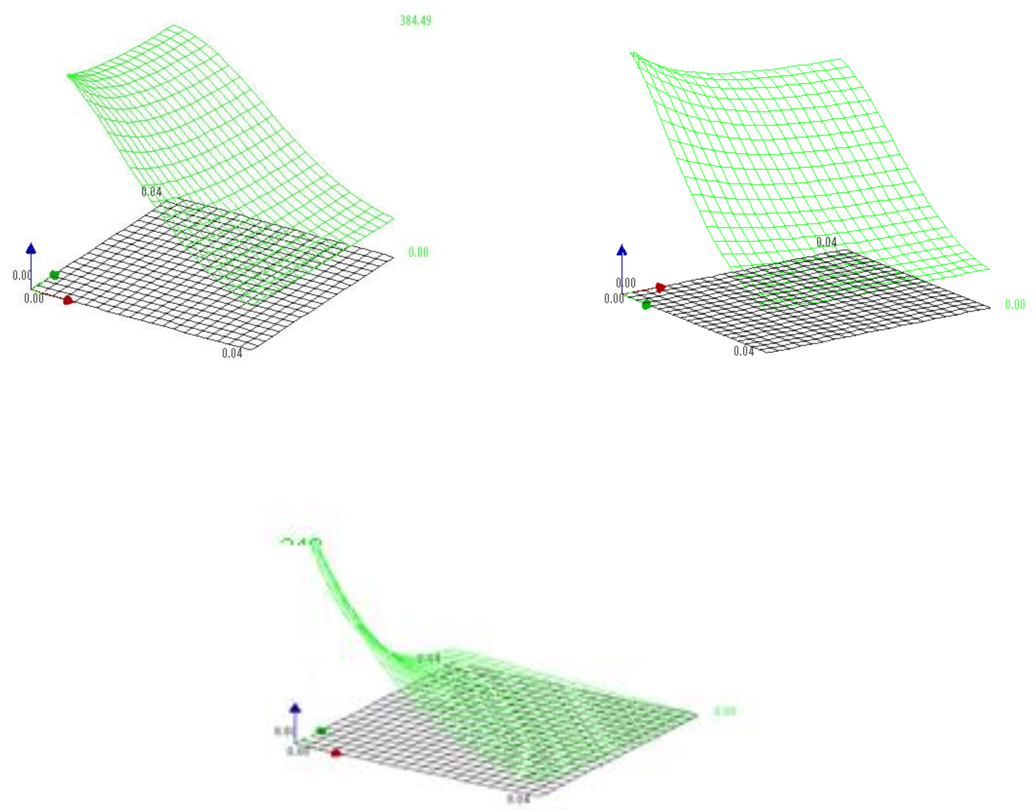


Figure D-4 Elastic Modulus (z-axis) in warp direction E_{1111} (left hand above), in weft direction E_{2222} (right hand above) and interaction between warp and weft direction E_{1122} (below) in dependence of the elongations in warp and weft (respectively stresses in warp and weft) [© Bögner-Balz]

Annex E

Review of partial factors in membrane analysis

This annex provides a review on the effect of applying partial factors on the actions for load analysis rather than applying these factors to the results or effects of the analyses.

Five models have been considered – the first four are those used on the “Round Robin” exercise [Gos13] with a 5th, a barrel vault, being included for completeness.

Load cases used are similar but slightly different to those used in the “Round Robin” study. Snow load has been reduced to 0.5 kN/m^2 and wind loading to 0.8 kN/m^2. Two additional cases have been included for the conic forms using the c_p values from [FM04] to represent a cross wind case in positive x-direction.

Details of the models used and the modelling assumptions are provided together with details of selected results – typically boundary reactions at perimeter fixed nodes.

The review is based upon analyses undertaken using the Tensys inTens software suite. Models used are: Model 1 – Cone 1 (Round Robin), Model 2 – Cone 2 (Round Robin), Model 3 – Hypar 1 (Round Robin), Model 4 – Hypar 2 (Round Robin), Model 5 – Barrel Vault 1. The models are shown in Figures E1 to E5.

Load cases are as follows: lc1 – Uniform snow load 0.5 kN/m^2, lc2 – Uniform wind suction -0.8 kN/m^2, lc3 – wind load in positive x-direction, c_p values as from [FM04] and q = 0.8 kN/m^2 (models 1 and 2).

The attached tables E1 to E5 provide a comparison of a selected set of results. Base data is provided using a factor of 1.0 for prestress and 1.0 for the applied loads. Two cases are then provided with a load factor of 1.5 and either a factor of 1.0 or 1.35 for prestress.

It can be seen from the tables E-1 to E-5 that for almost all cases the increase in load from the unfactored to the factored case using a prestress factor of 1.35 is of the order of 1.35 to 1.45. There are some variations but typically this is the increase that is being presented.

This then provides a lower value for use in the design than the option of using a uniform factor of 1.5 on the unfactored results.

The form that exhibits the greatest variation is the barrel vault. This has a relatively flat form and appears to therefore be sensitive to magnitude of wind suction load. The lateral load on the side arches increases by around 90% for the factored case.

Only a limited set of cases have been considered in this review. The forms generally have a high degree of double curvature with the exception of the barrel vault. From this limited set then the use of factored load cases cannot be guaranteed to provide a conservative set of design forces when compared with applying a partial factor to the unfactored analysis results.

As a conclusion, the review confirmed the basis of the work undertaken with confirmation of models used together with a summary of principle results. Overall, the results confirm that the use of partial factors on the actions rather than on the effects cannot guarantee a conservative set of design forces. However, it is also acknowledged that neither option is guaranteed to provide a conservative set of forces since the structures are highly non-linear and the precise variation in load sharing cannot be guaranteed.

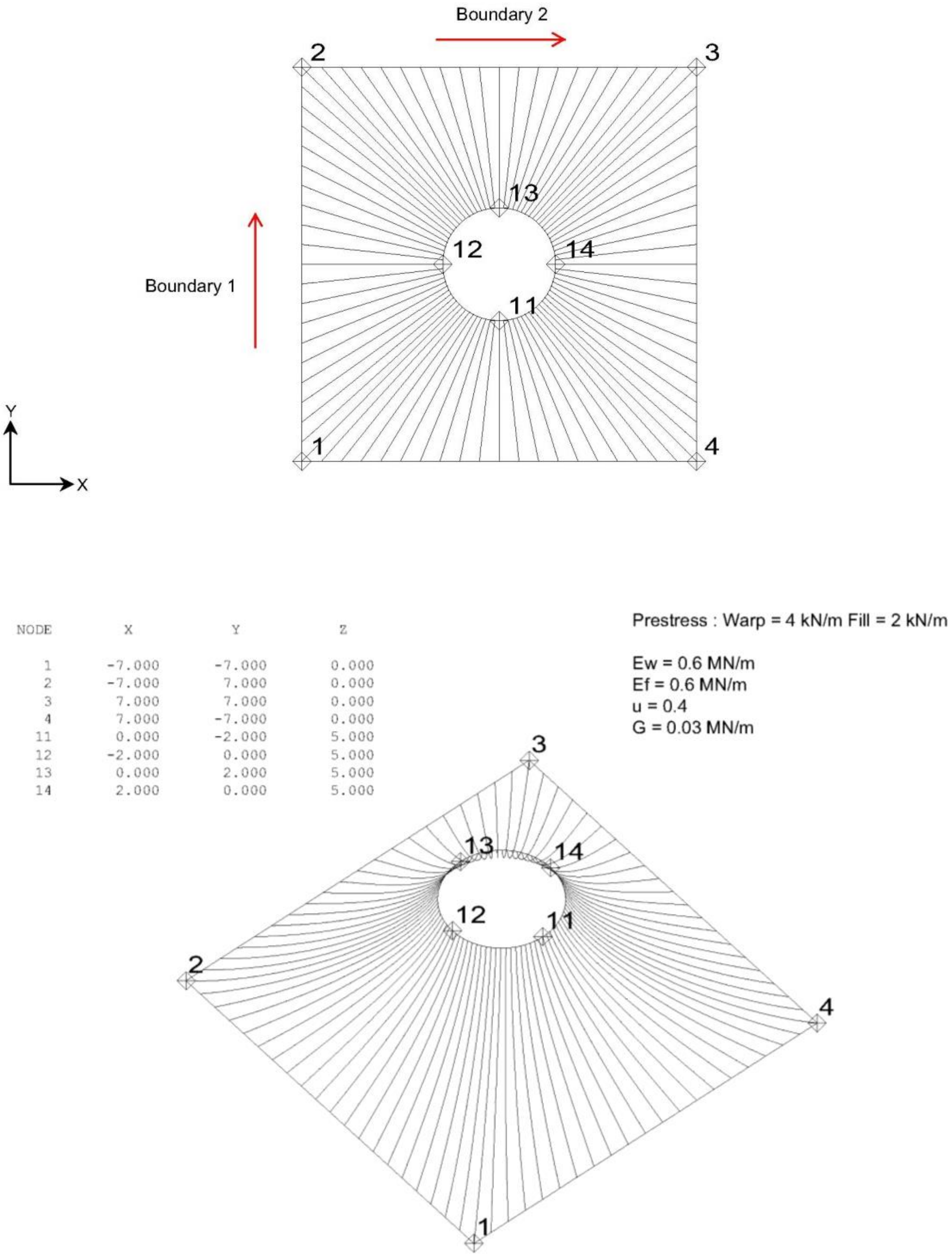
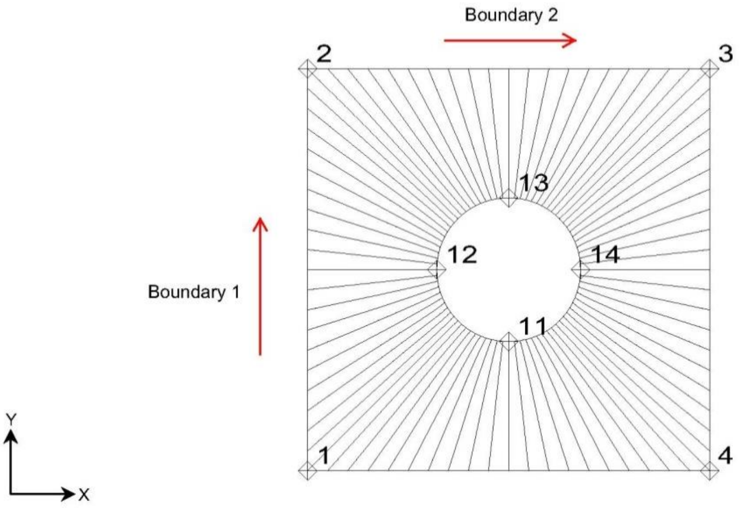


Figure E-1 Model 1 – Cone 1 Factored analysis review [© N. D. Gibson, TENSYS]



NODE	X	Y	Z
1	-7.000	-7.000	0.000
2	-7.000	7.000	0.000
3	7.000	7.000	0.000
4	7.000	-7.000	0.000
11	0.000	-2.500	4.000
12	-2.500	0.000	4.000
13	0.000	2.500	4.000
14	2.500	0.000	4.000

Prestress : Warp = 4 kN/m Fill = 4 kN/m

Ew = 0.6 MN/m
Ef = 0.6 MN/m
u = 0.4
G = 0.03 MN/m

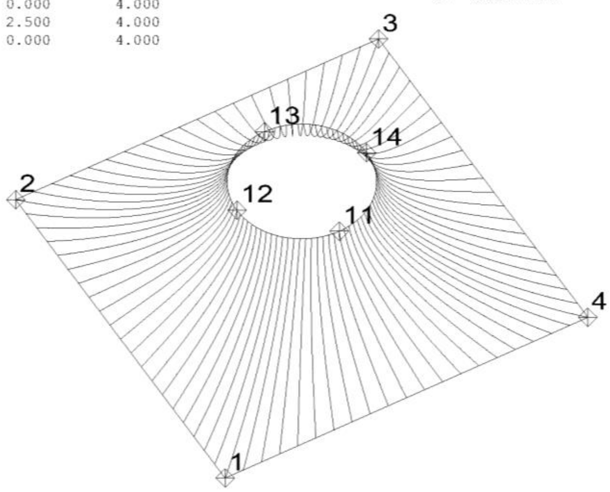
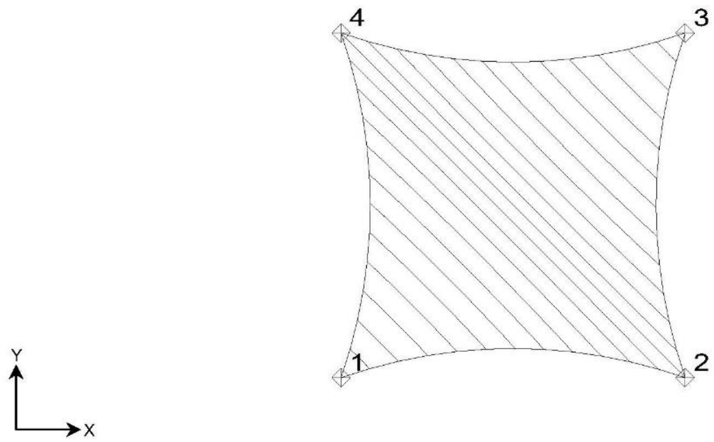


Figure E-2 Model 2 – Cone 2 Factored analysis review [© N. D. Gibson, TENSYS]



NODE	X	Y	Z
1	0.000	0.000	0.000
2	6.000	0.000	2.000
3	6.000	6.000	0.000
4	0.000	6.000	2.000

Prestress : Warp = 3 kN/m Fill = 3 kN/m

Ew = 0.6 MN/m
Ef = 0.6 MN/m
u = 0.4
G = 0.03 MN/m

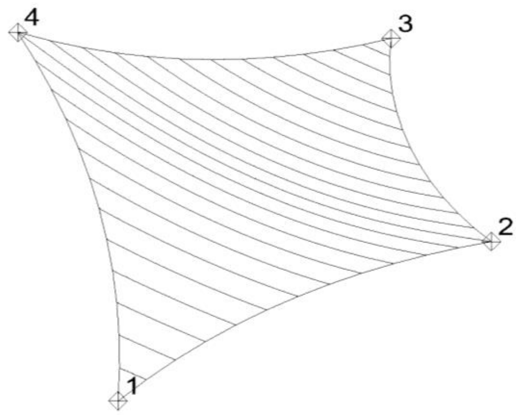


Figure E-3 Model 3 – Hypar 1 Factored analysis review [© N. D. Gibson, TENSYS]

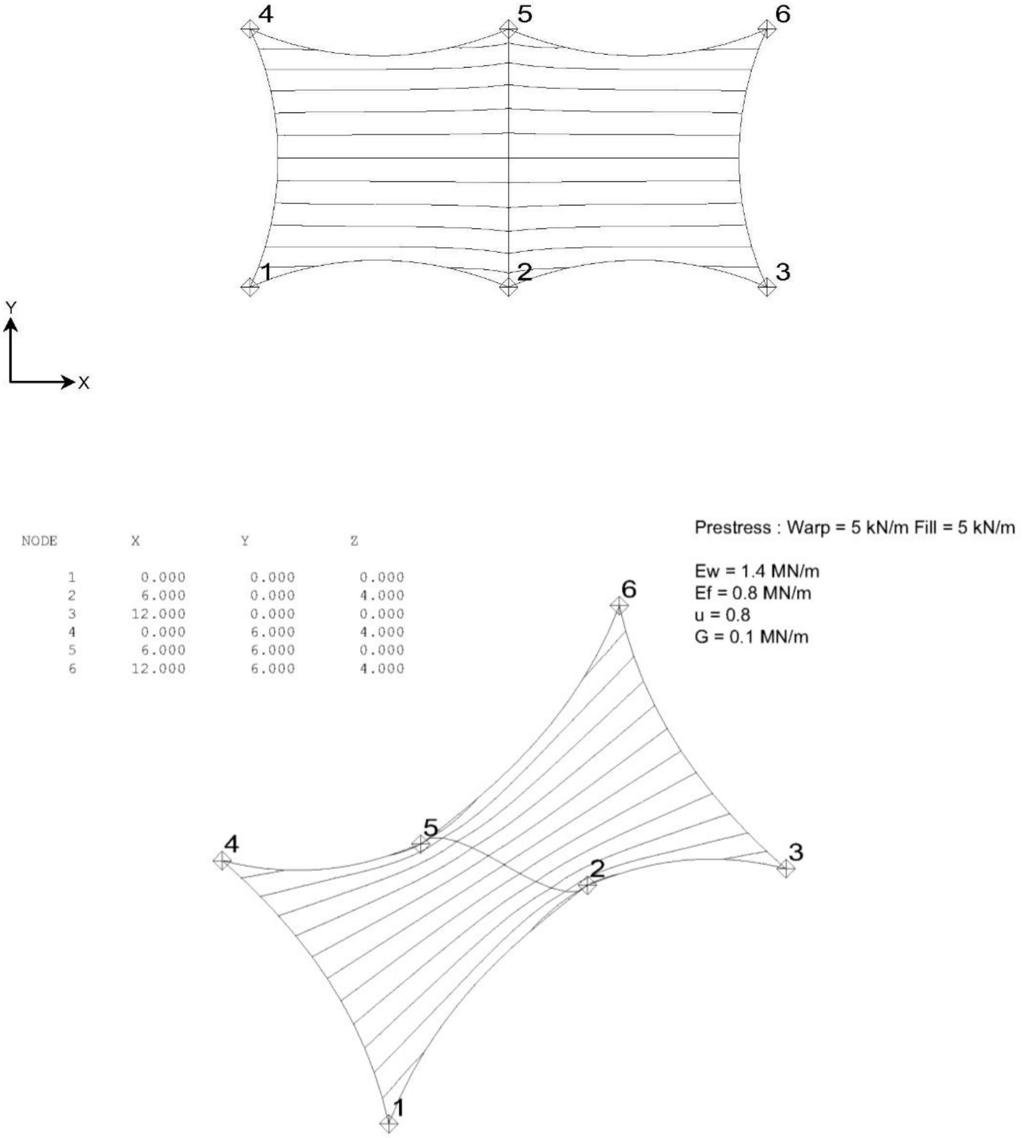


Figure E-4 Model 4 – Hypar 2 Factored analysis review [© N. D. Gibson, TENSYS]

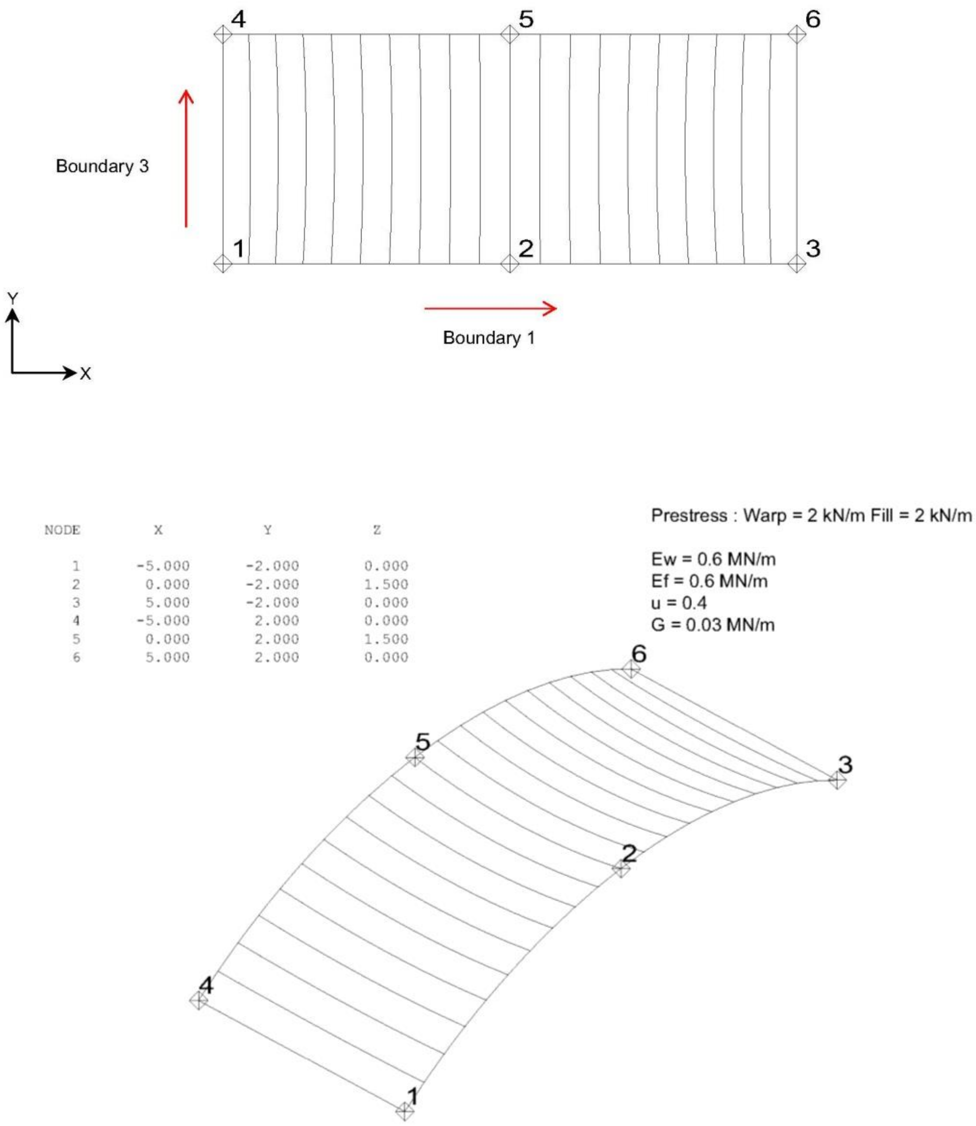


Figure E-5 Model 5 – Barrel Vault 1 Factored analysis review [© N. D. Gibson, TENSYS]

Table E-1 Model 1 – Cone 1

Loadcase	Description	Load factor	Prestress factor	Boundary reactions (kN) Headring Rz	% Δ	Lower edge 1 Rx	% Δ	Ry	% Δ	Rz	% Δ	Lower edge 2 Rx	% Δ	Ry	% Δ	Rz	% Δ
1	Snow	1	1	−128.4		28.2		0.0		9.2		0.0		−28.2		9.2	
		1.5	1	−171.7	34	35.1	24	0.0		8.5	−8	0.0		−35.1	24	7.5	−19
		1.5	1.35	−180.4	41	38.5	36	0.0		10.7	17	0.0		−39.5	40	10.7	17
2	Uniform wind suction	1	1	−29.4		61.7		0.0		44.3		0.0		−61.7		44.3	
		1.5	1	−13.4	−54	74.3	20	0.0		58.7	33	0.0		−74.3	20	58.7	33
		1.5	1.35	−35.3	20	83.9	36	0.0		64.2	45	0.0		−83.9	36	64.2	45
3	x+ve wind case	1	1	−59.1		69.8		0.0		33.3		6.4		−43.4		31.2	
		1.5	1	−57.8	−2	86.7	24	0.0		40.8	22	9.3	44	−49.6	14	39.8	27
		1.5	1.35	−77.1	30	94.9	36	0.0		45.0	35	9.2	43	−58.9	36	45.0	44

Table E-2 Model 2 – Cone 2

Loadcase	Description	Load factor	Prestress factor	Boundary reactions (kN) Headring Rz	% Δ	Lower edge 1 Rx	% Δ	Ry	% Δ	Rz	% Δ	Lower edge 2 Rx	% Δ	Ry	% Δ	Rz	% Δ
1	Snow	1	1	−122.4		52.0		0.0		8.5		0.0		−52.0		8.5	
		1.5	1	−156.4	28	55.7	7	0.0		5.9	−30	0.0		−55.7	7	5.9	−30
		1.5	1.35	−172.0	40	72.0	38	0.0		9.8	16	0.0		−72.0	38	9.8	16
2	Uniform wind suction	1	1	0.8		71.1		0.0		35.2		0.0		−71.1		35.2	
		1.5	1	1.5		93.3	31	0.0		52.8	50	0.0		−93.3	31	52.8	50
		1.5	1.35	1.2		97.8	38	0.0		52.9	50	0.0		−97.8	38	52.9	50
3	x+ve wind case	1	1	−31.1		75.6		0.0		22.5		5.5		−55.8		25.3	
		1.5	1	−29.2	−6	92.5	22	0.0		28.2	25	7.9	46	−64.6	16	33.9	34
		1.5	1.35	−40.0	29	103.4	37	0.0		31.0	38	7.4	36	−75.2	35	36.7	45

Table E-3 Model 3 − Hypar 1

Loadcase	Description	Load factor	Prestress factor	Node 1 Rx	% Δ	Node 1 Ry	% Δ	Node 1 Rz	% Δ	Node 2 Rx	% Δ	Node 2 Ry	% Δ	Node 2 Rz	% Δ
1	Snow	1	1	32.3		32.3		17.2		−41.8		41.8		−24.2	
		1.5	1	31.2	-3	31.2	-3	16.3	−5	−45.4	9	45.4	9	−26.8	11
		1.5	1.35	43.8	35	43.8	35	23.1	34	−57.3	37	57.3	37	−33.5	39
2	Uniform wind suction	1	1	46.2		46.2		27.6		−31.9		31.9		−16.4	
		1.5	1	57.0	23	57.0	23	35.0	27	−36.9	16	37.0	16	−18.3	11
		1.5	1.35	63.9	38	63.9	38	38.9	41	−43.8	37	43.9	37	−22.1	35

Perimeter reactions (kN)

Table E-4 Model 4 − Hypar 2

Loadcase	Description	Load factor	Prestress factor	Node 1 Rx	% Δ	Node 1 Ry	% Δ	Node 1 Rz	% Δ	Node 2 Rx	% Δ	Node 2 Ry	% Δ	Node 2 Rz	% Δ	Node 4 Rx	% Δ	Node 4 Ry	% Δ	Node 4 Rz	% Δ	Node 5 Rx	% Δ	Node 5 Ry	% Δ	Node 5 Rz	% Δ
1	Snow	1	1	55.1		53.2		57.2		0.0		35.8		−75.0		58.0		−58.1		−62.3		0.0		−26.0		56.9	
		1.5	1	56.8	3	54.4	2	58.4	2	0.0		39.7	11	−82.3	10	61.1	5	−61.7	6	−66.2	6	0.0		−25.1	−4	55.4	-3
		1.5	1.35	74.5	35	72.0	35	77.0	35	0.0		49.0	37	−102.7	37	79.0	36	−79.0	36	−85.2	37	0.0		−34.9	34	76.4	34
2	Uniform wind suction	1	1	63.4		62.6		68.8		0.0		27.0		−57.6		56.2		−56.0		−58.2		0.0		−38.3		81.8	
		1.5	1	70.5	11	69.9	12	77.5	13	0.0		27.4	2	−58.1	1	59.9	7	−60.0	7	−61.5	6	0.0		−44.1	15	94.2	15
		1.5	1.35	87.2	38	85.8	37	95.1	38	0.0		36.9	37	−77.9	35	75.5	34	−76.4	36	−78.7	35	0.0		−52.6	37	113.2	38

Perimeter reactions (kN)

Table E-5 Model 5 − Barrel vault 1

Loadcase	Description	Load factor	Prestress factor	Boundary reactions (kN)											
				Outer edge 1						Outer edge 3					
				Rx	% Δ	Ry	% Δ	Rz	% Δ	Rx	% Δ	Ry	% Δ	Rz	% Δ
1	Snow	1	1	−0.1		42.8		−10.5		3.3		−0.1		0.9	
		1.5	1	−0.1		54.7	28	−15.0	43	3.0		−0.1		0.5	
		1.5	1.35	−0.1		58.9	38	−15.7	49	4.8		−0.1		1.2	
2	Uniform wind suction	1	1	0.1		13.6		2.2		22.2		0.0		14.3	
		1.5	1	0.1		21.9	61	4.2	88	30.2	36	0.0		20.4	43
		1.5	1.35	0.1		25.8	89	4.0	79	31.0	39	0.0		20.8	45

Annex F

Formulas for the analysis of inflatable beams and numerical examples

F1 Cantilever beam

Cantilever beam, point load

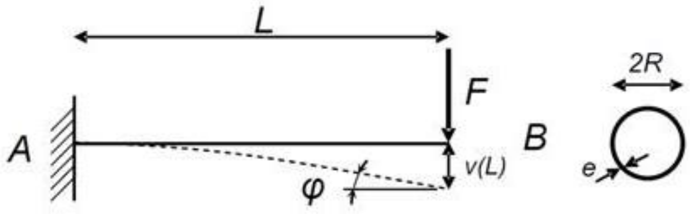


Figure F-1 A cantilever inflated beam with a point load at the free end

Deflection and maximum displacement at the cantilever free end:

$$v(x) = -\frac{F}{\left(E_\ell I + \frac{pI}{S}\right)}\left(\frac{Lx^2}{2} - \frac{x^3}{6}\right) - \frac{F}{p + kG_{\ell t}S}x$$
$$= -\frac{F}{\left(E_\ell + \frac{pR}{2}\right)I}\left(\frac{Lx^2}{2} - \frac{x^3}{6}\right) - \frac{F}{\pi R\left(pR + 2kG_{\ell t}\right)}x \tag{F.1}$$

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

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

$$\theta(x) = -\frac{F}{\left(E_\ell + \frac{pR}{2}\right)I}\left(\frac{x^2}{2} - Lx\right) \tag{F.3}$$

$$\theta(L) = -\frac{F}{2\left(E_\ell + \frac{pR}{2}\right)I}L^2 \tag{F.4}$$

Slope at x and slope at the free end:

$$\varphi(x) = \frac{dv(x)}{dx} = \frac{F}{\left(E_\ell + \frac{pR}{2}\right)I}\left(\frac{x^2}{2} - Lx\right) - \frac{F}{\pi R\left(pR + 2kG_{\ell t}\right)} \tag{F.5}$$

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

Collapse load:

$$F_\ell = \frac{p\pi^2 R^3}{4L} \tag{F.7}$$

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

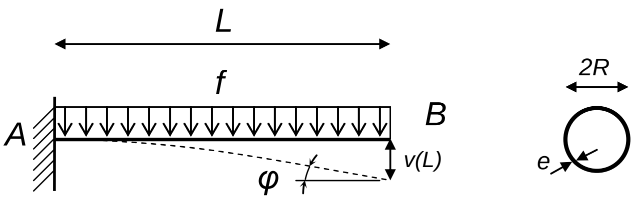


Figure F-2 A cantilever inflated beam with a distributed load

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

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

$$\varphi(L) = -\frac{f}{6\left(E_\ell + \frac{pR}{2}\right)I}L^3 \tag{F.9}$$

$$F_\ell = \frac{p\pi^2 R^3}{4L} \tag{F.10}$$

F2 Simply supported beam

Simply supported beam, point load

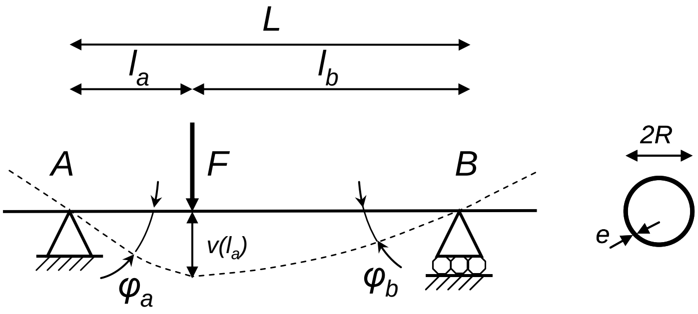


Figure F-3 A simply supported beam with a single point load

Maximum displacement and slope, collapse load:

$$v(\ell_a) = -\frac{F\ell_a\ell_b}{L}\left(\frac{\ell_a\ell_b\pi R(pR+2kG_{\ell t})+3\left(E_\ell+\frac{pR}{2}\right)I}{3\pi R(pR+2kG_{\ell t})\left(E_\ell+\frac{pR}{2}\right)I}\right) \quad \text{(F.11)}$$

$$\varphi(0) = \varphi_a = -\frac{F\ell_b}{L}\left(\frac{L+\ell_b}{6\left(E_\ell+\frac{pR}{2}\right)I}+\frac{1}{\pi R(pR+2kG_{\ell t})}\right) \quad \text{(F.12)}$$

$$\varphi(L) = \varphi_b = -\frac{F\ell_a}{L}\left(\frac{L+\ell_a}{6\left(E_\ell+\frac{pR}{2}\right)I}+\frac{1}{\pi R(pR+2kG_{\ell t})}\right) \quad \text{(F.13)}$$

$$F_\ell = \frac{p\pi^2R^3}{4}\frac{L}{\ell_a\ell_b} \quad \text{(F.14)}$$

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

$$v\left(\frac{L}{2}\right) = -\frac{FL^3}{48\left(E_\ell+\frac{pR}{2}\right)I}-\frac{FL}{\pi R(pR+2kG_{\ell t})} \quad \text{(F.15)}$$

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

$$F_\ell = \frac{p\pi^2R^3}{L} \quad \text{(F.17)}$$

Eigenfrequencies:

$$f_n = \sqrt{\frac{n^4\pi^4}{\rho_0 \pi R^2 \ell^2 \left(\frac{\ell^2}{\left(E_\ell + \frac{pR}{2}\right) I} + \frac{n^2\pi^2}{\pi R\left(pR + 2kG_{\ell t}\right)} \right)}} \tag{F.18}$$

Simply supported beam, distributed load

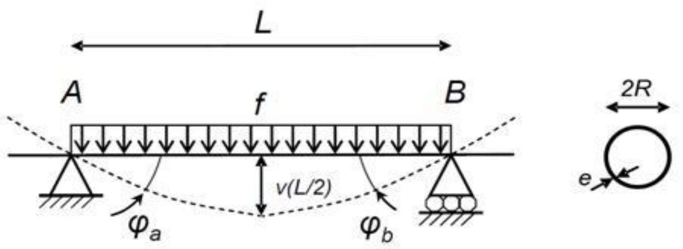


Figure F-4 A simply supported beam with a distributed load

Maximum displacement and slope, collapse load:

$$v\left(\frac{L}{2}\right) = -\frac{fL^2\left(5\pi R\left(pR + 2kG_{\ell t}\right)L^2 + 48\left(E_\ell + \frac{pR}{2}\right)I\right)}{384\pi R\left(E_\ell + \frac{pR}{2}\right)I\left(pR + 2kG_{\ell t}\right)} \tag{F.19}$$

$$\varphi(0) = \varphi_a = -\varphi_b = -\varphi(L) = -\frac{fL}{24}\frac{\left(\pi R\left(pR + 2kG_{\ell t}\right)L^2 + 12\left(E_\ell + \frac{pR}{2}\right)I\right)}{\pi R\left(pR + 2kG_{\ell t}\right)\left(E_\ell + \frac{pR}{2}\right)I} \tag{F.20}$$

$$F_\ell = 2\frac{p\pi^2R^3}{L} \tag{F.21}$$

F3 Propped cantilever beam

Propped cantilever beam, point load

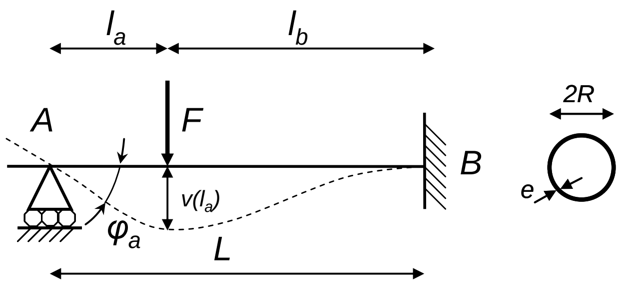


Figure F-5 Propped cantilever beam with a single point load

Maximum displacement and slope, collapse load:

$$v(\ell_a) = F\ell_a\ell_b \left(\frac{\pi^2 R^2 (pR+2kG_{\ell t})^2 \left(3L^3\ell_a - 5L^2\ell_a^2 + L\ell_a^3 + \ell_a^4\right)}{12L\pi R(pR+2kG_{\ell t})\left(E_\ell + \frac{pR}{2}\right)I\left(\pi R(pR+2kG_{\ell t})L^2 + 3\left(E_\ell + \frac{pR}{2}\right)I\right)} + \frac{12\pi R(pR+2kG_{\ell t})\left(E_\ell + \frac{pR}{2}\right)I\left(L^2 + L\ell_a - \ell_a^2\right) + 36\left(E_\ell + \frac{pR}{2}\right)^2 I^2}{12L\pi R(pR+2kG_{\ell t})\left(E_\ell + \frac{pR}{2}\right)I\left(\pi R(pR+2kG_{\ell t})L^2 + 3\left(E_\ell + \frac{pR}{2}\right)I\right)} \right) \tag{F.22}$$

$$\varphi(0) = \varphi_a = -\frac{F}{4L\left(\left(E_\ell + \frac{pR}{2}\right)I\pi R(pR+2kG_{\ell t})\left(\pi R(pR+2kG_{\ell t})L^2 + 3\left(E_\ell + \frac{pR}{2}\right)I\right)\right)} \cdot \left(\begin{array}{l} \pi^2 R^2 (pR+2kG_{\ell t})^2 \ell_a L^2 (L-\ell_a)^2 + \\ \left(E_\ell + \frac{pR}{2}\right)I\pi R(pR+2kG_{\ell t})\left(4L^3 - 6L\ell_a^2 + 2\ell_a^3\right) + \\ 12\left(E_\ell + \frac{pR}{2}\right)^2 I^2 (L-\ell_a) \end{array} \right) \tag{F.23}$$

$$F_\ell = \frac{p\pi^2 R^3}{4}\frac{(L+\ell_a)}{\ell_a(L-\ell_a)} \tag{F.24}$$

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

$$v\left(\frac{L}{2}\right) = -\frac{FL}{768}\frac{7\pi^2 R^2 (pR+2kG_{\ell t})L^4 + 240\left(E_\ell + \frac{pR}{2}\right)I\pi R(pR+2kG_{\ell t})L^2 + 576\left(E_\ell + \frac{pR}{2}\right)^2 I^2}{\left(E_\ell + \frac{pR}{2}\right)I\pi R(pR+2kG_{\ell t})\left(\pi R(pR+2kG_{\ell t})L^2 + 3\left(E_\ell + \frac{pR}{2}\right)I\right)} \tag{F.25}$$

$$\varphi(0)=\varphi_a=-\frac{F}{32}\frac{\pi^2R^2\left(pR+2kG_{\ell t}\right)^2L^4+22\left(E_\ell+\frac{pR}{2}\right)I\pi R\left(pR+2kG_{\ell t}\right)L^2+48\left(E_\ell+\frac{pR}{2}\right)^2I^2}{\left(E_\ell+\frac{pR}{2}\right)I\pi R\left(pR+2kG_{\ell t}\right)\left(\pi R\left(pR+2kG_{\ell t}\right)L^2+3\left(E_\ell+\frac{pR}{2}\right)I\right)} \tag{F.26}$$

$$F_\ell=\frac{3p\pi^2R^3}{L} \tag{F.27}$$

Propped cantilever beam, distributed load

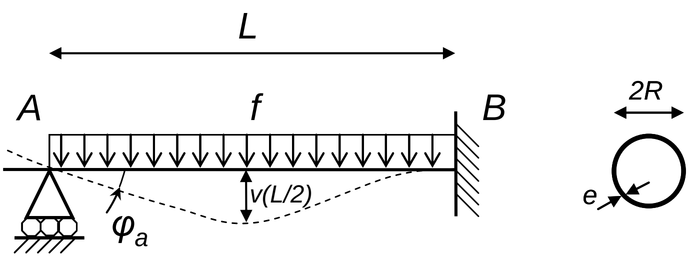


Figure F-6 Propped cantilever beam with a distributed load

Maximum displacement and slope, collapse load:

$$v\left(\frac{L}{2}\right)=-fL^2\frac{\left(2L^4\pi^2R^2\left(pR+2kG_{\ell t}\right)^2+63\pi R\left(pR+2kG_{\ell t}\right)\left(E_\ell+\frac{pR}{2}\right)IL^2+144\left(E_\ell+\frac{pR}{2}\right)^2I^2\right)}{384\left(3\left(E_\ell+\frac{pR}{2}\right)I+\pi R\left(pR+2kG_{\ell t}\right)L^2\right)\pi R\left(pR+2kG_{\ell t}\right)\left(E_\ell+\frac{pR}{2}\right)I} \tag{F.28}$$

$$\varphi(0)=\varphi_a=-fL\frac{\left(L^4\pi^2R^2\left(pR+2kG_{\ell t}\right)^2+30\pi R\left(pR+2kG_{\ell t}\right)\left(E_\ell+\frac{pR}{2}\right)IL^2+72\left(E_\ell+\frac{pR}{2}\right)^2I^2\right)}{48\left(3\left(E_\ell+\frac{pR}{2}\right)I+\pi R\left(pR+2kG_{\ell t}\right)L^2\right)\pi R\left(pR+2kG_{\ell t}\right)\left(E_\ell+\frac{pR}{2}\right)I} \tag{F.29}$$

$$F_\ell=3\frac{p\pi^2R^3}{L} \tag{F.30}$$

F4 Bi-clamped beam

Bi-clamped beam, point load

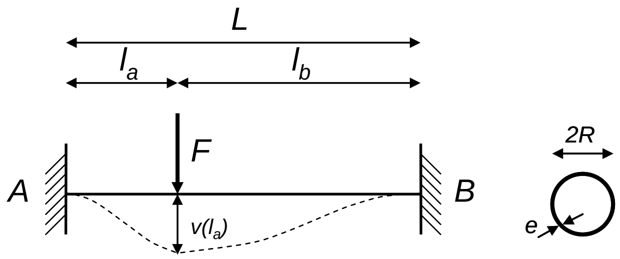


Figure F-7 Bi-clamped beam with a single point load

Maximum displacement, collapse load:

$$v(\ell_a) = -F\ell_a\ell_b \frac{\left(\begin{array}{l}\pi^2R^2\left(pR+2kG_{\ell t}\right)^2\ell_a^2\ell_b^2+\\ 3\pi R\left(pR+2kG_{\ell t}\right)\left(E_\ell+\dfrac{pR}{2}\right)I\left(L^2+L\ell_a-\ell_a^2\right)+36\left(E_\ell+\dfrac{pR}{2}\right)^2 I^2\end{array}\right)}{3L\pi R\left(pR+2kG_{\ell t}\right)\left(E_\ell+\dfrac{pR}{2}\right)I\left(\pi R\left(pR+2kG_{\ell t}\right)L^2+12\left(E_\ell+\dfrac{pR}{2}\right)I\right)} \quad \text{(F.31)}$$

$$F_\ell = \frac{p\pi^2R^3L}{2\ell_a\ell_b} \quad \text{(F.32)}$$

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

$$v\left(\frac{L}{2}\right) = -FL\frac{\pi R\left(pR+2kG_{\ell t}\right)L^4+48\left(E_\ell+\dfrac{pR}{2}\right)I}{192\pi R\left(pR+2kG_{\ell t}\right)\left(E_\ell+\dfrac{pR}{2}\right)I} \quad \text{(F.33)}$$

$$F_\ell = \frac{2p\pi^2R^3}{L} \quad \text{(F.34)}$$

Bi-clamped beam, distributed load

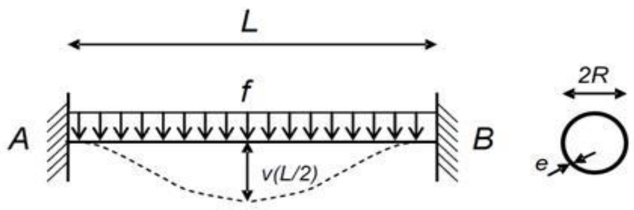


Figure F-8 Bi-clamped beam with a distributed load

Maximum displacement, collapse load:

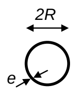
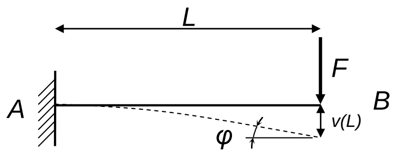
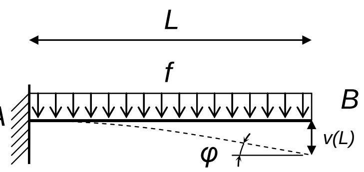
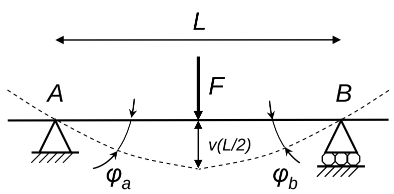
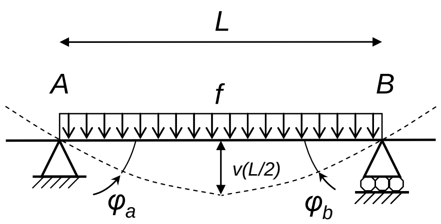
$$v\left(\frac{L}{2}\right) = -\frac{f}{384\left(E_\ell + \frac{pR}{2}\right)I}L^4 - \frac{f}{8\pi R\left(pR + 2kG_{\ell t}\right)}L^2 \tag{F.35}$$

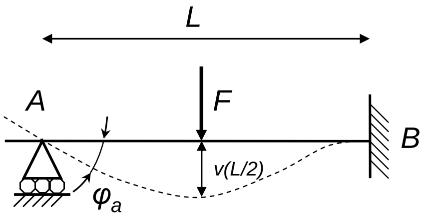
$$F_\ell = \frac{4p\pi^2 R^3}{L} \tag{F.36}$$

F5 Numerical examples

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

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

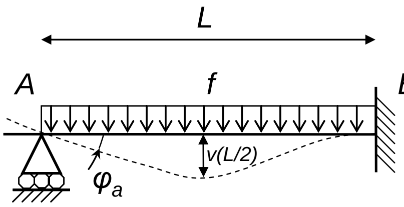
Numerical applications for the examined inflatable tubular beams		
	R = 0.10 m p = 200 kPa $G_{\ell t}$ = 20000 Pam	L = 2 m E_ℓ = 30000 Pam f = F/L
Configurations	**Displacement**	**Collapse load**
	For F = 160 N v(L) = 46 cm	F_ℓ = 246 N
	For F = f·L = 160 N v(L) = 17.7 cm	F_ℓ = 493 N
	For F = 500 N v(L/2) = 10.6 cm	F_ℓ = 937 N
	For F = f·L = 500 N v(L/2) = 6.3 cm	F_ℓ = 1973 N



For F = 800 N

v(L/2) = 9.6 cm

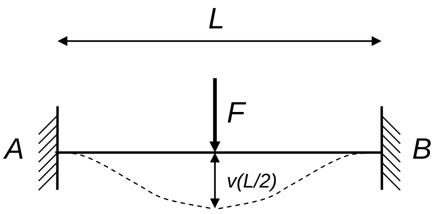
F_ℓ = 1480 N



For F = f·L = 800 N

v(L/2) = 5.3 cm

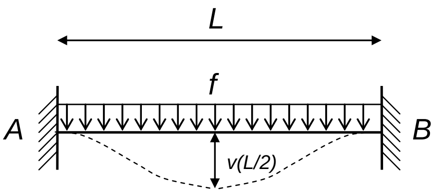
F_ℓ = 2960 N



For F = 1200 N

v(L/2) = 9.9 cm

F_ℓ = 1973 N



For F = f·L = 1200 N

v(L/2) = 4.9 cm

F_ℓ = 3947 N

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