Introduction

Understanding the structural behaviour is crucial.

Example: André Paduart did in 1958 a hand calculation for the design of a steel cable net to cover a band stand at EXPO 58 (Brussels).

Longitudinal hanging cables + transverse arching cables

Pretension = action of the hanging cables on the arching cables and vice versa

Pretension vertical (re)action of 25kg/m²

Report
19 hand written pages
Calculations in plane
Expressing equilibrium of forces
Easy to reproduce
Introduction

Load cases are simplified:

a. Self-weight of the construction: 6 kg/m²
b. Wind: 50 kg/m² (uniform upward, vertical); for the transversal wind: 45 kg/m²
c. Accidental loading: 10 kg/m² (downward)

Self-weight combined with the distributed loads representing the pretension (25 kg/m²):

a. Load on the longitudinal cables: 25 kg/m² + 3 kg/m² = 28 kg/m²
b. Load on the transversal cables: 25 kg/m² - 3 kg/m² = 22 kg/m²

The maximal vertical loading per cable direction:

a. Load on the longitudinal cables: -28 kg/m² - 5 kg/m² (accidental) = -33 kg/m² (~ -0.33 kN/m²)
b. Load on the transversal cables: 22 kg/m² + 25 kg/m² (wind) = 47 kg/m² (~0.47 kN/m²)

**ULS:**
The resistance (design value) according to the Eurocode has the same value as considered by A. Paduart, but he applied a safety coefficient of 2.5.
The wind loading according to the Eurocode (rough approximation of the shape, pressure coefficients 1.8, multiplied with a partial factor of 1.5) is higher than in the calculation of A. Paduart.

**SLS:**
The wind loading is not increased with a factor 1.5
Displacements were not checked by A. Paduart.

Since a long time the idea exists to create a commonly agreed design code for membrane structures.
The design guide of the European project TensiNet was a first step in this direction.
The experts in the field are able to design projects without a Eurocode, why should we have to work on a standard? There are as many different opinions and reasons as there are designers. A common reason is to increase the market and to have the technology seen as an established building technology and not only as a niche market with high risks.

With harmonised safety levels, and commonly agreed quality standards, the quality of the industry will improve. Membranes are often seen as cladding, treated as a pure add-on, neglecting an impact that might be beneficial or unfavourable.

The structure of the Allianz Arena for example has been designed without taking into account the cladding, only it’s self weight was considered. Therefore another 50% of steel was required to do the secondary structure. With an integrated design only half of this would have been required.

Also the Unilever façade has been treated as a simple façade. Therefore it was necessary to build stiff and heavy steel frames to couple the high tensile forces which could not be taken by the concrete building.

The proof engineer of the Dresden Castle ETFE roof answered: I do not check the roof tiles when he received the analysis of the cushions on the roof.

Integrated design is elementary for membrane structures, and without, membrane structures will never become economic. The standardisation process can ensure that in future others treat membrane structures with the required seriousness to the benefit of all.

Bernd Stimpfle, form-TL
The design guides developed in various countries have varying emphases on the factors which have to be combined to form a total safety factor ...

The strength of a membrane material (and its seams) is dependent on factors such as:
- the type of material, the method of jointing …
- age, fatigue, creep, temperature, environmental conditions …
- as well as some unevenness of the material introduced during manufacture.

The IASS Working Group Recommendations for the Design of Air Supported Structures (1986) proposes that the total safety factor (based on a permissible stress approach) is obtained by applying various coefficients:
- unevenness of material: $L_1 = 1.25$ for warp & $1.43$ for weft
- accuracy of calculations: $L_2 = 1.0$ when confirmed by experiment; otherwise: $L_2 = 1.3$
- uncertainty of loading, for application, and for execution: all normally: $L_3, L_4, L_6 = 1.0$
- material reliability / reliability of test results: $1.1 < L_5 < 1.3$
- other factors / unforeseen aspects: $L_7 = 1.2$ (min)

The product of these coefficients lies in the range: $2.1 – 2.5$ for warp, and $2.5 – 2.9$ for weft.

For environmental degradation (UV-radiation, cyclic loading, high temperatures, creep, humidity …) a factor in the range $2.0 – 2.4$ is suggested.

In summary, a total factor of safety for the membrane material lies in the range: $4.2 – 6.0$ for warp, and $5.0 – 7.0$ for weft.

In the ASCE Standard for tensile membrane structures permissible stress resultant values are assessed as follows:

In case of uniaxial loading:
$$T_p = \beta \cdot L_t \cdot T_{sm}$$

where:
- $\beta$ = Strength Reduction factor depending on loading systems = 0.27 for most loading combinations
- $L_t$ = Life Cycle factor
- $T_{sm}$ = specified minimum breaking strength (warp or weft)

In case of bi-axial loading:
$$T_p = \beta \cdot L_t \cdot (T_{sw} + T_{sf})$$

In summary:

For permanent or semi-permanent structures (and long term loadings):
- a minimum stress factor for the membrane material of 5 is frequently used.

For short term / gust loadings:
- factors between 3 – 4 are used.

For connections or stress concentrations:
- factors of up to 7 are used.

Within CEN TC 250 Structural Eurocodes Working Group 5 on structural membranes was created to elaborate the corresponding design code.
The use of tensile surface structures is a growing market.

Used in the form of small scale canopies, performance enhancing façades as well as large span roof structures and even formwork for light shell structures.

The SaP report contains:
1. General explanations for the design of membrane structures
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, which could be part of the future Eurocode for membrane structures.

A future Eurocode has to fit to the principles of the existing Eurocodes to achieve a harmonized level of safety:

1. Specifications of Eurocode 0 “Basis of Design” have to be considered
2. Loads specified in Eurocode 1 “Actions on Structures” have to be applied
3. Design rules for membrane structures have to be applicable simultaneously with other material based design standards (Eurocode 2 to 9 for concrete, steel, composite, timber ... aluminum structures).

For structural membranes life expectancy is not always 50 years but the overall structure could be made for 50 years and after a certain time the structural membrane could be replaced.

Since \( \beta \) is linked to the reference period \( \beta \) could be adjusted if a structural membrane is designed for a shorter lifetime.

Steel, aluminium and concrete structures show in most cases a linear behaviour.

Tensile membrane structures behave in a non-linear way.

This means that the relationship between the action and the action effect is over- or under-linear.

It has to be distinguished whether the partial factor has to be considered on the action or only on the action effect.
Factors are specified to take into account a strength reduction due to:

- $k_{\text{age}}$: environmental impacts (pollution, UV-rays, rain...)  
- $k_{\text{biax}}$: a biaxial stress state  
- $k_{\text{long}}$: the effect of long term loads  
- $k_{\text{temp}}$: the effect of elevated temperature  
- $k_{\text{size}}$: the size of membrane panels  

The design tensile strength of the membrane material or the joint is given by:

$$f_d = \frac{f_{k,23}}{\prod (k_{\text{age}}; k_{\text{biax}}; k_{\text{long}}; k_{\text{temp}}; k_{\text{size}}; k_x)}$$

with $k_i \geq 1.0$

Reference: lectures from Jean-Armand Calgaro and others at http://www.novelstructuralskins.eu/events/training-schools/

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1989: agreement for a mandate for 20 years  
Responsibility for the development: CEN TC 250  
First Eurocodes established  
2010: withdrawal of contradictory national standards  
2012: New mandate:  
  - Maintenance  
  - Harmonisation  
  - Develop new parts, like for membrane structures

Reference: EN-1990 Eurocode - Basis of structural design
The probabilistic approach of structural safety:
- Identify limit states
- Evaluate the risks
- Design in such a way that the probability of the mentioned risks is low

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Semi-probabilistic verification:
- Adopt representative values for actions, resistances...
- Apply partial factors \( \gamma \) to actions, resistances...
- Introduce safety margins in the models of actions, action effects...

EUROCODE
Verification SLS
\[ E_d < C_d \]
- Specific combinations of actions
- Recommended values for the partial factors \( \gamma \)

EUROCODE
Level II procedure
The reliability is defined by the reliability index \( \beta \)
\[ P_f = \Phi(-\beta) \]
EUROCODE

Definition of consequence classes and associated reliability classes

<table>
<thead>
<tr>
<th>Consequence Class</th>
<th>Description</th>
<th>Examples of buildings and civil engineering works</th>
<th>Reliability class</th>
<th>Recommended minimum value for the reliability index (1 year reference period)</th>
<th>70 year reference period</th>
</tr>
</thead>
<tbody>
<tr>
<td>CC1</td>
<td>High consequence for loss of human life or economic, social or environmental consequences very great</td>
<td>Residential and office buildings, public buildings where consequences of failure are low or medium</td>
<td>RC1</td>
<td>5.2</td>
<td>4.7                     (10^{-5})</td>
</tr>
<tr>
<td>CC2</td>
<td>Medium consequence for loss of human life, economic, social or environmental consequences considerable</td>
<td>Residential and office buildings, public buildings where consequences of failure are medium or high</td>
<td>RC1</td>
<td>4.7</td>
<td>3.8</td>
</tr>
<tr>
<td>CC3</td>
<td>Low consequence for loss of human life, economic, social or environmental consequences small or negligible</td>
<td>Apartment buildings where people do not normally remain inside</td>
<td>RC1</td>
<td>4.2</td>
<td>3.5                     (10^{-5})</td>
</tr>
</tbody>
</table>

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EN 1990 specifies failure consequences for ULS and SLS
Considering normal failure consequences with reliability class 2
the failure probability \( P_f \) ranges from \( 10^{-2} \) in SLS
up to \( 7 \times 10^{-5} \) in ULS
in which case the reliability index \( \beta = 3.8 \)

The target value \( \beta_{50} = 3.8 \)
corresponds to the 'acceptable' probability of failure \( P_f = 7.2 \times 10^{-5} \)

The \( \beta \)-value is a formal number to develop consistent design rules
It does not give a real indication of the structural failure frequency

EUROCODE

Basis for Partial Factor Design and Reliability Analysis

Target reliability index \( \beta \) for Class RC2 structural members

<table>
<thead>
<tr>
<th>Limit state</th>
<th>Target reliability index</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1 year</td>
</tr>
<tr>
<td>Ultimate</td>
<td>4.7</td>
</tr>
<tr>
<td>Fatigue</td>
<td>1.5 to 3.8</td>
</tr>
<tr>
<td>Serviceability (irreversible)</td>
<td>2.9</td>
</tr>
</tbody>
</table>

1) See Annex B
2) Depends on degree of inspectability, reparable and damage tolerance

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\( E \) and \( R \) are independently Normally distributed with parameters \( (\mu, \sigma) \) and \( (\mu, \sigma) \)
For a reliable design \( Z = (R_d - E_d) > 0 \)
\( Z \) also follows a Normal distribution
The reliability index \( \beta = \frac{\mu_d}{\sigma_d} \)
The target reliability index is \( \beta_{50} \)
For a reliable design \( \beta \geq \beta_{50} \)
The partial safety factors are function of the target reliability index $\beta$ (design point).

Verification with the partial factors:

$$g_F E_k < \left(\frac{1}{g_M}\right) R_k$$

Or

$$g_F g_M < g_k$$

Final remarks

Remaining questions:
- In Eurocode 0 a reliability index $\beta$ of 3.8 is specified for a complete structure. Is considering k-factors a compatible approach?
- Values for SLS and ULS are agreed upon by experts, is the current approach conservative?
- Reduction factors are multiplied. Are they independent?
- Different partial material factors for material and connections?
- …
Final remarks

'European codes can also be used for the analysis and design of unconventional structures'

Johannes Berger