TESTING METHODS AND STANDARDS

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**A3.1 Testing procedures with regard to a general approval**

This document sets out a basis for authorizing the use of textile membrane in building construction. It takes account of the EU Building Products Guidelines which are also valid in Germany in the form of the law dated 28.04.1998, and updated 15.12.2001.

Related documents are The German Model Building Regulations and the National Building Regulations insofar as they contain supplementary requirements on this subject. The standard to be observed is DIN 18200.

This document presents one option for approval testing. It is left to the applicant to carry out any further freewill testing or to try out other methods since in this area there are no standards and no other binding standards. This procedure is therefore written up according to section B of the Building Products Guidelines. The considerations presented here are ideal for high-quality PVC coated polyester fabrics of type III. It is certainly possible to transfer this procedure to other types of fabric but it would then be necessary to consider the individual details again in terms of procedure and acceptance criteria.

The six basis documents for the Building Products Guidelines are:

1. **Mechanical strength and structural stability**
2. **Fire protection**
3. **Hygiene, health and environmental protection**
4. **Operating safety**
5. **Sound protection**
6. **Energy saving and thermal protection.**

All the documents printed in bold above are relevant to membranes. The roles of basis documents 1, 2 5 and 6 are self explanatory. The role of basis document 3 however needs a little further explanation:

a) In the case of high air humidity levels there is the problem of the PVC being affected by moulds. This must be counteracted by means of suitable additives. This effect needs to be investigated. In addition over a long period of time the membrane will become contaminated. Precautions against this can be taken by the use of a particular top coat. Here again the soiling behaviour must be investigated.

b) Sound protection requires special consideration as described in more detail below.

Basis document 6 includes light since light is directly involved with energy.
The tests described can be classified as:

Tests required for the initial approval of the coating firm
Tests required for the self-monitoring of the coating firm
Tests required for the external monitoring of the coating firm
Tests required for the initial monitoring of the fabric manufacturer
Tests required for the self-monitoring of the fabric manufacturer
Tests required for the external monitoring of the fabric manufacturer.

In addition, and within the scope of the authorization required from the Building Inspection Authorities, it is necessary to present evidence of identity and reduction factors.

The evidence required of the mechanical strength and stability can be considered under the following headings and sub-headings.

**A3.1.1 STRENGTH AND STABILITY OF THE MATERIAL**

**A3.1.1.1 Short-term behaviour**

In general all strength investigations are carried out as uniaxial strip tests. It is generally understood that with a biaxial load the strength will be lower than that with a uniaxial load. For this reason a reduction factor is inserted which is not determined but simply assumed. The reason for this is that the biaxial strength is very difficult to measure. In the biaxial testing rig familiar to the authors it is the strength of the sample and not that of the material which is determined since the failure always starts from an edge. Another method would be the examination of a cylinder which is loaded by an axial compression load. In the manufacture of a cylinder however a seam is necessary at which point this sample body would also tear preferentially. A solution to this would appear to be the bursting test which is proposed in the standards, but which will first have to be examined more closely. (Corresponding tests in preparation.)

To obtain the uniaxial strip strength loaded parallel with the yarn direction we recommend the use of 100mm wide samples of fabric cut parallel to the warp and parallel with the weft as defined in DIN 53354, EN ISO 13934-1 and other standards. Although most European standards are still based on 50mm-strips, 100 mm wide samples lead to more consistent results because the number of threads has less influence. In setting the number of tests it is necessary to decide which evaluations are the most important. If only the average value is to be given then normally 5 tests are sufficient. If however more accurate information on the distribution of measured values are to be given, for example to calculate the 5% fractile, then significantly more tests are required. However if the 5% fractile can be safely given, this can then be used to establish a reduction factor for the lack of homogeneity in the fabric. It should also be noted that strength can depend on where the sample has been removed from the cloth. For example at the edge of a roll lower strengths are often measured compared with those taken from the middle. The values at the start of a roll can also turn out to be lower than those in the middle. It is therefore necessary to prepare a sampling plan so as to be able to interpret any non-homogeneous strength distributions.
For individual breaking test results it is necessary to give:

a) the type of break
b) width of strip
c) breaking stress
d) average value
e) standard deviation
f) 5% fractile
g) sample removal plan

If a device exists to measure elongation it should be checked and calibrated at the same time to comment on any differences in the elongation behaviour. Such a device can only operate on an optical basis and must not be a device relying on physical contact, since the latter could destroy the measuring equipment. If characteristic subsets are found in the results, should these be traced back to the sampling plan, then such subsets will have to be treated as separate statistics since they would falsify the latter.

The uniaxial strip test should be carried out at different temperatures: -20°C, 23°C and 70°C:

– At 23°C
  Test procedure: According to DIN 53354, EN ISO 1421 (EN ISO 13934-1) with the alteration that the width of the sample must be 100mm.
  Test type: Initial approval, self-monitoring, external monitoring
  Duty to provide evidence: Coating firm
  Test quantity: At least 5 in each direction warp and weft
  Initial test: 20 warps and 20 wefts at 23°C
  Self-monitoring: 10 warps, 10 wefts per batch
  External monitoring: Visit twice per annum, removal of a 2m wide piece at a random interface, 10 warp tests, 10 weft tests.

– At 70°C
  All other things being equal, the above prescription applies here, with the additional requirement that the samples must be brought up to the testing temperature for at least one hour before testing and that the clamps must also be at the sample temperature if at all possible.

N.B.: For a PVC coated polyester fabric a temperature of 70°C can be reached without any problems. For other fabrics however other testing temperatures must be used, so that under the effect of the sunrays they don't heat up too much. Until there is evidence of lower heating-up temperatures however 70°C should be set. The evidence of lower testing temperatures can either be determined by calculation using the absorption curves for radiation or by means of tests.
### Test procedure:
According to DIN 53354, EN ISO 1421 (EN ISO 13934-1) with the alteration that the width of the sample must be 100mm.

### Test type:
Initial approval, self-monitoring, external monitoring

### Duty to provide evidence:
Coating firm

### Test quantity:
At least 5 in each direction warp and weft

#### Initial approval:
- 20 warp samples, 20 weft samples

#### Self-monitoring:
- 5 warp samples, 5 weft samples per batch

#### External monitoring:
- 5 warp samples, 5 weft samples, for removal see above

- At -20°C

Here again, all other things being equal, the above applies. The test does not have to be carried out if the application is not expected to reach these temperatures.

### Test procedure:
According to DIN 53354, EN ISO 1421 (EN ISO 13934-1) with the alteration that the width of the sample must be 100mm.

### Test type:
Initial approval

### Duty to provide evidence:
Coating firm

### Test quantity:
20 warp samples, 20 weft samples

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### The bi-axial strength

In addition to the strip tests two-dimensional **bursting tests** should be carried out for the initial approval. The difficulties in carrying out bursting tests are due to the fact that the fabrics are anisotropic materials. This means that the deformation shape only approximates to a calotte shell and the determination of the failure load has many elements of uncertainty. The problem must however be investigated further.

### Test procedure:
Bursting test according to EN ISO 53861 with a circle diameter of 500 mm

### Test type:
Initial approval

### Duty to provide evidence:
Coating firm

### Test quantity:
To be established according to the spread of the tests but at least three

---

### The tear strength

The tear-type damage must be defined properly. What is needed is the load at which the tear will be subject to unstable propagation so that the membrane finally fails. The governing theory here is that of fracture mechanics in which the stress concentration factor is defined as the decisive variable. This material variable is defined on the basis of the linear theory of elasticity and it can be applied to anisotropic materials without problems. It can be shown that this theory is also valid as a good approximation for coated fabrics.
– Evaluation method by means of biaxial tear tests

The evaluation should be done according to linear-elastic fracture mechanics where a stress concentration factor $K_c$ is defined as following:

$$K_c = \sqrt{\pi a \sigma}$$

with $a$: half of the slit length,
$\sigma$: stress perpendicular to the slit direction ad infinitum.

It has been proved that this procedure can be applied to anisotropic fabrics with adequate accuracy. The stress concentration factor is a material constant from which can be calculated either the stress level at which a slit with a certain length is going to propagate or how long a slit could be when held at a particular stress level without propagation occurring.

For the formulation of a reduction factor it is proposed to start with a slit of 5cm and to take into the load/unit width at which the tear starts to propagate.

**Test procedure:** According to LBV P1111  
**Evaluation:** According to LBV P1111  
**Test type:** See comments  
**Duty to provide evidence:** See comments  

Comments: Whether a time-consuming tear growth test is really part of the approval process has still to be discussed. Normally textile structures are not at risk of tearing after erection.

– Uniaxial tear growth test (Trapezoidal test)

**Test procedure:** DIN 53363  
**Evaluation:** See standard  
**Test type:** Initial approval, external monitoring  
**Duty to provide evidence:** Coating firm  
**Test quantity:** At least 5 in warp and 5 in weft  
**Initial approval:** 10 warp samples, 10 weft samples  
**External monitoring:** 5 warp samples, 5 weft samples

In the textile industry the trapezoidal test has become well established since it is easy to carry out and is subject to DIN standard no. 53363. This test can however at the very best be used as a comparison test between different fabrics. No conclusion about actual tear strength can be drawn from this test. The test is only included for the sake of completeness.
A3.1.1.2 Long-term strength behaviour

- Strength loss following loading

The long-term strength behaviour test is carried out in exactly the same way as for the short-term strength test in uniaxial strip tests parallel with the yarns. The following load steps should be set:

10% of the short-time tensile strength at 23°C according to A3.1.1.1.
20% of the short-time tensile strength at 23°C according to A3.1.1.1.
50% of the short-time tensile strength at 23°C according to A3.1.1.1.
90% of the short-time tensile strength at 23°C according to A3.1.1.1.

Test series should be done to obtain a sensitive reduction factor for long-term-loading. After 1000 hours the residual strength is established.

**Test:** After uniaxial loading at 23°C over 1000 hours uniaxial strength according to A3.1.1.1
**Test type:** Initial test
**Duty to provide evidence:** Coating firm
**Test quantity:** At least three samples for each load in the warp direction and three in the weft direction

- Strength loss due to exposure to weather

After the pure loading tests artificial weathering tests are also required. In these weather exposure tests strips taken in the warp and weft directions are subjected to a standard climate. The exposure time is normally 1000 hours. At the end of this period the strengths are determined. A time acceleration of a factor of 10 can be achieved. In other words after 1000 hours of artificial weathering the strength loss after 10,000 hours can be determined. There exist calculation methods for the determination of the strength loss based on the tests. At the present time work is being done to formalize the calculation methods.

More test data of commonly used materials are needed.

A3.1.2 STRENGTH OF THE CONNECTING SYSTEM

A3.1.2.1 Welded seams

A3.1.2.1.1 Short-term behaviour

Seam strengths in uniaxial tests parallel with the yarns

Current industry practice is for the membrane fabricator to be responsible for the seam and its strength. On the other hand the seam strength depends to a great extent on the bonding strength of the coating on the fabric, for which the coating firm is responsible. There is
thus a split in responsibility here. The consequence of this is that the coating firm should show what can be achieved by optimizing the technology of bonding the coating onto the fabric. Prototype trials are necessary. By means of these trials the seam strength must be proven.

The strength of the seam for different seam widths needs to be established. The seam width is increased until no more increase in strength is possible. This permits the definition of an optimum seam width. Up to this optimum seam width the strength increases linearly with the width. From this and knowing the optimum width it is then possible to determine the minimum seam width. This then permits to know the seam strength based on the width.

It remains to be said that other seam arrangements may lead to higher seam strengths.

This leads to two further tasks:

- Determination of the dependence of strength on seam width at 23°C

<table>
<thead>
<tr>
<th>Test procedure:</th>
<th>DIN 53354/ EN ISO 1421 and LBV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test type:</td>
<td>Initial approval</td>
</tr>
<tr>
<td>Duty to provide evidence:</td>
<td>Coating firm, fabric manufacturer</td>
</tr>
<tr>
<td>Test quantity:</td>
<td>At least 5 in each direction warp and weft, 20 samples in warp direction, 20 samples in weft direction for both the coating firm and the fabric manufacturer</td>
</tr>
</tbody>
</table>

The fabric manufacturer needs to prove whether he can achieve the strength which has been achieved and proven by the coating firm or whether, for whatever reason, he has to make concessions. Accordingly he must establish his seam width and define and prove the corresponding strength.
- Determination of seam strength at 23°C for the seam width established by the fabric manufacturer as normal

  **Test procedure:** DIN 53354/ EN ISO 1421
  **Evaluation:** According to above mentioned standards or EN ISO 13934-1
  **Test type:** Initial approval, self-monitoring, external monitoring
  **Duty to provide evidence:** Fabric manufacturer
  **Test quantity:** At least 5 in each direction warp and weft
  **Initial approval:** 20 samples in warp direction 20 samples in weft direction
  **Self-monitoring:** 5 samples in warp direction, 5 samples in weft direction per 1000m² of fabric
  **External monitoring:** 10 samples in warp direction, 10 samples in weft direction

- Seam strengths at -20°C and +70°C

  Here it is only necessary to carry out parallel-yarn uniaxial tests. All other things being equal to the proposals outlined above. Biaxial tests are not required here.

  **Test procedure:** DIN 53354/ EN ISO 1421 fabric
  **Evaluation:** According to above mentioned standards or EN ISO 13934-1
  **Type of test:** Initial approval, external monitoring
  **Duty to provide evidence:** Fabric manufacturer
  **Test quantity:** at least 5 in each direction warp and weft
  **Initial approval:** 10 samples each in warp direction, 10 samples each in weft direction
  **External monitoring:** Inspection visits twice per annum, removal of a 2m wide piece from a random interface, manufacturing of the seam, 10 warp tests, 10 weft tests

- Biaxial seam strength

  So far the determination of seam strength has been suitably defined. In most structures the actual seam directions will not be able to align themselves exactly with the warp direction. Therefore in the tests for biaxial seam strength it is necessary to include a small angle of deviation. In the general situation this angle will be reduced as discussed later. However the strength of the seam will be dependent on this angle so this value should be determined. It cannot however be established in uniaxial tests since in that case shear distortions will occur which do not occur in practice. This strength can only be measured in biaxial tests. The standard biaxial tests however nearly always result in a failure starting from the edge so that it is really only the sample shape which is being tested and not the seam. It is only the bursting test which is capable of answering the question of the biaxial strength.
The bursting test is required here and the diameter of the base circle should be at least five times the seam width.

The results of the bursting tests will establish the reduction factor of the parallel uniaxial seam test as a result of biaxial loading.

**Test procedure:** According to EN ISO 52861-3
**Evaluation specifications:** Still to be prepared
**Type of test:** Initial approval
**Duty to provide evidence:** Coating firm, fabric manufacturer
**Test quantity:** To be established according to initial tests

A3.1.2.1.2 The long-term behaviour of the seam strength

- According to load

The strength in long-term behaviour is established in the same way as for short-term strength in single axis tests parallel with the yarns. The following loading steps are to be used:

**Prestress**
**Working stress**
**Mean value of prestress and working stress**
**75 % of the sum of prestress and working stress**
**25 % of the sum of prestress and working stress**

Ten samples are to be tested for each load step. After 1000 hours the residual strength can then be established. Prestress and working stress are defined with respect to the strength (see A3.1.3.1).

**Test:** Single axis strength after uniaxial loading at 23 degrees over 1000 hours according to ISO 4892-2
**Test type:** Initial test
**Duty to provide evidence:** Fabric manufacturer
**Test quantity:** Three samples for each load in the warp direction and three in the weft direction

- Strength reduction after exposure to weather

Beside the pure loading tests artificial weathering tests are also required. In this weather exposure test strips are taken in the warp and weft directions and are subjected to a standard climate. The exposure time is normally 1000 hours. After this time the strengths are determined. A time acceleration of a factor of 10 can be achieved. In other words after 100 hours of artificial weathering the strength loss after 10,000 hours can be determined. There exist calculation methods for the determination of the strength loss based on the tests. At the present time work is being done to formalize the calculation methods.
A3.1.2.2 Clamped connections

A3.1.2.2.1 Short-term behaviour

In a clamped seam the two edges to be joined together are both provided with a “Keder” edge and then perforated at a defined spacing. The two edges are then bolted together with clamping plates. The “Keder” bears against the edges of the clamping plates such that the force is transferred in direct bearing. The clamping pressure must never be so great that the force to be transferred between the two panels is only passed by friction, since the strength of the yarn is reduced by high transverse pressure. The “Keder” material must not be so soft that it can be dragged in between the clamp plates by the membrane tension. It’s also necessary to consider that a temperature range of -20°C to +70°C can arise. For this reason the “Keder” material should never be soft PVC, but rather an elastomer material having the requisite temperature resistance. The clamping force is produced by bolts and for these bolts the clamping plates have to be drilled and the membrane perforated. The hole spacings should match up with one another in the prestressed condition. For this purpose the spacing of the holes, when the membrane is lying, unstrained on the floor of the fabrication hall, have to be compensated for.

The stress distribution in the area around the hole shows a stress concentration from which stress singularities could affect the membrane. These must not lead to failure, therefore part of the membrane forces arising should be taken up by friction resulting from compression. Also the hole spacings must not be so small that such singularities, when combined with the other forces, could lead to damage.

In the prestressed condition the membrane pulls slightly into the clamps. Because of this it’s possible that the hole face could be forced against the clamping bolt and damage may develop at this point. The hole in the membrane must therefore always be greater than the bolt which passes through it.

Demonstrating the capacity of such connections is a task for the fabric manufacturer. He can do this via uniaxial strip tests with the yarns parallel with the applied load.

Determination of the strength of a clamped seam in a uniaxial test, parallel to the yarns at 23, -20 and 70°C:

- At 23°C
  
  **Test procedure:** According to DIN 53354/ EN ISO 1421 similar to the uniaxial seam test
  
  **Evaluation:** See above
  
  **Type of test:** Initial approval, self-monitoring
  
  **Duty to provide evidence:** Fabric manufacturer
  
  **Test quantity:** At least 5 in each direction warp and weft
  
  **Initial approval:** 10 strips in the warp direction, 10 strips in the weft direction
  
  **Self-monitoring:** 5 tests per 1000m of continuous clamped seam
- At 70°C
  Test procedure: According to DIN 53354/ EN ISO 1421 similar to the uniaxial seam test
  Evaluation: See above
  Type of test: Initial approval, self-monitoring
  Duty to provide evidence: Fabric manufacturer
  Test quantity: At least 5 in each direction warp and weft
  Initial approval: 10 strips in the warp direction, 10 strips in the weft direction
  Self-monitoring: 5 tests per 1000m of continuous clamped seam

- At -20°C
  Test procedure: According to DIN 53354/ EN ISO 1421 similar to the uniaxial seam test
  Evaluation: See above
  Type of test: Initial approval
  Duty to provide evidence: Fabric manufacturer
  Test quantity: 10 strips in the warp direction, 10 strips in the weft direction

For the testing of the clamped edge the above description for the clamped seam can be used. The test required is again the uniaxial, parallel-yarn strip test. As above it is essential to ensure that the clamps etc. are also brought up to the testing temperature.

- Long-term behaviour of clamped connections
  No tests are foreseen for the long-term behaviour of clamped connections.
A3.1.2.3 Pocket edges: Tubular and cable edges

A3.1.2.3.1 Short-term behaviour

For the testing of the pocket edge the above description for the clamped seam can be used.

N.B.: On a cable edge it is essential to ensure that the cable remains straight during the test and does not become bent since otherwise another form of failure will occur.

A3.1.2.3.2 Long-term behaviour

No tests on the long-term behaviour of pocket edges are proposed.

A3.1.3 DEFORMATION BEHAVIOUR

A3.1.3.1 Biaxial, parallel yarn tests

Biaxial tests are not intended for strength measurement. They are to establish the compensation data and to determine the moduli of elasticity. For this reason it is only necessary to carry out the tests in the relevant load range, which therefore needs to be defined. It is only possible here to provide general data and each individual case is the responsibility of the engineering consultancy and the building inspectorate. In general a safety factor of 5 is used, but this should always be discussed in accordance with the design engineer’s analysis and may vary from case to case. In the example given below how these tests could be carried out the working stress is one fifth of the strength measured in the uniaxial test. The prestress is nor-
mally about a fifth and may be up to one tenth of the working stress since it can depend on
the curvature of the surface and the orientation of the weave. Here the one-fifth figure should
be started with. Thus the prestress is about one twenty-fifth of the uniaxial strength. Now it
is not always true that the same prestress is found in the warp and weft therefore it is nec-
essary to start with tests in which the following are taken as the basis of testing:

\[
\begin{align*}
\text{Warp prestress : weft prestress} &= 1 : 2 = \frac{1}{50} \text{working stress : } \frac{1}{25} \text{working stress} \\
\text{Warp prestress : weft prestress} &= 1 : 1 = \frac{1}{25} \text{working stress : } \frac{1}{25} \text{working stress} \\
\text{Warp prestress : weft prestress} &= 2 : 1 = \frac{1}{25} \text{working stress : } \frac{1}{50} \text{working stress}
\end{align*}
\]

In addition it is necessary during biaxial tests to simulate the behaviour in the building
structure, in other words under real conditions. Real loads are snow and wind. If the main
anisotropic directions are approximately parallel with the warp and weft, then in this load
case one of the directions is loaded and the one which is perpendicular to it is relieved of
load. This procedure is then inversed and the previously loaded direction is unloaded and
the previously unloaded direction is then loaded. Which direction is the warp and weft
depends of course on the design.

Also it must be remembered that the loads for which the stresses are calculated only occur
very seldom if at all. For safety reasons it is always the highest load which is used. It is then
realistic not to assume that the working stress is the upper limit but only 80% of it. Therefore
the upper limit of the load in the test is 0.8 x working stress. A characteristic load history is
shown in Fig. A3.6.

![Characteristic load history](image)

**Fig. A3.6** Characteristic load history, red = stress in warp direction, blue is the stress in the weft direction

**Test procedure:** According to laboratory specification LBV P 1106

**Evaluation:** As described below

**Test type:** See comments

**Duty to provide evidence:** Coating firm

**Test quantity:** at least 2 of the same prestress ratio
Here it is necessary to differentiate between two cases: either the coating firm can prove that its product is homogeneous then the test can be limited to initial approval and external monitoring. However where the proof of homogeneity is unsuccessful, it is then necessary to carry out at least one corresponding biaxial test for each production batch. In the case of larger building projects the tendering engineer can specify self-testing in the tender. Who then has the duty of providing evidence should be discussed individually and this is then incorporated in the price.

– Determination of linear elastic moduli: Theory

The following nomenclature is used:
The index 1 indicates the warp direction, the index 2 the fill or weft direction
Stresses and strains have two indices since they are tensors of second rank
E-moduli and compliances have four indices since they are tensors of fourth rank
Stresses are indicated by \( n \), strains by \( \varepsilon \), E-Moduli by E and compliances by C
\( n_{11} \) stress in warp direction, \( n_{22} \) stress in fill direction,
\( \varepsilon_{11} \) strain in warp direction, \( \varepsilon_{22} \) strain in fill direction.

So we find the following abbreviations:

\( E_{1111} \) stiffness in warp direction, \( E_{2222} \) stiffness in fill direction, \( E_{1122} \) stiffness interaction between warp and fill, \( \nu_{12} = \frac{E_{1122}}{E_{1111}} \) Poisson ratio for the interaction between warp and fill \( \nu_{21} = \frac{E_{1122}}{E_{2222}} \) Poisson ratio for the interaction between fill and warp, \( C_{1111} \) compliance in warp direction, \( C_{2222} \) compliance in fill direction, \( C_{1122} \) compliance interaction between warp and fill.

In linear approximation we have the following relations:

\[
\begin{bmatrix}
\varepsilon_{11} \\
\varepsilon_{22}
\end{bmatrix} =
\begin{bmatrix}
E_{1111} & E_{1122} \\
E_{1122} & E_{2222}
\end{bmatrix}
\begin{bmatrix}
\varepsilon_{11} \\
\varepsilon_{22}
\end{bmatrix}
\]

with the inversion:

\[
\begin{bmatrix}
\varepsilon_{11} \\
\varepsilon_{22}
\end{bmatrix} =
\begin{bmatrix}
C_{1111} & C_{1122} \\
C_{1122} & C_{2222}
\end{bmatrix}
\begin{bmatrix}
n_{11} \\
n_{22}
\end{bmatrix}
\]

or, explicitly:

\[
\begin{align*}
n_{11} &= E_{1111} \varepsilon_{11} + E_{1122} \varepsilon_{22} = E_{1111} (\varepsilon_{11} + \nu_{12} \varepsilon_{22}) \\
n_{22} &= E_{1122} \varepsilon_{11} + E_{2222} \varepsilon_{22} = E_{2222} (\nu_{21} \varepsilon_{11} + \varepsilon_{22})
\end{align*}
\]

with the inversion:

\[
\begin{align*}
\varepsilon_{11} &= C_{1111} n_{11} + C_{1122} n_{22} \\
\varepsilon_{22} &= C_{1122} n_{11} + C_{2222} n_{22}
\end{align*}
\]

It should be noted that in general there are three moduli \( E_{1111}, E_{1122} \) and \( E_{2222} \).
The exact method to calculate the moduli in the tests reported here will be shown in evaluation of the first test results. It should be noted that one has to replace the stresses \( n \) and the deformations \( \Delta \) by \( \Delta n \) and \( \Delta \) if one wants to linearize a non-linear behaviour in an interesting interval. An example of this in a prestressed material is normally the interval between the prestress and the working stress.

### Evaluation method

First it should be noted that the elastic moduli need to be calculated between an assumed prestress of 1kN/m and an upper value of 10, 20 and 30kN/m as shown in the load history, figure A3.6. The evaluation method is explained in detail in the following sketches in figure A3.7 which is extracted from the measured strains of the applied stresses of figure A3.6. The procedure corresponds to a typical loading by wind followed by a loading by snow.

In the first part of the first cycles of the load history \( \Delta n_{11} \neq 0, \Delta n_{22} = 0 \). The analogue strain \( \Delta_{11} \) and \( \Delta_{22} \) values can be read from the results.

In the second part \( \Delta n_{11} = 0, \Delta n_{22} \neq 0 \). The analogue strain \( \Delta_{11} \) and \( \Delta_{22} \) values can be read from the results.

Thus for the first part the equations:

\[
\Delta n_{11} = E_{1111} \Delta_{11} + E_{1122} \Delta_{22}
\]

\[
\Delta n_{22} = E_{2222} \Delta_{22}
\]
For the second part we will find:

\[ \sigma = \epsilon_{1111} \Delta \epsilon_{11} + \epsilon_{1122} \Delta \epsilon_{22} \]
\[ \Delta n_{22} = \epsilon_{1122} \Delta \epsilon_{11} + \epsilon_{2222} \Delta \epsilon_{22} \]

With these equations the moduli \( E_{1111}, E_{1122} \) and \( E_{2222} \) can be calculated.

This procedure will be repeated for every part of the load history. Thus an impression of the elastic moduli over the range of loading can be obtained.

The method presented above describes one way of testing and evaluation as it stands in the current state of the art. Other approaches calculating "response surfaces" are being developed (Blum, Gosling et al).

A3.1.3.2 Shear behaviour

The fabric behaviour under parallel yarn stresses has been suitably described above. With the tests defined here nothing can be concluded about any possible shear stresses. For this purpose self-testing must be arranged. First however it is necessary to discuss the significance of the shear modulus in membrane construction.

For this purpose the situation on a seam is analyzed. At a seam an angle change of \( \alpha \) in the plane is necessary to generate a smoothly curved surface from the flat panels cut out of a roll. In the prestressed curved state this angle should approximate to zero, and the main anisotropic lines should run smoothly over the seam. Thereby the angle change over the seam \( \alpha \), corresponds to a shear deformation of \( \epsilon_{12}(\alpha) \). The respective shear stress is \( \epsilon_{12} \times E_{1212} \). This is then superimposed by the initial stress \( n_{11} \) so that the stress state can now be given as:

\[ n_{ab} = \begin{pmatrix} n_{11} & \epsilon_{12} E_{1212} \\ \epsilon_{12} E_{1212} & n_{22} \end{pmatrix} \]

Now the requirement is that none of the main stresses should be negative so the following must be valid:

\[ n_{11} n_{22} - E_{1212} \epsilon_{12} \epsilon_{12} > 0 \]

From this the following condition can be obtained:

\[ \frac{n_{11} n_{22}}{\epsilon_{12}} > E_{1212} \]

The shear modulus should therefore be limited by this condition. Or, if the shear modulus is known, it limits the possible angle change by the requirement that no negative main stresses should occur. The shear modulus itself does not play a significant role in the calculation of the stress distribution in a membrane structure.
It's possible to determine the shear modulus either by a biaxial test or by a uniaxial test.

- Determination of the shear modulus using a biaxial test

This test is very time-consuming and is only meaningful for the initial approval of a fabric.

The sample is shown in Fig. A3.8.

Using a system of coordinates parallel with the edges of the sample the stresses in this sample are given by:

\[
\mathbf{n'}_{\alpha\beta} = \begin{pmatrix}
\mathbf{n'}_{11} & 0 \\
0 & \mathbf{n'}_{22}
\end{pmatrix}
\]

If \( T \) is the matrix of rotation between the system of coordinates on the main anisotropic axes and those parallel to the edge then for \( T \) we can give:

\[
\overline{T} = \begin{pmatrix}
\cos \varphi & \sin \varphi \\
\sin \varphi & \cos \varphi
\end{pmatrix}
\]

where \( \text{Det}(\overline{T}) = 1 \) and \( \overline{T}^{-1} = \overline{T}^T \)

For the relationship between the components of the stress tensor in the two systems of coordinate,

\[
\begin{align*}
n_{11} &= \cos^2 \varphi \ n'_{11} + \sin^2 \varphi \ n'_{22} \\
n_{22} &= \sin^2 \varphi \ n'_{11} + \cos^2 \varphi \ n'_{22} \\
n_{12} &= -\cos \varphi \ \sin \varphi \ (n'_{22} - n'_{11})
\end{align*}
\]

and for \( \varphi = 45° \):

\[
\begin{align*}
n_{11} &= \frac{1}{2} (n'_{11} + n'_{22}) \\
n_{22} &= \frac{1}{2} (n'_{11} + n'_{22}) \\
n_{12} &= \frac{1}{2} (n'_{22} - n'_{11})
\end{align*}
\]

Therefore to create a linearly growing shear stress \( n_{12} \), it is necessary to increase linearly the difference between \( n_{11}' \) and \( n_{22}' \).
Test procedure: LBV
Evaluation: As described below
Shear stress determination: As described above
Shear distortion determination: As described below
Type of test: Initial approval
Duty to provide evidence: Coating firm

The elongations in the warp direction, in the weft direction and in the bisecting line of the angle between warp and weft are measured. First it is necessary to calculate both the stress as well as the strain tensors in the coordinate system of the main axes. Only in this coordinate system the stress-strain-relationship has the simple form:

\[ n_{12} = G \varepsilon_{12} = 2 E_{1212} \varepsilon_{12} \]

In general this can also be written as:

\[ n_{\alpha\beta} = E_{\alpha\beta\delta\gamma} \varepsilon_{\delta\gamma} \]

where all those indices from 1 to 2 which appear twice are summed (Einstein's summation convention). The factor 2 at \( E_{1212} \) stems from the fact that the distortion tensor is symmetrical and thus appears twice in the summation. \( 2 E_{1212} \) is also described as the shear modulus \( G \) for isotropic materials:

\[ 2 E_{1212} = G. \]

In the case of non-linear shear behaviour the tangential shear modulus \( G \) can be defined by:

\[ E_{1212} = \frac{\partial n_{12}}{\partial \varepsilon_{12}} \]
Now it is necessary to calculate all the variables in the coordinate system of the main anisotropic axes. The measuring is done as described above:

The strain in the warp direction $\varepsilon_{11}$
The strain in the weft direction $\varepsilon_{22}$
And the strain in the bisecting angle $\varepsilon_{11}'$.

The strain in the bisecting angle can be obtained according to the transformation rules of tensor calculation:

$$\varepsilon_{11}' = T_{1\mu} T_{1\nu} \varepsilon_{\mu\nu},$$

This equation thus has the following appearance:

$$\varepsilon_{11}' = T_{11} \varepsilon_{11} + 2 T_{12} \varepsilon_{12} + T_{22} \varepsilon_{22}.$$

This can be resolved according to $\varepsilon_{12}$ into:

$$\varepsilon_{12} = \frac{1}{2T_{11}T_{12}} (\varepsilon_{11}' - T_{11} \varepsilon_{11} - T_{12} \varepsilon_{22}).$$

For $\varphi = 45$ degrees:

$$T_{11} = T_{12} = \frac{1}{2} \sqrt{2}$$

and from that is derived:

$$\varepsilon_{12} = \varepsilon_{11}' - \frac{1}{2} (\varepsilon_{11} + \varepsilon_{22}).$$

The tensor of distortions in the main axis system of anisotropics therefore appears as follows:

$$\varepsilon_{\alpha\beta} = \begin{pmatrix}
\varepsilon_{11} & \varepsilon_{11}' - \frac{1}{2} (\varepsilon_{11} + \varepsilon_{22}) \\
\varepsilon_{11}' - \frac{1}{2} (\varepsilon_{11} + \varepsilon_{22}) & \varepsilon_{22}
\end{pmatrix}$$

with the measured variables $\varepsilon_{11}$ along the warp direction, $\varepsilon_{22}$ along the weft direction and $\varepsilon_{11}'$ along the bisecting angle. Now the coefficients of the distortion tensor still have to be indicated. In general it can be said that the distortion tensor (in the two-dimensional case) describes the change in a Cartesian system with the orthonormal dimensional vectors $E_1$ and $E_2$ subject to a deformation $\varepsilon_1$ and $\varepsilon_2$, and – more accurately stated, the change in the corresponding scalar products. The scalar products of $E_0$, because of the orthonormality, can be given by:

$$E_1 E_2 = \begin{pmatrix}
1 & 0 \\
0 & 0
\end{pmatrix}$$
And those of $e_\alpha$, since they are not orthonormal, are derived from:

$$e_1 e_2 = \begin{pmatrix} e_{11} & e_{12} \\ e_{12} & e_{22} \end{pmatrix}$$

Half of the difference between the scalar products $e_\alpha e_\beta$ and scalar products $E_\alpha E_\beta$ is described as distortion:

$$\varepsilon_{\alpha\beta} = \frac{1}{2} \left( e_\alpha e_\beta - E_\alpha E_\beta \right)$$

Thus for the square of the length in direction 1 in the deformed state:

$$|e_1|^2 = 1 + 2\varepsilon_{11}$$

and for the length itself:

$$|e_1| = \sqrt{1 + 2\varepsilon_{11}}$$

For small $\varepsilon_{11}$ it is possible to develop the roots in a series and hence we get:

$$|e_1| = 1 + \varepsilon_{11}$$

In this way $\varepsilon_{11}$ is the change in the length of the unit vector $E_1$. In the same way $\varepsilon_{22}$ is the change in length of the unit vector $E_2$. For $\varepsilon_{12}$, due to the orthonormality of $E_1$ and $E_2$, if the angle between $e_1$ and $e_2$ is set at $90 - \delta$ and taking account of the addition theorem for the cosine:

$$2\varepsilon_{12} = \cos(e_1 e_2) = \cos(90 - \delta) = \sin \delta$$

from which for $\delta$:

$$\delta = \arcsin (2\varepsilon_{12})$$

For small distortions and small angle changes $\delta$:

$$\sin \delta \delta = 2\varepsilon_{12}$$

Therefore it needs to be remembered that $\varepsilon_{12}$ should be given as an absolute rather than a percentage figure and that the angle should be given in radians. Thereby all the distortion variables have been defined.
For the measured results the linear elongation is given, since this is measured directly. Now it is not possible to state that the linear elongation is not accurate. Both definitions are accurate. What is decisive here is with which definition the material law is defined. If there are large elongations the definition of stresses will also have to be included here. Also there are various options which if carried out would be out of all proportion to the framework specified here. For a better estimation of the numerical differences between „linear“ elongation and the elongation defined by metric alteration the differences between the various elongation definitions are numerically listed in the following table.

<table>
<thead>
<tr>
<th>Linear elongation</th>
<th>Linear elongation</th>
<th>Metric elongation</th>
<th>Difference</th>
<th>Difference</th>
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<td>1.00 %</td>
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For the sake of completeness the relationship between the shear distortion $\varepsilon_{12}$ and the angle change $\delta$ for pure shear is summarized in a table and in the form of a graph.
In this figure the relationship between shear angle $\delta$ and shear distortion $\varepsilon_{12}$ is shown:

- Determination of the shear modulus using a uniaxial test

It is also possible to set up an alternative one-dimensional test, which is simpler to carry out and can be used for monitoring. It is shown in fig. A3.11.

For evaluation the angular change is measured as a result of the applied transverse force.

**Test procedure:** According to LBV  
**Type of test:** External monitoring  
**Duty to provide evidence:** Coating firm
### A3.1.3.3 Relaxation behaviour

Relaxation denotes a decrease in the initially induced stress with constant elongation. Biaxial relaxation tests are however very difficult to carry out. It therefore makes sense here to carry out uniaxial tests and then to attempt to work out the fabric behaviour by calculation. As a first approximation it can be assumed that the stress changes linearly with the relaxation behaviour of the yarn. The proportionality constants can be calculated from the E-modulus and the relaxation behaviour of the yarn by means of the following regulation in warp and fill direction:

\[
\text{stress in warp direction in dependance of time: } n_{11}(t) = n_{11}(0) \times f_1(t)
\]
\[
\text{stress in fill direction: } n_{22}(t) = n_{22}(0) \times f_2(t)
\]

where \( f_1(t) \) and \( f_2(t) \) are the relaxation functions of the threads in warp and fill directions.

Thereby the relaxation behaviour of the fabric has been traced back to the relaxation behaviour of the yarn, which needs to be established by experiment.

### A3.1.3.4 Creep

The creep behaviour of the fabric can also be traced back (in the same way as for the relaxation behaviour) to the creep behaviour of the yarn.

### A3.2 Proposal for a general approval of fabric materials for use in textile architecture

#### Table 1: Interpretative Document I

<table>
<thead>
<tr>
<th>Tested object</th>
<th>Measured variable</th>
<th>Device</th>
<th>Norm</th>
<th>Norm</th>
<th>Research</th>
<th>Centre</th>
<th>Manufacturer</th>
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#### Table 2: Material

<table>
<thead>
<tr>
<th>1.1.1. Short-term behaviour</th>
<th>1.1.2. Long-term behaviour</th>
</tr>
</thead>
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<tr>
<td>-1 Material</td>
<td>-1 Relaxation</td>
</tr>
<tr>
<td>-2 Tensile strength and stress</td>
<td>-2 Creep</td>
</tr>
<tr>
<td>-3</td>
<td>-3 Strength after loading</td>
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<tr>
<td>-4</td>
<td>-4 Strength after weathering</td>
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#### Table 3: Welded Seams

<table>
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<td>-1 Stitches/stitch length</td>
</tr>
<tr>
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### 1.2.1. Longterm behaviour

<table>
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<th>Width strip</th>
<th>strain in warp direction</th>
<th>23</th>
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<tbody>
<tr>
<td>1.2.1.</td>
<td>Width strip</td>
<td>strain in weft direction</td>
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### 1.2.2. Clamped connections

#### 1.2.2.1. Shortterm behaviour

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#### 1.2.2.2. Longterm behaviour

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### 1.2.3. Edges in pockets

<table>
<thead>
<tr>
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<th>Width strip</th>
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### 1.2.4. Identification tests

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### 1.3. Stress/strain behaviour

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<td>1.3.2.</td>
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<td>strength after weathering</td>
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### 1.3.1. Shortterm behaviour

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### 1.3.2. Longterm behaviour

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### 1.3.3. Edges in pockets

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</table>

Legend:
- red: Test in biaxial machine
- green: Longterm Stand
- blue: Bursting tests, Diameter of bursting area minimum 500 mm
- pink: Artificial weathering
### A3.3 Data sheet with commonly used standards

<table>
<thead>
<tr>
<th>Technical characteristics</th>
<th>Unit</th>
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<th>ISO standard</th>
<th>National standards</th>
<th>Alternative Proposal</th>
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| Poison’s ratio            |      |             | Te

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European Design Guide for Tensile Surface Structures
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(1) polyester (PES or PET), high tenacity polyester (PES HT), glass (G)  
EC6 means continuous E glass multifilament yarn of 6 µm diameter for each filament  
Polytetrafluoroethylene (PTFE)

(2) Weave pattern: plain weave fabric; 2 x 2 basket weave (or panama); 2 x 2 twill weave; 4 x 1 satin weave

(3) Count: linear density, 1 tex = 1g/1000 m; 1 dtex = 1g/10000m; 1 den = 1g/9000 m

(4) Twist = S or Z  

(5) Sizing or finish

(6) Polytetrafluoroethylene (PTFE)

(7) Measurement of the coating thickness between the top of the base fabric and the top surface of the coated fabrics by microscope.

(8) Acrylics (ACR), polyvinyl fluoride (PVF), polyvinylidene fluoride (PVDF)
A3.4 Fire reaction for building construction products

A3.4.1 Introduction

The directive for building construction products (DPC) 89/106/CEE of 21/12/1988 defines six kinds of safety requirements. One of these concerns fire safety requirement. Each European country has to transpose this into its own national rules. For instance France, by decree of 21 November 2002 relating to the fire reaction of products for building construction, abrogated the earlier decree of 30 June 1983, and introduced the “Euroclasses”.

According to the directive 89/106/CEE, one understands by building construction products any product which is manufactured with a view to being incorporated in a lasting manner in any work of construction, which covers both buildings as such and also civil engineering works.

A3.4.2 Classification of building construction products

The classification relating to the fire reaction of building construction products covered by the DPC directive, refers to the Euroclasses. The products are then considered according to their end-uses. From the fire reaction point of view, building construction products can be classified A1, A2, B, C, D, E or F, according to a procedure detailed in the standard EN 13501-1. A product classified F is a product having failed to obtain another classification, or not having undergone a test.

Additional classifications can also be determined concerning smoke production (classifications s1, s2, s3), and the production of ignited drops or debris (classifications do, d1, d2).

A3.4.3 Classification reports and CE marking

Building construction products covered by the DPC directive are liable to the delivery of a classification report. The DPC directive foresees that all building construction products put on the market and covered by the directive, will rapidly be subjected to EC marking. Thus each manufacturer should make sure to correctly apply the certificate of conformity (systems 1 to 4) according to his product and its application area. A manufacturer can find all the necessary information in each homologated European standard or technical approval covering his product family.

Up until now there has not been a mandatory proposal for the CE Marking of tensile membrane materials. But as transposition of classification exists in some countries (tables 1 and 2), and as the classifications and the tests for them are defined, it could be proposed by the materials producer and by the building fabricator to characterise their products for the fire reaction by the Euroclasses.
A3.4.4 TEST METHODS FOR FIRE REACTION EVALUATION OF EUROCLASSES EN 13501-1

In order to fulfill the Euroclasses new specific tests of fire reaction have been designed.

A3.4.4.1 Test of non-combustibility (EN ISO 1182)

This identifies those products which do not contribute, or contribute little to a fire, whatever be their end-uses, and applies to the classes A1, A2, only. The test material is placed in a tubular oven open at both ends, and heated to 750°C. The performance criteria are the loss of mass, the duration of ignition, and the rise in temperature of the ambient air.
A3.4.4.2 Heat of combustion (EN ISO 1716)

It determines the total release of the potential maximum heat from a product during a complete live combustion, whatever be its end-use, and applies to the classes A1, A2. The test is carried out using a calorimetric oven, in a medium saturated with O₂ at 30 bars, and one then determines the maximum calorific value (HCV) of the product.

A3.4.4.3 Test of an insulated object in fire: test SBI (EN 13823)

This evaluates the potential contribution of a product under its end-use conditions, to the development of a fire, in a fire situation simulating the conflagration of an element in the corner of a room close to the product tested. It applies to the classes A2, B, C, D (and possibly A1).

The principle consists in applying a flame from a 30kW burner for 20 minutes, in a right angle formed by two panels of 1.5 x 1 m and 1.5 x 0.5 m, made up from the product to be tested. The criteria observed are the total thermal release (THR600s), and the acceleration of the energy release (FIGRA, the propagation of lateral flame (LFs), the total smoke emission (TSP600s), and the acceleration of smoke production (SMOGRA) – all this for the classifications s1, s2 or s3, and the falls of ignited debris and drops for the classifications do, d1 or d2.

A3.4.4.4 Single flame source test (EN ISO 11925-2)

It applies to the classes A2, B, C, D, E and evaluates the ignitability of a product under its end-use conditions, exposed vertically to a small flame. One can then evaluate the time necessary for the flame to spread vertically over a distance of 150 mm (Fs) as well as the falling of ignited debris and drops for the d2 classification (the latter for building construction products other than floor coverings).

A3.5 References

(1) Bidmon, W. und Blum, R.  
«Spannungs-Dehnungs-Verhalten von Bauteiltextilen»  
Bidmon, W. und Blum, R.  
SFB 64 Mitteilung 74, 1987.

(2) Bridgens, Gosling  
«A new biaxial test protocol for architectural fabrics»  
abstract for IASS 2004