

# Increasing the Safety of Tensile Structures

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**Abstract:** An actual issue arising from daily work in the quality assessment of large structures is the safety of structures. Considering the most common failures of membrane roofs we can detect two main causes: either detail failures or failures of the material. To avoid failures of details in Germany, e.g., a quality assurance system for every project is being executed. Testing all structural important details of a structure before and during fabrication confirming the necessary safety factors minimizes risks very effectively. However this does not avoid all problems occurring on site as many failures are caused by harming the material itself. In this paper failures will be shown on which the origin of the problems will be demonstrated: mechanical damages, folding etc. caused during manufacturing, transport and use. The following questions will be discussed: Where do tears come from, how could they be avoided on one hand and on the other hand, in case they have happened: how can we predict the influence on the safety of the structure? Safety reducing aspects and test methods to elaborate the residual strength of materials will be presented.

**Key words:** quality assessment, safety of structures, residual strength, creases, folds, tear propagation

## 1. Introduction

In tensile architecture, we usually are dealing with coated fabrics or films. If we talk about coated fabrics we can basically distinguish three failure types: defect of the yarn, defect of the coating and propagation of a defect. Defects of the yarn are usually already detected during weaving or during the cloth inspection if not happening in the later process. Defects of the coating influence the long term resistance of the fabric. Damages of the coating could be damages of the surface, destruction of the adhesion between coating and fabric either through movements perpendicular to the fabric plane or in plane through shearing.

Before starting the origins of damages the relevant terms and definitions shall be mentioned.

Folds may be seen as a doubling of material around a diameter.

Creases are ridges in a material that are caused by a fold or wrinkle being placed under pressure.

These damages may occur in all materials used for tensile architecture. However the severity of the impacts varies strongly from material type to material type. While ETFE should be handled with special care to avoid scratches, creases and folds having a direct influence on the breaking strength by reducing the thickness of the film, scratches on PVC coated polyester fabrics have got a long term effect. They should only be used with special care and expert's knowledge for retractable roofs taking into account a shorter lifespan. Going into detail with all material types would lead too far for this publication. Thus here the main attention will be turned to PTFE coated glass fibre fabrics. It is a matter of common knowledge that glass fibres due to their residual stress condition are sensitive to mechanical impacts.

## 2. Origins of Damages

Having enough experience, in most cases the origin of defects can clearly be detected. A variety of folds

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and creases and their formation shall be explained below.

### 2.1 Damages Happening During Material Production

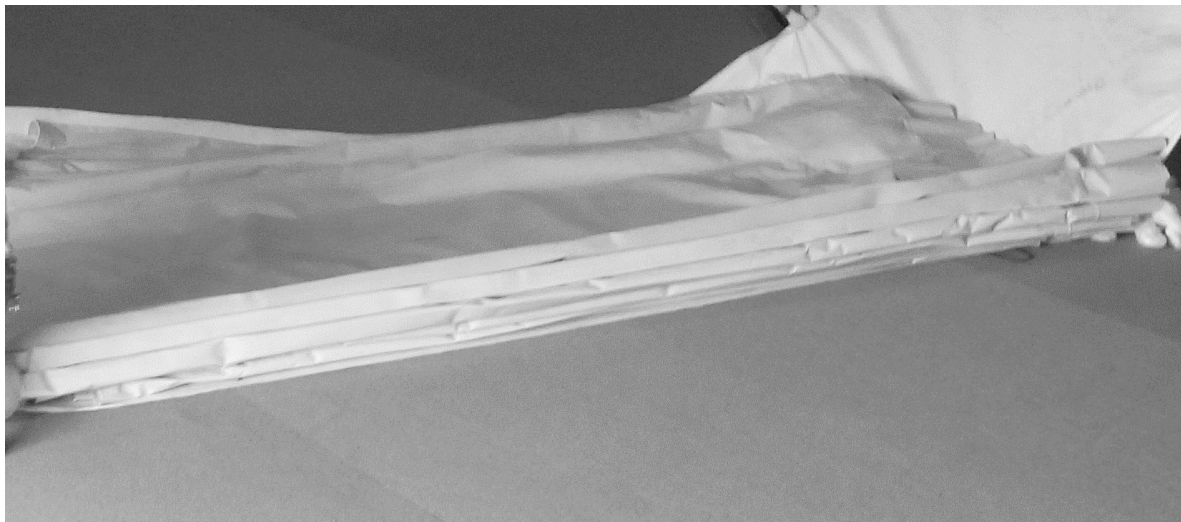
Damages happening from material production can either be classified as weave defects or coating defects. Furthermore the yarn direction in weft direction may deviate from rectangularity with the warp yarn direction either as a weft bow (largest deviation in the centre of the material width) or as an angle deviation over the total width. These types of defects should be detected and marked during a cloth inspection at the material supplier and later be considered during manufacturing (leaving out sections or respect the weft yarn direction for compensation if of remarkable size).

### 2.2 Damages Happening During Manufacturing

The first main origin of defects in coated fabrics results from handling during manufacturing. The material rolls will be delivered to the manufacturing company where the cutting process starts. This is usually being done by an automatic cutter, or also using (paper) templates. Then all pieces will have to be transported to the welding machines to connect them which may be done by transport wagons.

Adding one piece to the other the membrane panel is step by step getting larger and heavier. The panel or parts of it have to move along the welding machine or vice versa.

Loops may occur occasionally or where desired and necessary due to limited space for large panels (Fig. 1).



**Fig. 1 Looped material [DEKRA].**

As soon as these loops are loaded with more loops and material or due to inattention a sharp crease may happen.

Another type of folds occurring during manufacturing is the running fold. It happens when an unloaded crease — often perpendicular to a loop — is moving, e.g., by pulling the material parallel to the loop (compare Fig. 3).

The effect may be seen in the following Fig. 4.

A running double crease happens as soon as local double fold is torn out when moving the panel. This may happen over a great length and may harm the glass

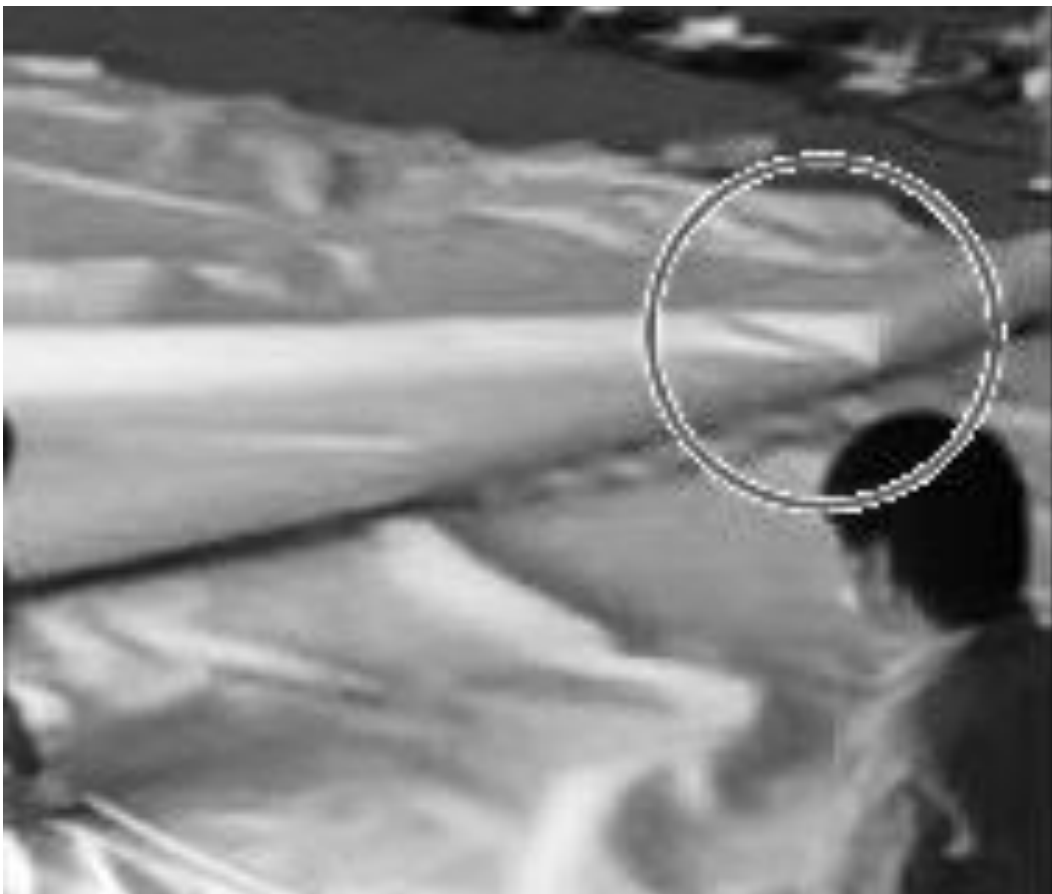
fibres severely.

### 2.3 Damages Happening During Packing and Transportation

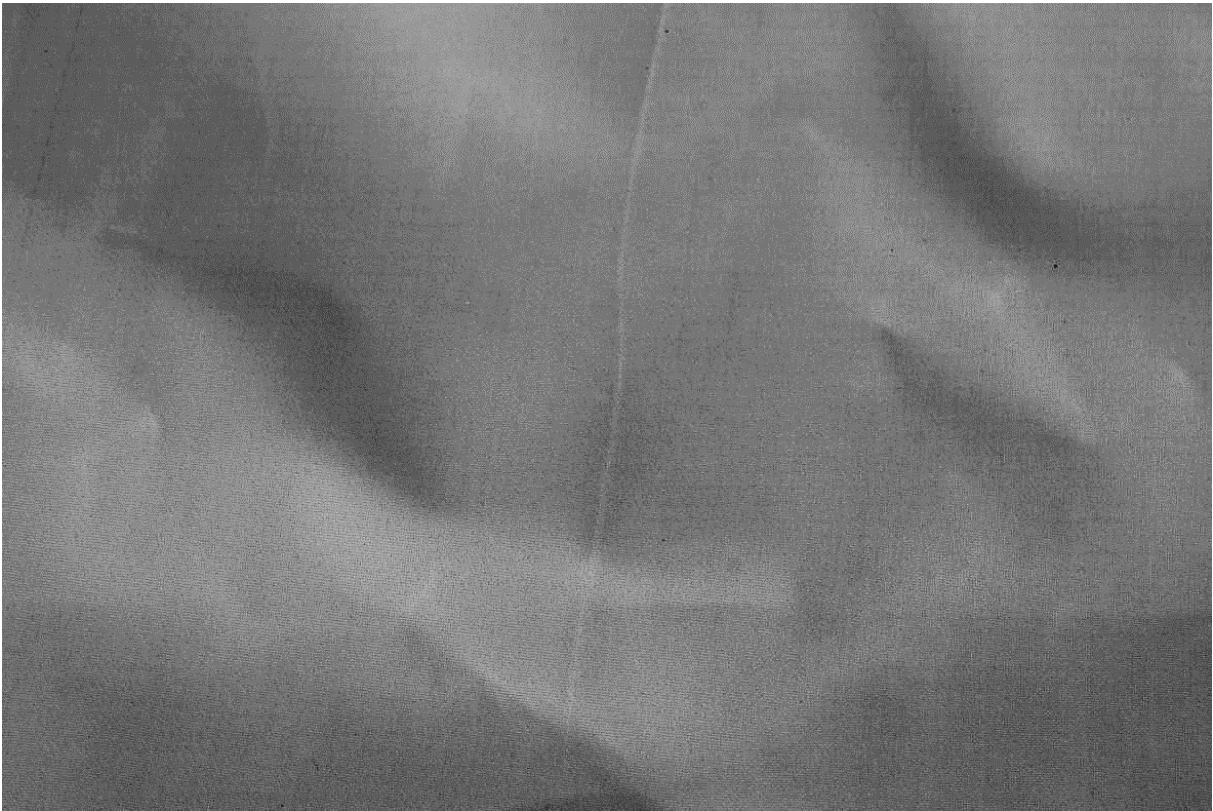
Due to the fact that membranes are typically wide-span doubly-curved structures the single panels are of a certain size and not easy to pack geometry. Thus the best method of packing should be planned in advance already taking into account the erection procedure and cutting pattern. The less the material will have to be moved the less damages will occur.



**Fig. 2** Typical crease, image post processed [DEKRA].



**Fig. 3** Creation of a running fold [DEKRA].



**Fig. 4** Rolling fold, image post processed [DEKRA].



**Fig. 5** Running double crease in the center of the picture and running folds from the center to the left corner and bottom, image post processed [DEKRA].

## 2.4 Damages from Unpacking and Installing

PTFE-glass membranes should be unpacked very carefully. The unpacking place should be clean, possibly layed out with carpets, free of objects which may harm the material. It is of advantage if the place where panels are being layed out is not accessible for untrained people.

Severe damages may already lead to panel rupture while stressing the panel due to the fact that an over stressing is necessary for the introduction of the pre stress.

Over the years initial damages are regions where deterioration may faster proceed.



Fig. 6 Typical creases resulting from packing, image post processed [DEKRA].

## 2.5 Damages in Use

Damages in use may happen from bird's picking, sharp parts falling onto the membrane, sliding sheets of ice, careless inspection etc.

## 3. Testing Procedures to Estimate the Level of Damage by Folds and Creases

### 3.1 ASTM Crease Fold Testing

For creases a standard test method may be used: Breaking strength after crease fold according to ASTM

D4851 - 07 (Reapproved 2011) [8].

### 3.2 Simulation of Running Folds

For the simulation of running folds DEKRA has designed an apparatus which creates the same folds as detected during inspections. Comparative tests between materials damaged by running folds taken from manufacturing and materials where the running fold has been applied in the running fold device have been compared and showed reliable results.

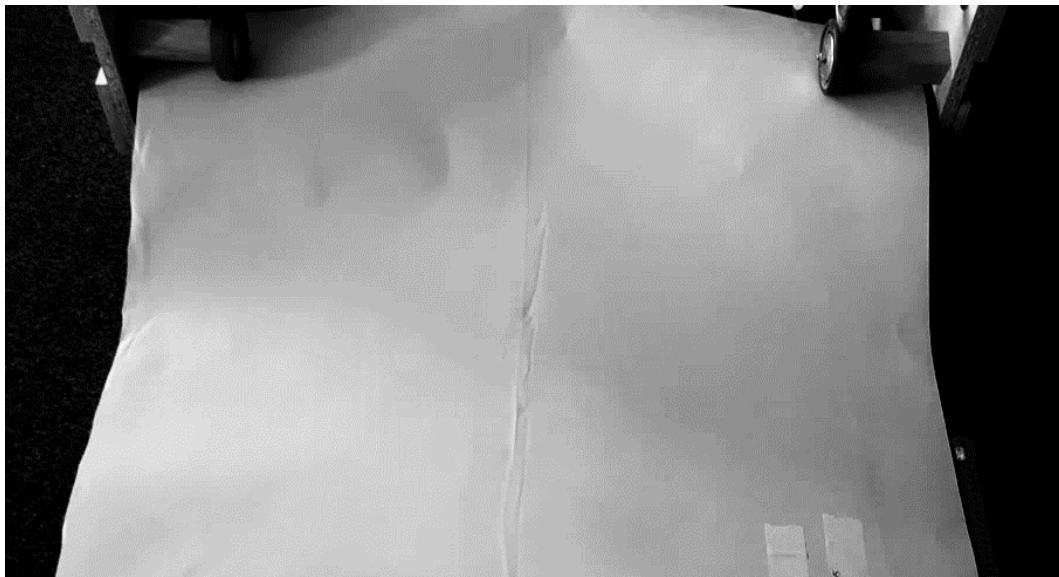
### 3.3 Simulation of Running Double Crease

Running double creases are produced by folding the material twice producing a sharp edge. This sharp edge is then torn out along the first fold. The glass fibres are sharply creased and might crack, “white cracks” occur.

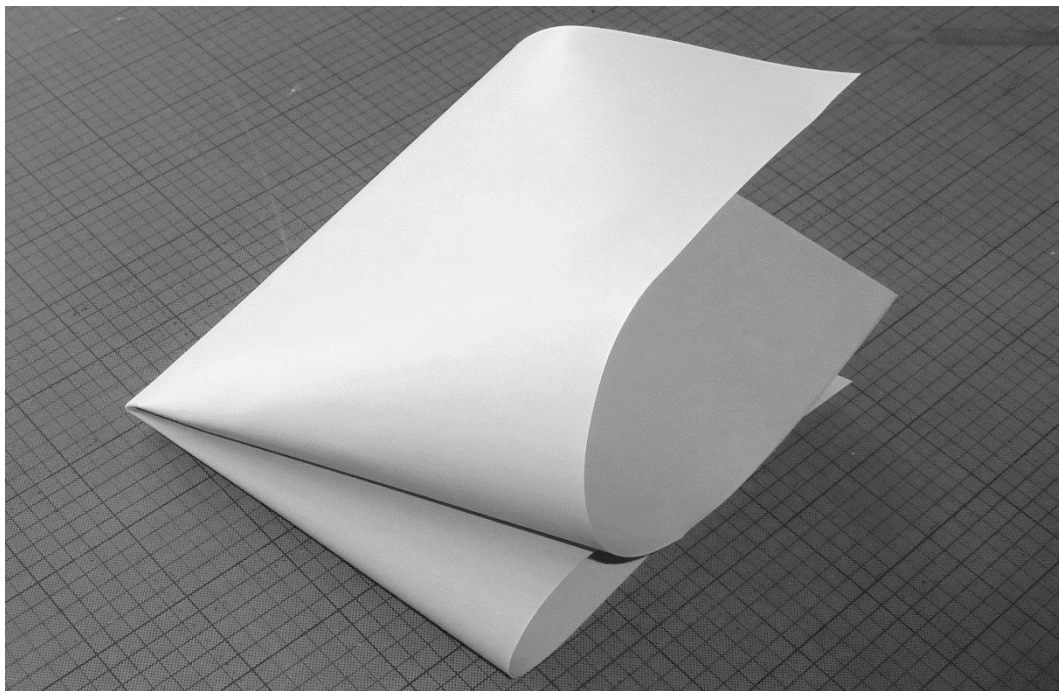
### 3.4 Biaxial Tear Propagation Testing with Simulated Running Double Creases

#### 3.4.1 Biaxial Tear Propagation Testing with Cuts

Uniaxial tear propagation tests do not refer to the practical stress states of large panel membrane structures. Thus it has become a state of the art procedure to execute large-panel biaxial tear propagation tests.



**Fig. 7** Application of running folds according to DEKRA method “Running fold” [DEKRA].

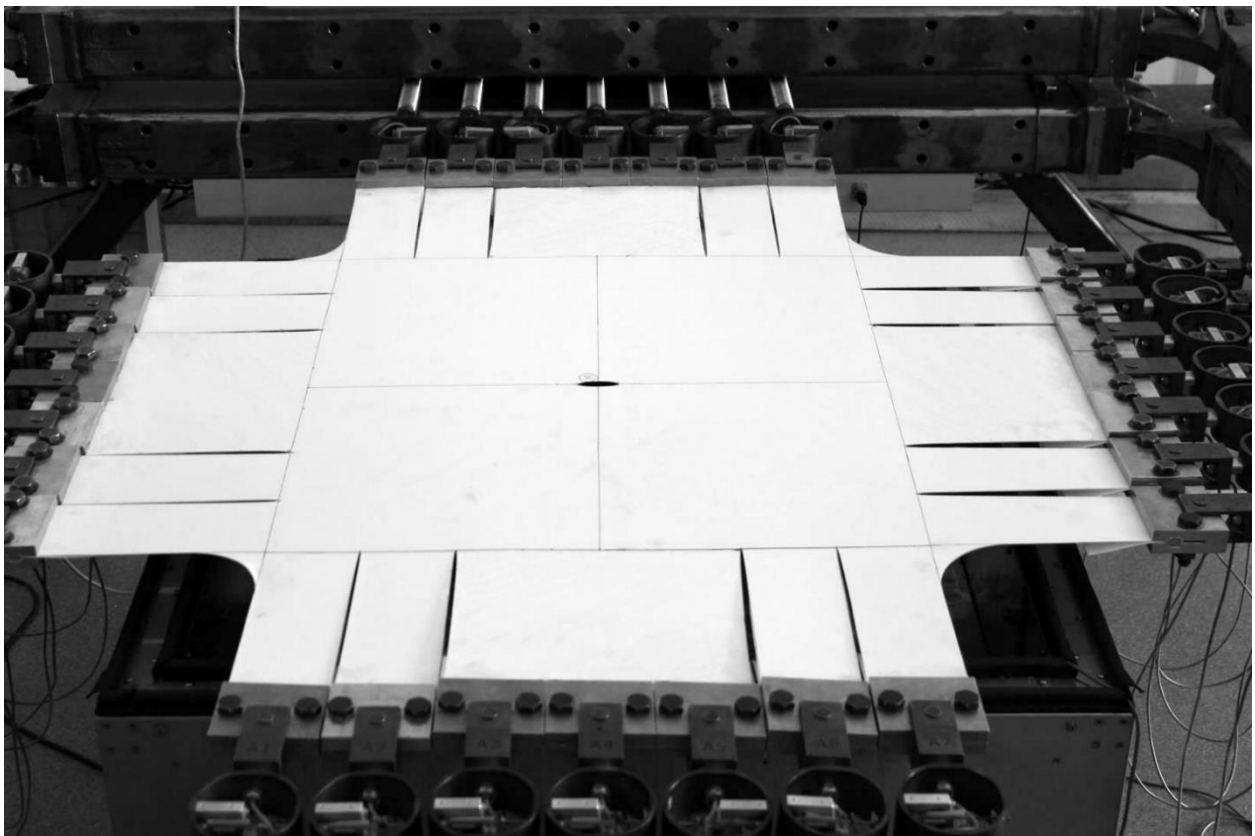


**Fig. 8** Application of running double crease, DEKRA method “Running double crease” [DEKRA].





**Fig. 9** Application of running double crease, DEKRA method “Running double crease” [DEKRA].

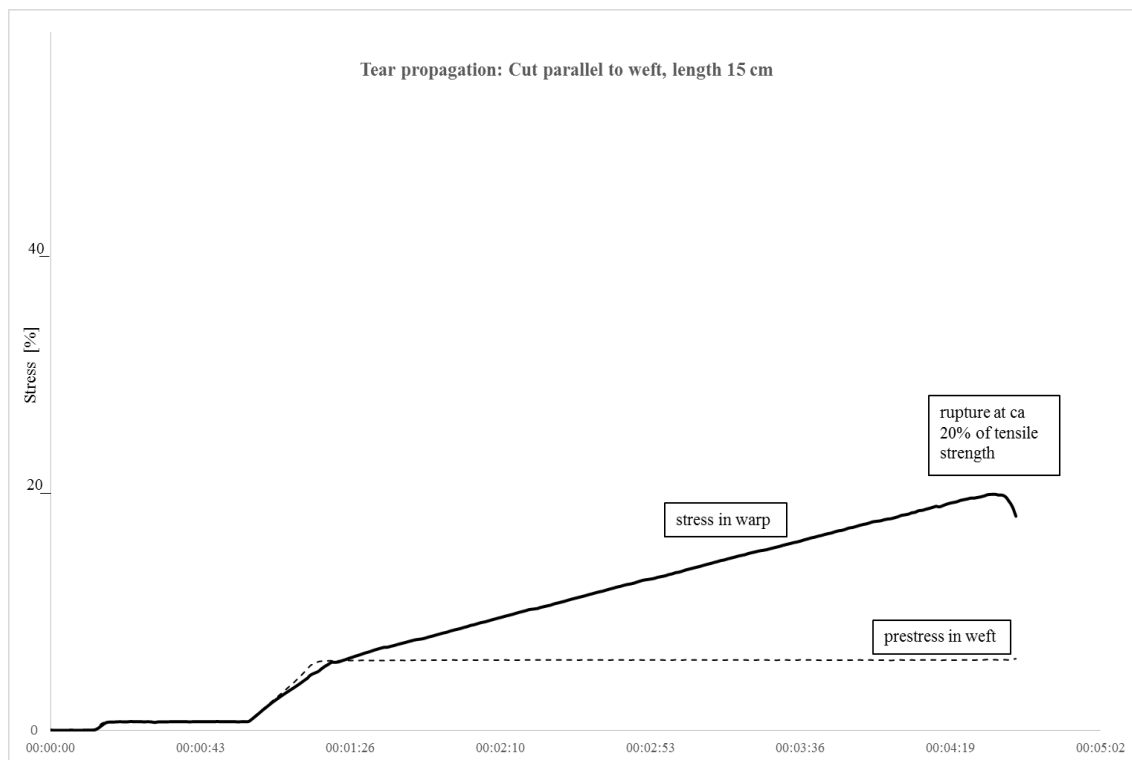


**Fig. 10** Biaxial tear propagation test at DEKRA [DEKRA].

The execution and evaluation of biaxial tear propagation tests have been described in Refs. [6-9]. Typically tear propagation were tested with applied cuts of different length in the centre of a biaxial sample

or as wide panel tear tests. An experimental set up with a 70 cm by 70 cm wide sample is shown in Fig. 10.

Example results for a 15 cm wide cut parallel to fill direction are shown in Fig. 11.



**Fig. 11 Results of biaxial tear propagation test with a 15 cm wide cut for material A [DEKRA].**

### 3.4.2 Biaxial Tear Propagation Testing on Samples with Simulated Running Double Crease

The procedure of biaxial tear propagation tests on folds is similar to the one described above. Here instead of a cut a damage with a defined fold will be applied in the centre of the sample. Then the membrane stress perpendicular to the damage will be increased until the failure of the sample.

Comparing the test methods one can state that the tear propagation for cuts of the same length as the running creases starts at lower fabric stresses. It starts slowly with one thread cracking after the other before the total rupture happens. Contradictory to this the rupture of the sample with an applied crease happens suddenly without advance notice. There is no need to emphasize that this might be very critical for a structure in use. The difference of breaking strength is not so

much influenced by the length of the damage in the tested range between 5 and 15 cm length (between 40 and 45% of uniaxial ultimate tensile strength) as it is typically for cuts.

## 4. Evaluation of Intensity of Folds of Different PTFE Coated Glass Fibre Fabrics

The breaking strength of different PTFE coated glass-fibre materials has been tested on 10 cm wide strips following the procedure of ISO 1421. To other sets of samples the three test methods described in here have been applied (ASTM Crease fold, running fold and running double crease). The 5%-fractile of the initial breaking strength of the material has been set to 100% and the decrease after folding has been expressed by the rel. strength compared to the initial strength.

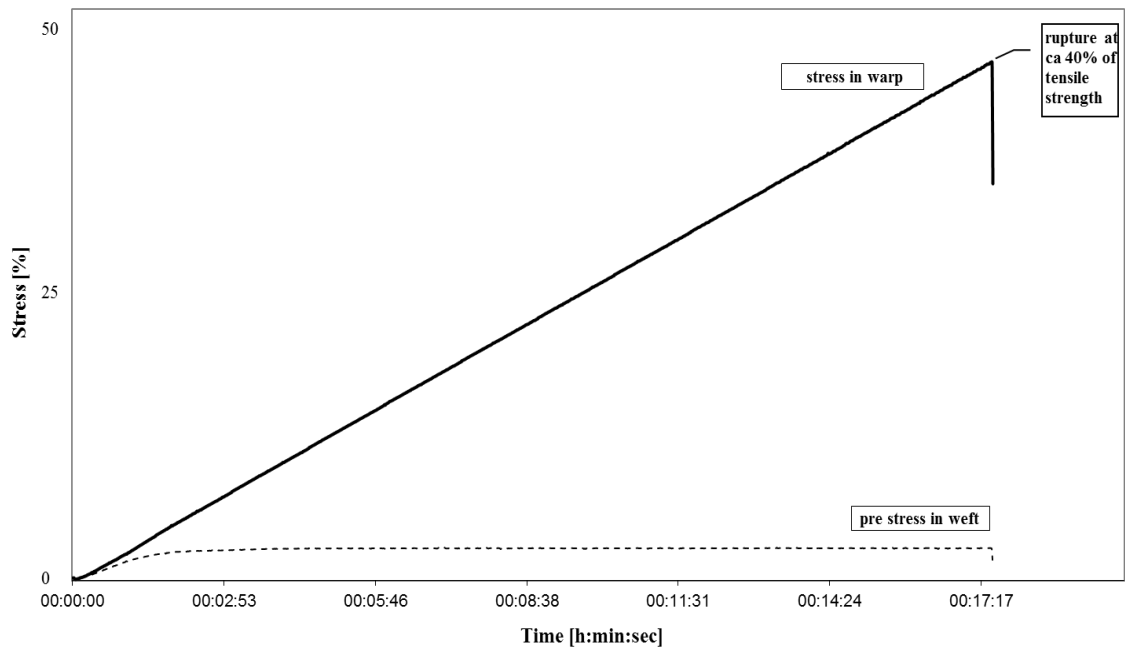


Two measured materials of two different producers are shown below.

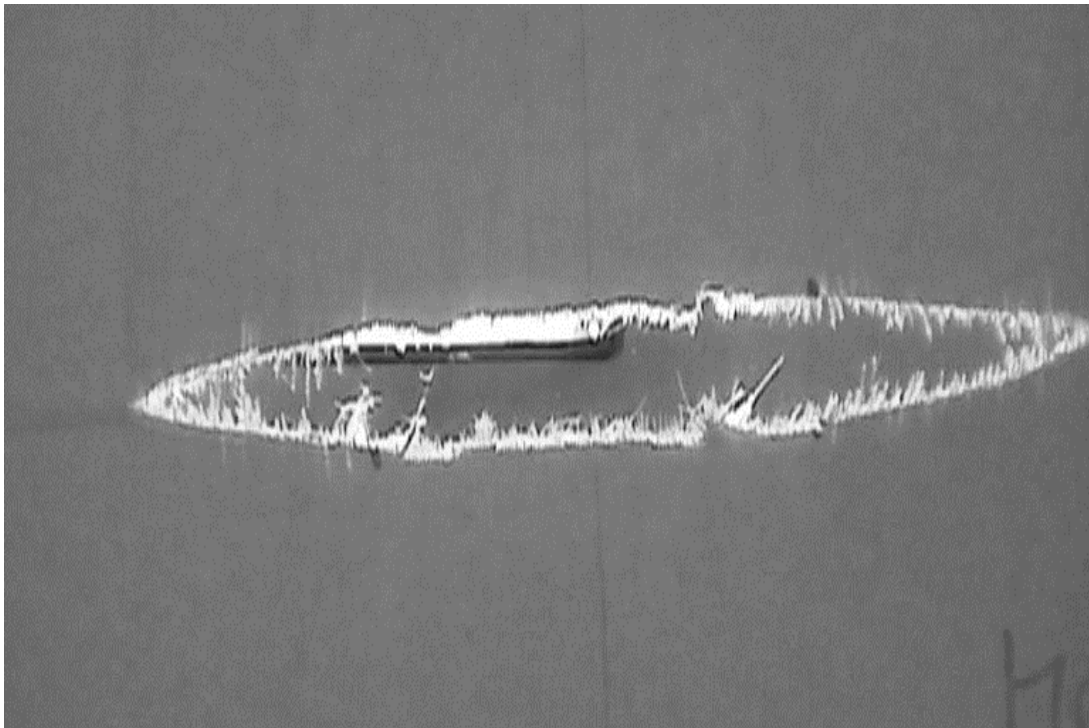
Tests executed on a material of another producer showed a different behaviour (Figs. 16-17).

The decay in strength depends on material type, direction, producer and sometimes even on a smaller measure on batches.

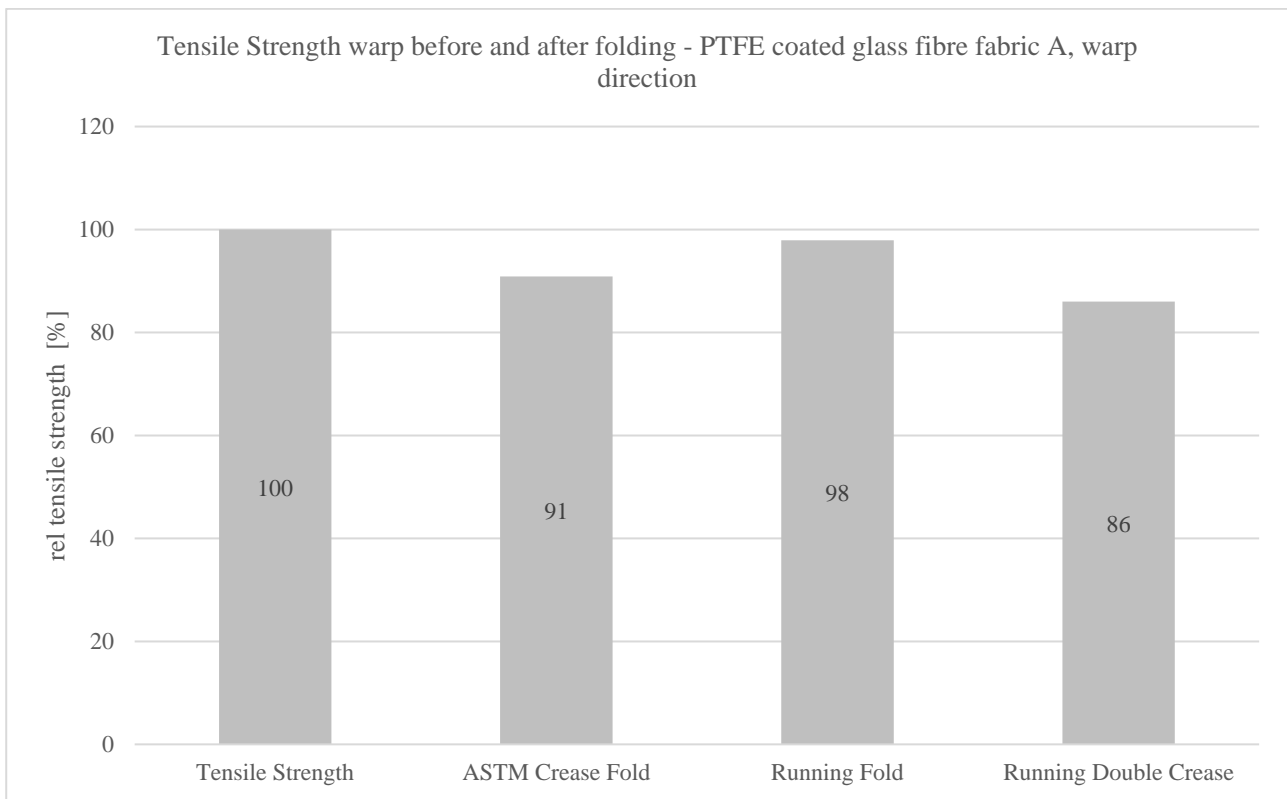
**Tear propagation: Running double crease parallel to weft, length 15 cm**



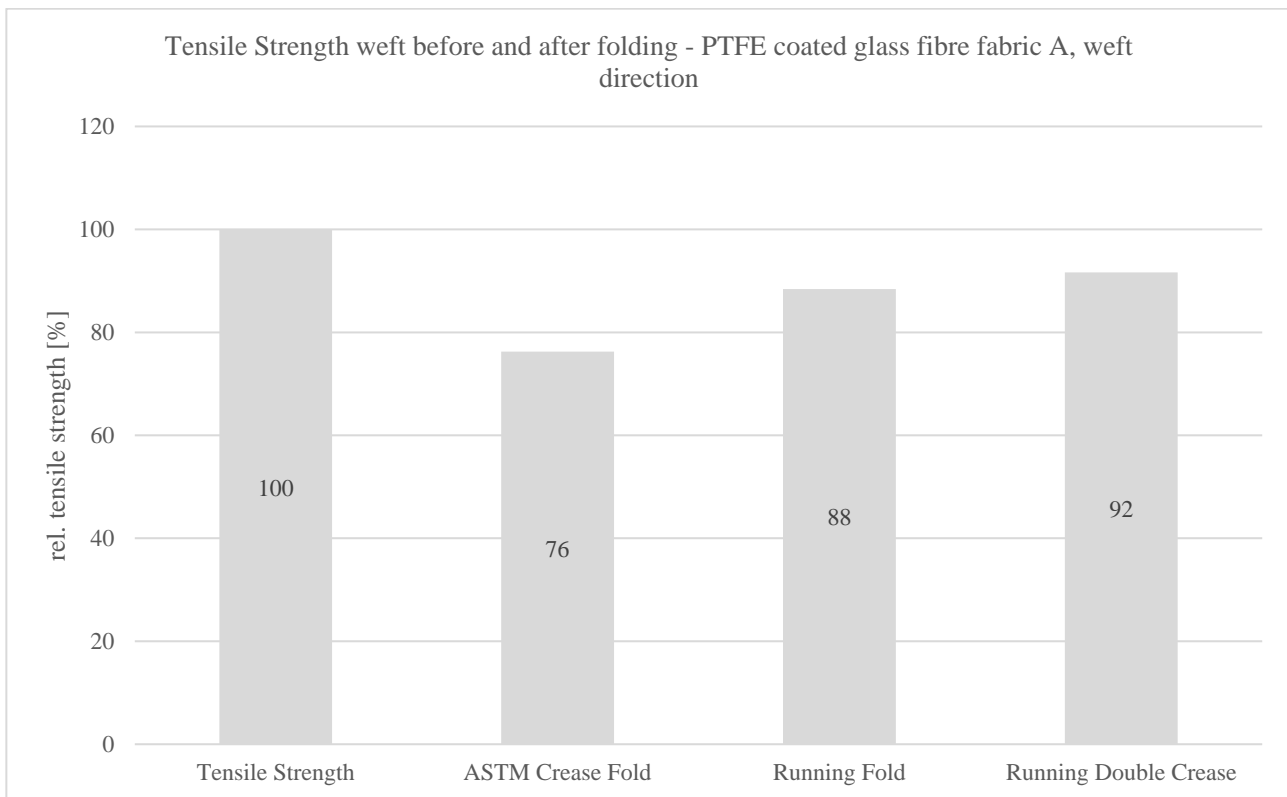
**Fig. 12 Results of biaxial tear propagation test with a 15 cm wide running double crease for material A [DEKRA].**



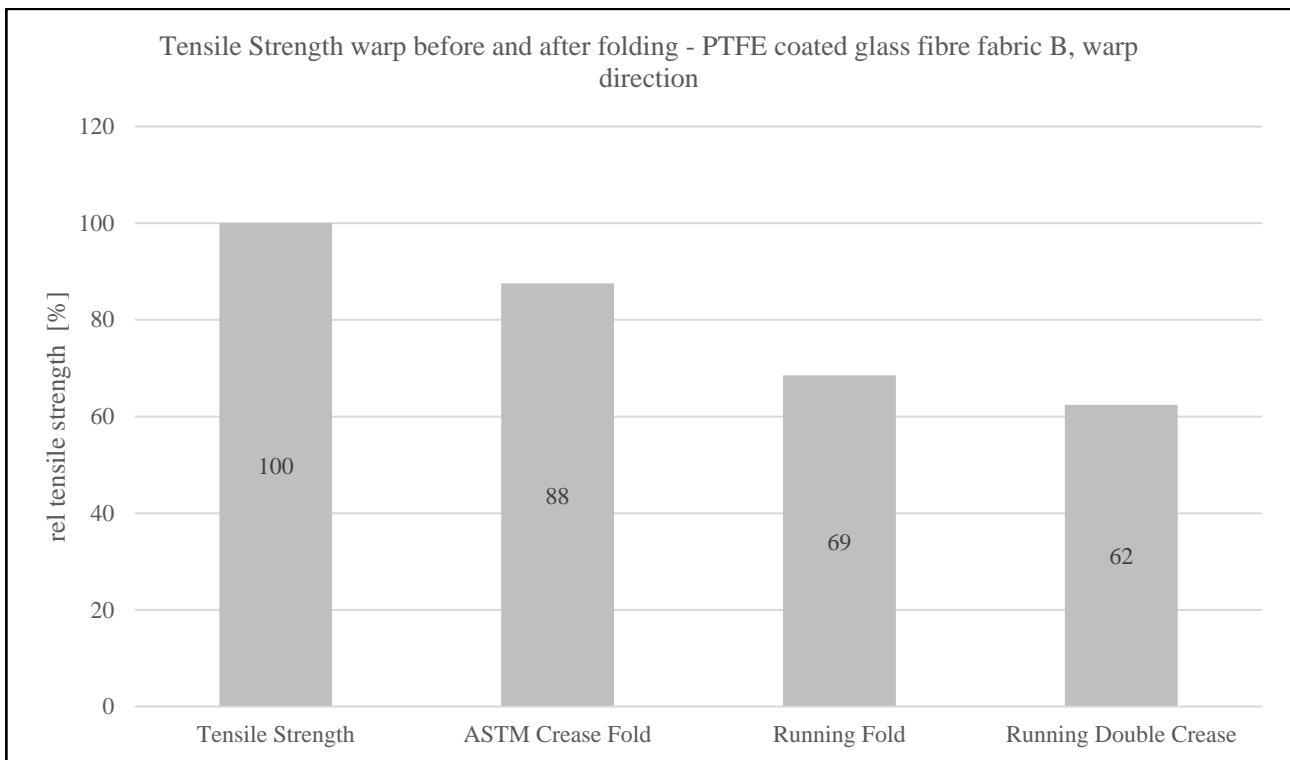
**Fig. 13 Suddenly propagating tear [DEKRA].**



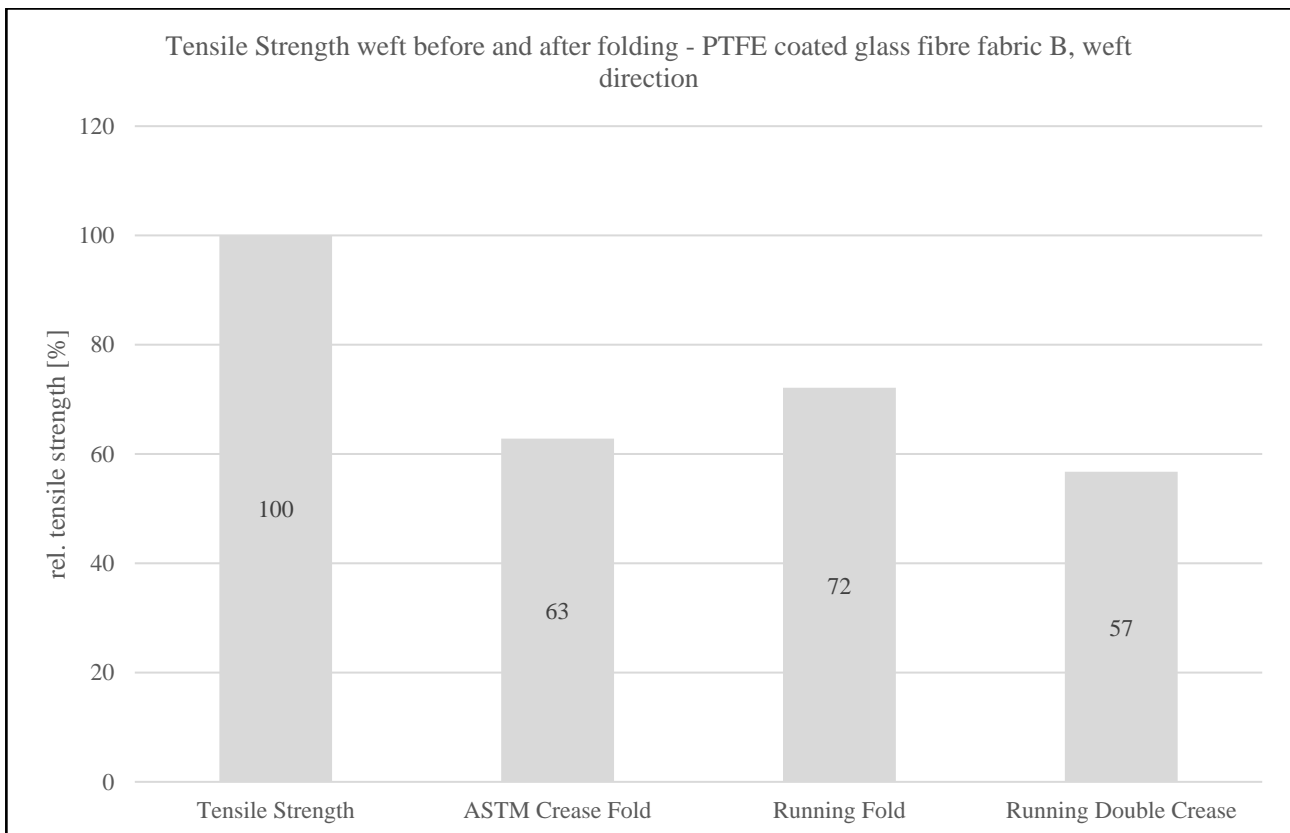
**Fig. 14** Comparison of relative tensile strength before folding (100% equal to 5% fractile according to DIBt guideline) and after folding, PTFE coated glass fibre fabric, material A in warp direction [DEKRA].



**Fig. 15** Comparison of relative tensile strength before folding (100% equal to 5% fractile according to DIBt guideline) and after folding, PTFE coated glass fibre fabric, material A in weft direction [DEKRA].



**Fig. 16** Comparison of relative tensile strength after folding compared to initial strength, PTFE coated glass fibre fabric, material B, warp direction [DEKRA].



**Fig. 17** Comparison of relative tensile strength after folding compared to initial strength, PTFE coated glass fibre fabric, material B, weft direction [DEKRA].

## 5. Consequences for the Practice — Guidelines for the Design

To prevent failures due to damages before use a detailed planning as and a well-organized and surveyed quality assurance system are essential. The life span of membrane structure is directly depending on the quality of the installed panel. In case of careful handling during manufacturing, transport and installation and regular inspections including minor repairs and in some cases cleaning, the life span of PTFE coated glass fibre structures may exceed 35 years.

On the basis of biaxial tear or wide panel tear tests the stress concentration factor may be calculated and a critical damage length may be evaluated [7, 8]. The reduction in strength may considered for design by applying a safety factor based on the proposed test results.

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