

RESEARCH INTO A REAL-TIME IN-SITU SENSOR-BASED MONITORING CONCEPT  
FOR BIAXIAL STRESS MONITORING IN TEXTILE ARCHITECTURE  
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**Key words:** Textile Architecture, Sensor Technology, Strain Monitoring.

**Summary.** This document provides first information about the real-time monitoring of a textile membrane structure with resistive sensors.

## 1 INTRODUCTION

In textile architecture, coated or uncoated fabrics made of natural or synthetic fibres are used as load-bearing elements in air-supported or mechanically pre-stressed membrane structures. Membrane materials are highly efficient building materials since they can cover large spans with a comparatively low weight per unit area merely by transmitting tensile forces. The load-bearing capacity and serviceability of an architectural textile structure are based on the designed prestress state, which is influenced cyclically over the service life by strongly varying weather conditions, temperature changes, UV-radiation accompanying with creep and relaxation effects [1]. If finally, the textile structure fails utterly due to extreme weather conditions, there is a risk of injury or even death. To prevent these cases of failure, membrane structures are currently subject to annual monitoring based on the subjective assessment of partly less highly specialised technical staff. Countermeasures are often ordered without knowledge of the amount of tension losses and their causes, such as damage to the textile structure. For the identification of tension force losses within a large area and localisation of structural damages in the fabric, an in-situ measuring system for objective quantification of the applied prestress level is the subject of the invention. Furthermore, architectural textile structures are dimensioned using idealized geometries, which can vary between the FE model and the built structure depending on the implied prestress. If an installed membrane does not have the prestress defined in the calculation model, it will behave in the real load case correspondingly differently from the way predicted in the design model. This circumstance can lead to non-calculated load scenarios and finally to the failure of the membrane structure. As a result of the unknown membrane prestress state and

the difficult to estimate the probability of failure depending on the load occurring over the service life, high material-side safety factors follow, which can lead to overestimated membrane materials and thus also to over-dimensioned primary structures. The resulting increased material and energy requirements lead to a worse ecological balance of the textile structure.

## 2 RESEARCH OBJECTIVES

Currently, there is no well-founded experience in the field of structural integration of fibre-based sensor networks in structural fabric membranes or developments in the field of applicable sensor patches for large-area monitoring of membrane structures. For this reason, this research aimed to develop an intelligent, functionalized membrane material that monitors the built structure during its lifetime.

The long-term stability, the system reliability and the application limits of the sensor network under weathering influences, UV radiation, temperature changes, will be validated on a demonstrator structure. In addition to the previously mentioned research objectives, the innovative sensor technology must be scalable and segmented (weave-technical reportable, i.e. repeatedly divisible) as well as flexibly contactable, so that a large-area in-situ sensor network can be achieved by joining the different membrane surface elements. This highly complex measurement task can be performed either by a fibre-based structural integration of the sensor network into the base fabric or by the application of an autonomous measurement patch.

Various laboratory test series were carried out, to validate the functional suitability of the sensor technology for the measuring task and different sensor designs were configured. A demonstrator structure was equipped with the most suitable sensor concept.

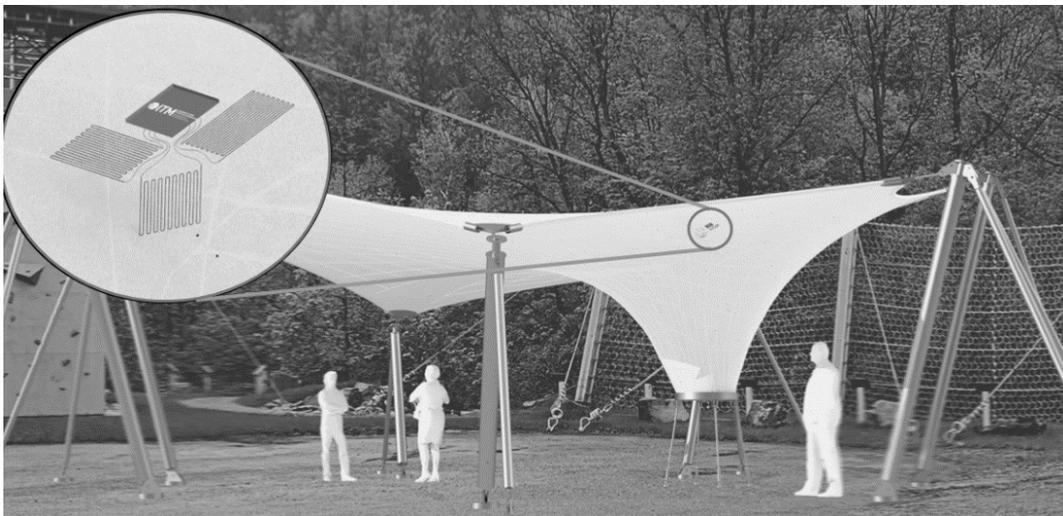


Figure 1: Visualisation of the demonstrator structure

The electrical resistance values from sensors are transferred to a cloud via wi-fi for software-based evaluation of the material strains. The calculation of the final material stresses is due to the highly non-linear, viscoelastic and anisotropic material behaviour of textile membranes very complex and thus the subsequent challenge and not part of the paper.

### **3 RESISTIVE STRAIN MEASUREMENT PRINCIPLE**

The measurement principle is based on resistive sensors. The operating principle of a resistive sensor is that the resistance of the sensor changes depending on the measured value (here length). When an external force acts on an electrical conductor, its length and cross-section change depending on the load. According to the laws of physics, this leads to a change in its electrical resistance. Once the electrical conductor gets bonded to a test object, any load-dependent deformation of the test object will also lead to a strain of the electrical conductor. The resulting change in its electrical resistance is directly proportional to the load-dependent deformation of the measured object within a specific range. The dependency is influenced by the current temperature, which has a great impact on the selection of the sensor material.

### **4 SENSOR TECHNOLOGY**

#### **4.1 Basic requirements**

This research investigates the application of a wide-area sensor system on PVC coated polyester fabrics, which is one of the commonly used membrane materials in textile architecture. All processes of the sensor technology must be integrable into the production process of polyester fabric with Panama weave. Due to the vast strain range with elastic and plastic parts, the sensor material is confronted with diverse and demanding tasks. The sensor material must guarantee an elastic strain behaviour of approx. 5 % and withstand a breaking strength until 15 %. Temperature stability and durability also play an important role, as the sensors are permanently exposed to outside environmental conditions.

#### **4.2 Sensor material**

The strain measurement is based on a resistive sensor principle, for which a comprehensive market analysis of available electrically conductive and textile-processable yarns and wires was carried out and these were systematically evaluated and compared, taking into account the identified basic requirements. To use commercially available electronic components for the configuration of the electronic component, the total resistance of the sensor must be in the range of approx. 120 Ohm or approx. 350 Ohm. The strain resolution rate of electronics with a resistance of 350 Ohm is higher than that of electronics with a resistance of 120 Ohm. Further investigations will show, if the 120 Ohm sensor achieve a proper strain resolution In this case the sensors can be made about half as short, thus saving costs and resources.

#### **4.2 Concept 1 – applied sensor patch**

An embroidery machine is used to stitch the high-resistance sensor meanders like a rosette onto the carrier material at defined angles (0-45-90), allowing the main strains to be calculated subsequently. The sensor thread (green) lies as straight as possible on the carrier material and an auxiliary thread fixes the sensor in place. To not distort the measurement result, the total length of one sensor meander must be in the direction of the respective rosette angle. The low-resistance distribution yarns (blue) are a rapid bridging to the central contact point, because each additional component influences the resistance measurement. The distribution yarns are

equipped with contacting plugs or similar at the end of the periphery of the patch.

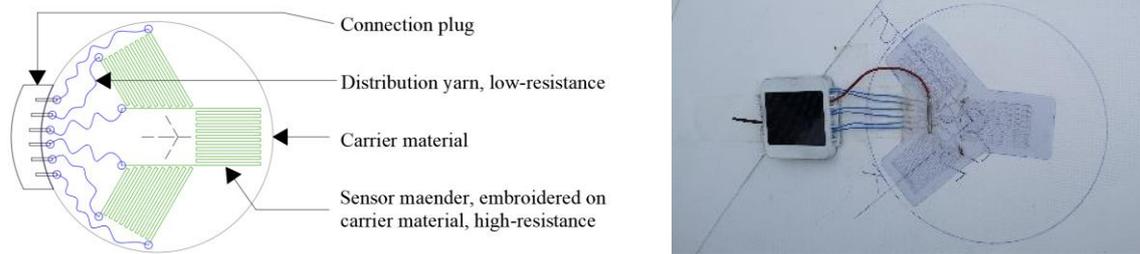


Figure 2: Visualisation (left) and real sensor (right) of the sensor concept 1 – applied sensor patch

The advantage is that the entire patch can be delivered prefabricated as a complete component to the workshop. During the final fabrication of the membrane structure, the patches can be applied via welding or glueing. An outstanding advantage is thus the flexible arrangement of the sensor patches on the membrane surface. The patch can be designed to act completely autonomously or several patches can be connected to a central power supply. For these reasons, the replacement of defective units is easily possible. With this patch option, it is possible to equip even existing structures with a monitoring system.

Negative is that the measuring accuracy is influenced by the type and durability of the application method (glueing / welding). For this reason, further investigations must be carried out on the durability in long-term tests. Furthermore, the yarns of the sensor meander are straight on the surface and do not follow the crimp of the initial weave. Therefore, the resulting strain values had to be investigated in detail.

The sensor patch was divided into the functional components embroidery base, sensor material, supply thread and application component. To assign suitable materials or technologies to the functional components, a test plan was created in which various combinations of potentially suitable materials were evaluated concerning defined parameters.

**Table 1:** Investigated materials for the sensor concept 1 – sensor patch

Embroidery base	Sensor material	Supply thread	Application method
PES-Vlies	ISAOHM wire NiCr20AlSi d = 0,07 mm	Copper wire	Saba Contact 70T
ETFE-Foil	Shieldex 110/34-2-ply-HC	Elektrisola® Lizwire	HF-welding
TPE-Foil 0,25 mm	Shieldex 117/17 dtex 2-ply-HC		Hotair welding
PVC Foil 0,50 mm	Shieldex 235/34-2-ply-HC		
PES knit with PVC coating	Shieldex 180 $\mu$ Monofil		

The laboratory tests were divided into three stages. In the first step, the embroidery processability of the embroidery base materials and the sensor thread materials was examined. For the second step, only the sensor patches successfully produced in the first step were further used. The uniaxial meanders were applied to the selected base material (PES/PVC) using different application methods and thus the application was evaluated. In the last step, a uniaxial cyclic tensile test was performed. The patch adhesion, a potential reinforcement of the membrane material by the patch with a negative effect on the measurement quality and the measurement signal of the sensors were determined and compared. The monoaxial, cyclic test series had carried out, that the combination of the following materials, in addition to the best properties in terms of processability and connection quality, also have the highest suitability in terms of measurement signal quality:

**Table 2:** Selected materials for the sensor concept 1 – sensor patch

Embroidery base	Sensor material	Supply thread	Application method
PVC Foil	ISAOHM wire NiCr20AlSi d = 0,07 mm	Copper wire or Elektrisola® Lizwire	HF-welding

In this combination, the Isaohm wire is applied as the sensor material to a 0.5 mm thick PVC foil with a defined meandering structure using the Tailored Fiber Placement (TFP) process. Compared to other potential sensor materials, the Isaohm wire does not exhibit any temperature drift. The set base impedance of 350 Ohm could be set repeatedly and with high accuracy over a defined measuring wire length. Using HF welding technology, the sensor meanders could be applied to the membrane with repeatedly high adhesion. No further coating is necessary to protect the sensor grid, as the sensor rosette is located between the membrane and the PVC foil and is thus protected against external influences.

#### 4.3 Concept 2 – integrated sensor cross

Integrated sensors are woven into the fabric of the base membrane material. This concept requires a net of sensor yarns, which is additionally inserted by special equipment of the weaving machine. This method results in the best possible bond between the sensor net and the original fabric and the sensors lie protected under the coating. The yarn paths in the warp (red) and weft direction (blue) have to be technically isolated at the crossing points to measure the electrical flow exclusively in the warp or weft direction. The density of the sensor net depends on the equipment options of the weaving machine and the required resistance of the yarn material. The coating of the base fabric and the sensor grid is simultaneously possible. At the time of cutting, the position of the sensors on the membrane structure must be known to set the marks, which show where the electrical connection must be set. With suitable processes (dissolving, lasing, milling), the coating must be removed locally to contact the electronic component with the textile-integrated sensor technology. The electronic component can then be applied later.

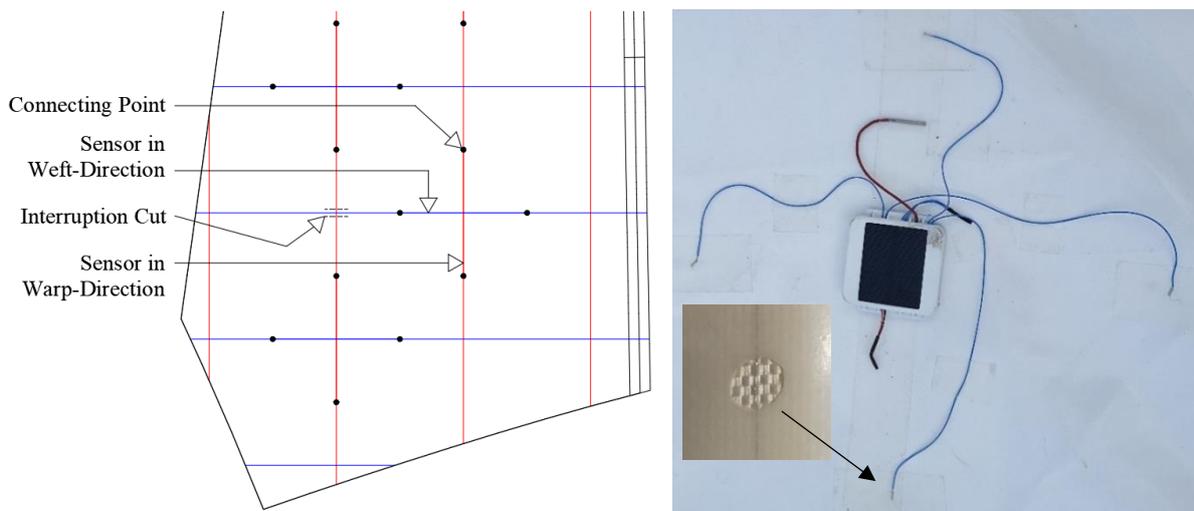


Figure 3: Visualisation (left) and real sensor (right) of the sensor concept 2 – integrated sensor cross

The advantage is that the sensors can be integrated during the weaving process. That means the sensors are directly woven into the fabric and need no additional application via a bonding layer. This method promises the most accurate strain measurement since the sensors will stretch analogous to the material. The sensors are protected under the conventional fabric coating.

Negative is that the integrated sensors are straight yarns (no meander) and therefore they become longer with increasing resistance demands. During the design process, it is maybe necessary to reduce the required resistance of the sensor to realize a dense sensor grid. The connection between in-plane sensors and the supply and transmitting unit poses different challenges depending on the process, which still needs to be evaluated.

The integrated sensor design includes the in-line integration of Isaohm sensor wires (NiCr20AlSi,  $d = 0.07$  mm) in the warp and weft directions, which measure the strains in these directions. From the previous experiments on the realisation of a sensor patch, this sensor thread has proven itself in every respect. Sensor wires are systematically incorporated into the Panama weave of the base material (PES/PVC) using a plain weave. The contact points of the sensor wires are protected in the first step by means of commercially available insulating tape, so that after the coating process of the fabric, the contact points can be exposed without much effort. However, manually applying the adhesive dots during the weaving process does not make sense from a process-technical point of view, which is why an automated process for exposing the contact points must be investigated.

## 5 LABORATORY TESTS AND DEMONSTRATOR STRUCTURE

The applied and integrated sensors were tested in uniaxial and biaxial tensile tests and the transfer function of resistance change to material strain was determined. In the final field test, the sensor technology is tested for its processability and functional suitability.

## 5.1 Initial situation

In the planning practice of membrane structures, FE-analysis are made for stress and deformation evaluation. This FE analysis is based on predefined material constants (E-modulus in warp and weft direction, as well as Poisson's ratio). As an example, the figures show an FE-analysis of the stress distribution of the demonstrator structure in the prestressed state and under snow load in the warp direction. With this information, laboratory material tests can be planned.

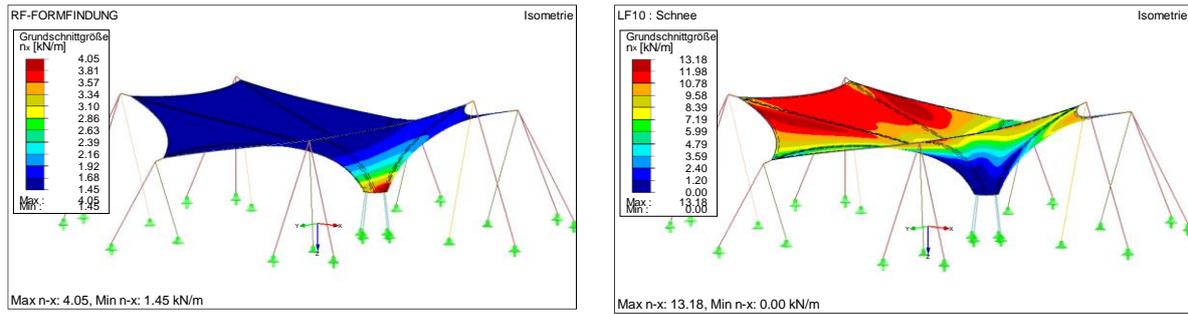


Figure 4: FE-analysis of the demonstrator structure

## 5.2 Laboratory material test – base material

According to all relevant load cases, a loading regime for a material test was carried out, to investigate the material behaviour and to set the strain range for the sensor configuration of this particular structure. The material test shows the following strain values:

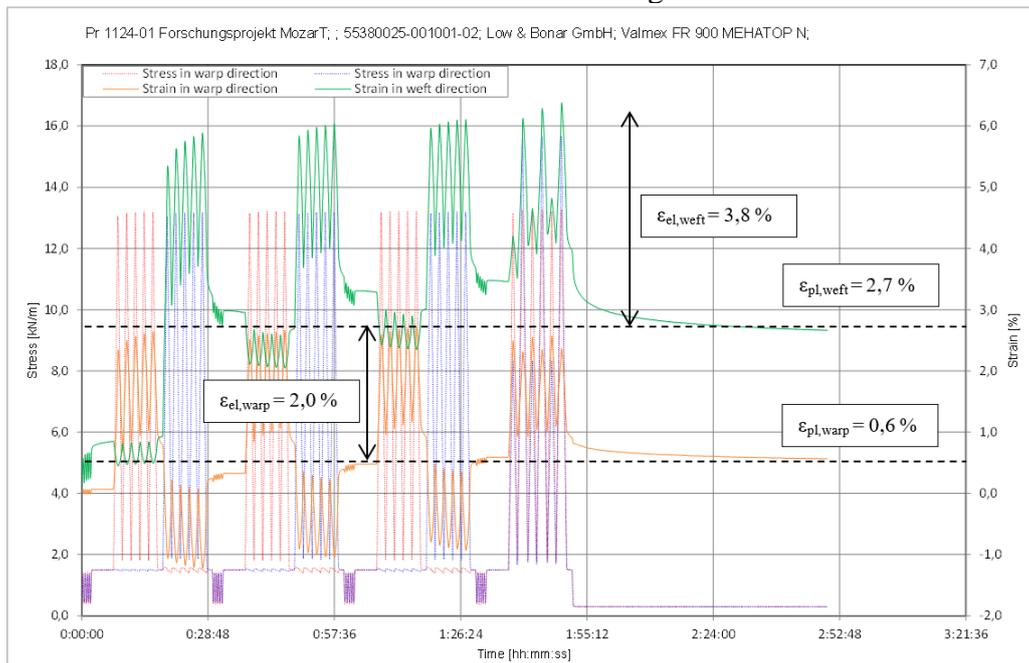


Figure 5: Strain evaluation base material

In the further process of the paper, the test procedure is explained for sensor concept 1. Concept 2 was tested in the same way.

### 5.3 Uniaxial tensile test

Based on the expected strain range ( $\sim \varepsilon_{\text{warp,max}}=3,0\%$ ), the load regime for the uniaxial tensile test of a sensor in warp direction with the previously defined configuration (table 2) is defined. The resistivity of a single meander of the applied sensor patches is 350 ohms, regardless of the direction. Since the resistance value changes analogously to the applied strain, the electrical resistance change is also recorded during the uniaxial tensile test in addition to the material strain values. The measured material strain and the resistance change can be compared in the evaluation and a transfer function for a sensor (here warp direction) can be derived.



Figure 6: Uniaxial tensile test – sensor concept 1

The graphs of material strain over time and the electrical resistance change show a very good correlation in the selected strain range. The transfer function can be derived from the ratio of material strain to the electrical resistance change of the sensor.

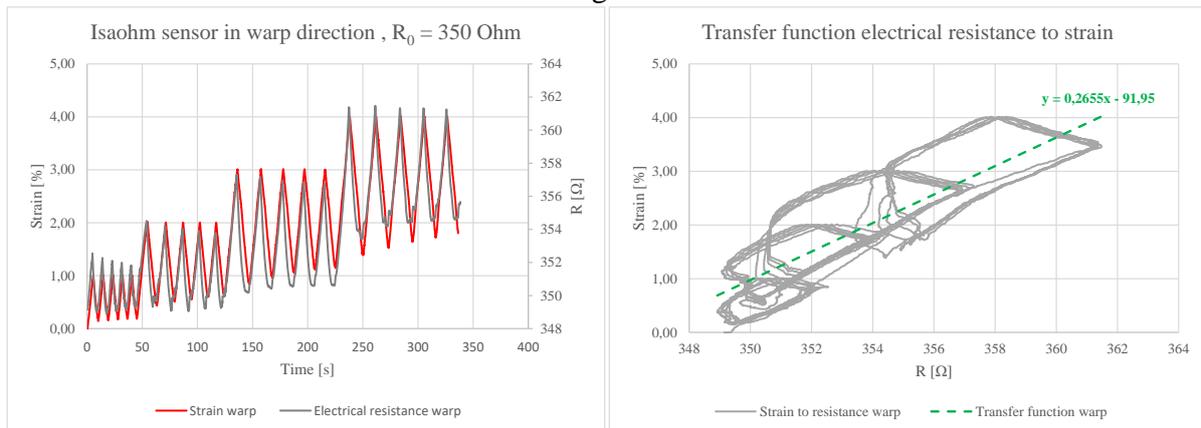


Figure 7: Strain and electrical resistance over time (left) and evaluation of the transfer function (right)

This transfer function is used to calculate the strains out of the measured change of electrical resistance of the sensor in warp direction. Investigations are currently being carried out to determine how reliably the sensors in the warp and weft direction can be reproduced in terms of process technology.

### 5.4 Biaxial tensile test

As an example, the sensor meander in warp direction was observed in the uniaxial tensile test and the transfer function was determined. The applied sensor patches are assembled from three identical sensors meander in a rosette-like manner at an angle of 0-45-90 degrees. For the

biaxial test, the sensors are perfectly aligned along the warp and weft direction ( $0^\circ$  = warp direction;  $90^\circ$  = weft direction;  $45^\circ$  = diagonal direction). Each sensor is connected to a resistance measuring device for the biaxial tensile test and the change in resistance is recorded analogue to the load regime. Afterwards, the transfer function determined in the uniaxial tensile test is numerically assigned, so that the calculated strain from the resistance change and the measured strain from the biaxial tensile test can be compared. As an example, the results of the sensor in the warp direction are further evaluated.

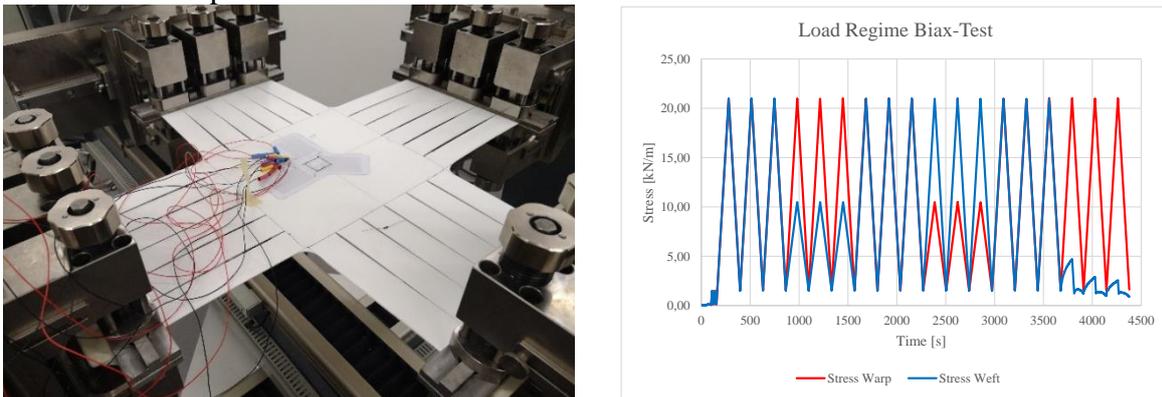


Figure 8: Biaxial tensile test with applied sensor patch (left); load regime warp and weft (right)

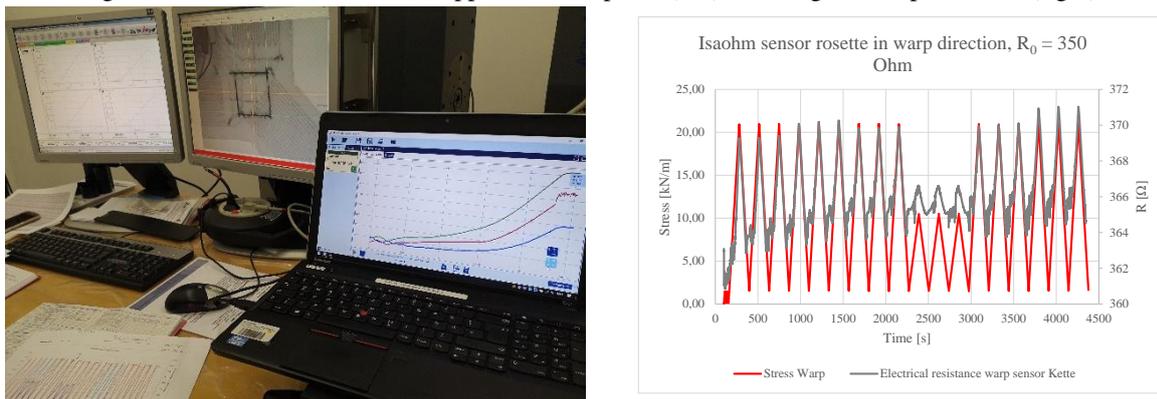


Figure 9: Recording test data and resistance data (left); comparison warp stress and sensor resistance (right)

The transfer function already delivers passable results in the first run, even though it was determined with the following deviations:

- The transfer function was determined using a cyclic uniaxial load regime, so the influence of warp and weft direction was not considered
- Process-related deviations in the production of the sensor meanders and in the welded connection cannot be excluded

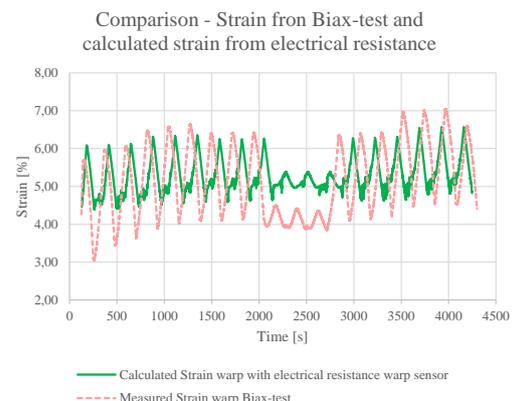


Figure 10: Comparison test strain and calculated strain from the warp sensor

It is relatively evident that the elastic and plastic behaviour of the membrane material can be detected by the sensor. The second sensor concept of the integrated sensor crosses showed similarly promising results. For this reason, both variants were installed in the demonstrator structure and they are currently tested in long-term studies.

### 5.5 Demonstrator structure and long-time monitoring

After the measurement feasibility of the sensor variants (1 = applied sensor rosettes; 2 = fabric-integrated sensor crosses) could be confirmed in principle in laboratory tests, the implementation of a demonstrator structure was planned and built. The sensor concepts were investigated and evaluated with regard to their ability to be integrated into existing processes in the planning and erection of membrane structures.

The sensors are equipped with a solar module for power supply, independent of the concept. The electronic unit also contains, among other features, a Wi-Fi component that sends the measured resistance changes to a cloud and provides them there for data processing. All further calculations (resistance values to strain values to stress values) are therefore possible locally on a computer after the sensors measured the resistance values.

Beyond the pre-stressing process, initial stress tests were carried out on the demonstrator structure with defined weights to test the measurement suitability of the sensors in field tests. As an example, the material strain results of the sensor S2 (concept 1) and sensor S3 (concept 2) are compared with the FEM calculations for the respective load case.



Figure 11: Built demonstrator; location of the considered sensors and load area

The load was applied progressively in the labelled area and held for a short time so that the material elongation could settle. After the load was applied, the loaded area was progressively relieved. During the loading, the sensors underwent a strain, which caused the change in electrical resistance of the sensor. This resistance change was sent to a cloud via the Wi-Fi transmitter. The resistance values are then translated into strain data via the transfer function. To validate the measured material strain data of the sensors, the numerical material strain values were calculated within the FE model of the structure and compared.

### Evaluation stress test

Sensors 2 (applied sensor patch) and 3 (integrated sensor cross) are located in the same region within the structure. Despite the different designs of the sensors, sensor 2 and 3 show an analogous strain behaviour in warp and weft direction, as expected. This fact indicates that both sensor concepts are basically suitable for measurement.

Even though the measured and numerical strain graphs are not completely congruent, the same tendency in the graphs can be seen. Even the brief drop in the strain values at the first load stage is recorded by the sensors. The slight differences in the measured values can be explained by the FE model. Here, the material strains are calculated via estimated material properties (E-modulus, transverse strain number) from the applied material stresses. If these material parameters differ from the actual values, the strains are logically not the same. Therefore, the trend is an important indicator of whether the sensors fulfil their measuring task sufficiently well. In the present case, this can be confirmed for both sensor concepts.

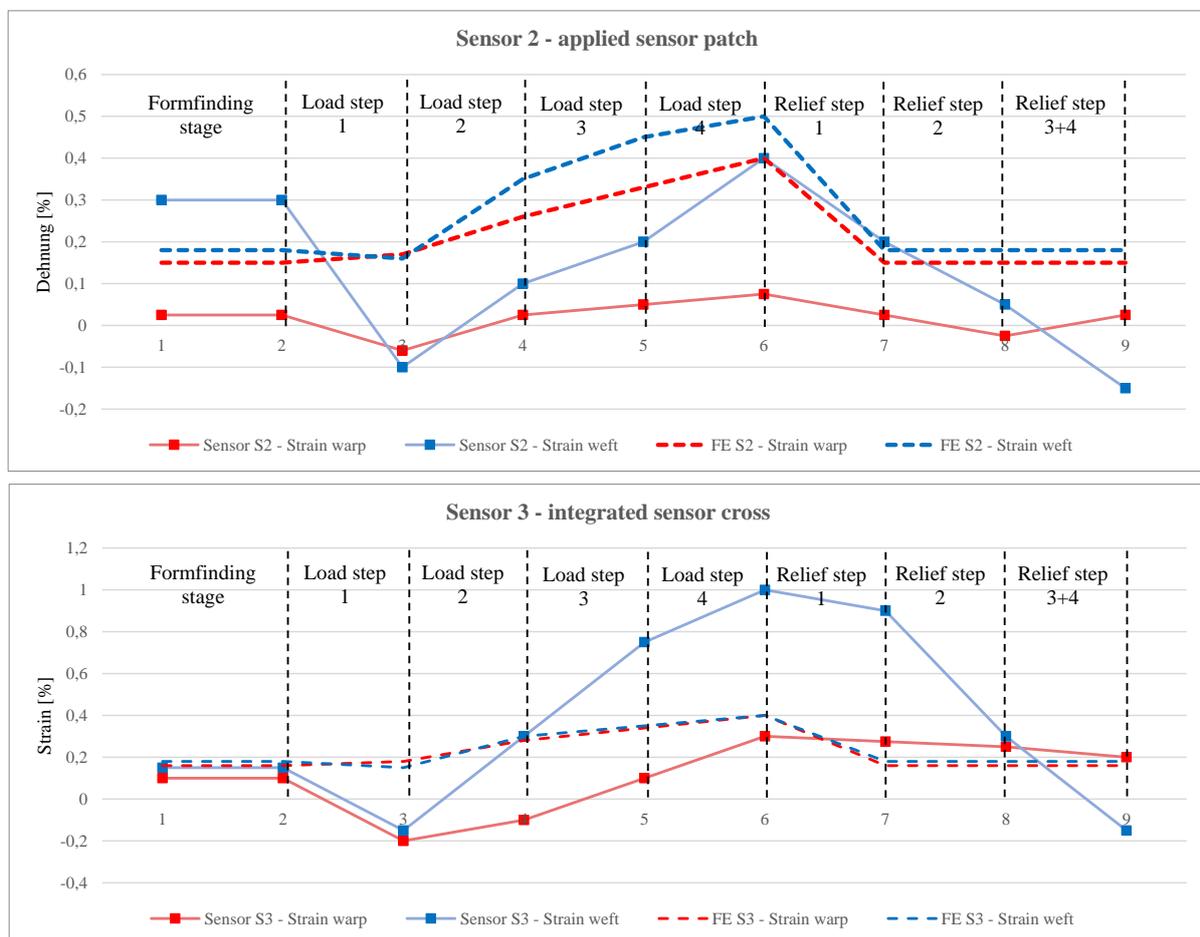


Figure 12: Comparison of the calculated strain behaviour in warp and weft direction of the FE-model and measured strain behaviour of the sensor technology; upper diagram: sensor 2 – applied sensor patch; lower diagram: sensor 3 – integrated sensor cross

## 6 OUTLOOK

The investigation has proven that yarn-based strain sensors can be integrated into the manufacturing process of a common membrane structure and that the load-based strain distribution can be revealed by the sensor technology. Both sensor concepts are currently under investigation with regard to their long-term stability and the results are being processed.

Under current research is the transformation method of the previously generated material strains into material stresses. The conversion requires knowledge of the material properties, which are based on the modulus of elasticity, separated according to warp and weft direction, as well as the Poisson's ratios. The non-linear, orthotropic and visco-elastic material behaviour of membrane materials depends for example on the weave and the production process of the fabric, on the load history, load extent and load duration, as well as the prevailing environmental influences, which can only be generalised within limits. Common for current practice is the reduction of the material behaviour to a plane stress state, which however leads to inconsistencies between the physical and theoretical description of the architectural fabric [2].

Therefore, the current research focuses on the display of the complex material behaviour via an artificial neural network, which is trained to predict the material stresses from the measured strains over the lifetime and under varying influences.

## 7 ACKNOWLEDGMENT

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