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Analysis of a Translucent Insulated Triple-Layer Membrane Roof for a Sport Centre in Germany

Jan Cremers[*a,b], Nansi Palla[a,b], Doris Buck[a,c], Andreas Beck[a,c]
Andreas Biesinger[a,d], Swen Brodkorb[e]

[a]*Stuttgart University of Applied Science, Schellingstrasse 24, Stuttgart 70174, Germany*
[b]*Centre for Integral Architecture,* [c]*Centre for Acoustic and Thermal Building Physics,* [d]*Centre for Sustainable Energy Technology*
[e]*fab_Architects, Industriestrasse 35, 68169 Mannheim, Germany*

Abstract

A new sport centre in Germany is presently under construction but already features an innovative and sophisticated membrane construction. It consists of a conical-shaped multi-ply membrane with an air gap and a translucent thermal insulation. The main advantages of textile construction materials are the outstanding design options and material properties, which enable to achieve large column-free spans, remarkable building shapes and -due to its light transmission- allows for high indoor daylight quality. In addition to the focus on translucent thermal insulation and membrane materials, the air and the moisture conditions within the ventilated air layer are also investigated by simulations and will be measured in-situ: The project is accompanied by a research project that will also consider monitoring of the building performances and the thermal and moisture behavior of the roof construction. The aim of the project is the methodical analysis and development of energy efficient structural measures for buildings with membrane constructions in Germany including the broad range of planning and building permission issues (due to federal fire regulations for example). The paper presents the project as a case study that offers the challenges and experiences gathered during the planning and construction, and the first simulation results with a focus on the performance of the ventilation air layer.

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Keywords: Membrane roof; light transmission; translucent thermal insulation; multi-layer membrane

* Corresponding author. Tel.: +49-711-8926-2620; fax: +49-711-8926-2594.
E-mail address: jan.cremers@hft-stuttgart.de

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1. Introduction

A new sport centre in Germany is under construction that presently features a roof structure that consists of a multi-ply translucent and insulated membrane and is the basic topic of this case study.

1.1. Project description

After an architectural competition in 2001, the construction phase finally started in 2013. The sport centre consists of an 45m x 27m athletic ground separable in 3 fields with a tribune along the field, adjoining rooms (e.g.14 changing rooms, storage rooms etc.), and a covered outdoor gallery with a tribune fronting the outdoor sport field, Fig. 1a.

The sport field has a maximum height of 8m to 11.50m and is located at the subterranean level; all the other rooms are distributed throughout the basement and ground floors. The membrane roof covers the sport field and overlaps the secondary rooms. The architects associate the shape of the roof with a “sprinter on the starting block” [1] while the white membrane material reminds of sportswear itself.

The multi-ply membrane roof is conical-shaped and consists of an outer and inner membrane layer separated with an air gap of around 0.40-1.80m. The thermal insulation of 400mm lies atop the inner membrane with an air gap of approx. 40mm, cp. Fig. 1b, 3, 4. The load-bearing construction consists of conical-shaped lattice girders made of steel that generate the shape of the membrane roof and also create the air gap space. This air gap is fully ventilated as the outside border areas are only covered by perforated sheets. All layers of the membrane roof are planned to be translucent. This provides the opportunity to create a sufficient, non-glare and resource conserving natural light exposure. Additionally, the inner membrane was originally planned with a low-emissivity coating but this had to be cancelled in the detailed planning phase because indoor light levels would have dropped inadmissibly.

Designing with textile materials enables to create emblematic construction projects through the unique design material, the outstanding design options and the large column-free spans that can be reached [2]. In addition, the possibility in textile materials is also created to use simultaneous high light transmitting materials and reduce the artificial lighting demand as mentioned by scattering of the incident light through the white translucent membrane.

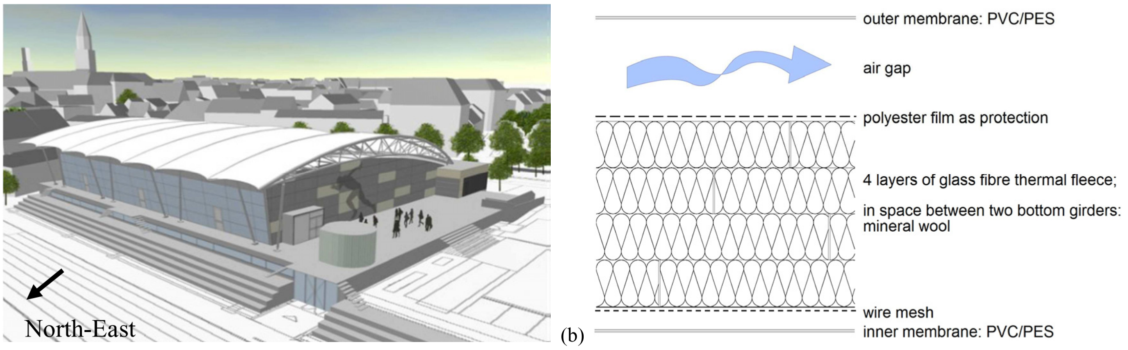
1.2. Used materials and their properties

- **Membrane**

For the sport centre, three different membrane materials have been considered; fluoropolymer-coated PTFE (Polytetrafluoroethylene) fabrics, PTFE-coated glass-fiber fabrics, and PVC-coated (Polyvinylchloride) polyester (PES) fabrics.

The main advantages of PTFE/glass are the higher possible light transmission of 8-20%, the high service life of >25 years and the very good UV-stability. PVC/PES can reach 5-15% light transmission (while the graying can reduce the transmission further), has a service life of 15-20 years and a good UV-stability depending on the coating thickness. But another relevant parameter are the costs of the material and manufacturing. PVC/PES fabrics are approximately 60% of the price of PTFE/glass. [3]

PVC/PES fabrics were selected as the outer and inner membrane of the sport centre due to these cost savings and because of the higher tensile stress necessary to support the PTFE/glass which would affect the load bearing structure.



(a) (b)

Fig. 1. (a) Rendering of the new sport centre in Germany (Rendering: City Fürth, Planning Agency) and (b) composition of roof layers and materials (fab_architects)

(b)

(a) (c)

Fig. 2. Sport centre during constructions; (a) in 2016 (fab_architects) and (b+c) in 2015.

- **Low-Emissivity-Coating**

To reduce the energy demand for heating and cooling, a coating with low-emissivity (low-E) can be applied on the inner membrane, which would reflect a larger part of the infrared radiation. Calculations for the sport centre have shown that a cost-effective low-E-coating would have only negligibly improved the thermal insulation and comfort (U-value), however, the light transmission would be significantly reduced. Therefore, the decision was made against a low-E-coating, especially because the overall transmission is already low (due to the fabric used and the thermal insulation) and a further reduction would not have been arguable. [4]

- **Translucent Thermal Insulation (TTI)**

Opaque insulation materials are mostly unwanted in buildings with textile materials, as it counteracts the possibility for light transmission. Thus, a special consideration to translucent (transmitting) thermal insulation materials was given in the project, because the thicker the insulation layer, the lower the light transmission [2]. Fiber spun fabric made of glass or polyester and synthetic resins or aerogel insulation material, which has currently the best insulating properties and light transmission, are possible TTI materials for the sport centre.

In the sport centre, 40 cm glass-fiber spun fabric with resin will be implemented in 4 layers with alternating abutments, see Fig. 1b & 4. Calculations have shown that PES-fiber spun as insulating material will result in visual transmission values that are too low [4].

- **Basic Challenges and Experiences**

The most noteworthy experience gathered during the implementation planning is the awareness of the fire safety aspects regarding materials used in the roof. According to the fire protection concept, the roof must be: B1 according to DIN4102-1 (difficult to ignite, low flammable), no flaming droplets. The reaction to fire of materials and products and the subsequent classification, regulation, and test methods are determined in the German standard DIN4102-1 (European standard DIN EN13501). For building materials and products that are not regulated in this standard, additional references are necessary e.g. a National Technical Approval from the German Institute for Structural Engineering or a specific approval in individual case. [5]

DIN4102-1 also specifies that all planar building materials that are in direct contact or adjoined to the material in question closer than 40mm can have an influence on the reaction to fire. Therefore, the potential application must then be considered in test procedures regardless of final implementation. Nevertheless, building-authority test certificates are already issued for most building materials, declaring the specific test and installation requirements.

The 40mm air space between the insulation and the inner membrane in the sport centre results from exactly this fact, Fig. 1b. Getting an ‘approval in individual case’ proved to be difficult over the construction period because of the fail of the material construction in fire reaction testing, which caused construction delays. Therefore, an air gap was added and the permission issued.

In addition, more attention had to be paid to the planning for the attachment of installations, like ventilation ducts, lamps, dividing walls etc., which are usually mounted on the ceiling. With auxiliary constructions, suspensions and fittings on the walls and membrane abutment joints, almost all installations could be placed while avoiding cutting through the membrane.

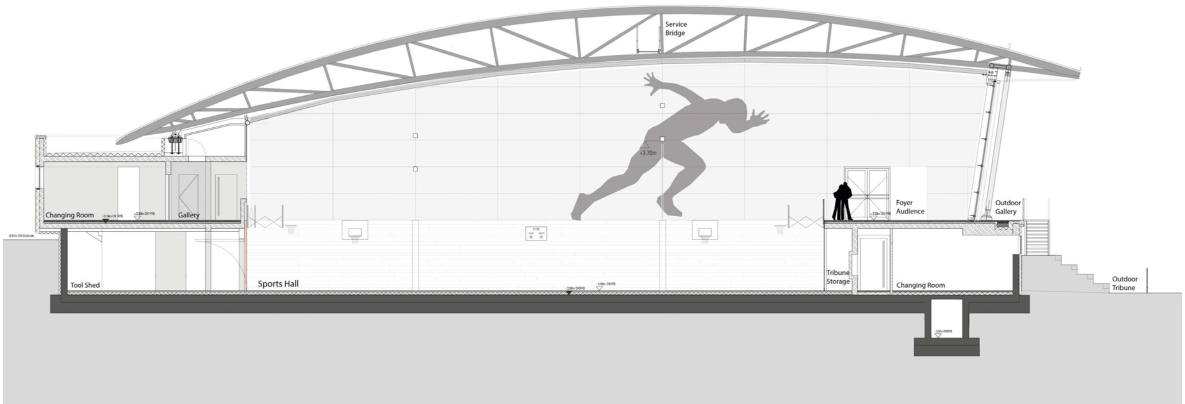


Fig. 3. Cross section of sport field (fab_architects)

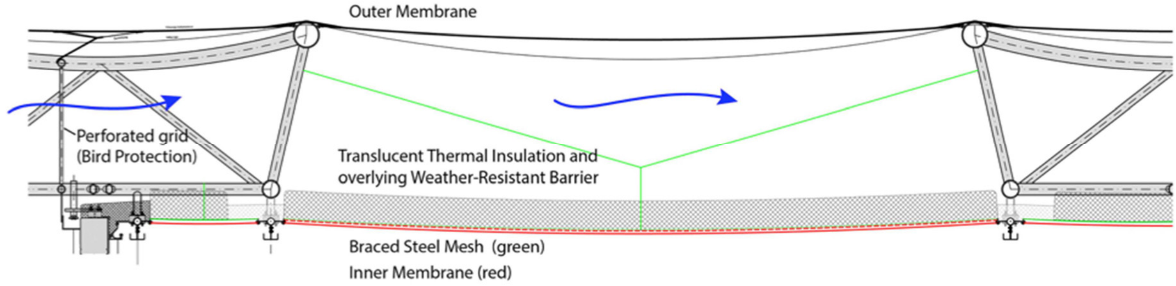


Fig. 4. Cross section roof construction (fab_architects)

2. Simulations

2.1. Air flow Simulations of the Roof Construction

Experimental and numerical simulations concerning the air flow conditions within the air gap between the top membrane and the inner part of the roof were performed to investigate the forces on the membranes and the load-bearing steel structure and the behavior of the air velocity, resulting in air exchange rates. The investigations in a wind tunnel and the numerical simulations using the CFD-software OpenFoam (OpenCFD Ltd, ESI Group) were done by the company Wacker Ingenieure and summarized in an internal report [6]. The two (long) sides of the roof where the top and bottom girders meet were assumed to be closed. The two open sides are protected against inflow of birds by perforated metal sheets, Fig. 6.

As can be seen in Fig. 5 the air velocities near the closed sides of the roof are very low, giving rise to concerns about moisture accumulation. However, it was decided to leave these two sides open, but protected by perforated sheet and textile netting. This way the roof is well ventilated for all wind directions. Table 1 summarizes some results for a wind speed of 0.85m/s for different perforated sheets and wire meshes. [6]

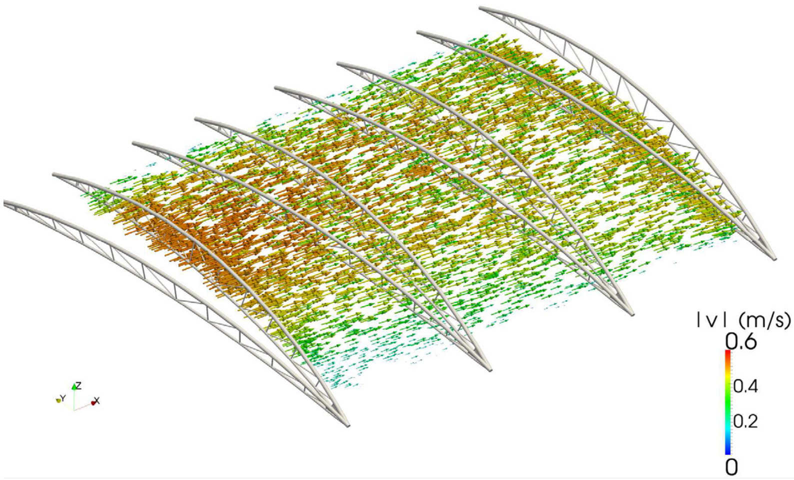


Fig. 5. Speed vectors of the air flow in the air gap (free inflow, 0.85m/s from 135° south-east, in roof height) [6]

(a) (b)

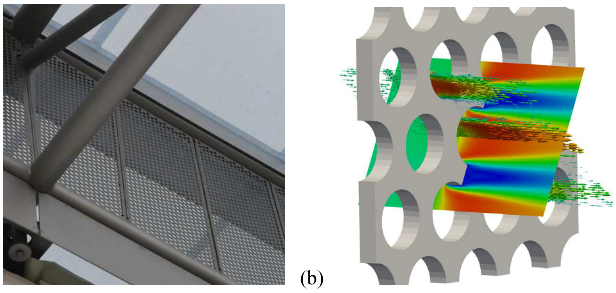


Fig. 6. View (a) and calculated air velocities (b) of perforated metal sheet [6]

Table 1. Calculation of different sheet or meshes [6]

Bird protection mash	Open fraction of area	Wind direction	Pressure loss coefficient	Air exchange rate
	(%)	(-)	(-)	(m³/h)
none	100	South-East	0	44,7
	100	East	0	43,5
wire mesh, coarse	69	South-East	0,3	35,2
	69	East	0,3	30,4
wire mesh, fine	81	South-East	0,6	34,9
	81	East	0,6	30,2
perforated sheet, diameter 30mm	51	South-East	3,7	20,2
	51	East	3,7	18,1
perforated sheet, diameter 300mm	51	South-East	4,2	19,3
	51	East	4,2	16,8

2.2. Humidity Calculation

The moisture conditions within comparable insulated membrane roofs are not yet well known. The middle parts of these roofs can be compared with conventional ventilated roofs. However, the membrane roof of the sports centre has only a slight or no slope. Thus, air moisture condensing on the inner surface of the top membrane may drip off, influencing the heat and moisture conditions on the polyester film cover of the thermal insulation. It is not clear whether this phenomenon has an important effect and how this can be calculated with common hygro-thermal software such as WUFI (Fraunhofer Institut für Bauphysik). So, as a first step, a PC-program was developed calculating the heat and moisture fluxes, temperatures, and water layers on both surfaces of the top membrane. A maximum water layer thickness was assumed, resulting in excess water dripping off.

With only a few exceptions on sunny days, the temperature of the top membrane remains below the outside air temperature throughout the year (Fig.7). This is due to radiative heat losses to the sky and the white membrane´s low absorptivity for solar radiation of only 15%. During times of high air humidity, this causes condensation on both surfaces of the top membrane. In Fig. 8, condensation has a positive sign for the outer surface and a negative indication for the inner surface. The maximum water layer thicknesses were assumed to be 0.6 mm and 0.4 mm. Fig. 9 shows the results for a whole year.

Further simulations are planned for the edges of the roof. These edges, which are protected only by the perforated sheets, are subject to input of rain and snow and give rise to concerns about moisture accumulation. Also, hygro-thermal simulations are planned for the joints of the inner part of the roof with the girders and its joints with the outer walls. These joints may suffer from condensation of air moisture on their internal surfaces.

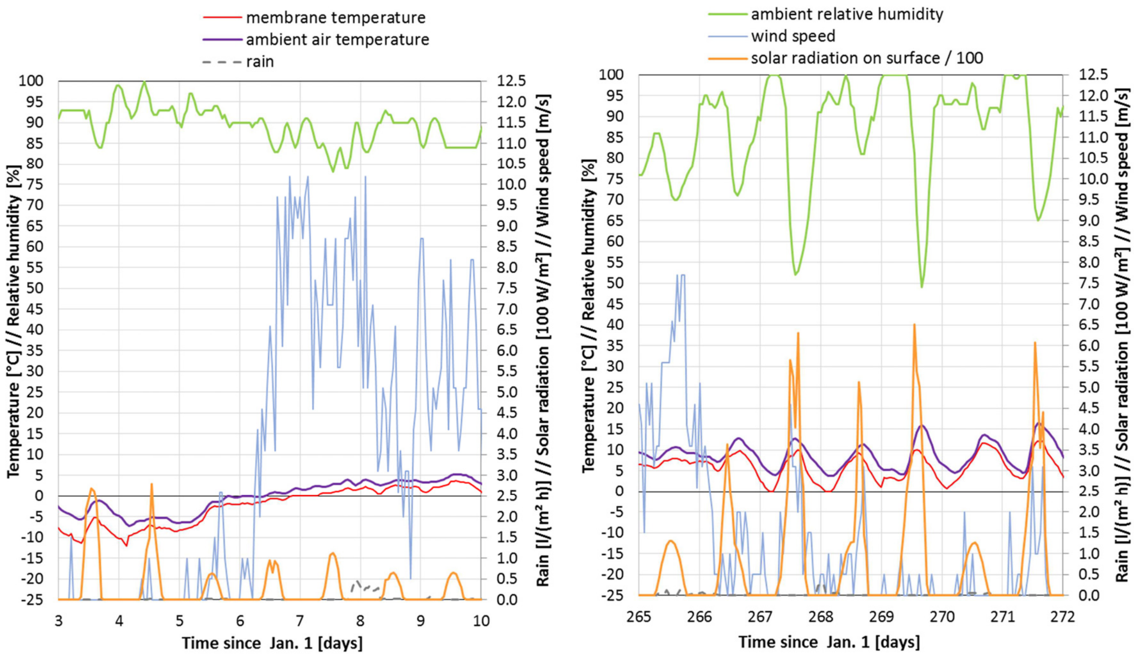


Fig. 7. Weather data and membrane temperatures shown for Jan. 4th-10th and Sept. 4th-10th.

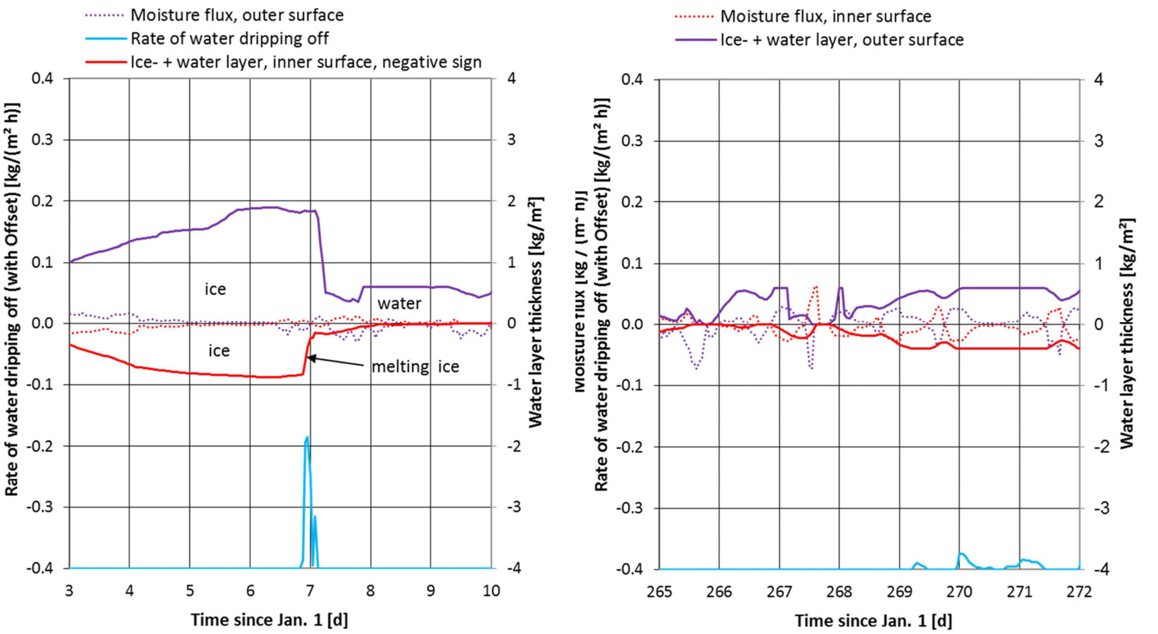


Fig. 8. Condensation and evaporation rates, water layer thicknesses and amount of water dripping off (blue line, with zero at the value -0.4 on the left axis) shown for Jan. 4th-10th and Sept. 4th-10th.

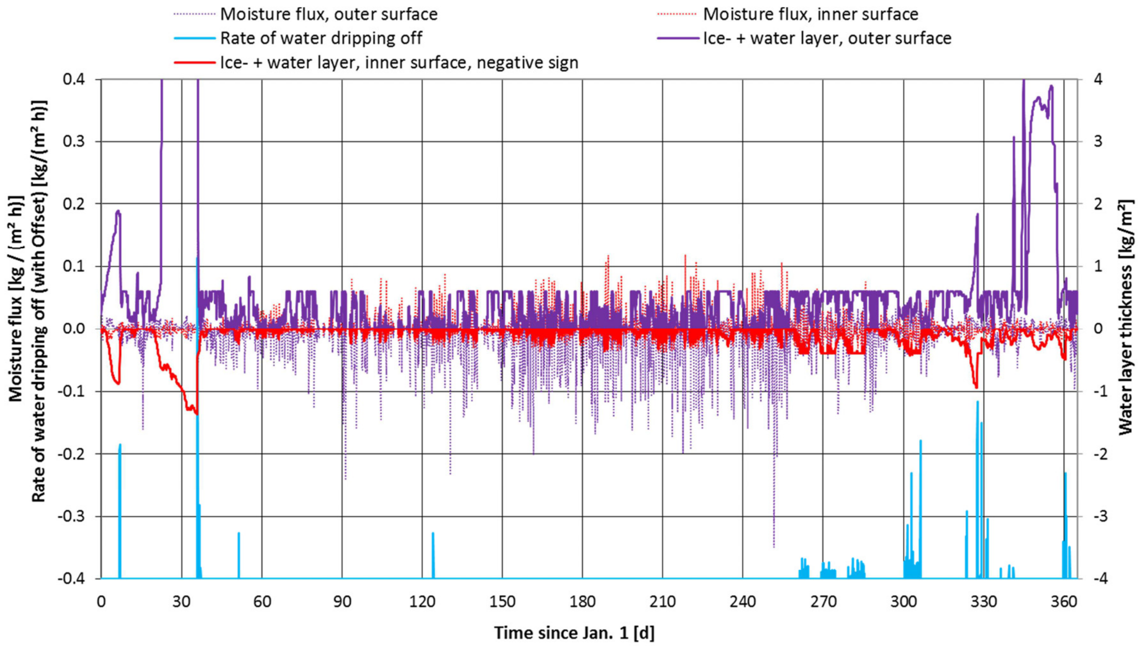


Fig. 9. Condensation and evaporation rates, water layer thicknesses and amount of water dripping off (blue line, with zero at the value -0.4 on the left axis) over the course of one year.

3. Monitoring concept

Comprehensive measurement data logging is necessary to analyze and visualize building behavior and to subsequently reduce energy consumption of the building by optimizing the building automation. For this monitoring phase, sensors and data logging devices will be installed: nine movable measure platforms have already been installed within the air gap of the membrane roof carrying sensors for temperature, air humidity, air velocity and air direction. As the thermal insulation of the roof will not be walkable, the measuring platforms have been attached to ropes stretched between the steel trusses, see Fig. 10. In this way, the platforms can be moved about to some extent. This enables to record different areas within the roof construction during a measurement period without having elaborate replacements measures.

Additionally, temperatures at the membranes and the steel structure, the indoor and outdoor climates will be measured as well as the basic building energy flows. All sensors are wireless. The data logger will be remotely accessible for data acquisition by Hochschule für Technik Stuttgart (HFT).

4. Results and Discussion

First simulations have been done to investigate e.g. how the air flow and moisture will behave within the air gap of the roof to prevent damages due to humidity and to investigate different membrane material options.

The aim of the data collection as mentioned, is on the one hand for the optimization of the building automation but also to evaluate the performance of ventilated multi-ply translucent roof constructions. Another aim is the validation of the simulation results with the measured data collected in the sport centre, which will lead to profound knowledge about the performance of such roof constructions. All results as well as a handbook for planers will be published at the end of the project.

Fig. 10. Measurement platform attached on the robes within the membrane interspace.

5. Conclusion

The aim of the project is the methodical analysis and development of energy efficient structural measures for sport centres with multi-ply membrane constructions. By choosing the right materials and combinations thereof, the comfort conditions will be ensured, the energy demand can be reduced and resources will be saved. The experiences gathered thus far in addition to those to come over the next months, will help overcome possible obstacles and provide other planers support during planning regarding different aspects like fire protection, heat and moisture, and lighting. The collected experiences with the detailed monitoring of the multilayer membran roof construction will help to develop and validate tools for calculation and simulation. The developed and optimized tools will help in further projects to simplify the planning process and to avoid mistakes.

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