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MULTIFUNCTIONAL ADAPTIVE FAÇADE AT IBA 2013; DESIGN STUDIES FOR AN INTEGRAL ENERGY HARVESTING FAÇADE SHADING SYSTEM

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Summary: *As part of the international exhibition 'Bauausstellung' IBA 2013 in Hamburg, Germany, architects from KVA MATx team and engineers from Knippers Helbig Advanced Engineering have developed an integral energy harvesting façade shading system for their 'Softhouse' project. Its overall concept includes an energy harvesting hybrid textile roof featuring flexible photovoltaics, which contributes to create a micro-climate for the building as a shading roof for the terrace and glass façade. This responsive façade is based on a textile hybrid system, using textile membranes and glass fibre reinforced plastics (GFRP) in an intricate form- and bending-active structure. This paper will discuss the multiple design studies that were undertaken to develop a system that satisfies the, at times, diametrically opposed demands from architecture, building physics, structural engineering and technical approval. Furthermore, detailed information will be given on the design specifications for using GFRP in bending-active elements and the Finite-Element simulation techniques used for the form-finding and structural analysis.*

1 INTRODUCTION

The textile façade of the 'Softhouse' undergoes two modes of shape adaptation: in a yearly cycle, the GFRP boards on the roof top change their bending curvature and therefore adjust the PV cells to the vertical angle of the sun, while the daily east west sun tracking and day-light harvesting is achieved by twisting the vertical membrane strips in front of the façade. The membrane strips are attached to cantilevering GFRP boards acting as compound springs compensating the change in length of the membrane strip through twisting. The form-finding and simulation of the initial system as well as its shape adaptations and the performance of all positions under wind and combined snow loads set a particular challenge to the engineering of the project. The basic shape changing modes are illustrated in (Fig. 1).

The adaptive façade shading system consists of a parallel arrangement of 32 individual strips which are combined in sets of 8 per housing unit. Each strip is a textile hybrid system with a 4m x 0.6m pre-stressed form-active membrane attached to a bending-active 6m pultruded GFRP Board (500mm x 10mm). Flexible photovoltaic cells are attached to the upper third of the membrane, continuing to the apex of the shape-adaptive GFRP board.

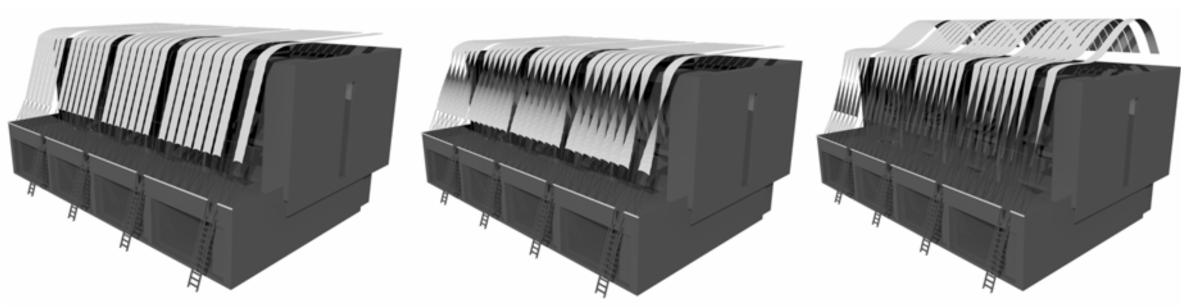

Figure 1: Two modes of shape adaptation and their combination

2 DESIGN VARIATIONS

The two modes of shape adaption described above can be achieved by various mechanisms. In all cases, a system had to be developed that is able to compensate the nonlinear change in length of the membrane strip due to twisting (Fig. 2)

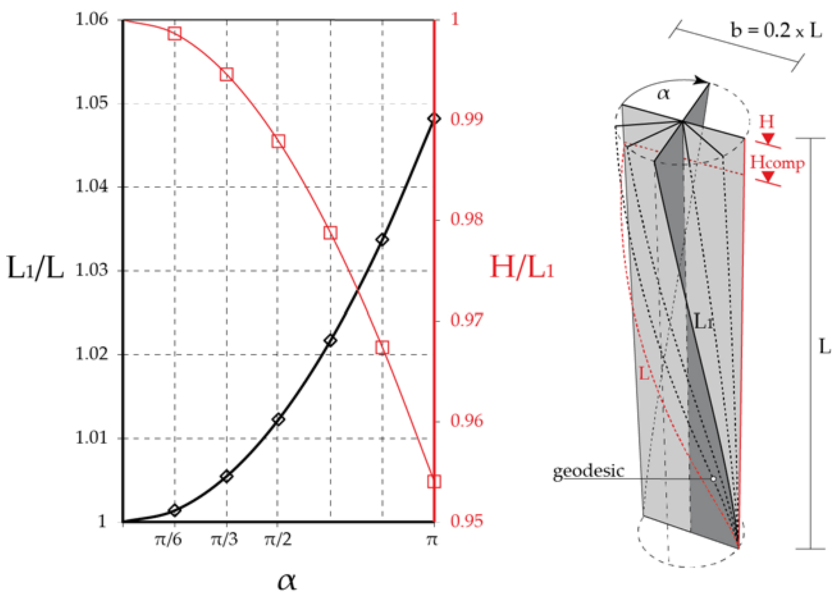

Figure 2: Edge elongation and height compensation during twisting of the membrane strip

An intricate system was developed in which a cantilevering GFRP board works as a compound spring to the attached membrane strips and therefore freely compensates the nonlinear change in strip length during twisting. On top of the roof, the cantilevering board

continuously evolves into a bending-active arch system which offers a change in rise and curvature due to the kinematics of the underlying steel structure.
For the twisting of the membrane strips, various mechanical systems were simulated and compared. Fig. 3a shows a kinematic cable rigging that induces a twisting motion to the membrane strip when two diagonally opposite cables are contracted. This very simple and efficient system, however, only allowed for a twisting range of 90°. In Fig. 3b the cross bar at the bottom of the membrane strip is directly actuated by cables. Here, the partially unproportional change in cable length of the two sides had to be compensated by springs, or else necessitated two separate cable winches. For reasons of enabling a twisting range beyond 180°, a directly actuated system with a turning drive was chosen as shown in Fig. 3c.

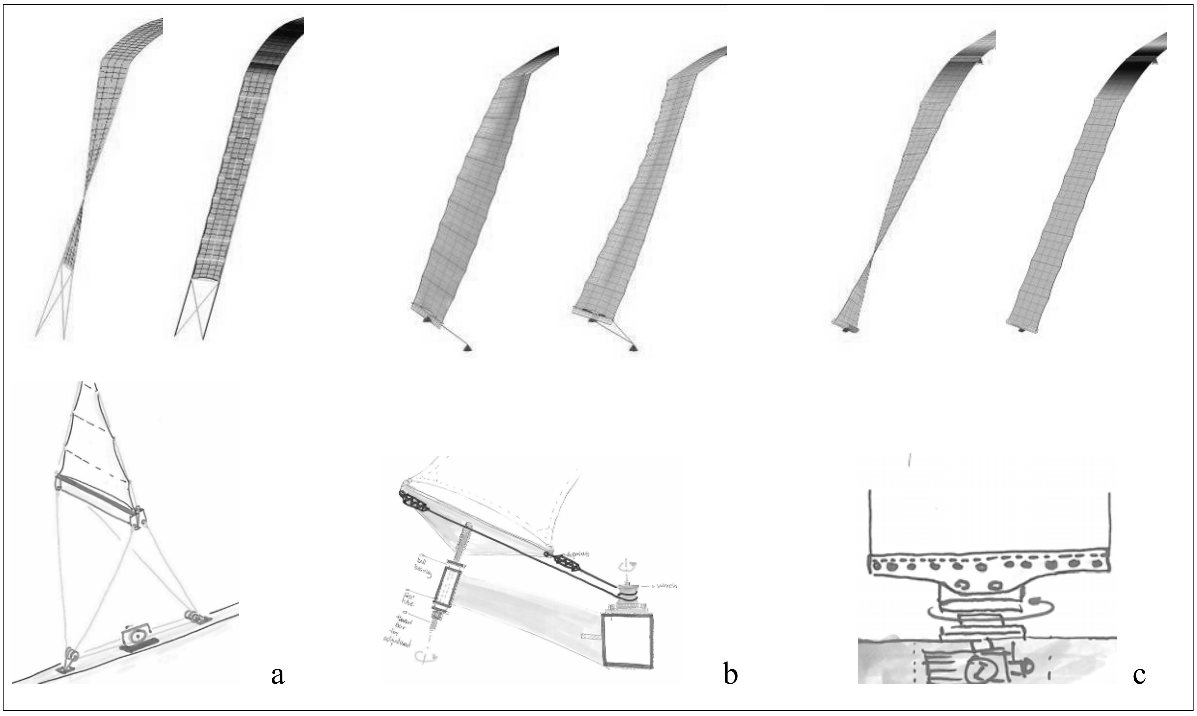

Figure 3: Various twist actuation mechanisms

3 MATERIAL

Several types of GFRP boards were investigated in the design and pricing phase. Even though hand lamination could have been a valid alternative in terms of costs and mechanical properties on paper, comparative 3-point bending tests quickly revealed that stiffness and strength reserves of industrially pultruded GFRP boards are significantly higher and more consistent than those of hand laminated elements. For the final structure, a GFRP product with national technical approval was selected(see below).

For the membrane strips, a non-coated open weave glass fabric was chosen, which offers excellent shading properties combined with translucency (see Fig. 8 right). The absence of a stiff coating also allows for shear deformation of the fabric and therefore enables twisting without wrinkles.

3.1 Design codes for GFRP

While building structures that include FRP in their load bearing elements still need individual technical approval in Germany (ZiE), there is an emerging development in the standardisation of FRP as building products. Next to the German guidelines, e.g. BÜV-recommendation [1], the Danish based company Fiberline Composites has been granted national technical approval (abZ approval) for their pultruded GFRP products in German building projects [2]. Both consider the influence of loading duration and environmental conditions by means of safety factors. Generally, three strength and stiffness influencing factors are recognized:

Load duration
Ambient media class
Member temperature

The safety concept of BÜV and abZ is based on a general material safety factor and a set of influence coefficients, resulting in different overall safety factors for various loading scenarios. The permissible stress is generally therefore given by equation (1):

$$\sigma_{Rd} = \leq f_{k0,05}/[\gamma_M (A1+A2+A2)] \qquad (1)$$

With $f_{k0,05}$: 5 % quantile of strength , γ_M (partial safety factor) 1,2 (machined) or 1,5 (hand laminated) [1] and A_i: influence coefficients. Within abZ, the influence factor A_1 is directly applied on the action side, while all other factors are considered on the resistance side. In general praxis, the design of bending-active structures should consider three main scenarios:

Dead load + residual-stress: long load duration, max. pos. temperature: $\gamma tot \approx 4$*
Wind load + residual -stress: very short load duration, mean temperature: $\gamma tot \approx 1.9$*
Snow load + residual -stress: mean load duration, low. neg. temperature: $\gamma tot \approx 2.3$*

*Average values for the 'Softhouse' Project from BÜV and abZ.

Note that the dead load + pre-stress scenario limits bending stress to 25% of the limit stress in the form-finding of the curved geometry.

In terms of the material stiffness, it must be noted that, especially for polyester resins, a loss of modulus has to be considered for ambient temperatures above 30°C, with a considerable influence for temperatures higher than 50°C. Here, the aforementioned guidelines introduce a secondary safety concept in which material stiffness is reduced based on equation (1) with stiffness specific influencing factors.

3.2 Breaking strength and material stiffness

For industrially produced profiles, mechanical properties are usually given based on standardised material tests. For practical reasons, the same values are given for all structural profiles with a typical longitudinal bending strength of 240MPa [3]. L-shaped profiles usually exhibit the lowest strength in the cross-sections of pultruded profiles with very small 5% quantile values due to production inaccuracies. Round bars, pipes and flat sections, on the other hand, offer the highest strength and reach bending strengths above 350MPa in all tests known to the authors. Since the profile shapes used in bending-active structures are predominantly round and flat sections, in a project it may be profitable not to rely on the standard values suggested by companies, but instead perform your own material tests. This, however, necessitates technical one time approval.

The elastic modulus, too, is usually given as a uniform value for all profile shapes which represents the lower limit of the various actual moduli. However, it was found that flat sections, as they are often used in bending-active structures, may have a lower modulus than other larger sections. This is due to the fact that all profiles must have at least two outer layers of fibre mats which have a much larger influence on the sectional properties for thin flat sections than for other cross-section types.

3 FORM-FINDING

The form-finding of the continuously shape-adaptive system is divided into several sub routines, starting with a straight GFRP board which is pulled onto its given support using the elastic cable approach [4] (Fig. 4c). Simultaneously, uniform pre-stress is assigned to the membrane strips which are coupled to the bent GFRP boards in a last form-finding step where equilibrium and stress distributions are harmonised by an equalisation routine that reiterates the equilibrium of the system without additionally applied loads. For the shading system of the ‘Softhouse’, only the support at the eaves was pre-defined in the geometry. For the other supports only the heights were defined. By attaching the cables to horizontally sliding supports, the form-finding guaranteed minimal constraining forces.

For the twisting membrane strips it was important to control symmetry and equidistance of the cross bars. This was difficult to maintain in a simultaneous form-finding with the cantilevering GFRP boards. Therefore, the membrane strips were form found separately (Fig. 4b). In a second step the membrane was coupled to an already elastically deformed GFRP board (Fig. 4c). The subsequent equalising calculation lead only to minimal change in the equilibrium position since the position of the cantilevering beam was already known from previous simultaneous form-finding investigations. In order to include the winter position of the GFRP boards with maximally bent arches in the FEM model, the kinematics of the steel structure were included to simulate the shape adaptation (Fig. 4d).

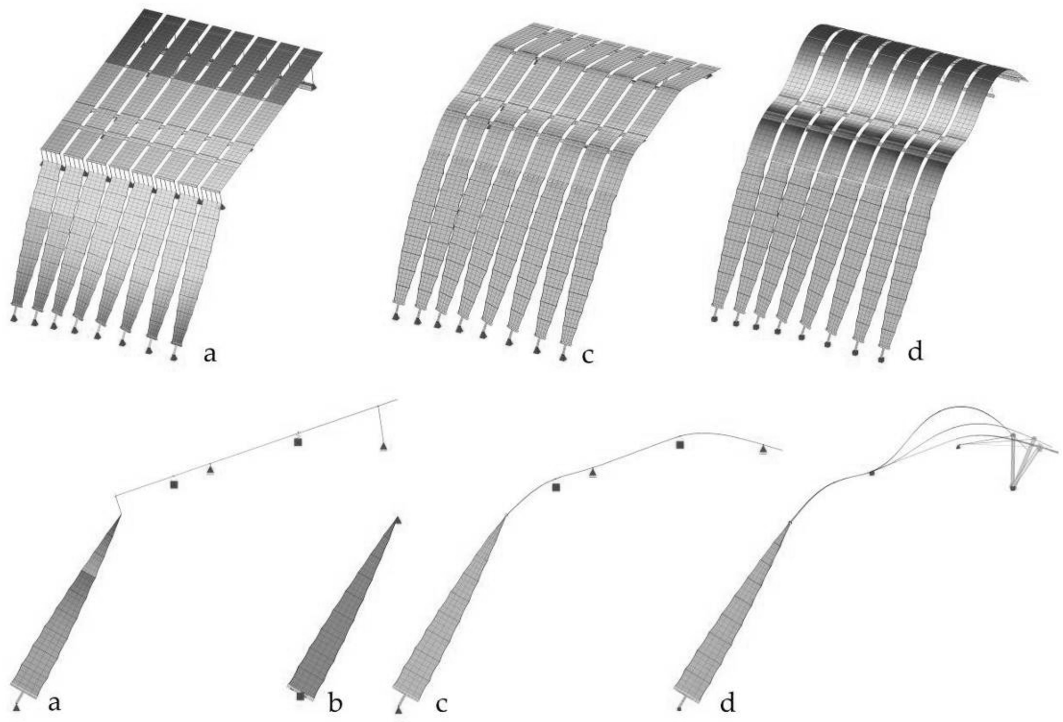

Figure 4: Form-finding sequence

4 STRUCTURAL BEHAVIOUR

The varying structural system and shape led to a highly differentiated load simulation, adapting snow loads according to the varying degree of incline and c_p pressure values for the various wind directions to the different twisting positions of the membrane, as well as the inclination of the GFRP boards on the roof. For the safety of the structure, a storm position was defined where the membrane strips are twisted 90° and therefore offer maximum stiffness due to double curvature. In the twisted position, the membrane strips are less susceptible to flagging due to continuously changing c_p values along the strip. On the roof top, the winter position of fully bent GFRP boards may only be adopted at wind speeds below 12m/s. Overall, the system is characterised by highly nonlinear behaviour which excluded superposition of loads and therefore led to a very involved and time consuming structural analysis. A FEM model of the system including the supporting kinematic steel structure was built which enabled both form-finding and simulation of the system in all modes of shape adaptation (Fig. 5).

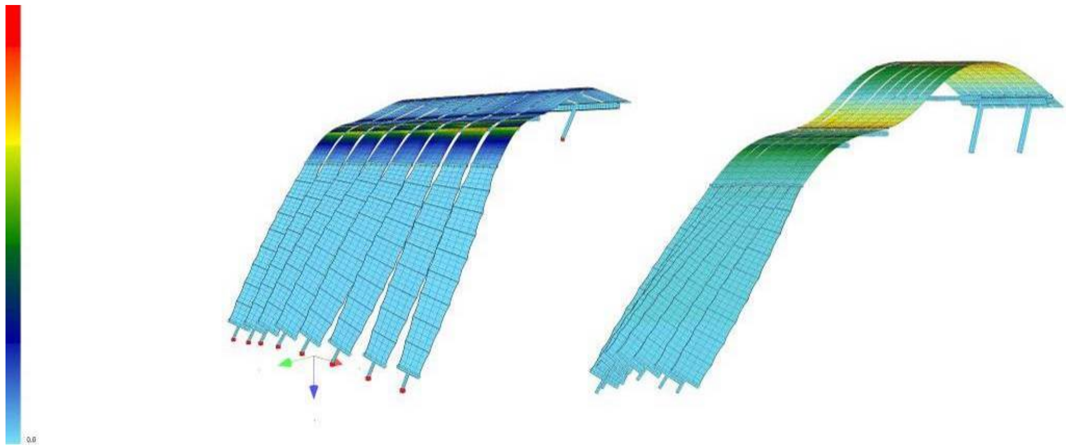

Figure 5: FEM analysis of storm and winter position in a coupled system including the steel kinematics.

Wind tunnel tests were performed to define minimal pre-stress and maximal wind speed in the untwisted position in order to control flagging of the membrane strips (Fig. 6). It was found that 0.3kN/m pre-stress provides sufficient aerodynamic stability to the twisted membrane strip. No critical flagging was observed in the untwisted configuration for wind speeds up to 10m/s.

Figure 6: Wind tunnel tests of twisted and planar membrane strips (Wacker Ingenieure - Wind Engineering).

5 FINAL RESULT

The building was completed at the end of March 2013 for the opening of the IBA. First tests showed that twisting of the membrane worked perfectly, in which the cantilevering beams where able to adjust to the shortening of the membrane strip as predicted. In combination with the open weave non-coated glass fibre mesh membrane, the twisting of the membrane strips does not lead to wrinkles (Fig. 7 and 8). The deflection of the cantilevering boards and the harmoniously pre-stressed membranes show that the form-found geometry and predicted behaviour match the FEM analysis.

Figure 7: Testing various modes of shape adaptation on the finished structure (Pictures by Textilbau GmbH)

Figure 8: Finished 'Softhouse' building with multifunctional adaptive facade at IBA Hamburg Mai 2013

6 CONCLUSIONS

While the adaptive basic system of twisting membrane strips and bending-active GFRP boards displays a high degree of structural and functional integration, its connection to the building structure was very challenging. Continuing changes to the function and design of the adaptive shading system had to be adapted to the, at times, diametrically opposed demands from architecture, building physics, structural engineering and technical approval.
Overall, the project was able to prove that GFRP in the unconventional context of a hybrid bending-active system can be realised within the strict rules of German building codes and individual case approval.

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Structural Engineer: Knippers Helbig Advanced Engineering

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