Abstract

A new type of kinetic façade system is presented which was inspired by flexible deformation principles found in plant movements. The project is a role model for a novel application of glass fiber reinforced polymers (GFRP) for deployable structures as well as for advanced biomimetic research and design.

Keywords: biomimetic research, deployable structures, GFRP, kinetic façade

1. Introduction

The kinetic media façade is an integral part of the Thematic Pavilion, a major and permanent building for the Expo 2012 in Yeosu, South-Korea which was designed by SOMA Architecture, Vienna [1]. Convertible systems in architecture are usually realized through the combination of stiff elements or soft textiles with particular movable elements like hinges, rolls, etc. The use of GFRP allows for large and reversible elastic deformations and enables us to think about a completely new interpretation of convertible structures. In nature, plants have evolved a multitude of kinetics based on elastic deformation without any hinges to serve the opening and closing of flowers, leaf orientations etc. The analysis of these principles inspired the kinetic façade system of the Yeosu pavilion.

The facade is 140m long and between 3 and 13m high. It consists of 108 kinetic GFRP louvers, which are supported at the top and bottom edge by fixed supports on one corner and extendable actuators on the other corner. These actuators push the upper and lower edges together and lead to an elastic bending combined with a side rotation of the GFRP elements.
In very strong wind conditions which occasionally occur at the South Korean coast, the façade will be closed and locked automatically. For the different open positions pressure values were derived from wind tunnel tests.

2. Operational Modes

2.1 General architectural intention

The operable louvers fulfil a climatic function and allow different modes of operation depending on the user’s needs. Within the operation mode the louvers are individually actuated and create animated patterns along the façade. The potential choreography ranges from subtle local motion to overall waves affecting the whole length of the façade.

After sunset the analogue visual effect of the moving louvers is intensified by linear LED bars, which are located at the inner side of the front edge of the louver. When open the LED can illuminate the next louver depending on the angle at which it is opened. Continuous GFRP flanges minimize the amount of light (artificial and natural) that enters when in the closed position.

2.2 Movement

The louvers are moved by actuators located on both the upper and lower edge, inducing compression forces to create the complex elastic deformation. They reduce the distance between the two bearings and in this way induce a bending which results in a side rotation of the louver.
The actuator of the louvers is a screw spindle driven by a servomotor. A computer controlled bus-system allows the synchronisation of the actuators. Each louver can be addressed individually within a specific logic of movement to show different choreographies and operation modes. The operation system requires feedback information from the electric servo motors regarding the actual position of the louvers and can be linked to internet. This allows uploading movement scenarios and information about façade condition to be sent to a maintenance company. Upper and lower motors often work with opposite power requirements (driving – braking). Therefore generated energy can be fed back into the local system to save energy.

The opening procedure of a 13m louver requires a movement of 450mm for an opening angle of 60°. The maximum movement speed of one actuator is about 3,80m/minute. Short louvers open less. A detailed geometrical analysis of the movement has been carried out in order to determine potential collisions. Those have been solved by minor adjustments of the movement paths and bearing locations [2].

3. Structural Design of GFRP Louvers

3.1 Design Verification Concept

Design rules for glassfibre-reinforced polymers, which exist in international and national guidelines are far from being complete and consistent. Therefore the safety concept applied consists of an ´action part´ where all relevant load combinations and accompanying safety factors have been considered according to Eurocode 0 (EN 1990) [3]. Reduction factors applied on the ´resistance part´ have been taken into account according to different German guidelines, e.g. BÜV-recommendation [4]. The short term material
properties determined for laminate build-ups as specified within DIN 18820 [5] are reduced in order to consider long-term behaviour, influence of media and temperature as well as a dynamic load history.

\[
f_d = \frac{f_k}{\gamma_M A_1(t) A_2 A_3 A_{\text{dyn}}}
\]

(1)

where: \( f_k \) = characteristic resistance \( t_0 \)
\( \gamma_M \) = partial safety factor
\( A_1(t) \) = reduction factor – loading duration
\[ = 1 + \eta [A(t=20a) -1] \]
\( A_2 \) = reduction factor – influence of media
\( A_3 \) = reduction factor – temperature influences
\( A_{\text{dyn}} \) = reduction factor – opening procedure

In terms of long-term behaviour, it has been assumed, that the louvers are subjected to max. stresses caused by opening process 1/3 of their lifetime, which is 20 years. The chosen reduction factor also covers effects of cyclic long-term loading (cp. Figure 5). Max. design temperature is 70°C (45°C ambient + 25°C ext. surface). Reduction factor \( A_2 \) for media influences has been determined under consideration of outside conditions (water combined with temperature influences). Based on the duration of one opening/closing process (about 30 seconds) and the natural frequencies of the louvers the dynamic amplification factor has been considered to be equal to 1,0 (cp. Figure 5).

![Figure 5. Determination of dynamic amplification factor / Fatigue Resistance (max. relative load) [2]](image)

Overall safety factor consisting of partial safety factor and reduction factors is between 1,9 for short term loading (wind loads) and 9,6 for stress in transverse fibre direction during opening process.

### 3.2 Load Assumptions / Wind Tunnel Tests

The facade had to be designed for very high wind speeds of up to 35m/s occurring on the South Korean coast under Typhoon conditions. The wind loads were derived from wind tunnel tests in order to achieve a safe and economic design of the louvers. Besides this realistic assessment of the local peak wind pressures acting on the louvers, the aerodynamic stability had to be determined, since slender or large spanned structures with a low stiffness tend to wind induced instabilities [6].

The operational concept based on the aforementioned studies basically identifies two different situations: As long as the wind is less than 12m/s (6 Beaufort) the façade can operate. If the
wind is stronger than 12m/s the façade will automatically close and pretension will be applied by pre-stressing the weak edge accordingly to increasing wind loads.

### 3.3 Numerical Models / Calculation Results

The structural analysis is based on the geometry of the longest (13.6m) and shortest (6.0m) louver. Assuming that the values of displacements, natural frequencies, reaction forces and stresses are critical values, these louvers have been chosen for exemplary investigations.

In order to obtain reliable results numerical calculations have been carried out using two different Finite Element Method (FEM) programmes SOFISTIK 23 by Sofistik AG, Germany and MSC Nastran by MSC Software, USA (cp. Figure 6).

![Figure 6. Numerical models and results for louver with max. length](image)

Through use of composite layered shell elements strains and stresses of the laminate and each ply can be calculated with MSC Nastran. Laminate failure index is representing results of a max. stress criterion (cp. Figure 6). This stress based criterion is a decoupled failure criterion, assuming a material failure occurs if one of the stress components within the local direction exceeds the relevant design stress resistance.

\[
\max \left( \frac{\sigma_{x,Ed}}{f_{x,Rd}} ; \frac{\sigma_{y,Ed}}{f_{y,Rd}} ; \frac{\tau_{12,Ed}}{\tau_{12,Rd}} \right) \leq 1.0
\]  

(2)
where: $\sigma_{x, Ed} = \text{design value of normal stress in local x-direction}$  
$\sigma_{y, Ed} = \text{design value of normal stress in local y-direction}$  
$\tau_{12, Ed} = \text{design value of in-plane shear-stress}$

For the analysis three major critical positions have been investigated:

Position 1 “Closed”: louveres are completely closed and pre-tensioned.

Position 2 “almost closed”: louveres are still in closed position but not pre-tensioned

Position 3 “max. opening”: louveres have been opened to their maximum opening angle, actuator is max. extracted

In addition exceptional load cases due to malfunction of the technical elements within the façade system have been carried out.

### 3.4 Dimensions / Connection Details

The 13-metre-long louveres consist of an isotropic laminate with a thickness of about 9mm, they are stiffened at both longitudinal edges with a 200mm rib and a 30mm rib respectively.

A hard rubber buffer bar protects the GFRP laminate, when the façade is closed and one louver rests on the other.

![Figure 7. Section - Dimensions of largest (13m long) louver in closed state [2]](image)

Different build-ups for isotropic and orthotropic laminates as specified within DIN 18820 have been used within schematic design phase (cp. Table 1). Further optimization of structural behaviour and maximum opening angle of louveres was a possible option within construction document phase.

| Table 1: Laminat layout for MW1 (t=9mm – 45°/-45°) and FM3 (t=30mm – 0°) [2] |
|---------------------------------|----------------|--------|--------|
| fibermass-content | [%] | 40 | 45 |
| thickness | [mm] | 8,96 | 28,94 |
| number of plies | [-] | 11 | 55 |
| orientation | [°] | 45°/-45° | 0°/90° |
| setup | | | |
| chopped mat | [g/m²] | 450 | 450 |
| woven fabric | [g/m²] | 580 | 580 |
| proportion | [x–y] | 2,2 : 2,3 | 2,2 : 2,3 |
| chopped mat | [g/m²] | 450 | 450 |
| UD-ply | | | |
| chopped mat | [g/m²] | 480 | 480 |
| UD-ply | [g/m²] | 300 | 300 |
| chopped mat | [g/m²] | 450 | 450 |

1) related to local x-y coordinate-system  
2) fiber-mass related to area
The connection detail between GFRP louver and actuator is realized by means of an inlay, fabricated out of steel sheets and steel sleeves, laminated in tapered parts of the louver (cp. Figure 8).

![Diagram](image)

**Figure 8. Detail `top connection of louver to actuator` [2]**

### 4. Performance Mock-Up Tests

Overall structural behaviour of the smallest and largest louvers respectively has been tested within a full scale performance mock-up test. In order to consider the stiffness and determine the influence on the overall load deflection behaviour, the louvers have been attached to a steel sub-structure consisting of steel hollow sections (cp. Figure ).

![Mock-Up Tests](image)

**Figure 9. Louvers during performance Mock-Up Tests**

Within a time period of 35 consecutive days, the louvers have been operated successfully.
5. Conclusions

During the planning phase different possible technical solutions for the kinetic media facade have been investigated and their aesthetical and architectural implications have been considered. Based on this process an optimal solution, supporting the initial idea of the design - a continuous building skin that changes shape in smooth movements - has been found. Furthermore the biomimetic approach meets the client’s wish to make the Thematic Pavilion a showcase of a future architecture that learns from nature [8], [7].

Structural design verification of GFRP louvers is based on a combined safety concept considering various safety factors. For the analysis different critical positions, including exceptional load cases due to malfunction of the technical elements have been investigated. Reliability of results has been double-checked by means of a second FEM-software. Overall load deflection behavior has been tested successfully within full scale performance mock-up.

6. References