FUNCTION-INTEGRATED GFRP SANDWICH ROOF STRUCTURE

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ABSTRACT

This paper reports on the design and construction of a lightweight GFRP roof structure in Basel, Switzerland. The sandwich construction allowed for an integration of static, building physical and architectural functions that enabled the prefabrication of the entire roof in only four lightweight elements that were easily transported to the site and rapidly installed. Cutting of foam blocks with a computerized numerical control machine and adhesive bonding proved to be advantageous procedures for the fabrication of the complex roof shape, without the use of expensive moulds. The applied design methods were validated through small- and full-scale experiments. The safety level of the design was adjusted during the design process through the experimental verification. Although some of the characteristic material properties were overestimated in the preliminary design, the design properties for the final design were higher than for the preliminary design since it was possible to reduce the resistance factors after testing by a factor of 2.0.

KEYWORDS

GFRP, multiple purpose structures, sandwich structures, structural design.

INTRODUCTION

Fiber-reinforced polymer (FRP) composites are promising construction materials that are increasingly used in civil infrastructure, particularly for strengthening and repair of existing structures. Furthermore, in bridge construction, FRP components such as pultruded profiles are also used for truss girders (pedestrian bridges) or bridge decks of new bridges (Bakis et al. 2002).

In building construction, however, FRP composites have not yet had the same success, even though they also offer promising material properties for this application domain. Glass fibre reinforced polymers (GFRP), for instance, have the added benefit of low thermal conductivity that enables GFRP load-carrying components to act as insulating elements, in addition to their structural functions. Furthermore, GFRP elements can be translucent or transparent and come in a large range of colours. The possibility of integrating these different functions into individual building components can allow for the merging of traditionally separated and layered structural and facade components into a function-integrated, single-layer building envelope (Keller et al., 2004).

This paper reports on the design and construction of the new Main Gate of the Novartis Campus in Basel, Switzerland, constructed in 2006, see Fig. 1. This building is covered with a large function-integrated GFRP sandwich roof structure that integrates load-carrying, building physical and architectural functions and, therefore, is in line with the aforementioned single-layer building envelope concept. The building – albeit quite small – must fulfill high architectural/aesthetic requirements and is also supposed to express innovation through the use of promising new materials and technologies. The paper describes the structural concept, design and construction of the GFRP roof structure.

BUILDING DESCRIPTION

Concept and dimensions

The building has a single story 4.50 m in height and is built on a large underground parking garage. The rectangular floor plan of 17.6·12.5 m² is formed by four glass walls. The walls consist of insulating glass (outer tempered glass, inner laminated safety glass, gas filling) and are stiffened every 1.7 m with vertical twin glass stiffeners, as shown in Fig. 2. The glass walls and stiffeners are connected with structural silicone and carry the GFRP sandwich roof without any other structural elements.
The roof structure has overhangs on all four sides to protect the glass walls from direct solar radiation. The largest overhang of 5.0 m is to the south, followed by 3.0 m to the west and 1.0 m to the north and east. The roof dimensions are 21.6·18.5 m², as shown in Fig. 2. Based on aesthetic considerations, the roof has the form of a wing, which tapers off from a maximum thickness of 620 mm in the middle to 70 mm thin edges at the overhang ends. An exception is the west side, where the wing shape is cut and the variable cross-sectional depth is exposed. The surface appearance is similar to that of a sailplane wing: white in color, very smooth and glossy. Inside the building, a 8.7·7.4 m² acoustic ceiling of 150 mm thickness is inserted into the sandwich, as shown in Fig. 2, whereby the lower sandwich face sheet runs around this insert. The total roof weight is 28 t or an average of 70 kg/m².

Figure 1. New Main Gate Building of Novartis Campus with GFRP sandwich roof

Figure 2. Plan view with glass walls, glass stiffeners, roof cantilevers, internal web grid, core density distribution, block, block-strip and element arrangement

Materials and Sandwich Concept

The roof must be lightweight due to the limited load-carrying capacity of the glass walls and, at the same time, it must provide thermal insulation and waterproofing for the building. Consideration of the complex double-curved geometry, furthermore, led to the use of a GFRP sandwich structure of variable depth.

The face sheets have thicknesses from 6 to 10.5 mm and consist of several layers of GFRP fabrics and mats. E-glass fibers and a polyester resin were used. The polyester is a filled, low-viscosity and self-extinguishing resin that shows low flammability and medium smoke formation.
The core consisted of a polyurethane (PUR) foam of three different densities and strengths. Since the shear load-carrying capacity of even the densest core type was not sufficient, the foam core had to be reinforced by an internal system of orthogonal GFRP webs spaced at 925 mm. Figure 2 (right) shows a plan view of the roof with the internal web grid and the distribution of the core densities (maximum density over the supporting glass walls). The internal thicknesses of the orthogonal webs vary between 3 and 9 mm. Over the roof supports (aligned with the glass walls), the webs were doubled with a maximum thickness of 2·9 mm. The spacing of the double webs is 14 mm with a special high strength foam filler between the webs.

Support Concept

The roof is supported at each intersection point between the glass walls and stiffeners, at a spacing of 1.7 m. One support point consists of two concentrated steel supports on the glass walls, on each side of the stiffeners and a slightly prestressed steel rod between the twin glass stiffeners. The steel rod is anchored in the foundations to prevent uplift of the roof. The glass walls are braced horizontally by the roof, which acts as rigid diaphragm. The roof itself is horizontally supported in the middle of each glass wall in wall direction. The wind loads on the upper half of the glass walls are transmitted into the roof at the roof supporting points and then transferred in the roof plane to the horizontal roof supports, where they are transferred as in-plane forces through the glass walls into the foundations.

Manufacturing and Installation

The base components of the roof are 900·900·d mm³ foam blocks between the orthogonal webs (d = variable roof depth). 460 blocks, each one with a different geometry, were cut with a computerized numerical control (CNC) machine. The complex roof geometry was achieved in this way without the necessity of expensive moulds. Furthermore, recesses for inserts and laminate overlaps were cut out directly, as shown in Fig. 3 (left) for the steel insert of the anchorage rods. Subsequently, four blocks at a time were assembled to a block-strip. The block-strips were then assembled into four roof elements of 18.50·5.63/5.63/4.70/5.63 m². Figure 2 (right) shows the arrangement of the block-strips and the four roof elements. Adhesive bonding was used to connect the webs of the block-strips thereby providing continuity of the longitudinal and transversal webs. Tolerances of ± 2 mm in the block-strip dimensions could be compensated for in these adhesive joints.

In the next step, the lower face sheet, which was on the upper side at this stage, was completed. In this configuration the whole roof element was turned, as shown in Fig. 3 (right). Subsequently, the upper face sheet was completed. In the last step, the elements were varnished with a 0.6 mm thick PU varnish for protection against environmental influences.

The four roof elements were transported on two trucks from Winterthur (the location of the roof manufacturer Scobalit Composites AG) to Basel and assembled on a movable scaffolding (see Fig. 1, right). Adhesive bonding was used again to connect the webs and laminates were bonded into 400 mm wide recesses kept open in the face sheets during element fabrication. In the last step, the glass walls and anchoring rods were installed. The construction of the roof structure was carried out in less than 7 months. Cutting of the foam blocks started in February 2006, lamination of the blocks was done in March 2006, the first element was turned on 9 May 2006, the fourth element on 21 July 2006, and installation of the roof was done from August 4 to 11, 2006.
DESIGN CONCEPT

The design of the roof was done in two stages: the preliminary and final design. Based on the preliminary design, the contract was awarded and the final design was then achieved in collaboration with the roof manufacturer. During the final design, assumptions on structural modeling and material properties were verified through an experimental program.

The roof was designed according to Swisscodes SIA 260 and 261 (Swiss Standards Association 2003a and 2003b), which are consistent with the corresponding Eurocodes. The serviceability and ultimate limit states were verified using the partial safety factor concept, with partial safety factors on the action side (load factor) and on the resistance side (resistance factor). The following actions were considered: permanent loads, prestress in the steel rods, creep, shrinkage of laminates, temperature (global changes and gradients), wind (horizontal pressure and vertical uplift), snow, walking on the roof for cleaning, construction stages, impact from overturning trees, failure of two adjacent supports or a corner support (due to partial collapse of glass walls), earthquake and fire. From these actions, hazard scenarios were formulated according to SIA 260. For the fire design situation, it was considered that a surface of 2.0·2.0 m² of the lower face sheets could fail without collapse of the roof. Furthermore, the material strength and stiffness in a 1.0 m wide strip around this surface were assumed to be reduced by 50%.

For the serviceability limit state, a deflection limit of span/350 was set for frequent load cases (e.g. wind load) and span/300 for permanent loads, according to SIA 261. In order to consider and limit creep, span/300 was not allowed to be exceeded for the double of the permanent load deflections according to EuroComp Design Code (Clarke, 1996).

The verification of the ultimate limit state mainly comprised the determination of resistance factors for FRP composites, since neither the Swisscodes nor the Eurocodes provide such values. For this reason, the resistance factor concept from EuroComp was used, which is in accordance with the Eurocode design philosophy. The resistance factors, \( \gamma_M \), were calculated according to Eq. (1):

\[
\gamma_M = \gamma_{M1} \cdot \gamma_{M2} \cdot \gamma_{M3}
\]

where, in the present case, the following values were applied: \( \gamma_{M1} = 2.25 \) (material properties calculated from fiber and resin properties) or \( \gamma_{M1} = 1.15 \) (properties resulting from laminate testing), \( \gamma_{M2} = 2.0 \) for hand lay-up, \( \gamma_{M2} = 2.0 \) for short term and \( \gamma_{M3} = 2.5 \) for long-term verification. In the preliminary design stage, the material properties were calculated from the constituents’ properties and fiber volume fractions using laminate theory, while in the final design properties were based on laminate testing. Accordingly, two different sets of resistance factors, given in Table 1, were used at the two design stages, each time for short- and long-term loading.

During the final design, the material strengths were determined through small-scale experiments. From these tests, characteristic strength values were determined that correspond to 5% fractile values according to the SIA codes. Dividing these characteristic strength values by the resistance factors (from Table 1), the set of design values was determined. Table 2 shows a comparison of a few selected short-term characteristic and design material properties of critical roof components for the preliminary and final design. For the verification of the serviceability limit state, \( \gamma_M = 1.0 \) was used for stiffness properties and the coefficients of thermal expansion.

<table>
<thead>
<tr>
<th>Resistance factor</th>
<th>Preliminary design (before testing)</th>
<th>Final design (after testing)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \gamma_M ) (short term)</td>
<td>4.5</td>
<td>2.3</td>
</tr>
<tr>
<td>( \gamma_M ) (long term)</td>
<td>11.25</td>
<td>5.75</td>
</tr>
</tbody>
</table>

KEY POINTS OF DESIGN

Static System, Section Forces and Deformations

The roof structure was modeled as a girder grid system using beam elements from the Cubus software Statik-5 (Cubus 2006). The beams cross-sections were I-beams consisting of the webs with varying depths, and the upper and lower face sheets. The foam core was not directly considered load-carrying. Its function (together with shape forming) is primarily to prevent wrinkling of laminates in compression, that is, the compressed laminates are assumed to be elastically supported against wrinkling by the foam. Second-order effects and shear deformations were considered. In the following sections the basic verifications of the face sheets and webs are summarized.
Verification of Face Sheets

The face sheet parts in tension were verified using the corresponding design values for short-term and long-term actions. For the face sheet parts in compression, the characteristic values of the wrinkling strength of the laminates, \( f_{wrk} \), were estimated according to Wiedemann (1996), using:

\[
 f_{wrk} = 0.5 \cdot \left( E_{foam,k} \cdot E_{FRP,k} \cdot G_{foam,k} \right)^{1/3}
\]

where, \( E_{foam,k} \) = elastic modulus of foam, \( E_{FRP,k} \) = elastic modulus of face sheets, and \( G_{foam,k} \) = shear modulus of foam.

Verification of Webs

The basic web shear strength, \( \tau_k \), was assumed to be 50% of the tensile strength of 45°/45° laminates. The strength was reduced to prevent wrinkling according to Wiedemann (1996):

\[
\tau_{wrk} = 0.5 \cdot f_{wrk} < \tau_k
\]

where, \( \tau_{wrk} \) = wrinkling shear strength.

Table 2. Comparison of selected short-term characteristic and design material properties for preliminary and final design. (Deviations from resistance factors according to Table 1 are marked.)

<table>
<thead>
<tr>
<th>Component</th>
<th>Material property</th>
<th>Characteristic values</th>
<th>Design values</th>
<th>Diff. [%]</th>
<th>Diff. [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Preliminary design</td>
<td>Final design</td>
<td>Preliminary</td>
<td>Final design</td>
</tr>
<tr>
<td>Face sheets</td>
<td>Tensile strength 0°/90° [MPa]</td>
<td>150</td>
<td>126</td>
<td>-16</td>
<td>33.3</td>
</tr>
<tr>
<td></td>
<td>Elastic tensile modulus 0°/90° [GPa]</td>
<td>10.0</td>
<td>11.2</td>
<td>+11</td>
<td>10.0</td>
</tr>
<tr>
<td></td>
<td>Compressive strength 0°/90°, foam 60 [MPa]</td>
<td>52.2</td>
<td>54.2</td>
<td>+4</td>
<td>11.6</td>
</tr>
<tr>
<td>Webs</td>
<td>Wrinkling shear strength, foam 60 [MPa]</td>
<td>26.1</td>
<td>27.1</td>
<td>+4</td>
<td>5.8</td>
</tr>
<tr>
<td></td>
<td>Shear modulus [GPa]</td>
<td>3.0</td>
<td>3.0</td>
<td>0</td>
<td>3.0</td>
</tr>
</tbody>
</table>

EXPERIMENTAL PROGRAM

To validate the roof design assumptions regarding material properties of the preliminary design, small-scale experiments were performed on laminate strips, double lap joints and through-thickness coupons. Furthermore, four full-scale beams were fabricated to experimentally validate the structural design of the roof structure and the applicability of the characteristic material properties from the small-scale tests, see Fig. 4. The same design models were used for the beam design as for the roof design.
DISCUSSION

Preliminary and Final design Properties

Table 2 shows how almost all design values of material properties could be markedly improved between the preliminary to the final design due to extensive material and structural testing. The main characteristic values for face sheets and webs changed only slightly from the preliminary to the final design and in some cases the values even decreased (e.g. tensile strength face sheets: decrease from 150 to 126 MPa). However, because it was possible to reduce the resistance factors after testing, the final design values were still higher than the preliminary design values (e.g. tensile strength face sheets increased from 33.3 to 55.0 MPa).

Experimental Validation of Roof Design

For the beam design, the same design models were used as for the roof design. The experiments on the sandwich beams showed that normal beam theory could be used to predict strength and stiffness. Since the roof structure was formed and considered as a grid system of orthogonally crossing beams, it was concluded that the design models validated for the experimental beams were also applicable for the roof to predict strength and stiffness.

CONCLUSIONS

A lightweight GFRP sandwich roof structure was designed and built in Basel, Switzerland. The main conclusions drawn from this experience are as follows:

1) The GFRP sandwich construction allowed for function integration. Structural functions (roof slab, facade stabilization), building physical functions (thermal insulation, waterproofing, acoustics) and architectural functions (complex shape, colour and surface appearance) were integrated in one building component already during the fabrication process. This made it possible to prefabricate the roof in only four elements that were easily transported to the site and rapidly installed.

2) CNC cutting of foam blocks and adhesive bonding were successfully implemented to fabricate complex shapes and recesses for inserts and laminate overlaps, without the use of expensive moulds.

3) Existing design models and test standards to determine material properties proved to be applicable. The applied models and methods could be validated through small- and full-scale experiments.

4) The safety level of the design could be adjusted during the design process through experimental verification. In the preliminary design (before tendering), material properties were estimated and higher resistance factors were used. Based on testing, the factors could be reduced in the final design by a factor of 2.0. Although some of the characteristic properties were overestimated in the preliminary design, the design values for the final design were higher due to this reduction of the resistance factors.

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REFERENCES


