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# Structural behaviour of RPC sandwich façade elements with GFRP connectors

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## Abstract

The paper focuses on the structural concept for the development of novel *smart* sandwich façade elements. The lightweight, non-loadbearing façade elements are single-story high and span vertically between two floors to which they are connected by an anchoring system. Due to their large area they carry and transfer significant horizontal (wind) and vertical (self-weight) loads to the building skeleton. The large size with the reduced thickness and the use of unconventional materials calls for a better understanding of the structural performance of the proposed concept. This requires advanced modelling and extensive laboratory testing at material, component and system level (including sublevels). With the knowledge gained from testing and modelling, simplified design methods can be developed to ensure efficient, safe and durable design of the façade elements.

# 1 Introduction

## 1.1 Background

There is a vastly growing demand for increased energy efficiency of the buildings we live and work in. The European construction sector attempts to tackle this great challenge by investigating energy efficient materials and processes. The project SESBE (Smart Elements for Sustainable Building Envelopes), funded by the European Commission, aims at developing sandwich façade elements with high insulating capabilities while providing a reduced thickness in conjunction with superior mechanical and durability properties (www.sesbe.eu).

The overall objective of SESBE is to develop *smart* façade components, which are more lightweight, thinner and multifunctional than existing solutions. In order to reach this overall goal, nanomaterials and nanotechnology are employed. By doing so, the following more specific objectives can be reached, which make the façade components *smart*:

1. Increasing energy efficiency by optimized sealing systems and inorganic insulation;
2. Increasing fire resistance of materials by surface functionalization;
3. Implementing easy-to-clean/self-cleaning properties of the façade elements;
4. Gaining cost efficiency and an affordable price of the façade elements by using cost effective raw materials and cost saving technologies.

## 1.2 Description of the proposed system

The elements developed in this project are composed of prefabricated façade elements, which are attached to the main load bearing structure in situ. These types of elements, often called architectural concrete cladding, provide aesthetic, structural and isolating function [1]. The cladding elements studied here are not part of the primary load bearing system, which typically consists of slabs and load bearing cross-walls. However, due to their large area (7-10 × 2.7-3.0 m) they carry and transfer significant horizontal (wind) and vertical (self-weight) loads to the building structure. The proposed concept is illustrated in Fig. 1.

Figure 1: a.) SESBE façade and b.) element concept.

The proposed façade elements comprises two thin (20-25 mm) panels of reactive powder concrete (RPC) reinforced by carbon fibre grids and an intermediate light weight foam concrete insulation. To allow for adequate load transfer between the RPC layers, they are linked by glass fibre reinforced polymer (GFRP) truss-like connectors (Fig. 1b.). Two types of elements are being developed within the project: full elements will be used as a tool to custom design functional and performance properties of façade sandwich elements for new constructions and half elements for refurbishment of existing buildings. A main difference pertaining to the half elements is such that the inner panel is omitted. This paper focuses on the development of the full sandwich elements.

One of the challenges when developing a new innovative façade element is to ensure that it will be an integral part of the building envelope and resist the anticipated structural loads. The present paper describes these challenges and the conceptual design process to ensure an adequate structural behaviour of the panels, which is essential to provide a safe and serviceable design.

# 2 Design considerations

## 2.1 General considerations

To ensure that the façade elements will perform as expected during the anticipated lifetime of the building, several aspects should be taken into account at the product design stage. These general considerations are not only useful for the current system, but in general for developing similar concepts.

Creation of a liveable, safe and sustainable built environment requires a compromise of architectural, functional, structural, economic and environmental goals (see Fig. 2). However, these efforts are often contradictory and to find a balance requires careful planning involving competences from several fields of knowledge. Furthermore, these aspects are often interconnected, such that energy performance of a building involves functional (e.g. building physics), economic (e.g. operation costs) and environmental issues (e.g. emission rates). Similarly, the choice of architectural form usually has a high influence on the decision about the structural skeleton of the building and consequently on the construction costs.

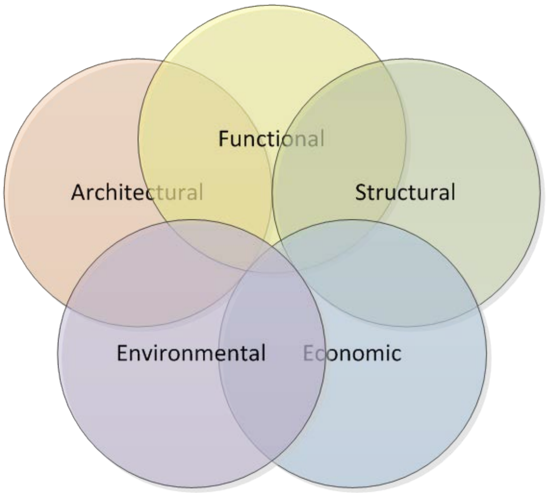


Figure 2: Concurring goals to be considered in design.

Within the SESBE project several of these aspects are addressed and developed in parallel to obtain an optimized, cost-effective and sustainable product. In the following, the structural aspects will be discussed more in detail.

## 2.2 Structural aspects

A fundamental function of a building envelope is to provide shelter for the occupants by ensuring their safety and comfort. These aspects have a direct impact on the development and design of façade elements. Nevertheless, the requirements for structural safety are defined by structural design codes, which should be fulfilled to ensure an adequate reliability against failure.

It is important to consider that even though these elements are not part of the main load-bearing structure, due to their significant weight, size and stiffness, they will have an effect on the overall structural behaviour. This might be considered when modelling the structural frame and calculating loads and structural response in terms of internal forces, stresses, strains or dynamic effects.

The structural behaviour of the panel is highly dependent on how it is anchored to the load bearing structure, i.e. how much movement and rotation is allowed at the joints. This is essential considering local failure at the anchorage zone. Furthermore, the anchorage should be designed to have sufficient strength to prevent the façade elements from falling out. Ductility and stiffness of these joint might be important to ensure robustness for the entire structural system for example in the case of an explosion.

One of the main concerns from a structural engineering perspective is the design of the connectors between the RPC panels, which need to adequately transfer shear forces. This will enable the composite action between the two panels, i.e. that the sandwich element resists bending moments as a whole: one panel taking up compression and the other one tension. The proposed solution should be verified through experiments and numerical modelling. It is also important that simplified calculation models should be established for practical purposes.

A design concept only works if it can be manufactured in a time- and cost-effective manner, which requires extensive discussions with material providers and manufacturer of the final construction product. Similarly manufacturing, handling, transportation and assembly issues should be carefully considered even at a rather early stage of the process. These considerations usually limit the overall weight and sizes of the façade elements. Lifting of the elements will provide special load cases that the panel should be designed for.

The typical loads and configurations that are expected to act on the panel should be carefully analysed. These loads usually include dead loads, imposed and environmental loads derived from typical building configurations assuming several locations with different climatic conditions. Exceptional load cases (e.g. earthquake, explosion, fire) might also be important to maintain safety. It is also essential that realistic boundary conditions should be assumed when calculating the load effects.

When combining different materials, special attention should be given to the compatibility of different materials due to relative deformations. Typical examples are different time and moisture-dependent behaviour (e.g. creep and shrinkage) and differences in thermal expansion and contraction. These phenomena could create significant stresses due to restraining effects and lead to increased maintenance costs and reduced service life.

### 2.3 Design targets at different levels

To meet the requirements of these complex aspects a top-down approach is needed. The main question is how to progressively propagate the top level design requirements (targets) to appropriate specifications for the various sub-system and component levels in a consistent and efficient way. This process, often called target cascading, is essential in the early development stages of complex products and systems [2]. It will be demonstrated, how the design targets of the different tasks should be cascaded down from the general structural concept to component behaviour and material properties as well as connection characteristics. Furthermore, necessary testing and modelling tasks could be identified and the structural performance could be validated by following a bottom-up direction. Accordingly a near optimal choice between different concurring alternatives within a reasonable time-frame will be enabled.

## 3 Structural behaviour and modelling

To be able to assess the top level requirements of a building a global model describing the structural behaviour is required. The level of detailing of the model should be consistent with the requirements defined at the relevant design stage. To investigate the overall structural behaviour a typical building was defined. It is assumed that the load bearing structure consists of floor elements between load bearing cross-walls and the main façades consist of non-load bearing sandwich elements. With the aid of the structural model the structural performance could be analysed both at system and component level.

Concerning structural performance, the requirements for safety and serviceability are usually translated into engineering terms, so-to-say as stresses and deflections. Structural codes usually address the design of components using the limit state concept (component level). The structural integrity of the entire building is ensured by appropriate measures for designing for robustness (system level).

## 3.1 System level

In the current project the primary aim of the global structural model is to determine the relevant loads acting on the façade element placed in a typical building. Therefore a simple analytical model seems to be sufficient to analyse different loading situations and estimate their effect on the sandwich element. Since the components (i.e. the sandwich elements) do not support other elements they are not essential for the structural integrity i.e. the robustness of the structure. If one element were to fail, the consequences are expected to stay localised and progressive collapse of the building would not occur. The design strategy for robustness is then allowing the local failure to occur, while preventing disproportionate consequences. Thus an important issue for non-loadbearing façade elements is to prevent them from falling, especially at larger heights. This should be taken into account when designing the anchorage system. However, in certain design situations it might be advisable to limit the strength of connections and components. For example if the anchorage of the façade elements to the primary structure is too strong an explosion might transfer forces to the main structure that could lead to progressive collapse of the building.

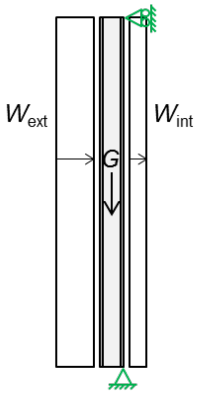
An important design choice is if the non-loadbearing façade elements should be fixed separately to the main structure or if they should be self-supporting, i.e. the façade is supporting itself and the elements are only anchored horizontally to the main structure. Another essential aspect at system level is to account for the settlements of the supporting structure. If the façade is fixed to reinforced concrete slabs or beams, their long-term deflections should be taken into account when designing supporting points of the façade.

## 3.2 Component level

To study the behaviour of the façade system in the SESBE project, structural modelling by means of Finite Element (FE)-calculations is carried out. A FE-model is used to evaluate stresses, deformations and subsequent cracking caused by the anticipated loads. Due to the combination of novel materials simple analytical relationships are not yet developed, therefore numerical simulation is extremely useful to understand the mechanical behaviour. The complex modelling task is supported by experimental data. Therefore, it is important to start developing the numerical model in parallel with the testing activities, to define which tests should be carried out and what kind of data should be extracted from them.

The mechanical properties of the materials and the interface will be used as input and the model will be verified by the ability to reproduce the findings in the component tests regarding deformations, crack formations, etc. This will include not only the single elements but also the anchorage system. The calibrated structural model will provide insights about the physical behaviour of the façade element and its interaction with the existing load bearing structure under different load conditions, which include dead loads, wind loads, impact loads, as well as temperature and moisture variations.

The main expected outcome is the geometric design requirements for the façade element and restrictions concerning the thickness, in particular of the RPC panels. It will also provide a base for the design of the anchorage system and other connection details. The verification of the structural performance of the façade elements is carried out according to the limit state principle of EN 1990 [3]. Accordingly, the loads acting on the panels should be calculated. Typically, two types of loads are included in normal design situations: vertical permanent loads due to the self-weight ($G$) of the panel and horizontal variable loads due to the effects of wind ($W$), see Fig. 4.



| Load case | Combination | Limit state |
|---|---|---|
| LC1 | $1.35G+1.5(W_{e1}+W_{i1})$ | ULS |
| LC2 | $1.35G+1.5(W_{e2}+W_{i2})$ | ULS |
| LC3 | $1.35G+1.5(W_{e3}+W_{i3})$ | ULS |
| LC4 | $1.0G+1.0(W_{e1}+W_{i1})$ | SLS |
| LC5 | $1.0G+1.0(W_{e2}+W_{i2})$ | SLS |
| LC6 | $1.0G+1.0(W_{e3}+W_{i3})$ | SLS |

Figure 4: a.) Structural loads (wind and self-weight) acting on the façade elements and b.) load combinations.

The wind could act on both the external ($W_{ext}$) and internal ($W_{int}$) surfaces of the panel according to EN 1991-1-4 [4]. Three load cases (LCs) are investigated for both the ultimate limit state (ULS) and the serviceability limit state (SLS). In LC1 and LC4, the external surface of the sandwich panel is under pressure, while the internal surface is under suction. In LC2 and LC5, the external panel of the sandwich element is under suction and the internal layer is under pressure. In LC3 and LC6, both the external and internal panels are exposed to wind suction. The considered load combinations are presented in Fig 4.

The above described load cases belong to different wind directions, which the building could be exposed to. Verification at ULS corresponds to the failure of the elements and related to human safety. Due to the application of high strength concrete in the panels, it is not expected to be a problem. However, ULS might be important for the design of the anchorage. Verification at SLS, representing a lower load level, usually relates to appearance, functioning and comfort of occupants. Since the current sandwich panels are very slender, SLS requirements are expected to be decisive in their design, especially for limitation of deflections and cracking. Cracking should be avoided as much as possible, since they are irreversible and disturb the aesthetic quality of the façade. Further design situations include loads at different constructional phases (e.g. demoulding) and accidents.

## 4 Experimental program

To provide valuable input for the verification of the structural model under different load scenarios, several laboratory tests have been and will be performed. The tests will follow a bottom-up approach from the material to component level. The material tests on the RPC together with small-scale panel tests are discussed in an accompanying paper [5]. From a structural point of view, the main purpose of the material tests is to obtain relevant material properties, i.e. stress-stain relationships for principal load cases, for the structural model.

The first test to be carried out at sub-component level will be a small-scale test of the connectors embedded in the concrete. Pull-out tests will be carried out with different geometrical configurations containing a small part of the connector and one concrete panel (see Fig. 5a). The tests will help to select the optimal geometry of connectors. As a consequence of new shapes, it might be necessary to modify the manufacturing technique or material from which the connector is made. Another main focus of the investigation is to determine the required concrete cover to prevent local failure. These tests are essential to decide if a thickening of the concrete at the connectors is needed.

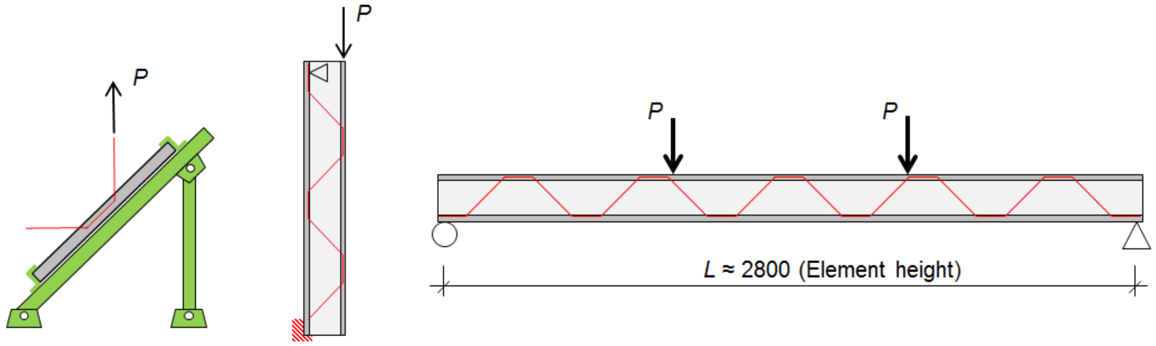


Figure 5: a) Local failure test of the connectors, b) shear test of the connectors and c) 4-point bending test of a panel strip.

The second series of sub-component testing will focus on the shear behaviour of the connectors. In this test, a short strip of the sandwich panel will be produced containing a single connector. One of the panels will be supported, while the other one will be loaded in its plane as shown in Fig 5b. Thus the panel (and the connector) is subjected to shear. A similar test setup has been used in previous works [6, 7].

In the third series of tests, a full-length strip of sandwich panel containing one single connector will be subjected to 4-point bending (see Fig. 5c). This test will serve as a verification of connector performance and composite action and calibration of the numerical model. Furthermore, the bending moment resistance of the panel will be determined. In addition to the pure bending case, constant axial forces will be applied to the specimens to study the effect of combined bending and compression, which will enable the determination of M-N curves (bending moment and axial force interaction diagrams) to assist with the design of the elements.

In the last series of testing, the entire component will be investigated. However, it will be slightly smaller than in reality due to the limitations of the testing device. Cyclic wind loading (both pressure and suction) will be applied in a pressure chamber (capacity ≈ ± 3 MPa). The maximum element size is approximately 3×3 m, which allows the testing of full storey height elements including several connectors (see Fig. 6). These tests will support the verification of structural performance and the validation of the numerical model taking into account connectors and anchorages.

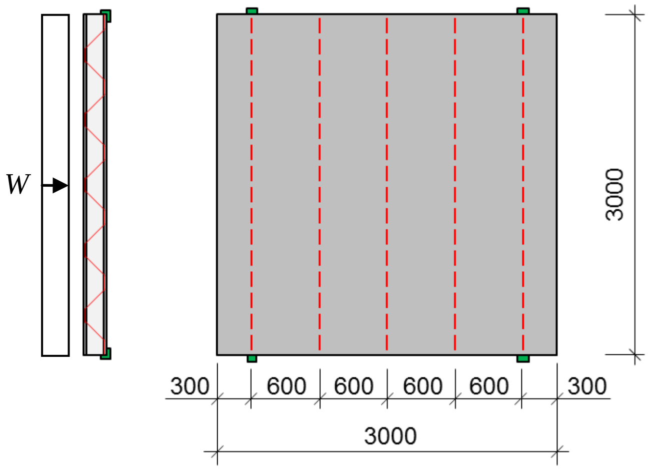


Figure 6: Whole panel wind load test.

## 5 Conclusions

This paper described how structural aspects are taken into consideration in the SESBE research project aiming to develop novel architectural façade elements. Because of the short timeframe of the project (42 month), compared to the traditional development of construction products and systems, a well-defined testing program needs to be carried out to verify the structural performance of the façade sandwich elements. It is therefore essential to break down the high-level design requirements to specific testing and modelling tasks, which has been illustrated in this paper.

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