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Innovative sandwich structures made of high performance concrete and foamed polyurethane

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ABSTRACT

The demands on contemporary buildings make new construction methods and materials essential. Sandwich elements with layers made of high performance concrete and additional specialized characteristics can fulfill the requirements of sustainable and durable building envelopes with esthetic appeal. Nevertheless, the standard production method by assembling slabstock core materials in freshly poured concrete hinders reliable bond quality, which greatly affects the load-bearing capacity. In order to overcome this problem and realize a homogenous bond quality, the cores were foamed between precast concrete layers, leading to enhanced load-bearing capacity of the sandwich sections. This article presents possible applications, the production method, and the major results of experimental investigations on the load-bearing behavior of sandwich sections with textile-reinforced concrete (TRC) and ultra-high performance fiber reinforced concrete (UHPFRC) as well as varying types of connectors and foam cores.

1. Introduction

Concrete reinforced with conventional steel reinforcement has historically been one of the most commonly used building materials due to the material's economic advantages and versatility in design. However, the steel reinforcement is vulnerable to corrosion in humid environments. Therefore, thick concrete coverings according to current design codes are necessary [1–3]. However, this addition leads to greater structural weight and clumsy appearance. Further, even with high concrete coverings, the corrosion resistance cannot be guaranteed over decades. Meanwhile, architecture has developed a distinctive trend that favors more slender structures. This issue can be addressed by replacing the conventional steel reinforcement with non-corrosive reinforcement materials, predominately made of AR-glass fibers or carbon fibers and with a high tensile strength (up to 3000 MPa). This alternative allows slender structures with high potential for economic savings in terms of materials and transport, as well as reduced time and effort during mounting. Applications for reinforcement meshing or bars, as well as pre-tensioned strands are feasible.

Combining these innovative concrete elements to load-bearing sandwich construction leads to modern building envelopes that require high strength to weight-ratios and simultaneously fulfill structural and physical demands such as heat and sound insulation by using polyurethane as the core material between the concrete facings.

The load-bearing behavior of sandwich members is determined by the stiffness and the strength of the facings and of the core material, as well as the bond strength between the concrete and core, which depends on the production method [4–6]. Typical production methods of sandwich panels with concrete facings are problematic for consistently ensuring high bond quality between the core material and concrete layers. These methods also impose a limitation in design freedom, since only flat panels can be produced efficiently. For this reason, a different process was applied in which polyurethane is foamed between hardened concrete layers [5,6].

This new construction method was investigated for typical loading condition of building envelopes, comprising tensile, shear, axial, and flexural loading conditions.

2. Architectural concept for sandwich elements

The desire to design durable buildings that fulfill the imminent demands of sustainable building concepts [7] makes the application of new materials and production methods necessary. Sandwich elements, which are optimized for such applications, exhibit an

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attractive choice for modern buildings, since they feature not only structural advantages, but also favorable physical properties, such as low heat conductivity and sound insulation. Using high performance concrete can lead to a high load-bearing capacity with low thickness, all while providing the desired physical properties. Furthermore, the fine-grained concrete layers enable superior surface qualities. These sandwich sections allow the production of slender integral elements for façade, wall and roof constructions, with high potential for economic savings in terms of material and transport as well as reduced time efforts during mounting [8,9].

To provide an effective modular construction system, the sandwich panels have to be dimensioned taking into account both production in and transportation from a precast plant and standard room sizes according to the function of the building (e.g. offices, administration, or residence). In general, maximum dimensions of approximately 3 × 10 meters fulfill all requirements. However, larger elements, particularly for roof constructions, can be provided, depending on the production method and applied materials.

The load-bearing wall elements (Fig. 1) span from the floor to the ceiling. Openings for windows and doors can easily be made through smaller standardized elements. The panels can be combined with either sandwich elements for ceiling and roof construction or with conventional building approaches.

For roof elements with medium or long spans, the methods developed for regular façade elements cannot be adopted. Hence, the conceptual design comprises folded shapes for medium spans and doubly curved elements for long spans (Fig. 2).Especially with the doubly curved HP sandwich shell beams spans of over 30 meters are imaginable.

Due to the spatial load-bearing behavior, a high stiffness and load-carrying capacity can be achieved. For a further increase in stiffness and load-carrying capacity, an ultra-high performance concrete is applied. For doubly curved elements, it is desirable to use as little reinforcement as possible. This is achieved with high-strength steel fibers. To prevent the filigree shell structures from deformation from cracking and shrinkage or corrosion, the shells are pre-tensioned with CFRP (carbon fiber reinforced polymer) elements. Fig. 3 shows an example of a potential design combining wall and roof elements.

The sandwich elements with layers of high performance concrete combine the advantages of conventional sandwich elements with steel-reinforced concrete or single steel layers. Aside from high load-carrying capacity, low weight, and high corrosion resistance, the high surface quality of the panels holds architectural appeal.

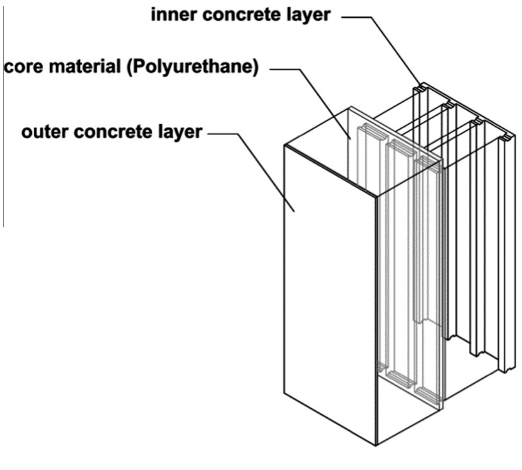

Fig. 1. Example for wall construction.

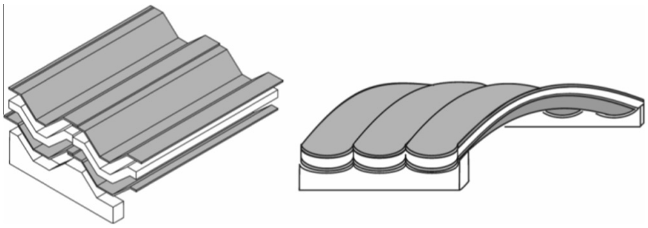

Fig. 2. Examples for medium (left) and long (right) span roof construction.

3. Characterization of applied sandwich components

3.1. High performance concrete

3.1.1. Fabrics

In the experiments described in this paper, two different fabrics were applied as reinforcement for concrete C1 (textile-reinforced concrete). In order to produce the textile reinforcement, hundreds or thousands of filaments made of alkali-resistant glass (AR-glass, filament diameter 14–27 mm) or carbon (filament diameter 7 mm) were bundled into rovings, which were then finished into a laid scrim, i.e. a mesh-like reinforcement structure (Fig. 4).

Finally, both fabrics were impregnated with an epoxy-resin. [10] describe the advantages of such resin-impregnated textiles in comparison to those without resin. Table 1 presents the geometric and mechanical properties of the fabrics used. Their tensile strength in the concrete has been determined by tensile tests on dog bone-shaped specimens [11].

These textile reinforcements have good handling and workability, which is necessary for using them for the production of large-scale sandwich elements under practical conditions in precast concrete factories.

3.1.2. Concrete mixtures

The properties of the textile reinforcement (Fig. 4) involve special demands on the concrete mixture. To enable the concrete to penetrate the fabric mesh, the maximum grain size was adjusted according to the openings in the textiles. Furthermore, a high flowability is necessary to achieve proper workability.

The layers of the sandwich elements were produced with two different types of concrete mixtures: a textile-reinforced concrete (C1) and an ultra-high performance concrete with high strength steel fibers (C2).

Concrete C1 features a maximum grain size of 8 mm. To enhance the performance in the serviceability limit state, short alkali-resistant glass fibers of 8 mm length were added.

The mixture of concrete C2 exhibited a maximum grain size of 0.5 mm. To enhance the ductility of the fine-grained concrete, high-strength steel fibers (length: 9 mm, diameter: 0.15 mm) with a fiber-ratio of 0.9 Vol.-% were used, enhancing the pouring quality. Higher ratios do not lead to significantly better ductility or bond behavior of strands [12] and result in ineffective pouring. Due to its high compression strength, stiffness and ductility, concrete C2 is especially suitable for pre-tensioned shell structures with membrane stress states (see Fig. 2).

The main properties of the hardened concretes are given in Table 2.

The compressive strength was determined according to DIN EN 196–1 [13] and DIN EN 206–1 [14]. The elastic modulus was evaluated by tests on specimens in accordance with DIN 1048-Part 5 [15].

3.1.3. CFRP tendons

Pre-tensioned CFRP tendons are applicable for slender concrete structures because of a high tensile strength of about 2,500 MPa