THE CARBON-REINFORCED CONCRETE BUILDING – CUBE | BOX MANUFACTURING AND ASSEMBLING

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The world’s first building made entirely of non-metallic reinforcement was constructed in Dresden, east Germany. It is 220 m² in size and represents the entire process chain of carbon-reinforced concrete construction. In Germany’s largest construction research project C³ – Carbon Concrete Composite, carbon-reinforced concrete and its implementation were researched and tested from 2014 to 2022. The results were culminated in a lighthouse project, the C³ technology demonstration house CUBE. Based on these results, the boundary conditions for material, architectural form finding, and construction were derived. The necessary structural, experimental and design verifications were provided as well as the approvals for the construction. Originally planned as a real cube, HENN Architects, Berlin gave the CUBE a bit of a twist. And so, an interplay of two essential building parts was created: the double-curved striking TWIST roof shells and the clearly designed, cuboid BOX. It is a precast complex that demonstrates the extraordinary and immediate application potential of carbon reinforced concrete. Details are presented in this paper. The BOX consists of semi-precast wall elements and precast slabs that can be manufactured with component thicknesses of just a few centimeters due to the use of carbon reinforcement. Manufacturing technology was tested in an automated precast plant and assembly was implemented at the construction site.

Keywords: Carbon fiber reinforcement, Sustainable construction, Automated production, Precast elements, Non-metallic reinforcement, Demonstration house.

1 C³ – CARBON CONCRETE COMPOSITE PROJECT

The Carbon Concrete Composite (C³) project had over 300 sub-projects with approximately 120 active research partners in its eight-year term, with more than 45 million euros of funding invested in research into application-oriented carbon-reinforced concrete. The C³ association has more than 150 members with a 70 percent share of companies dedicated to the development of products and processes in carbon-reinforced concrete (Lieboldt et al. 2018). From 2014 to 2022, around 60 joint projects were carried out, from which many developments have already been transferred into practice. These results were incorporated into the world’s first building entirely made of concrete with non-metallic reinforcement, mainly carbon reinforcement.
2 THE CUBE

The CUBE is a test and experimental stand with the appearance of a building (Fig. 1). At least that is, how the application to the Federal Ministry of Education and Research for the construction of the carbon-reinforced concrete building was described. The CUBE demonstrates what is currently technically feasible together with what is economically viable. The 220 m² building with a floor space of 7.9 × 24.4 m² contains the results of more than eight years of intensive research. The building is subject to all necessary building law requirements. Due to the still missing standardization, these are fulfilled by approvals in individual cases (Tietze et al. 2021, Curbach 2022, Curbach and Philipsenburg 2023).

Fig. 1. The technology demonstration house CUBE (courtesy: Gröschel, S.).

2.1 TWIST

The TWIST is a multi-layered shell construction that assumes the function of both the load-bearing shell and the weathering shell. This structure was chosen in order to construct two 24.4 m long wall-roof-elements with as little concrete as possible (Vakaliuk et al. 2022). The inside of the load-bearing shell consists of a 4 cm concrete layer reinforced with two-layers of carbon grids. It is followed by 17 cm high concrete webs. Blocks made of expanded polystyrene (EPS) are placed between these webs, which run both longitudinally and transversely forming a cassette-like structure. These prefabricated blocks serve both as thermal insulation and weight reducer. On top of them, another layer of 4 cm carbon-reinforced concrete was placed and sealed over the entire surface. The entire load-bearing shell of the TWIST element is 25 cm thick. In the further construction, a full-surface insulation made of extruded polystyrene (XPS) follows the sealed load-bearing shell. As a weathering and finish protection, shotcrete was used with a 4 cm thin shell of white concrete on top of it. Again, two layers of carbon grids were placed into the concrete. The shells were produced without joints. The weathering shell is supported by the load-bearing shell
through many bar-shaped glass fiber pins. Further information is given in Frenzel et al. (2022) and in Zavadski and Frenzel (2023).

2.2 BOX

The BOX shows how the semi-precast construction method can be transferred to carbon-reinforced concrete. A double-wall system with very thin carbon concrete shells of 4 cm was developed for this purpose. The concrete mix used gave an anthracite-colored concrete. Furthermore, two high-performance aerogel insulations, named Slentite® and Slentex®, BASF Polyurethans GmbH (now Aerogel-IT GmbH), Germany further reduced the wall thickness of the slim construction. The in situ concrete core was also reduced to the minimum possible in order to achieve a total wall thickness of only 27 cm. Both concrete wall shells are connected with glass fiber reinforcement bars, type Isolink, Schöck Bauteile GmbH, Germany. The applied materials are described in detail in Frenzel et al. (2023a). For the ceiling construction, prefabricated slabs were developed with a hollow-core cross-section with a thickness of 25 cm. This construction saves up to 50% of concrete in comparison to the conventional solid concrete slab (Ritter et al. 2023).

3 MANUFACTURING OF THE BOX

The BOX represents the economic part of the CUBE building. Above all from the perspective of being able to offer technically robust and at the same time competitive products in a mass market later on. The goal was to avoid manual processes as much as possible and to focus on automated prefabrication. The idea was to use processes similar to steel-reinforced concrete, so that the changeover to carbon-reinforced concrete could be realized as easily as possible. For this reason, the double wall system of the precast plant association Syspro-Gruppe Betonbauteile e. V. was used (Syspro 2024). The prefabricated carbon-reinforced elements were each based on existing principles or systems in order to make the transformation as simple as possible. In addition, this should make it possible to directly compare the resource savings potential compared to conventional applications. Approvals in individual cases (ZIE) were obtained for all components, as carbon reinforced concrete is an unregulated building material (Frenzel et al. 2023b).

3.1 Wall Elements

The Syspro-Gruppe double walls usually consist of two, approximately 6 cm thick, reinforced concrete shells connected by steel lattice girders, which are filled with concrete at the construction site. Once this has hardened, the overall cross-section of the two shells and in-situ concrete supplement work like a monolithically constructed wall. Furthermore, depending on the requirements, insulation, usually extruded polystyrene rigid foam (XPS) or pressure-resistant mineral wool, with a thickness of 10-20 cm can be placed between the shells (Syspro Thermowand). The monolithic, load-bearing cross-section then results from the filler concrete and the shell facing the inside of the room. The outer shell serves as façade and weathering protection. This concept has now been improved by the use of non-metallic reinforcement. The following illustration shows the wall development from reinforced concrete via a hydride solution (steel- and carbon-reinforced concrete) to a pure carbon reinforced element. Additionally, the insulation could be improved. A non-combustible aerogel high-performance insulation was available and inserted. It has got a thermal conductivity of 19 mW/mK. Usual XPS-insulation has a value of about 35 mW/mK which leads to significantly thicker insulation layers (Fig. 2). The production is a circulation process in which the shuttering, concreting, doubling, and drying are automated. Only the insertion of the reinforcement and of the built-in parts had to be done manually but can also be automated in the future.
Conventional P. W. steel-reinforced concrete

Hybrid P. W. carbon-/steel reinforced concrete

CUBE Precast Wall carbon-reinforced concrete with aerogel insulation

6 14 16 8

44

6 14 16 4

40

4 | 127 | 4

27

Fig. 2. CUBE wall development – reduction of construction space.

3.2 Slab Elements

The ceiling slabs were prefabricated elements with a total height of 25 cm. In cross-section, an upper and lower 3 cm thick girder concrete layer was reinforced with one layer of the carbon grid Q95/95-CCE 38 from the enterprise solidian GmBH, Albstadt, Germany. Unreinforced concrete webs with a width of 6 cm were arranged both every 33 cm in longitudinal direction and in transverse direction with a distance of about 110 cm. The cavity that forms between the upper and lower slab and between the unreinforced webs (looking from the structural point of view) was created by EPS or hollow wood-based material blocks which served as displacement bodies (see Fig. 3). The prefabrication of these elements took place in a non-automated production process, using classic wooden formwork and manual concreting (Ritter et al. 2023).

Fig. 3. Cross-section of CUBE slab elements (courtesy: Assmann, Beraten + Planen GmbH, Dresden).

4 ASSEMBLING OF THE BOX

The assembly of the Cube BOX took place in two steps, firstly in a technology test and secondly on the construction site. The technology test, for whom five walls and one ceiling slab were manufactured and mounted (Frenzel and Zschau 2020), served to completely rehearse the production and assembly process and to identify possible gaps in the planning and production. These were documented in a manufacturing and assembly manual.

The delivery of the wall elements to the construction site was carried out standing upright on steel frames, which were delivered one after the other and unloaded. The walls could be carefully assembled at the construction site independent of the delivery times. As it is typical for a double
wall system, the walls were erected, supported with inclined props, and aligned (Fig. 4). Afterwards, several connection reinforcement cages were installed at the joint and corner areas of the in-situ concrete core. For placing the concrete, all joints had to be sealed carefully, as a very free-flowing concrete was used, which needed to be vibrated only very little. The concreting speed was set to a maximum of 0.50 m/h to prevent failure of the fiber connector bars that held the inner and outer shell with only an embedment depth of 35 mm together. In future, recycled or ecologically sustainable concrete can be poured on site.

The prefabricated ceiling elements were delivered to the construction site in a horizontal position. Using the anchorage points on the upper side, the elements were elevated and placed by means of a site crane. The workers prepared mortar beds onto the supporting walls on which the elements were placed and aligned (Fig. 5). The element joints on the long slab sides and a required, surrounding ring beams were structurally reinforced with glass fiber bars of the type Combar, Schöck Bauteile GmbH and concreted on site. One challenge was to protect the surface of the outer wall shells against chemical and mechanical damage during the construction works. Because this is the finished and final surface of the later BOX façade. For protection against chemical effects, the surface was completely hydrophobized. For protection against mechanical effects on the façade, an enclosure made of maritime pine panels was produced (Stelzmann et al. 2023).

Fig. 4. Assembling wall elements at construction site of CUBE (TU Dresden, Institut für Massivbau).

Fig. 5. Assembling slab elements at construction site of CUBE (TU Dresden, Institut für Massivbau).
In order to provide fixing points e.g., for scaffolding, the 30 mm wide element joints were used. The entire electrical installation tubing was also prepared in the elements, so that the cables could be installed on site without any additional effort. Due to the prefabricated element construction of the wall and ceiling, an economical implementation of the BOX in carbon concrete could be realized in a short time (approximately 6 weeks).

5 FUTURE PRECAST WALL AND CEILING ELEMENTS

Further development in the area of wall and ceiling elements made of carbon-reinforced concrete is mainly aimed at further material savings while maintaining the same performance. In addition, complete demount ability with regard to deconstruction, recycling and the recyclability of the component are also becoming increasingly important. In this context, the factory processes must also be adapted to the new requirements of carbon-reinforced concrete. The first important experiences were gained in the production of the CUBE technology demonstration house. We would like to thank the Federal Ministry of Education and Research and all C³ partners for their support.

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