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Development and experimental validation of a lightweight Stay-in-Place composite formwork for concrete beams

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HIGHLIGHTS

- Cement composites are introduced as a new material for structural Stay-in-Place formwork.
- The new lightweight formwork concept eliminates the need for supporting mechanisms.
- The structural capacity of the formwork eliminates the steel reinforcement.
- 2.8 m span hybrid beams are tested under four point bending.
- The hybrid beams are 28% lighter and 87% stronger than traditional concrete beams.

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ABSTRACT

Context: Current formwork research aims towards new cost-competitive formwork systems and materials that focus on labour reduction and efficient material use. This labour cost is reduced when using Stay-in-Place (SiP) formworks. Besides its forming function, SiP formwork can moreover have a protective, an aesthetic or even a structural contribution to the hardened concrete element.
Objective: Using cement composites, the authors developed a new Stay-in-Place formwork concept for beams that is lightweight, easy to place and omits steel reinforcement.
Method: This paper describes the conceptual design, the analytical modelling of the loadbearing behaviour and the bending tests that demonstrate its structural feasibility.
Results: Unlike for steel-reinforced concrete beams, serviceability limit state becomes dominant for the developed hybrid beams. As experiments show, hybrid beams with equal stiffness as traditional reinforced concrete beams, have an increased load bearing capacity of 87%, while being 28% lighter.
Conclusion: This paper proves the feasibility and potential of structural SiP formworks in cement composites with hollow core elements for future structural applications.

1. Introduction

Formwork costs often transcend more than half of the overall cost of an in-place-cast concrete element [1]. To reduce the cost, reducing the complexity of the formwork system and facilitating the placing of the structural elements are the key to success in the future. Current formwork research aims therefore towards new cost-competitive formwork systems and materials that focus on labour reduction and efficient material use.

Over the last years, the increasing worldwide restriction on harvesting has challenged traditional timber and plywood formworks for in-place concrete casting [2]. Re-usable alternatives like prefabricated metal modules exist but are still time consuming due to the process of assembling, disassembling, cleaning and storing. This labour cost is reduced when using Stay-in-Place (SiP) formworks. Besides its forming function, SiP formwork can moreover have a protective, an aesthetic or even a structural contribution to the hardened concrete element.

SiP formworks in reinforced concrete are widely used for the erection of floor systems (e.g. half slabs, hollow core slabs). Unfortunately, these formworks retain a high surface weight, require machinery for placing on site and often demand supporting structures during casting. Lightweight alternatives that are

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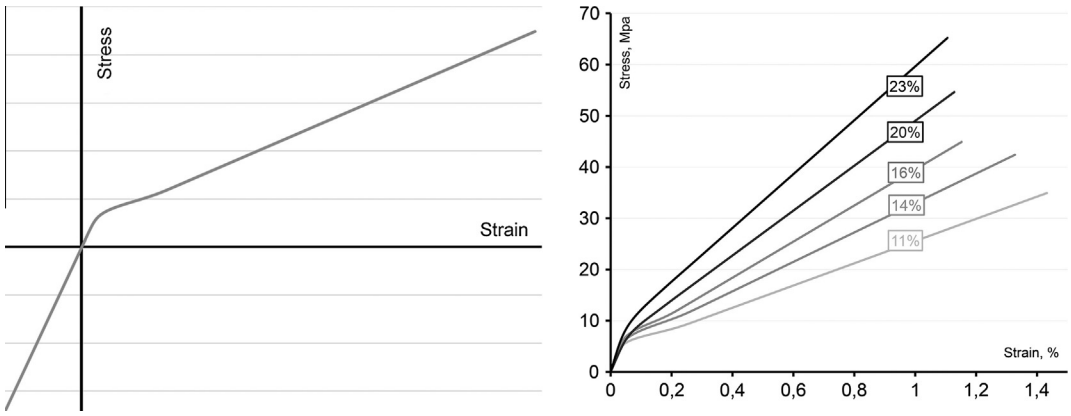

Fig. 1. (Left) The stress–strain diagram of TRC is linear in compression, whereas a bilinear behaviour can be considered in tension. (Right) A TRC, consisting out of mats with randomly oriented glass fibres and an inorganic phosphate cement can reach fibre volume fractions of up to 23%, which results in a high tensile strength, even after cracking [18].

currently being studied mostly use Fibre Reinforced Polymers (FRP) [3] for their high specific mechanical capacities. Deskovic et al. [4], Canning et al. [5], van Erp et al. [6], Hulatt et al. [7], Correia et al. [8] and Chakrabortty et al. [9] already performed research regarding the design of hybrid beams with a composite–concrete cross section. Still, FRP composites are little used in building applications due to the issues with their fire safety, essential in load bearing elements [10].

The use of fire safe composites such as Textile Reinforced Cements (TRC) [11,12] can create possibilities to meet the above enumerated shortcomings for structural SiP formworks. The recent evolution towards High Performance TRC Composites (HPTRCC) [13] with high fibre volume fractions (over 20% [14]) can contribute to a lightweight formwork design. The TRC considered in this work consists of an Inorganic Phosphate Cement (IPC) developed at the Vrije Universiteit Brussel (VUB) [16] in combination with E-glass fibre mats. The advantage of the IPC matrix is twofold: (i) phosphate cements are durable alternative binders for glass fibre reinforced cement composites as they are acidic when fresh, but pH-neutral after hardening [17]; (ii) its relatively small grain size (between 10 and 100 μm) creates the possibility to integrate continuous and dense reinforcement systems such as fibre mats, assuring a uniform fibre distribution and a higher fibre volume fraction.

In compression these TRC's behave as a linear elastic material (up to 80 MPa) [15] whereas in tension the development and evolution of cracks causes a bilinear constitutive behaviour. Cracking of the matrix due to the very low failure strain of the brittle cement (<0.1%), forces the fibres to take up all additional tensile forces, resulting in an initial un-cracked stage (E-modulus = 19 GPa), and a cracked stage with reduced stiffness (3.75 GPa for 18 fibre volume%, see also Fig. 1).

Using a smart combination of HPTRCC and FRP, the authors have developed a new formwork concept for moderate span beams (3–6 m). This beam formwork had to fulfil the following predetermined conditions: (i) span the total length without additional falsework during casting; (ii) consist out of lightweight elements; (iii) be fire resistant to protect the concrete beam; and (iv) contribute structurally to such an extent that the steel reinforcement becomes superfluous. These criteria assure a facilitated construction stage.

This paper first presents the new SiP formwork concept, and then demonstrates its structural feasibility by full scale mechanical tests. The paper discusses the different elements that constitute the beam formwork, their structural role as well as the specific use of materials. Then, an analytical model to predict the loadbearing behaviour of the hybrid beams is described. After, it summarises the results of an experimental study on two 3 m-long SiP formwork beams. It discusses the structural behaviour of the formwork during casting stage as well as that of the hardened beams under a four-point-bending test and compares it to the analytical model simulations.

2. Concept

This section summarises the conceptual development of the lightweight composite Stay-in-Place formwork discussed in this paper. During design, attention was given to two aspects. Firstly the ease of use during the casting of the concrete beam: the authors intended to create a system that eliminated the necessity of intermediate supports and aimed for a system that was light enough to be carried around and to be placed by hand power. Secondly attention was given to the structural capacity of the SiP formwork after casting. For the purpose of demonstrator for the future use of composites in construction the authors opted to fully replace traditional steel reinforcement with composite materials.

2.1. Formwork concept: casting stage

In order to allow a one span cast and yet end up with a straight concrete beam, the composite formwork needed to be both stronger and stiffer than traditional systems that do have intermediate supports. For this the authors imbedded a strong and stiff structural member (green[1] in Fig. 2) in the section of the formwork of which the cross section is dimensioned by the forces induced by the weight of the concrete. The insertion of a hollow element in the tensile part of the cross-section shall result in a significant reduction of concrete used, which in turn results in lower stresses on the formwork. The external shaping of the concrete member is done by a U-shape, which is attached to the hollow structural member. This U-shape is designed to resist the cross sectional concrete pressure. The rounded edges of both flanges are used for connecting the outer formwork with the internal hollow member. This allows a load transfer from the U-shape outer formwork to the hollow internal structural member. It furthermore stiffens the flanges in the longitudinal direction which allows a larger span between connecting points.

[1] For interpretation of colour in Fig. 2, the reader is referred to the web version of this article.