Participating Formwork with CFRP Textile for Shape-Optimised Concrete Beams: Opportunities and Challenges

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Abstract

Carbon emissions from concrete structural elements can be reduced by improving the material efficiency with shape optimisation. However, fabricating and reinforcing shape-optimised concrete beams is challenging due to the need for complex and curved geometries. This study conceptualises the use of dual-purpose stay-in-place participating formwork with CFRP textile for shape-optimised beams where the system acts as (a) the formwork for the optimised geometry, and (b) flexural and shear reinforcement. The development, preliminary analysis, and experimental results of a prototype beam with CFRP textile are presented in this paper. Participating formwork with CFRP textile offers an opportunity to reduce concrete consumption as a comparably easier construction method of shape-optimised beams but challenges persist in potential premature brittle failure modes.

1 Introduction

Minimising carbon emissions from the construction sector is key in the global strategy for tackling climate change. Cement production alone contributes approximately 6% of global carbon emissions caused by human activities [1]. Despite concerns about its impact on the environment, reinforced concrete is extensively used in the construction sector. As a result, it is essential to minimise the carbon emissions arising from concrete construction activities given the current climate emergency. Traditional approaches to design concrete structures rarely take advantage of the fluid nature of concrete to create complex and efficient structural designs. Instead, they rely on inflexible, flat formwork that produces solid, prismatic shapes, thereby hindering the opportunities for optimisation of structural elements.

The geometry of a reinforced concrete beam can be optimised to provide only the required amounts of materials throughout the length and width of the beam. Shape-optimised beams can be designed by considering bending moment and shear force profiles and verifying serviceability requirements [2]. Such geometries, which have curved complex surfaces, as shown in Fig.1, are difficult to achieve in terms of fabricating the reinforcement, and formwork into the required shape. This difficulty may be overcome through the use of a flexible FRP textile system with adequate mechanical properties that can act concurrently as reinforcement for the concrete. Therefore, this paper explores the opportunities and challenges in using CFRP textile materials as both formwork and reinforcement simultaneously.

2 Literature Review

A beam in a reinforced concrete frame can have different magnitudes of bending moment and shear forces along the beam depending on the loading and support conditions. Rectangular prismatic beams have been the conventional popular choice in the construction industry due to the easiness of manufacture. Whole life embodied carbon of a structural element is the amount of CO_2 emitted due to the

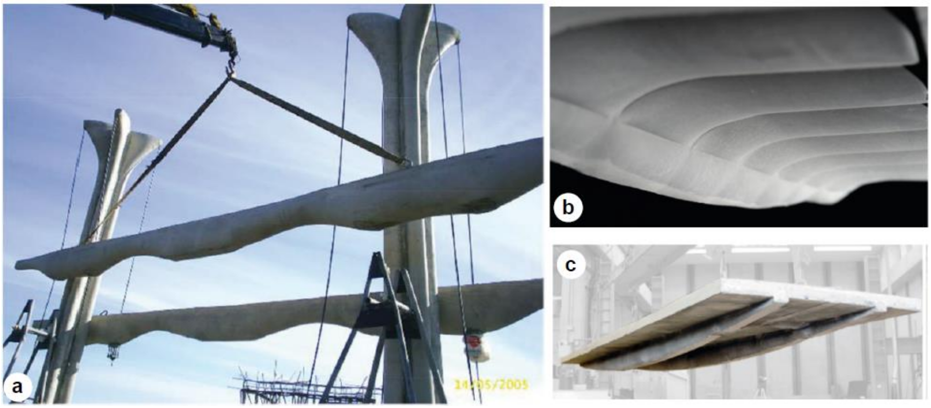


Fig. 1 Shape-optimised reinforced concrete beams cast using flexible fabric formwork (Hawkins et al. [3] for (a) and Orr [4] for (b) and (c))

activities performed during its lifecycle, starting from the extraction of raw materials, through construction, and to end-of-life activities [5]. Providing only an adequate amount of concrete and steel throughout the span to satisfy the Ultimate Limit State (ULS) and the Serviceability Limit State (SLS) can however theoretically minimise embodied carbon of the structural elements. Several researchers have illustrated the optimisation of the geometry of the beam and the reinforcement configuration simultaneously [6]–[8]. Hawkins et al. [3] reviewed that shape optimisation of reinforced concrete beams is proven to reduce the consumption of concrete by up to 44%. Jayasinghe et al. [6] further demonstrated that embodied carbon of shape-optimised beams can be reduced by up to 38% compared to conventional beam designs.

Despite the potential improvement in material efficiency, fabricating shape-optimised beams require unconventional formwork with curved geometries. Several researchers have fabricated shape-optimised elements using tailor-made sheet metal moulds [9], CNC-cut Styrofoam moulds [10], and wire-cut timber with expanded Polystyrene [11]. Orr et al. [2], Kostova et al. [12], and Veenendaal & Block [13] have illustrated a successful implementation of flexible fabric formwork for casting shape-optimised concrete members. Less wrinkly fabrics with high stiffness and tensile strength in both warp and weft directions are desirable as flexible formwork materials to limit excessive deformations and localised defects during concreting and curing [4]. Previous studies have used hessian and geotextiles [3], while experimental work in the recent past at the University of Bath and the University of Cambridge used woven polyester fabrics [2], [14].

Construction of shape-optimised beams is often challenging also due to the need for a reinforcement system with complex shapes. Orr et al. [2] used steel reinforcing bars to form the shape-optimised reinforcement cage in concrete beams. Orr et al. [15] further demonstrated methods of using the flexibility of FRP bars and helixes to provide reinforcement for curved geometries. Orr et al. [16] also illustrated the use of Ultra-High-Performance Fibre Reinforced Concrete instead of a shape-optimised transverse reinforcement system. Spadea et al. [17] improved the material efficiency of the FRP reinforcement systems by filament winding of CFRP tows around the longitudinal reinforcing bars to provide an optimised shear reinforcement profile. Fig.2 presents a few previous examples of providing formwork and reinforcement for shape-optimised concrete beams with curved geometries.

Several researchers have studied optimised concrete structures using stay-in-place formwork systems for various aspects. Lee et al. [18] illustrated a system where a resin-cured polyester textile as a stay-in-place formwork is used to keep together steel reinforcing bars and Aramid yarns as longitudinal and transverse reinforcement respectively. Popescu et al. [19] demonstrated the use of a prestressed knitted textile that is stiffened using GFRP bars and Aramid ribbons as stay-in-place formwork to cast a thin shell bridge. Bekaert et al. [20] investigated the performance of 3D-printed concrete elements as stay-in-place formwork. Gai et al. [21] studied the behaviour of composite formwork where FRP sections across the slab system perform as both formwork and reinforcement, whereas Sutter et al. [22] studied a similar concept for beams.

(a) Steps of the construction process of steel-reinforced shape optimised concrete beams (Orr (2012))

(b) Reinforcing shape optimised concrete beams with wound FRP cages (Spadea et al. (2016))

Fig. 2 Examples of providing formwork and reinforcement for shape-optimised beams (Orr [4] for (a) and Spadea et al. [17] for (b))

The focus of this study is to demonstrate the possibility of using a participating formwork and to identify potential issues in construction methods and failure mechanisms. A shape-optimised beam is therefore constructed to represent the aspect ratios of beam designs expected in practice but scaled down to investigate the potential caveats in construction methods.

3 Conceptualisation

This paper presents the conceptualisation of participating formwork for concrete elements, where the stay-in-place flexible formwork is utilised as the reinforcement in both longitudinal and transverse directions (Fig.3). The dual-objective participating formwork performs as:

(a) The formwork (or a part of the formwork system) to support the fresh concrete into the required optimised shape during the construction and for the curing period.
(b) The reinforcement in both longitudinal and transverse directions once the concrete is hardened.

The preliminary designs and experiments presented in this paper are based on using flexible CFRP woven textiles as the participating formwork material.

4 Development of the experimental prototype

The geometry of the beam is estimated as a 25% scaled-down version of the shape derived in Jayasinghe et al. [6] where 8 m long steel-reinforced concrete beams were parametrically shape-optimised. The sectional dimensions at the midspan and support are approximately scaled proportionally to the span of the beam in this study, and adjusted according to the variations that occurred in practice.

A beam with a 2 m clear span (having 150 mm overhang from the supports) with no flange was cast using a 0/90 bidirectional 375 gsm CFRP textile as participating formwork. The concrete mix used in this study had an average compressive strength of 20 MPa at 28 days. The cross sections at midspan and support were approximated to 150 mm × 75 mm and 80 mm × 150 mm, respectively, using flexible fabric formwork and timber falsework. The depth and width profile were parabolic in shape considering the practicality of the construction procedure. The estimations presented herein are to facilitate the discussion of the experimental outcomes.

In contrast to steel-reinforced concrete beams, over-reinforcing concrete members in flexure are often recommended for FRP-reinforced elements [2]. Under-reinforcing with steel rebar would result in a ductile failure mechanism in flexure by yielding steel. Due to the brittleness of the FRP fracture, under-reinforcing would result in a more brittle failure. Hence over-reinforcing with FRP is recommended to switch the failure mechanism in flexure to concrete crushing. This way, the brittle failure of the FRP-reinforced concrete is more controllable. Therefore, the geometry of this prototype was adjusted to achieve an over-reinforced section assuming that there is no premature debonding. The flexural and shear performance is analysed according to fib technical report for FRP reinforcement in reinforced concrete structures [23].

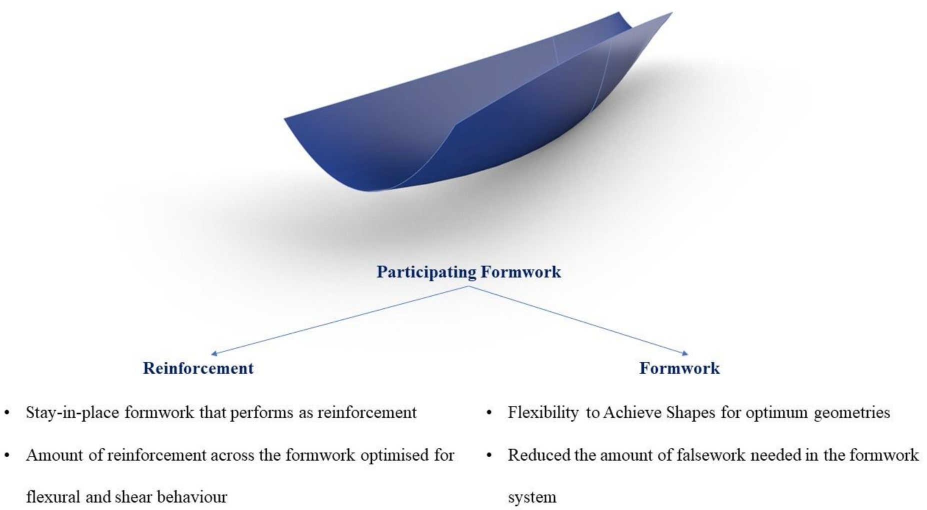


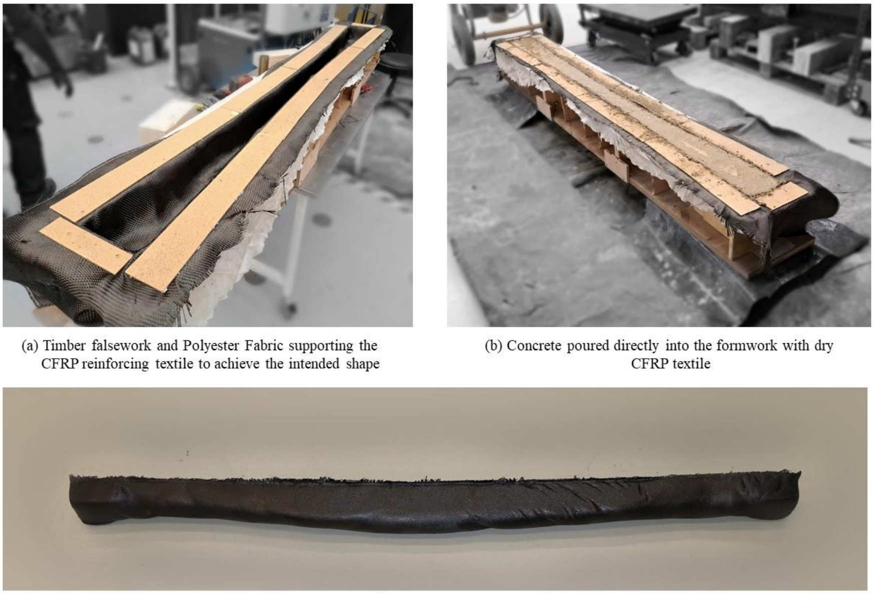
Fig. 3 Conceptualisation of participating formwork for shape-optimised concrete beams

Since the weaving of the CFRP textile is too loose to be used as an unsupported participating formwork at this stage, the required shape was achieved using a flexible polyester fabric formwork supported with timber falsework (Fig.4). The top opening of the timber falsework was cut to resemble the intended width profile of the optimised beam. The supporting polyester fabric was then fixed to the timber falsework to achieve the intended depth profile. The CFRP textile was laid within the formwork. No other internal reinforcement was used. The participating formwork was cured with 2-part resin after demoulding and removing excess parts of the CFRP textile.

5 Preliminary analysis

The performance of participating formwork can be governed by premature failure modes resulting from debonding, as shown by previous studies which used CFRP for structural retrofitting [24], [25]. As a starting point, this paper estimates an upper bound of flexural and shear failures at the ULS assuming a perfect bond between the concrete and the CFRP textile. The directions of fibres and thickness across the fabric are not optimised in these calculations but are only estimated for peak moment at midspan and peak shear force at the support. The authors are looking to extend the analysis to include the bond behaviour and serviceability aspects in future work.

The concrete stress block was derived as per the guidelines in BS EN 1992-1-1 [26]. When this section is cast with participating formwork, the CFRP textile below the neutral axis contributes to the tensile force. Due to the 0/90 weaving pattern, 50% of fibres are assumed to be working as longitudinal reinforcement. The CFRP textile was assumed to have a tensile strength of 3450 MPa, a tensile modulus of 230 GPa, a strain at failure of 1.5%, and a thickness of 0.213 mm, according to the manufacturer's datasheet. Fig.5 illustrates the idealised stress and strain profiles of the section at the midspan of the beam for flexural analysis. It is assumed that the CFRP textile on both the sides below neutral axis contributes to the tensile capacity. The strain and the stress at the bottom-most fibre are taken as the ultimate values, while stress and strain at the neutral axis are taken as zero. Hence, the tensile force is calculated as an integration from the bottom-most fibre to the neutral axis.



(a) Timber falsework and Polyester Fabric supporting the CFRP reinforcing textile to achieve the intended shape

(b) Concrete poured directly into the formwork with dry CFRP textile

(c) Final product after demoulding, excess CFRP textile cut off, fabric cured with two-part epoxy

Fig. 4 Construction process of the shape-optimised beam with CFRP participating formwork

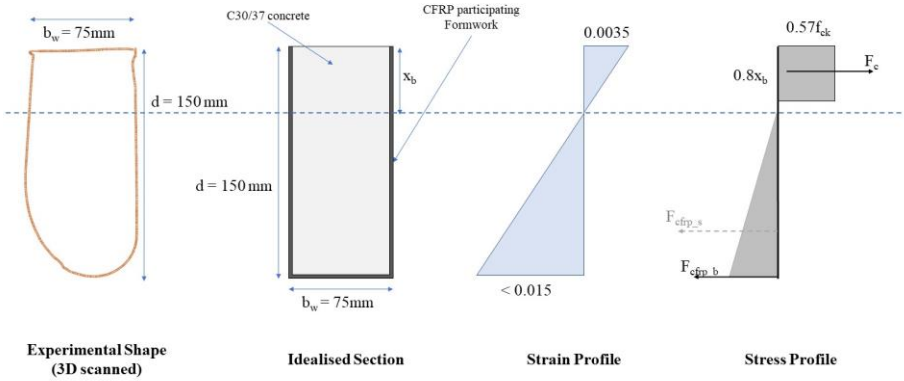


Fig. 5 Idealised stress and strain profiles for flexural analysis

$$\text{Compressive force in concrete } (F_c) = 0.8x_b b_w f_{ck} \tag{1}$$

$$\text{Tensile force in CFRP at the bottom } (F_{cfrp_b}) = 0.0035 \times \frac{d - x_b}{x_b} \times E b_w \left(\frac{t}{2}\right) \tag{2}$$

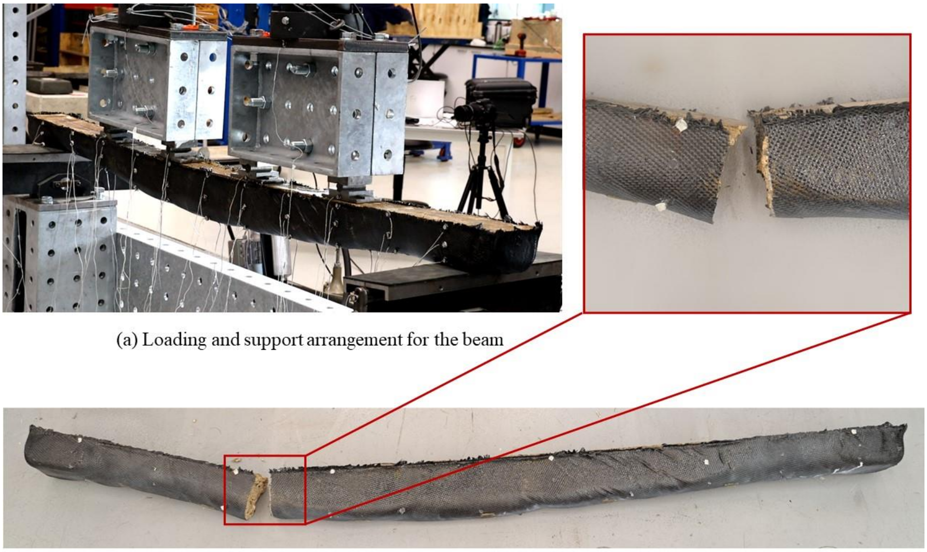
$$\text{Tensile force in CFRP on the sides } (F_{cfrp_s}) = 0.0035 \times \frac{d - x_b}{x_b} \times 0.5E(d - x_b) \times 2\left(\frac{t}{2}\right) \tag{3}$$

(E- Tensile modulus of CFRP, t- thickness of the textile, A_b- Area of CFRP reinforcement at the bottom, A_s- Area of CFRP reinforcement on the sides)

Considering the equilibrium of the tensile and compressive forces of the section using Equations (1) to (3), the depth to the neutral axis can be estimated after solving a quadratic equation. The upper bound for the capacity of the section was thereby estimated as 5.20 kNm with an expected failure by concrete crushing, while the strains at the bottom fibres of the CFRP are expected to be around 75% of the allowable limit. The width profile and the depth profile closer to the support in this experiment have been adjusted to obtain a flexural failure rather than a shear failure, following the preliminary estimations according to the fib technical report [23].

6 Experimental results

The beam was simply supported, and four equal point loads were applied to approximate the behaviour of a uniformly distributed load (Fig.6). The beam failed at a total load of 12.8 kN (3.81 kNm bending moment at midspan) in a sudden brittle manner at 450 mm away from the support. The specimen showed no sign of debonding observable to the naked eye throughout the testing period. The failure occurred at a load equivalent to 74% of the estimated upper bound moment capacity at midspan. The vertical failure plane suggests that the brittle failure was flexural, triggered due to lack of strain compatibility at the concrete/ CFRP interface and resulting stress concentration in the CFRP textile.



(a) Loading and support arrangement for the beam

(b) Failure of the beam

Fig. 6 Testing and failure of the prototype beam

7 Discussion and Conclusions

This paper presented an experimental prototype of a shape-optimised concrete beam using a CFRP textile as a participating formwork with no other reinforcement. The experimental weight of the beam was 55 kg. Compared to a prismatic beam with the same midspan depth and an aspect ratio of 2:3, this prototype has 33% less concrete. In contrast to the other construction methods of shape-optimised beams, participating formwork requires fewer steps in the manufacturing process since the aspects of the development of formwork and reinforcement are united. Therefore, participating formwork is a comparably simpler optimised construction method to reduce concrete consumption.

The experimental prototype in this study, which had no reinforcement other than the external participating formwork, showed a flexural failure before significant debonding occurred. The failure was sudden and brittle and happened at 74% of the estimated capacity. The failure occurred in the form of stress concentration. Stress concentration and brittle failures are common issues largely researched in the context of FRP reinforcement. Since fresh concrete was directly poured into the dry fabric and later cured with two-part resin, the bond behaviour may be different from the bond behaviour of CFRP with concrete when used as a retrofitting material. However, the influence of the premature failures in the bond between concrete and CFRP textile cannot be ruled out in the context of participating formwork. and this aspect will be further investigated in the next steps of the research. Further research is therefore needed in the directions of ductility, and potential premature failures due to stress concentrations and bond behaviour.

A 0/90 bidirectional CFRP textile available in the market was used as the participating reinforcement of the prototype. Optimising the thickness of the reinforcement throughout the specimen can further reduce the material consumption of the structural elements. Optimisation of the weaving patterns of the CFRP textile, and parametric shape optimisation coupled with the simultaneous design of the participating formwork will be studied in future.

Participating formwork with CFRP textile, therefore, provides an opportunity to improve the material efficiency of concrete beams by reducing the steps required to manufacture shape-optimised concrete beams. However, potential premature brittle failure modes due to the bond behaviour at the concrete/ CFRP interface remain challenges and need further research.

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