NEW FRONTIERS FOR THE USE OF FRP REINFORCEMENT IN GEOMETRICALLY COMPLEX CONCRETE STRUCTURES

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ABSTRACT

The development of flexible formwork has made it possible to cast optimised geometrically complex and thin walled reinforced concrete structures. At the same time, advanced composite materials offer the opportunity to solve the problem of steel corrosion, which can affect aging of concrete structures. With the goal of achieving sustainable design, being able to combine optimised geometries with durable construction materials is a major challenge for civil engineering.

New research at the University of Bath and the University of Miami aims to completely replace internal steel reinforcement in geometrically complex concrete structures with durable and ready-to-use cages made of fibre reinforced polymer (FRP) reinforcement. By fabricating the reinforcement in the desired geometry, it will be possible to provide the required strength exactly where needed, thereby reducing the amount of concrete required to resist internal forces and capitalizing on the extraordinary possibilities offered by both concrete and FRP construction materials.

The design of such optimized elements and the automated process of manufacturing the Wound FRP (W-FRP) reinforcement are presented in this paper.

KEYWORDS

W-FRP, RC beams, optimization, fabric formwork.

INTRODUCTION

Since its early age, concrete has been cast in rigid formwork, normally in the form of rectangular prismatic solids. Recent research has shown that nearly 40% of concrete that is currently used in building structures has little contribution to structural capacity, only adding extra self-weight to the building (Orr, Darby et al. 2011). Flexible formworks rely on the use of a system of flexible sheets of fabric to allow complex shapes to be easily cast, thus facilitating the construction of optimised structures (Orr, Darby et al. 2011, Veenendaal, Coenders et al. 2011). This is crucial for the sustainable design of concrete structure, provided that the saving in material use directly lead to saving in embodied energy.

In addition to the great possibilities of building unconventional concrete geometries and reduce the material consumption, the use of fabric formwork offers a technological advantage. By casting concrete into a permeable fabric membrane, excess pore water is allowed to bleed from the concrete during curing. The resulting reductions of water/cement ratio in the surface zone of concrete elements bring improvements in durability (Price 1999, Orr, Darby et al. 2013).

Nevertheless, the need to assemble quite complex reinforcing cages together with the low durability of steel reinforcement in thin walled structures, are some of the reason why a large-scale deployment of this technology has not occurred yet.

The use of FRP as internal reinforcement can help to overcome these kind of issue. The substantial disadvantage inherent in the use of FRP reinforcement is related to onsite flexibility. Whereas steel reinforcement can easily be bent into an extensive range of geometries at the construction site, FRP reinforcement needs to be carefully shaped during manufacture according to the final demand. This challenge turns in favour of the pursuit of material optimization, which require an increase in the level of control during the design and construction phases to produce complex geometries. Moreover, the terrific lightness of composite reinforcement suggests the opportunity to deliver prefabricated reinforcement cages to site, ready to be positioned and cast.

With all this in mind, coupling the geometric flexibility given by novel formworks systems with the enhanced durability offered by FRP reinforcement, gives the opportunity to depict a new paradigm of design for the reinforcement of concrete structures, aiming to pursue the sake of sustainability in the construction process. Further savings in emissions can be achieved using low-carbon cements, which further reduce the embodied energy of concrete. In fact, such cements cannot readily be used with steel reinforcement as they also reduce the alkalinity of the concrete mix. By contrast, a reduced alkalinity environment makes no difference when using a non-corrosive reinforcement, allowing the potential to achieve embodied energy savings through both geometry and material choices.
The present research aims to explore the possibility of fabricating FRP reinforcement in complex geometries by mean of an automated manufacturing system, in order to provide tensile strength exactly where it is needed by optimized RC structural elements. This will be transformative for concrete construction, as it will greatly simplify the design of more efficient, thin walled and architecturally daring concrete structures.

DESIGN PROCEDURE

Literature Review

FRP has excellent tensile properties in the direction of the fibres. Unlike steel, which exhibits yielding and plastic flow, it has a linear elastic stress–strain relationship. The Young's modulus of FRP reinforcement is usually lower than steel as it is primarily dependent on the stiffness of fibre used (Nanni 1993). For this reason the serviceability limit states, rather than the ultimate limit states, are normally governing the design of FRP reinforced structures. In particular, the control of deflection is very often the most decisive check in the design process (Ascione, Mancusi et al. 2010, Nanni, De Luca et al. 2014). Additionally, the lack of yielding of the FRP reinforcement suggests the design of over reinforced sections, in order to obtain concrete crushing flexural failure and prevent sudden FRP rupture. This circumstance produces, in any case, an overall less ductile behaviour of FRP RC members as compared to steel RC members.
Another relevant design problem is modelling the mechanisms of shear resistance in FRP reinforced concrete members. Shear failure of reinforced concrete structures is brittle and it can be tremendously sudden and dangerous when dealing with FRP shear reinforcement (Matta, El-Sayed et al. 2013, Ascione, Razaqpur et al. 2014, Razaqpur and Spadea 2015). Furthermore, the most up-to-date design codes do not provide specific guidance to analyze the shear strength of non-prismatic concrete members (Orr, Ibell et al. 2014).
In order to develop a model that can efficiently predict the structural behaviour of such structural elements and consequently perform the structural optimization of fabric–formed concrete beams reinforced with FRP, a method of analysis with broad applicability was developed into a Matlab code. The geometry of the fabric formed member and the distribution of the reinforcement was modelled in a closed form allowing for considering variation in section dimensions along the members. The optimization criteria aim to obtain the minimal mass of concrete and observing the capacity design requirements as per the mostly recognized design codes (CSA S806 2012, CSA S6 2014, ACI 440.1R 2015).

Computational Method

The computational procedure followed can be briefly outlined as below:

1. Setting static scheme, structural materials, geometric limitations, design standard, capacity design requirements.
2. Finding the applied bending moments and shear stresses from the given loading.
3. Optimization for strength is carried out to find the profile of the beam which satisfy the ultimate limit states for flexure and maximize concrete contribution to shear strength. This is done dividing the section geometry and layout of the longitudinal reinforcement for each section.

At this point, a FRP RC fabric formed beam without shear reinforcement, optimized for flexure, is obtained.

4. The serviceability behaviour of the member is then assessed (elastic deflection, crack width and time dependent behaviour checks).
5. If the member fails to meet serviceability limit state conditions, the applied bending moments and shear stresses are virtually increased by a scaling factor, and the computational procedure go back to point 3 until point 5 is satisfied.

The reason for increasing the design stresses rather than performing a specific optimization process for serviceability is related to the willingness of observing the capacity design rules.
At this point, a FRP RC fabric formed beam without shear reinforcement, optimized for flexure, and meeting the serviceability limit state conditions is obtained.

6. Optimization for shear strength is carried out to find the best geometry and the minimal quantity of web reinforcement which satisfy the ultimate states for shear. The web reinforcement geometry is limited to

shapes that can be obtained by fibre winding, hence they may results in being a certain type of spirals. Also in this case the method is based on a sectional analysis.

At this point, a FRP RC fabric formed beam, optimized for flexure and shear strength, and meeting the serviceability limit state conditions, is obtained.

The code is able to produce a STereoLithography (.stl output file) of the designed beam, which is suitable to embed all the information pertaining the geometry of the designed structural elements.

MANUFACTURING METHOD

As described in the following paragraphs, a computer controlled winding of impregnated carbon fibres around a set of FRP bars gave us the opportunity to obtain durable, lightweight, and ready-to-use reinforcement cages.

The manufacturing of web reinforcement is operated by mean of a process based on the filament winding fabrication technique, which consist on wrapping continuous fibres under tension over a rotating mandrel. While the mandrel rotates, a wind eye on a carriage moves horizontally, laying down the fibres in the desired pattern. In the wet winding method, the fibre picks up resin either by passing through a resin bath or from a metered application system. In the dry winding method, the reinforcement is in the pre-impregnated form. After several layers are wound, the component is cured and removed from the mandrel. This method of manufacturing provides a great control over fibre placement and uniformity of the material structure and it is generally used to produce continuous hollow shapes with constant cross section

In the present application, slightly curved CFRP bars - responsible for providing the flexural strength to the concrete beams - are attached to the mandrel according to the prefigured reinforcement geometry. A refined system of control allows the winding of a number of carbon tow layers in the form of spirals with variable cross section. After the winding and curing process occurs, the reinforcing bars are maintained in the curved configuration by the wound reinforcement.

The filament winding prototype, specifically designed and constructed at the University of Bath with the aim of producing this new class or reinforcing cages, is shown in Figure 1. The design includes the possibility of implementing either wet-winding, by means of a resin bath, or a dry-winding method.

In this work a continuous 50k carbon fibre tow (C T50-4.0/240-E100) produced by Sigrafil (SGL group) is adopted. The SGL Carbon tow is used in combination with Fyfe Tyfo S two-component epoxy to implement a wet-winding process. This class of epoxy resin, suitable for the wet-layup of external strengthening of structural members, can be applied at room temperature and air cured. Both are considerable advantages for this application as the resin bath does not need to be heated and the curing process can be simply operated by storing the cages at standard lab conditions for 48h-72h.

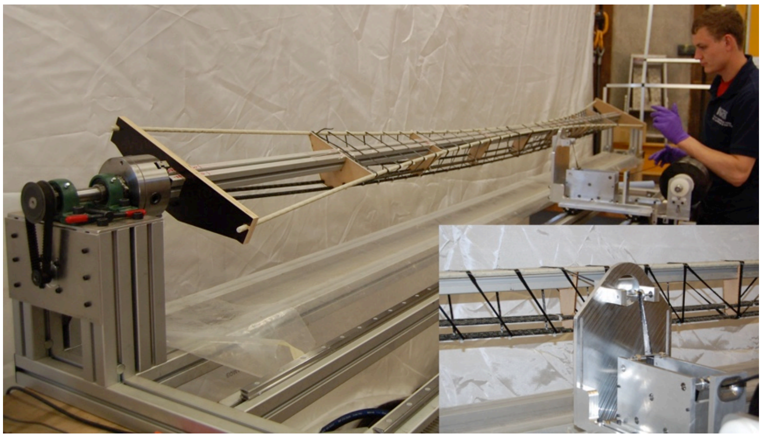


Figure 1: Filament winding of a W-FRP reinforcing cage.

FLEXIBLY FORMED BEAMS

With the aim of validating both the optimization procedure and the W-FRP reinforcement cages manufacturing method, six FRP fabric formed beams were designed and cast. The beams are currently being tested at the University of Bath.

Assumptions

The adopted static scheme is a simply supported beam with three meters span and half-meter overhang on each side. The entire beam is subject to a uniformly distributed load.

Two different study cases were taken in consideration:

1) The first set of beams (Set I) is intended to simulate a precast fabric formed joist supporting a lightweight floor (e.g. all-FRP or wood floor).
2) The second set of beams (Set II) aims to reproduce the use of a precast fabric formed beam with an in-situ casting of a concrete floor. In the experimental work described below, the beam and the slab elements were cast together for ease of construction.

Additionally, the following assumptions were made for design purposes:

- The dead load and the live load are 2.5 kN/m and 7.5 kN/m, respectively;
- The strength class of concrete is C30/37;
- The bottom and top reinforcement are respectively #3 Carbon and #3 Glass FRP Aslan bars produced by Hughes Brothers.

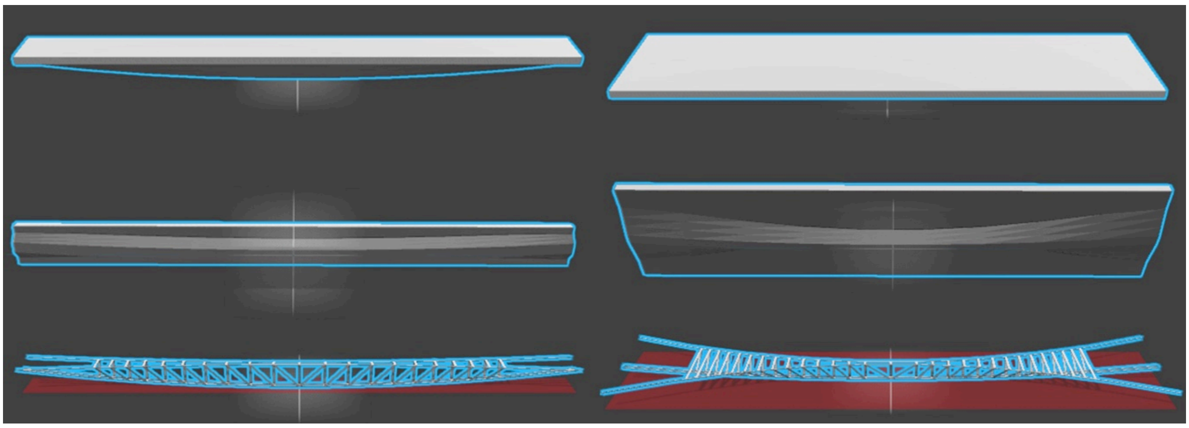
Optimization Results

Table 1 shows a comparison of the most relevant details of the beams. A 3D visualization of the beam's StereoLithography, as generated by the design code, is also shown in Figure 2.
Each set is composed of three beams having identical concrete geometry and longitudinal reinforcement but different W-FRP shear reinforcement. Whereas they all satisfy the points 1 to 5 of the above-mentioned computational procedure, only beams x.3 have the requested shear strength (point 6). In fact, beams x.1 and x.2 are purposely designed to exhibit a premature and sudden shear failure.
In detail:

1) Beams I.1 and II.1, having no shear reinforcement, are expected to fail in shear, due to shear tension failure;
2) Beams I.2 and II.2, having three layers of wound reinforcement, are also expected to fail in shear, due to shear tension failure and showing wound reinforcement rupture.
3) Beams I.3 and II.3, having 5 layers of wound reinforcement, are expected to fail in flexure, due to concrete crushing at midspan.

Table 1 – Details of the beams

	Set I	Set II
beam length	4100 mm	4100 mm
flange width	300 mm	900 mm
flange thickness	60 mm	60 mm
web minimum width	85 mm	85 mm
beam depth at midspan	265 mm	190 mm
beam depth at supports	180 mm	150 mm
beam depth at ends	95 mm	110 mm
top reinforcement at supports	2 × #3 GFRP	3 × #3 GFRP
bottom reinforcement at midspan	3 × #3 CFRP	4 × #3 CFRP
Concrete volume	0.14 m^3	0.27 m^3
number of wound CFRP layers (x.1 / x.2 / x.3)	0 / 3 / 5	0 / 3 / 5

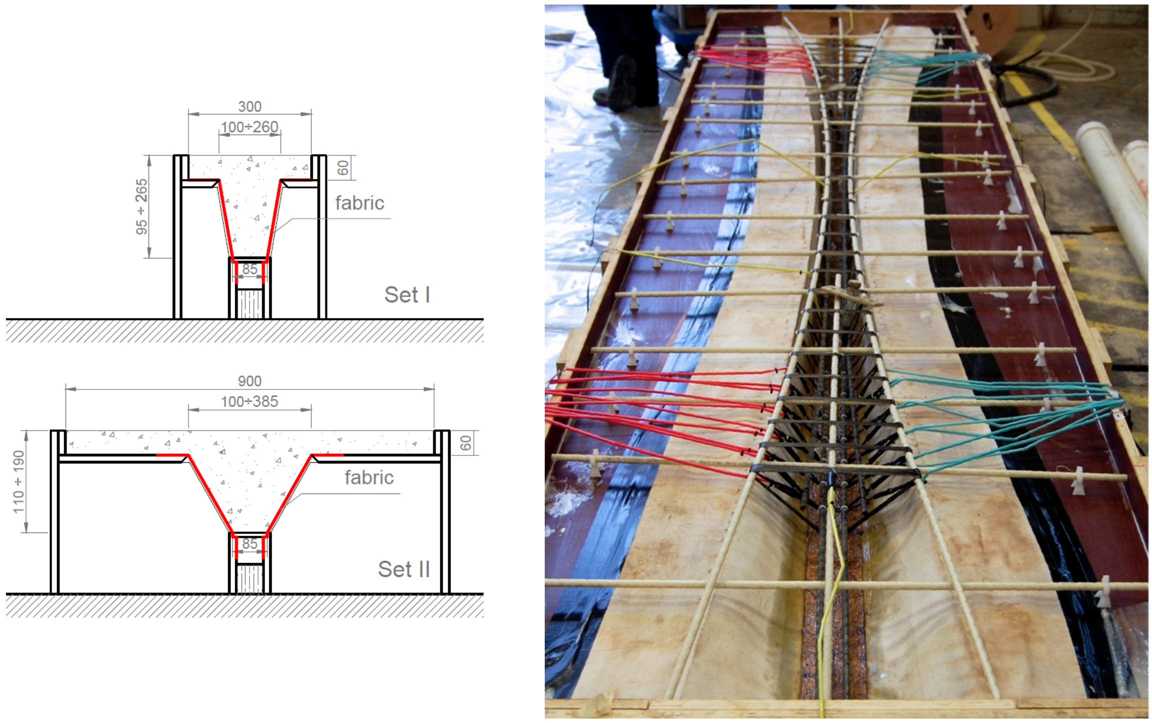


(a) Set I (b) Set II

Figure 2 - 3D visualization of the beam's StereoLithography

Construction

The essence of flexible construction is to secure the fabric on a supporting frame in order to achieve the desired form once the formwork is filled with concrete. In the present work, the fabric is draped into a plywood supporting frame to shape the non planar lateral surface of the stems whereas the control over the beam elevation is achieved using a keel, pre-cut to the desired elevation (Figure 3a).
Figure 3b shows the W-FRP cage of beam II.2 instrumented with strain gauges and installed into the fabric formworks before concrete casting.



(a) (b)

Figure 3: a) formworks cross-section diagram; b) instrumented W-FRP cages installed into the fabric formworks before concrete casting (beam II.2).

EXPERIMENTAL INVESTIGATION

The experimental setup (Figure 4) consists of two simple supports and seven hydraulic jacks attached to a rigid frame, each one instrumented with a load cell. Five jacks are equally spaced on the 3000 mm beam span and powered by the same oil circuit, as to apply a load P. The remaining three jacks are installed at the ends of the cantilevers (500 mm long), and powered by a separate different hydraulic circuit in order to apply a load equal to $0.5{\cdot}P$. This loading scheme allows to simulate a uniformly distributed load.

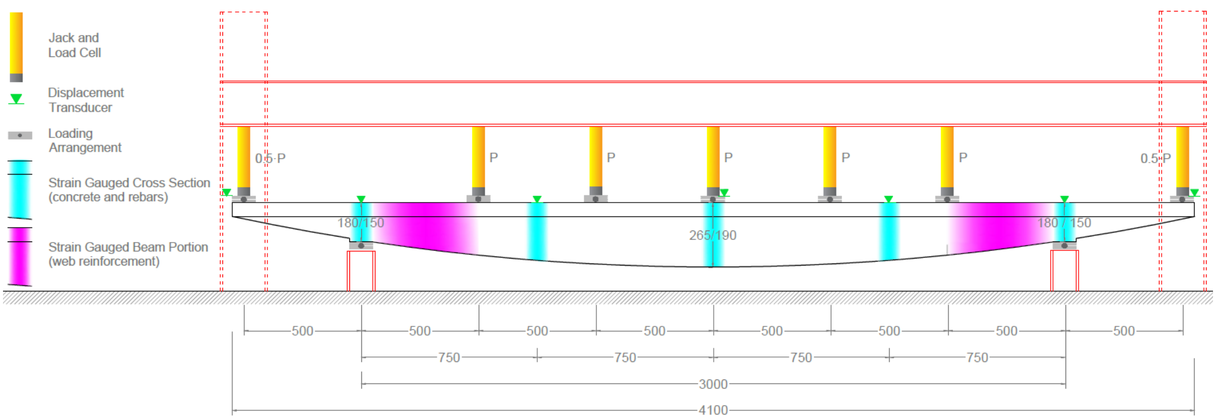


Figure 4: Experimental Setup.

Seven displacement transducers are installed: one at the beam midspan, two at the supports, two at the quarters span and two at the ends of the cantilevers.
Five cross-sections of the beams are instrumented with uniaxial strain gauges installed on the reinforcing bars and on the concrete (cyan sections in Figure 4) in order to monitor the flexural curvature of the beams.
The wound reinforcing cages of beams x.2 and x.3 are instrumented with uniaxial strain gauges mounted on each leg included between the supports and the closer point load in the span (magenta areas in Figure 4).
The front face of each beams is painted with a dotted bi-chromatic pattern. High resolution pictures, perpendicular to the observed surface, are taken at each 2kN increment throughout the entire loading cycle to enable subsequent analysis using Digital Image Correlation (DIC).

REMARKS AND FUTURE WORK

This paper presents an analytical tool able to show the potential of using bespoke CFRP reinforcement in RC optimised beam and the automated process of manufacturing the FRP reinforcing cages. Such structures have complex geometries, which are difficult to reinforce with conventional steel. The technical developments in this paper provide the basis for a novel alternative reinforcement technique that is well suited to automation and mass production.
The experimental validation is under development; hence some of the results will be presented during the CICE 2016 conference, in Hong Kong.

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DATA ACCESS STATEMENT

All data created during this research are openly available from the University of Bath data archive at http://doi.org/10.15125/BATH-00213

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