Development of new FRP reinforcement for optimized concrete structures

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ABSTRACT

With the goal of achieving sustainable design, being able to combine optimized geometries with durable construction materials is a major challenge for Civil Engineering.
Recent research at the University of Bath has demonstrated that fibre-reinforced polymers (FRP) can be woven into geometrically appropriate cages for the reinforcement of optimised concrete beams. This innovative construction method enables the replacement of conventional steel with non-corrosive reinforcement that can provide the required strength exactly where needed.
The manufacturing of the reinforcement is achieved by means of an automated process based on a filament winding technique. Being extremely lightweight, the wound-FRP (WFRP) cages are well suited to speeding up construction processes, as they can be delivered on site ready to be cast.
In this paper, the results of flexural tests on optimised full-scale flexibly formed concrete elements are reported and discussed. Two different case studies are taken in consideration:
- A structurally optimized joist supporting a lightweight floor;
- A structurally optimized beam with an in-situ casting of a concrete floor.

The optimization objective is to obtain the minimal mass of concrete required to achieve the structural capacity design requirements from widely recognized design codes.
The experimental results demonstrate the reliability of the technical solution proposed and provide the basis of a new concept for sustainable and durable reinforced concrete structures.

Keywords: WFRP, composites, reinforced concrete, optimisation, fabric formworks

INTRODUCTION

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). However, 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 since it can be accurately shaped during manufacture according to the final demand.

FRP has a linear elastic stress–strain relationship and excellent tensile properties in the direction of the fibres. The Young's modulus of FRP reinforcement is usually lower than steel as it is primarily dependent on the fibre stiffness (Nanni 1993). For this reason, serviceability limit states, rather than ultimate limit states, normally govern the design of FRP reinforced structures. In particular, the control of deflection is very often the most decisive check in the design process (Ascione et al. 2010; Nanni et al. 2014). Additionally, the lack of yielding of the FRP reinforcement requires the design of over reinforced sections to obtain concrete crushing flexural failure and prevent sudden FRP rupture. However, even this approach produces an overall less ductile behaviour of FRP RC members as compared to steel RC members. This issue is even more problematic when designing optimized structural shapes, which lead – by definition – to slender and deformable structures.

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 can be tremendously sudden and dangerous when dealing with FRP shear reinforcement (Ascione et al. 2014; Matta et al. 2013; Razaqpur and Spadea 2015). Furthermore, the most up-to-date design codes do not provide specific guidance to analyse the shear strength of non-prismatic concrete members (Orr et al. 2014).

In order to develop a model that can efficiently predict the structural behaviour of complex 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 (ACI 440.1R 2015; CSA S6 2014; CSA S806 2012).

DESIGN PROCEDURE

The computational procedure followed, suitable for statically determinate structures, can be briefly outlined as below:

1. Setting static scheme, structural materials, geometric limitations, design standard, and capacity design requirements.
2. Finding the applied bending moments and shear stresses from the given loading.
3. Optimization for flexural strength is aimed to find the profile of the beam which satisfy the ultimate limit states of bending.
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 goes 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. As a result, 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 then carried out to find the best geometry and the minimal quantity of web reinforcement which satisfies the ultimate limit state for shear. The web reinforcement geometry is limited to shapes that can be obtained by fibre winding, hence they result in being a certain type of spirals. In this case the method is based on a sectional analysis.

The code is then 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 and automate the reinforcement construction.

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 consists 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. After several layers are wound, the component is cured and removed from the mandrel. This method of manufacturing provides a satisfactory control over fibre placement and uniformity of the material structure and it is generally used to produce continuous hollow shapes with constantly uniform 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 designed 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 both the winding and curing processes occur, the reinforcing bars are maintained in the curved configuration by the wound reinforcement (Figure 1).

Figure 1. FRP optimized reinforcement cage.

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. 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.

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

Two different study cases were taken in consideration:

1) The first set of beams (Set J) 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 T) 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 for the concrete is C30/37;
- The bottom and top reinforcement are respectively #3 Carbon and #3 Glass FRP Aslan bars produced by Hughes Brothers (Hughes Brothers 2011).

Table 1 shows a synopsis 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 Figures 2a and 2b.

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 J.3-3, and T.2-2 have the required shear strength (point 6) to fail in flexure. Beams J.0, T.0, J.3 and T.3 are designed to exhibit a premature shear failure. In detail:

1) Beams J.0 and T.0, having no shear reinforcement, are designed to fail in shear, due to shear tension failure;
2) Beams J.2 and T.2, having two layers of wound transverse reinforcement, are designed to fail in shear, exhibiting wound reinforcement rupture.
3) Beams J.3-3, and T.2-2, having respectively 6 and 4 layers of wound reinforcement, are designed to fail in flexure due to concrete crushing. The wound reinforcement in beams J.3-3 and T.2-2 are arranged in two different patterns, composed by 3 and 2 layers, respectively.

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. Further details of the method of construction of similar beams can be found in Spadea et al. (2016).

Table 1. Details of the beams

	Set J	Set T
beam length (mm)	4100	4100
clear span (mm)	3000	3000
flange width (mm)	300	900
flange thickness (mm)	60	60
web minimum width (mm)	85	85
beam depth at midspan (mm)	265	190
beam depth at supports (mm)	180	150
beam depth at ends (mm)	95	110
top reinforcement at supports (mm)	2 × #3 GFRP	3 × #3 GFRP
bottom reinforcement at midspan (mm)	3 × #3 CFRP	4 × #3 CFRP
Concrete volume (m^3)	0.14	0.27
wound CFRP layers (#)	0 / 2 / 3+3	0 / 2 / 2+2

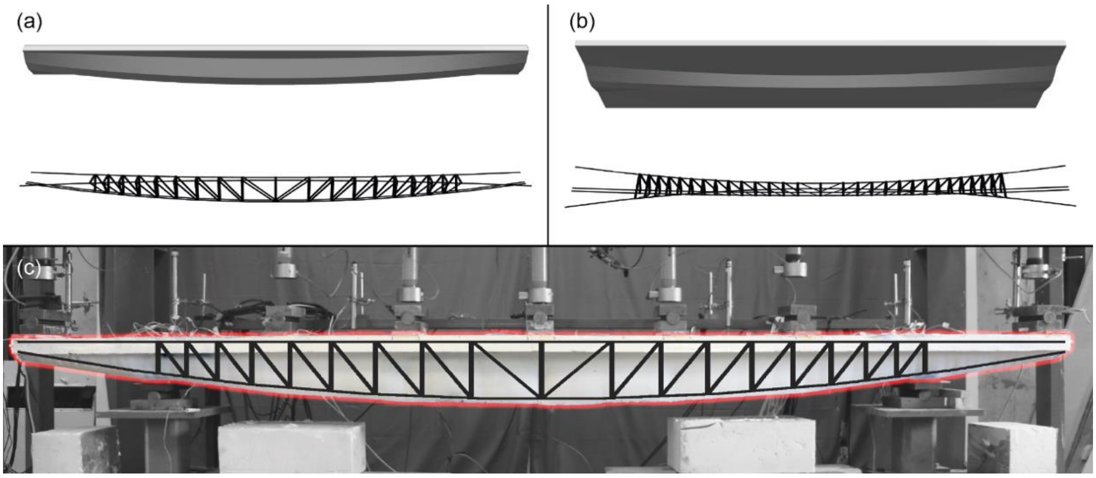


Figure 2. 3D visualization of the beams: a) Set J; b) Set T; c) test setup.

TEST ARRANGEMENT

The experimental setup (Figure 3) consisted of two simple supports and seven hydraulic jacks attached to a rigid frame, each one instrumented with a load cell. Five jacks were equally spaced on the 3000 mm beam span and powered by the same oil circuit, in order to apply the identical load *P*. The remaining two jacks were installed at the ends of the cantilevers (500 mm long), and powered by a separate different hydraulic circuit to apply a load equal to $0.5 \cdot P$. This loading scheme is designed to simulate a uniformly distributed load (UDL).

Seven displacement transducers were installed: one at the beam mid-span, two at the supports, two at the quarters span and two at the ends of the cantilevers. Five cross-sections of the beams were instrumented with uniaxial strain gauges installed on the reinforcing bars and on the concrete (highlighted on Figure 4) in order to monitor the flexural curvature of the beams. The wound reinforcing cages were instrumented with uniaxial strain gauges mounted on each leg included between the supports and the closer point load in the span (highlighted on Figure 4).

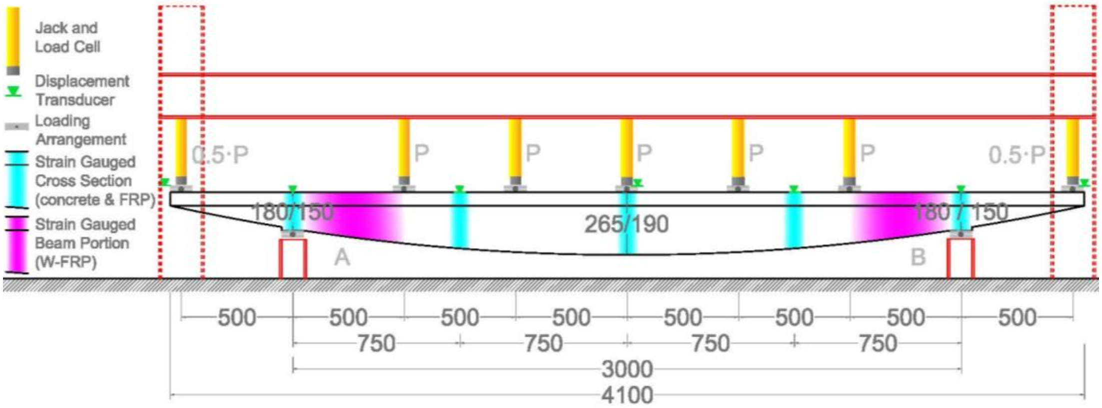


Figure 3. Experimental Setup.

RESULTS AND DISCUSSION

A synthesis of the experimental results obtained on each of the tested beams and the relative analytic predictions are reported in Table 2. In detail, f_c and f_{fb} are the average material strengths of concrete and shear reinforcement, respectively. Those values are employed to calculate the UDLs corresponding to flexural and shear failure, according to the provisions of CSA S806 (2012).

All specimens failed in the expected manner, and the results obtained were sufficiently consistent with the predictions. Only beam T.0 has showed an experimental capacity higher than expected.

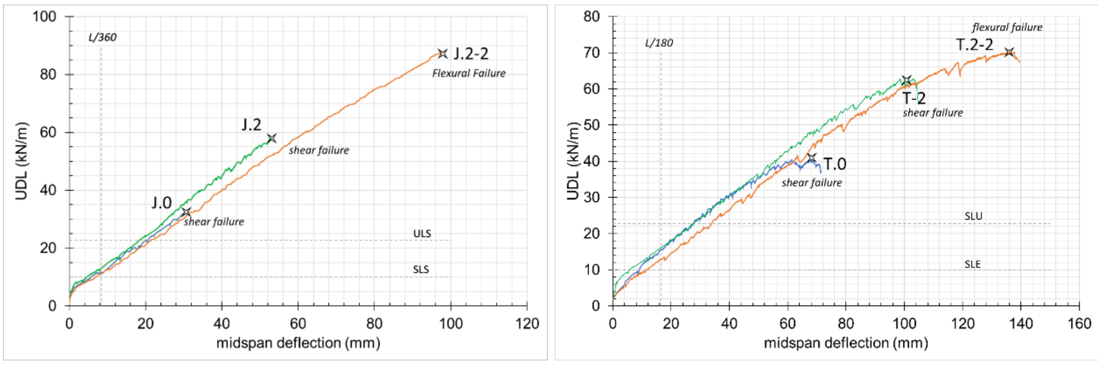
Table 2. Materials strength, Predicted Failure and Experimental Failure.

specimen	Materials strengths		Predicted UDLs at Failure		Experimental Failure			Predicted to Experimental UDL ratio
	f_c	f_{fb}	Flexure	Shear	mode	location	UDL	
	MPa	MPa	kN/m	kN/m			kN/m	
J.0	30.9	-	69.0	29.4	Shear[1]	side B[4]	32.2	1.10
J.2	41.6	605	78.4	60.0	Shear[2]	side B[4]	57.8	1.02
J.3-3	30.1	584	68.1	103.9	Flexure[3]	mid-span	87.6	1.16
T.0	30.9	-	75.4	26.3	Shear[1]	side A[4]	40.2	1.53
T.2	41.6	605	85.4	59.7	Shear[2]	side B[4]	62.7	1.11
T.2-2	30.1	682	74.5	87.0	Flexure[3]	mid-span	71.6	0.96

[1]Shear Tension Failure; [2]Shear Tension Failure and W-FRP rupture; [3]Flexural failure due to concrete crushing; [4]See Figure 3.

The load/mid-span deflection diagrams obtained from all beams are reported in Figures 4a and 4b. The experimental curves describing the behaviour of T beams show a progressive reduction of the members' stiffness with increasing load, likely due to the local debonding of FRP longitudinal reinforcement and shear cracking in addition to softening of compressed concrete (Figure 4a). This phenomenon is less evident in beams pertaining to set J (Figure 4b).

The maximum strain observed at failure in each different material – concrete, FRP longitudinal reinforcement, and W-FRP shear reinforcement - are finally reported in Table 3. The values in bold are the ones supposed to correspond to the global failure of the member.



a) b)

Figure 4. Uniformly Distributed Load (UDL) vs. midspan deflection: a) Set J; b) Set T.

Table 3. Maximum strains observed at failure.

material	Concrete	Longitudinal Reinforcement	Shear Reinforcement	
location	mid-span %	mid-span %	side A[1] %	side B[1] %
J.0	-0.13	+0.53	-	-
J.2	-0.16	+0.96	+0.53	**+0.92**
J.3-3	**-0.35**	>1.21 (76%)[2]	+0.69	+0.79
T.0	-0.14	+0.53	-	-
T.2	-0.21	+1.39 (92%)[2]	+0.66	**+0.95**
T.2-2	**-0.37**	>1.16 (50%)[2]	+0.67	+0.64

[1]See Figure 3; [2]The values in brackets indicate the percentage of the failure load at which the maximum strain was measured, in case the gauges did not work up to failure.

CONCLUSION

The technical developments in this paper provide the basis for a novel alternative reinforcement technique to reinforce structures having complex geometries, which are difficult to reinforce with conventional steel. A new method of manufacturing CFRP shear reinforcement for optimized concrete beams by winding carbon fibres around a bundle of FRP reinforcing bars is described. The method is well suited to automation and mass production of entire reinforcing cages, ready to be installed on-site. Thanks to fabric formworks technology and the flexibility of the winding process, there are no technical limitation in the shapes that can be built.

The effectiveness of the reinforcing material is established by mean of flexural tests conducted on real scale optimized beams subject to a uniformly distributed load. The results of those tests support the following conclusions:

- The W-FRP, if used in requested quantity and in the appropriate geometry, is able to prevent shear failure of such members;
- The existing FRP provisions can be conveniently used to predict the behaviour of FRP optimized beams, through a section-by-section analysis

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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/10.15125/12345.

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