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Concrete Plant International
Worldwide English Edition

October 2017 | 5

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Filament winding fabrication of FRP reinforcement cages

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This project has made progress towards the development of a novel alternative reinforcement technique for concrete structures with complex geometries, which are difficult to reinforce with conventional steel. Fibre-reinforced polymers (FRP) are woven into geometrically appropriate reinforcement cages to provide the required strength exactly where it is needed. Automated fabrication of the reinforcement utilises a modification of the filament winding technique. Being extremely lightweight, the resulting wound-FRP (W-FRP) cages are well suited to automation of the construction process, as they can be delivered ready for casting in optimized concrete elements. This is a key advance in research progress towards achieving minimum embodied energy, optimised, concrete structures. Experimental tests conducted on full-size W-FRP reinforced concrete beams demonstrate the reliability of the solution proposed, showing a new frontier for sustainable and durable reinforced concrete structures.

Flexible formworks use a system of flexible sheets of high strength, lightweight fabric to allow complex concrete shapes to be easily cast, thus facilitating the construction of optimised structures [1]. However, the need to assemble quite complex reinforcing cages together with the low durability of steel reinforcement in thin walled structures, are two reasons why large-scale deployment of this technology has not yet occurred. The use of FRP as internal reinforcement can help to overcome these kinds of issue since it can be accurately shaped during manufacture according to the final design demands.

Serviceability limit states, rather than ultimate limit states, normally govern the design of FRP reinforced structures, with the control of deflection being very often the most decisive check in the design process [2, 3]. Additionally, the lack of yielding of FRP reinforcement requires the design of over-reinforced sections to obtain concrete crushing flexural failure and prevent sudden FRP rupture. 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

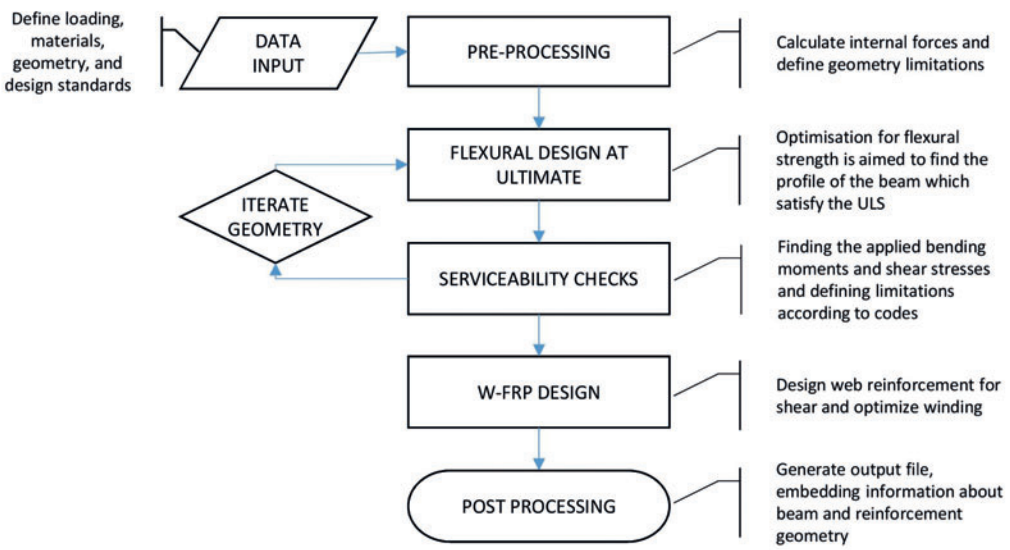

Fig. 1: Design Method

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and can be tremendously sudden and dangerous when dealing with FRP shear reinforcement [4-6]. Furthermore, the most up-to-date design codes do not provide specific guidance to analyse the shear strength of non-prismatic concrete members [7].

Design

To develop a model that can efficiently predict the structural behaviour of complex structural elements and consequently perform the structural optimization of flexibly-formed concrete beams reinforced with FRP, a method of analysis with broad applicability was developed. The geometry of the fabric formed member and the distribution of the reinforcement was modelled in a closed form allowing for variation in the section dimensions along the member length. The optimization parameters aim to obtain the minimal mass of concrete and observing the capacity design requirements as per the mostly recognized design codes [8, 9].

The computational procedure followed, suitable for statically determinate structures is briefly outlined in Fig. 1. Additional details of the design method can be found in [10].

The code produces a '.stl' output file of the designed beam, which details all the information pertaining to the geometry of the structural elements and is utilised in the automation of reinforcement construction.

Manufacturing

Computer controlled winding of impregnated carbon fibres around a set of FRP bars provides the opportunity to obtain durable, lightweight, and ready-to-use reinforcement cages. The manufacturing of web reinforcement is operated by means of a process based on the filament winding fabrication technique, which consists on wrapping continuous fibres under tension over a rotating mandrel. As the mandrel rotates, a carriage moves horizontally to lay down CFRP fibres in the designed pattern. After the required number of layers are wound, the reinforcement cage is cured and subsequently 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, curved CFRP bars responsible for providing the flexural strength to the concrete beams are attached to the mandrel according to the designed reinforcement geometry. The manufacturing system has sufficient control to allow the winding of any number of carbon tow layers in the form of spirals with variable cross section (Fig.2).

Fig. 2: Filament winding machine

Fig. 3: FRP optimized reinforcement cage

After both the winding and curing processes occur, the reinforcing bars are maintained in the curved configuration by the cured wound reinforcement (Fig. 3). Details of the raw materials used can be found in [11].

Flexibly Formed Beams

With the aim of validating both the optimization procedure and the W-FRP reinforcement cage manufacturing method, eight FRP reinforced fabric formed beams were designed and tested. The adopted static scheme is a simply supported beam with a three- meter span and a half-meter overhang on each end, subject to a uniformly distributed load (see Fig. 4). The design dead load was 2.5 kN/m and design live load was 7.5 kN/m. The design concrete strength was C30/37. Longitudinal reinforcement was provided by GFRP bars in the top and CFRP bars in the bottom of the section.

Two different study cases were taken in consideration:
- The first set of beams (Set J – beams J.0, J.2, J.3-3, J.6) is intended to simulate a precast fabric formed joist supporting a lightweight floor (e.g. all-FRP or timber floor).
- The second set of beams (Set T – beams T.0, T.2, T.2-2, T.4) aims to reproduce the use of a precast fabric formed beam with an in-situ casting of a concrete floor. In the experiments performed, the beam and the slab elements were cast together for ease of construction.

A 3D visualization of the beam's topology, as generated by the design code, is also shown in Figures 5a and 5b. Each set is composed of four beams having identical concrete geometry and longitudinal reinforcement but different W-FRP shear reinforcement. Whereas they all satisfy the first three points of the above-mentioned computational procedure, only beams J.6, J.3-3, T.4, and T.2-2 have the required shear strength to fail in flexure.

The wound reinforcement in beams J.3-3 and T.2-2 is quantitatively similar to the one employed in beams J.6 and T.4, respectively. However, it is arranged in two shifted patterns, aiming at increasing the wound reinforcement diffusion and ideally increase the overall efficiency of the cage.

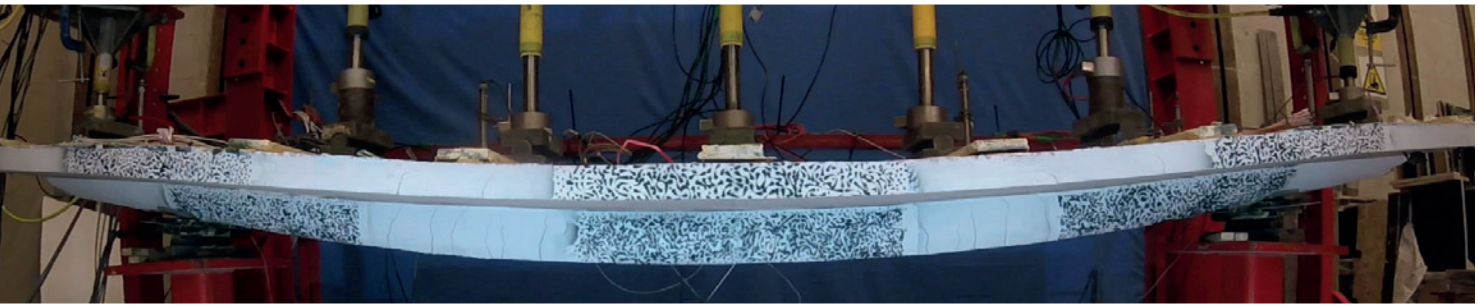

Fig. 4: Experimental setup

Figure 6 illustrates the T.2-2 beam reinforcement. The first pattern (highlighted in red) is composed by 2 layers arranged in the same geometrical configuration employed in beam T-2 (2 layers) and beam T-4 (4 layers). The second pattern (highlighted in blue) is composed by 2 additional layers, having the effect of halving the shear reinforcing spacing tough maintaining the shear reinforcement ratio employed in beam T-4. Similar criteria were used to design the reinforcement employed in beam J.3-3.

Table 1: Details of the beams

description	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 / 6 / 3+3	0 / 2 / 4 / 2+2
Specimen ID	J.0 / J.2 / J.6 / J.3-3	T.0 / T.2 / T.4 / T.2-2

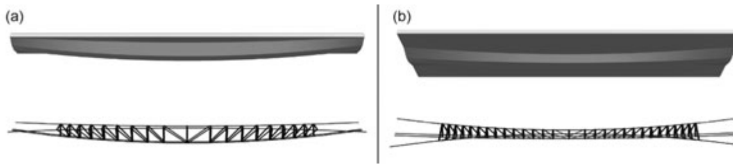

Fig. 5: 3D visualization of the beams: a) Set J; b) Set T

Fig. 6: 3D visualization of beam T.2-2: two shifted patterns are distinguished by red and blue colours

Fig. 7: Flexibly formed concrete beam.

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 web. Control of the beam elevation is achieved using a simple timber member (a "keel"), pre-cut to the desired elevation. Fig. 7 shows the intrados of a flexibly formed concrete beam.

Further details of the method of construction and results of the experimental tests can be found in [12].

Test Results

A synthesis of the experimental results obtained on each of the tested beams and the relative analytic predictions are reported in Table 2. Results obtained are sufficiently in agreement with the predictions. Only beam T.0 exhibited an experimental capacity significantly higher than predicted.

Final Remarks

A new method of manufacturing CFRP shear reinforcement for optimised concrete beams by winding carbon fibres around a bundle of FRP reinforcing bars was developed. The method is well suited to automation and mass production of entire reinforcing cages. Fabric formworks and flexibility of the winding process greatly reduces technical limitation on 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.

Table 2: Materials strength, predicted failure and experimental failure

specimen	Predicted UDLs at Failure		Experimental Failure		Predicted to Experimental
	Flexure kN/m	Shear kN/m	mode	UDL kN/m	UDL ratio
J.0	73.2	**25.1**	Shear[1]	33.3	1.33
J.2	83.4	**57.4**	Shear[2]	59.0	1.03
J.6	72.3	76.7	Flexure[3]	87.7	1.21
J.3-3	72.3	84.9	Flexure[3]	73.1	1.01
T.0	60.2	**18.1**	Shear[1]	41.3	2.28
T.2	68.7	**55.6**	Shear[2]	63.9	1.15
T.4	**59.4**	70.6	Flexure[3]	60.0	1.01
T.2-2	**59.4**	75.0	Flexure[3]	70.1	1.18

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

Future work will build on the success of this project to enhance the optimisation and analysis procedures and introduce pre- and post-tensioning and bespoke participating formwork.

Acknowledgments

This work was funded by the Engineering and Physical Sciences Research Council under grant EP/M01696X/1. The first author acknowledges the J. William Fulbright Foreign Scholarship Board for the opportunity of developing part of this research at the University of Miami. ■

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