**Fabric formwork for ultra high performance fibre reinforced concrete structures**

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**ABSTRACT**

Using fabric formwork, it is possible to cast architecturally interesting, optimised structures that use up to 40% less concrete than an equivalent strength prismatic section, offering potentially significant embodied energy savings in new concrete structures. Fabric formwork allows elegant designs to be realised but its use also presents some unique challenges, including the practical provision of transverse reinforcement in slender, non-prismatic beam elements. This paper details how these challenges have been overcome with the use of ultra-high performance fibre reinforced concrete. Methods for the design, optimisation and construction of such elements cast using fabric formwork are illustrated and structural tests data are presented.

**Key words:** Fabric formwork, material optimisation, UHPFRC.

**1 INTRODUCTION**

It can be recognised that a prismatic concrete beam with uniform transverse and longitudinal reinforcement supporting a uniformly distributed load is inherently inefficient, as its flexural and shear capacities are only fully utilised at the midspan and supports. By undertaking simple optimisation routines, structures whose flexural and shear capacities reflect the requirements of the loading envelope applied to them can be designed. However, the construction of such structures using conventional steel and timber formwork systems is difficult. Replacing these zero deflection moulds with a flexible membrane, fabric formwork provides a system that capitalises on the fluidity of wet concrete to take up almost any shape, thus facilitating the construction of non-prismatic, optimised, low embodied energy concrete structures.

**1.1 Fabric formwork**

Although fabrics have been used as concrete formwork since the early 1900s (Veenendaal et al., 2011) it was the availability of high strength, low cost fabric in the 1950s that precipitated its widespread use in the construction industry. Examples (Figure 1) have demonstrated the great potential of fabric formwork as a method for the construction of architectural concrete. A fundamentally simple construction technique, fabric formwork uses flat sheets of fabric to create unusual shapes, and in doing so facilitates the production of optimised concrete structures.

*Figure 1 – Concrete structures using fabric formwork (images courtesy Professor Mark West).*
In designing optimised concrete beams, it is often found (Orr et al., 2011) that the practicalities of construction (cover, transverse reinforcement and bar spacing requirements, for example) place a lower bound on feasible member sizes. Such considerations can result in elements that are larger than is ideally required to carry the design loads. The provision of concrete with high tensile strength (to resist shear failures), greater durability (to reduce cover distances) and better workability (to form thin, textured elements with complex geometries) could allow designers to realise highly optimised designs and the use of ultra-high performance fibre reinforced concrete (UHPFRC) has been identified as one potential solution. This paper reports on the use of the UHPFRC developed by Lafarge (Ductal®) in the design, construction and testing of two-metre span ‘Double-T’ beams cast in fabric formwork.

2 DESIGN
A two-metre span double-T beam with the cross section and internal reinforcement shown in Figure 2(left) was optimised for the loading envelope shown in Figure 2(right) using a sectional design approach which aimed to satisfy the bending and shear requirements of the beam at every point along its length.

Flexural analysis, using the plane section hypothesis, was undertaken using the steel reinforcement model of BS EN 1992-1-1 (2004) and the uniaxial concrete model for Ductal® illustrated in Figure 3(l), which is defined by three conditions: 1) The material is linear elastic up to 85% of its compressive strength (measured by compressive cube tests); 2) The material is assumed as rigid plastic in tension with a constant tensile strength of 10MPa, with this value applied up to a maximum tensile strain ($\varepsilon_t$) of 0.007 and 3) when $\varepsilon_t > 0.007$ the steel fibres are assumed to break and thus no longer provide tensile capacity to the section. By plotting moment-curvature relationships at each section the maximum flexural capacity was found to occur when the strain in the tensile reinforcement was equal to 0.0070, after which the steel fibres began to snap and the section capacity was reduced.

Shear design was undertaken following the method outlined by the AFGC (2002). The contributions of the concrete and its internal steel fibres were used to satisfy the entire shear requirements of the loading envelope. At every point along the length of the beam, the internal reinforcement depth and concrete layout was optimised to provide the required capacity while ensuring a ductile failure mode, with the resulting beam layout shown in Figure 3(r).

![Figure 2 – Typical cross section (left); Loading envelope for design (right).](image1)

![Figure 3 – Concrete model (l) after Graybeal (2006); Optimised beam design (r).](image2)
3 CONSTRUCTION
The construction of fabric formed beams is adaptable to most design requirements. Orr et al (2011) provide further discussion on construction methods. The beams described in this paper were constructed using a ‘keel mould’, as illustrated in Figure 4(left and centre), with the resulting element shown in Figure 4(right).

![Figure 4 – Double T construction using the ‘keel mould’ (left and centre); Demoulded element (right).](image)

4 TESTING
Two double T beams (Beams 1 and 2) were cast in the same mould using UHPFRC, and were tested in five point bending as shown in Figure 5(l). Both beams failed in flexure, as predicted by the design method. Results of both tests are provided in Figure 5(r), where good agreement with the design load envelope is seen although the two beams have some different characteristics.

![Figure 5 – Test set up (l); Load deflection results, Beams 1 and 2 (right).](image)

Beam 1 reached a peak load of 38.1kN. Post-peak, the load capacity reduced slowly during an increase in its mid-span deflection. This behaviour is explained by considering again Figure 3(l), from which it can be understood that as the steel fibres begin to snap, the section’s flexural capacity will decrease. Beam 1 exhibited a maximum mid-span deflection of 43.5mm before it was found to have failed by crushing in the top flange. Beam 2 reached a peak load of 33.2kN, slightly below the design load of 34.8kN. Post-peak, the load capacity of Beam 2 decreased more rapidly than that seen in Beam 1. Although some deformability was again seen, failure in Beam 2 occurred when the bottom reinforcing steel snapped at a maximum midspan deflection of 22mm.

This unusual failure mode was determined by an intrusive investigation after the test to have arisen from a construction error in the longitudinal steel arrangement, as a vertical spacing bar had been incorrectly welded to the longitudinal steel.
4.1 Beam response
Using the material model presented above a simple program was written to predict the load deflection behaviour of the double T beam cast using Ductal®. The program uses double integration of the curvature at each of 16 sections taken along the length of the beam to determine the midspan deflection during loading. The results are presented alongside the test data in Figure 5(r), where good agreement is seen. The post-peak phase presented the greatest difficulty and has a reduced degree of accuracy when compared to the elastic and cracked stages, but a general trend is seen in which the longitudinal steel fibres are seen to crack and the moment capacity of the section reduces under increasing curvature.

5 CONCLUSIONS
By combining fabric formwork with UHPFRC, new opportunities for the design of architecturally interesting, optimised concrete structures have arisen. Fabric formwork allows complex geometries to be quickly and economically cast, and the tests presented in this paper have demonstrated that simple design techniques may be used to achieve significant material savings, thus offering a new, sustainable construction method.

Furthermore, the tests have demonstrated the potential for using ultra-high performance fibre reinforced concrete without transverse reinforcement. In variable section beams, such an approach offers significant advantages in both the design and the construction process. The initial work undertaken in the preparation for this paper suggests that woven polyester or polyolefin fabrics are suitable for use as formwork for UHPFRC beams.

This paper has presented a simple method for the design of fabric formed UHPFRC beams in both flexure and shear. Whilst the behaviour of such elements in flexure has been verified by the tests described in this paper, more detailed tests and analysis are required to provide a method for the shear design of UHPFRC beams with a variable cross section, and this will form the subject of future research. In a continuing partnership, Lafarge and the University of Bath are currently looking at the use of Ductal® in long span precast fabric formed beams and fabric formed shell elements to achieve low carbon concrete construction.

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