Fibre reinforced polymer reinforcement for fabric formed concrete structures

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Every year approximately 2.8Gt of cement is produced worldwide, resulting in a global concrete usage approaching 1.5m^3 per person per year (USGS, 2008). Whilst the components of concrete are easily found and extracted, our most widely used man made material has a moderately high embodied energy (Hammond, 2008) and cement manufacture alone is estimated to account for 3% of global CO_2 emissions (WRI, 2005). This suggests that concrete should be cast in optimised, variable section structures that minimise material use and capitalise on the fluidity of concrete.

By following the compression and tension forces that arise from the loads applied to a structure, it is quite feasible to place material only where it is required. Such constructions not only minimise material use, but are also structurally efficient and aesthetically pleasing. The downside to such an approach comes during construction, where traditional formwork systems can be complex and uneconomical.

Fabric formwork may now provide a simple solution to these concerns. Developed initially for offshore and geotechnical engineering, where concrete filled fabric bags are used in underwater construction, fabric formwork uses sheets of fabric secured in predetermined locations using simple connections to create almost any shape, as illustrated in Figure 1. This innovative construction process gained architectural recognition in the late 1960s, precipitated by the availability of high strength, durable, low cost synthetic fabrics (Lamberton, 1989). Early work by Miguel Fisac led to innovative projects in Japan, America and Canada, where Professor Mark West now leads a dedicated fabric formwork research team at the University of Manitoba's Centre for Architectural Structures and Technology (CAST).

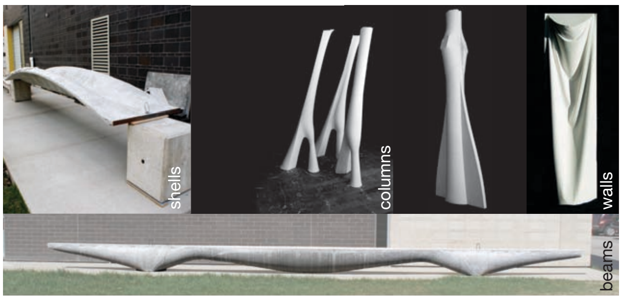

Figure 1 — Fabric formwork opportunities (courtesy CAST)

In addition to developing reliable methods to predict the shape of the fluid filled fabric membrane (Figure 2), research at the University of Bath is currently focused on the structural design and construction of fabric formed concrete elements, building on previous work in which it was demonstrated that beams cast in fabric can achieve material savings of up to 40% when compared to an equivalent strength prismatic section (Garbett, 2008). Structures formed using fabric can thus achieve significant reductions in their embodied energy.

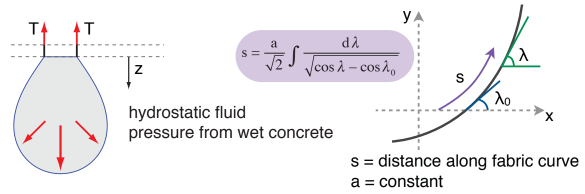

***Figure 2** — Shape predictions*

Casting concrete in a permeable fabric has two notable consequences. First, excess water is allowed to bleed from the mould, thereby reducing the water:cement ratio and providing a small increase in compressive strength. Secondly, surface density is greatly improved, as air bubbles no longer get trapped between wet concrete and a solid formwork system. The resulting high quality, expressive finish (Figure 3(r)) may sensibly be used as an exposed internal surface which does not require covering and provides significant exposed thermal mass for passive heating and cooling purposes. These interlinked advantages are highlighted in Figure 3(l).

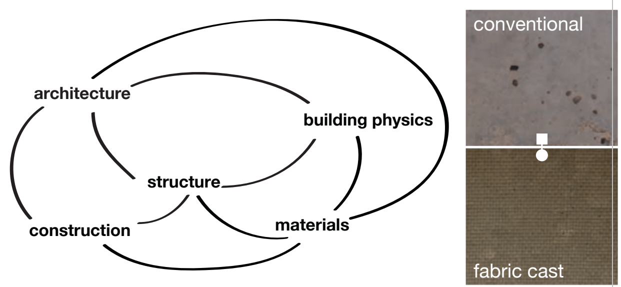

***Figure 3** – Advantages (left) and improvements in surface quality when using fabric formwork (right).*

Reinforcing fabric formed beams has previously been undertaken using single steel bars, with anchorage provided by a welded connection to an external steel plate (Garbett, 2008). However, the potential for brittle failures when using welded connections, combined with an increased risk of corrosion precludes this technique in many situations. Fibre reinforced polymer bars provide an obvious alternative, yet cannot be welded and thus also require a new anchorage method.

The splayed bar (Figure 4) delivers such an alternative, utilising wedging action to provide anchorage. Its efficacy has been shown in cube pull out tests, where order of magnitude increases in both load and displacement capacity were seen in comparisons between straight and splayed glass fibre reinforced polymer (GFRP) bars (Darby et al., 2007), as illustrated in Figure 4. The provision of aramid fibre helices around the splayed bar was shown to provide the greatest increase in pull out resistance by confining the concrete and delaying tensile splitting failure.

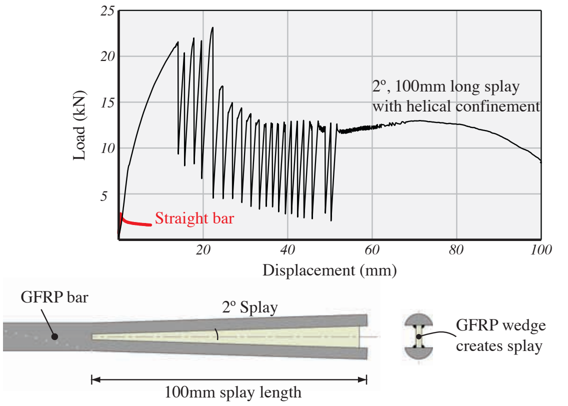

Figure 4 *— Splayed bar behaviour (after Darby et al., 2007).*

Further tests on carbon fibre reinforced polymer (CFRP) reinforced two metre span fabric formed beams have verified that the splayed bar method can provide full anchorage for both advanced composite and steel reinforcement (Chawla, 2010).

Further reductions in the embodied energy of concrete can be obtained through the use of super-sulphated cements in lieu of ordinary Portland cements. However, the low alkalinity of such mixtures ensures that the protection afforded to steel reinforcement in ordinary concrete is lost and corrosion occurs rapidly, precipitated by the presence of air and moisture within the concrete. Using FRP bars as reinforcement neatly bypasses these concerns and by combining composite reinforcement with low carbon cements, cast in fabric formwork, it is now possible to create low embodied energy optimised concrete structures.

The provision of ductility in FRP reinforced concrete structures is a primary design concern, with an over reinforced section required to ensure failure occurs by crushing of the compression concrete. In addition, the bond between the reinforcement and its surrounding concrete must be carefully assessed, since too great a bond can result in local failures in the FRP bar after the section has cracked. By creating bending moment shaped beams using fabric formwork, uniform stresses in the longitudinal reinforcement result in a requirement only for end anchorage of the bar and concerns surrounding the concrete bond may therefore be avoided.

While advanced composite reinforcement holds many advantages for fabric formed concrete structures, high working strains in passive reinforcing bars can potentially result in poor behaviour at the serviceability limit state. By prestraining the reinforcement the full tensile capacity of the material can be utilised, which in turn increases the moment capacity of the section. By combining fabric formwork with prestressed advanced composite reinforcement, high strength, durable, architecturally interesting structures can be cast rapidly and economically. High performance, fibre reinforced concrete offers additional advantages for such structures, allowing greater levels of prestress and providing additional transverse reinforcement capacity to the section.

Fabric formwork may quite feasibly be used in the construction of uniform strength, long span concrete beams, in which the extreme fibres are at their limiting stress everywhere along the beam span. Combined with composite reinforced fabric formed shells, a new system for concrete structures is envisaged (Figure 5).

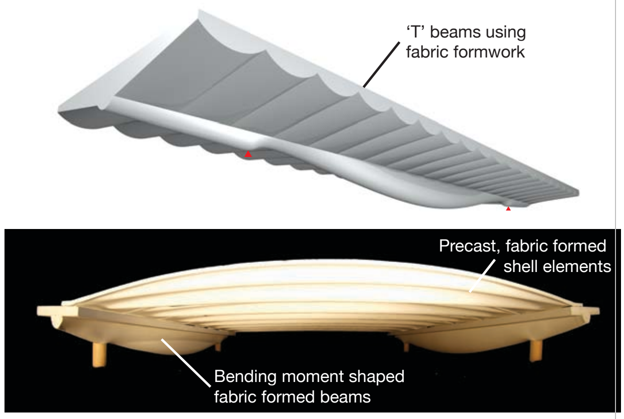

Figure 5 *— Long span fabric formed beams and shells.*

Although fabric formwork can be reused multiple times, future work may consider the use of fabric as permanent participating formwork. By three-dimensionally weaving carbon fibres and high strength, durable fabrics, it may be possible to prefabricate a flexible fabric 'cage' that not only supports the wet concrete during pouring but also provides the flexural and transverse reinforcement required by the element.

Fabric formwork provides a simple construction method that has the potential to significantly reduce material use. The design, optimisation and construction processes for these beautiful structures are well established and the use of FRP reinforcement offers new and exciting opportunities for the field of fabric formwork.

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