# Flexible formwork for visual concrete

John Orr, Antony Darby, Tim Ibell and Mark Evernden.

## Abstract

Replacing conventional concrete formwork with a system comprised of flexible fabric sheets, it is possible to cast architecturally interesting, structurally efficient and visually appealing concrete structures. This article reports on recent research in this expanding field.

## Introduction

Concrete is our most widely used man-made construction material, and the manufacture of its primary constituent part is estimated to account for up to 5% of global carbon dioxide emissions[(1)]. Legally binding carbon budgets and emissions reductions targets now mean that there is an increased emphasis on designers to place material only where it is required, and in doing so to help reduce the current impact that constructing the built environment has on our natural environment.

Once mixed, concrete has a unique fluidity that enables it to be cast into almost any shape, providing ample opportunity for designers to create optimised forms with greatly reduced material consumption. Yet this advantage is rarely capitalised on, with architects and engineers instead using rigid timber and steel moulds to create prismatic concrete structures with relatively little emphasis placed on their structural efficiency.

The ubiquitous use of such orthogonal moulds as formwork has resulted in a well-established vocabulary of forms for concrete structures, yet such rigid formwork systems must resist considerable fluid pressures, may consume significant amounts of material and can be expensive to construct. One simple alternative is to cast fluid concrete into a flexible fabric formwork whose layout is determined such that material is placed only where it is needed. Such an approach is described below.

### Fabric formwork

Using sheets of fabric draped between timber beams as formwork for a reinforced concrete slab, Gustav Lilienthal effectively initiated the use of fabric formwork in concrete construction in the late 1890s. Following closely from the work of Lilienthal, but having the distinction of being rather more prolific, James Waller used hessian fabrics in a patented method for the construction of structural elements that he named the *Nofrango* system. Similar patents used fabric as formwork for canals and in riverbed protection, while Waller later used sheets of hessian draped between temporary arched formwork to create thin, efficient corrugated shells in a construction system later named *Ctesiphon* after the Iraqi city of the same name (Figure 1).

Initial interest in the architectural possibilities of construction with fabric formwork can be attributed to the Spanish architect Miguel Fisac, whose work in this field culminated in patented methods for the construction of prefabricated fabric formed wall panels[(3)], as shown in Figure 2, facilitated by the new availability of high strength, low cost synthetic fabrics.

Since then, multiple design and construction methods for fabric formwork have evolved. In Japan, Kenzo Unno's 'zero-waste' system for casting fabric formed walls[(6)] has been successful, while in North America significant savings in both material and labour costs have been recorded as a result of using fabric formwork in the construction of columns and footings[(7)]. Additional and ongoing research, led by Professor Mark West at the University of Manitoba's Centre for Architectural Structures and Technology (CAST), has further considered the architectural possibilities of fabric formwork for beams and trusses, in addition to its use for shells, panels, columns and walls[(8)], Figure 3.

In the UK, research at the University of Edinburgh, the University of East London and the University of Bath has focused on both architectural forms and the structural behaviour of optimised, fabric cast elements[(9-11)]. By following structural optimisation routines, materially efficient elements whose form reflects the requirements of their loading envelope are quickly designed using simple computer programs. The variable section shapes that result are then cast in flexible

moulds to provide a cost-effective and rapid construction method. In following this process, it has been shown that fabric cast elements can provide overall material savings of up to 40% when compared to an equivalent strength prismatic sections, thus demonstrating how the technique may be used to facilitate a sustainable future for the concrete construction industry.

The provision of guidance for designers is a key aim of current research at the University of Bath, where the behaviour of variable section beams in both flexure and shear is currently under investigation. Research is also considering how additional savings in embodied carbon for optimised structures can be achieved through the use of low-carbon cement mixes, and how the design of optimised beam shapes can be adapted for use with ultra-high performance concrete mixes (such as Ductal®, provided by Lafarge) to create incredibly efficient forms – with preliminary work providing highly elegant solutions (Figure 5).

Fabric formwork has many advantages over and above its ability to create structurally optimised, low-material use, architecturally interesting forms. Low-cost synthetic fabrics are lightweight, easily transported and handled, and their strength can resist the fluid pressures generated in large elements. Once used, the formwork material is easily stripped from the concrete and release agents are not usually required. The fabric may then be cleaned and reused, although when appropriate its low cost makes it ideal for use as sacrificial formwork that can be recycled.

Additional advantages for the provision of highly visual concrete arise as a result of using a fabric mould. During the curing process, the permeable fabric mould allows excess pore water and air to be expelled from the formwork, resulting in a high quality surface finish free from blow-holes and surface defects. The concrete surface is further enhanced by its texture, which reflects that of the fabric used during construction (Figure 6), offering new opportunities for the provision of aesthetic concrete finishes.

In addition to the provision of new possibilities for concrete textures, fabric cast concrete offers improvements in concrete durability. Research at the University of Bath has shown that fabric cast concrete can provide up to 50% improvement in resistance to both carbonation and chloride ingress[13], with these effects being attributed to both a reduction in average pore size and an increased cement concentration in the surface zone.

For structures where the concrete grade specified is governed by durability rather than strength concerns, permeable formwork therefore offers opportunities for new embodied energy savings. For example, a C20 concrete mix cast in permeable formwork has been found to have a lower carbonation depth after 11 months than a C50 mix cast in conventional formwork[14], with such a reduction in concrete grade providing embodied energy savings of approximately 38% – in addition to those savings already achieved simply by using fabric formwork to cast a structurally optimised form. Long term cost savings for concrete cast in permeable moulds have also been reported[15] and arise primarily from a reduction in maintenance and repair requirements.

The high quality surface finish of concrete cast in fabric further encourages the use of exposed internal concrete surfaces, the consequence of which is two-fold: extraneous wall and ceiling coverings can be omitted and the now exposed thermal mass may properly be used in the provision of thermal comfort.

## Conclusions

Fabric formwork provides a novel method for the construction of architecturally interesting, structurally efficient and visually appealing concrete structures. In contrast to conventional formwork systems, which require moulds that do not deform under loading, fabric formwork embraces these deformations to its advantage to create columns, walls, beams, and shells using simple timber frames and flat sheets of untailored fabric. Tailored moulds, formed by cutting and stitching together multiple flat sheets of fabric, add a further dimension to the possibilities of fabric formwork.

By designing optimised concrete structures, significant savings in material use can be achieved, with concomitant reductions in both embodied carbon and construction cost. Fabric formwork not only provides a simple means by which such structures can be cast, but by allowing excess pore water to bleed from the surface of the concrete the resulting element is both durable and beautiful. Fabric formwork thus offers exciting opportunities for engineers and architects in the move towards a more sustainable construction industry.

Research at a number of institutions around the world is now focused on the advanced development of techniques using fabric formwork from architectural, structural and construction perspectives. Much of this state of the art research is due to be presented at the Second International Conference on Flexible Formwork (icff2012), which will be held at the University of Bath's Building Research Establishment Centre for Innovative Construction Materials from the 27$^{th}$-29$^{th}$

June 2012[16]. Alongside technical presentations, keynote presentations will be given by two of the main proponents of fabric formwork (Professor Mark West (University of Manitoba Centre for Architectural Structures and Technology) and Professor Remo Pedreschi (University of Edinburgh Department of Architecture)). In addition, a hands-on fabric formwork workshop led by Professor West will give delegates a unique opportunity to find out how this novel construction technique can help them to achieve sustainable design in concrete.

## References


1. WRI, *Carbon Dioxide Emissions by Source 2005*, Earthtrends Data Tables: Climate and Atmosphere, 2005
2. CONLON, C., *The Innovations and Influence of Irish Engineer James Hardress de Warenne Waller*, School of Architecture, Landscape and Civil Engineering, University College Dublin, MSc Thesis, 2011
3. VEENENDAAL, D., WEST, M. and BLOCK, P.: 'History and overview of fabric formwork: using fabrics for concrete casting', *Structural Concrete*, **12**(3), 2011, p.164-177
4. FISAC, M., *Centro de Rehabilitación para la Mutualidad del Papel, Prensa y Artes Gráficas*, Fundacion Miguel Fisac, 1969
5. ARNARDOTTIR, H. and MERINE, J. S. *House in La Moraleja (Madrid), by Miguel Fisac*. 2006 [cited 2012 18/03]; Available from: http://tinyurl.com/87xzxhx.
6. WEST, M., *Kenzo Unno, Fabric Formed Walls*, University of Manitoba, ND
7. FABFORMINDUSTRIES. *Fastfoot Commercial Edging Video*. 2010 [cited 2010 27/05]; Available from: http://www.fab-form.com/products/fastfoot/fastfoot_commercial_edging_video.html.
8. WEST, M., *C.A.S.T Construction*, University of Manitoba, 2007
9. ORR, J. J., DARBY, A. P., IBELL, T. J., EVERNDEN, M. C. and OTLET, M.: 'Concrete structures using fabric formwork', *The Structural Engineer*, **89**(8), 2011, p.20-26
10. LEE, D. S. H., *Study of construction methodology and structural behaviour of fabric formed form-efficient reinforced concrete beam*, School of Architecture and Landscape Architecture, The University of Edinburgh, PhD Thesis, 2010
11. CHANDLER, A. and PEDRESCHI, R., *Fabric Formwork*, RIBA, 2007
12. ORR, J. J., DARBY, A. P., IBELL, T. J. and EVERNDEN, M., Fabric formwork for ultra high performance fibre reinforced concrete structures. in *fib symposium: Concrete structures for Sustainable Community*. Stockholm, June 2012, 2012
13. ORR, J. J., DARBY, A. P., IBELL, T. J. and EVERNDEN, M., Durability enhancements using fabric formwork. in *fib symposium: Concrete structures for Sustainable Community*. Stockholm, June 2012, 2012
14. PRICE, W. F. and WIDDOWS, S. J.: 'The effect of permeable formwork on the surface properties of concrete', *Magazine of Concrete Research*, **43**(155), 1991, p.93-104
15. PALLET, P., *Introduction to the formworks scene*, in Concrete Magazine, (accessed 1994
16. ORR, J. J., EVERNDEN, M., DARBY, A. P. and IBELL, T. J., *Proceedings of the Second International Conference on Flexible Formwork (in press)*, University of Bath, 2012, *www.icff2012.co.uk*

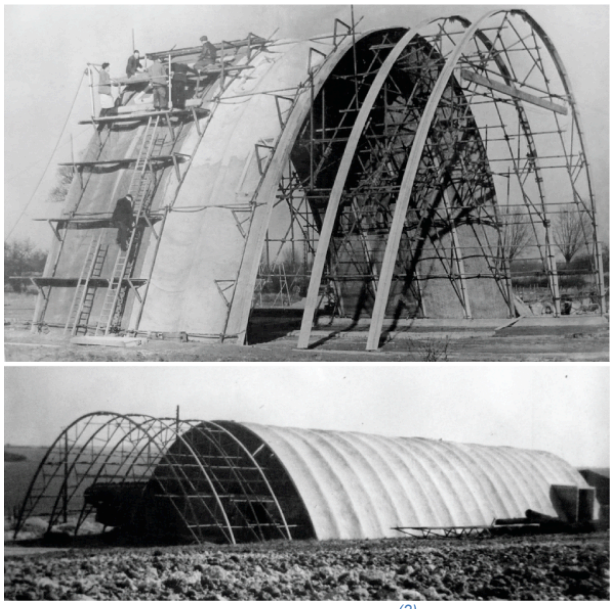

*Figure 1: A Ctesiphon roof in construction*[2]

*Figure 2: Fabric formed façades by Miguel Fisac. Left: MUPAG centre, Madrid*[4]*; Right: House in La Moraleja*[5]

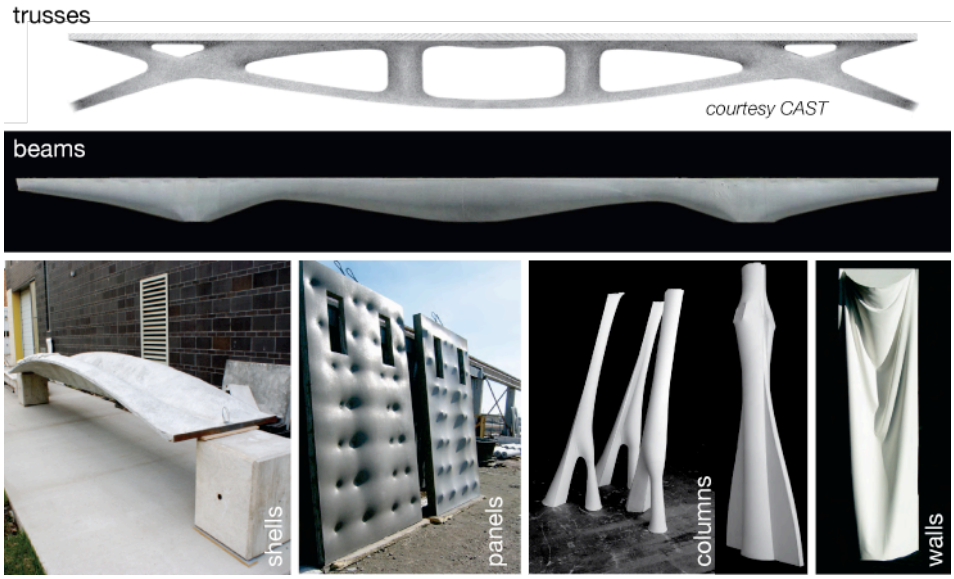


*Figure 3: Research by Mark West (CAST)*

*Figure 4: Structurally optimised T beams cast using flat sheets of fabric. Left: Orr et al.[9]; Right: Lee[10].*

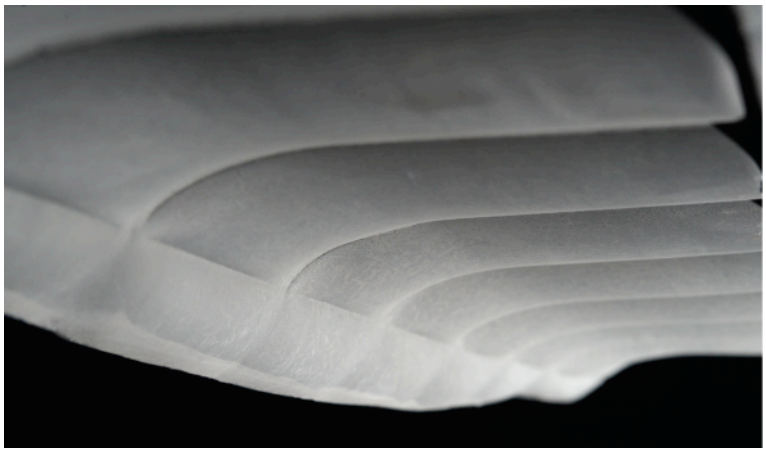

*Figure 5: Ultra-high performance concrete beams cast in fabric formwork[12].*

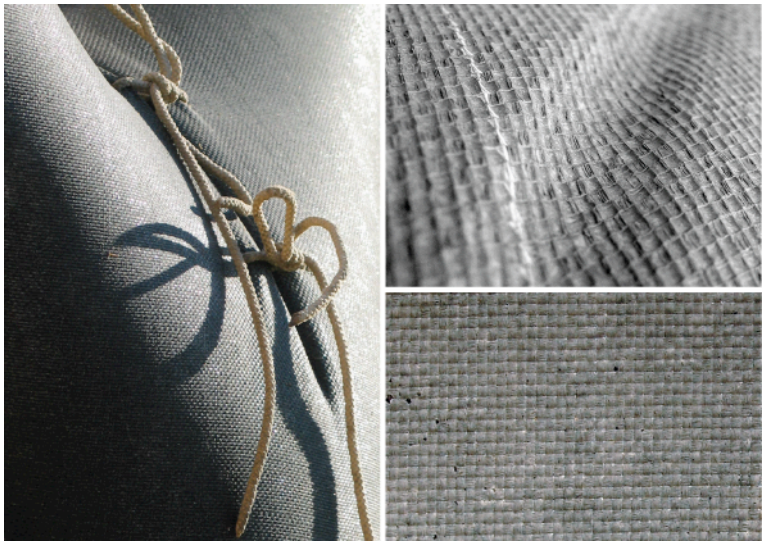

*Figure 6: Visual concrete finish using fabric formwork (images courtesy CAST)*