INTRODUCTION

The use of fabric formwork for concrete structures can be traced back to the early 1900s, and the methods involved mainly stem from work in offshore and geotechnical engineering. In 1922 it was proposed to use concrete filled fabric bags in the construction of underwater concrete structures but it was not until the late 1960s that any real headway was made in this field, precipitated by the new availability of low cost, high strength, durable synthetic fibres that allowed the forming of complex shapes (Lamberton, 1989). Initial interest in the architectural possibilities of fabric formwork can be attributed to the Spanish architect Miguel Fisac, who in 1969 completed the Centro de Rehabilitación para la Mutualidad del Papel (MUPAG) in Madrid. It was here that the first patented method for pre-fabricated fabric formed wall panels was developed.

Subsequent developments have occurred simultaneously yet independently of each other. Whilst both Kenzo Unno and Rick Fearn have developed successful systems and techniques for fabric formed structures, the most influential work has come from Mark West, founder of the Centre for Architectural Structures and Technology (CAST) at the University of Manitoba in Canada, which is the first research centre dedicated to the development and promulgation of fabric formwork for concrete structures. It is this architecturally led work that has formed the basis for previous research at the University of Bath.

This paper begins by considering the principles behind fabric formwork, before focusing on the current state of the art in design, optimisation and construction of fabric formed beams.

1.1 Traditional practice

Concrete has been primarily cast in orthogonal timber or steel moulds since the mid-1800s, resulting in the well established formwork practices that exist today. Rigid formwork systems tend to be simple to construct, but consume more material than an equivalent variable section member, increasing both cost and structural dead weight. Variable section members can feasibly be produced on an industrial scale, but their geometry remains governed by primarily prismatic forms.

1.2 Fabric formwork

Forming concrete in a flexible membrane (typically a high strength polyester fabric) provides a simple method for the construction of efficient, optimised and aesthetically pleasing concrete structures that offer several advantages for engineers.

The material required for a fabric formed structure is lightweight, cheap and ubiquitous – 12m span beams have been formed using under 10kg of fabric (West, 2007). Pouring concrete into a permeable fabric results in a filtering effect in which air and water are allowed to bleed from the structure, the effect of which is twofold. First, small increases in concrete compressive strength occur that are attributable to the reduction in water:cement ratio. More significant are the increases in surface density that occur as a result of there being very few air bubbles trapped between the formwork and concrete. Increases in surface density prevent in-service moisture and air ingress into the section, thereby slowing corrosion processes and potentially allowing for a reduction in cover to steel in fabric formed struc-
tues when compared to their conventional counterparts. The distance to which this ‘case hardening’ effect extends into the member is unclear at present.

Fabric formwork can be stitched into almost any configuration and the boundary conditions, including support locations and degree of pretensioning, can be altered to achieve the desired form. The construction of façade panels, columns, trusses, shells and beams has already been achieved, as illustrated in Figure 1. This paper will investigate the current state of the art in fabric formed beams.

![Fabric formwork](after West, 2007; Garbett, 2008)

**Figure 1. Fabric formwork (after West, 2007; Garbett, 2008)**

## 2 DESIGN

Design methods for fabric formed beams are currently in a state of flux. Work at CAST has previously taken an empirical approach, and many beams were not reinforced or structurally tested. The final shape of such a beam is determined by the material properties of the fabric and boundary conditions imposed during construction (§3).

The hydrostatic shape obtained from a given set of these boundary conditions can be accurately predicted using elastic theory, although dynamic relaxation has also been used to model the interaction between fabric and concrete (Veenendaal, 2008). In addition, Bailiss (2006) and Garbett (2008) used an empirical method to determine the area, perimeter and shape of fabric structures that was moderately successful.

The design of fabric structures has, up to now, been approached primarily from an architectural perspective. Structural verification is now required, and this has been the focus of previous work at the University of Bath. Garbett (2008) implemented a sectional analysis method, as outlined in Figure 2, to design singly reinforced beams that were unreinforced in shear to BS 8110-1 (1997).

![Sectional design method](

**Figure 2. Sectional design method.**

### 2.1 Optimisation

Optimisation can be considered as the process by which variables are used to determine the best option for a given set of parameters. Physical modelling techniques used in the past have now been all but replaced with numerical simulation methods such as evolutionary structural optimisation, solid isotropic material penalisation and sensitivity analysis that are described in detail elsewhere (Rozvany, 2008).
Structural and material optimisation is a key component of fabric formwork. Up to now bending moment shaped beams (Figure 1) have been optimised using the previously described sectional analysis method and material reductions of up to 50% have been obtained when compared to an equivalent rectangular beam. This is remarkable given the simplicity of both the design and construction of these beams and offers a real opportunity for material use reductions in entire building systems.

More complex approaches utilising evolutionary optimisation are currently being considered that offer two opportunities to further reduce material usage. First, through more accurate modelling of the hydrostatic shape and concrete-fabric interaction during pouring and second through improved analysis of the reinforced concrete section under loading to ensure that material is provided only where it is required. However, computational methods must always consider construction processes to ensure the optimised beam design can feasibly be built using fabric formwork.

3 CONSTRUCTION

Construction methods for fabric formed beams are continually improving. This section details four methods for the construction of variable section beams, three of which were developed by researchers at CAST (Veenendaal, 2008).

The spline method (Figure 4) uses a metal bar to vertically pretension a single rectangular sheet of fabric held on a timber forming table. Pretensioning the fabric reduces the volume of concrete in the tension zone, thus providing an optimised design. Beams constructed using this method have previously had a parabolic elevation, although the final layout is determined by varying the locations and magnitude of the applied pretension.

The keel mould (Figure 5) uses two sheets of fabric, held vertically and secured between sheets of plywood (the keel) that are cut to the desired beam elevation. The fabric is then draped over a forming table and pretensioned to both obtain the desired shape and to prevent wrinkling during construction.

The pinch mould (Figure 6) is used to create beams and trusses by sandwiching two sheets of fabric between a rigid timber mould. At designated locations protrusions from the timber mould ‘pinch’ the fabric to create openings in the web of the beam. The method allows the rapid construction of optimised beam elements, but constructing the formwork is more labour and material intensive than other methods. In addition, the structural behaviour of these beams is governed by Vierendeel action, which somewhat complicates their analysis.

The fourth method, developed by Bailiss (2006) and Garbett (2008) utilises solely the wet concrete weight to form the beam. By predicting the shape of the fluid filled fabric, fixing points along its perimeter are determined. The fabric is then hung between two supports before being filled with concrete to obtain the desired forms, some of which are illustrated in Figure 1.

3.1 Structural tests

A total of six 2m span singly reinforced beams, designed as described in §2, have been tested in five point bending at the University of Bath (Ibell et al., 2007). Of these, five were found to fail in shear close to the supports, although two tests failed to reach their design load due to incorrect positioning of the longitudinal reinforcement.

Fabrication of the beams was generally successful, and empirical methods were employed to predict the hydrostatic section shape. In general, elastic and plastic methods for the prediction of failure loads were accurate as was the prediction of load-deflection responses by double integration of curvatures along the length of each beam.

The testing highlighted two areas that require further work. The predominance of shear failures in
bending moment shaped beams was unexpected and highlights deficiencies in the current design procedure. In addition, anchorage methods for longitudinal reinforcement (Figure 3) leave steel bars exposed to corrosion and cannot be used if advanced composite reinforcement is to be used, an area of future development that is discussed below.

4 THE FUTURE

Fabric formed beams have, to date, been fairly similar in form, reinforcement and scale. Alternative designs incorporating some recent innovations in this field are presented in Figure 7.

Figure 7. Future design directions.

The addition of easily manufactured and installed shear reinforcement is key for the future of fabric formed beams. The use of Carbon Fibre Reinforced Polymer (CFRP) sheets, acting as reinforcement and permanent formwork, is currently being investigated at the University of Bath. The high tensile strength and durability of advanced composites also makes them a logical alternative to steel as longitudinal reinforcement, but introduces new design problems.

As welded end plates cannot be used for the anchorage of longitudinal FRP reinforcement, current research is investigating the use of an innovative wedging anchorage method for Carbon Fibre Reinforced Polymer (CFRP) bars. The concept has been proven in cube pull out tests (Darby et al., 2007) where order of magnitude increases in load and displacement capacity were seen and verification by beam tests is now required.

However, advanced composites have high working strains and are therefore inefficient when used in passively reinforced structures. Burgoyne (2001) argues that advanced composites are most effectively used in prestressed structures, where greater moment capacity can be obtained and the full tensile strength of the tendon utilised. Post tensioned fabric formed beams are an exciting prospect, and offer potential improvements in moment and shear capacity. By sewing ducts into the formwork, tendon positioning within the section can be ensured, and the use of unbonded advanced composite rope bypasses potential corrosion concerns.

4.1 Alternative areas

The field of fabric formwork is by no means limited to beams. Shells, working efficiently in membrane action, offer great advantages, but their design and construction is more complex than bending elements and they are rarely used in commercial building systems. However, the construction of shell structures using fabric formwork is well established at CAST, and work is being undertaken by the authors to investigate the potential for large scale uses of fabric formed shell structures that will bring further material and cost savings to concrete construction.

5 CONCLUSIONS

Fabric formed concrete beams offer significant advantages for designers, including material reductions, ease of construction and aesthetic appeal. The forms are predictable and the development of robust methods for their design and optimisation is well under way. New materials, including advanced composites, prestressed reinforcement and fibre reinforced concrete offer additional advantages for fabric formed beams that will be investigated in future work.

REFERENCES

ACI 318:2005. Building code requirements for structural concrete. ACI.