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Practice-based research, testing and application of fabric formwork to build reinforced concrete buildings in Cambodia

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Abstract

This paper follows practice-based research into fabric formwork, structural analysis and use in a 'real-life' project: a pair of two-storey buildings for a community centre in Cambodia (Bomnong L'Or), built in just eight weeks by a team of UK volunteers and a mix of skilled and unskilled local people. We present preparatory practice-based research and physical testing, structural modelling processes, falsework detailing and construction sequencing. Lessons learned from the construction process are presented and the benefits and challenges of using fabric formwork are discussed. Finally, we make recommendations for further work. We hope this paper demonstrates the potential of fabric formwork and encourages its use in commercial buildings. As demonstrated, the system also has benefits in a humanitarian context.

Keywords: fabric formwork, fabric formed reinforced concrete, practice-based research, humanitarian, building structure, construction

1. Introduction

There are a number of excellent historical reviews of fabric formwork, most notably by Veenendaal et al. [1] in 2011 and Hawkins et al. [2] in 2016. Therefore, we have set out a summary of the historical context.

There is evidence that fabric has been used by engineers for casting concrete since Roman times, although modern structural exploration began in the early 20th century; most significantly James Waller investigated its structural merits. It was in the 1960s that architects began to take an active interest in its possibilities, led by Miguel Fisac. However, recent computer modelling methods and material developments have increased the focus on material efficiency and led to a surge of structural research into fabric formwork, such as at the universities of Manitoba, Bath and ETH Zurich.

Fabric formwork has four principle advantages over traditional formwork: structural efficiency, new architectural possibilities, improved strength and durability, and simplified construction.

Structural efficiency: The forces within a continuous beam vary along its length, with peak moments at the supports and mid-span and peak shear at the supports. A prismatic beam, whose dimensions are determined by these peak values, will therefore have more material than necessary elsewhere along the beam. Not only does this mean that the beam will require more material than is strictly necessary, but this extra weight will accumulate down the building, requiring larger columns and foundations. Non-prismatic beams, where the section changes along the length of the beam, can therefore result in material savings throughout the building. These can be formed using curved rigid moulds, but they are expensive to make and only economic if the element occurs many times. Fabric formwork is a cost-effective alternative to using curved rigid moulds, as shown in Figure 1a.

Architectural expression: By liberating the designer from the straightjacket of traditional prismatic members, fabric formwork makes possible wholly new architectural forms – beams that visually express the forces inside: nipping in where the forces are low and swelling out where they are high; monolithic concrete trusses with soft curves; and columns that fork like branches of a tree. More than this, and contrary to traditional or moulded formwork, fabric formwork structures express the liquid state of concrete when it's cast, as the shape of the member is determined by the hydrostatic pressure of the wet concrete that deforms the fabric (see Figure 1b). Furthermore, the choice of fabric determines the surface texture of the concrete finish, creating new visual and tactile possibilities.

Figure 1a: Optimised fabric cast beam
[Prof. Mark West, CAST, University of Manitoba]

Figure 1b: Fabric formed retaining wall
[Studio Bark and University of East London]

Improved strength and durability: The permeability of fabrics has the effect of allowing excess water to escape from the wet concrete during pouring. This results in a reduced water:cement ratio at the surface which leads to improved concrete strength and durability, an outcome first noted by Karl Billner in 1936. More recently, this has been investigated in some depth by Orr et al. [3] in 2013, who observed that concrete cast in permeable formwork has a 50% reduction in carbonation depth and chloride diffusion coefficient, which may allow reduction in cover requirements or concrete grade for equivalent durability.

Construction: Traditional formwork requires skilled carpenters to build the formwork, even when reasonably simple. This must be done on site and 'just in time', therefore it cannot be removed from the critical path. In contrast, fabric formwork is prefabricated and can be made in a controlled and clean environment. On site, the fabric is hung on falsework frames that are simple and quick to assemble, deskilling the construction process. Rigid formwork moulds can be prefabricated too, but these are expensive to manufacture, transport and difficult to store, whereas the fabric formwork is cheaper to manufacture and can be folded up, making it simple and economic to transport and store.

However, there are obstacles to using fabric formwork. At the design stage, the structural performance of non-prismatic elements is more difficult to analyse and, perhaps more significantly, the final form of the flexible fabric and wet concrete during casting is not straightforward to predict. The construction can be straightforward and bending longitudinal steel reinforcement bars is relatively simple; however, manufacturing many different sizes of rigid steel links, to suit the varying non-prismatic section, can be expensive to manufacture and difficult to locate accurately on site.

To overcome this problem there has been work on flexible reinforcement using wound fibre reinforced polymer for concrete beams with optimised geometries by Yang et al. [4] and steel fibre reinforcement concrete in flexible fabric moulds using robotic manufacturing methods for the 'MARS Pavilion', an optimised geodesic dome by Culver et al. [5].

At StructureMode we were keen to use fabric formwork on a real-world structural building project, so we undertook in-house practice-based research and physical testing to allow us to predict the fabric formwork geometries using computer analysis and to design the resulting curved structural sections.

2. Preparatory practice-based research and physical testing

Fabric formwork is fundamentally different to traditional formwork, as it can only carry tension and so behaves non-linearly. Traditional formwork is essentially static so that the final form of the concrete is just the negative space bound by the formwork before the concrete is poured, whereas fabric formwork changes shape significantly due to hydrostatic pressure from the wet concrete. While traditional formwork can be left to a contractor, fabric formwork needs to be designed by the engineer, together with the element that it will be used to cast.

To allow us to predict the final form of fabric formed beams and columns, we investigated the behaviour and properties of a particular fabric, through physical testing and computational analysis.

The most common kind of fabric used is woven polypropylene, developed initially for geotextile applications. It's robust, does not tear readily, has a controlled permeability, consistent mechanical properties and is easily stripped from the hardened concrete surface. We used a single-layer polypropylene woven fabric, manufactured by Proserve Ltd (reference B37/F0899), which is commonly used for casting concrete underwater to repair piers, etc. The key properties we wanted to determine through our physical testing were the elastic moduli and Poisson's ratio. Other reasons for carrying out the physical tests were to validate our computational analysis, determine a suitable concrete mix design and investigate the general behaviour of the fabric when filled with wet concrete. Fundamentally, it also allowed us to gain experience, as we hoped to learn enough to use it for a real building.

We carried out two column casting tests, one with the warp aligned with the vertical axis and the other with it following the circumference – see Figure 2.

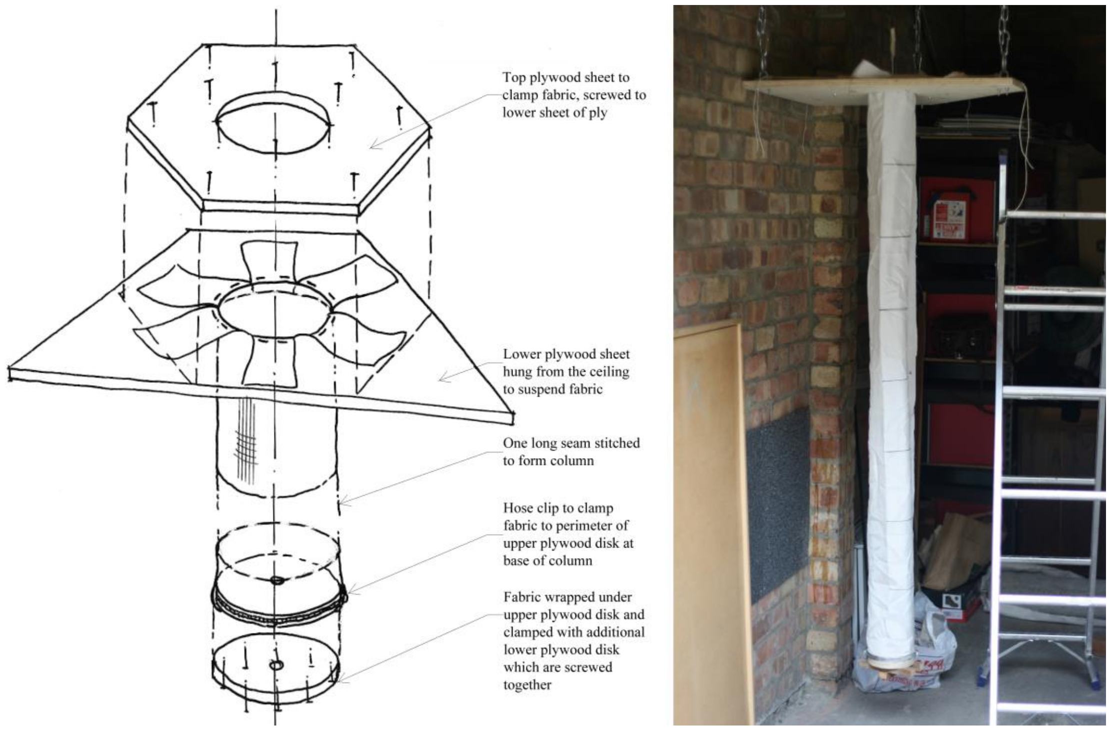

Figure 2: Column casting test diagram and the actual test assembly

The formwork was stitched into a precise cylinder of equal and known diameter along its full length, with one longitudinal seam, and hung from its top with lines (rings) marked on the fabric at 200mm vertical centres, so the vertical and circumferential strains could be measured accurately.

We cast two columns with different water:cement ratios, first with a w/c ratio of 0.50 and then 0.55. As some of the water leaks through the fabric it is generally advised to use a relatively wet mix, with a w/c ratio of 0.55–0.60. Our experiment corroborated this, as we found the 0.50 w/c mix to be difficult to compact, resulting in a poor finish to the concrete, as shown in Figure 3. During pouring, compaction and curing we collected the water that bled through the fabric, so we could calculate the final w/c ratio which was 0.36.

The first thing we noted was that Column 2 strained noticeably more than Column 1. This is because the concrete mix for the first column was too dry and did not flow properly. Therefore, we ignored the results from Column 1.

 

Figure 3: Column 1, w/c ratio = 0.50   Column 2, w/c ratio = 0.55

In Column 2 we did not pour concrete in the top 200mm, therefore the fabric in this area was subjected to vertical stress only, equal to the weight of all the concrete and fabric, etc. This allowed us to calculate the elastic modulus in the vertical direction using the following formula:

$$\varepsilon z(z=0) = \frac{\sigma z}{Ez}$$

$$Ez = \frac{\sigma z}{\varepsilon z} = \frac{W}{2\pi Rzf} \times \frac{1}{\varepsilon z} = \frac{60 \times 9.81}{0.045 \times 450}$$

$$Ez\ (\text{weft}) = 29\ \text{kN/m}$$

The fabric formwork for Column 2 had been fabricated with its weft (or fill) orientated in the vertical direction, therefore this is the elastic modulus of the fabric in the weft direction.

In our calculations, we assumed the vertical stress in the fabric was constant from top to bottom of the column, which is a reasonable assumption since the column was suspended by its top only and we ignore any vertical component of hydrostatic pressure on the nominally curved fabric surface and friction effects. Therefore, by measuring the vertical and hoop (circumferential) strains at each line marked on the fabric, we were able to measure the variation of strain in the warp and weft directions, where there was constant weft stress and variable warp stress, generated by hydrostatic pressure from the wet concrete which we could calculate at each line.

$$\varepsilon\theta(z=0) = -\frac{\sigma\theta}{E\theta}$$

$$\sigma\theta = \nu\sigma z$$

therefore

$$\varepsilon\theta(z=0) = -\frac{\nu\sigma z}{E\theta} = -\frac{\nu}{E\theta} \times \frac{W}{2\pi R_{f0}}$$

$$\varepsilon\theta(z=h) = \frac{1}{E\theta}[\sigma\theta - \nu\sigma z] = \frac{1}{E\theta}\left[\rho g z R_{fh} - \nu\frac{W}{2\pi R_{fh}}\right]$$

and

$$U_r = R_i \varepsilon\theta$$

therefore

$$U_r(z=0) = -\nu\frac{R_i}{E\theta}\frac{W}{2\pi R_{f0}} \quad \text{so} \quad E\theta = -\frac{\nu}{U_{r0}} \times \frac{R_i W}{2\pi R_{f0}} \quad [1]$$

$$U_r(z=h) = \frac{R_i}{E\theta}\left[\rho g z R_{fh} - \nu\frac{W}{2\pi R_{fh}}\right] \quad \text{so} \quad E\theta = \frac{R_i}{U_{rh}}\left[\rho g z R_{fh} - \nu\frac{W}{2\pi R_{fh}}\right] \quad [2]$$

equating and rearranging [1] and [2]

$$\nu \frac{W}{2\pi}\left[\frac{1}{U_{rh}R_{fh}} - \frac{1}{U_{rh}R_{fh}}\right] = \frac{\rho g z R_{fh}}{U_{rh}}$$

$$\nu \times 60 \times \left[\frac{1}{2.99 \times 490} - \frac{1}{-3.38 \times 450}\right] = \frac{2350 \times 10^{-9} \times 1408 \times 490}{2.99 \times 2\pi}$$

therefore

$$\nu \text{ (Poisson's ratio)} = 1.07$$

and from [1]

$$E_\theta \text{ (warp)} = 31 \text{ kN/m}$$

Table 1: Summary of fabric properties

Fabric property	**Values calculated from test results**	**Values specified by the manufacturer**	**Units**
Elastic modus – E_z (weft) vertical for Column 2	29	27	kN/m
Elastic modus – E_θ (warp) hoop for Column 2	31	30	kN/m
Shear modulus – G $G = \frac{0.5(E_{xx} + E_{yy})}{2(1 + 0.5(\nu_{xy} + \nu_{yx})}$	7.5	not available	kN/m
Poisson's ratio – ν	1.07	not available	

Using these physical characteristics, we were able to model and design the column fabric using a finite element model in OASYS GSA. This analysis used dynamic relaxation methods to model the behaviour of the fabric and wet concrete, by reiterating the calculations until geometric equilibrium was reached.

The strains and displacement of the fabric were almost identical to those measured in our Column 2 test. This was great news as it meant our fabric properties were accurate and our modelling of the fabric was reliable in predicting the effect of the concrete being poured inside the fabric, as defined by the elastic moduli and Poisson's ratio.

The vertical stress in our fabric analysis models varied by less than 10% from top to bottom. This indicates that the weight of the concrete was supported almost entirely through the base of the column, and only a small amount through friction and vertical components of hydrostatic pressure on the fabric over the column height.

Now we were confident that we could model fabric formwork accurately, and all StructureMode needed was a 'real' project on which to use our new skills.

3. Bomnong L'Or (Goodwill Centre) project, Cambodia

In December 2014, StructureMode were invited to design a new school in Cambodia with Orkidstudio, a UK-based humanitarian architecture charity which has since relocated to Nairobi, Kenya.

A key element of the brief was that the buildings should be economical and able to be built by a low-skilled workforce in just eight weeks. To reduce the construction time, we wanted to prefabricate as much of the structure as possible and simplify the site construction processes. The budget, monsoon floods, and proximity of the site to the coast, necessitated the use of reinforced concrete as the primary structural material. However, traditional cast-in-place concrete with trapezoidal plywood formwork was undesirable because it would require skilled labour on site, would take too long to construct, and would have used a lot of timber. Using timber was undesirable because sustainable supplies were not available, and therefore its use would have encouraged illegal deforestation. Prefabricated RC beams and columns were available locally, but it would have been expensive, access to the site was difficult, and it would have required mechanical lifting equipment that wasn't readily available – adding further cost.

StructureMode informed Orkidstudio about the research they had undertaken with regard to fabric formwork, and explained the system to them. It seemed to be a perfect match for the project, as it offered desirable benefits as follows: it completely avoided the use of large section timbers, it simplified the construction process on site, it allowed prefabrication of the fabric formwork which accelerated the site construction time, it deskilled the site construction process, and tailoring skills were readily available in the local area to prefabricate the formwork following our patterns.

So the course was set, leaving StructureMode with a number of challenges to overcome: how to design and detail the fabric formwork junctions between the beams and columns; how to analyse and design the non-prismatic structural elements for the final geometry dictated by the fabric; and how to design and detail the falsework system to hold up the fabric securely yet simply, so it could be erected quickly on site by unskilled labour using only small section timbers (branches pruned from nearby trees).

3.1. Concrete mix design and delivery

In our tests we found a w/c ratio of 0.55 was required to make the concrete flow and compact properly. However, the local ready-mix supplier had a plasticiser available, so we conducted some tests on site and found that a w/c ratio of 0.52 worked well, as follows in kg/m3:

Cement 350 : Sand 899 : Aggregate 1007 : Water 181 (plus 4.08 litres of plasticiser)

However, it quickly became apparent that the ready-mix trucks were unable to access the site, due to very narrow lanes and tight corners in the last 50 metres. To overcome this, we used a small flatbed lorry, offloaded the ready-mix concrete into buckets, and drove them the last stretch to site for pouring. This made us glad to have a plasticiser in the concrete mix, as it retarded curing slightly and made it ‘last’ longer in the buckets, waiting to be poured into the fabric formwork.

3.2. Falsework detailing and sequencing

The use of fabric formwork to cast reinforced concrete structures was completely new to us, and very little guidance was available for structural design, detailing or construction methods.

We worked largely in isolation, as we now realise many others have done in the history of fabric formwork, instead of building on the knowledge gained by others before us. This situation is lamented in papers by Veenendaal et al. [1] and Hawkins et al. [2]. However, we hope this paper will share our experience effectively and help accelerate the use of fabric formwork in future.

Due to limited time and resources on this project, we had to use the same fabric that we had tested, as we already knew its structural properties for modelling and design. Luckily, the manufacturer (Proserve Ltd) generously donated a sufficient amount of fabric to build both structures. However, we were unable to ship the fabric out to Cambodia, as our budget was too tight – the full construction cost being met by private philanthropic donors to Orkidstudio. Instead, we transported the fabric in small folded sections within the checked luggage of each Orkidstudio UK volunteer. However, because of weight restrictions, we could only transport sufficient fabric for one of the two buildings. This meant all the detailing had to be arranged in such a way that the fabric could be stripped off without damage, cleaned and reused. Initially this was a daunting prospect but looking back it was an exciting exploration into reuse and demonstrates further sustainability in the system of fabric formwork.

3.3. Column formwork and concrete pour

Starting with the columns, we had tubes of fabric with one longitudinal seam. However, this seam had to be detachable without damaging the fabric. Therefore, instead of sewing the seam we sandwiched the fabric between two small sections of timber, with folded seams to stop the edges pulling through and the timbers were bolted together to clamp the fabric. Removal was then a simple process of unbolting the timbers and unwrapping the fabric, which remained in perfect condition.

However, this meant that one edge of the column was forced to remain straight, and the fabric deformation was slightly asymmetric. However, the chosen fabric was sufficiently stiff that deformations were small, so this asymmetry was not significant. In any case, cover to the reinforcement was maintained throughout, as the timber sections were located appropriately over the column height.

The column fabric formwork was top hung, clamped by a section of plywood with a hole in it and supported by four timber branches. This plywood was reused for each column. As seen in the sequencing diagrams of Figure 4, the column timber falsework was erected first, the reinforcement was fixed, the fabric was hung and then the column concrete was poured.

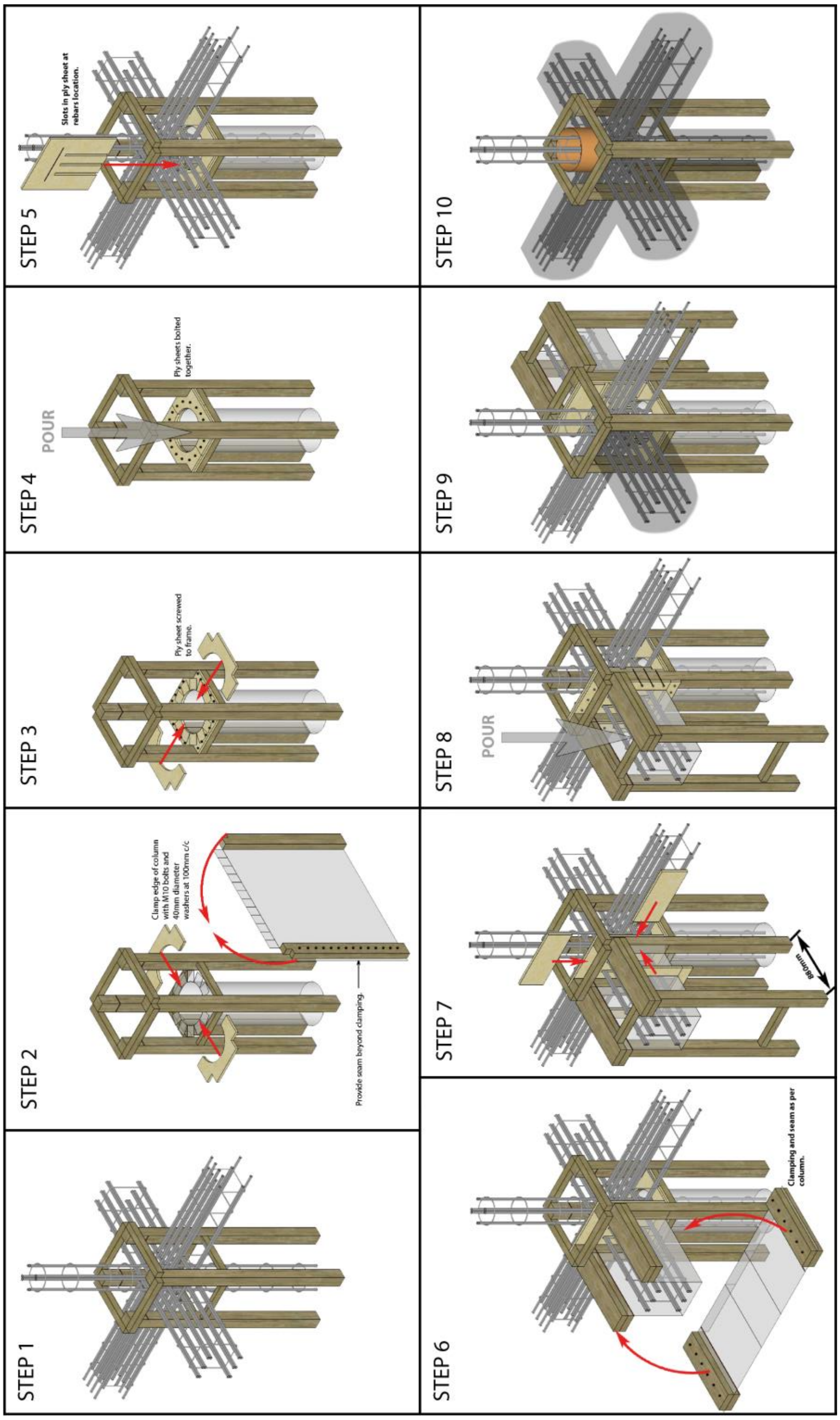

Figure 4: Falsework and construction sequence

However, there were problems on site when concrete was poured into the first 500mm of the column formwork, as the concrete tended to slump to one side or the other. The operatives had to push it back into shape manually, to ensure sufficient cover to the reinforcement was achieved. However, they found that once the pour rose above this height, the fabric became much stiffer and it maintained its correct alignment without assistance. A vibrating poker was used to compact the concrete.

During these first column pours the base of the fabric column formwork was free to move, which in theory should not be a problem, as gravity would tend to keep everything in line. However, during the first concrete pour there is no stress in the fabric, so it is very floppy and cannot resist any lateral momentum from the concrete being thrown into place. After more than 500mm of concrete has been poured, though, there are sufficient hoop stresses and vertical stresses in the fabric to keep it stiff, so that it can resist lateral forces without assistance. For the first-floor columns, we clamped the base of the fabric column formwork to help hold it in place during the first-stage pouring, which worked well – see Figure 5a.

3.4. Beam formwork and concrete pour

We would have loved to use curved reinforcement to create beams with variable cross-section along their length, which would have allowed us to optimise their structural utilisation and minimise the volume of concrete used. However, curved reinforcement was not available locally, and the cost of fabricating many links of different sizes, as well as the complexity of fixing them in the correct location, would have been prohibitive, so it was not possible on this project. Therefore, to minimise costs and keep construction as simple as possible, we decided to use straight reinforcement and continuous cross-section beams. This meant the reinforcement was simple and could be manufactured locally.

However, we still had to design and formfind the fabric to ensure it achieved the correct cover to reinforcement throughout the entire length of all elements and in order take full advantage of the cross-section that was being cast.

A significant challenge was deciding how to join four fabric formed beams together at the column junctions. This had to be simple and quick to construct, yet elegant. We decided the best way to achieve this would be to form a cuboid at the top of the column heads, into which the four beams would join – see Figure 5b and Figure 6a. This was easily achieved by using the falsework necessary to suspend the column fabric, which required four timber posts. We clamped the beam fabric to these posts on both sides, plus batten on its the bottom edge.

Our fabric analysis enabled us to predict the form that the fabric would take once the concrete was poured, taking account of the easily definable boundary conditions. We considered several sections along the length of the beam and overlaid the reinforcement cage to verify cover was adequate but not too much. We adjusted the amount of fabric in the fabric pattern along the length of the beam, to control cover and to minimise the volume of concrete.

As a safeguard, we specified spacers on the bottom longitudinal reinforcing bars, just in case the fabric formfinding was inaccurate. However, observations from site showed no evidence of the spacers pinching upon the fabric, therefore we are confident the spacers were unnecessary.

Figure 5a: Column clamped at base during first pour

Figure 5b: Column falsework to receive beams

Figure 6a: Fixing top of column fabric formwork   Figure 6b: Beam fabric ready to be clamped

3.5. Cantilever beam ends

The end of the cantilever beams presented us with a unique problem, as there was no column and therefore no cuboid into which the fabric would be clamped. Therefore, the fabric would bulge and the reinforcement cage would not have sufficient cover.

We decided to clamp the fabric into a sheet of plywood with an aperture cut in it – the same shape as the formfound beam fabric. This meant that if the formfinding was inaccurate, there would be creases in the beam around the end of the cantilever. Thankfully, as shown in Figure 7, there was no creasing, which is further evidence that the formfinding and plywood template were accurate.

Figure 7: Finished buildings

4. Lessons learned and challenges of using fabric formwork

When using Proserve fabric, the concrete mix may be as detailed above; however, different fabrics will require different mixes, as they may have varying porosity and flexibility.

Column pours require clamping plates, or alternatively semi-circular moulds, at their base. However, these should be removed before the pour proceeds above 600mm, to allow the column fabric to stretch naturally and avoid necking, creasing or other distortions in the column.

Accurate formfinding of fabric can be carried out, provided the fabric properties are known and the boundary conditions are controlled and representative of the actual conditions on site.

5. Benefits of using fabric formwork

With careful detailing, fabric formwork can be easily stripped off without damage and reused many times. Proserve advise that their fabric can be used up to six times without affecting the surface finish, and much more than that if the surface variation is not a concern.

Site construction is simple and fast, as demonstrated by the construction of these two, two-storey buildings in Cambodia in only eight weeks, using mostly unskilled volunteers and local contractors.

6. Areas for further work

The success of using fabric formwork for a building structure in Cambodia demonstrates the commercial viability of this technique. This project differs from most fabric formwork precedents in that the focus was on the cost, speed and simplicity of construction, not material efficiency or aesthetics. For this reason, the beams and columns were constant cross-section. The next step would be to use the knowledge gained from this project to create a building with structurally optimised members using traditional steel reinforcement. This would mean standard reinforced concrete codes could be used and there would be no problem gaining building regulations approval.

Following this, woven carbon-fibre reinforcement would be the next step. This method is fully justifiable from first principles but it may be challenging to convince local authorities. Fibre reinforcement would also be great but it may be more difficult to prove that the built structure satisfies code requirements.

A larger and fully optimised project would involve the analysis and design of many complex beam and column geometries. However, this process could be automated and accelerated by writing a Grasshopper script that uses Karamba to undertake analysis, formfinding and design for the structural elements. The script could also generate the necessary cutting patterns for fabric fabrication.

7. Conclusions

The advantages of using fabric formwork for casting concrete – new architectural possibilities, optimised structural designs, durability and ease of construction – have been well documented. However, the use of fabric formwork for commercial building projects is still rare. This project demonstrates the practical viability of using this system on a ‘real-life’ project with a low cost, and even in a humanitarian context.

One of the primary obstacles to using fabric formwork is the difficulty of predicting the behaviour of the fabric during casting. However, this was achieved successfully using a fabric formfinding analysis which facilitated generation of the necessary cutting patterns for manufacture.

The two buildings at Bomnong L’Or were built by a team of unskilled volunteers, together with some skilled local labour, in eight weeks. This clearly demonstrates how fabric formwork can simplify and accelerate construction, resulting in beautiful architectural forms and concrete finish.

Bomnong L’Or represents an important step towards the adoption of fabric formwork into mainstream construction, opening new design possibilities and reducing the environmental impact of construction.

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