FABRIC AS FLEXIBLE FORMWORK

Ankeeta Acharekar[1], Purnanand Savoikar[2]

1. PG Student, Goa College of Engineering, Farmagudi-Goa 403401
2. Professor, Goa college of Engineering, Farmagudi-Goa 403401

ABSTRACT. The most widely used construction material, concrete, has a fluid property that offers opportunity to create structures of almost any geometry. Yet this unique property is rarely utilised, with concrete being cast into prismatic shapes using rigid formwork leading to structures with high material use with large carbon footprints. Thus, by replacing conventional rigid formwork with flexible system comprising primarily of low cost, high strength fabric sheets, the fluidity of concrete can be utilised to create architecturally interesting and structurally optimised concrete structures. Flexible formwork therefore has the potential to facilitate the change in design and construction philosophy that will be required for a move towards more sustainable, and a materially efficient construction industry. Recognising the impact of construction on the environment, the need for design philosophies wherein the material is used only where it is required are becoming increasingly desirable. This can be achieved by replacing rigid formwork by flexible fabric sheets. This is a step towards change in the way we think about our future concrete structures. This paper gives an overview and background of fabric formwork, and a demonstration that by casting concrete using flexible fabric formworks, structurally optimised and architecturally interesting structures can be produced.

Keywords: Flexible formwork, Optimisation, Fabric sheets.

Miss Ankeeta M Acharekar is a PG Student, M.E. Structural Engineering at Goa College of Engineering, Farmagudi-Goa. Her research interest includes design of concrete structures using fabric formwork and its behaviour.

Dr Purnanand Savoikar is a Professor in Civil Engineering Department of Goa Engineering College, Goa. His research interest includes use of recycled plastic waste in concrete, use of supplementary cementitious materials in concrete and nano materials in concrete construction, steel structures and Geotechnical Earthquake Engineering. His joint research work on plastic waste in concrete with Bath University, UK has been awarded prestigious Atlas Award (April 2018) by Elsevier Science Direct Publishers.

INTRODUCTION

Although Concrete has low embodied energy, its extraordinary rate of consumption means that the manufacture of cement alone accounts for almost 5% of global CO_2 emissions; this suggests that concrete structures should be optimised. Concrete in particular has an unlimited potential to create structures of any shape. However, the economic constraints lie not with the material in its liquid form but in the materials and skills available to manufacture the formwork. Conventional formwork systems depend on flat, rigid materials such as timber or metals. These materials and their fabrication processes generally lead to simple, prismatic and orthogonal geometries. But Optimised structural geometries have complex cross-sections and are generally non-prismatic, thus expensive to construct using these conventional methods.

Moreover, rigid formwork systems have to resist considerable fluid pressures, which may consume large amounts of material and may be expensive to construct. In addition, the resulting member will require more material and will have a greater deadweight than one cast with a variable cross section. Some optimisation techniques may be undertaken to design a member with variable cross section in such a way that the flexural and transverse force capacity at any point on the element will reflect the requirements of the loading applied to it.

Fabric formwork technique provides a method in which these reductions can be achieved by facilitating production of members that have variable cross sections. This shows the potential of fabric formwork to reduce the embodied energy of new building structures. Fabric formwork does not only facilitate reductions in material use but the concrete formed in a permeable mould allows the air and water to escape from the formwork and thus provides a high quality surface finish that can be easily distinguished from a similar concrete cast in an impermeable mould. Thus, by casting concrete using a flexible fabric formwork, architecturally interesting and structurally optimised members that require less material and take the real advantage of the fluidity of concrete can be produced.

Due to rapid developments in concrete pumping technology and synthetic production, fabric formworks have become considered as a practical and economic alternative to the conventional formworks of Wood & Steel. The fabric forms are usually permeable sheets made up of synthetic fabrics, which when used in association with concrete, have the ability to hold, thus giving the concrete its final and required shape. Since synthetic fabrics are by-products of the petroleum industry, its use in concrete applications in petroleum countries can have a positive economical and environmental impact in addition to adding value to the concrete quality.

OVERVIEW OF RESERCH INTO FABRIC FORMWORK

Gustav Lilienthal initiated the use of fabric formwork in concrete construction. He invented a fabric-formed suspended floor, using sheets of impermeable fabric or paper draped between timber floorboards as formwork for a reinforced concrete floor slab. His idea, used in a number of projects in Germany, was patented in 1899 [1]. Following the work of Lilienthal and being more prolific James Waller used hessian fabrics in a patented method for the construction of structural elements which he named the “Nofrango” system. Similar patents used fabric as formwork in hydraulic structures including canals [2] and later he used sheets of hessian draped between temporary arched formwork to create thin, efficient, corrugated shells in a construction system later named ‘Ctesiphon’.

Further development of fabric formwork was found in the fields of offshore and geotechnical engineering. As early as 1922, Johann Store proposed the use of concrete filled fabric bags in the construction of underwater concrete structures and was a successful implementation of technology.

A patent application by Hillen described a method for the production of concrete ‘mattresses’, formed using layers of material joined at regular intervals and pumped full of concrete. Hilen’s method was successful in both Netherlands and the United states and was quickly refined into what is now known as ‘filter point’ mattressing [3]. Further innovations included systems for pile jacketing and vertical formwork. Filter point linings are widely used nowadays in offshore construction, primarily because they avoid uplift issues by allowing the water pressures to dissipate through the filter points.

Miguel Fisac was the first person who acknowledged the aesthetic and architectural possibilities of fabric formwork. He developed a form of construction to produce articulated cladding panels which were highly textured, by controlling the fabric deformations during casting.

Research at the University of Bath

The University of Bath has a history in research on fabric formwork. Initial studies were intended at finding empirical relationships for shape of fabric-formed beams cast using simply hung fabric [4][5] followed by an iterative numerical method developed based on theory of elasticity [6]. A number of fabric-formed double T-beams were designed and tested and the results showed that a material saving of up to 40% could be achieved [7]. The study also incorporated investigation on shear behaviour and suitable methods for shear design of tapered beams.

Research at the University of Edinburgh

Research at the University of Edinburgh was concerned with understanding the methodology encompassing both the architectural and structural applications of which two studies into complexity of form included: an over-lapping wave form and a highly complex perforated frame. The studies have also included various forms of shells. Other studies, focused on the design and behaviour of optimised structural components such as beams and columns developed the optimum geometry of a simply supported beam by an iterative process of repeated test and analysis of various shapes and cross-sections. The final geometry of the beam was a non-prismatic Tee–section of which the web varied in depth according to the bending moment and the flange varied in thickness according to the shear forces [8]. Although there was great complexity in the geometry, it was very simple to construct using a single sheet of textile and a flat sheet of plywood as a formwork. He found that the beam had a reduction of approximately 30% in the embodied energy compared to a structurally comparable beam using conventional formwork.

DESIGN METHODOLOGY FOR BEAMS

The design procedures for bending moment shaped beams as developed at University of Bath consist of sectional approach to satisfy the bending moment and shear force requirements of the beam at every point along its length as summarised in Figure 1. Final shape of the fabric formed beam after construction can be determined by a combination of fabric properties and its support conditions.

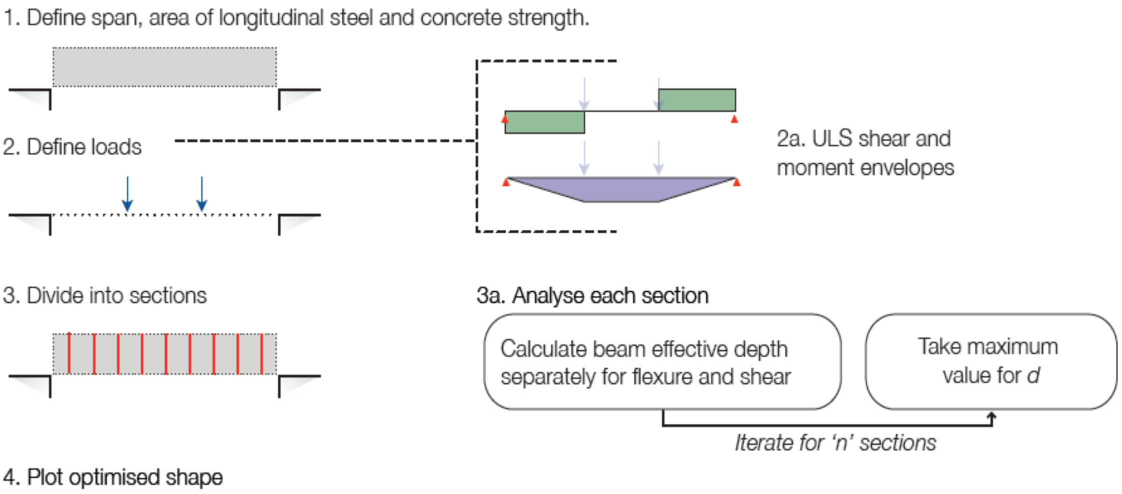

Figure 1 Sectional analysis technique for fabric formed elements [5].

Form finding

When concrete is poured in a hung fabric mould, it develops a hydrostatic shape. This hydrostatic shape Prediction of fluid filled fabric can be done in a number of ways. Empirical relationships determined by [5] provide a simple solution. Study carried out at university of Bath found equations to relate the top breadth, b, and the depth, d, of the hung shape to the required perimeter, P, of the fabric and the cross sectional area, A. By using various top breadths and different lengths of fabric for test sections the following empirical relationships were derived.

$$P = \frac{-(0.212b-d) \pm \sqrt{(0.212b-d)^2 - 4 \times 0.396 \times (-0.49b^2)}}{2 \times 0.396} \quad (1)$$

$$A = \left[\left(\frac{\left(\frac{b}{P}\right) - 0.05}{0.65} \right)^{-0.3} - 0.34 \right] \times (b \times d) \quad (2)$$

Cross section design

The beam should have sufficient capacity at every point along its length in both, flexure and shear for any given loading envelope. Calculations for flexural strength are undertaken using the plane section hypothesis, which is widely accepted as reliable and accurate design method. For reinforced concrete structures it is assumed that the longitudinal steel has yielded, thus the lever arm required to resist the applied moment can be easily determined as shown in Figure 2, which in turn defines the depth of section, as given by Eq. (3).

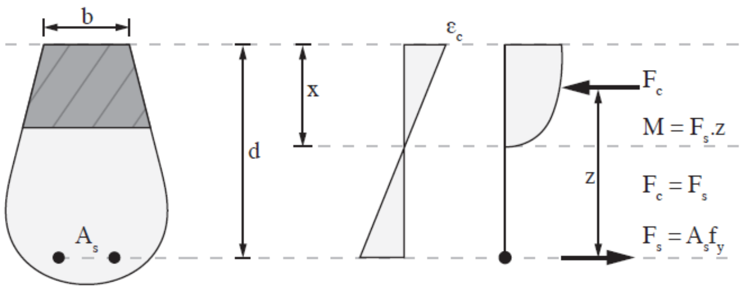

Figure 2 Flexural design basis

$$d = \left(\frac{0.45F_c}{0.67 f_{cu}(0.9b)}\right) + \left(\frac{M}{F_s}\right) + \left(\frac{\emptyset}{2}\right) + c \quad (3)$$

Where, F_c = force in the concrete compression block;

f_{cu} = concrete compression strength;

b = breadth;

M = moment;

F_s = force in steel;

ϕ = bar diameter, and

c = concrete cover.

This depth may further be increased depending upon the shear force requirements. The shear capacity of fabric formed beams is presently determined using BS 8110-1 [9]. Equation (4) gives the expression for determining the shear capacity of the section, resulting in the Eq. (5).

$$V = (bd)0.79\left(\frac{100A_s}{bd}\right)^{1/3}\left(\frac{400}{d}\right)^{0.25}\left(\frac{f_{cu}}{25}\right)^{1/3} \quad (4)$$

$$d' = \left(V/0.79b\left(\frac{100A_s}{b}\right)^{1/3}(400)^{0.25}\left(\frac{f_{cu}}{25}\right)^{1/3}\right)^{12/5} \quad (5)$$

where, b = breadth of section;

d' = effective depth of section;

A_s = Area of reinforcement;

f_{cu} = concrete compressive strength.

Thus, the Eq. (3) and (5) can directly be used to find the depth required at any point along the beam due to bending moment and shear force respectively.

DETAILED DESIGN

Design Example of a Beam

A detailed study of a simply supported beam of span 3m was carried out. The longitudinal tensile steel with two HYSD 12mm bars as bottom reinforcement and two HYSD 10mm bars as top reinforcement was assumed. Material properties assumed are given in Table 1. The beam was designed using sectional analysis method for a simplified loading envelope as summarised in Figures 3 consisting of uniformly distributed load so as to obtain a smooth curve for the beam profile. A dead load of 2.2 kN/m and a live load of 2kN/m were imposed. Initial standard beam with 150mm top width was assumed.

Table 1 Material Properties

VARIABLE	VALUE
Top steel	2T10
Bottom steel	2T12
Steel yield strength, f_y	500N/mm^2
Concrete strength, f_{cu}	30N/mm^2
Top breadth	150mm
Cover to steel	20mm

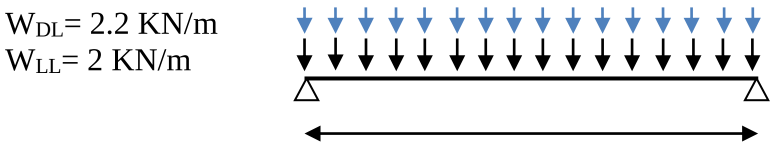

Figure 3 Layout and load summary of Beam

The analysis of this beam gave bending moment and shear force diagrams for the loading envelope as shown in Figure 4. The section depths required, to satisfy the flexural and shear requirements were calculated separately and are illustrated in Table 2.

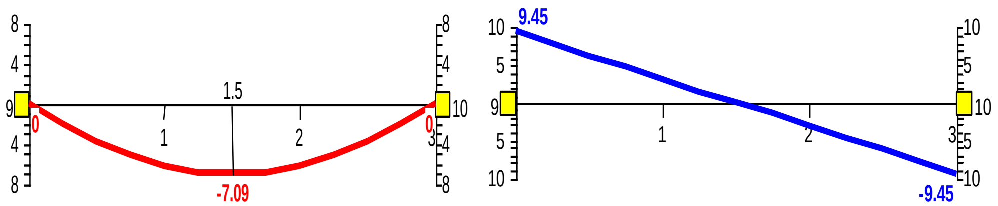

Figure 4 Moment and Shear envelopes

The final beam profile thus obtained was plotted in elevation in Figure 5. The depths of the beam when plotted resemble a curve similar to its bending moment diagram except at the supports where the depth is governed by shear force. Cover should be provided for outer layer of reinforcement in the direction perpendicular to the line of steel. The shape of the beam may be plotted in three dimensions using the section prediction techniques or by using advanced computational methods. This is done to ensure that reinforcement clashes do not occur. Visualisation of the beam can be done by creating a suitable scale plaster model by using a scaled fabric and timber mould to form accurate beam geometry.

Table 2 Required beam depth calculations

DISTANCE (m)	BENDING MOMENT (KNm)	SHEAR FORCE (KN)	DEPTH REQUIRED FOR FLEXURE (mm)	DEPTH REQUIRED FOR SHEAR (mm)	DEPTH PROVIDED (mm)
0.00	0.00	9.45	44.74	15.74	45.00
0.25	-2.17	7.88	63.94	10.18	64.00
0.50	-3.94	6.30	79.60	5.95	80.00
0.75	-5.32	4.73	91.82	3.00	92.00
1.00	-6.30	3.15	100.50	1.13	101.00
1.25	-6.89	1.58	105.71	0.22	106.00
1.50	-7.09	0.00	107.50	0.00	108.00
1.75	-6.89	-1.58	105.71	0.22	106.00
2.00	-6.30	-3.15	100.50	1.13	101.00
2.25	-5.32	-4.73	91.82	3.00	92.00
2.50	-3.94	-6.30	79.60	5.95	80.00
2.75	-2.17	-7.88	63.94	10.18	64.00
3.00	0.00	-9.45	44.74	15.74	45.00

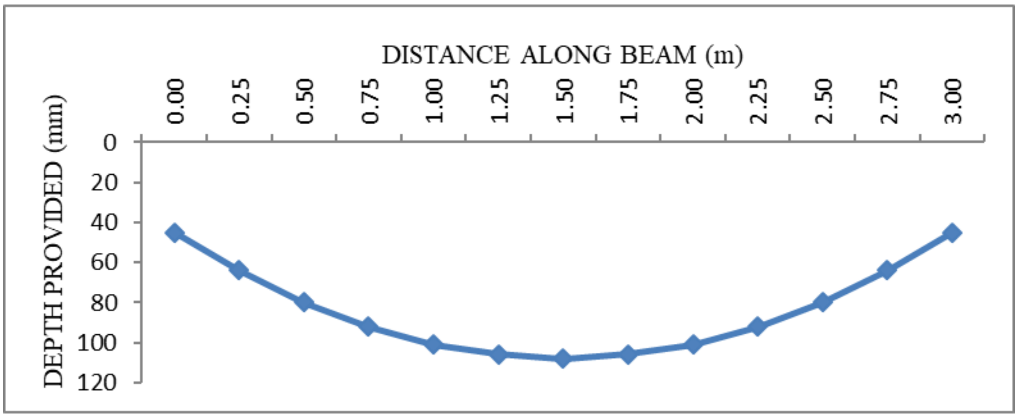

Figure 5 Beam profile obtained

Material use

The method described provides a beam design which uses material efficiently and is simple to construct. Additional savings can be made by introducing ‘pinch’ at the centre of beam profile. Concrete quantity of fabric formed beam designed with variable section is compared with its equivalent prismatic beam in Table 3. The volume of concrete in fabric formed beam is calculated using the equations provides by Bailiss (2006).

The fabric formed beam has significant savings in material compared to its equivalent prismatic section. The beam designed provided an overall saving of about 22% in concrete quantity, which is slightly less than that been achieved in previous works. However, more savings can be achieved by using advanced computational methods for form finding and calculating material quantity. The real advantage of fabric formwork can be made in prestressed sections, where the concrete's compressive capacity can be utilised efficiently.

Table 3 Material use comparison

VOLUME (m^3)		SAVING
VARIABLE SECTION BEAM	EQUIVALENT PRISMATIC BEAM SIZE (mm) 100 x 120	
0.0281	0.0360	21.89%

Fabric formwork not only provides a method for material saving, improvements in surface durability and quality, but also allows engineers and architects to understand their more unique designs.

COST ANALYSIS

Construction costs excluding labour and operational costs may be determined in terms of material costs. The modern importance on low carbon structures will have a new beginning in construction techniques which facilitate structures with low material use. Fabric formwork has the potential for development of concrete structures with any geometrical shape thus providing low impact on construction industry.

Table 4 Cost comparison of materials used

SR. No.	ITEM	QUANTITY	RATE	COST (Rs.)	TOTAL COST
1	*Conventionally cast prismatic beam*				
a	Timber	0.71 cft	600 per cft	426.00	
b	Concrete	0.036 m^3	6500 per m^3	234.00	
					660.00
2	*Flexibly formed variable section Beam*				
a	Fabric	4.38 m^2	35 per m^2	153.30	
b	Concrete	0.028 m^3	6500 per m^3	182.00	
					335.30
	TOTAL SAVING IN COST				49.20%

Construction techniques using flexible fabric sheets lead to a significant savings in materials and in turn reduce the construction cost. Comparison of cost of materials used in casting the variable section beam designed in this paper to its equivalent prismatic beam cast using conventional rigid formwork has been illustrated in Table 4. Comparison has been done only for the two main components i.e. concrete and the formwork used. The reinforcement component has not been taken into account as it is assumed to be same in both cases. However, for a beam with variable section transverse reinforcement required in the form of stirrups will be less due to variation in depth as compared to the prismatic section with constant depth. Providing stirrups for variable cross section might be a complex process thus increasing the cost of construction. Thus the savings achieved in steel quantity can be considered to be compromised with the difficulty in achieving it.

The results show significant savings of about 49% in costs of constructing simple single span beam. Thus applying this technique in lager building structures wherever possible can lead to large savings not only in materials but also in cost of constructing them. A large variety of fabrics can be used as a formwork, but for the purpose of cost analysis it is assumed that the beam is casted using woven geo textile. Also, it is assumed that the beam is cast using simply hung fabrics as it is easier to predict their shape and thus the keel moulds are not considered while estimating the cost.

CONCLUDING REMARKS

Design, optimisation and cost analysis presented in this paper has shown that optimised beams cast using flexible fabric formwork can be easily achieved with the methods provided. A summary of conclusions made throughout this paper is given below.

- Design and optimisation methods based on sectional approach considering flexural and shear behaviour offers a quick means for design of optimised concrete beams;
- Overall savings of about 22% in concrete was achieved in reinforced concrete beam by undertaking simple optimisation methods and using fabric sheets as formwork for construction process;
- Reduction in concrete material eventually leads to reduced embodied carbon, proving a step towards green, sustainable environment;
- Flexible fabrics that can be used as formworks are cheaper than the conventional formwork materials like timber and steel, thus the cost of construction using fabric formwork is considerably reduced due to inexpensive fabrics in addition to the savings in achieved in material use. Material cost savings of up to 49% compared to equivalent conventionally cast prismatic beams can be easily achieved.
- Fabric formwork being permeable, allows excess water and air to escape, leading to a void free, smooth pleasing surfaces, thus eliminating the need for external coverings which in turn helps in saving construction cost. If required various surface finishes can also be provided when fabric is used as formwork.

REFERENCES

1. LILIENTHAL L W G, Fireproof Ceiling. USA, United States Patent Office Number 619,769. (1899).
2. WALLER J H W, Methods of building with cementitious material applied to vegetable fabrics. USA, US Patent Number 1,955,716. (1934).

3. LAMBERTON B A, Fabric Forms for Concrete. Concrete International, December 1989, 59-67.

4. BAILISS J, Fabric-formed concrete beams: Design and analysis. MEng Thesis, University of Bath. 2006.

5. GARBETT J, Bone growth analogy for optimizing flexibly formed concrete beams. MEng Thesis, University of Bath, Department of Architecture and Civil Engineering. 2008.

6. FOSTER R, Form finding and analysis of fabric formed concrete beams. MEng Thesis, University of Bath, Department of Architecture and Civil Engineering. 2010.

7. ORR J J, Flexible formwork for Concrete structures. PhD Thesis, University of Bath, Department of Architecture and Civil Engineering. 2012

8. Lee S H, A Study of Construction Methodology and Structural Behaviour of Fabric-Formed Form-Efficient Reinforced Concrete Beams. PhD Thesis, University of Edinburgh. 2011.

9. BS 1880-1, Structural use of concrete – Part 1: Code of practice for design and construction, BSI, 1997.