Title: Flexible formwork technologies: A state of the art review

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Abstract

Concrete is our most widely used construction material. Worldwide consumption of cement, the strength-giving component of concrete, is estimated at 4.10 Gt per year, rising from 2.22 Gt just ten years ago [1]. This rate of consumption means that cement manufacture alone is estimated to account for 5.2 % of global carbon dioxide emissions [2].

Concrete offers the opportunity to economically create structures of almost any geometry. Yet its unique fluidity is seldom capitalised upon, with concrete instead being cast into rigid, flat moulds to create unoptimised geometries that result in high material use structures with large carbon footprints. This paper will explore flexible formwork construction technologies which embrace the fluidity of concrete to facilitate the practical construction of concrete structures with complex and efficient geometries.

This paper presents the current state of the art in flexible formwork technology, highlighting practical uses, research challenges and new opportunities.

Keywords: Fabric formwork, Flexible formwork, Disruptive Innovation, Optimisation, Construction.

1 Introduction

1.1 Overview

Concrete has been cast in rigid moulds since its invention in antiquity. The traditional use of rigid, flat formwork panels has thoroughly embedded uniform cross-section prismatic structural shapes into design codes and engineering and construction methods. As a result, simple uniform cross section shapes have become practically a forgone conclusion in concrete construction. Yet concrete is a plastic material that can assume any shape, and uniform section prismatic shapes are not always the most desirable, either in terms of aesthetics or in terms of structural and material efficiency.

Designers now have the ability to describe, analyse, and construct more complex and efficient shapes in concrete, challenging those conventional assumptions that previously restricted structural and architectural forms.

Fundamentally, using a flexible membrane in place of conventional rigid mould panels simply replaces one material in a formwork assembly with another. However, even when everything else – the formwork framing, the reinforcing, the concrete itself – remains exactly the same, the approach is fundamentally altered. Inviting flexibility into the casting process opens up new structural, architectural, and manufacturing possibilities through a physically simple means. This paper explores the past uses, current research and future prospects of this potentially transformative technology.

The use of flexible moulds is not new. Fabric moulds have been used successfully, and profitably, in a wide range of structures since the late 1800s. Relatively new synthetic fibre textiles and very new, rapidly evolving, digital modelling techniques have created a vast array of new possibilities and fuelled recent interest and innovation.

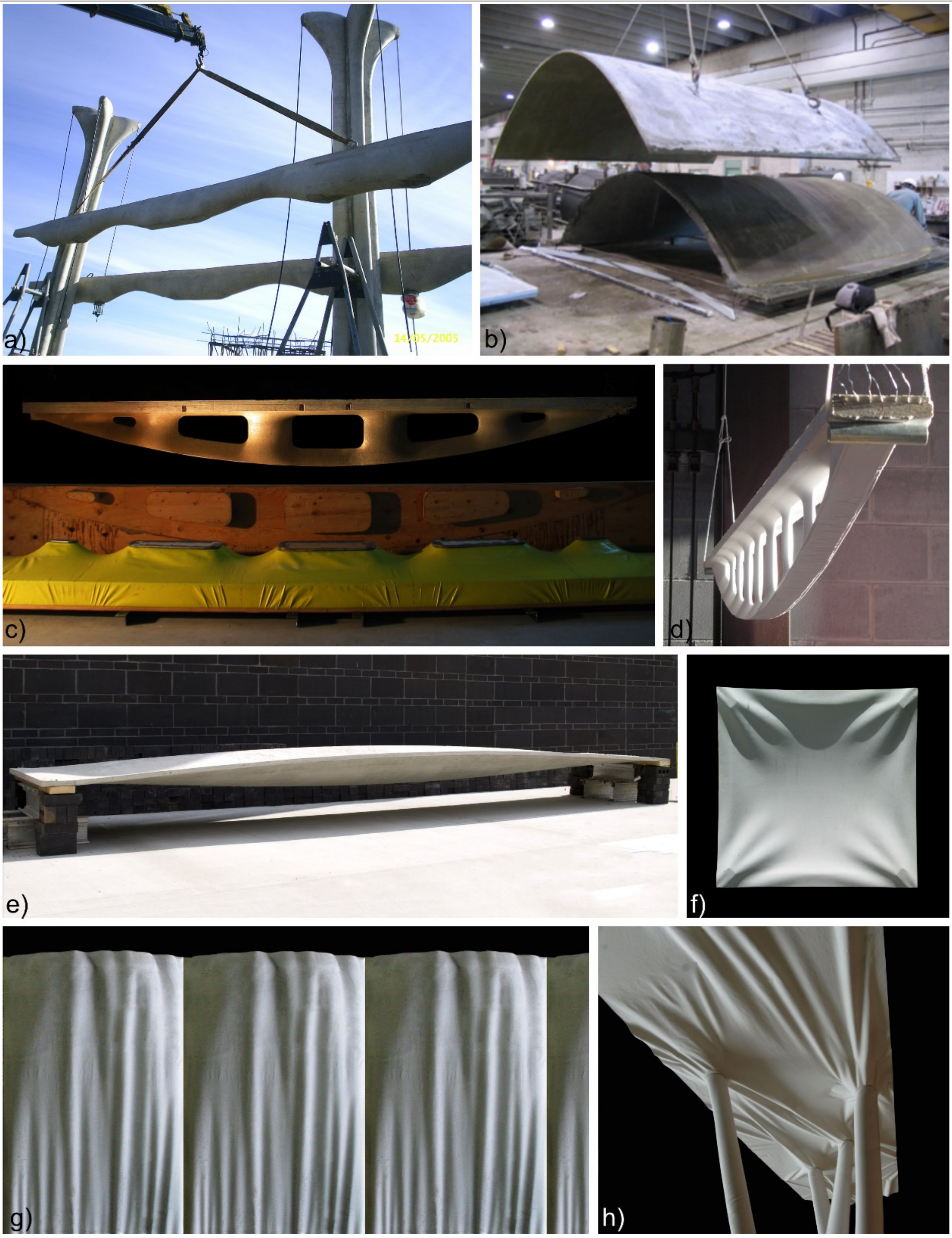

Figure 1 – Flexible formwork creates a multitude of new possibilities for structural forms in concrete. Photos: Mark West (C.A.S.T.)

Flexible moulds present new questions and complexities. In terms of structural design and performance, more complex, curved or funicular geometries create the potential to design more materially efficient structural forms. Structural design and analysis in this case may include three-dimensional structural analysis, rather than the traditional sectional methods that are native to both prismatic geometries and the slide rule. In terms of architectural design, there are new formal freedoms that come with flexible mould techniques. For construction, the questions are all about mould-making: the availability of complex CAD/CAM multi-axis routers that can produce complex, variable section rigid moulds may be weighed against the simplicity, and geometric limitations, of flexible sheet moulds. The use of non-rigid moulds also requires consideration of geometric prediction, control, and construction tolerance.

1.2 Energy efficient concrete construction

Climate change is a significant and growing threat to human prosperity and stability, as extreme weather events become more frequent and natural systems struggle to adapt to increasing average temperatures. Man-made greenhouse gas emissions are the primary cause of climate change, and must be reduced if these widespread and destructive effects are to be limited [3, 4]. In response, EU countries have agreed on a binding target of a 40% reduction of greenhouse gas emissions from 1990 levels by 2030, leading towards an 80% reduction by 2050 [5].

Concrete is the world's most widely used construction material. The principle source of embodied CO_2 in concrete comes from Portland cement, the production of which was estimated to account for 5.2% of global CO_2 emissions in 2014 [2]. In the past decade global cement production has increased from 2.22 Gt to 4.10 Gt, with the bulk of this increase occurring in China [1]. There are two approaches to reducing the associated emissions of concrete structures: 1) reducing the embodied CO_2 of the materials through improving manufacturing efficiency, reducing cement content or using alternative binders, or 2) by designing more efficient structures which use less material through optimisation of form, reinforcement layout and manufacturing process.

In even the simplest structures, the distribution of forces is predominantly non-uniform and the required strength is therefore similarly variable. The curved geometries created using a flexible mould present an opportunity not only for architectural expression but also for considerable material savings through elegant structural optimisation, by placing material where it is used most effectively. The amount of formwork material required is also minimised, further reducing the embodied energy of the structure.

2 Applications

This section details existing examples of flexibly formed concrete structures, introducing a wide range of commercial applications, novel construction techniques and experimental structures. Flexibly formed concrete has a history in architecture and structural engineering, across both academic research and industrial application. Veenendaal *et al.* [6] and Veenendaal [7] present comprehensive overviews of historical flexible formwork applications. The technique has seen a resurgence since the start of the 21st century, driven in part by the widespread availability of high strength fabrics and modern computational analysis techniques. This led to the founding of the International Society of Fabric Formwork (ISOFF) in 2008, who aims include fostering communication between researchers, contractors and manufacturers in both engineering and architecture, communicating the advantages to the wider public and to helping to develop innovative fabric forming solutions.

2.1 Typology

Two categories of flexible formwork emerge when the nature of the loading of the formwork is considered [6], filled moulds and surface moulds (Figure **2**). Tables 1 and 2 provide a reference for the flexibly formed structures featured in this paper for each of these categories respectively.

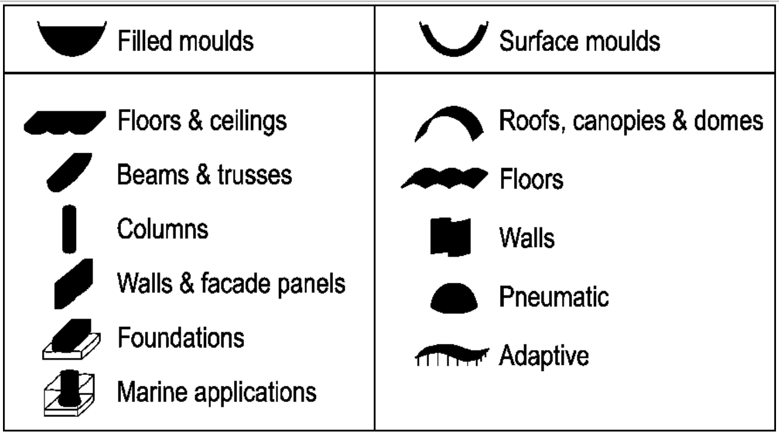

Figure **2** – Flexibly formed structure classification (adapted from Veenendaal *et al.* [6])

2.1.1 Filled moulds

Concrete cast in a filled mould exerts a hydrostatic pressure on the formwork. The flexible formwork assumes the geometry required to resist this load, which is dictated by both this fluid pressure and internal stresses of the formwork material. In this way the final shape of the cast can be controlled by prestressing the formwork or selecting the desired formwork stiffness characteristics (by setting the orientation of the warp and weft directions of a fabric mould, for example). Section 2.2 describes applications using filled flexible moulds.

Table 1 – Filled mould flexible formwork applications

	Year	Reference	Institution	Type	Description	Design Concept
Floors and slabs	1899	Lilienthal [8]	Terrast-Baugesellschaft	Application	In-situ floor slab cast on supporting beams	Variable section slab with steel mesh reinforcement
	2012	West and Araya [9]	C.A.S.T. University of Manitoba	Application	Hospital entrance canopy with fabric formed columns and roof	Column to slab connections strengthened with ribs from buckling of fabric
	2014	Lawton [10]	Arro Design	Architectural application	Cantilevered slab with undulating soffit created using fabric formwork	Variable depth allows stiffening and local strengthening
Beams and trusses	2006	West [11]	C.A.S.T. University of Manitoba	Architectural research	Trusses cast in plaster using the pinch-mould method	Structural depth following bending strength requirements
	2007	Ibell *et al.* [12]	University of Bath	Experimental research	Parametric study of cross sections using hanging moulds	Relationships formed amongst depth, perimeter and breadth of section
	2008	Garbett *et al.* [13]	University of Bath	Structural optimisation	Form-finding of beams to resist shear and bending	Sectional analysis procedure led to optimised beams of various shape
	2010	Foster [14]	University of Bath	Form-finding	Form-finding of beams under given loading conditions	Hydrostatic form-finding successfully developed for hanging moulds

	2011	Lee [15]	University of Edinburgh	Experimental research	Construction of 11 fabric formed beams with focus on material efficiency	Designed using British Standards and verified with finite element modelling and physical testing
	2012	Hashemian [16]	C.A.S.T. University of Manitoba	Experimental research	Structural behaviour and optimization of moment-shaped reinforced concrete beams	Beams optimised for bending strength, modelled using finite element analysis and tested
	2012	Orr [17]	University of Bath	Experimental research	Pinch mould simply supported variable section beams	Beam optimised for bending and shear strength, confirmed as accurate through structural testing
	2012	Kostova *et al.* [18]	University of Bath	Experimental research	Variable section fabric formed beams with FRP reinforcement	Three beams constructed and tested to ultimate load
	2012	Lawton and Miller-Johnson [19]	Arro Design/Engineering Ventures	Structural application	Reinforced concrete arch for outdoor pedestrian stair	Use of conventional reinforcement and uniform section
	2015	Morrow [20]	StructureMode	Application	Fabric formed concrete frame (columns and beams) for a school in Cambodia	Computational fabric form finding with standard strength design methods (prismatic sections)
	2016	Kostova [21]	University of Bath	Experimental research	Successful anchorage of reinforcing bars using wedging	Experimental verification that bars can be anchored using splayed anchorage
Columns	1934	Waller [22]	Ctesiphon Construction	Application	Circular, prismatic fabric-formed column	Similar outcome to conventional formwork with reduced material requirements
	2004	West [23]	C.A.S.T. University of Manitoba	Architectural research	Construction of fabric formed columns for private villa in Puerto Rico	Cylindrical RC columns designed using standard methods
	2008	Cauberg *et al.* [24]	WTCB, University Brussels, Centexbel	R&D project demo	Cast columns, surface structuring	Customisation of prefabricated formwork allows control of column shape
	2011 - present	Fab-form [25]	Fab-form Industries	Commercial application	‘Fast-tube’ formwork for circular columns	Similar design to standard column with savings in formwork weight and cost
	2012	Verwimp *et al.* [26]	Vrije Universiteit Brussel	Experimental research	Slender columns with permanent formwork as reinforcement	Fire resistance of TRC allows reduction of required section sizes
	2013	Pedreschi [27]	University of Edinburgh	Architectural research	Numerous non-prismatic column forms created using tailored fabric sheets with plywood clamps	Allows control and customisation of column geometry
	2014	Pedreschi and Lee [28]	University of Edinburgh	Experimental research	Investigation of strength of non-prismatic columns created using fabric formwork	Structural testing of convex and concave columns of equal volume
	2015	Milne *et al.* [29]	University of Edinburgh	Architectural research	Variable section columns with tailored fabric moulds	Physical prototyping to explore range of possible forms
	2016	Kostova [21]	University of Bath	Architectural research	Doubly-curved columns using stitched fabric	Physical testing to determine geometric possibilities
Walls and façade panels	1969 - 2006	Veenendaal *et al.* [6]	Independent (Miguel Fisac)	Architectural application	Fabric formed precast facade panels	Non-structural
	1995	Redjvani and Wheen [30]	Flexible Formwork, University of Sydney	Structural application	10m tall concrete wall using flexible formwork	Ties control wall thickness
	1997 - present	Umi Architectural Atelier [31]	Umi Architectural Atelier	Architectural application	Eight projects incorporating fabric formed walls	Ties within the formwork keep the wall thickness uniform
	2007 - present	Lawton [10]	Arro Design	Architectural application	Multiple small projects using walls constructed with fabric formwork	Fabric combined with a rigid frame
	2008	Pronk *et al.* [32]	Eindhoven University of Technology	Structural/Architectural application	Bone like structures in fabric formwork	Casting of bone structures, form of the mould is based on the elastic behaviour of the membranes
	2011	Chandler [33]	University of East	Application	30m long fabric formed retaining wall	Similar in form to a conventional retaining wall

			London/Studio Bark			
	2012	Jack [34]	Walter Jack Studio	Architectural application	40 metre long concrete wall with large corrugated texture	Sculptural form created using a rubber membrane formwork
	2012	West and Araya [9]	C.A.S.T. University of Manitoba/Byoung Soo Cho Architects	Architectural application	Fabric formed corrugated walls cast horizontally	Convex and concave curves formed using PVC pipes and hanging fabric
Foundations	2000s - present	Fab-form [25]	Fab-form Industries	Commercial application	'Fastfoot' strip footing simplifies formwork	Conventional reinforcement and similar in form to standard structures
Marine	1960s - present	Pilarczyk [35]	Various	Commercial application	Double layered mattress for ground applications	Filter points allow dissipation of groundwater pressures while protecting against erosion
	1980s - present	Hawkswood [36]	Various	Commercial application	Fabric pile jackets for marine applications	Commonly used for repair of existing piles
	1990s - present	Hawkswood and Alsop [37]	Various	Commercial application	Foundations to precast marine structures	Flexible form ensures full contact with bed

2.1.2 Surface moulds

Surface moulds are used predominantly to form shell structures. Usually only a single forming surface is required, onto which concrete is applied. If the surface is inclined, the concrete must be self-supporting in order to prevent flow. Geometry is again dictated by the relationship between applied forces and internal stresses in the formwork. When casting concrete shells, the formwork can hang under the weight of the concrete, be prestressed mechanically, supported by air pressure (in the case of pneumatic formwork) or actuators (in the case of an adaptive formwork). These applications are described in Section 2.3.

Table 2 - Surface mould flexible formwork applications

	Year	Reference	Institution	Type	Description	Design concept
Roofs and	1953	Waller and Aston [38]	Ctesiphon Construction	Application	'Ctesiphon' system of corrugated shell roofs for medium spans	Fabric suspended between a series of parallel catenary arches and acting as permanent reinforcement
	2007	Pronk *et al.* [39]	Eindhoven University of Technology	Experimental Structure	Sprayed concrete textile reinforced prototype shell structure	Experiments with an alternative construction method using fabric

						formwork for the 1958 Philips pavilion by Le Corbusier
	2010	Tysmans [40]	Vrije Universiteit Brussels	Experimental research	Textile reinforced doubly-curved shell structure	Demonstrated thin section possibilities using double curvature and TRC
	2012	Seracino *et al.* [41]	Belgian Building Research Institute	Experimental research	Doubly curved shotcrete shells with comparison between textile and steel reinforcement	Formwork modelled using the force density method. Finite element modelling of shell with corresponding physical tests
	2012	Adderley [42]	University at Buffalo	Architectural research	Double layered textile formwork filled with concrete and suspended. Each formwork layer is tied creating a structure of uniform thickness.	Hanging form creates catenary structure. Formwork material is bonded and acts as permanent reinforcement.
	2012	Belton [43]	University of Florida	Architectural research	Rigid, fabric and cable formwork system combined to create spiralling 'bow-tie' column	Finite element analysis used to calculate formwork stresses and performance in-use
	2013	Oldfield [44]	University of Bath	Acoustics research	Parabolic shells to focus sound for sculptural, hospital and restaurant uses	Hanging mould used to create parabolic shapes
	2014	Pedreschi and Lee [28]	University of Edinburgh	Experimental research	Catenary, hypar and domed concrete shells constructed using fabric formwork stretched from rigid frames	Inspired by work of Eladio Dieste and Felix Candela
	2014	Veenendaal and Block [45]	ETH Zurich	Experimental research	Two prototype anticlastic shells constructed using a hybrid cable-net and fabric formwork system	Varying individual cable tensions allows fine control of shell geometry for improved performance
	2015	Pedreschi and Tang [46]	University of Edinburgh	Experimental research	Construction of two concrete shells using a hybrid flexible gridshell and textile formwork	Gridshell can be adapted to create shells of differing geometry
	2015	TSC Global [47]	TSC Global	Application	Thin shell concrete hyperbolic paraboloid roof	Concrete pasted onto fibre mesh to create lightweight thin shell structure
Floors	1958	Ramaswamy *et al.* [48]	Central Building Research Institute	Application	Modular shells cast in fabric and inverted	Inversion of hanging shape creates optimal shape for under self-weight
	2009	West [49]	C.A.S.T. University of Manitoba	Architectural research	Pre-cast sprayed GFRC barrel vaults acting as structure and formwork for in-situ concrete floor	Hanging form creates funicular mould which is inverted (no numerical analysis)
	2009	West [49]	C.A.S.T. University of Manitoba	Architectural research	Cantilever floor shell structure (plaster casts only)	Membrane prestressed and shaped by applying force at column locations
	2009	West [49]	C.A.S.T. University of Manitoba	Architectural research	Stiffened precast shell flooring unit	Application of point load to fabric creates wrinkle
Walls	1934	Waller [22]	Ctesiphon Construction	Application	Fabric stretched over frames and plastered to create thin walls	Fabric remains in place as permanent reinforcement
	2009	West [49]	C.A.S.T. University of Manitoba	Architectural research	Sprayed GFRC wall panel using hanging geotextile formwork	Folds in fabric provide stiffness (no numerical analysis)
Pneumatic	1926	Nose [50]	Independent	Commercial application	Pneumatic formwork for concrete pipe or culvert construction	Tubular formwork creates void for in-situ casting
	1941	Neff [51]	Independent	Commercial application	Concrete dome constructed using pneumatic formwork and sprayed concrete	Waterproofing and insulation layers added where required
	1967	Bini [52]	Binishells	Application	Reinforced concrete shell houses	Reinforcement laid out flat and lifted into position upon inflation
	1984	Nicholls [53]	Independent	Commercial application	Pneumatically formed domes of multiple layered cement and fabric composite	Cement and reinforcement applied prior to inflation
	1986	Schlaich and Sobek [54]	Schlaich and partner	Application	Circular rainwater tank with ribbed segmental dome concrete roof	Pneumatic formwork with additional cables creating stiffening ribs for large span roofs
	1990	South [55]	Monolithic Dome Institute	Commercial application	RC domes cast in-situ using pneumatic formwork	Polyurethane foam applied to formwork prior to concrete sets form and provides insulation

	2007	PRONK *et al.* [56]	Eindhoven University of technology	Patent	System for the production of irregular shell structures with synclastic and anticlastic surfaces	Irregular shell structures made with standardised inflatables in combination with a wire mesh
	2008	Hove [57]	Eindhoven University of Technology and ABT	Commercial application and patent	System for the manipulation of an inflatable formwork	System to realise a catenary optimized cross vault with an inflatable mould in combination with fibre reinforced shotcrete
	2009 - present	Huijben [58]	Eindhoven University of Technology	Research	Vacuumatic formwork	Form is adaptive and given stiffness by the application of vacuum pressure
	2014	Kromoser and Kollegger [59]	Vienna University of Technology	Experimental structure	Doubly curved domes created from flat segments	Pneumatic formwork lifts precast segments into place when inflated
	2015	Bartlett School of Architecture [60]	Cloud 9/Bartlett School of Architecture	Experimental structure	Elliptical domed pavilion with large organic voids	Double layered pneumatic formwork with wooden void formers
Adaptive and supported moulds	1863	Munro and Walczyk [61]	Independent	Patent	First known patent on pinbed moulding	The tip of the pins describe points on a three-dimensional surface.
	1952	Hawes [62]	Independent	Patent	Single sided and singly curved formwork for arch roofs	Series of adjustable length supporting rods dictate arch profile
	1969	Piano [63]	Architect / Milan Politechnical University	Application / Research	Doubly curved freeform pavilion in fibre-reinforced plastics	Flexible mat with mechanically controlled actuators
	1979	Eisel [64]	Independent	Patent	Pin-bed double sided mould for creating curved panels	Large number of adjustable pins covered with plastic foil to create variety of architectural elements
	1998	Kosche [65]	Independent	Patent	Pin-bed method for producing three dimensional shell sections	Flexible mat with computer controlled actuators
	2003	Helvoirt [66]	Eindhoven University of Technology	Experimental research	Doubly curved adjustable moulding surface	Flexible mat with computer controlled actuators
	2005 - present	Concrete Canvas Ltd [67]	Concrete Canvas	Commercial application	Cement impregnated fabric which hardens upon hydration	Durable layer used for erosion control, slope stabilisation and waterproofing in civil engineering applications
	2008	Vollers and Rietbergen [68]	Independent	Patent	Doubly curved precast concrete cladding panels	Flexible mat with computer controlled actuators
	2011	Kristensen and Raun [69]	Independent	Patent	Dynamically reconfigurable moulding surface consisting of a flexible mat with actuators	Specially constructed flexible mat consisting of rigid rhomboidal segments
	2012	Grünewald *et al.* [70]	Delft University of Technology	Research	Panels deformed after flat initial casting using a flexible membrane and multiple actuators	Careful control of concrete mix and rheology
	2015	Pronk *et al.* [71]	Eindhoven University of Technology	Research/application	Flexible mould by the use of spring steel mesh	Flexible Moulding surface based on rubber mat with weaving of a spring steel mesh. Surface can be manipulated by actuators.
	2015	Pronk *et al.* [72]	Eindhoven University of Technology	Research/application	Moulding method for mass production of unique precast concrete elements.	The combination of vacuum forming and adaptive moulding is used to produce formwork for unique doubly curved elements in cast concrete.
	2015	Hoppermann *et al.* [73]	Delft University of Technology	Application	Doubly curved precast concrete cladding panels	Flexible mat with computer controlled actuators

2.2 Filled Moulds

2.2.1 Floors and ceilings

In 1899 Gustav Lilienthal obtained a patent for a floor system marketed under the name 'Terrast Decke', Figure 3. The system was constructed by hanging fabric or paper between floor beams before pouring concrete on top [8]. Similar incarnations of this idea were patented throughout the 20th century [6].

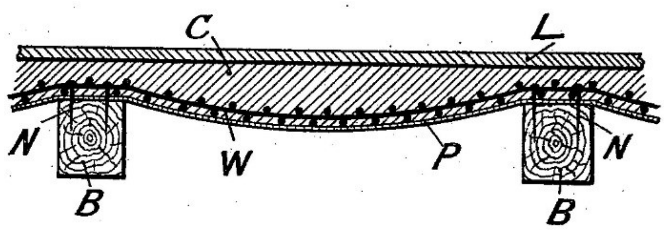

Figure 3 - Early flexibly formed concrete floor patented by Lilienthal [8]

A recent built example of a flexibly formed canopy is presented by West and Araya [9], and shown in Figure 1f. Another example of a rib stiffened floor is given by the architecture and construction firm ArroDesign [10], in the form of a cantilevered slab with a profiled soffit.

2.2.2 Beams and trusses

Compared to floor systems, developments in fabric-formed beams and trusses occurred more recently, most effectively by West [11] who developed several methods of manufacture for the construction of beams with varying geometries and structural characteristics. The formwork material is fixed rigidly along both sides of the beam, and either hangs freely between these supports or can be drawn downwards to create a deeper section by using the 'spline' or 'keel' methods. A development of this system led to the pinch mould and the creation of concrete trusses (Figures 1c and 1d).

The primary focus of this work has been on structural optimisation, utilising the flexible mould to place material only where it is required. Lee [15] developed a fabric formed beam prototype and achieved 20-40% savings in embodied energy when compared to the equivalent prismatic structure. Other work has shown 25-44% savings in concrete compared to equivalent strength prismatic beams, and has included testing of T-beams, combining flexibly formed beams with conventional slabs [17].

After considerable research activity, examples of practical application of fabric formed beams have begun to appear. Flexible formwork has been used in the construction of a school in Cambodia by London based StructureMode, Figure 4 [20]. Prismatic beams and columns were cast using a woven marine geotextile supported on falsework, by a team who had no previous experience in the technique. The principle advantages were that the formwork could be constructed off site and transported easily, and that skilled labour was not required for construction. This application demonstrates the efficacy of the method, and its global potential.

Figure 4 - Fabric formed beams and columns. Photo: Lindsay Perth.

2.2.3 Columns

James Waller, arguably the most prolific inventor in the field of flexible formwork [74], patented several ideas in the 1930s including that of a circular, prismatic, fabric formed column [22]. Similar systems were patented in the 1990s and have been successfully commercialised [23].

Providing that tensile strains in the fabric are small, a circular prismatic column can be constructed using a very simple tube of fabric, significantly reducing the weight and bulk of formwork material required compared to conventional methods. Initial work by West [75] focused on various experimental methods to build and shape fabric formed columns, departing from the simple prismatic column. Pedreschi [27] continued with even more irregularly shaped columns by combining flexible and rigid formwork. Additional work by Pedreschi and Lee [76] tested the load capacity of a series of variable section circular columns, which were simply constructed by modifying simple tubular fabric formwork (Figure 5). It was found that concave columns showed a higher axial load capacity than prismatic columns using the same amount of material, demonstrating the potential for material savings [77].

Figure 5 – Variable section columns. Photo: Remo Pedreschi

2.2.4 Walls and façade panels

From 1969 onward, Miguel Fisac used fabric formed panels in many of his projects in Spain, employing smooth polyethylene sheets hanging from a rigid frame as formwork for precast facade panels. More recently, West [78] cast several large fabric formed panels and Pedreschi [79] a large array of smaller panels which were incorporated into a proprietary cladding system.

The large fluid pressures arising from tall concrete pours require some method of restraining the fabric in order to control wall thickness. This has been achieved either by using a rigid frame in combination with flexible formwork, or by using the ‘quilt point’ method, restraining the fabric at points. Both techniques were pioneered by Kenzo Unno in the late 1990s [80], whose practice Umi Architectural Atelier have successfully applied these methods to many projects in Japan. Redjvani and Wheen [30] developed a 10m tall fabric formed wall, poured monolithically without any scaffolding or bracing. Figure 6 shows a recent example of the quilt point method from a 2011 collaboration between architects Studio Bark and the University of East London [33].

Figure 6 – Fabric formed retaining wall. Photo: Wilf Meynell/Studio Bark.

ArroDesign have also independently developed a frame-support method of flexibly formed wall construction and have since applied this to several fabric-formed projects in North America [10]. While the above systems are cast in-situ, the Spanish company Arquitectura Vertida applies Fisac's concepts for prefabrication in new building projects, using flexibly formed façade panels which are cast horizontally and lifted into position as the structural element in prefabricated sandwich walls.

2.2.5 Foundations

Flexible formwork can allow strip and pad footings to conform to ground profiles, as illustrated in Figure 7. This reduces formwork complexity and is particularly useful where ground is uneven and excavation is challenging. Patented in 1993, the 'Fast-Foot' system has been used in many buildings predominantly throughout Canada and the US [25].

Figure 7 – Fabric formed strip footing. Photo: Fab-Form [25].

2.2.6 Marine applications

Flexible formwork has seen significant use in marine applications. Early patents for concrete-filled burlap mattresses as river or coastal revetments [81] were followed by pile jackets and bags, which are still produced today. The concrete mattress is in essence a ground bearing slab cast between two sheets of fabric, and such systems have been applied throughout North America since 1967 [82]. Typically the concrete is fully contained by a porous fabric, which can be constructed on land, prevents washout in use and improves concrete strength [83]. They can be filled in situ by pumping the concrete from above the surface. Hawkswood [84] presents an overview of various marine applications of fabric formwork, including porous mattresses for erosion protection, pile jackets for repair of existing structures and foundations to precast structure, as shown in Figure 8.

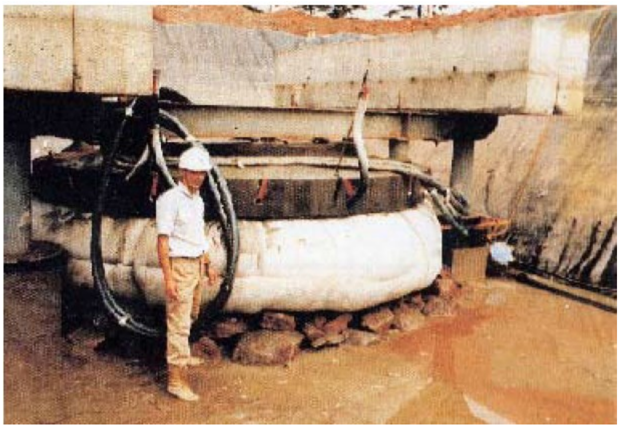

Figure 8 - Footing for precast marine structure. Photo: Proserve Ltd. [84].

2.3 Surface Moulds

2.3.1 Resistance through form

Efficient shells carry load primarily through membrane forces [85]. The absence of large bending forces keeps stresses low, reducing material demand. A shell's structural performance is therefore dictated by its form, particularly its curvature. The fluidity of concrete allows these required geometries to be realised. This was first exploited by Romans to create unreinforced shell structures which have stood for millennia [86]. As the use of steel reinforced concrete became commonplace in the early 20th century, another period of innovation began. High material costs during two world wars drove the desire for efficient designs, and the availability of cheap labour made more complex and involved manufacturing methods economically viable. This led to the peak of concrete shell construction during the middle of the century, driven by innovators such as Maillart, Candela, Nervi, and Isler [87]. Offering both robustness and limitless possibilities of form, concrete was the material of choice for bold and futuristic architecture during this period of optimism and rapid technological advance.

Nevertheless, concrete shells all but disappeared form mainstream use after the 1960s. Whilst it may simply be that this radical architecture was prematurely seen as old fashioned, there are a number of other factors. The balance of labour and material costs shifted significantly during this time. This made labour intensive formwork no longer economically viable, and prioritised simplicity and speed of construction. In addition, whilst being efficient structurally, shell forms require challenging detailing and can create impractical or inflexible architectural spaces. Shell structures were also difficult and costly to analyse before advances in computational power and methods, and the lack of codified design rules added risk. Further improvements in glass and steel manufacturing technology led to these materials becoming the most common for large span structures, the primary advantages being reduced weight and increased natural lighting.

Figure 9 – Reinforced concrete canopy by Heinz Isler. Photo reproduced under CC-BY-SA/© Chriusha (Хрюша) [88].

Modern technological advances in both digital analysis and manufacturing have gone some way towards making modern concrete shells a more attractive proposition. However manufacturing costs remain high [89]. Flexible formwork has the potential to solve this key issue by simplifying the construction process.

Shell and membrane structures are constrained by the laws of physics, since their design is based on the integration of force, geometry and material. Minimising bending moments and shear forces optimises material utilisation, however the design of such a structure requires a form-finding process that dictates the resulting shape [90]. Since membrane or cable net structures can resist form through tensile in-plane forces only, the same form inverted will act purely in compression [91], although bending stiffness is required in practice for stability and to resist variations in loading arrangement. This principle of 'inversion' forms the basis for the design of funicular shell structures, and therefore any of the form-finding methods discussed in section 4.1 can also be applied to the design of shells. This is most famously illustrated by the hanging models used by Gaudi [92] and Isler [85] to design full-scale structures. These were not built using flexible formwork, but flexible systems were instrumental in their design.

Figure 10-Recreation of Gaudi's hanging model for the Sagrada Familia, Barcelona. Photo reproduced under CC-BY-SA/© Canaan [93].

In practice, a shell's form is often dictated by the construction method. The geometry created with flexible formwork is dictated by the behaviour of the mould, and therefore it may not be possible to reproduce an optimal compression only shape. The challenge in creating shell structures with flexible formwork is to maximise structural efficiency using only the family of forms which can be created using membranes. There are several construction approaches which may be taken:

1) The formwork can hang freely under gravity. A flexible membrane hanging under its own weight, or with the weight from freshly applied concrete, creates a funicular geometry that is purely in tension. The structure can therefore be inverted in order to create a compressive form [94]. As such, this method cannot be used to create a shell in-situ. The inversion procedure is a practical challenge which potentially limits the possible size of each element, as well as introducing unusual temporary stress conditions where the shell is not supported in its final configuration.
2) Concrete can be applied to a mechanically prestressed membrane. This gives the formwork a degree of stiffness, and the resulting shells have anticlastic (negative) curvature typical of a stressed membrane.
3) Air pressure can be used to support the wet concrete (pneumatics). Curvatures are synclastic (positive), and can therefore create domed geometries in-situ. Additional pneumatic equipment is however required on-site for inflation of the mould.
4) The shell can be divided into smaller, precast elements, manufactured with the use of a flexible mould. These elements are then assembled on site into the final shell structure, by tensioning them together or casting an in-situ top layer for example.

2.3.2 Roofs and canopies

Shells are well suited to domes and roof structures where height and free geometry are relatively unrestricted. James Waller is known for constructing hundreds of fabric formed shells in the mid-20th century [95], using fabric hanging from rigid arches to create ribbed single-spanning domes. The work by Kersavage [96] and Knott and Nez [97] during the 1970s led to dozens of fabric formed roofs, most recently by TSC Global [47]. Here, flexible reinforcing mesh is stretched around a timber frame and coated with concrete to a thickness of 10mm. The prestress in the flexible mesh creates a doubly curved anticlastic shell form, which, combined with a low self-weight, improves the structure's earthquake resistance [98].

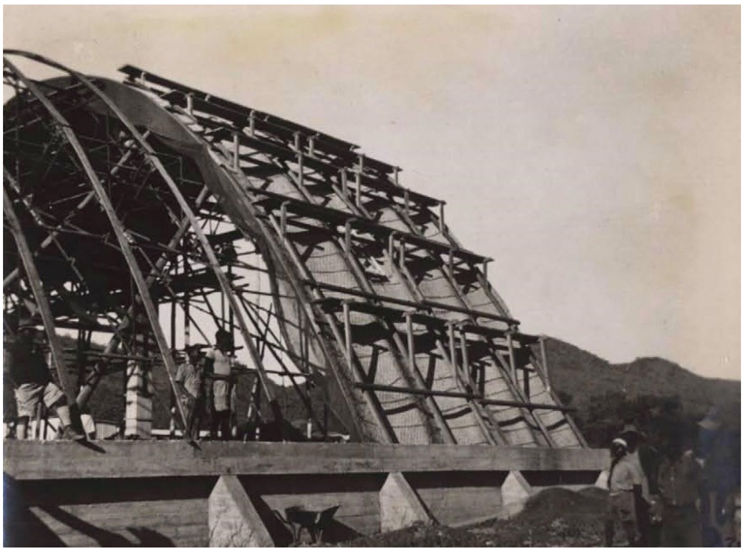

Figure 11 – Ctesiphon shell constructed by James Waller. Photo: the Irish Architectural Archive (Waller album).

In the past decade, prototype anticlastic flexibly formed shells have been constructed by West [99], Pronk *et al.* [39], Tysmans [40], Pedreschi and Lee [28], Seracino *et al.* [41] and Veenendaal and Block [45]. Veenendaal and Block [45, 100] have used a hybrid of fabric formwork with an adjustable cable-net to provide increased flexibility of form, as shown in Figure 12.

Figure 12 – Hybrid cable net and fabric formed shell Photo: Block Research Group, ETH Zurich [45].

2.3.3 Floors

Using shell structures for floors is made challenging by height restrictions, variations in load patterning, robustness requirements and the need for a flat top surface. However, floors are a suitable target for material savings, since they contain the majority of the embodied energy in a typical multi-storey concrete building [101].

Ramaswamy and Chetty [74] developed and patented a method of casting medium-sized doubly curved modular shells in fabric and inverting them as a flooring system [9]. This system was adopted in the construction of thousands of buildings in their native India and abroad [75], and was claimed to provide 20-50% material savings [74].

West [49] presents a number of concepts and manufacturing methods for pre-cast fibre reinforced compression vaults using fabric formwork. Thin, lightweight pre-cast units act as the principle structure as well as formwork for later in-situ concrete. An interesting concept to create buckling resistant shells through selective prestressing of a flat fabric sheet is also presented by West and Araya [94] as a flooring option. Large corrugations in the fabric are created by applying prestress at points, which adds stiffness and stability to the shell forms as shown in Figure 13.

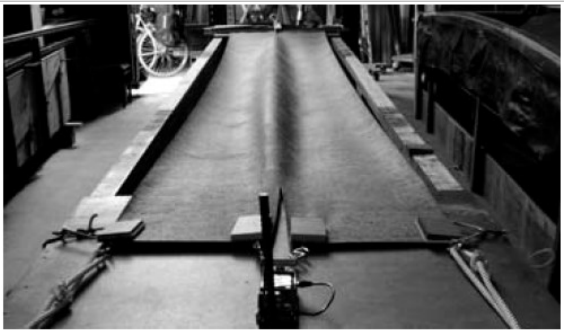

Figure 13 –Funicular shell formwork created by selective prestressing. Photo: Mark West (C.A.S.T.) [94].

2.3.4 Walls

Alongside the filled flexible moulds used to create reinforced concrete walls discussed in §2.2.4, there are also some instances of flexible formwork being used to create thin shell walls with concrete applied to the forming surface. In his 1934 patent, James Waller describes stretching and plastering fabric over a framing to create walls or pitched roofs [22]. The method was marketed under the name 'Nofrango', and was used in the construction of terraced houses in Dublin as early as 1928.

West [49] again experimented with folds and corrugations in order to address the low strength and stiffness of thin planar shells. Hanging sheets of fabric were sprayed with fibre reinforced concrete to create wall panels as shown in Figure 14. Despite the simplicity of the manufacturing process, a very complex form is created using this method. Further investigation is required to predict the form and assess the performance of these structures.

Figure 14 – Thin shell precast wall panel created with sprayed concrete. Photo: Mark West (C.A.S.T.) [49].

2.3.5 Pneumatic moulds

One of the first applications of pneumatic formwork was a method of producing cylindrical concrete pipes patented by Nose [50] in 1926. Since then a common application of pneumatic formwork has been the construction of cost-efficient single storey dome-like houses, pioneered by Neff [51] as a low cost housing solution and later refined by Heifetz [102].

In the 1960s Dante Bini utilised pneumatic formwork for shell-houses, using a circular reinforced concrete foundation [52, 103]. Reinforcement is laid flat on the ground and each reinforcing bar is surrounded by a steel spiral spring. Concrete is then cast over the reinforcement and membrane, which is subsequently deformed into a doubly-curved shell by inflating the formwork before the concrete has set. The reinforcing bars are able to move through their surrounding springs during the inflation, to ensure reinforcement remains in the correct position. Over 1000 ‘Bini-shells’ had been constructed with this method by 1986 [104], and today the company continues to operate and innovate with new structural systems and architectural applications [105].

South [55] invented another construction method where concrete is sprayed on an inflated pneumatic formwork. In contrast to the already described methods by Neff and Heifetz, South not only sprayed from the inside of the mould, but also added a layer of polyurethane which stiffens the formwork before the concrete is applied [106]. This method remains in use today [107], as shown in Figure 15, as part of a wider group of building companies using pneumatic formwork for domes [108, 109].

Figure 15 - Shell house. Photo: Monolithic [107]

Heinz Isler also experimented with pneumatic formworks, inflating and spraying them with different materials like concrete, gypsum, clay, and water [110]. As described by Sobek, large pneumatic formworks can be significantly deformed during the production process [111, 112]. Schlaich and Sobek [54] addressed this issue by using precast concrete segments to take up the deformations during assembly, with any gaps between these filled later with in-situ concrete.

A new construction method using pneumatic formwork has been invented by Kromoser and Kollegger [59], [113], in which free-formed concrete shells originating from an initially flat plate can be built. During the transformation process, the hardened concrete plate consisting of petal shaped elements is bent with the aid of pneumatic formwork until the required curvature is reached, as shown in Figure 16. The construction method can be used for a large variety of forms with positive Gaussian curvature [114].

Figure 16 - Pneumatic forming of hardened concrete. Photo: TU Wien

2.3.6 Adaptive and supported moulds

The final group of applications discussed are those for which the flexible mould is supported regularly along its entire surface. The geometry is therefore no longer determined solely by the force equilibrium of the mould, but also by its interaction with the supporting structure (Figure 17).

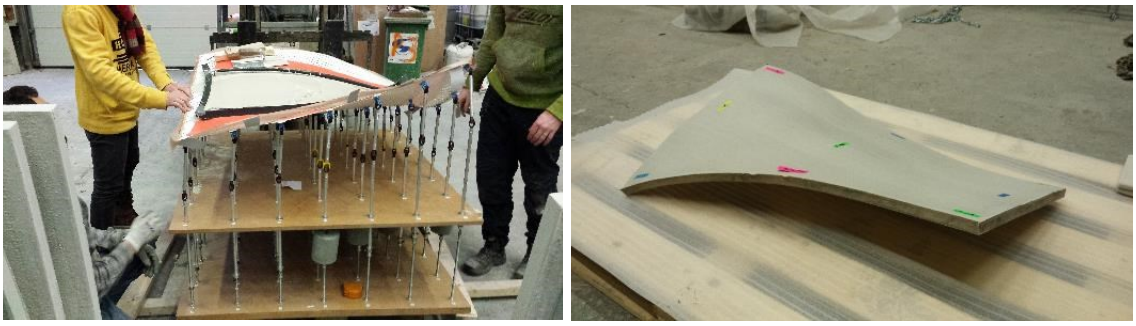

Figure 17 - Adaptive formwork (left) and manufactured freeform concrete element (right) [115]. Photos: Roel Schipper

Adaptive moulds can be reshaped between uses, taking advantage of a flexible mould's ability to conform to multiple geometries depending on support conditions. Significant developments for an adaptive mould to create doubly-curved panels have been made.

Schipper [116] presents a comprehensive overview of historical patents for adaptive flexible moulds. Although reconfigurable surfaces for forming or moulding materials in various industries date as far back as the mid-nineteenth century [61], the oldest patent found using actuators to define a flexible, adjustable doubly-curved shape in concrete is from Eisel [64] in 1979. A patent of Kosche [65] extensively describes various issues when using a flexible moulding for hardening materials such as concrete. To avoid forming onto a curved surface (by spraying for example), it is possible using adaptive moulds to cast the concrete flat and apply curvature after some setting has occurred. However, this requires careful control of concrete mix and rheology to prevent both cracking and flow [70, 116].

Several prototypes for a flexible mould system have been designed, and in some cases built, by researchers and architects over the years [63, 68]. A number of commercial applications have also been developed for flexible moulds [69, 73].

3 Materials

Flexible formworks have been applied to a vast range of structures and incorporated in many novel construction methods. This section looks more closely at the construction implications and possibilities of flexible formwork by focusing on materials.

3.1 Formwork

Whilst it is possible to use non-woven membranes as a formwork material, woven fabrics are usually preferred, due to their availability, low cost, high strength and positive effect on surface finish [117]. A tough and durable material is desirable if the formwork is to be handled, prestressed and used multiple times.

It is usually desirable to avoid wrinkling of the fabric, due issues of demoulding, aesthetics and repeatability. Furthermore, the geometry and occurrence of wrinkling can be difficult to predict [118]. There are notable exceptions, such as the deliberate exploitation of wrinkling to design stiffened shells [49] and canopies [9]. Wrinkling occurs due to a flexible material's inability to carry compression, and fabric can be prestressed where necessary to ensure that stresses are tensile throughout and wrinkles are eliminated.

High stiffness fabrics such as geotextiles have proven to be a popular material choice for such applications, since large prestress forces and fluid pressures can be withstood without large strains resulting in unwanted deformations. Conversely, a deliberate use of a more compliant formwork material such as spandex can create unique sculptural forms [119].

The weight and bulk of required formwork can be significantly reduced when using flexible formwork. For example, the marine geotextile used in the creation of fabric formed beams by Orr [17] has a weight of 0.23 kg/m^2, compared to over 10 kg/m^2 for typical 18mm plywood formwork [120]. Flexible formwork can therefore be easily packed and transported to site if necessary. This presents an opportunity for prefabrication of formwork off-site, reducing construction time and improving scheduling flexibility [20].

Figure 18 – Easily transportable flexible formwork. Photo: Mark West (C.A.S.T.).

Historically, the majority of fabrics used in formwork applications have been adapted from other uses. However as the practice of using fabric formwork has become more widespread, concepts for specialised materials have been developed which could be woven to have customised stiffness or porosity characteristics, for example. The idea of permanent participating formwork has also been explored, where the formwork material (typically having a good tensile capacity) acts as reinforcement after the concrete hardens. This has been explored for concrete floors [121], beams [122], columns [26] and shells [123]. The shear bond between the formwork and concrete is critical, and exposure of the reinforcement to fire and damage remains a concern. Three-dimensional fabrics, which have a multi-layered open structure, have also been proposed [124].

Flexible formwork can incorporate structures other than two-dimensional sheets. Cables and cable nets can be combined with fabrics to create further possibilities for shape control [43, 45, 100, 125], as shown previously in Figure 12. It is also possible to use articulated rigid segments, giving the designer control over the direction of flexibility [69, 126]. Gridshells have also been tested as concrete formwork in combination with a fabric [46, 127]. This provides flexibility to distort into doubly curved forms yet also sufficient stiffness to support the unhardened concrete.

3.2 Concrete

Fundamentally, the choice of formwork material has no influence on the requirements of the concrete to be used. The material properties of concrete are, however, modified as a result of using a permeable formwork material such as a woven fabric. By allowing water and air to escape through the formwork, a high quality and uniform finish is created with a cement-rich surface layer. The texture of the formwork material is picked up by the concrete surface, as can be seen in Figure 19. As well as creating an attractive finish for exposed concrete, this improves strength and reduces porosity, leading to as much as a 50% reduction in carbonation and chloride ingress [117]. The evidence therefore shows that further material savings could be made by decreasing cover requirements, although further investigation and standardisation is required for this to become recognised practice. The same effect is achieved using controlled permeability formwork [128], involving the addition of a permeable lining to a rigid mould.

Figure 19 –Textured concrete finish free of imperfections. Photo: Mark West (C.A.S.T.).

When casting shells against a single surface, flow due to gravity can no longer be permitted and hence the rheology of the concrete mix becomes an important consideration [129]. Mixes cast as thin layers must have appropriate aggregate sizes, flow and consistency to ensure they remain in place on the surface. The concrete can be applied by hand and trowelled, or alternatively sprayed concrete can be used where cement, water and a fine aggregate are projected at high velocity onto the surface [41, 49], allowing a large area to be formed more rapidly. The dynamic placement of concrete causes compaction, and the formwork must also be sufficiently stiff to limit deformation. Accelerating agents can be used, so that each successive layer can support itself more rapidly [130].

3.3 Reinforcement

The nature of flexible formwork leads to structures featuring non-planar and irregular forms. This is the basis for creating optimised structures, however reinforcement must also be shaped to provide strength where needed. Conventional steel reinforcement can be draped to follow these forms only where curvatures are low and bars are sufficiently thin and flexible [41]. Where thicker bars or significant curvatures are required, steel reinforcing bars can be bent to shape [17]. For large scale applications this may incur significant labour costs and the required tolerances may be difficult to achieve. As a result, a number of alternative reinforcing strategies have been used in flexibly formed structures.

Construction can be simplified if the reinforcing material is sufficiently flexible. Fibre reinforced polymer (FRP) reinforcement consists of high tensile strength flexible fibres (usually carbon, glass or basalt) in combination with a polymer matrix. Polymeric reinforcement is less dense than steel reinforcement (1.6 g/cm^3 for carbon, compared to 7.8 g/cm^3 for steel), has a high tensile strength, and is corrosion resistant [131].

Commercially available FRP reinforcing bars are similar in form to conventional steel bars[132], and have been used in variable section fabric formed beams [133]. A key issue is the provision of anchorage to such bars. Kostova [21] developed a splayed-anchorage system which is shown to successfully prevent slippage.

Further research is being carried out to design and construct bespoke reinforcement cages using woven carbon fibres (Figure 20) [134]. Since the fibres are flexible prior to the setting of the resin, this process can be easily automated. The precise geometric control of the manufacturing method enables optimisation in both external form and internal reinforcement layout.

Figure 20 – Bespoke carbon fibre reinforcement for non-prismatic beams. Photo: John Orr.

Glass, basalt or carbon fibres fibres can also be woven into open meshes. Alternating layers of concrete and fibre mesh can be combined to create textile reinforced concrete (TRC), a material with a high tensile strength [135, 136]. This type of material is sometimes described as a cement-based composite, being similar in construction to common composite materials such as CFRP, but with a cementitious matrix. TRC is particularly suited to curved shell structures and complex detailing due to its inherent flexibility. Since there are no cover requirements for corrosion protection, the minimum section thickness can be lower than steel reinforced shells. Along with the material's high strength, this means that textile reinforcement can compare favourably in terms of embodied energy with an equivalent strength steel reinforced section [137].

The height of fabrication simplicity, especially for curved and variable section forms, is the use of unreinforced concrete, or reinforcement which is part of the concrete mix itself.

Fibre reinforced concrete (FRC) introduces uniformly distributed and randomly orientated fibres into the mix in order to improve characteristics such as shrinkage cracking resistance, ductility and tensile strength [138]. There are a number of examples of FRC used to create thin shell structures in combination with flexible formwork [9, 116, 125, 127]. Fibres can be made from steel, glass, polymers or natural materials, and these can be used to partially or sometimes completely substitute for conventional reinforcement [139]. However, maximum tensile strengths are limited by the achievable fibre content and control of their orientation [136]. In combination with fibre reinforcement, careful optimisation of constituent materials can create concrete with significantly improved mechanical properties. Reactive powder concrete (RPC) uses fine and carefully graded aggregates, heat-treating, steel fibres and controlled casting conditions to produce ultra-dense concrete with compressive and flexural strengths of over 800 MPa and 140 MPa respectively [140]. Significant research has led to the commercial availability of ultra-high-performance concretes which incorporate this technology [141].

4 Analysis and design

Using a flexible mould can present specific challenges for designers, mostly due to the added geometric complexity compared to traditional rigid moulds. This geometry is not arbitrary but determined by the physical deformation of the mould, and hence an additional form-finding process is required before structural analysis can be undertaken. The geometric freedom of flexible formwork can lead to efficient structural design by linking these two processes.

4.1 Form-finding of flexible formworks

Flexible structures such as membranes, fabrics and cables are ‘form-active structures’, meaning that their geometry changes to ensure equilibrium with the applied loads. The shape cannot be set arbitrarily, as is possible with rigid formwork, but is governed by the applied loads, boundary conditions and formwork material characteristics. Form-finding is the process of determining this geometry. When using flexible formwork, the aim of the form-finding process is typically to design the formwork in order to create the desired final geometry. Accurate knowledge of a structure's final form prior to manufacture is necessary for structural modelling as well as designing interfaces with other elements such as facades or services.

The loads acting on the formwork arise from not only from the weight of wet concrete but also applied prestress, interaction with rigid surfaces, and possibly additional pneumatic pressure. In the case of filled moulds, the wet concrete exerts a fluid pressure on the formwork. This acts normal to the surface and is proportional to the depth of concrete, with the exception of very tall or slow pours where the effects of friction or hardening can reduce this pressure considerably [142]. The loading on surface moulds is somewhat different due to friction between the concrete and the mould.

Each application of flexible formwork has its own unique form-finding requirements, and the complexity of the analysis can often be reduced by making appropriate simplifying assumptions. For example, a stiff or lightly stressed formwork material may be modelled as inextensible, or a three dimensional object can be simplified as a series of two dimensional sections in some cases [133].

Even after careful form-finding, verification of built geometry should also be made through measurement. This can be done manually, or if a complete assessment of geometry is required, digital 3D scanning technology [143] or photogrammetry [115] may be useful. Greater confidence can be achieved through the use of an adjustable mould, which permits fine-tuning based on measurements made during manufacture.

It should be remembered that many flexible formwork applications do not require detailed form-finding. It may be that calculating the precise form is not important, since the shape is dictated primarily by a rigid surface. This is the case for many fabric formed walls, beams created using keels or pinch moulds, and applications where the fabric formwork makes contact with the ground. Form-finding is also trivial in the case of circular fabric formed columns or piles. It is notable that the majority of existing commercial and practical applications of flexible formwork fall into these categories, where form-finding methods are trivial or unnecessary. The extra level of complexity required for form-finding would seem to be a barrier to commercial adoption at present.

4.1.1 Form-finding techniques

In a typical form-finding problem, a designer with a hypothetical flexible formwork arrangement wishes to calculate the resulting geometry after casting. Analytical formulae (mathematically derived from a physics based model) or empirical formulae (calculated through experimentation) are desirable since they allow geometry to be predicted without the need for computational processes or testing. However, analytical solutions are only practical for the simplest form-finding problems, and empirically derived solutions are only valid under conditions similar to those of the underlying tests, are also exposed to experimental error.

Physical modelling was once the standard method for the form-finding of shells, masonry and tension structures, most famously by Isler [85], Gaudi [92] and Otto [144] respectively. The additional load carried by flexible formwork from the wet concrete adds a complication to these methods. In order to correctly model a flexible formwork system at scale, both the fluid density and fabric stiffness must also be scaled accordingly. An important advantage of physical modelling is the discovery of potential construction issues and unforeseen behaviour. A large number of scale models have been built using plaster at C.A.S.T [94], and further examples are given by Veenendaal and Block [145]. However, the purpose has always been to explore and demonstrate flexible formwork techniques, rather than for accurate form-finding of full scale structures.

The advantages of computational form-finding are substantial. Many different alternative designs can be analysed quickly, allowing a wide range of options to be explored and creating opportunities for optimisation (when combined with an analysis procedure). Designing digitally also has practical advantages when working as part of a project team, allowing communication of designs to others and integration with other digital models. If requirements change, the model can be updated immediately. Several computational form-finding methods have been applied to flexible formwork, including dynamic relaxation [146, 147] (used by Veenendaal [148] and Tysmans *et al.* [149]) and the force density method [150-152] (used by Guldentops *et al.* [153] and Van Mele and Block [154] to design flexibly formed concrete shells). A more comprehensive overview of computational form-finding methods for flexibly formed structures is given by Veenendaal and Block [145].

4.2 Structural analysis

Structural design is based on simplified analysis models, idealised material properties and hypothetical design scenarios which are necessarily conservative. However, an overly simplistic or cautious approach will lead to either a feasible structural solution being overlooked or unnecessary over-design (and material waste). A suitably accurate analysis approach must therefore be developed and verified if a novel structural system is to be used in practice. Analytical methods are continually having to 'catch up' with advances in construction, and the use of flexible formworks is a prime example of this. One of the main drivers for the use of flexible formworks is the potential for material savings through optimisation of form. Many flexibly formed structures have been built, often with structural efficiency in mind, but without structural analysis or testing being carried out [11, 21, 27, 29, 49, 58]. Despite being technically possible, analysing these non-standard structures may require advanced or novel modelling methods for which specialist knowledge is necessary.

Finite element analysis has become the industry standard for analysing concrete structures with irregular geometry. Non-linear material models for reinforced concrete structures are also well established. Hashemian [16] used finite element analysis to model bending moment optimised concrete beams, which was found to accurately predict deflections within the elastic range. Shell structures created using flexible formwork have typically been analysed using linear finite element analysis in order to determine stresses and deflections [41, 43]. The behaviour of a reinforced concrete shell can be approximated as being linear only within the stress limits of cracking or crushing [135]. Shells are particularly sensitive to buckling and initial imperfections [155], and thus ultimate limit state assessment requires a non-linear (large displacement) analysis.

In some cases finite element analysis is unnecessary. For example, structural testing of non-prismatic, flexibly formed beams has shown that standard analytical design methods are accurate for prediction of flexural but not shear strength [156]. Tayfur et al (2016) has adopted the partial interaction theory of Visintin *et al.* [157] in order to better predict cracking and deflections in simply-supported and continuous fabric-formed concrete beams. This work is important in being able to include serviceability criteria in the optimisation process of such structures.

Many computational methods, including finite element analysis, rely on assumptions of material continuity during deformation which are inappropriate for brittle materials, like concrete, when cracking occurs. It is only with accurate analytical tools that the full potential of the material can be exploited. One such tool currently being developed for this application is peridynamic modelling, a mesh-free analysis method which allows inherent modelling of cracking [158].

4.3 Structural optimisation

Optimisation is a branch of mathematics which aims to select an 'optimal' solution from a user-defined set (design space) based on a numerical measure of performance (fitness value). Each solution has a specific value of fitness, and this creates what can be visualised as a 'fitness landscape' from which the aim is to find the 'peak'. Depending on the problem, this landscape may be simple and smooth or rough, with multiple peaks smaller than the global optimum. Iterative methods for optimisation include gradient methods such as Newton-Raphson, suitable only for smooth optimisation landscapes without local optima. For more complex, multi-dimensional design spaces, a number of stochastic methods have been developed which utilise randomness. Examples include simulated annealing [159], particle swarm optimisation [160] and genetic algorithms [161].

Any number of input variables can form the design space, although the complexity of the problem and computational time required increases as more of these are added. The designer therefore needs set up the optimisation procedure carefully in order to create an appropriate design space. In the case of a flexibly formed structure, a design exploration involving a form-finding procedure may be necessary in order to search through geometries which can be formed using a flexible mould. From an engineering perspective, the fitness of a particular structural geometry is likely to be related to its structural performance, and hence a structural analysis procedure must also be integrated within the optimisation process. The desired outcome may be to maximise stiffness or minimise weight for example.

The creation of non-planar concrete forms using only a small number of formwork components brings new opportunities for effective structural optimisation with flexible formwork. The variables which determine the final geometry are first defined, such as the location of a fixing point or an applied prestressing force, and then optimised as part of a procedure which includes form-finding and analysis. Several flexibly formed elements have been computationally optimised in this way including beams, trusses [162] and shells [45]. Another approach to optimising flexibly-formed shells, demonstrated by Van Mele and Block [154], is to calculate an idealised target surface (a funicular form) and then try to approach this with a fabric membrane using an optimisation method.

5 Alternatives to flexible formwork

When evaluating flexible formwork it is necessary to acknowledge other technologies available for the construction of complex shapes in concrete. Aside from traditional timber and steel formworks used in prefabrication, recent technological advances have facilitated the use of: CNC milling of wax, foam or timber; CNC hotwire cutting of foam; direct additive manufacturing and 3D printing as novel methods for construction. Overviews of these technologies can be found in Schipper [116], Lim *et al.* [163], Lloret *et al.* [164] and Naboni and Paoletti [165]. There are also interesting prospects for future work combining rigid CAD/CAM milled moulds shaped to fit flexible form-liners, enhancing construction and geometric flexibility whilst retaining the advantages of the flexible mould. An inexpensive fabric mould-liner can also protect the more expensive milled mould surface, while eliminating de-moulding forces.

Additive manufacturing using cementitious materials is receiving increasing amounts of interest. Current examples of printing at full scale include the D-Shape printer [166], Contour Crafting [167] and a 3D-concrete printer at TU Eindhoven [168]. However, the practical 3D printing of concrete structures still has many challenges to overcome, including the reinforcement of realistic spans using continuous bars, which cannot yet be printed, and the high embodied-carbon of the cement rich pastes used in the printing processes.

Another method of producing curved forms in concrete is to use articulated precast segments, as in the FlexiArch system which has been applied to over 40 projects in the UK and Ireland [169].

Many of these methods require sophisticated machinery which may not exist in parts of the developing world, or may be prohibitive economically. In these cases flexible moulds, particularly flat-sheet fabric moulds, provide extremely simple and inexpensive formworks for casting complex curvatures and structurally efficient forms.

6 Research questions

6.1 Commercial adoption

The history of fabric formworks presents repeated stories of successful, profitable techniques abandoned after their individual inventor/builder(s) ceased working. The main exceptions to this pattern are inflatable formworks for dome construction, underwater and geotechnical fabric formworks, and the Fab-Form line of products for foundation footings and columns, which have all established and sustained niches within their respective construction sectors.

The most difficult barrier to the broad adoption and use of flexible formwork is the contractor’s reluctance, or inability, to give a price for an unfamiliar kind of construction project. While the world of flexible materials is native to technical traditions such as rigging, tailoring or tent structures, flexibility is not native to conventional building construction materials or culture. Despite the fact that many flexible moulds are extremely simple to construct, their unfamiliarity alone may preclude them from being used. Inflatable moulds (used for example in dome construction) have an advantage in this regard, because they present, to a builder, an ostensibly rigid mould surface.

The balance of labour and material and costs drives the extent to which a structure is designed for simple and fast construction or high material efficiency. Ideally, material use is reduced without adding labour costs, which flexible formwork has the potential to do. Higher risks also increase cost. Uncertainty can be reduced by demonstrating reliability of structural performance and accuracy of design methods. As a result, a continued research and wider communication effort is necessary to increase commercial uptake of flexible formwork technology.

A number of specific research questions relate to the commercial adoption of flexible formwork:

- How can knowledge be most effectively collated and disseminated in order to stimulate widespread adoption?
- How do flexible formwork systems compare economically with current construction practice?
- What potential reductions in environmental impact could the use of flexible formwork achieve?

6.2 Construction

Flexible moulds can reliably provide repeated shapes and dimensions, although there are special considerations. For example, the final geometry can be sensitive to the boundary conditions, prestress and material properties of the fabric mould [143]. The choice of the formwork membrane material matters for the successful prediction of strain. Even initially loose formwork fabrics can produce nearly identical casts in subsequent pours, though predicting the shape of the first casting may be difficult in some complex moulds. Pretensioning the mould provides both a higher rigidity and additional control over the final form.

A practical and commercially-focused design guide for constructing with flexible formwork could encourage practical application significantly. In order to achieve this, the following research questions regarding construction are proposed:

- What effect does the use of flexible formwork have on construction tolerance, and how can this be controlled?
- To what extent are different types of flexible mould suitable for multiple uses?
- How might the speed of construction compare to conventional formwork for a large scale application?
- What potential benefits and challenges might arise when scaling up from the lab to larger commercial projects?
- How might precasting and assembling of smaller elements compare to in-situ use of flexible formwork?

6.3 Structural innovation

Despite considerable research and experimentation, flexible formwork still offers a vast range of unexplored opportunities for structural innovation. Thanks to previous research and modern developments in computational power and methods, there now exists the ability to analyse the forms which can be easily created with flexible formwork.

One important goal of future research in this field is to assist in the reduction of greenhouse gas emissions by developing practical methods for designing and constructing efficiently-shaped structures that use less cement than their conventional prismatic equivalents. Maximum material savings can be made by concentrating on applications using large volumes of concrete and where it is presently used least efficiently. In multi-storey concrete framed buildings the majority of material is usually contained within the floors [101]. Floor slabs or beams act primarily in bending, meaning that much of the concrete is ignored in structural analysis (due to cracking) and is lightly stressed in practice. It is possible that a more efficient system can be created using flexible formwork in conjunction with structural optimisation.

Until now, flexibly-formed variable-section beams and slabs have been reinforced using passive reinforcement. The flexibility of post-tensioning cables could make them potentially very well suited to non-prismatic beams and slabs, following on from the work of Guyon [170] who designed and built variable section prestressed beams in the 1950s. Post-tensioning also offers further improvements in material efficiency where stiffness dominates design.

Future research questions might include:

- Where are further and alternative structural efficiency gains to be made using flexible formwork?
- What advantages could post-tensioning bring to optimised fabric formed structures?
- How much embodied energy could be saved in an optimised concrete flooring system cast from a flexible mould?

6.4 Materials

Sometimes overlooked, an important influence on the final form is the stiffness characteristics of the formwork material itself. To date, the majority of flexibly formed structures have been created using materials intended for other purposes, such as geotextiles. Some investigations into creating customised materials have been undertaken [171], and many potential opportunities have been identified.

The established benefits that permeable formwork has for concrete finish and durability can potentially reduce cover requirements and create longer lasting structures [117, 172], as described in section 3.2. At present there is no provision for this in design codes. Further work is required for these potential benefits to be recognized by industry, which will add to the advantages of permeable fabric formwork in practice.

Many developing reinforcement technologies are complementary to flexible formwork, including textiles, fibres and fabrics. There is a very large scope of research to be undertaken in order to further the understanding of these new materials and find suitable applications.

Topics of research yet to be explored include:

- How can flexible formworks be customised to create more structurally efficient forms?
- What is the potential of participating flexible formwork in creating efficient and durable structures?
- How can the benefits to concrete surface finish and durability be maximised through optimal design of permeable formwork?
- What standardised methods of assessing changes to concrete surface properties and durability through use of permeable formwork could be developed?
- How can ongoing developments in concrete and reinforcement materials be combined with flexible formwork to improve performance and application potential?

6.5 Analysis and design

Whilst much theoretical and experimental work has been carried out on form-finding of flexibly formed structures, as of yet these methods are rarely used in mainstream practice. The structures that rely on form-finding, such as shells and beams, are also perhaps the most unusual and carry the most perceived risk for builders and clients. It is therefore important to continue improving form-finding methods and evaluating their performance through physical testing and measurement.

Serviceability often governs the design of concrete structures, although it can often be overlooked in the modelling and testing of novel concrete structures. Deflections in structures with complex geometries can be analysed through, for example, finite element modelling, although the development of analytical methods would be of practical advantage. Optimising for serviceability can be challenging without costly computational methods.

There are many outstanding research questions on the analysis and design side for flexibly formed concrete:

- Which standard testing protocols might be developed to verify form-finding methods?
- How might serviceability criteria influence the design and optimisation methods for non-prismatic structures?
- How might design methods be extended from individual elements to whole structural systems?
- How can new, more realistic computational models for concrete be adopted to guide optimisation methods and improve potential embodied energy savings?

6.6 Design codes

A barrier prohibiting the use of optimised and non-uniform concrete structures is the lack of recognised design methods. The likely need for detailed analysis and physical testing adds considerable cost when designing beyond the limits of codified design. As such, most commercially successful flexibly formed structures are prismatic in shape and can be analysed using existing design codes.

Widespread adoption of curved and optimised structures can only be achieved once the required analysis techniques are identified, verified and standardised. An important research question must therefore be answered:

- How can a set of design codes for optimised concrete structures be produced and what should it contain?

6.7 Global applications

Another promising area of future work is in low-capital, low-tech, building cultures, where the simplicity and material efficiency of flexible fabric formwork can help replace wooden forms, thus addressing issues of deforestation whilst also reducing cement consumption. Although most of the recent research has been carried out in Europe and North America, the first practical applications of new fabric formed concrete technologies is often carried out in developing countries [20, 47]. Regions with fast growing economies and urbanising populations are likely to see the largest amount of new construction in the coming decades, and should therefore be a focus for potential applications. In 2015 for example, China alone accounted for 57% of global cement production [1]. Proposed research questions are:

- Which specific global construction challenges could be solved using flexible formwork?

- How might flexible formwork technology be focused towards regions with the highest construction demand?

7 Conclusions

Flexible formwork has been used to create a wide range of concrete structures, and has produced exciting new structural and architectural possibilities. Replacing rigid moulds with flexible materials offers many practical advantages as well as opportunities for improved structural efficiency.

The technology has a proven commercial record, however structural applications which achieve material savings require more complex and novel design methods. More development and evidence of successful projects is required to increase industrial confidence, and to enable more widespread adoption. Whilst a significant amount of research and innovation has been done, a number of important questions still remain. A large number of research institutions have been involved, and international collaboration is vitally important for further research to be carried out most effectively. The technology could then make a transformative contribution to improving the sustainability of construction.

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