

Flexible formwork technologies: a state of the art review

Citation for published version (APA):

Hawkins, W., Herrmann, M., Ibell, T., Kromoser, B., Michaelski, A., Orr, J., Pedreschi, R., Pronk, A. D. C., Schipper, R., Shepherd, P., Veenendaal, D., Wansdronk, R., & West, M. (2016). Flexible formwork technologies: a state of the art review. *Structural Concrete*, 17(6), 911–935 . <https://doi.org/10.1002/suco.201600117>

DOI:

[10.1002/suco.201600117](https://doi.org/10.1002/suco.201600117)

Document status and date:

Published: 15/12/2016

Document Version:

Accepted manuscript including changes made at the peer-review stage

Please check the document version of this publication:

- A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
- The final author version and the galley proof are versions of the publication after peer review.
- The final published version features the final layout of the paper including the volume, issue and page numbers.

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DOI: 10.1002/suco.201600117

Flexible formwork technologies – a state of the art review

Concrete is the most widely used construction material. World-wide consumption of cement, the strength-giving component in concrete, is now estimated to be 4.10 Gt per year, having risen from 2.22 Gt just 10 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 create structures with almost any geometry economically. Yet its unique fluidity is seldom capitalized upon, with concrete instead being cast in rigid, flat moulds to create non-optimized geometries that result in structures with a high material usage and large carbon footprints. This paper will explore flexible formwork construction technologies that 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, optimization, 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 in design codes and engineering and construction methods. As a result, simple, uniform cross-section shapes have become practically a foregone 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.

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Submitted for review: 06 July 2016; revision: 03 October 2016; accepted for publication: 30 October 2016. Discussion on this paper must be submitted within two months of the print publication. The discussion will then be published in print, along with the authors' closure, if any, approximately nine months after the print publication.

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

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 mouldmaking: 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 results in a need to consider geometric prediction, control and construction tolerances.

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]. EU countries have responded by agreeing on a binding target of a 40 % reduc-

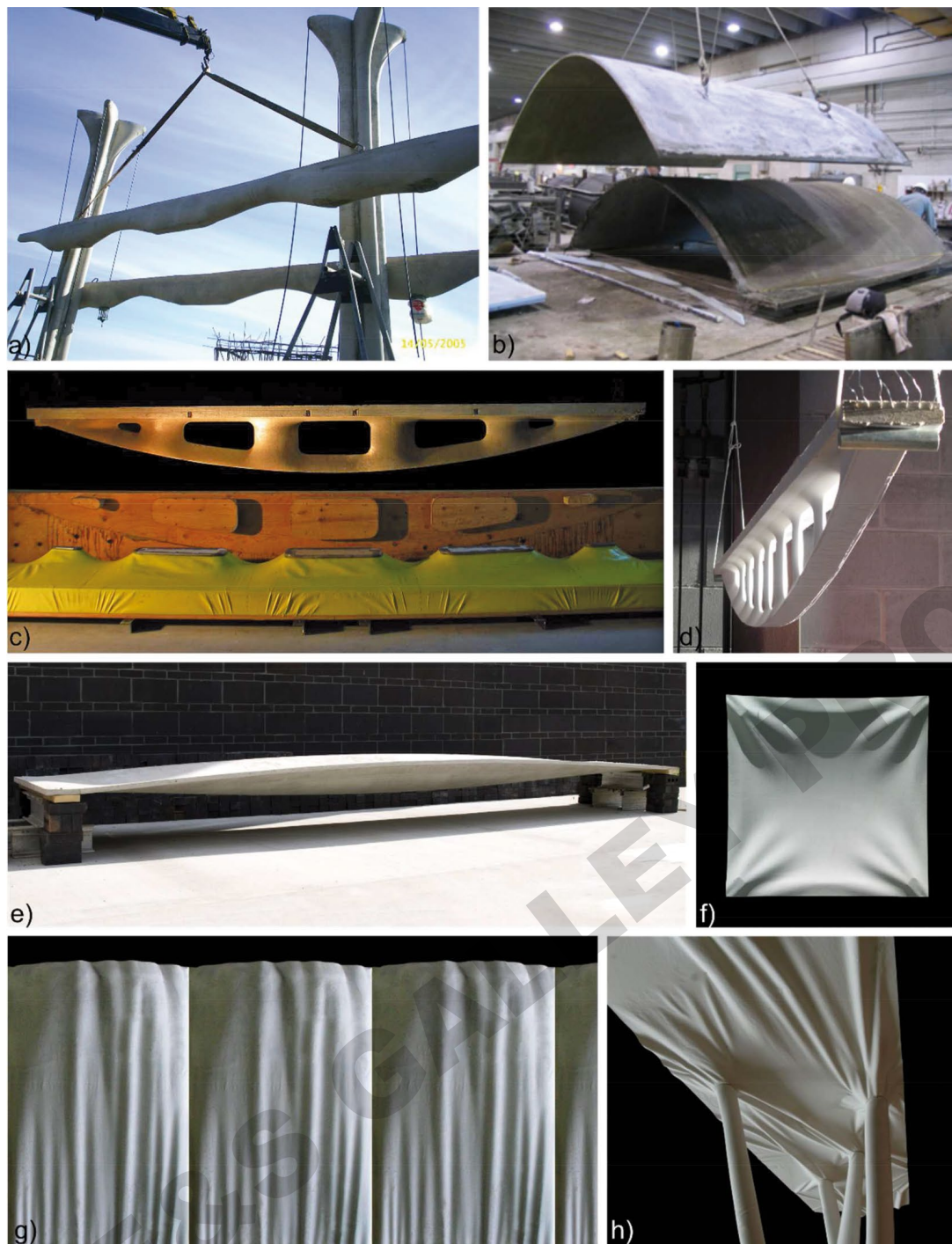


Fig. 1. Flexible formwork creates a multitude of new possibilities for structural forms in concrete; photos: Mark West (C.A.S.T.)

tion in greenhouse gas emissions (from 1990 levels) by 2030, leading to an 80% reduction by 2050 [5].

Concrete is the world's most widely used construction material. The principal 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 to 4.10 Gt, with the bulk of this increase occurring in China [1]. There are two approaches for reducing the associated emissions of concrete structures:

1) reducing the embodied CO_2 of the materials by improving manufacturing efficiency, reducing cement content or using alternative binders, or

2) designing more efficient structures that use less material through optimization 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 varied. The curved geometries created with flexible moulds present an opportunity, not only for architectural expression, but also for considerable material-savings through elegant structural optimization, by placing material where it is used most effectively. The amount of formwork material required is also minimized, further reducing the embodied energy of a structure.

2 Applications

This section describes 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, whose aims include fostering communication between researchers, contractors and manufacturers in both engineering and architecture, communicating the advantages to a wider public and helping to develop innovative fabric forming solutions.

2.1 Typology

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

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 in the formwork material. In this way, the final shape of the casting 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 2.3 describes applications using filled flexible moulds.

2.1.2 Surface moulds

Surface moulds are used predominantly to form shell structures. Usually, only a single forming surface is re-














 Filled moulds	 Surface moulds
 Floors & ceilings	 Roofs, canopies & domes
 Beams & trusses	 Floors
 Columns	 Walls
 Walls & facade panels	 Pneumatic
 Foundations	 Adaptive
 Marine applications	

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

quired, on which the concrete is cast. 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 or be supported by air pressure (in the case of pneumatic formwork) or actuators (in the case of adaptive formwork). These applications are described in section 2.4.

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', see Fig. 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].

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

2.2.2 Beams and trusses

Compared with floor systems, developments in fabric-formed beams and trusses have been more recent, and were demonstrated most effectively by West [11], who developed several methods of manufacture for the construction of beams with various 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 (Figs. 1c and 1d).

The primary focus of this work has been structural optimization, utilizing 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 in comparison to the equivalent prismatic structure. Other work has shown 25–44% savings in concrete compared with prismatic beams of equivalent strength, and has included testing of T-beams, combining flexibly formed beams with conventional slabs [17].

Following considerable research activity, examples of practical applications of fabric-formed beams have begun to appear. Flexible formwork was used in the construction of a school in Cambodia by London-based StructureMode, see Fig. 4 [20]. Prismatic beams and columns were cast using a woven marine geotextile supported on falsework by a team that had no previous experience in the technique. The principal 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.

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 between depth, perimeter and width of section
	2008	Garbett et al. [13]	University of Bath	Structural optimization	Form-finding of beams to resist shear and bending	Sectional analysis procedure led to optimized beams with various shapes
	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 optimized 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 optimized 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]	Structure-Mode	Application	Fabric-formed concrete frame (columns and beams) for a school in Cambodia	Computational fabric form-finding with standard strength design methods (prismatic sections)
Columns	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
	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 of Brussels, Centexbel	R&D project demo	Cast columns, surface structuring	Customization of prefabricated formwork allows control of column shape
	2011 to date	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

Table 1. continued

	Year	Reference	Institution	Type	Description	Design concept
Columns	2012	Verwimp et al. [26]	Vrije Universiteit Brussel	Experimental research	Slender columns with permanent formwork as reinforcement	Fire resistance of TRC allows reduction in 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 customization of column geometry
	2014	Pedreschi and Lee [28]	University of Edinburgh	Experimental research	Investigation of strength of non-prismatic columns cast 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	Double-curvature 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 façade panels	Non-structural
	1995	Redjvani and Wheen [30]	Flexible Formwork, University of Sydney	Structural application	10 m tall concrete wall using flexible formwork	Ties control wall thickness
	1997 to date	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 to date	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 London/Studio Bark	Application	30 m long fabric-formed retaining wall	Similar in form to a conventional retaining wall
	2012	Jack [34]	Walter Jack Studio	Architectural application	40 m 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 to date	Fab-Form [25]	Fab-Form Industries	Commercial application	'Fastfoot' strip footing simplifies formwork	Conventional reinforcement and similar in form to standard structures

Table 1. continued

	Year	Reference	Institution	Type	Description	Design concept
Marine applications	1960s to date	Pilarczyk [35]	Various	Commercial application	Double-layer mattress for ground applications	Filter points allow dissipation of groundwater pressure while protecting against erosion
	1980s to date	Hawkswood [36]	Various	Commercial application	Fabric pile jackets for marine applications	Commonly used for repairing existing piles
	1990s to date	Hawkswood and Alsop [37]	Various	Commercial application	Foundations to precast marine structures	Flexible form ensures full contact with bed

Table 2. Surface-mould flexible formwork applications

	Year	Reference	Institution	Type	Description	Design concept
Roofs and vaults	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 double-curvature shell structure	Demonstrated thin-section possibilities using double curvature and TRC
	2012	Seracino et al. [41]	Belgian Building Research Institute	Experimental research	Double-curvature shotcrete shells with comparison between textile and steel reinforcement	Formwork modelled with force density method, finite element modelling of shell with corresponding physical tests
	2012	Adderley [42]	University at Buffalo	Architectural research	Double-layer 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, hyper and domed concrete shells constructed using fabric formwork stretched between rigid frames	Inspired by the 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

Table 2. continued

	Year	Reference	Institution	Type	Description	Design concept
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 self-weight
	2009	West [49]	C.A.S.T. University of Manitoba	Architectural research	Precast sprayed GFRC barrel vaults acting as structure and formwork for in situ concrete floor	Hanging form creates a 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 multi-layer 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 creates stiffening ribs for long-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 standardized 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 create a catenary-optimized cross-vault with an inflatable mould in combination with fibre-reinforced shotcrete
	2009 to date	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	Double-curvature 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-dome pavilion with large organic voids	Double-layer pneumatic formwork with wooden void formers	

Table 2. continued

Year	Reference	Institution	Type	Description	Design concept
1863	Munro and Walczyk [61]	Independent	Patent	First known patent on pin-bed moulding	The tips of the pins describe points on a three-dimensional surface.
1952	Hawes [62]	Independent	Patent	Single-sided and single-curvature formwork for arch roofs	Series of adjustable-length support rods dictate arch profile
1969	Piano [63]	Architect/ Milan Politechnical University	Application/ research	Double-curvature free-form 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 a 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	Double-curvature adjustable moulding surface	Flexible mat with computer-controlled actuators
2005 to date	Concrete Canvas Ltd [67]	Concrete Canvas	Commercial application	Cement-impregnated fabric that hardens upon hydration	Durable layer used for erosion control, slope stabilization and waterproofing in civil engineering applications
2008	Vollers and Rietbergen [68]	Independent	Patent	Double-curvature 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	Grünwald 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 with spring steel mesh	Flexible moulding surface based on rubber mat with interwoven 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, double-curvature elements in cast concrete.
2015	Hoppermann et al. [73]	Delft University of Technology	Application	Double-curvature precast concrete cladding panels	Flexible mat with computer-controlled actuators

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 commercialized [23].

Provided 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 with conventional methods. Initial work by West [75] focused on

various experimental methods for building and shaping 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 (Fig. 5). It was found that concave columns showed a higher axial load capacity than prismatic columns using the same amount of material, thus demonstrating the potential for material-savings [77].

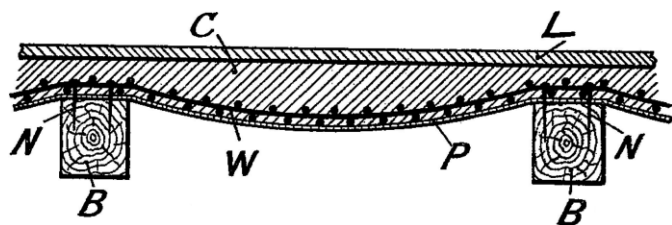


Fig. 3. Early flexibly formed concrete floor patented by Lilienthal [8]



Fig. 4. Fabric-formed beams and columns; photo: Lindsay Perth



Fig. 5. Variable-section columns; photo: Remo Pedreschi

2.2.4 Walls and façade panels

From 1969 onwards, 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 façade panels. More recently, West [78] cast several large fabric-formed panels and Pedreschi [79] a large array of smaller panels that were incorporated into a proprietary cladding system.

The large fluid pressures arising from tall concrete pours call for some method to restrain the fabric in order to control wall thickness. This has been achieved either by

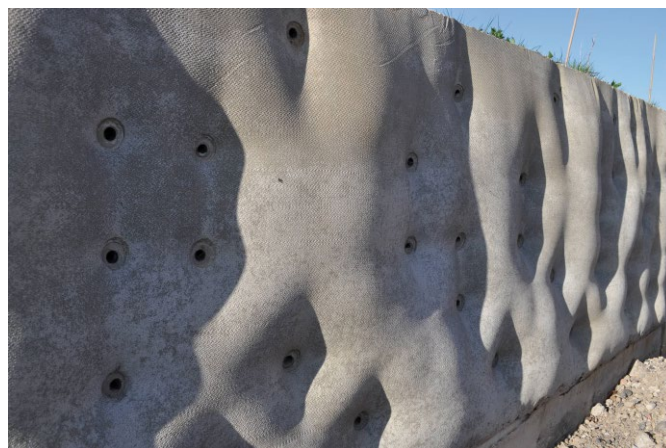


Fig. 6. Fabric-formed retaining wall; photo: Wilf Meynell/Studio Bark

using a rigid frame in combination with flexible formwork, or by using the ‘quilt point’ method, i.e. restraining the fabric at points. Both techniques were pioneered by Kenzo Unno in the late 1990s [80], whose practice Umi Architectural Atelier has successfully applied these methods to many projects in Japan. Redjvani and When [30] developed a 10 m tall fabric-formed wall, poured monolithically, without any scaffolding or bracing. Fig. 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].

ArroDesign has also independently developed a frame-support method of flexibly formed wall construction and has since used this in several fabric-formed projects in North America [10]. Whereas 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 that 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 Fig. 7. This reduces formwork complexity and is particularly useful where the ground is uneven and excavation is challenging. Patented in 1993, the ‘Fastfoot’ system has been used in many buildings, predominantly throughout Canada and the USA [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 used 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 sur-



Fig. 7. Fabric-formed strip footing; photo: Fab-Form [25]



Fig. 8. Footing for a precast marine structure; photo: Proserve Ltd. [84]

face. Hawkswood [84] presents an overview of various marine applications of fabric formwork, including porous mattresses for erosion protection, pile jackets for repairing existing structures and foundations to precast structures, as shown in Fig. 8.

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 realized. This was first exploited by the Romans to create unreinforced shell structures that 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 20th century, driven by innovators such as Maillart, Candela, Nervi and Isler [87]. Offering both robustness and limitless possibili-



Fig. 9. Reinforced concrete canopy by Heinz Isler; photo reproduced under CC-BY-SA/© Chriusha (архива) [88]

ties 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 from mainstream use after the 1960s. While it may simply be that this radical architecture was prematurely seen as old-fashioned, there were 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 prioritized simplicity and speed of construction. In addition, although they are structurally efficient, 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 long-span structures, the primary advantages being reduced weight and increased natural lighting.

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. Minimizing bending moments and shear forces optimizes material utilization. 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 the 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



Fig. 10. Recreation of Gaudí's hanging model for the Sagrada Família, Barcelona; photo reproduced under CC-BY-SA/© Canaan [93]

design full-scale structures. These were not built using flexible formwork, but flexible systems were instrumental in their design.

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 maximize structural efficiency using only the family of forms that can be created using membranes. Several construction approaches are possible:

- 1) The formwork can hang freely under gravity. A flexible membrane hanging under its own weight, or the weight of 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 and also introduces 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 the 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 to inflate 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

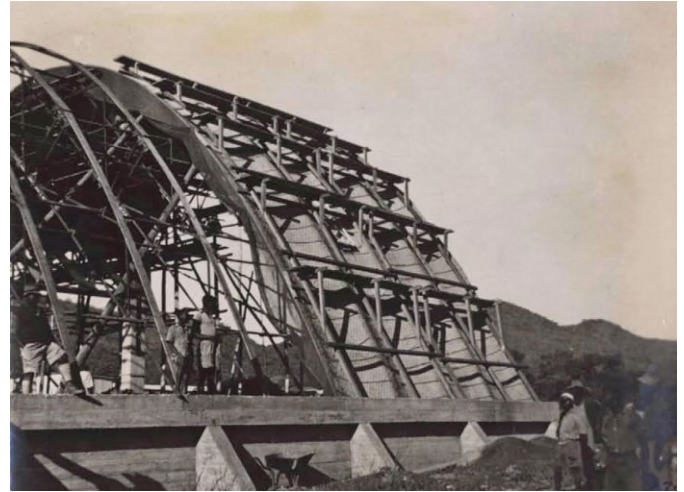


Fig. 11. Ctesiphon shell constructed by James Waller; photo: Irish Architectural Archive (Waller album)

structure by tensioning them together or casting an in situ topping, for example.

2.3.2 Roofs and canopies

Shells are well suited to domes and roof structures where height and 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-span 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 10 mm. The prestress in the flexible mesh creates a double-curvature anticlastic shell form, which, combined with a low self-weight, improves a structure's earthquake resistance [98].

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 Fig. 12.

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 double-curvature modular shells in fabric and inverting them to form 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 achieve 20–50% material-savings [74].



Fig. 12. Hybrid cable-net and fabric-formed shell; photo: Block Research Group, ETH Zurich [45]

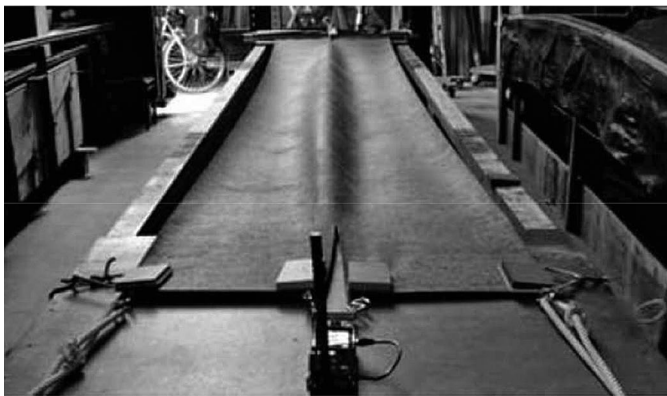


Fig. 13. Funicular shell formwork created by selective prestressing; photo: Mark West (C.A.S.T.) [94]

West [49] presents a number of concepts and manufacturing methods for precast fibre reinforced compression vaults using fabric formwork. Thin, lightweight, precast units act as the principal structure and 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 Fig. 13.

2.3.4 Walls

Alongside the filled flexible moulds used to create reinforced concrete walls discussed in section 2.3.4, 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 frame 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 Fig. 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.

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



Fig. 14. Thin-shell precast wall panel created with sprayed concrete; photo: Mark West (C.A.S.T.) [49]



Fig. 15. Shell house; photo: Monolithic [107]



Fig. 16. Pneumatic forming of hardened concrete; photo: TU Wien

[51] as a low-cost housing solution and later refined by Heifetz [102].

In the 1960s Dante Bini utilized 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 double-curvature 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 the 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 onto an inflated pneumatic formwork. In contrast to the methods of Neff and Heifetz already described, South not only sprayed from the inside of the mould, but also added a layer of polyurethane that stiffens the formwork before the concrete is applied [106]. This method remains in use today [107], as shown in Fig. 15, as part of a wider group of building companies using pneumatic formwork for domes [108, 109].

Heinz Isler also experimented with pneumatic formwork, inflating and spraying the forms with different materials such as concrete, gypsum, clay and water [110]. As described by Sobek, large pneumatic formwork 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 being filled later with in situ concrete.

A new construction method using pneumatic formwork has been invented by Kromoser and Kollegger [59], [113] which enables the construction of free-form concrete shells from an initially flat plate. 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 Fig. 16. This construction method can be used for a large variety of forms with positive Gaussian curvature [114].

2.3.6 Adaptive and supported moulds

The final group of applications discussed is those for which the flexible mould is supported regularly over 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 (Fig. 17).

Adaptive moulds can be reshaped between uses, taking advantage of a flexible mould's ability to conform to multiple geometries depending on the support conditions. There have been significant developments in adaptive moulds for creating double-curvature panels. Schipper [116] presents a comprehensive overview of historical patents for adaptive flexible moulds. Although reconfig-

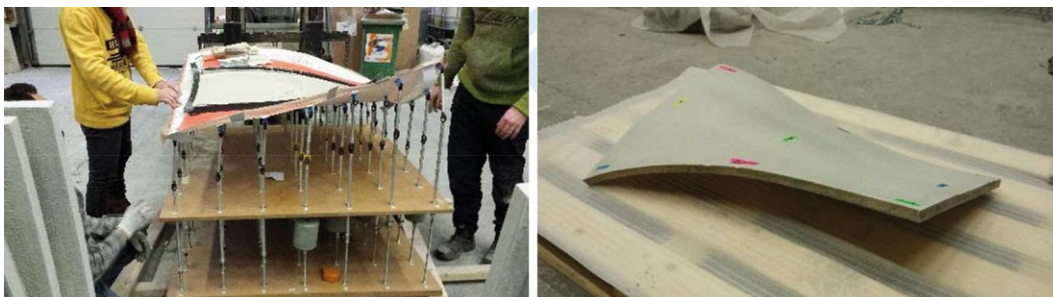


Fig. 17. Adaptive formwork (left) and manufactured free-form concrete element (right) [115]; photos: Roel Schipper

urable surfaces for forming or moulding materials in various industries date back as far as the mid-19th century [61], the oldest patent found using actuators to define a flexible, adjustable, double-curvature shape in concrete is that of Eisel [64] dating from 1979. A patent of Kosche [65] extensively describes various issues when using a flexible mould for hardening materials such as concrete. To avoid forming on a curved surface (by spraying, for example), adaptive moulds allow the concrete to be cast flat and the curvature to be applied after some setting has taken place. 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 formwork has been used for 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

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

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



Fig. 18. Easily transportable flexible formwork; photo: Mark West (C.A.S.T.)

Historically, most of the 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 specialized materials have been developed which could be woven to achieve customized stiffness or porosity characteristics, for example. The idea of permanently 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 the concrete is critical, and exposure of the reinforcement to fire and damage remains a concern. Three-dimensional fabrics, which have a multi-layer 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 in Fig. 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 the flexibility needed to distort into double-curvature 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, 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 Fig. 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

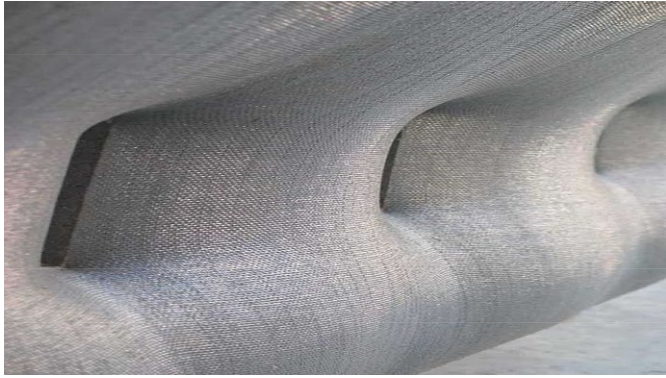


Fig. 19. Textured concrete finish free of imperfections; photo: Mark West (C.A.S.T.)

ingress [117]. The evidence therefore shows that further material-savings could be made by decreasing cover requirements, although further investigation and standardization is required for this to become recognized practice. The same effect is achieved by using controlled-permeability formwork [128], which involves adding a permeable lining to a rigid mould.

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 optimized 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 small 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 might 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 flexible fibres with a high tensile strength (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 with 7.8 g/cm^3 for steel), has a high tensile strength and is corrosion-resistant [131].



Fig. 20. Bespoke carbon fibre reinforcement for non-prismatic beams; photo: John Orr

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 for such bars. Kostova [21] developed a splayed-anchorage system that has been shown to prevent slippage successfully.

Further research is being carried out on the design and construction of bespoke reinforcement cages using woven carbon fibres (Fig. 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 optimization in terms of both external form and internal reinforcement layout.

Glass, basalt or carbon 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 that for steel-reinforced shells. Along with the material's high strength, this means that in terms of embodied energy, textile reinforcement can compare favourably with a steel-reinforced section of equivalent strength [137].

The height of fabrication simplicity, especially for curved and variable-section forms, is the use of unreinforced concrete, or reinforcement that 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 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 for either the partial or complete replacement of conven-

tional reinforcement [139]. However, maximum tensile strengths are limited by the achievable fibre content and control of the fibre orientation [136]. In combination with fibre reinforcement, careful optimization of constituent materials can create concrete with significantly improved mechanical properties. Reactive powder concrete (RPC) uses fine and carefully graded aggregates, heat treatment, steel fibres and controlled casting conditions to produce ultra-dense concrete with compressive and flexural strengths exceeding 800 MPa and 140 MPa respectively [140]. Significant research has led to the commercial availability of ultra-high-performance concretes that 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 with 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 for flexible formwork

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 for designing interfaces with other elements such as façades or services.

The loads acting on the formwork arise not only from the weight of wet concrete, but also from 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 ge-

ometry 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 (derived mathematically 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, and are also liable to experimental error.

Physical modelling was once the standard method for form-finding for shells, masonry and tension structures, most famously by Isler [85], Gaudi [92] and Otto [144] respectively. The additional load of the wet concrete carried by flexible formwork adds a complication to these methods. In order to model a flexible formwork system correctly at a reduced 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 accurate form-finding for 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 optimization (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, idealized material properties and hypothetical design scenarios that 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 wastage of materials). 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 formwork is a prime example of this. One of the main drivers behind the use of flexible formworks is the potential for material-savings through optimization 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-optimized concrete beams, which was found to predict deflections accurately 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 predicting flexural but not shear strength [156]. Tayfur et al. (2016) has adopted the partial interaction theory of Visintin et al. [157] in order to predict cracking and deflections better in simply supported and continuous fabric-formed concrete beams. This work is important in being able to include serviceability criteria in the optimization 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 such as concrete when cracking occurs. Only by using accurate analytical tools is it possible to exploit the full potential of the material. One such tool currently being developed for this application is peridynamic model-

ling, a mesh-free analysis method that allows inherent modelling of cracking [158].

4.3 Structural optimization

Optimization 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 visualized 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 optimization include gradient methods such as Newton-Raphson, suitable only for smooth optimization landscapes without local optima. For more complex, multi-dimensional design spaces, a number of stochastic methods have been developed which utilize randomness. Examples include simulated annealing [159], particle swarm optimization [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 to set up the optimization 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 that 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 optimization process. The desired outcome may be to maximize stiffness or minimize weight, for example.

The creation of non-planar concrete forms using only a small number of formwork components presents new opportunities for effective structural optimization with flexible formwork. The variables that determine the final geometry are first defined, such as the location of a fixing point or an applied prestressing force, and then optimized as part of a procedure that includes form-finding and analysis. Several flexibly formed elements have been computationally optimized in this way, including beams, trusses [162] and shells [45]. Another approach to optimizing flexibly-formed shells, demonstrated by Van Mele and Block [154], is to calculate an idealized target surface (a funicular form) and then try to approach this with a fabric membrane using an optimization 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. Apart from traditional timber and steel formwork used in prefabrication, recent technological advances have facilitated the use of the 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 for fitting flexible form liners, thus enhancing construction and geometric flexibility while retaining the advantages of the flexible mould. An inexpensive fabric mould liner can also protect the more expensive milled mould surface while eliminating demoulding forces.

Additive manufacturing using cementitious materials is attracting ever more attention. 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 Flexi-Arch system, which has been used in more than 40 projects in the UK and Ireland [169].

Many of these methods require sophisticated machinery that 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 formwork solutions for casting complex curvatures and structurally efficient forms.

6 Research questions

6.1 Commercial adoption

The history of fabric formwork includes recurring stories of successful, profitable techniques abandoned after their individual inventors/builders 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. Whereas 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 cultures. 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 materials 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 the 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, although predicting the shape of the first casting might 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 building with flexible formwork could encourage practical applications 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 tolerances 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 with 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 the precasting and assembling of smaller elements compare with the 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 that can be easily created with flexible formwork.

One important goal of future research in this field is to assist in reducing 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 achieved by concentrating on applications requiring large volumes of concrete and where that con-

crete is currently used least efficiently. In multi-storey concrete-frame buildings the majority of material is usually contained in 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 optimization.

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 optimized fabric-formed structures?
- How much embodied energy could be saved in an optimized concrete flooring system cast in 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 customized 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 if these potential benefits are 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 very large scope for research to be undertaken in order to further the understanding of these new materials and find suitable applications.

Research topics yet to be explored include:

- How can flexible formwork be customized to create more structurally efficient forms?
- What is the potential for allowing flexible formwork to participate in creating efficient and durable structures?
- How can the benefits for concrete surface finishes and durability be maximized through optimal design of permeable formwork?
- What standardized methods of assessing changes to concrete surface properties and durability could be developed by using permeable formwork?
- How can ongoing developments in concrete and reinforcing materials be combined with flexible formwork to improve performance and application potential?

6.5 Analysis and design

Although much theoretical and experimental work has been carried out on the form-finding of flexibly formed structures, these methods are currently 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 with, for example, finite element modelling, although the development of analytical methods would offer practical advantages. Optimizing for serviceability can be challenging without costly computational methods.

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

- Which standard testing protocols might be developed to verify form-finding methods?
- How might serviceability criteria influence the design and optimization 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 optimization methods and improve the potential for saving embodied energy?

6.6 Design codes

A barrier prohibiting the use of optimized and non-uniform concrete structures is the lack of recognized 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 optimized structures can only be achieved once the required analysis techniques have been identified, verified and standardized. One important research question must therefore be answered:

- How can a set of design codes for optimized 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 while 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 urbanizing populations are likely to see the largest amount of new construction in the coming dec-

ades, 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 by 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 that achieve material-savings require more complex and novel design methods. More development and evidence of successful projects is required to increase industrial confidence and enable more widespread adoption. Although a significant amount of research and innovation has been carried out, a number of important questions still remain. Many research institutions have been involved, and international collaboration is vitally important if further research is to be carried out most effectively. The technology could then make a transformative contribution to improving the sustainability of construction.

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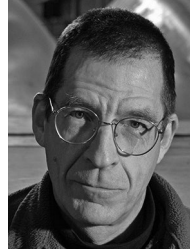
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