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KnitCrete

Stay-in-place knitted formworks for complex concrete structures

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Contents

Abstract

To address the increasingly urgent requirement of decreasing embodied energy and waste in construction, this dissertation presents a novel type of flexible and cost-effective formwork for casting concrete using 3D weft-knitted textiles as mould. Designing structures that intelligently include structural performance and architectural geometry leads to beautiful, economical and structurally optimised systems that use very little material. Concrete, specifically, is a favourite material for these structures, as it can be moulded into almost any shape desired. However, their expressive, intricate and bespoke geometries can be challenging to build with traditional formwork methods that rely on single-use cut timber or milled foam. These custom constructions account for approximately one-half to as much as two-thirds of a structure's cost. To harness the full potential of non-standard and non-repetitive efficient concrete structures, the formwork systems used for construction need to be rethought. Using knitted technical textiles as stay-in-place moulds for concrete structures can be a solution for building without the need for expensive, wasteful and time-consuming moulds.

In contrast to the traditionally used woven textiles, knitted materials can be tailored to doubly curved and spatially complex 3D shapes, allowing for the integration of features and the design of very specific properties without the need for glueing, welding or stitching several parts together. Knitted textiles can be easily prefabricated by programming industrial knitting machines. A computational pipeline consisting of algorithms and design tools is developed for translating any given 3D geometry into a knitting pattern in an automated way. With this pipeline, commonly available CNC knitting machines produce intricately knitted textiles, that are light, compact and can

be effortlessly transported to the construction site. Through tensioning the custom-tailored textile is formed into the desired shape and coated with a special cement-paste to obtain the mould, which becomes a basis for efficient, lightweight structures. The feasibility of the system is demonstrated with a series of prototypes from component to architectural scale. They show that the super-lightweight moulds drastically reduce the need for additional support and scaffolding, simplify logistics on site and have the potential to increase efficiency throughout the complete design-to-production chain.

Zusammenfassung

Um der immer dringender werdenden Forderung nach der Reduktion grauer Energie und des Abfallaufkommens im Bauwesen gerecht zu werden, stellt diese Dissertation eine neuartige Art von flexibler und kostengünstiger Schalung für Betonstrukturen unter Verwendung von 3D-Stricktechnologie vor. Das Einbeziehen tragstruktureller und geometrischer Kriterien in den Entwurfsprozess birgt das Potential Bauwerke in besonderem Masse ästhetisch, wirtschaftlich und materialeffizienz auszugestalten. Für die Herstellung dieser Strukturen kommt meist Beton zum Einsatz, da er sich in fast jede gewünschte Form bringen lässt. Dennoch stellt deren Bau unter Inanspruchnahme traditioneller Schalungstechniken, welche auf Einwegschalugen aus Holz oder gefrästen Schaumstoff basieren, eine grosse Herausforderung da. Diese aufwändigen Sonderkonstruktionen machen etwa die Hälfte bis zu zwei Drittel der Kosten eines Bauwerks aus. Um das Potenzial von nicht standardisierten und massgeschneiderten Betonkonstruktionen voll auszuschöpfen, müssen die für den Bau verwendeten Schalungssysteme überdacht werden.

Die Verwendung von gestrickten technischen Textilien als verlorene Schalung für Betonkonstruktionen stellt eine mögliche Lösung dar, ohne dass teure, materialintensive und zeitaufwändige Schalungsbauten erforderlich sind. Im Gegensatz zu den traditionell verwendeten Geweben können gestrickte Textilien auf doppelt gekrümmte und räumlich komplexe Formen angepasst werden, was die Integration von Details und die Einbettung spezifischer Eigenschaften ermöglicht, ohne dass mehrere Teile miteinander verklebt, verschweißt oder vernäht werden müssen.

Gestrickte Textilien können durch die Programmierung von industriellen Strickmaschinen einfach vorgefertigt werden. Eine digitaler Prozess beste-

hend aus Algorithmen und Entwurfswerkzeugen wurde im Rahmen dieser Arbeit entwickelt, um beliebige 3D-Formen automatisiert in ein Strickmuster zu übersetzen. Mit Hilfe dieser Software-Pipeline können mit handelsüblichen CNC-Strickmaschinen aufwendig gestrickte Textilien, die leicht, kompakt und mühelos zur Baustelle transportiert werden können produziert werden. Durch Spannen wird das speziell vorgefertigte Textil in die gewünschte Form gebracht und mit einer eigens entwickelten Zementpaste beschichtet und ausgesteift. Dieses Prinzip und Schalungssystem liefert die Grundlage für die effiziente Herstellung komplexer Betonstrukturen.

Die Umsetzbarkeit des Systems wird mit einer Reihe von kleineren Prototypen bis hin zu grossmasstäblichen Demonstratoren aufgezeigt. Sie zeigen, dass die ultraleichten Schalungen den Bedarf an Stützstrukturen und Gerüstaufbauten drastisch reduzieren, die Logistik auf der Baustelle vereinfachen und das Potenzial haben, die Effizienz entlang der gesamten Prozesskette vom Entwurf bis zur Herstellung zu steigern.


Photo credit: Alessandro Dell'Endice

Part I

Introduction

Chapter 1

Background

This chapter introduces and contextualises the research presented in this thesis. Chapter 2 crystallises the motivation for the problem statement detailed in Chapter 3 through a review of concrete construction practices and existing approaches to formwork. This includes an overview of flexible formwork systems using textiles and a brief overview of technical textiles and their fabrication. Finally, based on the conducted literature review, Chapter 3 outlines the research objectives and gives an overview of the thesis structure.

1.1 Context

Today, advancements in computational design tools have enabled architects to explore intricate geometries with ease. Simultaneously, computer numerically controlled (CNC) machinery has facilitated their fabrication giving the impression that any imaginable geometry can be built. These developments have caused the onset of a paradigm shift from the mass standardisation of the 1960s and 1970s to mass customisation and fabrication starting with the 1990s. While digital fabrication has opened up new opportunities for the construction of complex and optimised structures, it has yet to address cost and material efficiency in custom concrete construction. Formwork for bespoke geometries can usually not be reused; it is a one-off product and therefore becomes waste. This is a problem both in terms of cost and sustainability.

The following introduction frames this context, outlining the problem statement and offering a vision for the forming of complex concrete structures using a flexible knitted formwork approach.

1.1.1 Architectural geometry

Structures with intricate doubly curved geometries are increasingly designed and constructed stemming from different design logic. They can be purely the result of an architectural expression characterised by advancements in digital modelling, a fascination with the curvilinear, and a general paradigm shift towards mass customisation instead of mass production. Buildings such as the Heydar Aliyev Center by Zaha Hadid Architects (Figure 1.1a), the Arnhem Central Station by UN Studio (Figure 1.1b), the EPFL Rolex Learning Centre by SANAA (Figure 1.1c) or the Taichung Opera House by Toyo Ito and Associates (Figure 1.1d) demonstrate how advances in computational design, combined with improvements in fabrication techniques, have enabled the building of large-scale complex architectural expressions. Unfortunately, without being informed by structural performance, they require material intensive structural solutions, which are costly and limit their application to iconic buildings.

While freeform geometries can be motivated by individual creativity, form-found geometries are equally expressive, but are a result of structural optimisation, generally aimed at lightweight construction. In this sense, they become a basic component for building in a performative way while decreasing material use. For their stiffness, structures with less material have to rely on geometry and the placement of material strictly where needed according to, for example, the natural flow of forces.

Using physical form-finding techniques, structural engineers and architects throughout the 20th century have reintegrated the two fields. The introduction of reinforced concrete made it possible to not only explore but also build analytical geometries that marry architecture and structure. For example, the filigrane curved shell structures of Heinz Isler's (Figure 1.2a), Félix Candela's Los Manantiales (Figure 1.2b) or Eduardo Torroja's roof for La Zarzuela Racetrack in Madrid, Spain (Figure 1.2c) could be built to effortlessly span large areas with little material.

Pier Luigi Nervi developed "ferro-cement" and focused on building any structure with the highest possible performance by working with material, geometry and prefabrication. He employed undulations, corrugations, and stiffening ribs to construct structures with large dimensions and high structural performance while reducing deadweight (Leslie, 2017; Halpern et al., 2013). Well-known examples being the Gatti Wool Mill (Figure 1.3a) and the Palazzetto dello Sport in Rome (Figure 1.3b).

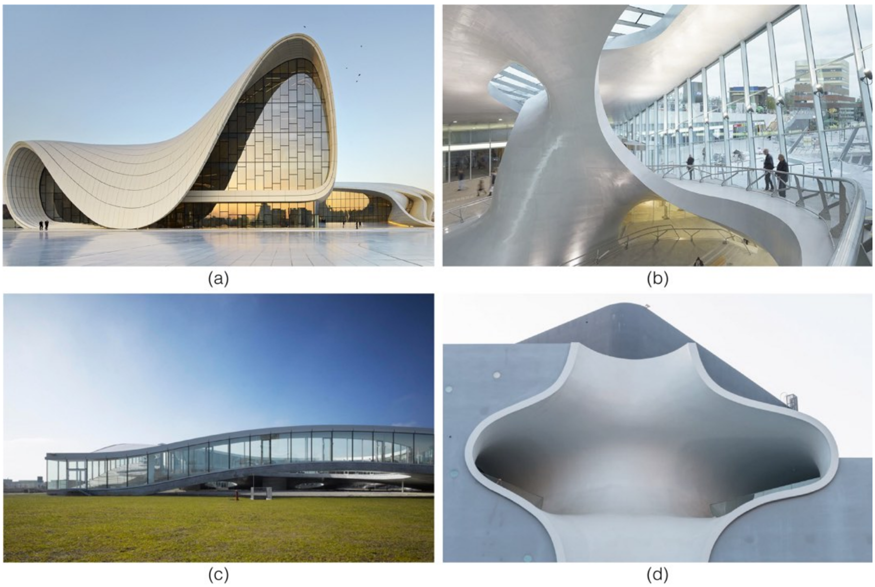
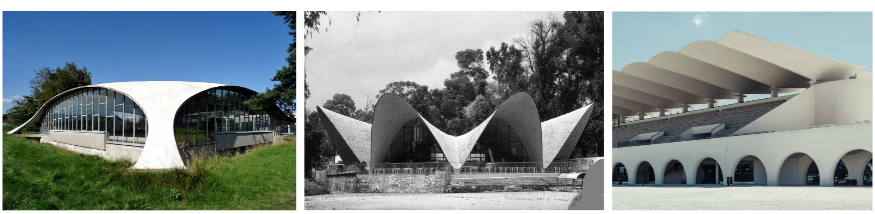


Figure 1.1: Contemporary examples of curved architectural geometries: (a) Heydar Aliyev Center, Baku, Zaha Hadid Architects 2012; (b) Arnhem Central Station, Eindhoven, UN Studio, 2015; (c) EPFL Rolex Learning Centre, Lausanne, SANAA Architects 2010; (d) Taichung Opera House, Taichung, Toyo Ito and Associates 2016. (photo credit: (a) Hufton + Crow; (b) Ronald Tilleman; (c) Roland Halbe; (d) Lukas K. Doolan).



(a) (b) (c)

Figure 1.2: Shell structures in the 20th century: (a) Kilcher shell roof, Recherswil, Heinz Isler 1965; (b) Los Manantiales Restaurant, Xochimilco, Félix Candela, 1958; (c) La Zarzuela Racetrack, Madrid, Spain, Eduardo Torroja 1930 (photo credit: (a) Wikimedia Commons; (b) RIBA Collections; (c) Ximo Michavila).

(a) (b)

Figure 1.3: Examples of intricate geometries of undulating and rib-stiffenned thin concrete surfaces: (a) Palazzetto dello Sport, Rome, Pier Luigi Nervi, 1957; (b) Gatti Wool Mill, Rome, Pier Luigi Nervi 1951 (photo credit: (a) Ernest Delaville; (b) P.L. Nervi).

Doubly curved and rib-stiffened surface configurations offer the possibility of increasing the load bearing capabilities of a structure in a material efficient and economical way. This category of geometries is increasingly important in the current climatic context where the building industry accounts for more than 35% of the global energy consumption and 40% of energy-related CO_2 emissions (Abergel et al., 2017).

Arguably, concrete has made it possible to build the modern world (Powell, 2011). It is the most widespread building material in use (Chudley, 2012; Orr et al., 2013*a*) and a favourite for building complex geometries as it can be moulded into any shape desired. Regardless of the reasoning behind a given geometry, concrete needs a formwork to be cast in. Formwork is a construction in itself, albeit most of the time temporary.

1.1.2 Problem statement

Concrete relies heavily on the use of aggregates and freshwater and cement, which accounts for 6 to 8% of the yearly global carbon-dioxide emissions (Lehne and Preston, 2018). According to Orr et al. (2019), by 2050 a building's embodied energy is predicted to be the main energy consumption component by 2050. Therefore, it is not only important to reduce the amount of material used in terms of structural volume, but also the amount needed during construction (De Wolf et al., 2017).

Though optimised and form-found structures are more materially efficient, because of their complex geometry, their construction remains challenging.

This is especially because bespoke concrete elements built with traditional methods require single-use cut timber or milled foam moulds. Formwork typically accounts for approximately 50% of the structure's cost (Hanna, 1999; Lab, 2007) and more than 70% when casting custom geometrically intricate structures (García de Soto et al., 2018). Figure 1.4 shows the comparative cost distribution for building a straight and a doubly curved concrete wall using traditional formwork approaches[1]. Moreover, placing reinforcement and the integration of additional functional elements are not trivial for bespoke geometries.

Other than the high cost associated with bespoke formworks, traditional fabrication strategies are generally slow, needing months of carpentry work or CNC milling (>240min/m^2 (Søndergaard et al., 2018) and up to 940min for a fully finished mould (Gardiner et al., 2016)). If prefabricated, the major challenges remain transportation and on-site handling as structures need to be both within allowable transportation and weight limits (Hanna, 1999).

As such, traditional approaches to formwork are economically and ecologically not viable for non-standard, doubly curved and reinforced structures. Therefore, there is a need to develop better, more efficient building methods for non-standard and non-repetitive concrete structures. These methods need to reduce embodied energy, waste, labour and cost while increasing customisability, productivity and construction times.

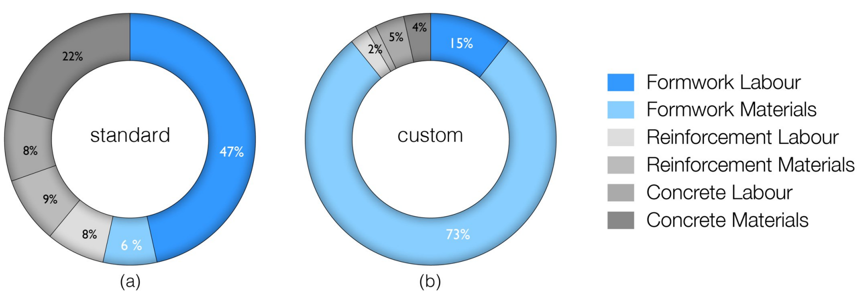


Figure 1.4: Cost of formwork relative to the structure's cost for (a) standard and (b) custom doubly curved concrete wall according to García de Soto et al. (2018).

[1]Figure 1.4 does not reflect the cost difference between a standard and doubly curved concrete wall. A standard wall costs roughly a third as much as a doubly curved wall.

1.2 Vision

In traditional formwork systems, rigid and often heavy moulds are held in place by scaffolding, which needs foundations, and other temporary elements that make up a falsework (Figure 7.44a). Using a flexible membrane or fabric instead of a rigid mould can offer an alternative forming system needing minimal or no scaffolding (Figure 7.44b) (Veenendaal et al., 2011; Brennan et al., 2013).

Instead of being propped up, textiles achieve the desired geometry by tensioning. This tensioning into shape can be done using rigs, frames and external supports (West, 2016). Tensioning can also be done using a hybrid approach where a cable net (Veenendaal and Block, 2014), bending-active elements (Thomsen et al., 2015; Lienhard and Knippers, 2015; Cuvilliers et al., 2017) or inflatables (Ahlquist et al., 2017) form a self-supporting system with the textile (Pronk and Dominicus, 2011; Veenendaal et al., 2011).

Flexible membranes instead of a rigid formwork have proven to be a feasible solution for the creation of lightweight, waste-reducing formwork for a wide variety of complex architectural elements (Hawkins et al., 2016). Moreover, because of their compactness and lightness, they can be effortlessly transported to the construction site (West, 2001). The NEST HiLo roof prototype, built at ETH Zurich, is the most recent example of a large-scale thin concrete shell structure to be successfully built using a cable-net and woven fabric formwork (Echenagucia et al., 2019). Figure 1.6 shows the cable-net and woven textile fabric formwork during construction of the HiLo roof on-site at EMPA in Dübendorf, Switzerland.

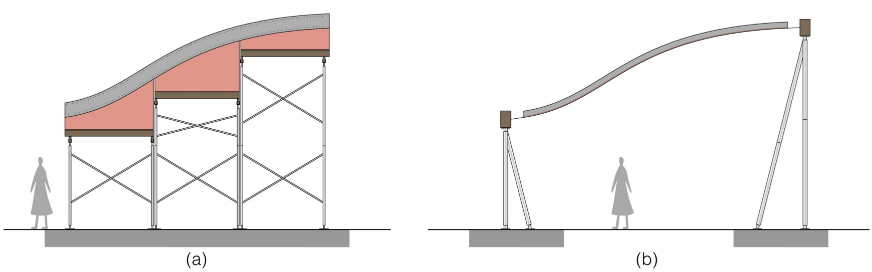


Figure 1.5: Principle representation of rigid and flexible formwork systems: (a) traditional rigid formwork system; (b) flexible formwork system using a textile.

With these systems in mind, the ambition of this research is to construct bespoke geometries cheaper than standard systems, wasting less material and creating efficient prefabrication solutions. Figure 1.7 gives an overview of the vision to create a lightweight, stay-in-place mould using a tailored textile.

Figure 1.6: Cable-net and woven fabric formwork of the NEST HiLo roof at EMPA, Dübendorf by the Block Research Group, ETH Zürich (photo credit: Juney Lee).

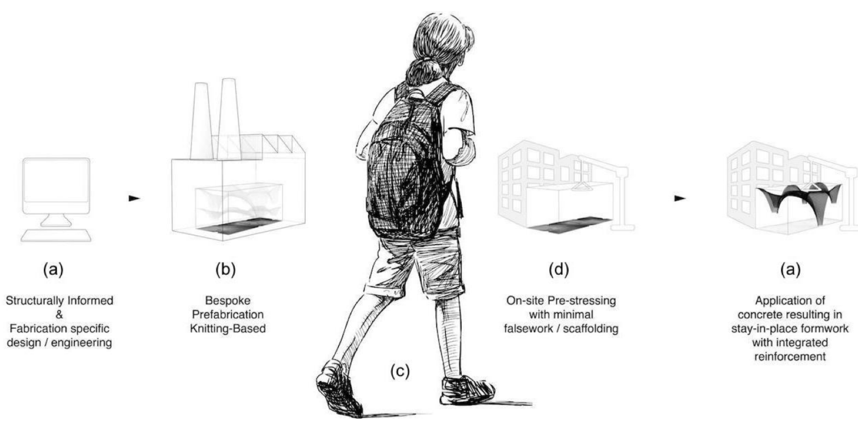


Figure 1.7: Envisioned formwork system using a tailored fabric as mould for concrete: (a) informed design of bespoke textile; (b) prefabrication of textile with integrated features; (c) compact and light transportation of textile to worksite; (d) tensioning of the textile into shape using external or internal elements; (e) casting of concrete structure.

Fabric formwork systems generally use single-layered woven fabrics with uniform texture and properties. To accommodate for tensioning and the insertion of auxiliary systems, textiles need to be fitted with functional details such as channels and openings. If wrinkles want to be avoided in non-developable geometry, the shaping and integration of other features relies on extensive tailoring and joining of different flat sheets of material.

In this case, the ambition is to create a textile that can be prefabricated in a controlled environment including all the needed features and having accurate placement of material according to an informed design. The produced fabric is foldable, easy to pack, and transport to the work site, where it is tensioned into shape. Together with the minimal frame and scaffolding, the textile now creates a formwork system for the concrete to be cast.

Chapter 2

State of the art

This chapter discusses the current formwork developments in concrete construction. Section 2.1 gives an overview of existing formwork systems with a focus on newly developed subtractive and additive digital fabrication techniques, stay-in-place or lost formworks and flexible formwork systems. As the flexible formwork system this thesis is focused on employs a knitted textile, Section 2.2 will discuss the different fabrication strategies for two and three-dimensional textiles and their application areas focusing on construction. Finally, Section 2.3 will present uses of knitting in architecture and construction outlining the opportunities and current practices for fabricating knitted textiles.

2.1 Formwork systems

Formwork is a temporary structure that supports concrete until it has cured and gained enough strength to hold structurally. Formwork systems are made up of several components that shape and contain the concrete and elements that support and brace the moulds. According to (Chudley, 2012) formwork systems can be subdivided into the two following elements:

- **Falsework** - all of the temporary scaffolding, supporting, shoring or bracing elements that support the forms (Figure 2.1a), and
- **Formwork shuttering or moulds** - the elements that come into direct contact and form the shape of the concrete (Figure 2.1b).

In the past, formwork systems used to be mainly made of timber, built in place and discarded after a single or limited use. With prefabrication and standardisation, formwork could be reused, making concrete construction more economical and sustainable in a constrained repetitive context. However, with the current trend of moving towards bespoke and geometrically complex structures, formwork moulds have again become a custom one-off product, which can no longer sustainably rely only on extensive carpentry. Digital fabrication has made it possible to produce these doubly curved moulds in a more streamlined and precise way. An example of digitally fabricated timber moulds is the system developed by DesignToProduction for the construction of UNStudio's Mercedes Benz Museum in Stuttgart (Figure 2.2a) and SANAA's EPFL Rolex Learning Center (Figure 2.2b).

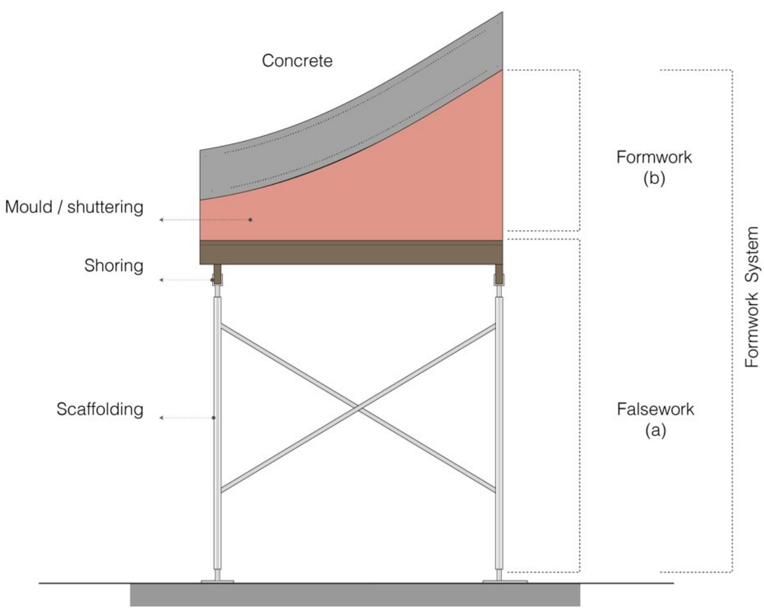


Figure 2.1: Typical formwork system components: (a) falsework comprised of scaffolding and wooden shoring; (b) formwork shuttering or mould.

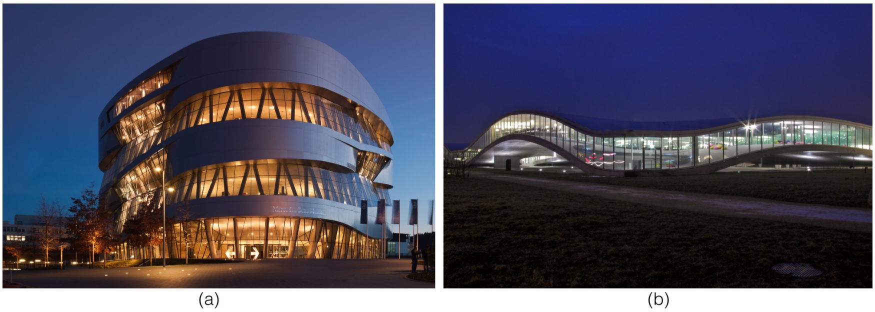


Figure 2.2: Buildings constructed using digitally fabricated timber moulds developed by DesignToProduction: (a) Mercedes Benz Museum by UN Studio, 2005, Stuttgart, Germany; (b) EPFL Rolex Learning Centre by SANAA, 2010, Lausanne, Switzerland (photo credit: (a) Wikimedia Commons; (b) EPFL).

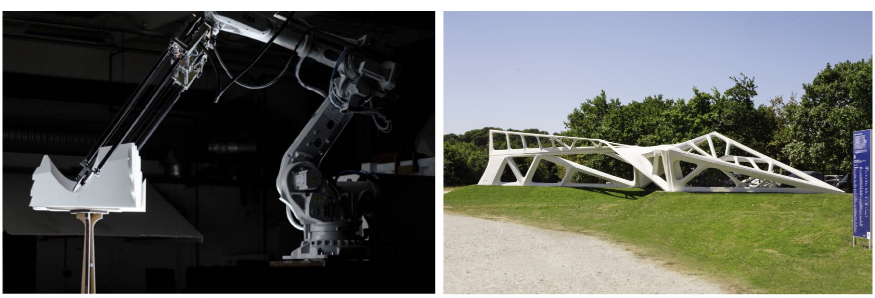
Figure 2.3: Timber formwork system used for the construction of the EPFL Rolex Learning Centre: (a) table formwork mould made of cut plywood sheets; (b) discarded formwork mould materials after formwork was dismantled (photo credit: (a) Design to Production; (b) Fabian Scheurer).

For the latter, borrowing principles used in shipbuilding, the formwork was constructed out of 1500 wooden tables made of CNC-cut flat plywood sheets covered with cold formed chipboard panels (Weilandt et al., 2009) (Figure 2.3a). After the concrete structure cured, the entire formwork was dismantled and the timber mould was discarded (Figure 2.3b).

Other possible solutions for efficient manufacturing of bespoke elements not relying on timber have been investigated more extensively recently. Various systems have been developed by researchers in academia and industry, ranging from manufacturing of varied shapes using an adaptable mould to stay-in-place and fabric formwork.

(a) (b)

Figure 2.4: CNC milled EPS moulds: (a) Spencer Dock Bridge, Amanda Levete Architects, 2010, Dublin, Ireland; (b) Stadel Museum, Schneider + Schumacher Architects, 2012, Frankfurt, Germany (photo credit: (a) top: Wikimedia Commons; bottom: Nedcam; (b) Norbert Miguletz).



(a) (b)

Figure 2.5: Topology optimised pavilion structure: (a) fabricated by Odico using hot-wire cutting of EPS blocks; (b) installed concrete pavilion at the Aarhus School of architecture (Søndergaard et al., 2018)

2.1.1 Subtractive fabrication of moulds

CNC-milled Expanded Polystyrene (EPS) or Polyurethane (PU) foams are commonly used as moulds instead of timber. The advantage of using such an approach lies in the ease of machining, affordability and lightness of the material, which make the forms simple to transport, support and handle on site. The Spencer Dock Bridge, designed by Amanda Levete Architects, was constructed using milled EPS foam blocks supported by standard scaffolding (Lavery, 2013) (Figure 2.4a). Similarly, the moulds for the Stadel Museum designed by Schneider + Schumacher Architects were fabricated using a robotic milling process (Otto and Vasudevan, 2014)(Figure 2.4b).

Although milled foam moulds have some advantages in terms of precision and fine detailing, the milling process is time-consuming as it relies on successive removal of material in layers. Hot-wire cutting techniques have been proposed and explored as a solution to this problem (Raspall et al., 2013; Martins et al., 2015; McGee et al., 2013) and convincingly demonstrated by (Søndergaard et al., 2018) with the production of a topology optimised pavilion (Figure 2.5a and b). Rust et al. (2016) investigated the possibilities of extending hot-wire cutting techniques for geometries beyond ruled surfaces. Regardless of the fabrication approach, EPS moulds are generally coated and sealed with glass-fibre mats or polyurea (Lavery, 2013; Otto and Vasudevan, 2014) and are not reusable or easily recyclable (Verhaegh, 2010).

Alternative methods deal with the reuse or complete recycling of the mould by milling ice (Sitnikov, 2018), (frozen) sand (Gericke et al., 2017) or wax (Mainka et al., 2016; Liebringshausen et al., 2017).

2.1.2 Reconfigurable moulds

Adaptive or reconfigurable moulds focus on creating a system that can be easily adapted to various geometries. Through systems such as PERI's RUNDFLEX (PERI, 2019) or Doka's Circular H2O (DOKA, 2019), the industry provides good solutions for creating single curved geometries with ease. However, these types of systems cannot be used to create doubly curved geometries, which are often needed.

Reconfigurable solutions addressing doubly curved elements have been developed in research environments and recently adopted in the industry. The adaptive moulds produced by Adapa (Figure 2.6a), Kine-mould and Tailor-Crete all use a grid of linear actuators for creating various doubly curved

(a) (b)

Figure 2.6: Adaptable moulds using linear actuators: (a) Adapa D300 adaptive mould for concrete (Adapa, 2019); (b) TailorCrete reusable wax moulds (Oesterle et al., 2012).

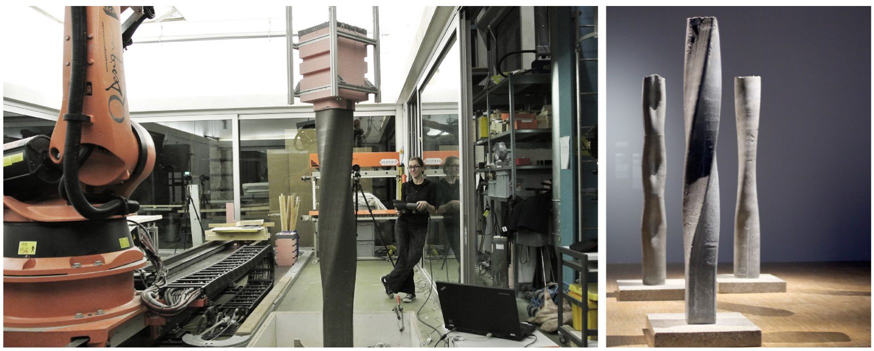


Figure 2.7: Smart Dynamic Casting for robotically casting columns with variable sections (Lloret et al., 2015; Lloret-Fritschi et al., 2018).

geometries (Schipper et al., 2015; Adapa, 2019; Oesterle et al., 2012). The elements are either the panels themselves or wax forms (Figure 2.6b) that can then be used as moulds on site. Similar solutions have been used in industry for the curvaceous concrete facade of UNStudio's Arnhem station (Hoppermann et al., 2015).

While the above-mentioned solutions address efficiently the problem of mould reusability, they face challenges in terms of geometric freedom as panels are either limited in their curvature or size.

For curved linear elements such as columns or mullions, Smart Dynamic Casting, developed at ETH Zurich, uses a robotically controlled and mechanically adaptable mould to cast concrete in a process similar to slipforming (Figure 2.7) (Lloret et al., 2015; Lloret-Fritschi et al., 2018). The same process is also being explored for casting folded plate structures (Szabo et al., 2018).

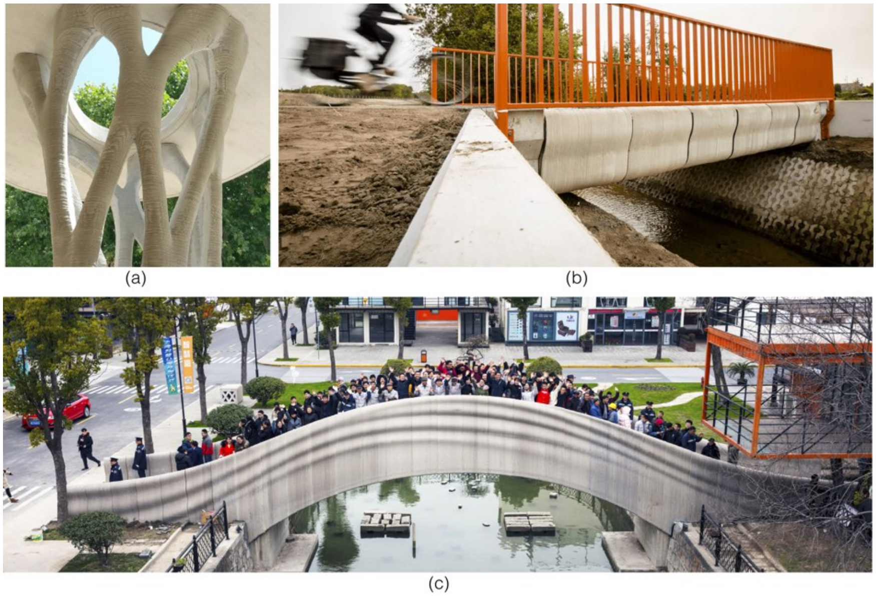


Figure 2.8: Structures built by 3D printing concrete techniques: (a) Pillar in Aix-en-Provence by XTreE 2016 (Duballet et al., 2017); (b) Bycicle bridge in Gemert, The Netherlands by TU Eindhoven and BAM Infrastructure; (c) pedestrian bridge in Shanghai, China by Tsinghua University (photo credit: (b) Bart Maat; (c) Tsinghua University).

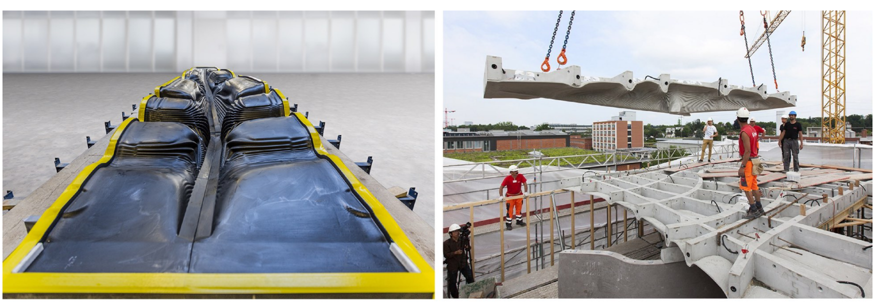
2.1.3 Additive manufacturing for concrete

Subtractive methods for making moulds come with the disadvantage of waste, and alongside reconfigurable moulds, they are limited to geometries that have no undercuts or inner voids. Additive manufacturing techniques address both issues related to geometry and waste. Recent developments in digital fabrication have made various 3D printing approaches widespread (Buswell et al., 2018). Work by Contour Crafting (Khoshnevis, 2004), D-Shape (D-Shape, 2019; Cesaretti et al., 2014), research at Loughborough University (Lim et al., 2012), XTreeE (Gaudillière et al., 2019; Duballet et al., 2017) (Figure 2.8a), TU Eindhoven (Salet et al., 2017) and ETH Zurich (Anton et al., 2019; Szabo et al., 2019) have demonstrated the potential of printing techniques involving layered extrusion and the deposition of concrete to reduce or even eliminate formwork altogether. Though still in a nascent stage, concrete-3D-printing techniques developed in research environments are already being used to construct small permanent structures. For example, the pedestrian bridge built in Gemert, The Netherlands by TU Eindhoven in collaboration with the contractor BAM infrastructure (Figure 2.8b) (Salet et al., 2018), or the 26m long pedestrian bridge built by researchers from Tsinghua University (School of Architecture) in Shanghai, China (Figure 2.8c) (Ravenscroft, 2019).

However, the direct production of curved 3D-printed concrete elements is still relatively slow and requires further developments to overcome some of the remaining practical limitations. Furthermore, unless designed according to unreinforced construction principles (Bhooshan et al., 2018), structural elements that are compliant with design standards such as Eurocodes cannot yet be produced because reinforcement cannot be introduced as part of the extrusion process. Therefore, 3D-printed concrete elements are mostly used as formwork components (Bos et al., 2016; Wangler et al., 2016).

When used as moulds, 3D printed structures can be produced in various ways. Binder jetting is a 3D printing method which is well-suited for the production of articulated sand moulds for three-dimensional triangulated trusses (Morel and Schwartz, 2015) or complex surface geometries. Examples of 3D printed sand moulds being used on an architectural scale are the “Incidental Space” installation for the Swiss pavilion at the 2016 Architecture Biennale in Venice and the “Smart Slab” in the recently completed DFAB House (Aghaei Meibodi et al., 2018; Dfab, 2019) (Figure 2.9).

While 3D-printed moulds offer geometrical freedom with relative ease (Ruffray et al., 2017), they are non-recyclable, heavy, need significant scaffolding, and add additional weight to the structure if used as lost or stay-in-place formwork.



(a) (b)

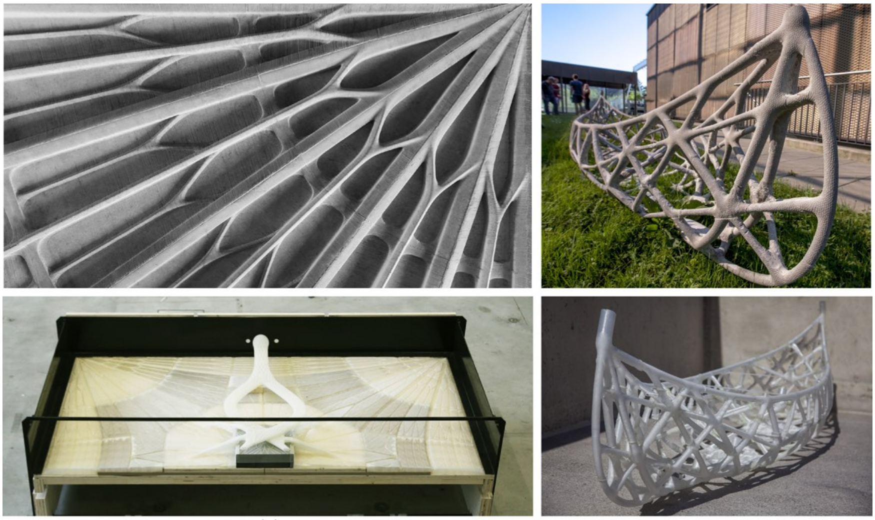
Figure 2.9: “Smart Slab” of the DFAB house at Nest EMPA Dubendorf, Switzerland built using 3D printed sand moulds: (a) binder jet sand printed mould for a section of the slab; (b) assembly of precast slab sections on-site (photo credit: (a) Andrei Jipa; (b) Tom Mundy).

Figure 2.10: FreeFab Wax moulds produced by 3D-printing and milling wax with a robotic arm (FreeFab, 2019).

Using alternative materials in the printing process addresses the need of easy recyclability. For example, the FreeFab™ Wax moulds developed by Laing O'Rourke (FreeFab, 2019) and fabricated using a combination of 3D printing and milling can be 90% recycled (Figure 2.10).

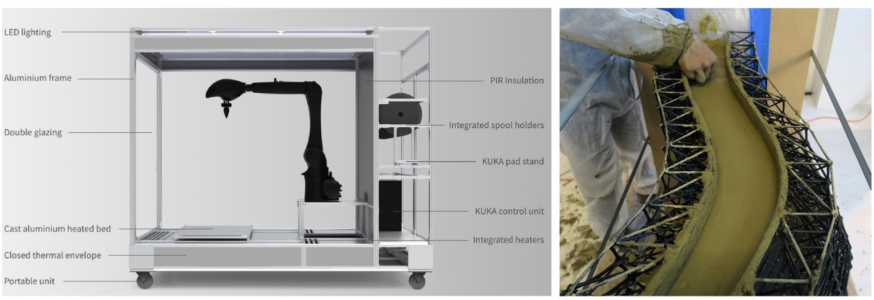
The drawback of using wax moulds is their heaviness which has consequences for transportation and supports on site (Eisenbach, 2017). Lighter and recyclable moulds can be manufactured using Fused Deposition Modelling (FDM) techniques, which produce thin plastic moulds for intricate structures and are easy to recycle. Such thin plastic moulds have been used for moulding a weight-saving funicular concrete slab (Jipa et al., 2019) (Figure 2.11a) or the skeletal structure of a canoe (Figure 2.11b) (Jipa, Bernhard, Ruffray, Wangler, Flatt and Dillenburger, 2017; Jipa, Bernhard and Dillenburger, 2017).

Commercial start-ups such as BASF (BASF, 2019) and BigRep (BigRep, 2019) or AI-Build (AIBuild, 2019) and KUKA Robotics (KUKA, 2019) are working on large scale 3D-printing solutions to be used in construction (Figure 2.12). FDM plastic printing is also currently being used in combination with Smart Dynamic Casting (described in Section 2.1.2) to produce more varied and branching geometries (Burger, 2019).



(a) (b)

Figure 2.11: Thin 3D-printed plastic moulds: (a) Funicular floor slab; (b) SkelETHon concrete canoe (photo credit: (a) and (b) Andrei Jipa).



(a) (b)

Figure 2.12: Commercially available large scale 3D printing: (a) The AI-Maker of AI-Build; (b) concrete formwork case study (photo credit: AI-Build).

2.1.4 Stay-in-place formwork

Formwork that does not need to be removed can provide a way for optimising concrete construction in terms of reducing cost and minimising labour.

Two types of stay-in-place formwork can be distinguished: lost formwork and structurally permanent formwork. The first does not fulfil any additional role upon completion of the structure, while the latter, becomes an

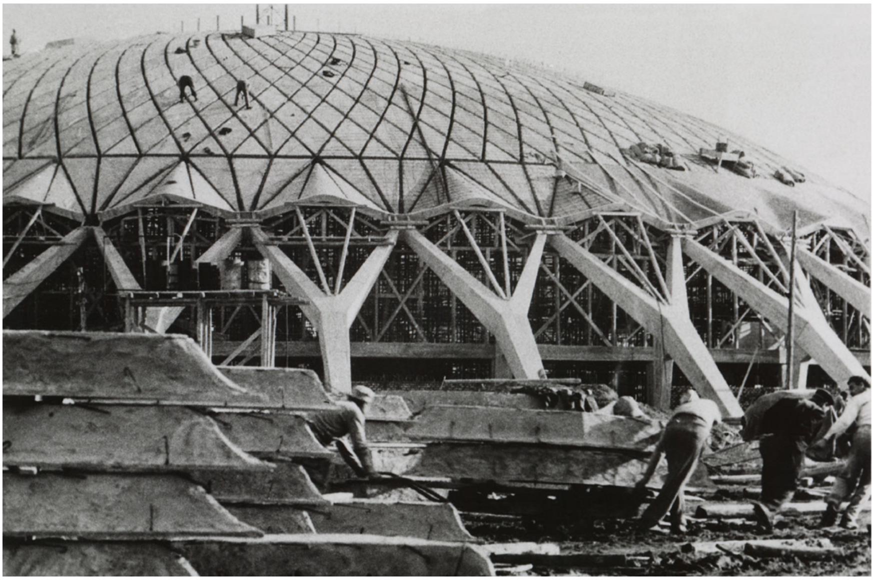


Figure 2.13: Pier Luigi Nervi's Palazzetto dello Sport under construction, showing the precast stay-in-place formworks (photo credit: Fondazione MAXXI, P. L. Nervi Archive).

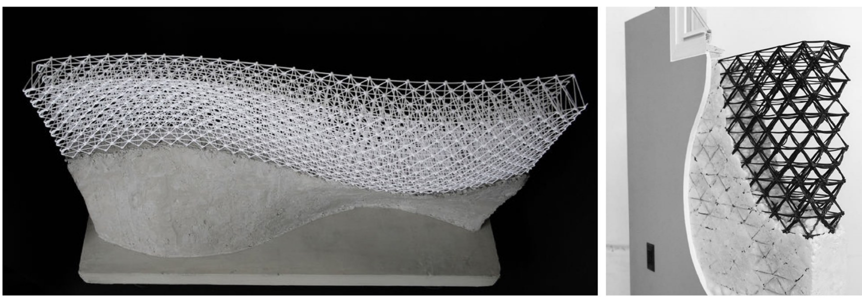
active part of the structure. This can be both in terms of structural system or other aspects such as building physics and insulation.

Pier Luigi Nervi routinely used precast ferrocement elements as structurally active stay-in-place formwork for his domes and other optimised structures. One such example is the Palazzetto dello Sport, built in 1957 (Iori and Poretti, 2013) (Figure 2.13).

Similarly, the Uyllander bridge built over the Amsterdam-Rhine Canal uses prefabricated Glass Fibre Reinforced Polymer (GFRP) panels as permanent formwork for the concrete deck. This allowed for an optimised building procedure (Mathijsen, 2013). By using precast GFRP elements the deck could be cast in place without the need for additional supports, significantly reducing the hindering of traffic underneath the bridge.

Fibre-Reinforced Polymer stay-in-place formworks are not an uncommon practice in bridge building, a state-of-the-art review can be found in (Nelson et al., 2014). Nonetheless, these solutions still rely on a mould for the prefabrication of the stay-in-place formwork, which may lead to serialisation or limited diversity.

Figure 2.14: CFRP filament winding stay-in-place formworks developed at Institute of Building Structures and Structural Design (ITKE) Stuttgart (Waimer and Knippers, 2015).



(a) (b)

Figure 2.15: Robotically printed plastic meshes used as leaking formwork: (a) MeshMould concrete wall prototype; (b) Branch Technologies wall section with insulation (photo credit: (a) Gramazio Kohler Research; (b) Branch Technology).

(a) (b)

Figure 2.16: Reinforcement cages used as leaking stay-in-place formwork for concrete: (a) complex reinforcement cages of the Taichung Metropolitan Opera House, designed by Toyo Ito, Taichung, Taiwan; (b) robotic fabrication of MeshMould wall of the DFAB house at EMPA Dubbendorf, Switzerland (photo credit: (a) Kai Nakamura; (b) EMPA).

Using other composite fabrication processes, such as filament core winding, research conducted at the Institute of Building Structures and Structural Design (ITKE) in Stuttgart addresses the problem of serialisation in the production of curved geometries. The developed hybrid composite construction method produces a sandwich composite consisting of a foam core and two Carbon Fibre Reinforced Polymers (CFRP) layers (Waimer and Knippers, 2015; La Magna et al., 2016). Figure 2.14 shows a concrete bench prototype built with this method.

Alternatives such as MeshMould (Hack et al., 2013) (Figure 2.15a) and Branch Technologies (Branch-Technology, 2019) (Figure 2.15b) strive to reinvent the mould altogether by 3D printing plastic curved lattice structures (meshes) that are later filled with concrete or foams. While these plastic meshes are considered lost formwork, the same type of leaky formwork approach could be used to create a system where the formwork acts as reinforcement.

Perhaps one of the most impressive examples of stay-in-place formwork is that of the Taichung Metropolitan Opera designed by Toyo Ito in collaboration with Cecil Balmond at Arup Advanced Geometry Unit. The doubly curved surfaces would have been extremely costly to produce and reinforce with traditional approaches. The extensive, complex reinforcement was used as formwork (Hauschild and Karzel, 2012)(Figure 2.16a).

Further development of MeshMould was targeted at using robotic fabrication to weld the meshes out of steel rebars that can act as a leaking formwork and reinforcement for specially engineered concrete that is cast or sprayed. The developed formwork was recently used to build a curved wall in the DFAB House (Dfab, 2019; Hack et al., 2017) (Figure 2.16b).

2.1.5 Flexible formworks

Flexible formwork systems move away from the use of solid materials that are milled, printed or otherwise shaped to form a rigid mould. Flexible systems use prestressed membranes, cable nets or bending-active elements to form concrete.

The use of textiles as formwork for concrete has a long history in terms of experimental work throughout the 20th century (Veenendaal et al., 2011). Due to its lack of rigidity compared to other materials, fabric formwork has not made it into an established production method, most probably due to the lack of tools for designing and calculating such structures (Veenendaal

Figure 2.17: Flexible formwork technologies employing fabrics and hybrid systems consisting of cable-nets, bending-active elements or inflatables: (a) Fabric formed concrete trusses by C.A.S.T, University of Manitoba, Canada (Cauberg et al., 2012); (b) NEST HiLo roof prototype built on a cable-net and fabric formwork by the Block Research Group, ETH Zurich, Switzerland; (c) concrete shell built on a bending-active GFRP grid-shell at Ecole des Pontes, Paris, France (Cuvilliers et al., 2017); (d) domed concrete housing units built with the Bini system. (photo credit: (b) Michel Lyrenmann; (d) binishells.com).

and Block, 2014). Nevertheless, the ever-increasing need for bespoke formwork geometries has fuelled renewed research into the topic, which resulted in the development of fabric-formed concrete elements for various architectural and structural applications (Orr et al., 2013*b*; West, 2016). The developments are focused on the technology as a whole, tackling aspects related to architecture, structure and computation. The former Centre for Architectural Structures and Technology (C.A.S.T.), founded by Mark West at the University of Manitoba, Canada, focused on the development of fabric formwork technology for various types of columns and beams (Orr et al., 2014; West, 2016; Hawkins et al., 2016; Kostova et al., 2017) (Figure 2.17a). At the University of Bath, research is being carried out mainly into fabric formed beams focusing on structural performance and analysis of fabric formed structures (Orr and Darby, 2012; Tayfur et al., 2016). Simultaneously, research conducted within the Block Research Group at ETH Zurich focuses on the development of computational tools aiding in the design and optimisation of such formwork.

The NEST HiLo roof prototype is the most recent construction-scale example of a structure built with a flexible fabric formwork system. The carbon-fibre reinforced concrete structure was built on a prestressed cable-net falsework and textile shuttering. The optimised and actively controlled formwork system allowed a geometrically complex and highly efficient structure to be built (Block et al., 2017; Echenagucia et al., 2019).

While these flexible systems can allow for an efficient construction without the traditional material and labour costs, they can be challenging in terms of layered integration, predicting and controlling the geometry while pouring the concrete, and for calculating the final deformed shape. Solutions to the problems of prediction and control in their construction have been developed by (Liew et al., 2018; Stürz et al., 2016) (Figure 2.17b). Furthermore, tensioned fabric systems are limited to anticlastic geometries, although further geometric freedom can be achieved when fabrics are combined with bending-active systems (Coar et al., 2017; Cuvilliers et al., 2017) (Figure 2.17c) or pneumatic and inflatable systems (Pronk and Dominicus, 2011), for example Wallace Bird's Radome system (Bird and Kamrass, 1956). These also have a relatively long history in the forming of concrete structures, starting with patents for hollow-core concrete dating as far as 1907 (Boyle, 1907). Similar techniques have then been patented and used throughout the 20th century for constructing shells. Some examples being the low-cost housing of Neff (Wallace, 1945), the construction method patented by Harrington (Horrall, 1964), the shells built by Bini (Roessler and Bini, 1986; Bini, 2019, 1967) (Figure 2.17d) or Heinz Isler (Chilton and Chuang, 2017).

An in-depth overview of the history of flexible formwork technologies and their current use is given in Veenendaal et al. (2011) and Hawkins et al. (2016).

Combining textiles with additional flexible elements can internally support the formwork to create a hybrid structure that eliminates much of the need for falsework. They also enable the fabrication of synclastic-like geometries and self-stressed, stable formworks.

While fabric formwork may be an approach that successfully reduces the amount of material used, thus reducing overall waste, it has some disadvantages related to the need for extensive patterning. The textiles used for such formwork are usually woven materials, which need stitching and pattern optimisation in order to avoid wrinkling when taut.

The potential of using advanced textiles for fabric formwork is discussed by (Brennan et al., 2013). Some of the main identified points for future formworks are :

- using materials with anisotropic properties,
- improving structural performance by introducing high-strength textiles, and
- using textiles as sacrificial formwork and/or reinforcement for complex curved geometries.

2.2 Textiles, composites and forming

Fabric formwork can be a promising solution for both waste reduction and overall material saving in concrete construction. Some of the challenges associated with the typical fabrics used in these systems are the need for complicated cutting patterns, extensive stitching, sewing or otherwise joining of parts to form complex components, the directional material properties of the textile, which can cause wrinkling. Moreover, the textile material characteristics and mechanical properties depend greatly on the textile formation process and the fibres used.

With the aim to better understand how the use of fabric formwork could be improved, this section gives an overview of the different textile formation processes, the resulting properties and common uses in construction.

2.2.1 Technical textile composites

From their introduction in the 1930s fibre composites have been used in a great range of lightweight applications needing high strength. Applications can be found in areas such as aerospace, automotive, nautical, infrastructure, medical and sports equipment. Their outstanding properties in terms of strength and lightness make them ideal for these specialised applications.

Some of the main advantages of composites are as follows (Cherif, 2016):

- lightweight,
- high specific stiffness and strength,
- excellent fatigue resistance,
- outstanding corrosion resistance (compared to metals),
- fabrication of directional mechanical properties,
- low thermal expansion, and
- high dimensional stability.

In construction, their main application is in infrastructure projects, reinforcement of high-performance concrete structures or retrofitting and strengthening of existing structures (Motavalli et al., 2010). Glass, carbon and aramid fibres are the most common fibres used in construction.

2.2.2 2D and 3D technical textiles

Fibre composites are generally an assembly of fibre textiles bound together by a matrix material[1]. The final desired shape formed by the textile composites is traditionally created by layering multiple textile sheets, called plies. Plies need to be cut, layered and stitched together to create the final three-dimensional form. For complex components this can be a laborious process in which a number of laminates need to be joined by co-curing or adhesive bonding. These have low through-thickness mechanical properties and are prone to delamination (Hu, 2008).

[1]Most commonly the matrix material is a thermo-hardening polymer, but it can be any range of polymers or cementitious materials in the case of concrete construction.

However, with current textile technology, three-dimensional textiles can also be produced (Mouritz et al., 1999)[2].

Three-dimensional textiles become very attractive given the advantage of creating the form directly into the desired shape and the lack of cutting, stitching, and layering. Most commonly textile structures are classified in terms of the technique used for their production. As such textiles can be manufactured by Fangueiro et al. (2011)[3]:

- weaving - interlacement of two yarns at angles of 0 (weft) and 90 (warp) (Figure 2.18a),
- braiding - interlacing of yarns forming a tube (Figure 2.18b),
- knitting- interlocking of one or more yarns producing a textile with loops (Figure 2.18c), and
- non-woven - sheets of fibres formed by any means and bonded together by any means except for knitting or weaving (Figure 2.18d).

However, according to Fangueiro et al. (2011); Fangueiro and Soutinho (2011) a meaningful classification can be made in terms of the orientation of the fibres within the textile structure, regardless of the fabrication technique.

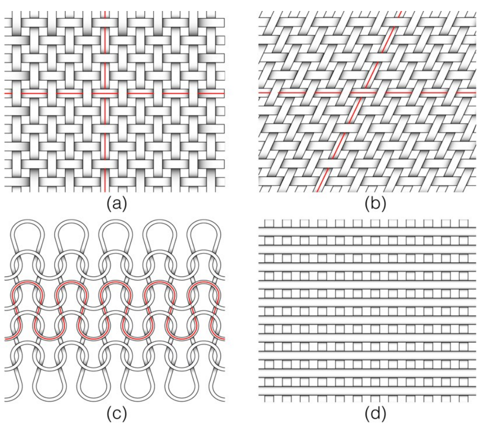


Figure 2.18: Types of textiles by production method: (a) woven textile; (b) braided textile; (c) knitted textile (weft-knitted); (d) non-woven textile.

[2]Weather produced as 2D plies that are layered or as 3D textile preforms, a mould is always used to produce the final composite part.

[3]This classification leaves out Automated Fibre Placement and Filament Winding Techniques as they form structures directly and not textiles.

Most notably:

- planar two-dimensional (2D) - produce sheets of material that can be non-woven, woven, braided or knitted,
- three-dimensional (3D)[4] - solid structures with fibres oriented in the third dimension or 3D shaped geometries,
- directionally oriented (DOS) - fabric structures that include reinforcing yarns as inlays oriented according to main forces directions, and
- hybrid structures - combining properties of two different formation techniques in one process, commonly produced by sewing or warp-knitting.

An overview of the classification in terms of dimensionality and production method is shown in 2.19.

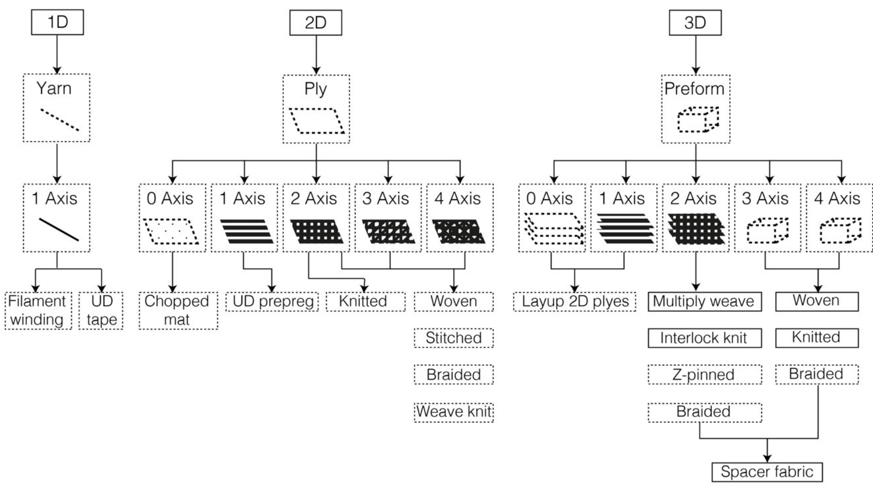


Figure 2.19: Classification of textiles according to their dimensionality.

[4]Three-dimensional fabric structures are difficult to classify. They can be considered three-dimensional due to fibre orientation, or the geometry of the resulting piece (e.g. a plain knitted textile in the shape of an elbow - the fabric structure itself is two-dimensional but the resulting form is three-dimensional).

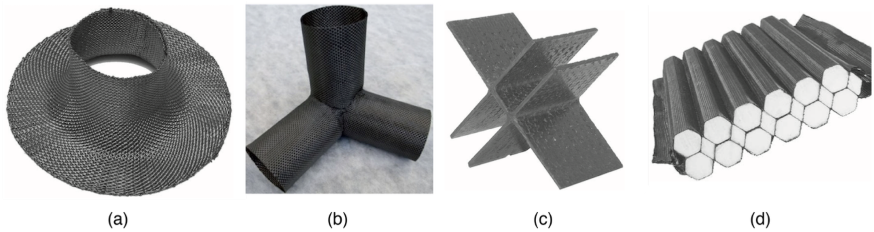


Figure 2.20: Examples of 3D woven structures: (a) polar/orthogonal woven structure (Amirul Islam, 2012); (b) formed LI-node structure (Schegner et al., 2019); (c) hexagonal cell structure (Amirul Islam, 2012); (d) double blade joint (Amirul Islam, 2012).

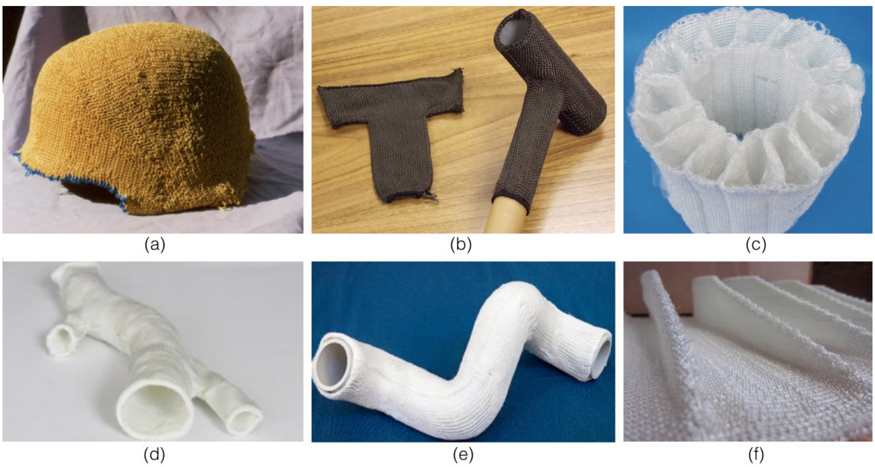


Figure 2.21: Examples of 3D knitted structures: (a) aramid fiber helmet (De Araújo et al., 2004); (b) carbon fibre t-section tube (Preform-Technologies, 2017); (c) biaxial reinforced tubular spacer fabric (Abounaim et al., 2009); (d) tubular branching structure (Pandey and Kumar, 2016); (e) biaxial reinforced shaped tubular structure (Bollengier et al., 2017); (f) biaxial reinforced rib-stiffened structure (Bollengier et al., 2017).

Compared to other production methods, weaving and knitting have the advantage of not needing specialised equipment. Existing looms and knitting machines, common in the textile industry, can be easily modified to create technical textiles (Hong et al., 1994; Mouritz et al., 1999).

Woven fabrics are the most commonly used textiles for structural applications, having good stability in warp and weft directions and offering higher strength and stability compared to other fabric formations due to the straightness of the fibres Sondhelm (2000). A large variety of 3D woven fabrics can be made, including contoured and polar fabrics (Figure 2.20a), various joint configurations (T, Pi, I, Li) (Figure 2.20b and c), multilayered structures and hollow or spacer structures (Figure 2.20d). The possibilities of creating such 3D woven structures and methods for their manufacture is well documented in literature (Amirul Islam, 2012; Sennewald et al., 2016; Chen, 2012; Chen et al., 2011; Schegner et al., 2019).

One of the main drawbacks of weaving is the strict fibre orientation of 0°and 90°, though some solutions exist for introducing other orientations, but at limited angles (Bilisik, 2012; Labanieh et al., 2016). Further drawbacks are related to the limited achievable curved geometries and the fixed material width. Though the straightness of the fibres provides high strength, it makes for a textile that is not as easily drapable to complex curved shapes.

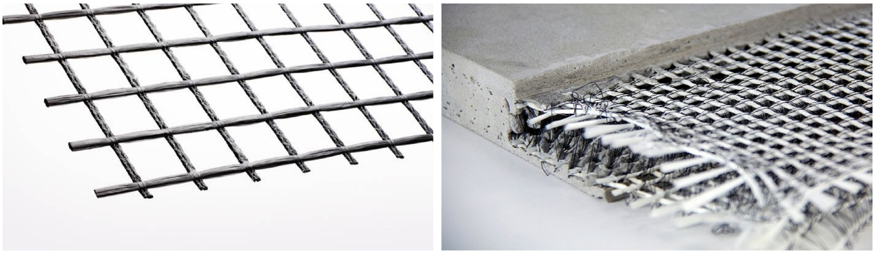
Knitting, on the other hand, is the most flexible textile production process (Ishmael et al., 2017). Knitted textiles conform easily to complex geometries and can be produced in a variety of geometries (Figure 2.21). This production and geometrical flexibility has recently gained them a more wider acceptance in composite manufacturing despite their lower mechanical properties. Comparative overviews between the different manufacturing techniques, the resulting advantages, limitations and applications are discussed in publications such as Ishmael et al. (2017), Mouritz et al. (1999) or Hu (2008).

2.2.3 Technical textiles in construction and architecture

Textiles and textile composites are becoming increasingly more popular in the construction sector due to their desirable properties such as lightness, strength and resistance. This popularity is driven by the desire for higher performing and sustainable structures, which could be achieved by replacing materials such as wood, concrete and steel (Kumar, 2016).

In construction, some of the earliest and most common use of high-strength textiles has been in geotechnical applications (Rawal, 2012). However, their more recent use as textile reinforcement for concrete (TRC) is one of the more promising application areas in construction (Fangueiro and Gonigho-Pereira, 2011; Curbach and Jesse, 1999).

TRC uses of fibrous formations as the replacement for steel rebars in the reinforcement of concrete. These formations are generally woven or warp knitted out of strands of technical grade yarns and coated with a polymer matrix. Flat and lightly shaped textile reinforcement is commercially available and used in architectural and construction applications, facades and



(a) (b)

Figure 2.22: Textile concrete reinforcement: (a) Solidian CARBONGRID; (b) Hering - betoShell® spacer fabric textile reinforcement (photo credit: (a) Solidian; (b) R. Thyroff).

(a) (b) (c) (d) (e)

Figure 2.23: Textile reinforced concrete structures: (a) U-shaped bridge - TU Dresden, Germany; (b) Hypar concrete shells - RWTH Aachen, Germany (Scholzen et al., 2012); (c) concrete shell - TU Chemnitz; (d) NEST HiLo concrete shell roof prototype - ETH Zurich, Switzerland; (e) branching structure - University of Stuttgart, Germany (Jonas et al., 2018) (image credit: (a) Wikimedia Commons; (c) Sandra Gelbrich; (d) Michael Lyrenman).

for retrofitting (Solidian, 2019) (Figure 2.22a). Unlike steel, textile reinforcement does not corrode, minimising the need for covering and resulting in minimised concrete thickness. Examples such as the spacer fabric betoShell® system (Hering, 2019) (Figure 2.22b) used for facade panels in the Arnhem train station prove the feasibility of using textile reinforcement to create lightweight and material-efficient solutions.

Other than minimising material use, TRC can provide components with a longer service life than conventional concrete and can be used to extend the life-span of existing structures. It is an economical material in architectural cladding, 3D shaped elements and permanent formwork (Peled et al., 2017; Tsesarsky et al., 2013; Verwimp et al., 2014, 2016; Remy et al., 2011; Remy, 2011). The fibrous nature of textiles allows for greater flexibility in the shaping of reinforcement compared to steel, which has made them an interesting area of research for light, thin and doubly curved concrete (shell) geometries. Moreover, fibres within the textile can be positioned in multiaxial orientations such that the load-bearing capacity of the constructed elements is improved (Hegger et al., 2004; Weiland et al., 2008; Hegger et al., 2017).

Examples of the possibilities offered by using textile reinforcement are the U-profile pedestrian bridge built at the TU Dresden (Michler, 2013) (Figure 2.23a), the hypar roof structure of the University RWTH Aachen (Scholzen et al., 2012) (Figure 2.23b), or the more recent carbon-fibre-reinforced concrete shell pavilion built by TU Chemnitz (Petzoldt et al., 2015) (Figure 2.23c), the NEST HiLo roof prototype built at ETH Zurich (Echenagucia et al., 2019) (Figure 2.23d), or the branching glass and carbon-fibre braided structure from the University of Stuttgart used as stay-in place mould (Möhl et al., 2017; Jonas et al., 2018) (Figure 2.23e). An overview of textile reinforced shells built in Germany is given by (Scheerer et al., 2017; Rempel et al., 2015).

Some of the challenges that come with textile reinforcement of concrete are the need for patterning and proper spacing of different reinforcement layers. Textile reinforcement mats are largely based on woven textile principles which can be limited in directional properties. This results in a need for several layers of materials to cover every possible load case. Additionally, patterning of reinforcement from flat mats results in discontinuous fibres and challenges in approximating surfaces with a high degree of curvature.

Composites in construction are not only used in conjunction with concrete but also directly as lightweight structures. Moving away from industrial weaving processes, research at the University of Stuttgart investigates the possibilities of using complex fibre structures for architectural geometries using integrated design and fabrication strategies inspired by principles in nature (Knippers and Speck, 2012). Several pavilions designed and built by the Institute for Computational Design (ICD) and the Institute of Building Structures and Structural Design (ITKE) use a mould-less winding technique in conjunction with digital fabrication techniques to produce economic and composite structures with structurally dependent fibre orientations (Dörstelmann et al., 2014; Weigele et al., 2013; Schieber et al., 2015; Reichert et al., 2014; La Magna et al., 2016; Solly et al., 2018) (Figure 2.24).

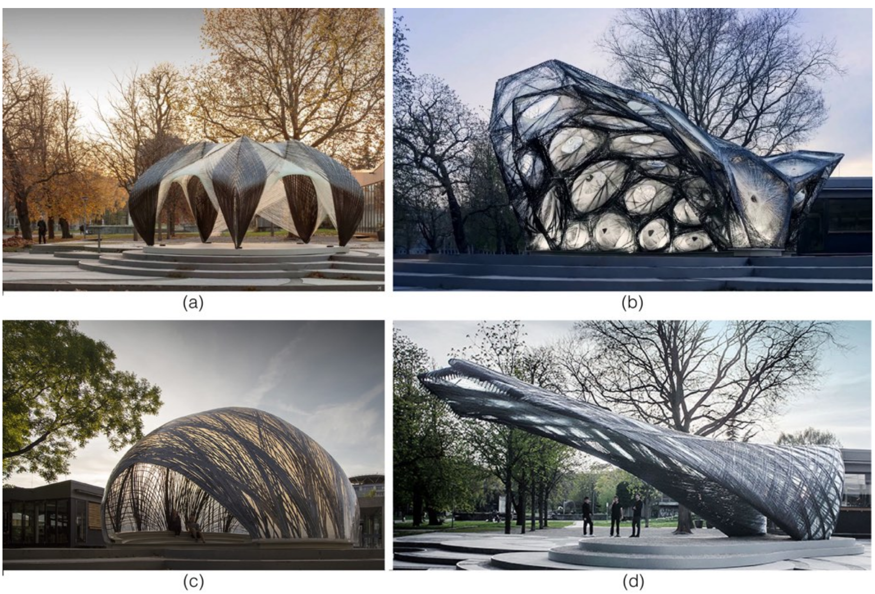


Figure 2.24: Carbon and glass fibre research pavilions built by ICD and ITKE at the University of Stuttgart using various fibre winding approaches: (a) 2012-2013 pavilion built with one robotic arm; (b) 2013- 2014 pavilion built using two robotic arms; (c) 2014-2015 pavilion built using one robotic arm and an inflatable formwork; (d) 2016-2017 pavilion built using a combination of robotic arms and drones (image credits: (a) Heiko Stachel; (b) - (d) ICD/ITKE Stuttgart).

2.3 Knitting

Knitting[5] has been used extensively in the garment industry and has a long industrial development history dating back to 1589 when the first manual knitting machine was invented by William Lee (Gries et al., 2015).

Today, CNC knitting technology has made it possible to directly fabricate complex three-dimensional geometries with integrated features. Knitting is being successfully used in performance (sports) wear and medical applications and has slowly gained attention in the field of technical textiles and composites due to the ease of manufacturing, afforded by the well-developed process, and their exceptional formability. The process is not only easily adaptable to form various geometries, but also to use varied fibres, including high E-modulus yarns such as glass, carbon or aramid fibre (Brennan et al., 2013; Leong et al., 2000; Hong et al., 1994).

The same characteristics have also made knitting an attractive process in an architectural context where it is being used to explore new sensorial environments (Ahlquist, 2015, 2016) (Figure 2.25a) or develop hybrid lightweight structural systems (Tamke et al., 2016; Thomsen et al., 2015; Lienhard and Knippers, 2015) (Figure 2.25b). Knitted textiles are being used in temporary architectural installations (Sabin et al., 2018) (Figure 2.25c) and as permanent facade cladding (Vonk, 2019) (Figure 2.25d).

Despite all its advantages, knitting also poses a series of challenges when used in a structural context (Rudd et al., 1990; Bruer et al., 2005; Padaki et al., 2006): high E-modulus fibres can get damaged during production, the high degree of curvature in yarn decreases the strength of the textile compared to a woven one, mechanical properties are hard to model and predict, and yarn architectures can vary significantly in loop length and density and therefore local mechanical properties are more difficult to predict. Some of these problems have been addressed through the introduction of straight fibre inlays, which act similarly to a woven fabric, or tailoring the local material properties to make them suitable for technical application (Cebulla et al., 2002; Cherif, 2016; Jiang et al., 2003; Li and Bai, 2010; Philips et al., 1997; Andersson and Eng, 1994).

Knitting technology is well documented, explained and available in technical literature, including publications such as Spencer (2001*a*) Spencer (2001*b*)

[5] This section specifically refers to weft-knitting.

(a) (b) (c) (d)

Figure 2.25: Knitted textiles in architecture: (a) sensory environments - Taubman College, University of Michigan, USA; (b) Hybrid tower - CITA, Copenhagen, Denmark; (c) MoMa PS1 - Jenny Sabin, Museum of Modern Art, New York, USA; (d) knitted lace composite cladding of VAVO, ROC Tilburg - Mariette Adriaanssen and Petra Vonk, The Netherlands (image credits: (a) Sean Ahlquist; (b) Anders Ingvartsen; (c) Pablo Enriquez; (d) Petra Vonk).

and Cherif (2016). A brief overview of knitting technology and the working of machinery used in the production of weft-knitted textiles will be given in Chapter 5 alongside existing and developed strategies for producing weft-knitted textiles for used for moulding.

2.3.1 CNC production of knitted textiles

Knitted textiles are produced using machines that have been developed to produce shaped textiles in a highly efficient computer-controlled process. This automation also required the development of programming methods for steering the CNC process. In general, this is proprietary software developed by the manufacturer. These are CAD systems that allow a user to design a knitting pattern, which is translated into code that makes it possible to operate the machine. A knitting pattern is designed as a 2D rectangular diagram consisting of rows and columns of symbols that describe the actions of the machine.

Knitting software produced by Shima Seiki, Stoll or Steiger all include functions for design, evaluation, simulation and production giving the user control over machining preferences and settings (ShimaSeiki, 2019; Stoll, 2019; Steiger, 2019). However, these functions need to be designed and programmed by a skilled technician in a manual process where each symbol is deliberately decided. While all of the proprietary software provide some strategies for shaped knits, these are focused on garments.

2.4 Summary

The solutions presented within this section have proven to be viable and efficient solutions for issues of mould reusability, waste reduction, cost effectiveness, labour reduction and reinforcement of bespoke geometries within concrete construction. However, each solution focuses on a optimising one single problem of the many faced when dealing with bespoke geometries.

Alternatives to traditional formwork are in a nascent stage in the realm of digital fabrication, such as Mesh Mould, Smart Dynamic Casting, layered extrusion as well as spraying processes onto woven textiles. These processes are at this stage rather slow and technologically complex in the construction step and need substantial human assistance and knowledge onsite or in prefabrication.

Flexible moulds effectively address the problem of mould reusability, but not other challenges related to on site assembly and labour intensiveness. On the other hand, stay- in-place formwork addresses the issue of labour intensiveness but not implicitly the problem of material waste or reinforcement.

Finally, fabric formwork and textile reinforcement effectively address the issue of waste and material saving within a structure, but with woven textiles, shapes are limited to those that can be approximated by sheets or need to be stitched from a large count of elements. Therefore, they are faced with challenges related to patterning, positioning and directionality of material properties. Therefore, a more integrated approach to formwork and reinforcement is desirable. One which would take advantage of prefabricated solutions in order to minimise waste, cost, labour and have optimal material placement.

Knitting offers a vast range of geometrical freedoms, for example allowing for doubly curved surfaces, integrating features (channels and openings), multi-layer and multi-material textiles and hybrids between knitting and woven textiles (introducing textile reinforcement). All this can be done in a highly automated fashion on existing industrial knitting machines. However, while the machines are well described, mechanically advanced and offer a very flexible production process, their programming is still a specialised labour intensive process. The time-consuming, manual process associated with the patterning of complex geometries not based on known primitives can be a bottleneck in the production of non-standard, non-repetitive construction scale textiles.

Chapter 3

Summary

Based on the presented literature review summarised in Chapter 2.4, this chapter discusses the resulting research goal and the necessary objectives to achieve this goal.

3.1 Research objectives

The main objective of this dissertation is to:

Develop a feasible, efficient and economical stay-in-place knitted mould needing minimal falsework and is part of a flexible formwork system for complex concrete structures.

Fabric formwork systems generally use single-layered woven fabrics with uniform material properties. To accommodate for tensioning and the insertion of auxiliary systems, textiles need to be fitted with functional details such as channels and openings. If wrinkles want to be avoided, producing a shaped textile with integrated features relies on extensive tailoring and joining of different flat sheets of material. In contrast, knitted textiles can be tailored to drape doubly curved and three-dimensional shapes. Furthermore, they can be designed and fabricated directly to include very specific local properties, channels, grooves and openings, without the need for glueing, welding or stitching several parts together. They can be easily prefabricated using CNC knitting machines and therefore have the advantage of lowering the cost and labour of manufacturing complex formwork parts.

Transforming the tensioned knitted formwork into a load-bearing concrete structure represents an innovative and exciting challenge. The objectives related to this are threefold:

1. **Design:** conceptualise/investigate a moulding system using a weft-knitted fabric at a component and structural level.
2. **Fabrication:** create the necessary computational tools that enable a streamlined fabrication process of the textile.
3. **Construction:** Demonstrate the opportunities of such a system by investigating possible constructions and concreting strategies.

3.2 Thesis structure

This thesis is structured in four parts. Part I presented the context and motivation for the research, gave an overview of the relevant state of the art and resulting research objectives. The other parts describe the developed physical and computational methodologies constituting the moulding approach, present the experiments and prototypes and offer a reflection on the contributions and possible future work. A brief overview of each part and chapter is given below.

Part II: Approach

Chapter 4: Forming system

This chapter describes the proposed forming system (KnitCrete) and it's possible applications. The system specifically uses a custom 3D-knitted textile as shaping element for concrete structures. In this approach, after tensioning or draping over a falsework, the textile is first coated with a thin and lightweight layer of fast-setting cement paste that reduces textile deformations while casting. Depending on the size, the stiffened textile can be used as a standalone mould or as part of a flexible fabric formwork system. Applications for such an approach range from simple building components such as beams and columns, to complex nodes and surface elements, which can be both structural and non-structural in nature.

Chapter 5: Weft-knitted textile formations

Industrial CNC knitting machines are used to produce the knitted textiles used in this research. This chapter briefly describes knitting technology, specifically flat bed weft-knitting, which is a flexible production process for complex and doubly curved geometries. Existing and developed strategies for producing various textile configurations are presented, focusing on their relevance for use as moulds for concrete.

Chapter 6: Computational knitting

A knitting pattern is needed to fabricate a knitted textile. The knitting pattern defines a set of instructions for the CNC knitting machine to follow. Current software offers only limited possibilities, any custom, non-repetitive, non-developable knit pattern needs to be programmed by the user in a manner requiring detailed manipulation and understanding of knitting operations. This chapter presents the developed computational algorithms and tools developed for translating any given 3D geometry into a knitting pattern in an automated way. These patterns are used to fabricate physical objects.

Part III: Results

Chapter 7: Prototypes

This chapter presents the results achieved using the developed computational framework and system. It describes a series of prototypes which deal with the various aspects of designing, fabricating, assembling and constructing using the system. Three categories of prototypes are presented. First, a collection of components that present the various possibilities offered by knitting. Second, a small-scale bridge prototype that presents the system and highlights the advantages of using a lightweight scaffoldless system. Finally, a concrete shell (KnitCandela) shows an integration of the explored features throughout the research, tests the applicability of the developed computational approach and shows the possibility of scaling the system to an architectural size.

Part IV: Reflection

Chapter 8: Conclusions

This chapter presents the conclusions that can be drawn from the presented research. This is done by means of comparing the investigated forming method with existing methods in terms of material use, cost, assembly and labour. The chapter also gives an overview of the contributions of this dissertation with respect to the research objectives outlined in Chapter 3.1. Finally, a reflection on the advantages and limitations of the approach is presented outlining recommendations for possible future research.

Part II

Approach

Chapter 4

Forming system

This chapter describes the approach to building concrete (and concrete-like) structures using a lightweight, weft-knitted fabric as mould. In this approach, the weft-knitted textile is prefabricated using industrial flat-bed knitting machines, which are able to produce textiles with varied geometries and features. The lightweight textile is tensioned and coated with a thin stiffening material, in this particular case, a high-performance cement paste. The coated textile is used directly as mould or as part of a scaffold-less flexible formwork system. After a general description of the approach and possible applications in Section 4.1, this chapter discusses some of the functional and geometric design requirements for the moulds (Section 4.2) and presents possible approaches to assembling and tensioning the textile formworks (Section 4.3).

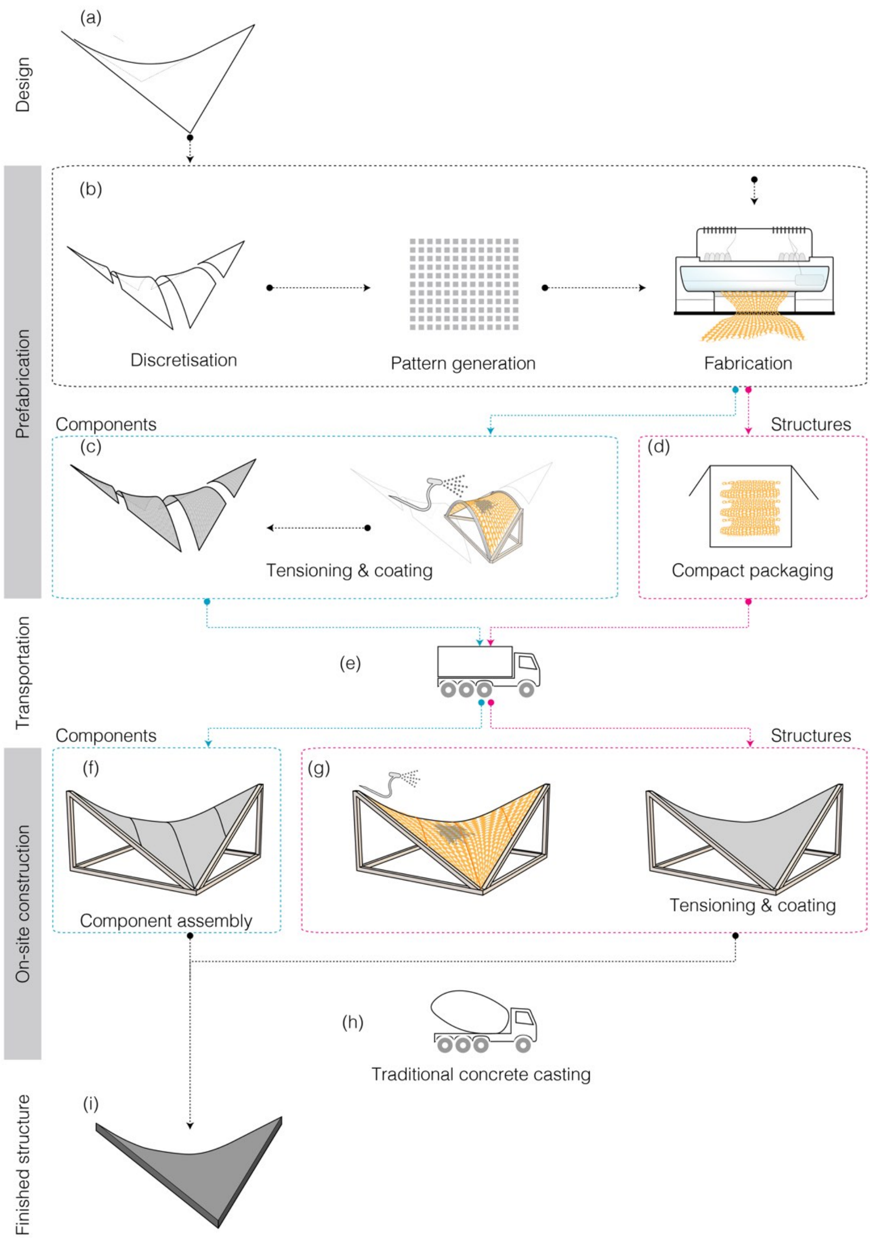


Figure 4.1: From design to finished structure overview of KnitCrete system: (a) design; (b) textile prefabrication steps; (c) components prefabrication by tensioning and coating the knitted textile; (d) packing of prefabricated textile; (e) transportation of coated components or uncoated textile to the construction site; (f) on-site assembly of components; (g) on-site tensioning and coating of prefabricated textile; (h) traditional concrete casting; (i) finished concrete structure after formwork is removed.

4.1 KnitCrete

Geometric detailing of custom formworks using traditional materials (timber, foam etc.) comes at the cost of labour and offcuts resulting in waste. Knitting offers a vast range of geometrical freedom, for example allowing for doubly curved surfaces, integrated features (channels and openings), multi-layer and multi-material textiles and hybrids between knitting and woven textiles, for example, to introduce textile (i.e. flexible) reinforcement. Furthermore, the prefabricated textile is lightweight and compact, making it easily transportable.

4.1.1 Transportable, lightweight, stay-in-place formwork

Figure 4.1 gives a principle overview of the proposed transportable, lightweight, stay-in-place formwork strategy. The system relies on a prefabricated weft-knitted textile (Figure 4.1b) which is either used to prefabricate mould components by tensioning and coating (Figure 4.1c), or transported to the construction site to be tensioned and coated (Figure 4.1g). On-site, the moulds are used to cast the concrete normally (Figure 4.1h).

The weft-knitted textile is produced in an automated fashion using existing industrial CNC flat-bed knitting machines. To fabricate the appropriate textile, the given 3D geometry needs to be translated into a 2D knitting pattern (Figure 1a-b). This pattern is a pixel-based diagram describing the actions of the machine during the fabrication process. This research developed algorithms to generate the patterns in an automated way directly from a given 3D geometry. This computational approach for generating these patterns will be described in Chapter 6.

The produced textile can:

- include channels for the insertion or guidance of extra reinforcing or shaping elements,
- be multilayered (e.g. spacer fabric) with differentiated material properties by layer,
- have specifically tailored surface textures and varied material distribution,
- allow the alignment of reinforcement or other functional elements such as hydronics, electrical wires etc.,

- be produced with the direct insertion of the above-mentioned elements during the knitting, and
- produce geometries with inner voids that are otherwise difficult to assemble out of individual parts.

Chapter 5 will give an overview of these features and fabrication strategies, both existing and developed in this research.

Depending on the element size and topology, several pieces of textile need to be connected to form the whole (see Subsection 4.3.1).

Next, the textile is tensioned and shaped into the desired geometry using rigid or flexible guides included within the textile, a rigid or flexible external frame or a combination of the two. Some of these assembly and tensioning possibilities will be discussed in Subsection 4.3.2.

The assembly can be approached as an on-site or a prefabrication process. Therefore, the textile can be:

- deployed on-site by tensioning into shape and coated to serve as stay-in-place moulding surface for a larger structure (Figure 4.1d, Figure 4.1e, Figure 4.1g),
- used off-site to form lightweight components consisting of coated weft-knitted textiles, which are prefabricated and then brought and assembled on-site to be used as stay-in-place formwork (Figure 4.1c, Figure 4.1e, Figure 4.1f).

This thesis mainly explored the latter strategy taking advantage of the fact that the prefabricated textile is lightweight and compact, making it easily transportable.

Once tensioned into shape, the textile can be used for casting concrete. However, using knitted textiles directly as the mould is not immediately evident, because they are softer/more flexible by comparison to similar shapes made of woven textiles. The downside of their lower stiffness can be offset by combining them with a stiffening coating. This can be done using a variety of materials that can be applied in a thin and lightweight layer[1]. This thesis only explored cementitious coatings.

[1] Coating materials may be: polymers (thermoplastic, uv-hardening, thermo-hardening etc.), gels, foams, and cementitious materials. The materials may be applied to the textile once tensioned, or can be pre-impregnated.

Finally, after stiffening, the resulting mould can be used for the application of concrete in a standard manner through manual troweling, spraying or regular casting[2].

Depending on the size and span of the final structure, strength is built up gradually by applying or pouring the concrete in one or more subsequent (thin) layers. Once the concrete has cured, external supports are removed and the stiffened textile remains part of the structure.

4.1.2 Application range

Though mainly targeted at complex geometries, the presented approach can be applied in a variety of cases, both standard and non-standard. The advantages of the approach lie not only in its geometrical freedom when it comes to doubly curved surfaces but in the possibility of integrating a large variety of features and properties in one production process.

The moulds can be used at different scales, for shaping building components or structures as a whole. Owing to the lightweight nature of the mould, the minimal need for scaffolding resulting in limited demand on foundations, and the ability to fabricate a perfectly fitting sleeve, this type of flexible formwork system can be used to:

- build structures in areas with low accessibility:
    - high-density urban locations,
    - places with no easy crane access, or
    - remote locations,
- build structures in areas with a need to not hinder traffic:
    - bridges over water, highways, ravines, train tracks, or
    - infrastructure upgrades,
- deploy structures quickly:
    - in temporary situations, or
    - in post-disaster cases,

[2] Though the approach does not exclude closed moulds, the work presented in this thesis has mostly focused on concrete shell structures that require a single sided and do not have to take hydrostatic pressure into account.

- retrofit existing structures with minimal intrusion:
    - in historically or otherwise protected areas, or
    - in fragile structural situations,
- build in environmentally sensitive conditions:
    - in protected areas, or
    - fragile structural situations,
- create complex transitions between standard formwork elements or building components.

Construction elements

The system can be used to produce both structural and non-structural elements. As the system is based on fabrics, it can be used to cast at least the same range of elements as the traditional fabric formwork techniques described in Chapter 2 and in Hawkins et al. (2016), Veenendaal et al. (2011), West (2016), and Pedreschi (2013). These can be categorised as follows:

- linear elements such as columns, beams, trusses and girders,
- surface elements such as walls, roofs, floors/slabs, folded plate structures, domes, vaults, shells,
- connections such as multi-directional nodes,
- foundations,
- facade elements, and
- furniture and other objects.

What sets this approach apart from other fabric formworks is the underlying fabric formation. Due to the specific use of a weft-knitted fabric as stay-in-place mould, both formal and functional possibilities can be extended.

Tailoring functionality

Tailoring the properties of the used knitted textile offers further performance enhancing possibilities in terms of the structure's construction and function. The textile may present anisotropic properties, with locally varying surface textures, densities or alignment and placement of material only where needed. Such features may assist during construction with the infill or retainment of material and offer resistance to localised loading.

The yarns that make up a single- or double-layered knitted textile can be varied with ease within each layer. This makes it possible to enhance performance by including high-strength technical yarns, specifically, technical fibres and reinforcing materials such as carbon-, glass-, aramid fibre bundles, and steel wire or strands. These yarns may be used as primary materials or straight inlays.

Other than providing guidance and alignment for extra reinforcing or shaping elements, the moulds can offer additional functionality for the finished structure, for example, through voids or channels for including hydronics, electrical wires, monitoring devices, climatisation or insulation materials. Voids may also be used for material saving or weight reduction in the finished structure and aid in building geometries that are otherwise difficult to demould.

Given the tailoring possibilities offered by the underlying textile formation, the moulding system begets combined functionality as shaping and functional or reinforcing element within the finished structure.

4.1.3 Material considerations

Two material parts need to be taken into consideration within the presented systems. These are the fibrous materials that make up the yarns of the weft-knitted textile, and the cement-paste coating. This subsection summarises these considerations.

Yarn choice

The choice of fibrous materials to be used for the knitted textile relies heavily on the requirements imposed onto the mould, interaction with other materials, and their suitability for being knitted. Some of these requirements may be related to:

- mechanical properties
    - if used for reinforcement,
    - to sustain pre-stressing.
- alkali resistance (being coated or integrated into concrete),

- hygroscopic or hydrophobic properties,
- conductivity,
- fire resistance,
- UV resistance,
- damage during machine knitting.

The used yarns can vary from common natural fibres such as cotton or jute to synthetic and technical yarns such as glass or carbon fibre. Ultimately, the range of possible materials is only limited by the machining process itself[3].

The materials experimented with in this thesis are:

- aramid fibre,
- viscose,
- cotton,
- PES.

Cement-paste coating

The development of the cement-paste coatings used in this thesis was done at the Chair of Physical Chemistry of Building Materials, ETH Zürich in the context of a collaboration within the NCCR Digital Fabrication (NCCR, 2019). This section gives a short overview of the material challenges that informed the development.

Because the cement-paste coating is applied in a very thin layer, evaporation is very rapid. In low relative humidity, this results in the material drying before it has the chance to harden (hydrate). To ensure proper strength, the coating material needs to be engineered such that the coating is applied to the textile in a way that prevents evaporation.

One solution is to apply the cement-paste coating in a high humidity environment (e.g. climate chamber). However, this limits the size of the moulds and does not allow for on-site construction in ambient conditions.

[3] Yarns are pulled through a series of tensioners and need to be flexible enough to bend in acute angles. Furthermore, to make loops, yarns are pulled transversely by needles, meaning their brittleness and strength plays a role in whether they can be knitted without being damaged or breaking.

Therefore, the other solution is to accelerate the hydration of concrete[4], creating a fast-setting cement-paste. However, if the cement-paste hydrates too fast, there is not enough time to apply the coating. The solution is to continuously accelerate the cement-paste. This approach is also known as set-on-demand (Reiter et al., 2018).

The types of coatings and the different method of application are described for each built prototype in Chapter 7.

4.2 Mould functional requirements

This section presents some of the general requirements that formwork needs to fulfil and discusses possible geometrical and structural features it can incorporate.

Formwork needs to fulfil the following basic functions:

- be the correct geometry,
- withstand the weight or hydrostatic pressure of fresh concrete,
- have the required surface finish, and
- have a good bond to concrete (if used as stay-in-place).

Veenendaal et al. (2011) classify fabric formwork moulds as filled (Figure 4.2a) or surface moulds (Figure 4.2b).

Filled moulds may be open or closed and are generally used for elements such as beams, tubular or branching structures, which create columns, beams, or transitions between these elements[5].

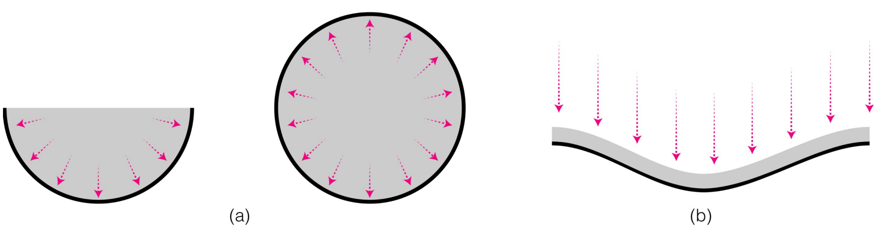


Figure 4.2: Types of fabric formwork moulds: (a) filled moulds; (b) surface moulds.

[4]Special cements, specifically Calcium Aluminate Cement (CAC) and blends of CAC with Calcium Sulfate (C$), are used to achieve the fastest possible hydration.

[5] Filled moulds can be used for all building elements (floors, ceilings, walls etc.). In this thesis, they are only considered for columns, beams or nodal structures.

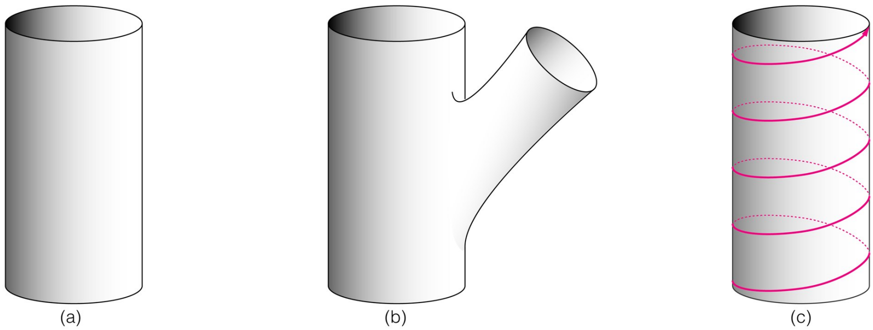


Figure 4.3: Filled moulds for (a) column components, (b) branching or nodal components and (c) reinforcement of filled mould.

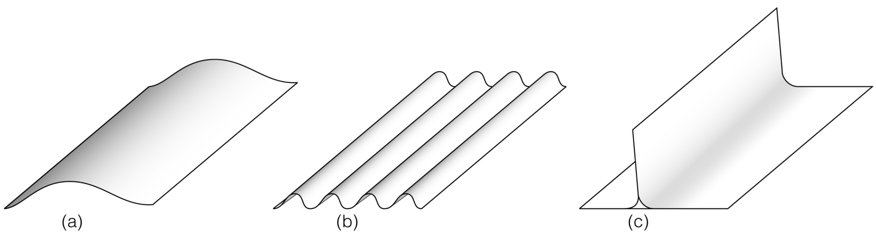


Figure 4.4: Surface mould geometries: (a) doubly curved surface; (b) corrugations; (c) surface stiffeners.

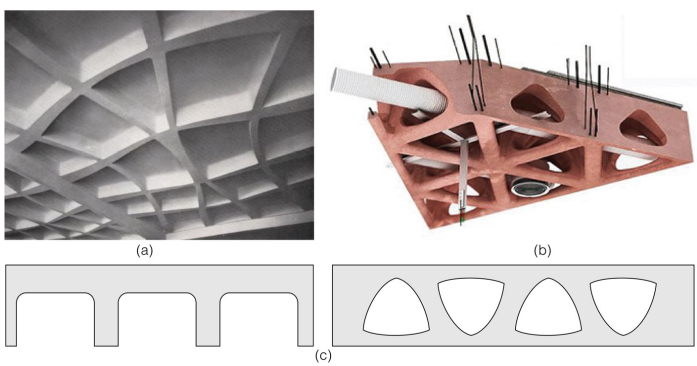


Figure 4.5: Slab geometries with cavities for weight-saving: (a) Floor slabs in Palazzo dello Sport (Halpern et al., 2013); (b) Holedeck waffle slab system (Holedeck, 2019).

Moulds for such elements are largely tubular or branching (Figure 4.3a) geometries, which can be produced as prefabricated components. Beyond the component scale, hydrostatic pressure needs to be taken into account when designing the textile formwork. One way to achieve this would be to modulate the textile material properties to include reinforcement (Figure 4.3c).

Surface moulds are most commonly used for larger-scale structures. These structures can be roofs, canopies, walls or floors, and may span large areas. At these scales, geometry plays an important role in the efficiency of the structure, but more importantly in this case the efficiency of the mould, which needs to be stiff enough for concrete to be applied. Shell and shell-like structures may be used as they can be designed to minimise bending moments, resulting in reduced stresses and material demand.

However, extremely doubly curved geometries are not always desirable or cannot always be used. Other than a globally curved geometry (Figure 4.4a), stability can be enhanced through corrugations, local undulations, folds or stiffeners (Figure 4.4b) that increase the structural depth. Therefore, the mould needs to be designed to accommodate elements that allow such shaping.

In floors, which are generally more shallow constructions, stiffeners or ribs can be added (Figure 4.4c) when global geometry is not enough.

Moreover, floors are often the target of material saving strategies aimed at producing lighter and more structurally efficient structures. Examples are Pier Luigi Nervi's isostatic ribbed floor slabs (Figure 4.5), or the more recent standardised Holedeck system which produces a height saving waffle slab (Figure 4.5) (Holedeck, 2019). Building these lighter slabs requires formwork that can create voids or cavities in the structure. Typical contemporary (standardised) approaches are to create cavities or air pockets by placing plastic air bubbles or boxes (Bubbledeck, 2019; Airdek, 2019).

Concrete building elements such as roofs, floors and walls or facades are usually designed to fulfil more than just the structural requirements. Often they are used for climate control and come with integrated functionality such as electric wiring, hydronics or lighting, which can be placed in cavities and channels within the structure. These features have to be taken into account in the moulding process to provide spacing or guides for placement.

Finally, if planned as a stay-in-place formwork, a good bond between the

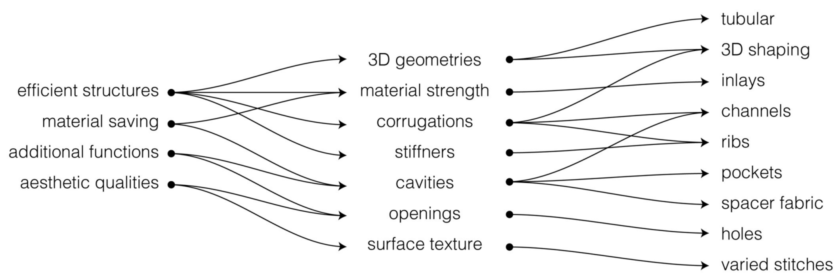


Figure 4.6: Relationship between desired qualities and textile features.

mould and the concrete structure is needed. The mould should, therefore, have sufficient surface texture or even shear connectors.

Figure 4.6 shows an overview of the possible desired building qualities, the geometries needed to achieve them and the corresponding knitted textile features. An overview of the techniques needed to produce textiles with these features is given in Chapter 5.

4.3 Assembly and construction

The forming system relies on having a prestressed knitted membrane as mould. Therefore, to create the mould, the produced textile needs to be assembled and tensioned into shape. Tensioned fabric structures are characterised by having every part of the structure loaded with only tensile stresses. This means that the range of possible shapes is limited to anticlastic surfaces (Figure 4.7a). However, depending on the elements and strategy used for tensioning the textile, globally synclastic(-like) shapes may be built by introducing splines, bending-active elements or rigid elements (Figure 4.7b).

The tensioning can be done in various ways. Standard techniques used in the building of prestressed membranes or other tension-based systems are all applicable. These can use rigid or flexible guides connected to or inserted in the textile, a rigid or flexible external frame or a combination of the two.

4.3.1 Textile assembly

Though weft knitting produces 3D geometries without the need for patterning, tailoring and sewing several parts together, some size limitations exist. The size of the produced textile is dependent on the characteristics of the available knitting machine and chosen settings. Weft-knitted textiles are only limited by the machine in their width (needle-bed width), their length is virtually infinite. Currently, the widest available needle-beds are 2.5 metres (Abounaim, 2011). Therefore, architectural structures that are wider than 2.5m require the assembly of several pieces of textile. However, because pieces of fabric can be in themselves shaped and tailored, discretising the larger geometry is significantly simpler than for flat sheet materials, because each knitted patch can be designed to drape a non-developable target geometry.

The techniques used for joining the fabric pieces may be as simple as sewing, stapling, pinning, or glueing the fabrics together (West, 2016). Knitted fabrics may also be joined together through known joining techniques in knitting. Joining may be done in an automated way (using linking machines) and does not change the local stretching and strength properties of the textile as is the case with sewing woven textiles.

Other types of fabric-to-fabric connections can also be devised. For example, through the use of rods inserted into channels on the adjacent edges of fabrics to be joined (Figure 4.8).

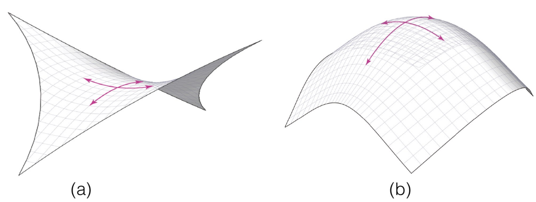


Figure 4.7: Doubly curved geometries: (a) anticlastic with Gaussian curvature K>0; (b) synclastic with Gaussian curvature K>0.

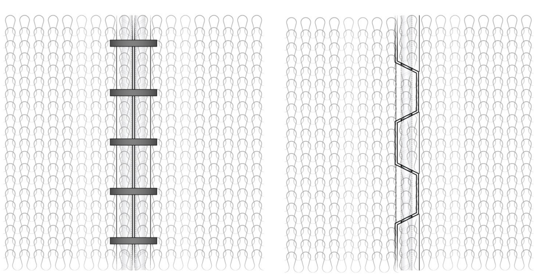


Figure 4.8: Fabric-to-fabric connections with rods and channels at the edges of fabric panels.

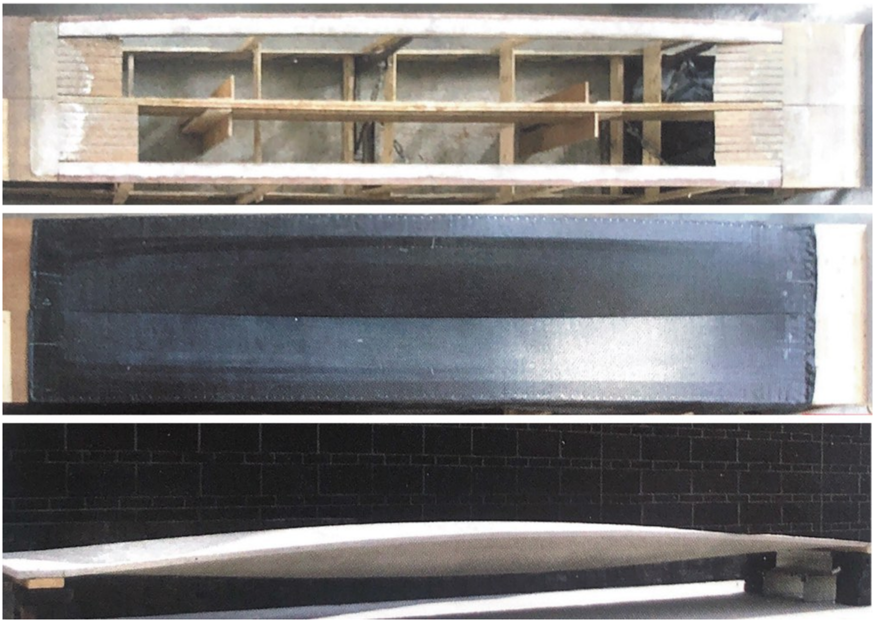


Figure 4.9: Thin concrete vault built using a tensioned fabric on a timber rig (West, 2016).

Figure 4.10: Construction of NEST HiLo roof showing the timber edge beams used for tensioning the cable net into shape (image credit: Juney Lee).

4.3.2 Frames and tensioning strategies

The assembled knitted textiles need to be tensioned into shape using a permanent or temporary frame. These frames may be rigid or flexible and may be external or included within the textile.

The most common way of tensioning textiles, for fabric formwork, is using timber edge beams or frames. Figure 4.9 shows a thin concrete shell built using two curved plywood halves with a central keel and a stretched fabric stapled in place (West, 2016).

When constructing larger scale structures, the fabric needs additional support. To avoid the excessive use of timber frames, this support can be achieved by using a hybrid system. For example, the NEST HiLo roof construction (Echenagucia et al., 2019) uses a timber edge beam for prestressing a cable-net and fabric formwork (Figure 4.10). The KnitCandela prototype described in Chapter 7.3 used a similar approach.

Additionally, any of the strategies traditionally used in erecting tensile structures may be used in these cases. For example through the use of pillars, masts and scaffolds to shape a number of possible 'tent' like geometries supported along points or lines (Figure 4.11). A detailed description of the construction and tensioning, detailing of such structures is given in Seidel (2009) and Llorens (2015).

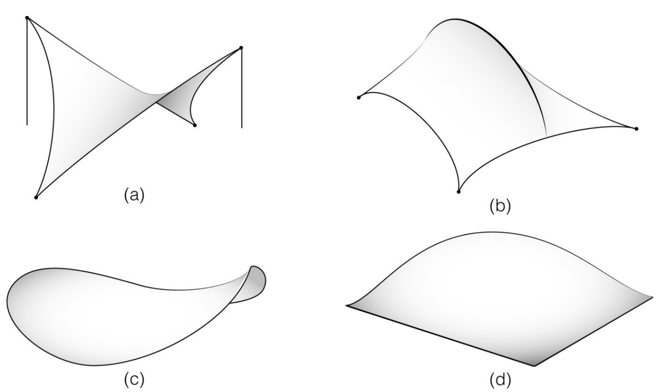
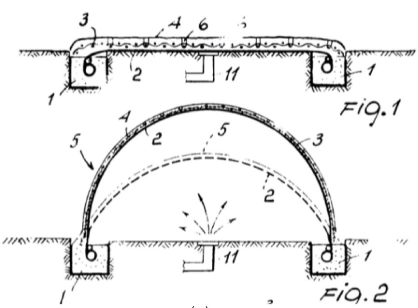


Figure 4.11: Strategies for introducing prestress in membranes: (a) point supported; (b) line supported; (c) edge supported; (d) inflatable.

The knitted textiles may also be supported and shaped by bending-active elements that form a self-supporting structure (La Magna et al., 2018; Lienhard and Knippers, 2015; Lienhard et al., 2013) (Figure 4.12). A hybrid approach was used in tconstructing the KnitCrete Bridge prototype described in Chapter 7.2.

Finally, the textiles may also be supported using inflatable pillows to form domes (Veenendaal et al., 2011; Pronk and Dominicus, 2011; Brewin and Crawford, 2010; Pronk et al., 2007) (Figure 4.13a), or pneumatic tubes strategically inserted in the structure of the textiles (Ahlquist et al., 2017) (Figure 4.13b). Inflatables were also used in the KnitCandela prototype described in Chapter 7.3.

Figure 4.12: Example of bending-active and textile hybrid: Isoropia - installation at Venice Biennale 2018 by CITA (image credit: Anders Ingvartsen).



(a)

(b)

Figure 4.13: Examples of textiles tensioned with inflatables: (a) dome construction using an inflatable membrane (Cappellini and Zucchi, 1979); (b) tensioned textile by integrated inflatable tubes (Ahlquist et al., 2017).

4.3.3 Cement-paste coating application

Coating the knitted textile with the designed cement-paste (see Section 4.1.3) can be approached in several ways depending on the size of the structure. Components are small in size and can be produced as prefabricated elements. At this scale, they can be coated in a controlled environment such as a high-humidity chamber. This simplifies the demands on the coating composition and allows for a longer open time for handling. The textile can be dipped into a cement-paste bath and tensioned once impregnated (see Chapter 7.1). Alternately, the cement-paste coating can be painted or sprayed on the tensioned textile (see Chapter 7.2).

At a larger scale, the moulds have to be coated on site after tensioning. In ambient conditions, the coating needs to be a fast-setting one as described in Section 4.1.3. As a result, the coating is applied by spraying or misting. The spraying pressure and equipment for this step are more similar to painting setups rather than shotcreting (see section 7.3 and Appendix B). The spraying can be done manually or in an automated manner using robotic processes or remote deposition strategies (e.g. with drones).

Finally, both for components or entire structures, the textile could be pre-impregnated with the dry coating material mixture and activated with water when needed as The Concrete Canvas system developed for temporary shelters (Brewin and Crawford, 2010).

4.4 Summary

This chapter presented the overall approach to creating moulds for concrete structures through the use of a weft-knitted textile. A general description of the approach is given and the possible applications are discussed. The different manufacturing steps are presented. Fabrication and assembly of these lightweight compact deployable moulds consists of the following steps:

- prefabrication of a custom weft-knitted textile,
- assembly of the prefabricated textile, which can include attaching several pieces and inserting stiffening, reinforcing or other elements,
- deployment or tensioning into shape of the assembled textile, and
- coating of the deployed textile structure in a controlled prefabrication environment or on-site.

The fabric is built specifically by weft-knitting, allowing for customisation and conforming to predefined geometrical and structural needs. The features to be included in the fabric were discussed in relation to the qualities required of the mould. These range from the global shaping of the textile using channels or pockets, to the local manipulation of its texture. Existing and developed techniques for fabricating weft-knitted textiles with such features will be presented in Chapter 6.

Compared to similar building techniques, the main feature in this approach is mass-customisation using existing industrial machines. The produced geometries have a weight and packaging size allowing for inexpensive transport and immense freedom for geometric detailing and functionalisation. This technique allows to essentially build without the need for disposable moulds.

Chapter 5

Weft-knitted formations

On a knitting machine, the needles are arranged on needle-beds and activated individually by a carriage passing over them. In a knitted textile, a row of loops in the width is called a course and represents the weft direction, while a column of loops in the length represents the warp direction. Various textile configurations can be achieved by alternating which yarns, needles or needle-bed are used per machine carriage pass. The final shape of the fabric is mainly a result of the careful loop control during the knitting process.

This chapter presents a brief overview of flat-knitting technology and machinery alongside fabrication strategies for achieving different weft-knitted configurations for shaped geometries and features.

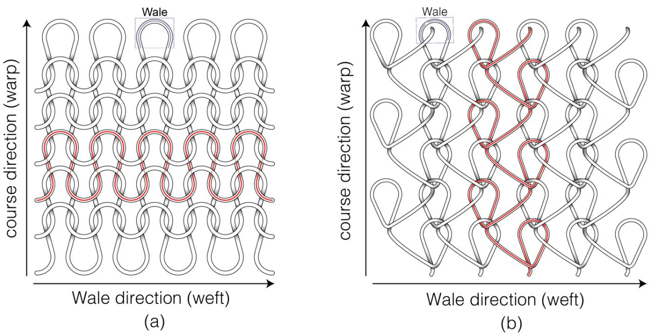


Figure 5.1: Types of knitted textiles: (a) weft knitted textile; (b) warp knitted textile.

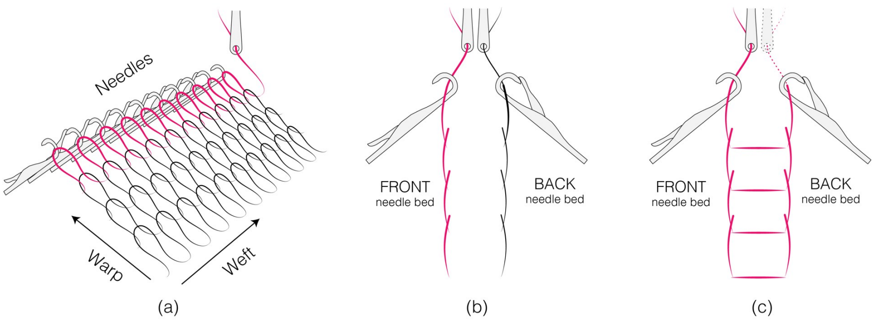


Figure 5.2: Industrial flat-bed knitting machine typical needle-bed layout: (a) needle-bed: array of needles creating loops course-wise by pulling yarn fed by a yarn guide; (b) V-bed: needle-beds facing each other and producing separate textiles.(c) V-bed layout and producing connected or spacer fabrics between the two beds.

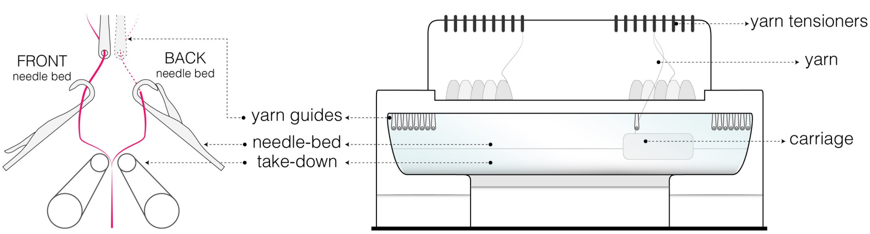


Figure 5.3: Components of a knitting machine.

5.1 Basic principles

Different types of knitting can be identified depending on the direction in which loops are formed, the needle-bed geometry and the number of yarns used in the process. When the loops are formed in courses by the passing of the carriage, usually with one yarn, the textile is a weft knitted textile (Figure 5.1a). When the loops are formed by separate yarns in columns, the textile is a warp knitted textile (Figure 5.1b). Based on needle-bed geometry, knitting machines may be flat or circular. This section will describe flat-bed weft-knitting.

5.1.1 Weft-knitting machine components

Flat-bed machines can be equipped with multiple needle-beds (Banerjee, 2014). Most commonly, these knitting machines use an array of needles (Figure 5.2a) laid out onto two beds facing each other in an inverted "V" layout. With each pass of the machine carriage, to form loops (stitches), a thread/yarn is pulled by the needles through loops created in a previous pass. This array of created loops is called a course (magenta in Figure 5.2a). The fabric can be created on the two beds separately (Figure 5.2b) or interconnected (Figure 5.2c). This makes it possible to create diversified loop types, loop arrangements and spacer fabrics. The basic knitting machine components are listed below and shown in Figure 5.3[1]:

- needle-bed with needles (Figure 5.2a)[2],
- carriage with *cams* that describe the movement of the needles,
- yarn guides that move with the carriage and bring the yarn,
- sinkers/presser jacks (optional: needed for laying in yarns),
- take-down system for rolling and pulling down the formed textile.

The carriage passes back and forth activating needles, which makes them rise, catch the yarn, descend to form a loop and return to their neutral position.

[1]Knitting machines are be fitted with many mechanical parts, only the absolute minimum needed number of components is described here.

[2]There are several types of needles: latch needle, spring needle, slide needle and compound needles. The process described in this section is considering a latch needle.

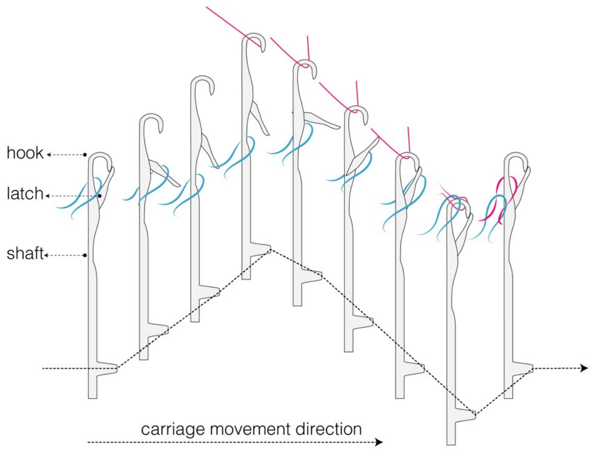


Figure 5.4: Needle movement to form a new loop.

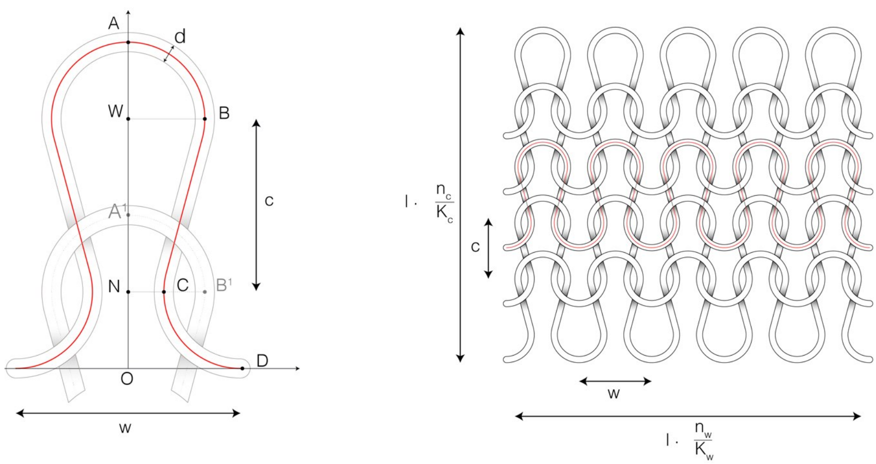


Figure 5.5: Parameters of loop geometry as described by Munden (1959)

Figure 5.4 shows the movement sequence to form a loop using a latch needle. The needle is pushed up from its neutral position. In the process the already existing loop moves to the shaft of the needle, opening the latch. When it reaches the highest point, the hook of the needle catches the yarn brought by the yarn-guide and starts descending. The previously formed loop pushes the latch to close and glides over the hook, forming a new loop. The formed textile is pushed down by the take-down system.

5.1.2 The loop

The loop is the defining unit for a knitted textile, influencing the textile properties and dimensions depending on the loop width and height.

A loop always consists of a head, leg and foot and it can be described in terms of width, height and length. Figure 5.5 illustrates these characteristics. Loops are symmetrical over axis OA, the wale spacing (w) is defined by segment OD, and course spacing (c) is defined by the distance WN between the widest point of the loop (WB) and the narrowest point of the loop (NC). Wale and course spacing influence the height and width of the fabric, which are defined as loop length (l) times the number of courses (n_c) or wales (n_w) and constants K_c and K_w. These constants are dependant on machine gauge[3], knit point, yarn diameter (d) and tension settings[4]. Loop geometry and characteristics have been investigated and described in more detail by (Munden, 1959).

5.1.3 Basic weft-knitted formations

The basic types of weft-knitted fabrics can be described by the number of needle-beds needed to produce them and the layering of the resulting fabric. The most basic single-layered weft-knitted fabric is called *single jersey* and only requires a single needle-bed (Figure 5.6). A piece of single jersey fabric has distinguishable front and back faces.

[3]The machine gauge represents the number of needles found in one inch of needle-bed width. For example, a gauge 7 machine will have 7 needles/inch.

[4]The tension of the yarn, or tightness is an adjustable setting on knitting machines.

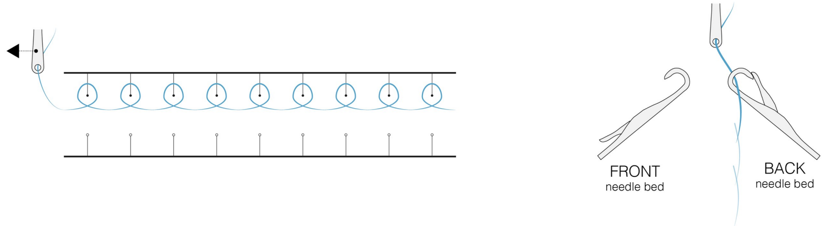


Figure 5.6: Single jersey weft-knitted fabric created on one needle-bed.

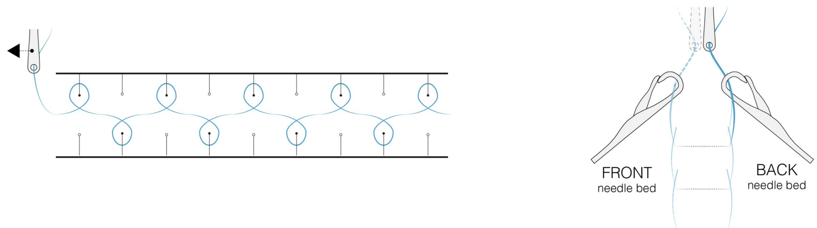


Figure 5.7: Double jersey weft-knitted fabric created by alternating needle-beds during one pass of the machine carriage.

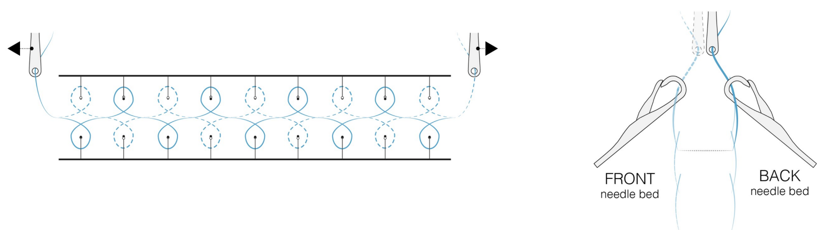


Figure 5.8: Interlock weft-knitted fabric created by overlaying two different double jersey passes of the machine carriage.

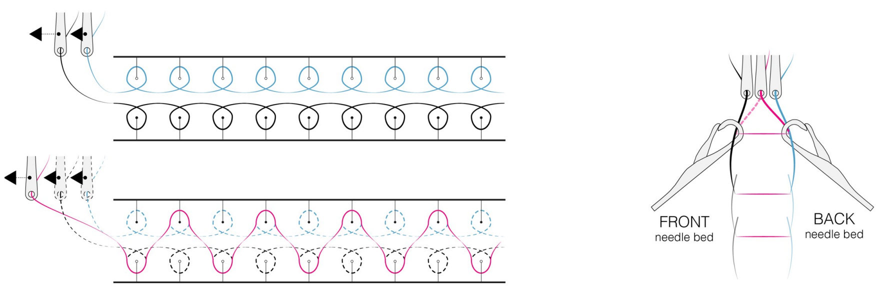
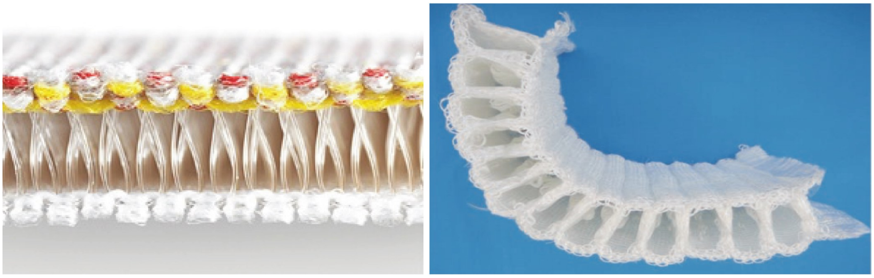


Figure 5.9: Conventional spacer fabric created using three separate yarn guides. Two separate single jersey layers are connected with a pile yarn.



(a) (b)

Figure 5.10: Spacer fabric examples: (a) conventional spacer fabric formation; (b) shaped spacer fabric with knitted connections developed by (Abounaim, 2011).

A *double jersey* knitted fabric is considered to be a two-layered fabric. It is created by alternating the direction in which loops are pulled through existing loops and therefore requires the use of both needle-beds (Figure 5.7).

An *interlock* knitted fabric can be seen as two double jersey fabrics combined or overlayed. This type of fabric has an identical front and back face (Figure 5.8).

Finally, *spacer fabrics*, which are 3D textile structures, can be created by knitting two single jersey surface layers and connecting them with a so-called pile yarn. The connection is done by laying the pile yarn over the needle without creating a loop (*tuck stitch*). A conventional spacer fabric layout is shown in Figure 5.9. Depending on the type of machine the spacer fabric configuration can be created in one or multiple passes of the carriage.

These conventional types of spacer fabrics are limited in their thickness between 2 and 10 mm (Anand, 2016). To overcome this limitation, strategies for knitted spacer fabrics have been developed where the connections between layers are knitted instead of pile yarns (Abounaim et al., 2009, 2010; Abounaim, 2011; Abounaim and Cherif, 2012; Ciobanu, 2011) (Figure 5.10).

5.2 Shaped geometries

To produce a shape, textiles are normally cut and pieced together from flat sheets of rolled material. Knitting technology allows the production of varying doubly curved and 3D geometries directly in the machining process. This is generally referred to as *shaping* (Van Vuure et al., 2003).

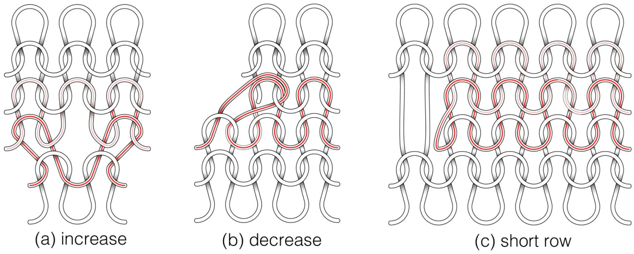


Figure 5.11: Operations used for shaping: (a) increasing loop count from course to course, used for widening; (b) decreasing loop count from course to course by transferring a loop to the adjacent position, used for narrowing; (c) short or incomplete row, used for shaping in the warp direction.

Figure 5.12: Examples of shaped weft-knitted geometries (De Araujo et al., 2011).

Figure 5.13: Non-orientable surface knitted in one single process.

Shaping can be done through a structural variation in the loop itself (see Section 5.5)or by varying the number of loops in weft and warp directions.

Two basic operations are used to shape a knitted fabric to a desired outer contour: narrowing and widening. These are done through decreasing (Figure 5.11a) or increasing (Figure 5.11b) the number of loops within a course.

To increase the number of loops in a course, extra needles are activated on the side of the piece[5].

To decrease the number of loops, existing loops are transferred to the adjacent position and the needle is inactivated. These strategies allow not only for the shaping of a given outer contour but also creating openings within a panel of fabric.

Short or incomplete rows are used to shape doubly curved and 3D geometries. These short rows are created by forming new loops only over a part of a course, inactivating needles over the rest of that course (Figure 5.11c). The remaining loops are held in place on the inactive needles until they are reintroduced in the knitting process. This is equivalent to locally increasing the number of courses, resulting in spatial contouring of the textile.

A wide variety of geometries, close to the finished products, referred to as near-net-shapes, can be produced using the three above-mentioned basic shaping techniques. These can be shaped objects such singly or doubly curved objects (spherical and conical objects, Figure 5.12)[6](Hong et al., 1994; Cebulla et al., 2002).

More importantly, these techniques make it possible to create nondevelopable geometries that are otherwise impossible to create without introducing a cutting pattern and stitching several flat panels together. An example that convincingly demonstrates the shaping capabilities offered by the knitting process, is the generation of non-orientable surfaces. Figure 5.13 shows such a surface knitted in a single process using the techniques described above, but also using the possibility of flat-bed knitting of transferring loops from one needle-bed to another. A step-by-step description is given in Appendix A.1.

[5]Depending on the position to insert extra loops a transfer step may be needed. If the added loops are on the edge, needles are activated. If the extra loops are within the piece, loops are transferred to make room for the extra loop.

[6]Boxes are also common examples of shaped geometries that can be produced in one piece. They are not detailed here as their shaping is less relevant to the applications in this research.

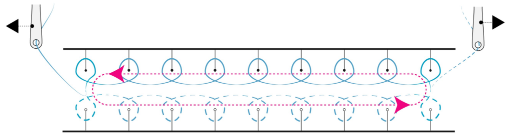


Figure 5.14: The principle behind tubular knitting.

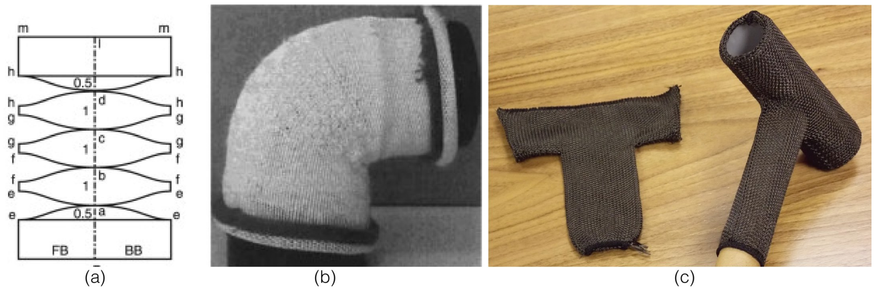


Figure 5.15: Examples of simple and branching tubular weft-knitted formations: (a) rationalised knitting pattern for (b) a shaped tubular knit with a knee (De Araujo et al., 2011); (b) tubular T connection made of weft-knitted carbon fibre (Preform-Technologies, 2017).

Figure 5.16: Six-directional weft-knitted nodal structure.

5.3 Tubular and node geometries

Other than surface structures, flat knitting can produce tubular structures with ease. To make a tube, knitting alternates between the two needle-beds with each pass of the knitting machine. At the end of each pass, when the knitting switches from one bed to the other, a connection is made between the start of the course and its end, thus creating a circular course for the tubular structure. Figure 5.14 shows the principle behind producing a tubular knit on a flat-bed knitting machine.

Tubular structures can be angled and shaped to form ”knees” using the same principles of varying loop count in weft and warp direction (Hong et al., 1994; De Araujo et al., 2011) (Figure 5.15). Tubular knits can also be shaped as branching or nodal structures. Various examples of relatively simple branching structures such as Y and T sections have been presented by Hong et al. (1994). Underwood (2009) describes a variety of approaches to creating out-of-plane branching or nodal connections with up to four members.

Combining tubular knitting with surface shaping makes it possible to create 6-directional nodes as the one shown in Figure 5.16. A step-by-step description for fabricating such a node is given in Appendix A.2.

5.4 Rib-stiffened surface configurations

Strategies for manufacturing several types of non-manifold joints have been developed. These include T and I joints (De Araújo, 2011; Trümper et al., 2016; Bollengier et al., 2017), while possible X joint configurations can be deduced from spacer-fabric formation strategies (Abounaim et al., 2009). While these strategies create ribs in weft/course direction, strategies for creating stiffeners (ribs) in the warp/wale direction needed to be developed. Approaches to creating rib-stiffened surface configurations in both weft and warp directions are shown below.

Three types of rib formations can be identified:

- single-layered rib (Figure 5.17a),
- double-layered rib with no connection at the bottom of the rib (Figure 5.17b),
- double-layered rib connected at the bottom (Figure 5.17c).

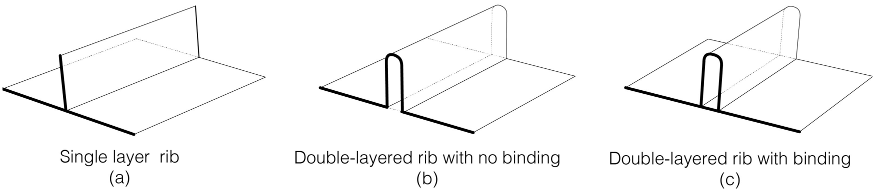


Figure 5.17: Types of ribs: (a) single-layered rib; (b) double-layered rib with no connection at the bottom; (c) double-layered rib connected at the bottom.

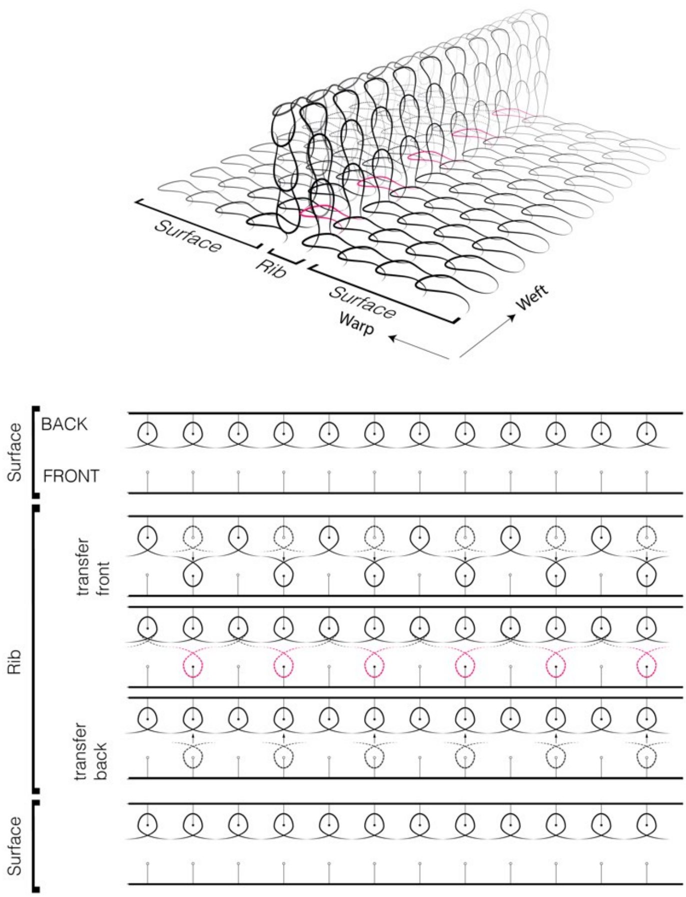


Figure 5.18: A principle for fabricating a double-layered rib in the weft direction.

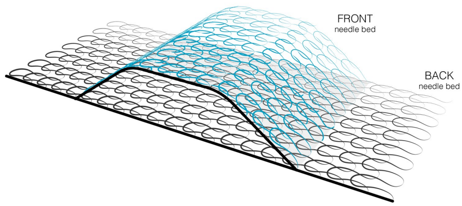


Figure 5.19: Example of weft-knitted girder using principle described in Figure 5.18.

In the course direction, ribs are formed by alternating the needle bed on which the fabric is knit or by selective transfer of loops between the beds. Figure 5.18 shows the pattern principle for creating a double-layered rib in the course direction. Elements such as girders (Figure 5.19) can be created using the same principles of alternating needle-beds and transferring.

In warp direction, ribs can be created by alternate knitting between the front and back needle-bed. Strategies for creating warp-direction ribs can differ depending on the number of yarn guides used. Figure 5.20 shows the method used for creating a single-layered rib in warp direction using a single system[7] and single yarn guide. The rib is knitted on the front needle-bed, while the surface is knitted on the back bed. A connection between the rib and the surface is made where the knitting crosses over from the front bed to the back bed and vice versa (magenta in 5.20). In this case, the direction of the carriage movement is important for connecting the rib to the surface on the desired side and leaving it unconnected on the opposite side. If the carriage direction is not taken into account a tubular structure would be formed instead of the rib. Because these ribs are knit folded over the needle-bed, their height is dependent on the needle-bed width. Furthermore, the height and spacing of warp direction ribs are interdependent (Figure 5.21).

To create an array of warp-direction ribs the principle can be generalised as illustrated in Figure 5.22. Experiments investigating the possibility of aggregating multiple ribs of various orientations in one single process have been carried out in collaboration with the Institute for Textile Machinery and High-Performance Materials at TU Dresden. The aim was to investigate the constraints in size, orientation, repetition of the ribs on the surface and the development of possible strategies for creating these configurations with biaxial reinforcement (see Section 5.5, Figure 5.25). The experiments are described in Appendix A.3.

[7] Refers to the number of cams (see Section 5.1.1) the carriage is equipped with.

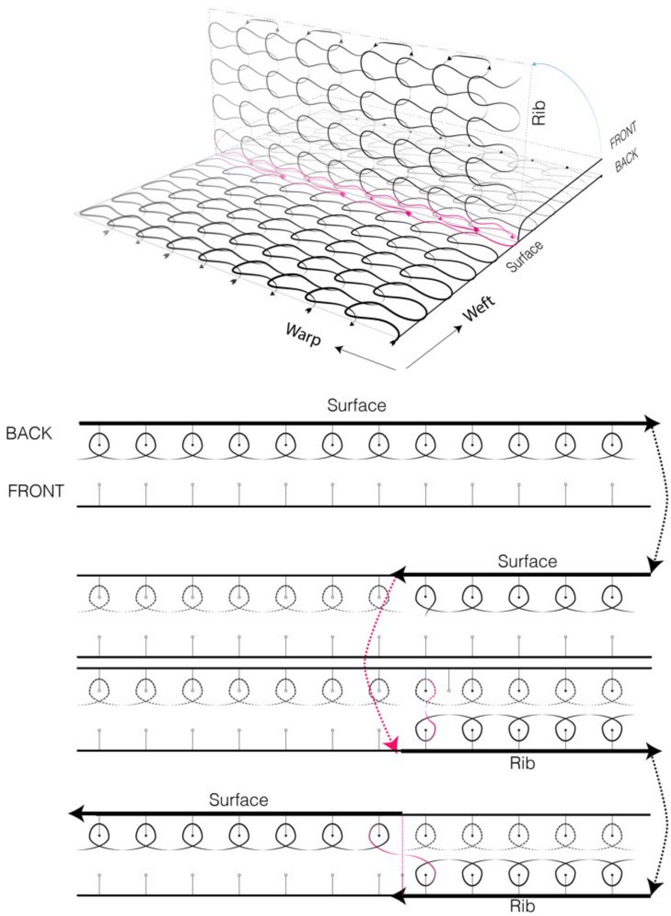


Figure 5.20: A principle for fabricating a rib-stiffened formation in warp direction using a single yarn guide and a single system on the knitting machine.

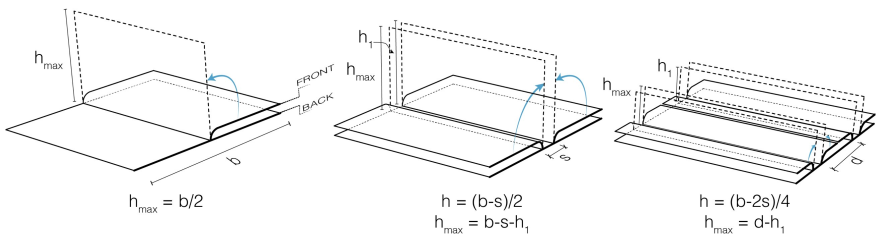


Figure 5.21: Possible repetitions of ribs in the warp direction and the resulting height and spacing dependencies.

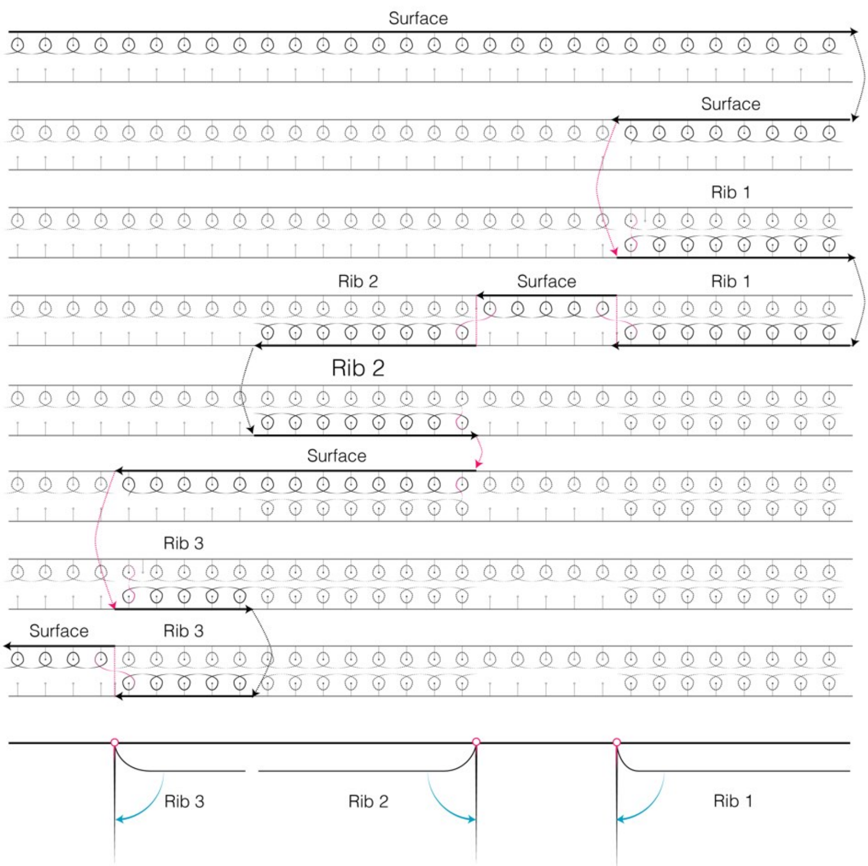


Figure 5.22: A generalised principle for creating multiple ribs in warp direction using a single yarn guide and a single system.

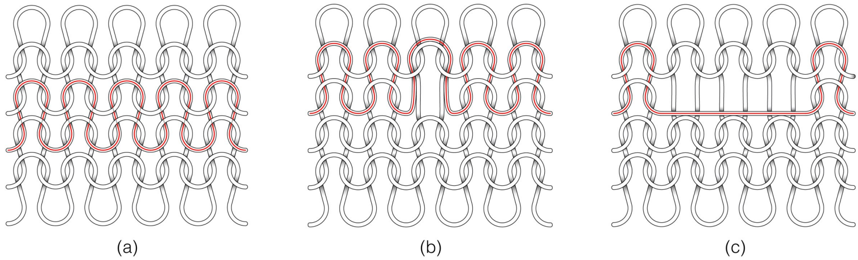


Figure 5.23: Basic loop types: (a) plain loop/stitch;; (b) tuck loop/stitch; (c) float loop/stitch.

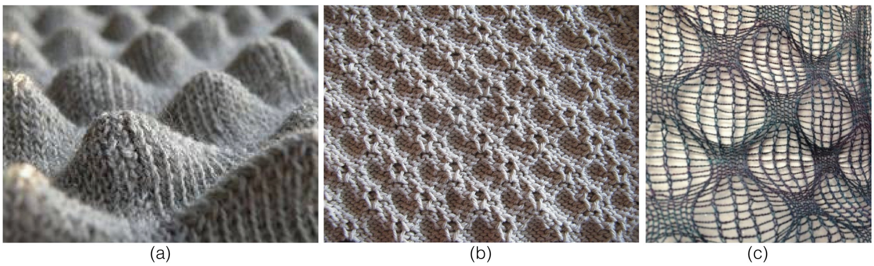


Figure 5.24: Examples of surface texturing and material property variation: (a) bumpy surface created through needle-bed racking; (b) surface texture created with tuck stitches; (c) varying densities and loop sized created by varying tension or dropped stitches.

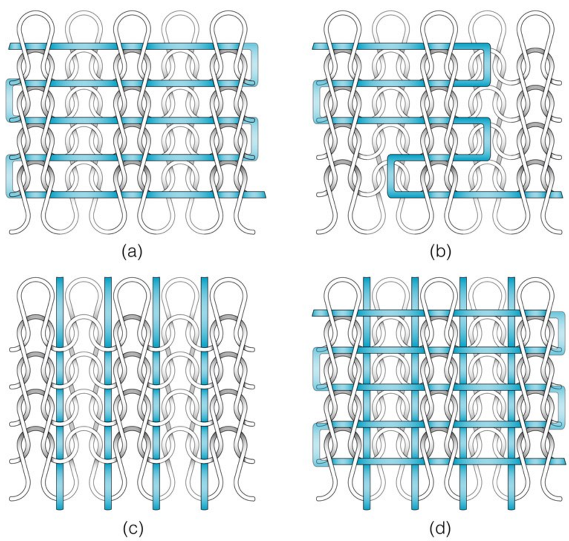


Figure 5.25: Inlay possibilities: (a) weft inlay; (b) varying width weft inlay; (c) warp inlay (d) biaxial reinforcement.

5.5 Functional integration

Knitting is not only ideal for the shaping of geometries, but also for the tailoring of material properties at yarn and loop level. This is partly because the yarn introduced in the knitting process can be varied at every course, or even every loop if the knitting machine is equipped as such. Other than changing local material properties, knitting makes the integration of additional functional features possible through manipulations that can be done at loop level (e.g. loop size). Some of the features detailed here are surface texturing, multi-directional reinforcement through lay-in yarns and the inclusion of channels and openings.

A loop is the basic unit of a knitted textile. The size of the loop may be varied from course to course or within the same course by adjusting the tension settings on the machines.

There are three basic loop types (Spencer, 2001*b*):

- plain loop - the standard loop created by pulling the yarn through previously formed loops (Figure 5.23a),
- tuck loop - yarn is not pulled but just laid onto the needle (Figure 5.23b),
- float loop - the needle is not active and the yarn is neither pulled not laid onto the needle (Figure 5.23c).

The properties of a knitted fabric can be adjusted by combining the basic weft-knitting formations with the basic loop types and adjusting machining parameters (e.g. tension setting, bed racking). Examples of surface texture can be seen in Figure 5.24.

The inherent softness and flexibility of knitted fabrics can be controlled through the insertion of straight inlay yarns. This makes it possible to integrate reinforcing fibres in multiple directions.

Inlays in weft direction are a standard possibility on industrial knitting machines (Steiger, 2019; Stoll, 2019; ShimaSeiki, 2019) and have been known for a long time (Trümper, 2011). They are horizontal straight yarns held in place by the knit structure (Figure 5.25a) They can be inserted for the entire length of a course or across partial sections (Figure 5.25b).

Warp inlays are straight yarns inserted vertically between needles (Figure 5.25c). Arrangements other than vertical can be achieved through displacement of the yarn (guide). While these warp inlay techniques have been mentioned in patent literature as early as the 1930s, they have not yet been adopted in industrial practice (Cherif, 2016).

However, extensive research and developments are being undertaken in an academic setting. Detailed descriptions and techniques for shaping such multi-axially reinforced structures (Figure 5.25d) as flat or shaped panels, and tubular geometries are given in (Cherif et al., 2012; Trümper et al., 2016; Bollengier et al., 2017). Inlay techniques can be used to integrate, amongst others, reinforcement or functional elements such as heating/cooling or electrically conductive yarns and sensors.

Finally, features such as channels, openings and pockets can be included effortlessly in the knitting process. These may be used for the guidance of elements that cannot be integrated into the textile directly during the manufacturing process.

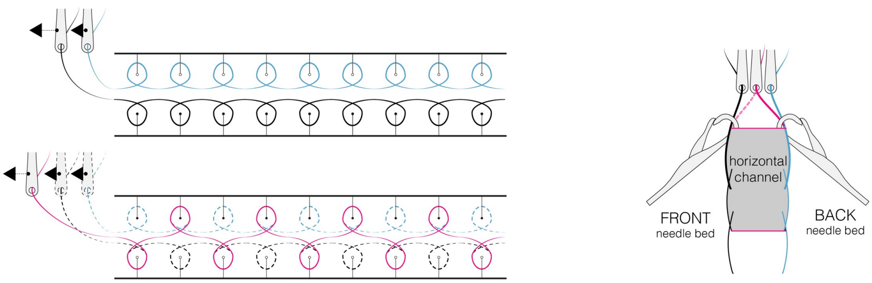


Figure 5.26: Strategy for creating horizontal channels by knitting separate single-jersey panels on the two needle-bed and selectively connecting with a double-jersey course.

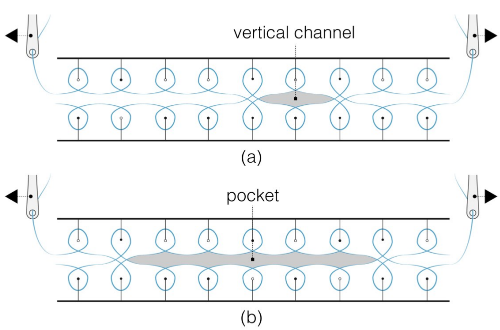


Figure 5.27: Strategy for creating vertical channels and pockets by alternating knitting between needle-beds: (a) vertical channel; (b) pocket.

Channels may be formed in any arbitrary direction over the surface of a knit using the following strategies:

- in weft direction: knitting parallel single-jersey fabrics on separate needle-beds and transferring to connect (similar to creating double-sided weft ribs, as described in Section 5.4),
- in weft direction: knitting parallel single jersey fabrics on separate needle-beds connected by a double-jersey course (Figure 5.26),
- in warp direction: selectively switching between the needle-beds within a given course (Figure 5.27a).

Pockets are created in the same manner as channels, they can be viewed as longer or wider channels (Figure 5.27b).

5.6 Summary

Existing and explored strategies for fabricating these types of textiles have been presented. These include the basic knitted structure types and loops, 3D shaping possibilities for surface or tubular structures, the insertion of stabilising straight fibres, surface texturing, and further functional integration (e.g. channels and pockets).

These advanced textiles are digitally designed and fabricated by varying the knitting pattern to allow the precise following of 3D curved shapes. Chapter 6 will detail the computational approach developed for automating the generation of knitting patterns for 3D geometries.

Chapter 6

Computational knitting

Knitting offers the possibility to directly create 3D geometries without the need for tailoring or stitching. A two-dimensional line-by-line set of instructions for the CNC-knitting machine to follow during the knitting process, known as knitting pattern, is needed to fabricate a given piece of weft-knitted textile. Currently, these knitting patterns are designed directly in 2D based on developed surfaces, primitives or rationalised schemes for non-developable geometries. Any custom, non-repetitive, non-developable knitting pattern needs to be programmed by the user in a manner requiring detailed manipulation and understanding of knitting operations. Creating such patterns is time-consuming and very difficult for geometries not based on known primitives.

In contrast to other industries, such as the garment and shoe or automotive industries, where knitting is used for mass production, the construction sector has a greater demand for non-repetitive modules using bespoke geometries. Therefore, creating knitting patterns for various 3D geometries in a fast and flexible way is especially important.

This chapter presents a computational approach for the automated generation of knitting patterns on a given 3D geometry without being constrained to developable surfaces[1]. A step-by-step description of the approach and its implementation in a design tool is described in Section 6.1 and Section 6.3 respectively. Subsection 6.4 will show how the generated knitted pattern is

[1] Parts of this chapter are based on the publication by Popescu et al. (2017).

translated into machine code and Section 6.5 will discuss the calibration of the pattern generator to reach the target tensioned geometry after the textile is fabricated.

6.1 Pattern generation strategies

Technological advancements in the development of flat-bed knitting machines have turned the 'potential' of 3D-shape knitting into reality. While the machines can fabricate virtually any shape, the barrier to flexibly produce these geometries lies in the programming of the knitting process.

Commercial software provided by the knitting machine manufacturers offer a variety of templates and knit pattern design possibilities (ShimaSeiki, 2019; Stoll, 2019; Steiger, 2019). However, being geared primarily towards the garment or fashion industry, these are limited in their scope and programming possibilities. Their automation, though extensive, remains in the realm of flat patterned panels and limited 3D shaping of tubular or spherical structures (e.g for sleeves, socks, gloves, helmets etc). Any design not fitting these existing templates needs to be created laboriously by specifying each needle operation based on experience, but nonetheless through a tedious iterative process.

Recognising the potential of using knitted textiles in the technical composites sector, the research community has developed some strategies for patterning three-dimensionally shaped geometries. These rely mostly on mathematical descriptions of shapes for known primitives such as cylinders, spheres (Figure 6.1) and boxes (Hong et al., 1994; Van Vuure et al., 2003).

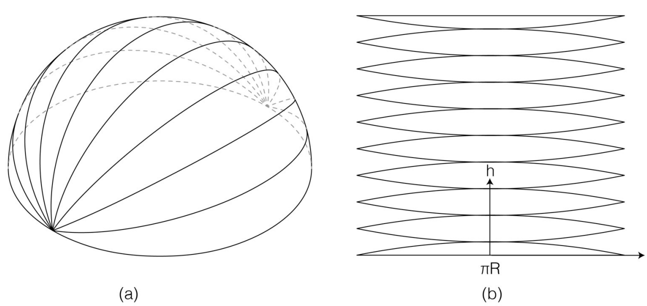


Figure 6.1: Knitting approach for spherical form, after de De Araújo (2011): (a) theoretical 3D form; (b) repeating knitting pattern.

Underwood (2009) developed a ”Shape Lexicon” linking 3D geometry and a parametric approach to designing patterns. However, this is developed as a package-based library specifically for Shima Seiki Wholegarment machines and is still a stitch-level design process as the library deals with operations for specific types of geometries and features.While it does extend the programming possibilities, it is still akin to having combinable templates.

More recently, McCann et al. (2016) developed a knitting compiler bypassing commercial software, which allows for easier manipulation of two-dimensional knitting patterns. The compiler bases patterns on sheet and tube primitives chosen by the user and simulates the resulting three-dimensional shape.

While these developments go a long way in bridging the gap between machine capabilities and the specialised technical knowledge needed for steering them, they all start from the manipulation of a two-dimensional pattern to result in a three-dimensional shape. This process still relies heavily on the proficiency of the user and his/her ability to place shaping operations in the correct sequence for producing the desired spatial geometry. If the process is not automated starting from the 3D geometry, it may be very difficult or impossible to achieve accurate, weft-knitted fabrics for shapes beyond basic geometric primitives.

Starting from a 3D geometry and devising a 2D fabrication strategy is the more typical approach in an architectural context. The common employed strategies focus on translating a 3D shape into a 2D knitting pattern through the unrolling of developable surfaces and overlaying a two-dimensional grid (Ramsgard Thomsen and Hicks, 2008; Thomsen et al., 2015; Sabin, 2013). For non-developable surfaces the strategy usually relies on some form of (mesh) relaxation that produces a good enough unrolled approximation (Ahlquist, 2015; La Magna et al., 2018). This does not fully solve non-developable geometries, and relies mostly on the flexibility of knitted textiles to deform and conform to the shape.

Though it has been proven that (theoretically) any surface can be knit (Belcastro, 2009), to achieve accurate results, machining constraints need to be taken into consideration. These are not only related to the variation in the knitting logic, but also to the accurate representation of the heterogeneous material behaviour.

The Computer Graphics community has offered robust approaches to simulating and generating yarn-level patterns for knitted textiles (Cirio et al., 2015; Sha et al., 2017; Yuksel et al., 2012; Kaldor et al., 2008) starting from the 3D geometry. Some focus on devising patterns for crocheting, that requiring only increase and decrease operations, but can only be hand-knitted (Igarashi et al., 2008*a*,*b*). Wu et al. (2019) extended the approach developed by Yuksel et al. (2012) such that physical knitted objects may be produced. The approach goes beyond increases and decreases and presents a visual interface to help the knitter. Though it imposes more constraints on the pattern, it remains an approach for hand-knitting.

Specifically for machine knitting, similar approaches have been developed by Popescu et al. (2017), which will be presented in this chapter, and more recently by Narayanan et al. (2018). The presented approach relies on geometric descriptions, surface topology, loop geometry and course direction for the generation of accurate knitting patterns. In addition, the method accounts for the creation of short-rows, which follow the principles of machine knitting fabrication techniques.

6.2 Knitting pattern generation (compas_knit)

This section gives an overview of the methods used to generate knitting patterns for a given 3D geometry[2].

Considering the loop as geometrical unit, a knit topology is developed directly onto the input geometry. The topology is a graph made up of nodes (referred to as vertices, Figure 6.2a) connected by edges (Figure 6.2b) representing the warp and weft directions.

These form predominantly quad faces that represent loops (Figure 6.2c) and triangular exceptions that represent shaping operations (increases, decreases, or the starts/ends of short-rows).

[2]Then knitting pattern generation approach creates a pattern that produces a textile which can be draped to fit to the given geometry with a given uniform loop size. This generation process does not simulate or take into account any prestressing or tensioning of the textile. How this is accounted for will be described in Section 6.5 and individually discussed for the prototypes in Chapter 7.

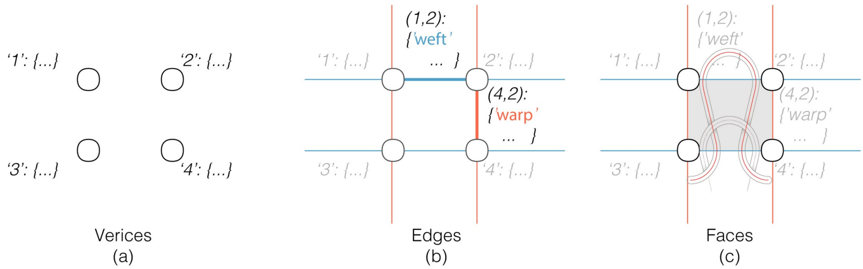


Figure 6.2: Elements of the graph representing the 3D knit topology: (a) the nodes of the graph; (b) the edges of the graph showing warp and weft directionality; (c) a face of the graph representing a loop.

The graph is generated in three steps:

- **Course generation:** The input geometry is contoured and courses (which run in the weft direction) are defined based on the given course/ loop height. The generated courses include short-rows.
- **Loop generation:** The number of loops within each course are defined based on the defined loop width.
- **Knit-pattern generation:** The resulting graph is translated into a two-dimensional knitting pattern. The pattern contains each course to be knit with the corresponding number of loops.

6.2.1 Basic parameters

Knitting is a directional process where the fabric is formed through successive courses consisting of several loops. Therefore, a knitting direction for the geometry needs to be explicitly defined[3]. A minimum of two guide curves in course direction mark the start and end of the piece coursewise. Figure 6.3a shows the knitting direction and the two guide curves, highlighted in blue, defining the start and end of the piece.

Furthermore, the loop geometry determines the height of a course and the number of loops that can be included in a course. Figure 6.3b depicts the loop geometry and resulting parameters:

- course height c in warp direction, and
- loop width w in weft direction.

[3]The direction may be chosen by the user or found/generated algorithmically.

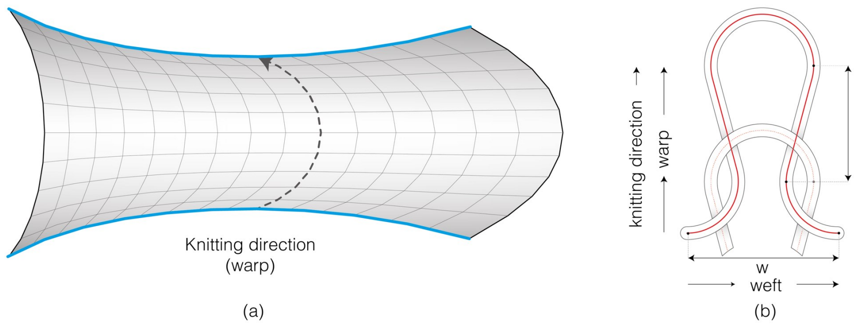


Figure 6.3: Knitting direction and loop geometry parameters: (a) 3D input geometry for knitting pattern generation indicating chosen knitting direction and both start and end edges in course direction; and (b) loop geometry where c is the course spacing in warp direction (course height) and w the loop width in weft direction (loop width).

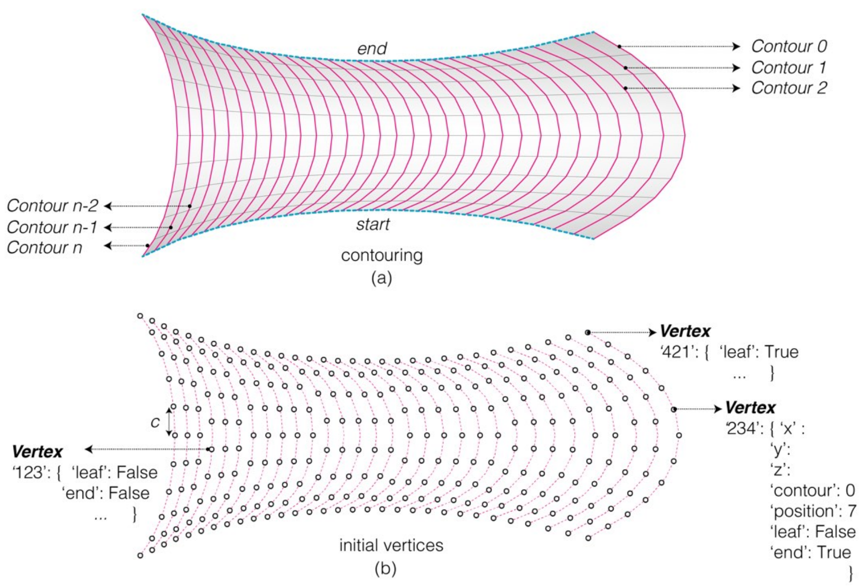


Figure 6.4: Contouring and sampling with course height: (a) Contouring of the patch perpendicular to the course direction and ordering the contours; (b) sampling contours with defined course height c, with examples of initial vertex attributes.

These loop parameters are considered fixed[4] user inputs as they are directly related to the chosen knitting machine and yarn parameters (tension, knit point, gauge, yarn diameter etc.).

The following subsections will schematically describe the pattern generation process for a given 3D geometry.

6.2.2 Course Generation

First, the input geometry is contoured perpendicular to the course direction. The contours shown in Figure 6.4a are created using level-sets computed on a distance field based on the loop height. These are ordered and sampled with the course height. The resulting points are the initial nodes of the graph, which will be referred to as vertices (Figure 6.4b).

Each vertex stores information about its position in space and in relation to other vertices. The vertices are initially described by the following attributes (Figure 6.4b):

- *'x', 'y', 'z'* : coordinates in space
- *'contour'*: contour line index
- *'position'*: position within contour line
- *'leaf'*: True if the vertex is at the start or the end of a contour
- *'end'*: True if the vertex is on the first or last contour position

To generate the courses of the knitting pattern, vertices need to be connected by edges. The edges describe the directionality of the knitting, representing the weft and warp directions of the knitting pattern (Figure 6.2b).

In the course generation step only *'weft'* edges will be added.

Before edges are added, a set of potential connection vertices is defined for each vertex. Two sets of a minimum of four closest vertices on the adjacent contours are stored in the vertex attributes *'connection_forward'* and *'connection_backward'* (Figure 6.5a).

[4]While loop sizes in a knitted textile can be varied in reality, the pattern-generation approach described here only allows for one size of loop to be defined for the geometry the pattern is generated for. To include different loop sizes the geometry can be split into multiple parts/patches for which patterns are generated separately. This is described in Section 6.3.2.

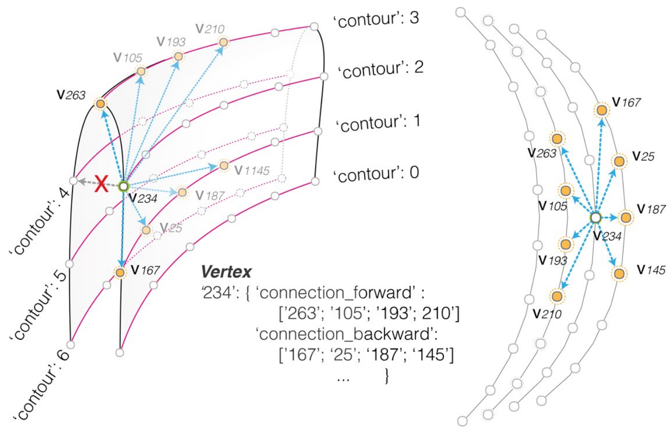


Figure 6.5: Set of connection candidates: (a) four closest connections in the forward and backward set; (b) excluding the closest connection candidates for input geometries with extreme curvature, based on 'contour' attribute.

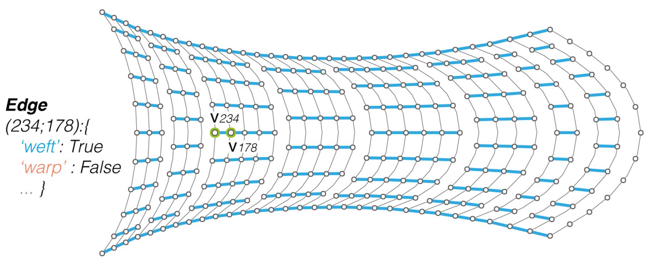


Figure 6.6: Edges added to all 'leaf' vertices and equal numbers of vertices between contours.

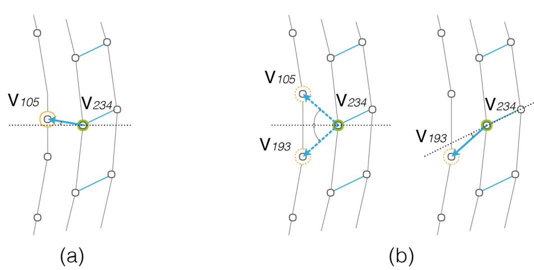


Figure 6.7: Chosen connection: (a) chosen connection based on minimum angle deviation from perpendicular to the current contour; (b) preferred connection out of similar candidates based on minimum angle change from previous 'weft' connection.

By restricting the search for connections to vertices on the adjacent contours the approach can be applied to geometries with extreme curvature. The *'contour'* attribute ensures that vertices that may be geometrically close but not part of the adjacent contour are ignored (Figure 6.5b).

First, edges are added between *'leaf'* vertices, so forming the start and end course of the knitting pattern for that patch. Then, the connecting edges are added between contours with equal numbers of vertices (Figure 6.6).

To form the courses, edges must be added until each vertex is connected to:

- at least one other vertex if the *'end'* attribute is true, and
- at least two other vertices if the *'end'* attribute is false.

Vertices that do not fulfil these connectivity requirements are revisited and a candidate vertex is chosen from the list of possible connections stored in the *'connection_forward'* or *'connection_backward'* attributes. The preferred connection candidate is the vertex that forms an edge closest to perpendicular to the current contour (Figure 6.7a). However, when the angle formed by the two best connection candidates is similar[5] (e.g. the angles formed by the two edges are within 5°of each other), as shown in Figure 6.7b, the edge forming the smallest angle with the 'weft' edge from the previous contour is preferred. The resulting graph with all *'weft'* edges is shown in Figure 6.8.

Next, using the graph in Figure 6.8, all vertices with valency >2, so with more than two edges connected to it, which represent the ends of short-rows, are set as *'end'* = *True*. Then, *'warp'* edges are added for all *'end'* vertices by connecting to their immediate neighbours (one position number difference) on the same contour (Figure 6.9). Finally, all vertices connected by a *'warp'* edge are also set as *'end'*.

6.2.3 Loop Generation

In this step, the individual loops per course are defined by adding all edges representing the *'warp'* direction. To do so, the courses, represented by all *'weft'* edges, will be sampled with the loop width. This is done by dividing each segment of *'weft'* edge chains between two *'end'* vertices in n segments, where n is the rounded up value of the segment length divided by the loop width. The resulting division points constitute the final vertices of the graph,

[5]The similarity is defined by an angle tolerance parameter which may be set by the user. The smaller the angle tolerance the more often the perpendicular solution will be chosen.

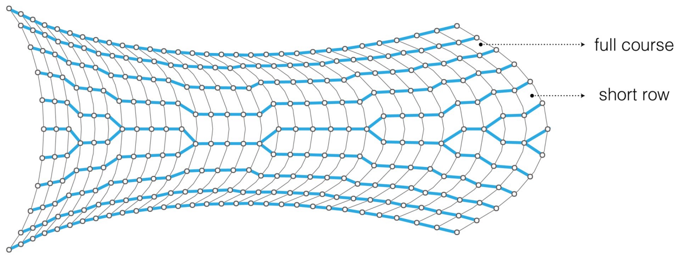


Figure 6.8: Resulting edges in weft direction defining the full courses and short-rows.

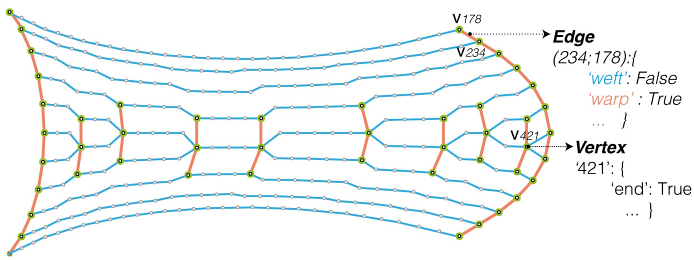


Figure 6.9: Adding *'warp'* edges (orange) and vertices with the attribute *'end'* = True, highlighted in green.

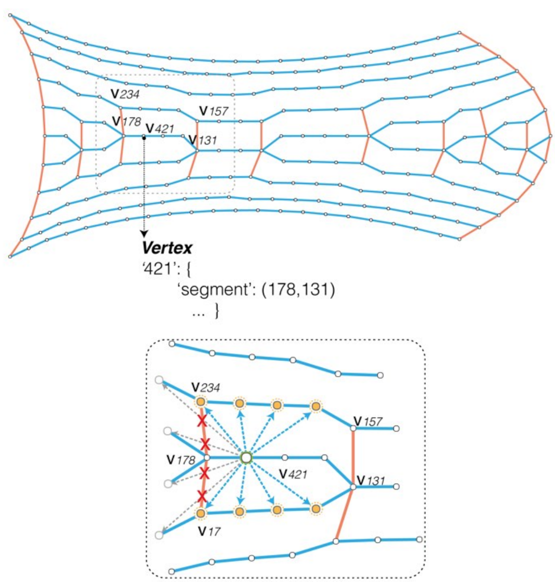


Figure 6.10: Final vertex distribution based on loop width and segment attribute determining the possible connections for each vertex.

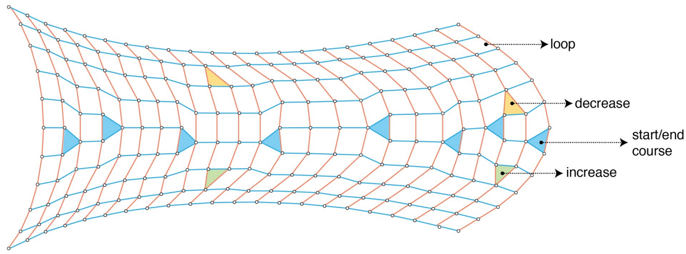


Figure 6.11: Final topology representing the knitting pattern where quad faces represent loops and triangular faces represent shaping operations (increases, decreases, start/end of short-rows).

which represents the knit topology, while the previous vertices are discarded. These new vertices are no longer identifiable by a *'contour'* attribute. Instead, they are identified by a *'segment'* attribute, which is defined by its two *'end'* vertices (Figure 6.10a).

The strategy for adding all *'warp'* edges is the same as for the *'weft'* edges, as outlined before, the only difference being that the possible connections are now determined by *'segment'* adjacency instead of *'contour'* adjacency (Figure 6.10b).

Figure 6.11 shows the final knit topology consisting of vertices connected by *'warp'* and *'weft'* edges. Each quadrilateral face of the graph represents a loop. The triangular exceptions represent:

- the start or end of a short-row in *'weft'* direction, and
- an increase or decrease in *'warp'* direction.

6.2.4 Knitting pattern generation

In this step, the graph is translated to a grid that represents the knitting pattern. A dual graph is created where each vertex represents one loop and the edges retain the *'weft'* and *'warp'* directionality (Figure 6.12a). Knowing the connectivity of the vertices through the edges, the topology can now be drawn as a pattern where each loop is represented by a square (Figure 6.12b). The blue, green and yellow squares in Figure 6.12b show the loops representing the triangular faces of the graph, which are start/end of short rows, increases or decreases respectively.

The generated pattern is an accurate representation of the needed number

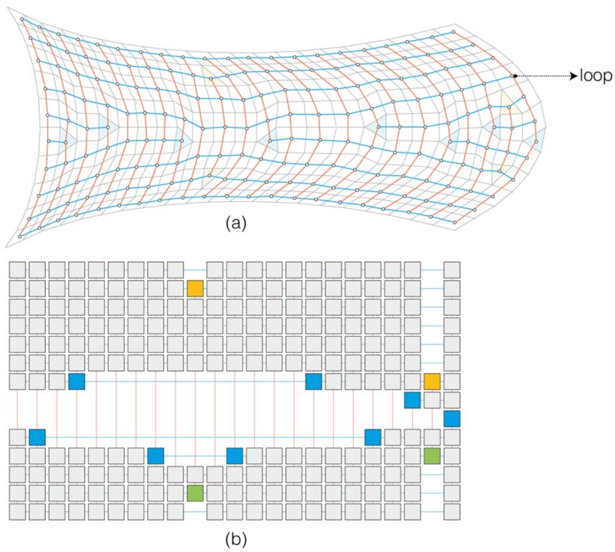


Figure 6.12: Dual of the knitted topology graph in 3D (a) and (b) its translation into a 2D grid representation where the triangular faces representing start/end, increases and decreases are highlighted in blue, green and yellow.

of loops in both warp and weft directions. It gives the positioning of the short-rows and number of loops within each course such that the desired geometry is knitted. However, this pattern is not the final set of instructions for the knitting machine. Specific machining instructions such as transfers, yarn guides, and needle actions are not included in this diagram and need to be input in the knitting machine software. Section 6.4 describes how the generated pattern is translated to machine code.

6.3 Implementation and interface

The computational approach described above was developed using Python 2.7. (Anaconda, 2019) and is based on the COMPAS framework (Mele et al., 2017). The compas network data-structure is used as the basis for the graph describing both the connectivity and the geometry of the knit. The approach is implemented as a pattern-generating tool *(compas_knit)* in Rhinoceros 3D [6] (McNeel, 2019), which is used as design and user-input environment. The tool can be controlled using a toolbar (Figure 6.14) or

[6]The implementation is compatible with version 5 and 6.

by calling the functions through the command line. Because the tool is accessed through Rhinoceros 3D, *IronPython* is the default solver, which would make the following packages or libraries inaccessible:

- NumPy (NumPy, 2019): used for the computationally more expensive operations such as calculating distance matrices and closest points.
- PIL (Clark and Contributors, 2019): used for exporting the knitting pattern to a .bmp file format for importing into the machine software.

To overcome this, the functions using these libraries are run as external processes with the help of compas utilities such as *XFunc* (CompasAPI, 2019).

The tool is separated into several functions centred around the pattern-generation steps described in Section 6.2. Data is collected from Rhinoceros 3D, processed and returned for display (Figure 6.13). Though displayed in Rhinoceros 3D, the intermediate steps and the final pattern are stored independently as JSON files. Splitting the generation into steps coupled with storing data independently gives the user the possibility to intervene or revert to any step of the generation process without needing to start from scratch.

6.3.1 Rhinoceros 3D interface

The pattern generation commands are clustered in a typical Rhinoceros 3D toolbar (Figure 6.14). These can be divided into two categories: main functions needed to generate the pattern, and auxiliary functions that help draw, combine, mark and export the generated patterns. Descriptions of the buttons, their command names, and functionality is given below.

Initialise *(knit_init)***:** initialise the default settings values and creates the layer structure needed for the display and control.

Settings *(knit_settings)***:** The user may input settings for loop geometry and other pattern parameters which need to be taken into account when drawing the final graph and the 2D pattern. These are:

- Width: the loop width
- Height: course spacing/loop height
- Refinement: resolution for densifying computed contours
- Result count: number of possible connections for each vertex
- Angle tolerance: angle difference between best connection candidates

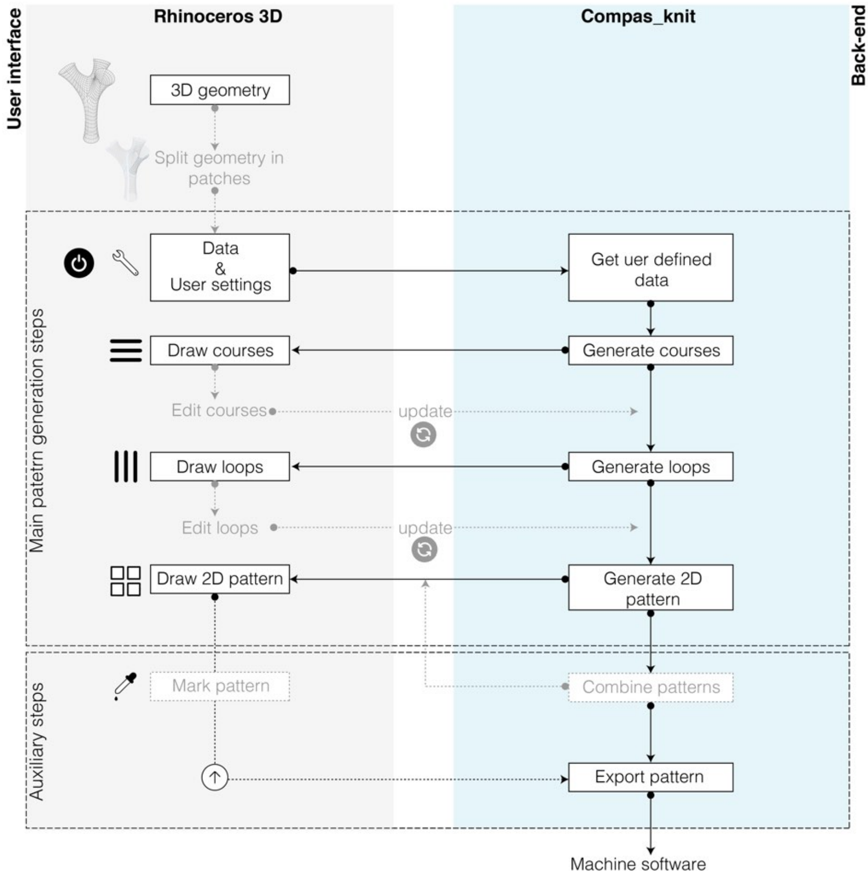


Figure 6.13: Flow chart of the knitting pattern generating tool showing the different generation steps in relationship with the Rhinoceros 3D user interface, and the times where user interventions are possible.

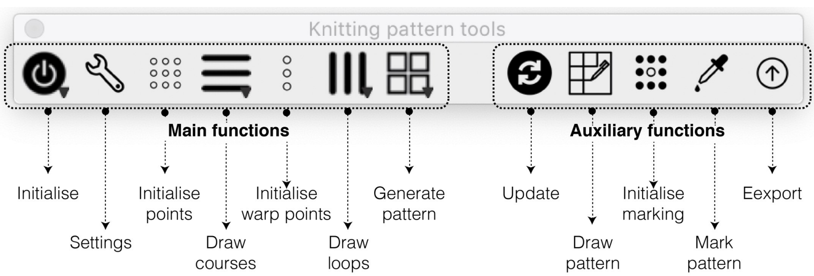


Figure 6.14: Rhinoceros 3D toolbar layout and functions overview

under which the straightest connection to the previous is prefered over most perpendicular connection (see Section 6.2.2)

- Spacing weft: number of loops within the given width
- Spacing warp: number courses for given height
- Path: preferred path for storing JSON data

Initialise weft points *(knit_init_pts)*: the user may chose the layer containing the start and end curves or contour curves, if these have been previously generated. The user also choses a curve representing the knitting direction. This step performs the ordering and sampling of contours with the course width and computes the *'connection_forward'* and *'connection_backward'* attributes of each vertex using NumPy (described in Section 6.2.2).

Draw courses *(knit_courses)*: used to generate the courses by adding all the *'weft'* edges. The network edges and nodes are drawn as lines and points on the corresponding Rhinoceros 3D layers (described in Section 6.2.2).

Initialize warp points *(init_warp)*: used to sample the courses with the loop width creating the final vertices and assigns their *'segment'* attribute. Identifies the possible connections for each vertex. The new vertices and connecting *'weft'* edges are drawn on the corresponding Rhinoceros 3D layers (described in Section 6.2.3).

Draw loops *(knit_warp)*: used to add all the *'warp'* edges that make up the final knit topology in 3D. The edges are drawn on the corresponding Rhinoceros 3D layers (described in Section 6.2.3).

Generate pattern *(knit_pattern)*: used to generate the dual of the final 3D topology and translates it to a 2D pattern. The pattern is displayed as rectangles on the corresponding Rhinoceros 3D layers (described in Section 6.2.4).

Update *(knit_update)*: used to update the topology of the *'weft'* or *'warp'* edges after the user has manually edited the 3D pattern. Data is collected from the relevant Rhinoceros 3D layers and the network is updated to reflect the changes brought on by the user.

Draw pattern *(knit_draw_pattern)*: used to draw one or more patterns previously created. The option to draw multiple patterns makes it possible to automatically combine (or virtually stitch together) several generated patches into a single pattern.

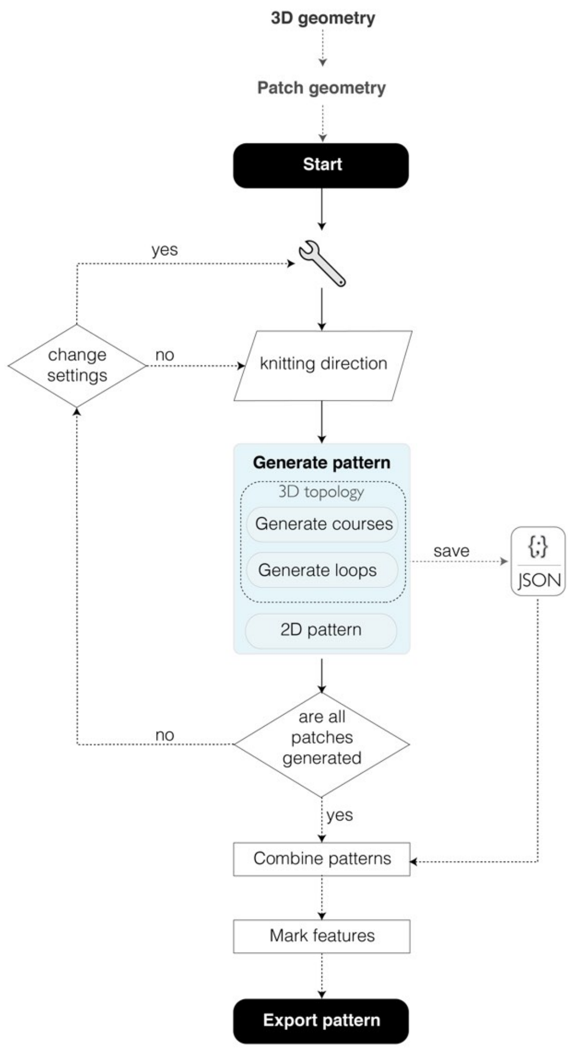


Figure 6.15: Pattern-generation workflow within Rhinoceros 3D.

Initialise marking *(knit_init_mark)*: combines data correlating the 3D topology to the 2D representation.

Mark pattern *(knit_mark)*: used to mark features defined in 3D directly onto the 2D pattern. Can also be used vice-versa, to mark the 3D position of a feature defined on the 2D pattern.

Export pattern*(knit_export)*: used to generate a BMP file with the 2D pattern that can be imported into the machine specific software.

6.3.2 Pattern generation workflow

Using the tool described in this chapter, patterns can be automatically generated, prepared and exported for use with knitting-machine specific software. The process requires user input at certain steps and offers control options throughout the generation process.

The user models or imports the 3D geometry into Rhinoceros 3D and decides on the knitting parameters and direction. If needed, the geometry is split into several parts (patches) before generating the patterns.

Figure 6.15 shows the pattern-generation workflow. The patterning process is initialised and applied for each part individually. The user has to choose the knitting direction for each part and has the option of changing pattern-generation settings. After all parts have been generated, the user can chose to combine the pattern patches into a single knitting pattern, mark the position of specific features (e.g. channels, openings, colour patterns) onto the 2D pattern or adjust it. Finally, the user can export the pattern as an image and import it into the machine knitting-machine software (Figure 6.15).

Patching

Depending on its complexity, the input geometry is segmented into several patches. These patches can coincide to the different pieces of material that need to be put together once the fabric is produced. For example, the node shown in Figure 6.16a would need to be put together by producing the four parts shown in Figure 6.16b. Patterns could be generated for each of the four parts. However, the primary role of the patches is to simplify the geometry and give better control over the pattern generation. This means they can be more numerous than required for the fabrication of the final piece (Figure 6.16c). In other words, the pattern for a fabric knitted in a single piece can be generated using multiple patches. A benefit of using multiple patches is varying textile properties within a piece because the basic parameters (direction, loop size) have to be defined for each patch individually. These variations can be physically produced in a single process in reality.

The patches can also be used to control and align the pattern to specific constraints or desired features (e.g. making sure that there is a full course, and not a short row, along the division lines). The pattern generation is set up to produce patterns where courses are aligned to both the start and end edges of the patch, in the knitting direction. This results in matching courses between different patches.

Because a given geometry can be knitted in several ways, the patching of the geometry can have an influence on the ease with which the patterns are generated and the physical object is knit. Therefore, it is preferable that the user has some understanding of knitting when manually splitting the geometry. The patching may be informed not only by the knitting process, but also by other criteria such as structural needs or alignment to desired directions. In such cases, an automated approach as the one described in (Oval et al., 2019) would be preferable.

Specific subdivision strategies have not been developed in this thesis. However, many manual and fully automated approaches exist. A good overview of possible strategies for splitting a surface into quadrilateral patches is presented in (Campen, 2017).

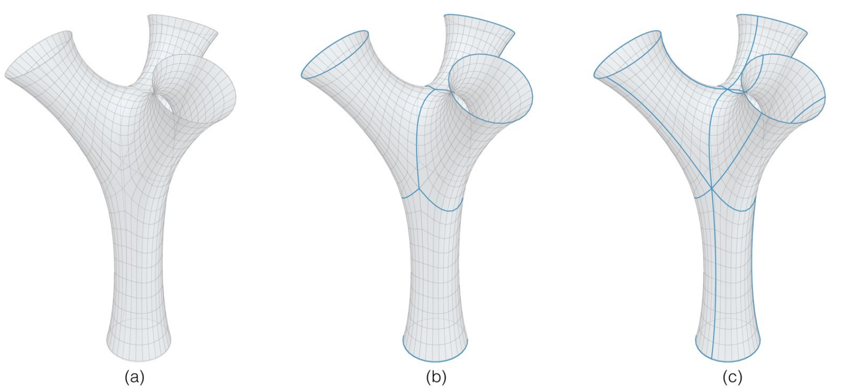


Figure 6.16: Patching of 3D geometry: (a) given 3D geometry; (b) possible divisions into parts to be put together once knitted; (c) further patching for the pattern generation.

Editing patterns

At each step of the pattern-generation process, the vertices and edges of the resulting 3D knitting pattern are displayed in Rhinoceros 3D as point and line objects. The objects are added to a predefined layer structure, which is initialised together with the parameter settings before the pattern generation starts. These line and point objects may be edited manually after both the course and loop generation step. This allows the user to change the positioning of short rows or loops directly on the three-dimensional input geometry. Editing may be:

- adding or deleting objects,
- changing the start and end positions of lines, or
- changing positions of points.

Nevertheless, as visualised in Figure 6.17, the user needs to make sure that the following connectivity rules are not broken:

- all 'leaf' and 'end' vertices are connected to at least one 'weft' and one 'warp' edge (Figure 6.17a);
- all 'end' vertices are connected by at least one 'weft' and two 'warp' edges (Figure 6.17c); and,
- all other nodes are connected by at least two 'weft' and two 'warp' edges (Figure 6.17b and d).

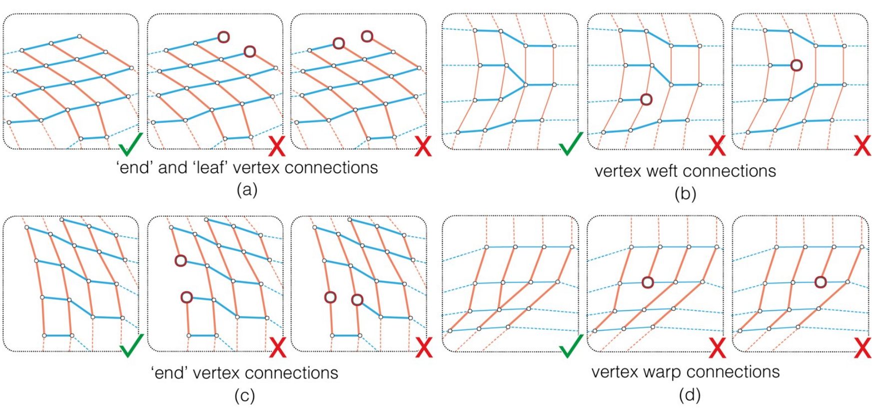


Figure 6.17: Connectivity rules for the knit topology

If these rules are not met, a warning will be given during the updating step. Furthermore, duplicate lines or points may not exist. Once generated, the 2D pattern is displayed as a grid of Rhinoceros 3D rectangle objects, which may also be edited by the user.

First, several patterns can be connected to form one if a geometry has been generated using several patches. When combining patterns, the tool creates a correlated 3D and 2D representation of the knitting pattern. These combined patterns may be used to mark features from the 3D geometry onto the 2D pattern and vice-versa. The marked features may be:

- channels, openings, pockets etc.,
- inlays or other inserts,
- regions where the material should be varied (e.g. different yarns or tension),
- colour patterns, etc.

Regardless of type, marking is always done by assigning a predefined colour to the corresponding rectangle object in the 2D pattern. Finally, the 2D grid can be exported as a bitmap image where every pixel represents a loop.

6.4 Translation to machine code

Knitting machines generally come with proprietary software for constructing and editing patterns, setting machining parameters, processing and checking, and exporting machine code for production. While each software has its own set-up and workflow, the pixel-like knitting pattern is universal. Because knitting is extensively used in the garment industry where colour patterns and designs are commonplace, all machine software allow for an image to be imported. Instead of using the imported image for decoration, it can be used to import custom shaped knitting patterns. The colours are used to identify and assign knitting functions and not necessarily different yarn guides. This approach has been tested and proven to work with three different machine setups:

- Brother - Electronic KH-970, with img2track (Davisworks, 2019),
- Shima Seiki - SWG 091N, with SDS-One apex (ShimaSeiki, 2019),
- Steiger - Libra 3.130, with Model 9 (Steiger, 2019) .

6.4.1 Creating a knitted article

These are the steps to create a knitted article on the knitting machine[7]:

1. Designing the article by assembling a series of symbols,
2. Generating operations for knitting,
3. Running a simulation to detect errors,
4. Exporting machine code file (EDS file).

A rectangular grid represents the knitting design. The width of the grid is the number of needles, while the height of the grid is the number of machine carriage passes[8]. To create the design, symbols are placed at desired positions on the grid. A symbol describes the operations[9] of the knitting process at that position, for example knitting a loop on the front needle-bed (Figure 6.18). The article can contain many different symbols, each used several times. Symbols are either specifically created for the article or imported from an existing library[10]. Libraries may contain symbols that represent a single grid position or clusters representing multiple positions (Figure 6.18).

In this approach the grid is imported from the bitmap image generated by the algorithm described earlier in this chapter. The colours on the imported pattern mark zones where features are placed. These zones are not always the exact colour representation for the symbol sequence needed to create the represented feature. For example, Figure 6.19 shows a fraction of an imported pattern, where a vertical channel is marked in magenta. However, making a channel requires a combination of operations (see Chapter 5.5), hence, more than one symbol. If needed, the colour zones are filled[11] with predefined clusters representing the needed feature (Figure 6.19). Finally, each colour is assigned a predefined symbol creating the knitting design[12].

[7] Steps for Model 9 the software for Steiger knitting machine. Though the workflow has its specificities, the overall approach is generally applicable to other software.

[8] Each grid position is defined by a zone, a symbol, and a colour. The zone defines which yarn guide is used and the symbol defines the operation performed at that position. The colour is not taken into account for generating the machining code. It is only a design aid.

[9] There are two types of operations: knitting (with yarn), and transfer (without yarn). Both types can be used in a symbol.

[10] Symbols can be created by the user and stored in custom libraries

[11] Model 9 has built-in functions that for filling zones or substituting symbols/colours.

[12] Note that a colour does not represent a fixed symbol. Different colours may be assigned the same symbol. Also, the same colour may be assigned to different symbols within different parts of the article design.

Once finished, the design can be exported as machine code. First, it is translated into a succession of operations and selections. Then, the machine knitting process is simulated (carriage traverse direction, movement of yarn guides etc.) to detect any errors. If needed, corrections are made to the design and the process is repeated. Finally, an EDS file is written with the instructions and uploaded to the machine.

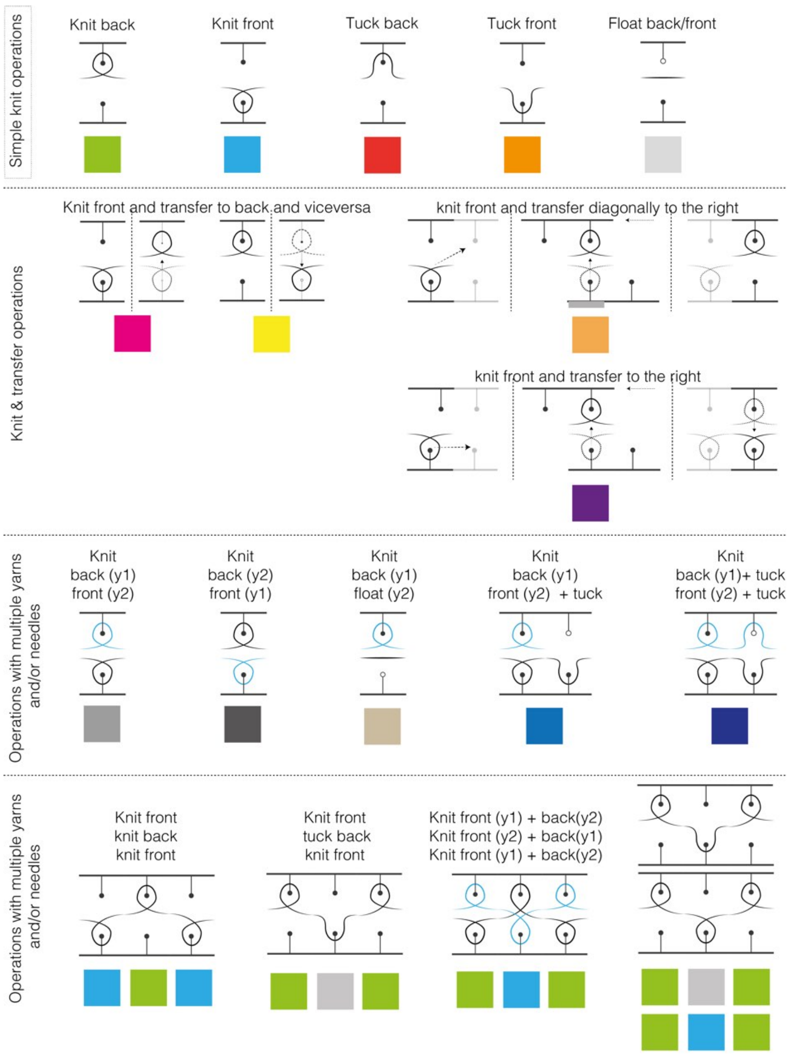


Figure 6.18: Symbols and symbol clusters examples and the knitting operations they represent.

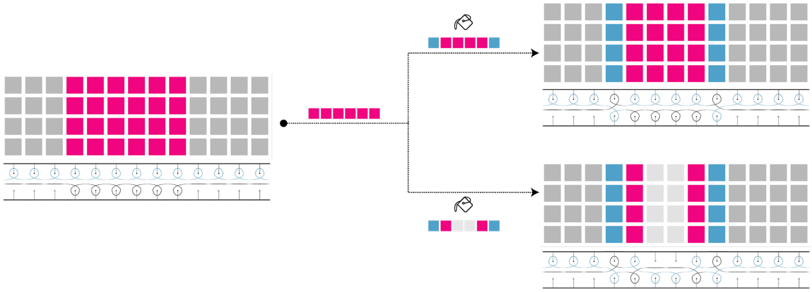


Figure 6.19: Example filling a colour zone with predefined clusters representing the desired functionality.

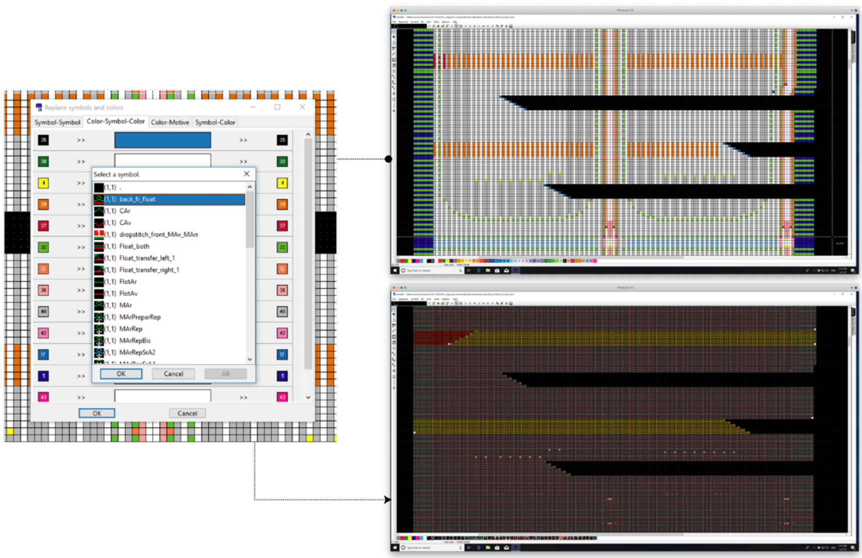


Figure 6.20: Model 9 software interface showing the colour view, pattern design view and the assignment of symbols by colour.

6.5 Calibration

Reaching an accurate physical result is highly dependent on using accurate loop dimensions in the pattern-generation process. The loop geometry is dependent on a series of machine characteristics and design factors such as:

- gauge (spacing between needles),
- knit point (depth of needle when loop is formed),
- tension settings,
- type and diameter of the yarn,
- knitting speed, etc.

With this in mind, the model can be calibrated by determining the accurate loop dimensions for the produced fabric. However, these parameters are different for every machine, meaning there is no universal loop dimension. Furthermore, the knitting settings on the machine can be varied for each produced fabric design. Methods for determining the loop dimensions for plain-knitted fabric in relaxed state have been described by Munden (1959), and more recently by Ramgulam (2011).

The moulding approach presented in this thesis relies on prestressed fabrics. The prestressing of a membrane or network to reach equilibrium implies that the initial, unstressed shape (net-shape) is different to the final shape (target shape). Consequently, the tensioning needs to be taken into account when deciding the parameters for the pattern generation. An approach is to calculate the initial, unstressed geometry to be produced knowing the target geometry and applied stresses. Such approaches have been demonstrated by Van Mele and Block (2010), and Veenendaal and Block (2012) for cable-net and membrane fabric formworks. To do so, a material model is needed to compute the expected deformations. While good models exist for woven fabrics, knitted textiles have different properties in different directions. Moreover, if the loop topology of the fabric is very diverse, the material model becomes more complex and highly anisotropic. This increases the difficulty of computing the initial geometry. Within the scope of this thesis, an empirical approach was used to ensure the knitted shape approximates the target geometry when tensioned. Samples of textiles are knitted with the desired loop configurations and machine parameters. These samples are tensioned bidirectionally in a rig until a locked knitted state is reached. The loop height and width are measured in this state and used as parameters for the pattern generator. By calibrating the pattern generator with stretched loop parameters, a pattern is generated for a textile that comes close enough to the desired tensioned target geometry[13].

6.6 Summary

Weft-knitted textiles can be produced using industrial CNC knitting machines, which require a 2D knitting pattern. The typical process for designing a pattern can be laborious, time-consuming, and requires expert knowledge of the knitting process. As knitting is most commonly used in the garment industry, commercial software focus on repetition and known forms. While the shaping potential of weft-knitted fabrics is generally accepted in technical applications, scientific literature documents limited patterning strategies to create 3D-shaped or doubly-curved geometries. Flexible and automated strategies for translating a complex 3D geometry into a 2D pattern are needed to fully benefit from the advantages of these textiles in an architectural context, where objects are much larger and less repetitive.

This chapter presented a computational approach to automatically generate knitting patterns for a given 3D geometry. These patterns are generated as a graph onto a 3D model of the desired shape and represented as a 2D pixel-grid diagram. The 2D patterns include accurate placement of shaping operations such as increases, decreases and short-rows. The model accuracy in comparison to the real object is highly dependent on precise measurements of loop geometry, which are directly correlated to the knitting machine parameters. Knowing these parameters, a good draping of the model with minimal loop distortion is achieved.

The implementation of the approach as design tool in Rhinoceros 3D was presented and the control given to the user was described. The user can set the knitting parameters, choose the knitting direction, manipulate the pattern and mark features such as channels, openings or colour patterns. Once generated, the patterns are exported as bitmap image files, which can be imported for processing in the knitting machine software. The workflow for generating and processing the patterns for the machine has been presented.

[13]Note that these empirical material models are based on rather homogeneous knitted textiles. To reach the target geometry with accurate control over tensioning, the inverse problem described above needs to be solved. This is especially necessary at larger scales with truly varied knitted material properties.

Photo credit: Angelica Ibarra

Part III

Results

Photo credit: Alessandro Dell'Endice

Chapter 7

Prototypes

This chapter presents the prototypes built using the formwork system and computational setup described in Chapters 4 and 6. The prototypes are divided into three categories, presenting components, a small-scale prototype and architectural scale prototype[1]. Section 7.1 presents a series of experiments that investigate the potential of knitting for creating doubly curved geometries and integrating additional features. The prototypes focus on the development of the needed knitting techniques and sequencing logics. They serve as a first validation of the automated pattern generator presented in Chapter 6, and the tensioning and coating for stiffening. These experiments are the precursors to the architectural prototypes presented in Sections 7.2 and 7.3. Section 7.2 presents a small bridge prototype built using a knitted textile with channels and openings that are used to guide bending-active elements and belts for tensioning the textile into shape. The bridge prototype is 1.2m wide, 2.1m long and 0.26m high. It is coated manually inside a climate chamber and demonstrates the feasibility of using the knit formwork and realising the structure through gradual strength and stiffness build-up. Finally, Section 7.3 presents an architectural scale pavilion built to investigate the scaling possibilities of the system. The 5.8m x 5.8m x 4.1m pavilion has a surface of 50m2 and was built on a cable-net falsework tensioned in a timber and steel scaffold with a knitted textile mould. The pavilion not only tested the scaling possibilities in terms of construction but also in terms of computational work-flow and machining.

[1] Parts of this chapter are based on Popescu et al. (2018) and Popescu et al. (2019).

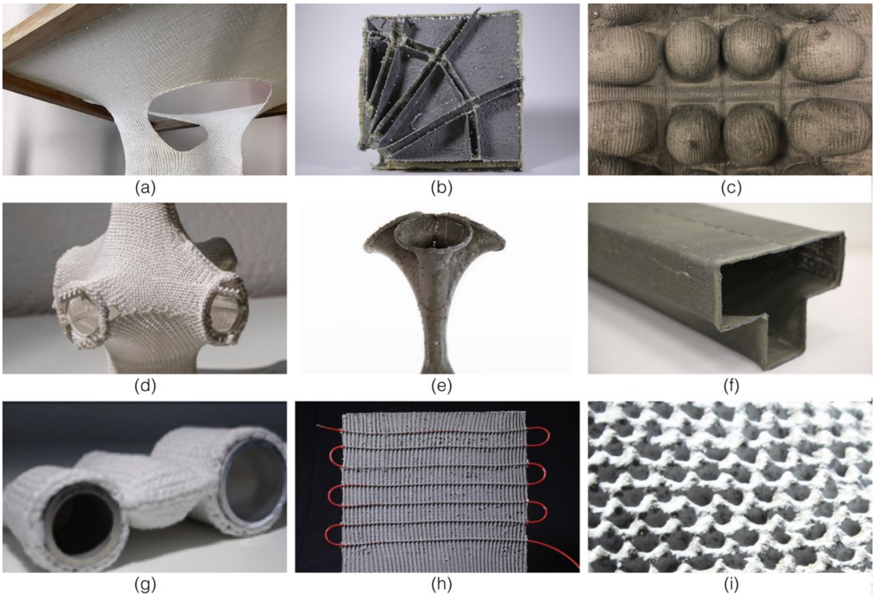


Figure 7.1: Selection of possibilities afforded by knitting: surfaces that are (a) non-orientable (b) stiffened with ribs (c) have pockets forming cavities; components forming a (d) freeform, six-directional node, (e) four-directional node, (f) T-section beam; and, elements that (g) integrate channels for inserting tubes (h) knit in hydronics; or (i) add surface texturing.

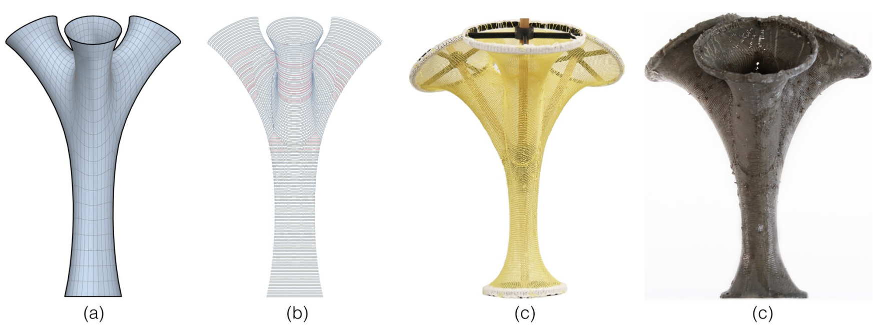


Figure 7.2: Four-directional node from 3D model to physical node: (a) 3D input geometry; (b) generated 3D knitting pattern; (c) tensioned knitted textile; (d) cement-paste coated knitted node.

7.1 Components

This section presents experiments built to explore the range of possibilities and highlight the potential of using knitted textiles as bespoke formwork for complex geometries. These components can be divided into three categories: three-dimensional and non-developable surfaces (Figure 7.1a-c), linear elements and nodes (Figure 7.1d-f), and components with extra features for further functional integration (Figure 7.1g-h).

The prototypes presented here were used to develop strategies for fabricating, tensioning and coating the knitted textiles[2]. These strategies and features inform the formwork system design for the KnitCrete bridge and KnitCandela prototypes, hinting at further possible developments.

7.1.1 Nodes and linear elements

One of the advantages of knitting is the possibility of easily creating branching structures, which could be used to cast monolithic joints. The case studies on nodes looked into fabrication strategies and knitting sequencing to create multi-directional nodes. A six- and four-directional node illustrate the versatile geometric possibilities offered by knitting (Figures 7.1d-e)[3]. The four-directional non-developable node was used as a first validation of the pattern-generation workflow and as a first coating test (Figure 7.2)[4].

Patterning and fabrication

Although composed of tubular geometries, the node is non-developable and knitting patterns as primitives do not readily exist. The geometry needed to be split into four parts, as shown in Figure 7.3, and patterns were generated for each part using the computational approach described in Chapter 6.

Figure 7.4 gives an overview of the resulting, generated pattern, highlighting in magenta the short-rows used for the shaping of the geometry (Figure 7.4a), the schematic course-by-course knitting pattern for a piece of the node (Figure 7.4b), and the short rows as they appear in the knit piece (Figure 7.4c).

[2]All components in this section were coated with a cement-paste coating, developed at the Chair of Physical Chemistry of Building Materials, ETH Zürich.

[3]Appendix A.2 shows the fabrication strategy for a six-directional node.

[4]The node's knitting pattern was generated only considering draping, not tensioning; hence, the difference between the 3D model and the physical node in Figure 7.2.

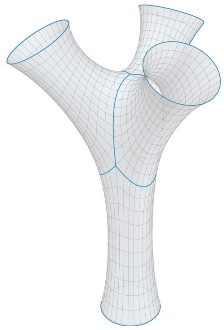


Figure 7.3: Patching of the 3D surface geometry for pattern-generation.

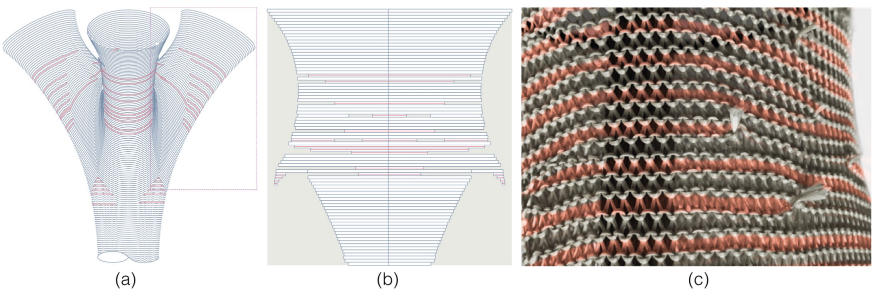


Figure 7.4: Three-dimensional knitting pattern for the four-directional node: (b) knitting pattern for the right branch (box in a); (c) short row features on knit prototype colourised for illustrative purpose.Patching of the 3D surface geometry for pattern-generation.

Tensioning and coating

The node was tensioned by attaching each of the four openings of the textile to a ring and fixing the rings to a wooden skeleton. Because of its small size, the textile could be coated before tensioning into shape. With the rings attached, the textile was placed in a container (Figure 7.5a) and the cement-paste coating poured on top (Figure 7.5b) making sure all sides of the textile were covered (Figure 7.5c). The cement-paste covered textile was removed from the container (Figure 7.5d), the rings were fixed to wooden rods to be tensioned into shape (Figure 7.5e-f), and the node was left to harden in a climate chamber with constant humidity. Once hardened, the rods and rings were removed, revealing a stiff, lightweight component (Figure 7.6).

Figure 7.5: Coating and tensioning of the node: (a) untensioned textile in a container; (b) cement-paste coating is poured into the container; (c) and (d) the fully coated textile; (e) tensioning of textile by fixing the rings to wooden rods; (f) coated and tensioned node.

Figure 7.6: Coated and hardened lightweight node prototype (photo cedit: Alessandro Dell'Endice).

(a) (b) (c)

Figure 7.7: Tensioning and coating of T-section profile: (a) compact textile clamped to wooden profiles; (b) covering the textile in the cement-paste coating; (c) finished T-section prototype (photo credit: (a) and (b) Oliver Knepper).

The same tensioning and coating strategy was applied to the T-shaped beam shown in Figure 7.7. The T-shaped beam was built with an off-the-shelf spacer fabric, clamped to wooden profiles on two sides, and tensioned with steel bars that can be removed and reused.

7.1.2 Rib-stiffened surfaces

Rib-stiffened surface configurations offer the possibility of increasing the load-bearing capabilities of a structure in a material efficient and economical way. In an architectural context, undulations and stiffening ribs have long been used for the construction of large-span lightweight structures or efficient slabs (Bechthold, 2008; Halpern et al., 2013).

Rib-stiffened floor

The great material-reducing capacities of a structurally informed design of rib-stiffened slabs have recently been demonstrated with a lightweight, unreinforced funicular floor (Figure 7.8). The floor system relies on the structural principle of arching action for compression with stiffening ribs for the live loads. This optimised solution significantly reduces the weight compared to standard systems (Liew et al., 2017).

A quarter of a similar floor geometry was used to investigate the possibility of building complex, rib-stiffened surfaces using weft-knitting. To build such rib-stiffened geometries, knitted textiles with ribs oriented in various directions are needed. This requires the possibility to create fins on a surface in

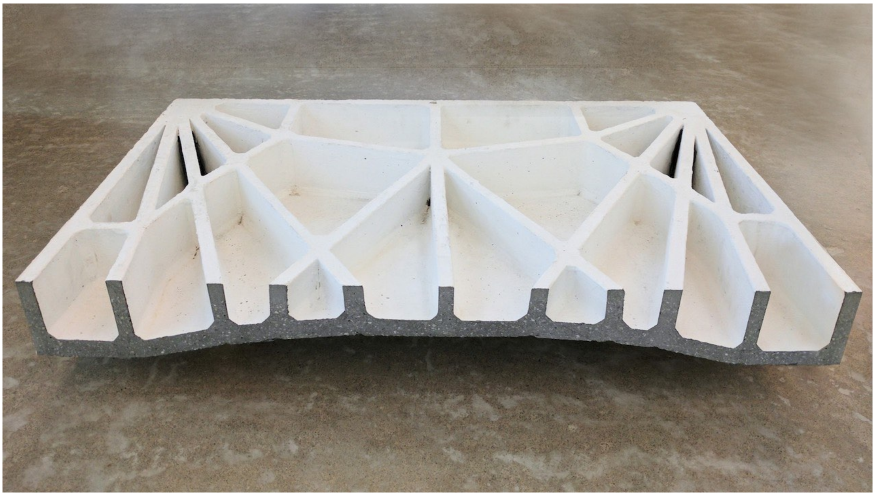


Figure 7.8: Rib-stiffened funicular floor slab (photo credit: Block Research Group, ETH Zürich).

both weft and warp direction[5].

The knitting pattern for the prototype was generated for the geometry using the approach detailed in Chapter 6. Figure 7.9 shows the strategy applied to create angled ribs in weft direction on a rectangular surface. The knitting direction was chosen and the knitting pattern generated accordingly, directly onto the 3D geometry (Figure 7.9a). This 3D pattern is translated into a pixel diagram (Figure 7.9b), which can be used as input for the specific knitting machine software. Figure 7.9b shows the pattern for the surface of the floor and omits the pattern for the ribs. The place where the patterns for the ribs can be added is marked with dotted lines, while non-weft ribs are marked on the pattern in magenta. The prototype in Figure 7.10 was knitted following the developed knitting patterns in Figure 7.9, tensioned in a wooden frame and coated. It is to be noted that the vertical connection between ribs in weft and warp direction cannot yet be done in a single process, the ribs must be connected manually. To avoid the need for stitching, textile connecting strategies using channels could be envisioned.

[5] Further Experiments investigating the possibility of knitting textiles with ribs of various orientations in one single process have been carried out in collaboration with the Institute for Textile Machinery and High-Performance Materials at TU Dresden and are presented in Appendix A.3.

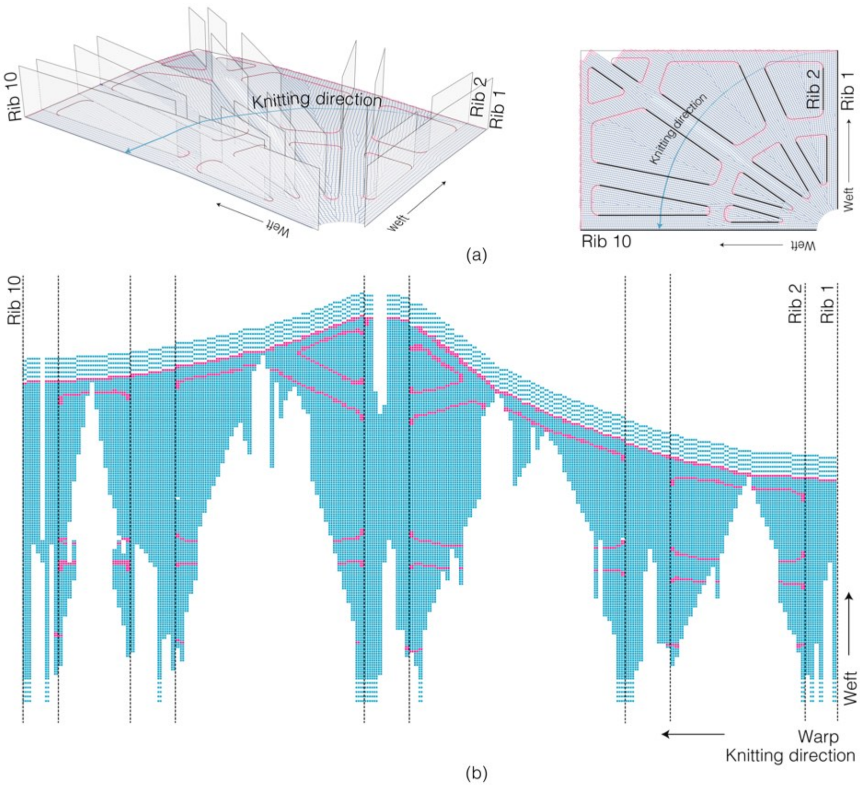


Figure 7.9: Knitting pattern for a quarter of a rib-stiffened floor: (a) axonometric and plan view of the knitting pattern generated in 3D; (b) Knitting pattern as pixel diagram to be used for knitting.

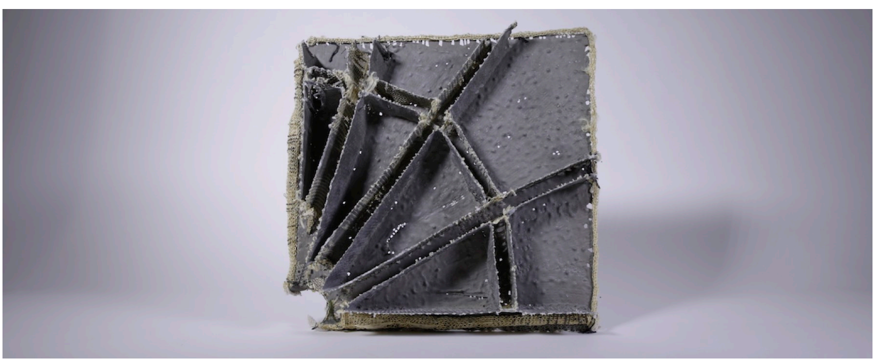


Figure 7.10: Coated part of a quarter prototype of a rib-stiffened floor (photo credit: Achilleas Xydis).

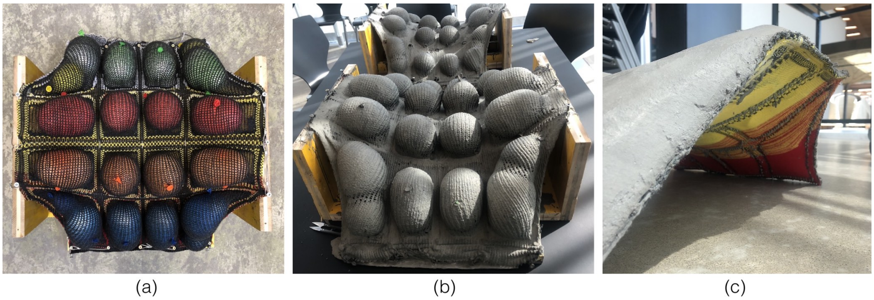


Figure 7.11: Waffle-shell prototype with cavities formed by balloons: (a) tensioned knitted textile with inflated balloons; (b) coated prototype; (c) the finished prototype.

Waffle-shell formwork

Another approach to building rib-stiffened structures is by creating a mould that shapes the cavities formed between the ribs. This can be achieved by creating pockets in the knitted textile, which can be filled or inflated to form cavities in the final structure. Figure 7.11 shows an example where pockets in the knitted textile are filled with balloons and used to create cavities. This type of approach is a precursor to the system used for the KnitCandela waffle shell, presented in Section 7.3.

7.2 KnitCrete Bridge

The bridge prototype (Figure 7.12) was built to test the feasibility of using a low-tension, textile formwork that is gradually stiffened and strengthened to carry the casting of concrete with minimal deformation[6]. The custom, weft-knitted textile includes channels for inserting bending-active elements and ribbons, which are used for tensioning the textile into shape. The resulting spline-stiffened, corrugated geometry offers support during the application of the stiffening coating and mortar that make up the formwork.

Figure 7.12: Finished KnitCrete Bridge prototype.

7.2.1 Design

The bridge is a corrugated shell. The corrugated geometry is created by tensioning a membrane into shape alternating integrated bending-active and tensioning elements to create ridges and valleys, respectively. In this case, five 8mm glass-fibre reinforced polymer (GFRP) rods and four 30mm braided Aramid ribbons were used. By increasing the effective structural depth geometrically, the corrugation acted as a local stiffening scheme for

[6]To asses deformations, measurements were taken throughout the concreting process. These are strictly used to assess the effect of the coating with regard to the tensioned geometry. As this was not simulated (or necessary), no relevant comparison can be made between the built geometry and the digital one.

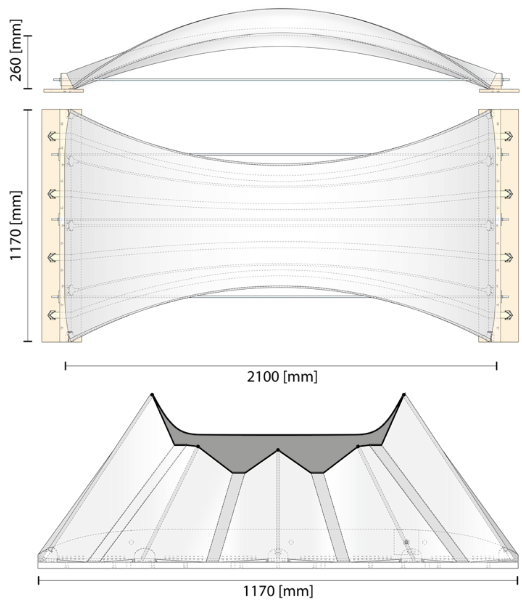


Figure 7.13: Elevation, plan and cross-section views of the final bridge design.

the structure (Figure 7.13). The dimensions of the prototype were limited by practical considerations of available space and manoeuvrability within the concrete laboratory. Therefore, the prototype has a 2.10m span, 1.17m width at the supports and 0.60m width at mid-span, and a rise of 0.26m.

7.2.2 System

Figure 7.14 shows an exploded axonometric view of the formwork system, which consists of the following components:

- The stay-in-place formwork layer is made of a custom knitted textile (c) with integrated channels for the insertion of shaping elements,
- Once tensioned into shape, the formwork is made rigid using a light layer of high-strength cement paste (f) and one of mortar (g),
- These paste and mortar layers are light enough not to load the structure excessively and provide sufficient strength and stiffness to support the final layer of structural concrete (h).

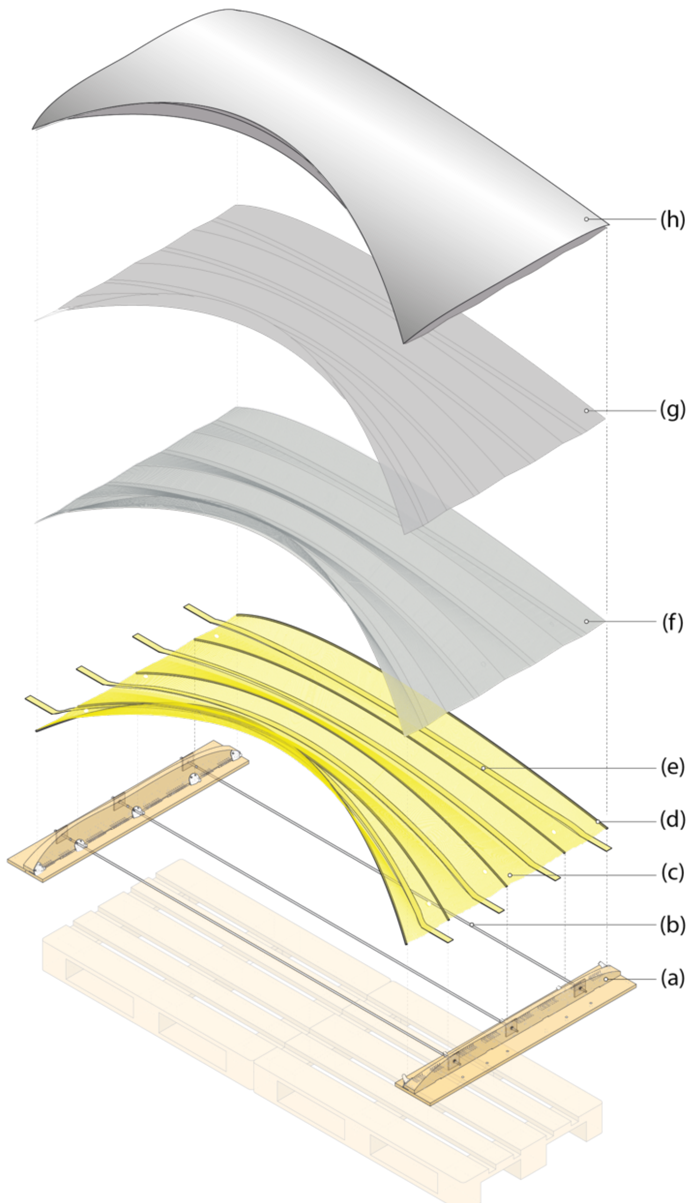


Figure 7.14: Exploded view showing the layered formwork concept: (a) timber edge supports; (b) threaded-rod ties; (c) 3D knitted textile; (d) bending-active rod; (e) tensioning ribbon; (f) cement-paste coating; (g) mortar; and (h) structural concrete.

Figure 7.15: Brother KH-970 computerised knitting machine, equipped with a second needle bed (ribber).

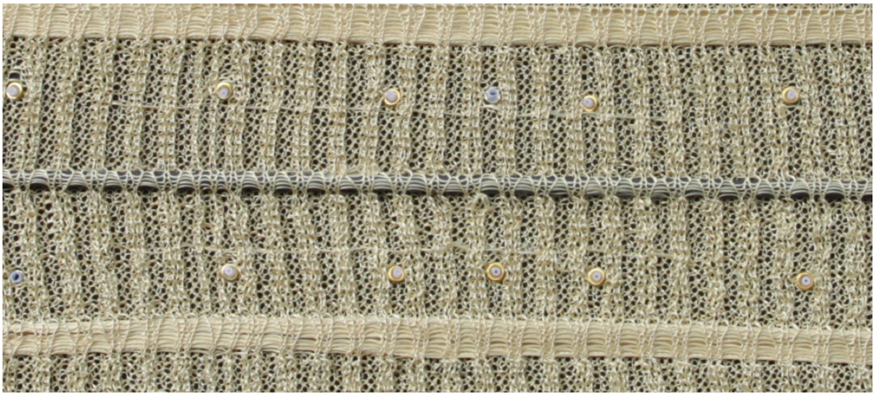


Figure 7.16: Untensioned textile with inserted GFRP rods and Aramid fibre ribbons, riveted markers and textured surface.

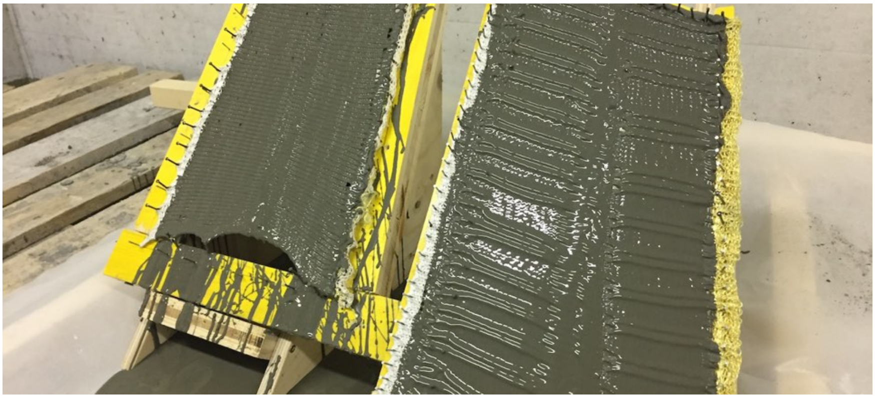


Figure 7.17: Coverage tests showing that a textile with a ribbed surface performs better. Left: single-jersey knitted textile; right: double-jersey knitted textile.

7.2.3 Fabrication

The knitted formwork for the prototype was made with Aramid yarn (160 TEX) on a computerised Brother KH-970 knitting machine, equipped with a second needle bed, also known as a ribber (Fig. 7.15). Due to the limited width of the machine (90 cm), the textile was manufactured in three pieces, that were stitched together to form the whole.

Textile features

The final knitted textile included:

- channels for inserting and guiding the GFRP rods and Aramid ribbons,
- openings that allow the bridge's steel tension ties to pass through the shell surface,
- openings for inserting riveted markers, which are holders for elements used to control the concrete thickness and as registration points to measure the structure, and
- a textured surface, which creates small ridges that help with the coating process and allows for a better mechanical bond with subsequent mortar layers.

Figure 7.16 shows the appearance of the untensioned textile with the GFRP rods, braided ribbons inserted into the channels, and the riveted markers.

Coating tests were done to find the appropriate knit density and knitting logic. These helped determine the maximum hole size and surface texture such that the cement-paste coating has optimal coverage. Figure 7.17 shows the behaviour of the coating on a plain-knit (left) and textured-knit (right) sample. The tests showed that the textured knit performed better by slowing down the flow of the cement-paste, resulting in better coverage. The coverage tests also showed that holes up to 5mm in diameter could be coated with ease.

Knit pattern generation

The knitting pattern for the bridge was generated using the computational approach described in Chapter 6. Sample material pieces were knit to determine the loop geometry parameters for the pattern generations. The

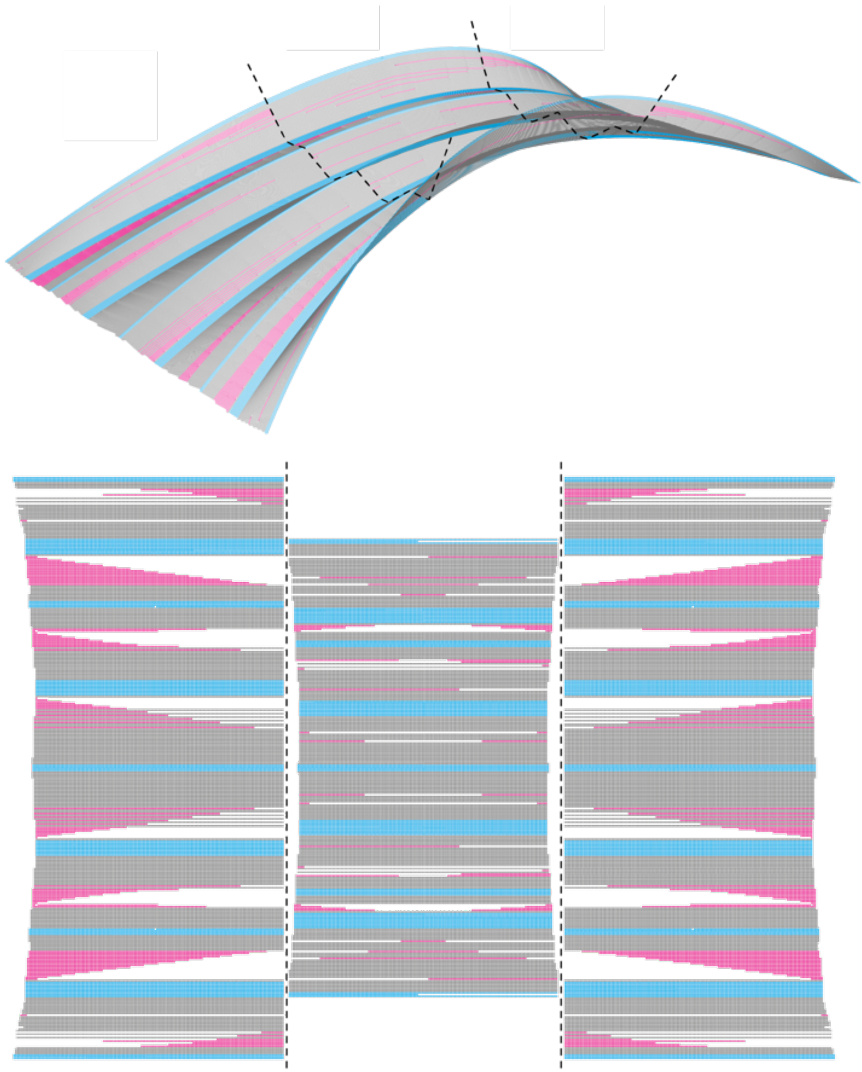


Figure 7.18: Generated knit patterns needed for the fabrication of the textile.

material pieces of 60 loops in width by 100 loops in length were knit with the chosen yarn (Aramid 160 TEX) and tension settings. The loop dimensions were measured after samples were tensioned in a rig[7]. A target loop dimension of 3.5mm x 5mm was chosen based on the stretch and coating tests. The 3D geometry was split into three parts, corresponding to the three pieces of textile to be fabricated. Patterns were generated only for parts one and two since parts one and three are mirror-identical. The parts were then split into patches coinciding with the areas between ridges and valleys. By generating patterns for each of these patches separately, the channels are aligned with the knitting direction. This alignment makes it easier to knit the channels. Figure 7.18 shows the generated knitting patterns and the layout of the three sections in the complete textile. The total weight of the knit amounted to only 430g. When combined with the tensioning ribbons, rods and registration markers the flexible formwork weighed approximately 900g, less than 0.5% of the total weight of the final structure.

7.2.4 Construction

Three separate concrete layers were applied onto the tensioned textile to create the structure. First, the thin cement-paste stiffening coating (Figure 7.14c) was applied. Then, to give the formwork sufficient stiffness and strength, a mortar layer was sprayed on once the cement-paste coating hardened (Figure 7.14d). Finally, with the first two layers making up the lightweight formwork, the final layer of concrete (Figure 7.14e) could be cast.

Formwork Assembly

Timber edge beams with a cross-section of 60mm x 80mm were fixed onto two Euro-Pallets. The edge beams were fitted with custom 3D-printed fixtures for clamping the GFRP rods, and slots for passing the aramid ribbons through. First, the five GFRP rods (with an 8mm outer and 6mm inner diameter) and four 30mm wide Aramid ribbons were inserted into the textile while flat on the ground. Then, the rods were inserted into their respective 3D-printed supports and ribbons were passed through the slots in the edge beam to be secured using ratchet straps.

[7] The set up and results of the stretch tests for determining loop geometry are presented in Appendix D.

Figure 7.19: The knitted textile layer of the formwork, tensioned into shape using GFRP rods to create ridges and aramid ribbons for valleys (photo credit: Achilleas Xydis).

The two ends of the textile were fixed to hooks fitted onto the edge beams and secured in place using rubber ”U” profiles. Finally, using the ratchet straps, the ribbons were tensioned until the desired shape was achieved. Temporary GFRP struts were placed along the length of the bridge between the bending-active rods. This was done to maintain the correct distance between rods and to prevent them from deflecting inwards when tensioning the textile. The resulting tensioned structure can be seen in Figure 7.19.

The resulting tensioned geometry was measured using a flush tape measure. This measurement was used as the reference geometry to check the deformations resulting from the casting steps. The measurements were done on a grid of 391 reference points placed every 10 cm along each rod, ribbon and midpoint between the two.

Coating and concrete

The special cement-paste coating used for this prototype was developed at the Chair of Physical Chemistry of Building materials, ETH Zurich. It is a stable highly fluid suspension consisting of a blended ordinary Portland cement, a polycarboxylate ether based superplasticizers and stabilising nanoparticles (Fontana et al., 2015). A small funnel was used to apply the

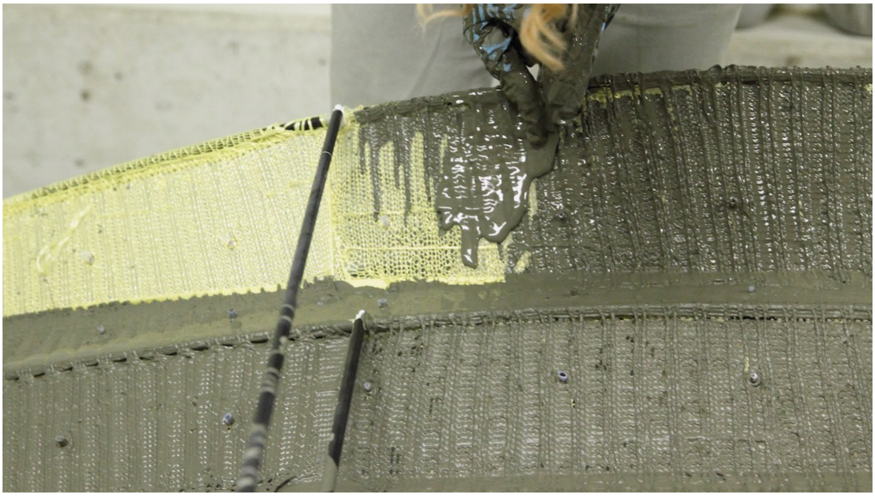


Figure 7.20: Applying the cement-paste coating to the textile using a funnel (photo credit: Lex Reiter).

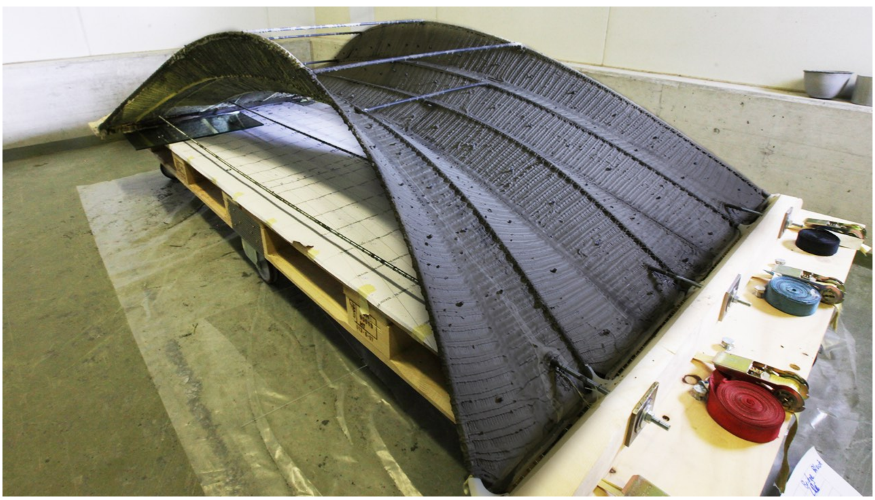


Figure 7.21: Stiffened knitted textile after the cement-paste coating layer had hydrated (photo credit: Demetris Shammas).

coating to the textile manually (Figure 7.20). This was done in symmetrical strips along the length of the bridge, starting from the middle and working towards the supports. The coating was allowed to cure for seven days in a climate chamber at 95% relative humidity and 20°C. The resulting coated textile was 1.5mm thick and weighed approximately 12kg (Figure 7.21).

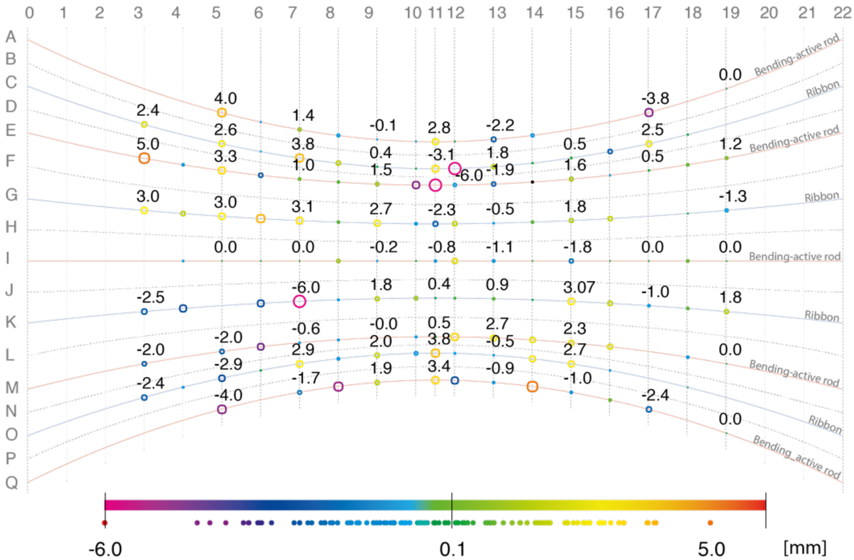


Figure 7.22: Overall deformations after application of the cement-paste coating, compared to the initial geometry, showing an average deviation of 0.1mm.

The prototype was measured 48 hours after the coating was applied. The maximum deformation compared to the previous state was found to be 6.0mm, while the average deformation across the prototype 0.1mm (Figure 7.22). Then, a commercial repair mortar was sprayed onto the stiffened textile using pressurised air and a conveying pump (Figure 7.23). The resulting formwork layer was roughly 4mm thick and weighed approximately 40kg. This layer was allowed to cure for three days after which the structure was decoupled from the pallets, activating the tension ties. Deviations following the application of the second mortar layer were in the range of 2-5mm relative to the previous cement-paste coated geometry. Finally, an easy-to-compact, steel-fibre-reinforced concrete with a target yield stress of 1200 Pa and a water-to-cement ratio of 0.38 is the structural concrete layer. This layer was cast manually, in the same manner one would cast into a traditional formwork. Figures 7.24 and 7.26 show the concrete casting process and the result.

A comparison was made between the measured geometry[8] after the final

[8]The geometry measured once the textile was tensioned. No meaningful comparison can be made with the modeled 3D geometry.

Figure 7.23: Mortar spraying on the coating-stiffened textile shell (photo credit: Demetris Shammas).

Figure 7.24: Final concrete layer cast manually into the stiffened fabric formwork (photo credit: Alessandro Dell'Endice).

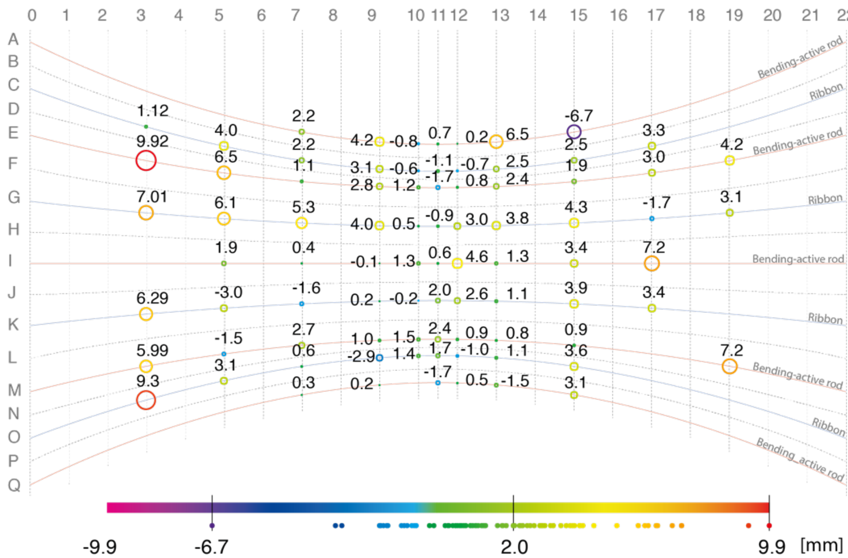


Figure 7.25: Overall deformations of the formwork with respect to the initial geometry, showing an average deviation of 2mm.

concrete layer and the initial measurement. deviations were on average 2mm (Figure 7.25). The measurements of the cement coating and mortar layer compared well to the initial geometry, proving that a flexible fabric geometry that is stiffened in layers, provides a feasible formwork strategy with low deformations.

7.2.5 Discussion

The prototype was built to investigate the possibility of constructing a concrete structure using a self-supporting tailored knitted textile formwork in combination with bending-active elements and stiffened using cement paste and mortar. The corrugated nature of the cross-section was structurally advantageous and the textured bottom surface was well-suited for applying subsequent cover. Through the application of a thin layer of cement-paste on the knitted textile, the fabric formwork was stiffened sufficiently to support the application of the incoming thicker concrete layers, while maintaining the original shape of the tensioned textile. A two-step process was needed for the buildup of the formwork layer as the coating could not be directly applied in one pass to the needed thickness of 4mm. Measure-

Figure 7.26: Finished bridge prototype (left: Mariana Popescu, right: Lex Reiter; photo credit: Pieter Bieghs).

ments performed on the structure after each step of the construction process showed that deformations as a result of coating, spraying and concrete casting were low, at only 2mm on average in total. Moreover, tensioning stresses could be kept low as the thin coating did not place a significant load on the knitted textile. The knitting pattern-generation worked well, producing the designed geometry of the formwork in its tensioned state. For this, it was important to calibrate the pattern with material tests that took into account the desired machine setting and material behaviour when combined with the cement-paste coating. The orientation of the ribbed texture on the textile surface played an important role, as it helped with bonding in the cement-paste coating process. As expected, this texture was most effective when the ripples were orthogonal to the principal flow direction of the liquid cement paste. Furthermore, the ripples provided improved bonding with the subsequent thicker mortar layer. Scaling-up the system could be approached in two different ways: by scaling the entire system, or by the construction and assembly of multiple smaller pre-fabricated components. For the latter solution the system is already considered at scale; remaining challenges relate to the assembly of the discrete components and their mechanical connections. A scaling up of the system, using a cable net instead of bending-active elements as support, is presented in the next section.

Photo credit: Angelica Ibarra

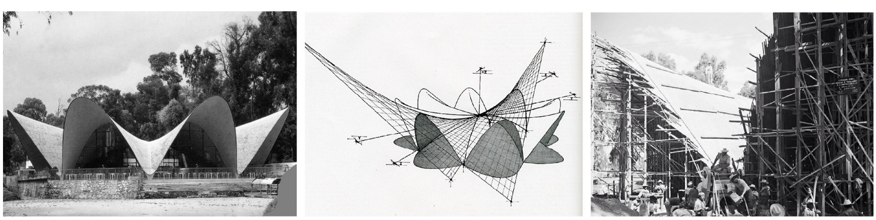
7.3 KnitCandela

KnitCandela is a thin freeform concrete waffle shell built using a custom prefabricated knitted textile as shuttering and a form-found cable net as the main load-bearing formwork. The digitally designed and fabricated textile provided integrated features for inserting and guiding elements such as cables and inflatables that helped shape the sophisticated mould.

With a total weight of 55kg, the 50m2 formwork was easy and compact to transport to site for its deployment where it was tensioned in a timber and steel rig and coated with a fast-setting cement-paste. Fibre-reinforced concrete was manually applied onto the formwork to realise a 3cm-thick shell with rib stiffeners with a height of 4cm. The shell was built at the Museo Universitario Arte Contemporáneo (MUAC) in Mexico City as part of the first exhibition of Zaha Hadid Architects in Latin America and on exhibit from October 2018 to March 2019. The final design was developed by the Block Research Group, at the Institute for Technology in Architecture, ETH Zurich in collaboration with the Computational Design Group of Zaha Hadid Architects (ZHCODE). The full credits are given in Popescu et al. (2019).

7.3.1 Design

Designed as a homage to the Spanish-Mexican shell builder Félix Candela (1910 - 1997), the curved geometry of the shell is reminiscent of Candela's restaurant in Xochimilco (Figure 7.27a), while its fluid form and colourful interior surface are inspired by the traditional Jalisco dress.Candela relied on hyperbolic paraboloids ("hypars") to efficiently build doubly curved concrete shells.



(a) (b) (c)

Figure 7.27: Hyperbolic paraboloid shell structure by Félix Candela: (a) Los Manantiales restaurant in Xochimilco, Mexico City; (b) hypar representing one bay of the structure; (c) construction of the hypar structure with straight formwork elements only (photo credit: (a) RIBA Collections; (b) Felix Candela; (c) Juan Guzman - Colecction Fundacion Televisa

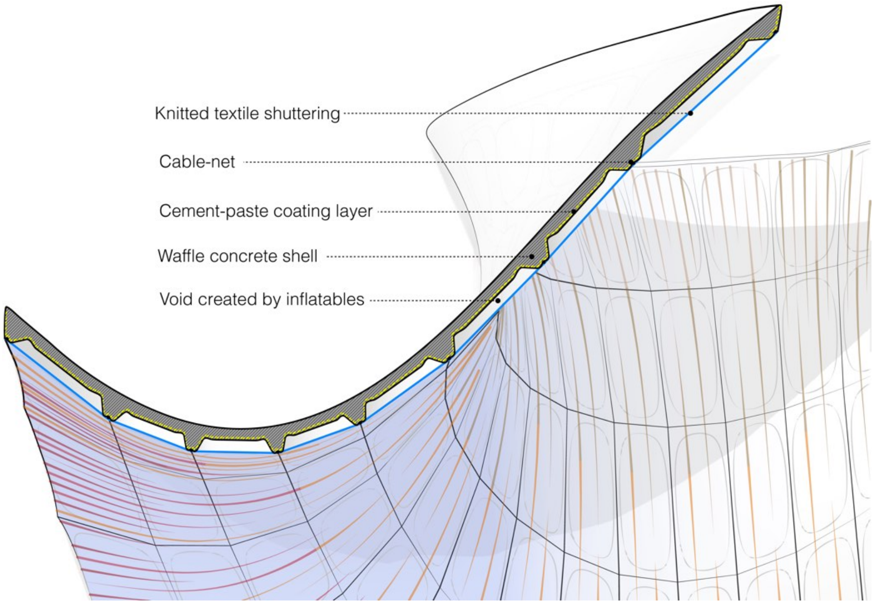


Figure 7.28: Detail section through the pavilion showing the final, concrete waffle-shell geometry.

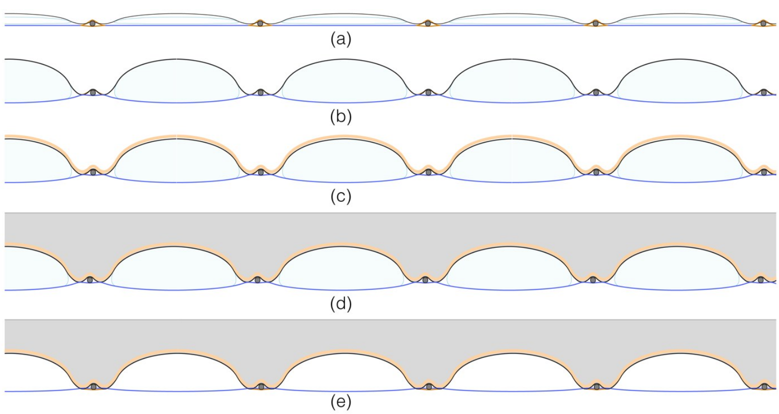


Figure 7.29: Principle diagram of inflation and building up strength in layers for the Knit-Candela textile: (a) custom knitted textile with pockets for cables and balloons; (b) pockets inflated using standard modelling balloons; (c) fast-setting cement-paste coating is applied to the textile; (d) concrete is cast onto the stiffened textile; (e) balloons can be deflated and form the cavities of the concrete structure.

Hypars are ruled surfaces, meaning they are curved geometries that can be described entirely by rulers, i.e. lines. Candela used this property to rationalise the formwork of his shells where the straight rulers are thin wooden beams (Figure 7.27b). While they may be relatively easy to build, the geometrical variety of these doubly-curved surfaces is limited (to ruled surfaces) and relies on extensive scaffolding (Figure 7.27c). Unlike in Candela's work, the design of KnitCandela does not rely on ruled or developable surfaces to efficiently build doubly-curved concrete shells. Figure 1 shows the plan and elevation of the built shell, providing the overall dimensions of the pavilion.The geometry of the pavilion's formwork, defining the final shell, was form-found with a force-density approach (Schek, 1974) using a target geometry. The target geometry was defined through a series of design iterations with the goal of balancing the aesthetical and structural targets of the project. Both the target geometry and the final geometry were designed using a non-uniform distribution of force densities, making the geometry neither based on hypars, nor on minimal surfaces (Mele and Block, 2011).

7.3.2 System

The formwork system behind KnitCandela was made up of three elements:

- a external timber and steel frame/scaffolding,
- a load-bearing steel cable-net falsework, and
- a custom 3D weft knitted textile shuttering/mould.

The cable net was integrated within the textile and tensioned in the timber frame to form the formwork for the concrete casting.

The structure was designed as a 3cm-thick concrete shell with 4cm high stiffening ribs in both directions, thus resulting in a waffle shell. The cavities shown in Figure 7.28 are formed by inflating balloons inserted in the pockets designed in the knitted textile.

As with the KnitCrete bridge prototype presented in Section 7.2, strength is built-up in layers. Figure 7.29 shows the steps for building the formwork with cavities. This is done by inflating standard modelling balloons in the pockets of the textile (Figure 7.29b), coating the top layer of the textile with a fast-setting cement-paste coating (Figure 7.29c), and casting concrete onto the stiffened textile (Figure 7.29d). Finally, when the concrete has hardened, the pockets are deflated, leaving the textile in place and visible on the inside

Figure 7.30: Edge clamp solution(photo credit: Paola Figuero).

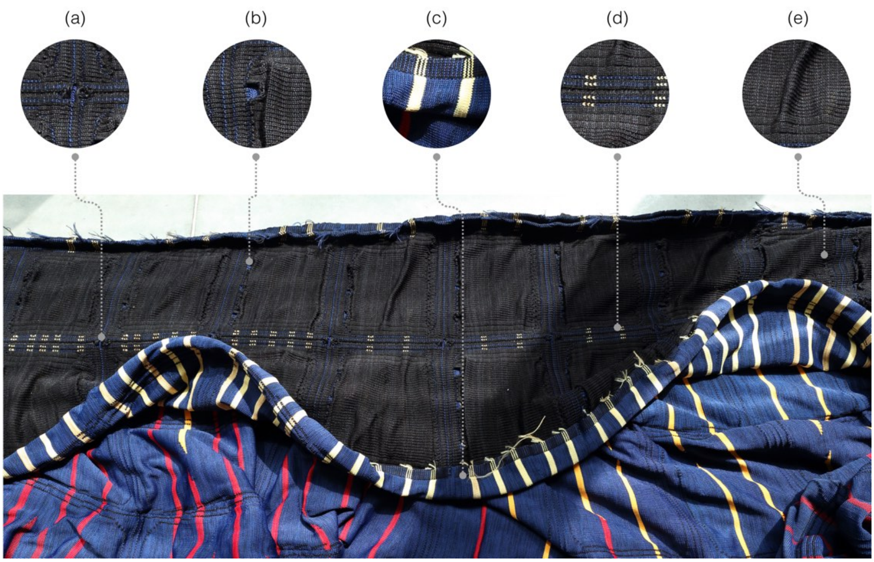


Figure 7.31: Double-layered knitted textile produced in one piece, featuring an aesthetic front face and a technical back face that includes for controlling the position of cables, inflatables and edge detailing: (a) openings for the cable-net nodes; (b) openings for inserting balloons; (c) textile border for joining pieces together; (d) channels for cables; and (e) variable loop densities and sizes.

of the structure (Figure 7.29e). The weft-knitted textile is not only used to guide the cables and keep the inflatables into position, but also to control the side and degree of inflation. Because the pockets and the properties of the textile control the size and inflation, standard balloons can be used for all cavities. This means custom solutions can be created with standard elements. The same is true for the edge details that are created by inserting steel rods into the edge/outside-boundary channels and held up by laser-cut wooden profiles (Figure 7.30). Finally, the textile is also used as an aesthetic element on the inside of the finished structure.

7.3.3 Textile features

The knitted fabric shuttering used for the construction of the KnitCandela shell (Figure 7.31) further demonstrates the integration and shaping possibilities offered by knitting at the architectural scale.

The included features are:

- a double-layered textile, with an aesthetic and a technical side,
- pockets and openings for inserting inflatables to form cavities in the final shell,
- varied loop sizes and densities for controlling inflation depth,
- channels and openings for inserting cables and inflatables,
- seam strategy and detailing to connect different knitted parts, and
- the inclusion of edge detailing for guiding concrete finishing.

Figure 7.31 shows the double-sided textile used as shuttering. The two layers of the textile fulfil different tasks. The visible aesthetic inner layer displays a colourful pattern. The outer, technical layer includes the features for inserting, guiding and controlling the position of the cables and other formwork elements. The pockets created between the two layers were inflated using standard modelling balloons, controlling the inflation depth using different knit densities.

7.3.4 Fabrication

The elements needed for the construction of the concrete shell were fabricated in Mexico and Switzerland. The textile shuttering was fabricated at

Figure 7.32: Steiger Libra 3.130 flat-bed knitting machine (photo credit: Lex Reiter).

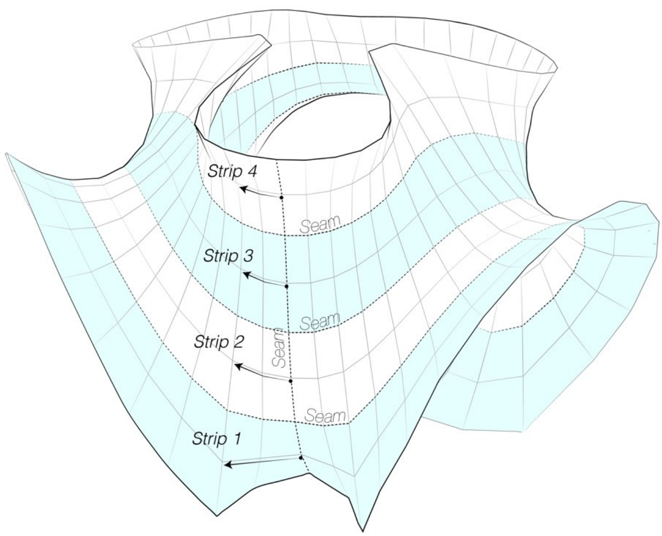


Figure 7.33: Division of the shell's surface into four strips for fabrication.

ETH Zurich and transported to Mexico in two suitcases, as checked luggage. The timber and steel frame for tensioning and the cables comprising the cable net were fabricated in Mexico City.

Textile shuttering

The 50m2 textile shuttering that comprises KnitCandela's formwork, was produced on a gauge 7 Steiger Libra 3.130 CNC flat-bed knitting machine (Figure 7.32). The textile dimensions are only limited by the machine's 1.3m-wide needle bed.To take advantage of the machine's ability to create infinitely long pieces, the geometry was divided into four long strips ranging from 16 to 26 metre in length.

Figure 7.33 shows the division of the geometry into strips, which resulted in a total of four seams over the entire surface. Three long seams, between the parts, and one final seam, connecting the start and end of a part, to form the tubular geometry. The seams were placed along cables both in the longitudinal direction and for the final vertical seam. Each of the four strips is a double-sided, weft-knitted textile produced in one fabrication process.

Pattern generation

Because the geometry is radially symmetrical, it was sufficient to generate the knitting patterns for a sixth of the surface. These are then mirrored and repeated to create the pattern for the full strip. The knitting patterns were generated using the approach detailed in Chapter 6 and Popescu et al. (2017). Because knitting is a directional process that produces a textile with different properties in width (weft direction) and length (warp direction), a knitting direction needs to be chosen and a target loop size determined. The knitting direction was defined by splitting the geometry into strips. To find the loop width and height parameters to be used in the pattern generation process, a series of textile prototypes were knitted. The textile prototypes helped investigate the needed parameters, develop the material formation needed for the system and calibrate the pattern generator for the needed tension. In this case the steel cable net is the main load-bearing component of the formwork. Therefore, the textile needs to be loose enough not to interfere with the tensioning of the cable net and tight enough to make a smooth inner surface and control the inflation of the balloons. The tightness was determined empirically by testing the interaction between the textile,

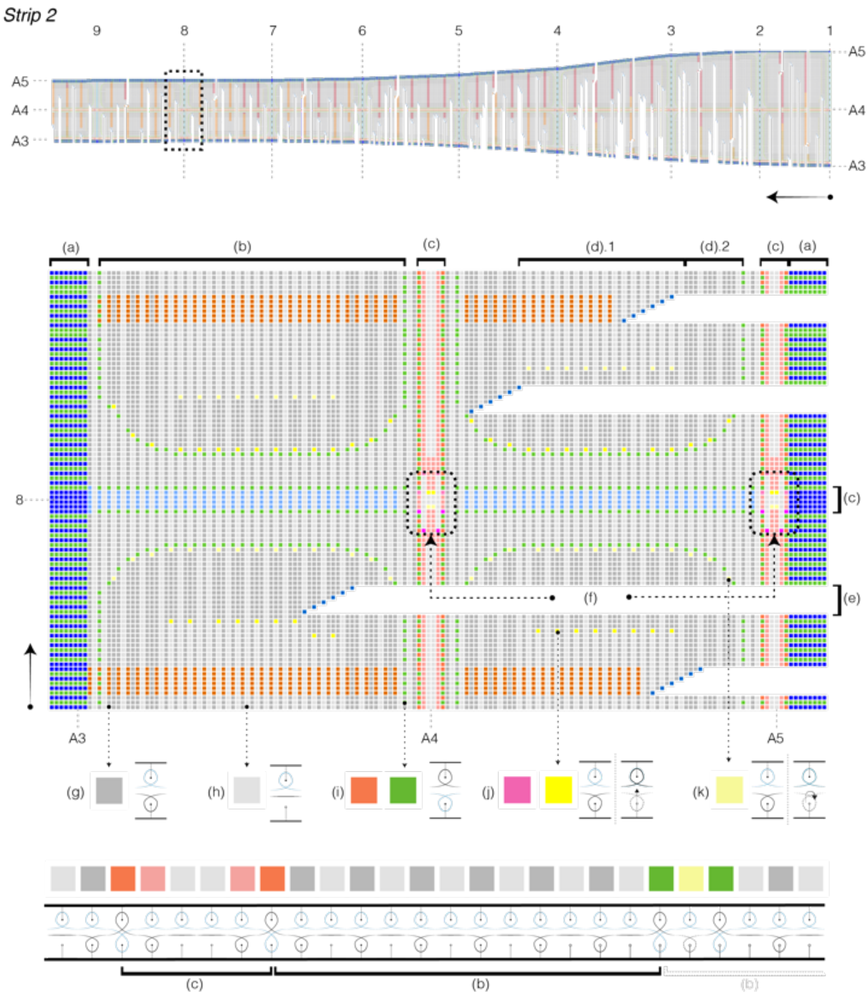


Figure 7.34: Generated knitting pattern for Strip 2 showing the features and functions needed to achieve them: (a) seam detail; (b) pocket; (c) vertical and horizontal channels; (d) varied loop densities; (e) short row; (f) openings in channels at their intersection; (g) knit front and back (yarn 1 and yarn 2); (h) float front and knit back (yarn 1 and yarn 2); (i) knit front and back (yarn 2 and yarn 1); (j) knit front and back, then transfer front to back; and (k) knit front and back, then drop front stitch.

cable net and inflatables in a 1:1 mock-up of part of the shell structure and adjusting the textile as needed Because the determined loop dimensions are very small (3.5mm x 2mm), to speed up the computational process, a larger unit was chosen for the pattern generation. The final parameters for the pattern generator were as follows:

- width: 7mm
- height: 12mm
- spacing weft: 2
- spacing warp: 6

The spacing in the weft and warp directions represents the number of loops included in the generated 7mm x 12mm unit. To generate the patterns, each strip was further split into patches coinciding with the quadrilaterals formed between cables. Generating the patterns in discrete patches makes the computation less intensive. Additionally, it naturally aligns the patterns to the cable directions, which makes the fabrication of the channels simpler.

After patterns were generated for all patches of a given strip, the 2D patterns were combined into one single pattern[9]. The locations of the cables and aesthetic colour lines were automatically marked with a colour code on the combined pattern. The final pattern is then exported as a BMP format pixel image. Each colour zone on the pixelated diagram represents a predefined function or set of functions for the machine to perform (Figure 7.34). The BMP image is imported into the machines' software, called Model 9, where each colour is assigned a symbol from a library developed for this project.

Library functions

A library of symbols (representing knitting functions) was developed in the knitting machines' software. To create all of the different textile features, needles on both beds of the knitting machine were used. Two different yarn guides fed the needles on any given machine carriage pass. One yarn guide fed the needles on the back bed and the other those on the front bed (Figure 7.35). This strategy creates two separate knitted panels, which are connected where the yarns change between the two needle-beds, forming the final double-layered knitted textile. A selection of the developed symbols

[9] Note that while the combining of patterns is a largely automated process, some manual editing was necessary to align the different patches properly.

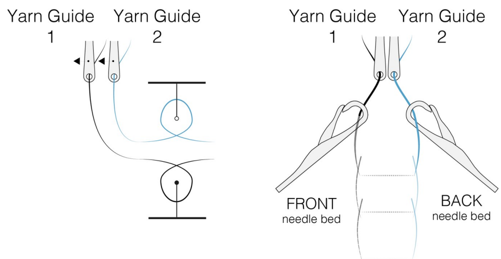


Figure 7.35: Yarn guides and their working on the needle-beds.

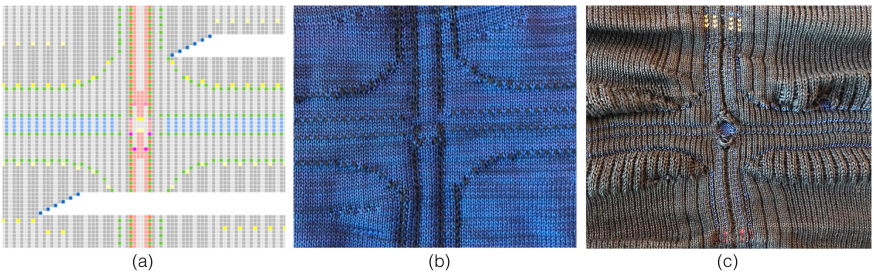


Figure 7.36: Knitting pattern and corresponding textile front and back face.

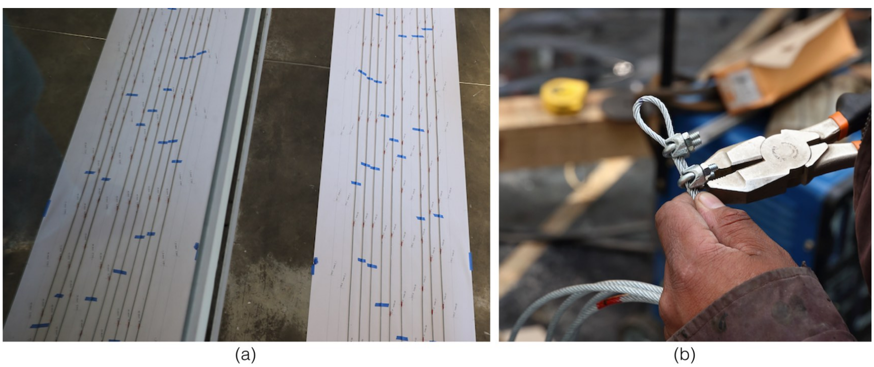


Figure 7.37: Cable-net marking and preparation: (a) cables laid out on plotted drawings with the position of the nodes; (b) loops at the end of cables for attaching the the frame.

and their functions is shown in Figure 7.34g-k. Also shown is an example pass of the machine carriage, the developed functions used in that pass and the resulting features in the knitted textile. Figure 7.36 shows an example of the generated knitting pattern and the relationship with the corresponding front and back faces of the produced textile.

Cable-net falsework

The cable net was made of 3mm steel cables with a plastic coating. All of the cables were cut to the predefined length and laid out onto plotted drawings with each node intersection marked along the length of the cable(Figure 7.37a)[10]. Loops were created at the top ends of the short/vertical cables using standard cable connectors (Figure 7.37b). These loops were used to attach the cable net to the frame used for tensioning. One of the two ends was left open until assembly when turnbuckles were attached.

7.3.5 Construction

The concrete shell was constructed on site over a period of four weeks. First, the timber and steel frame was assembled and fitted with all of the hooks for hanging and tensioning the cable-net and knitted textile formwork (Figure 7.38a). The cables were inserted in the knitted textile shuttering and fitted with turnbuckles at the ends. This package was then attached to the frame and taut into shape using the turnbuckles (Figure 7.38b). Once tensioned, balloons were inserted into the pockets in the textile, to create the waffle shell's weight-saving cavities described in Section 7.3.2 (Figure 7.38c). The entire textile was sprayed with a cement-paste coating for stiffening (Figure 7.38d). Then, concrete was applied manually onto the formwork (Figure 7.38e). Finally, once the concrete hardened, the cables were released and the frame removed (Figure 7.38f).

Frame assembly

The timber and steel frame for tensioning was built on site by local construction workers. First, a levelling concrete slab was cast to form the base of the shell pavilion, and the timber base frame was fixed onto the slab. Four steel poles, fixed to the middle of the base frame, supported the connected timber edge beams at the top of the frame. The three arched timber edge beams on the side of the frame were assembled flat on the ground and then raised into position. Then, the arched timber edge beams and the top edge beams were connected by tubular steel profiles welded to steel plates and bolted to the joints of the arched timber boundary.

[10] The positions of the nodes were marked onto the cables roughly with a wide red stripe and then precisely with a black line on top.

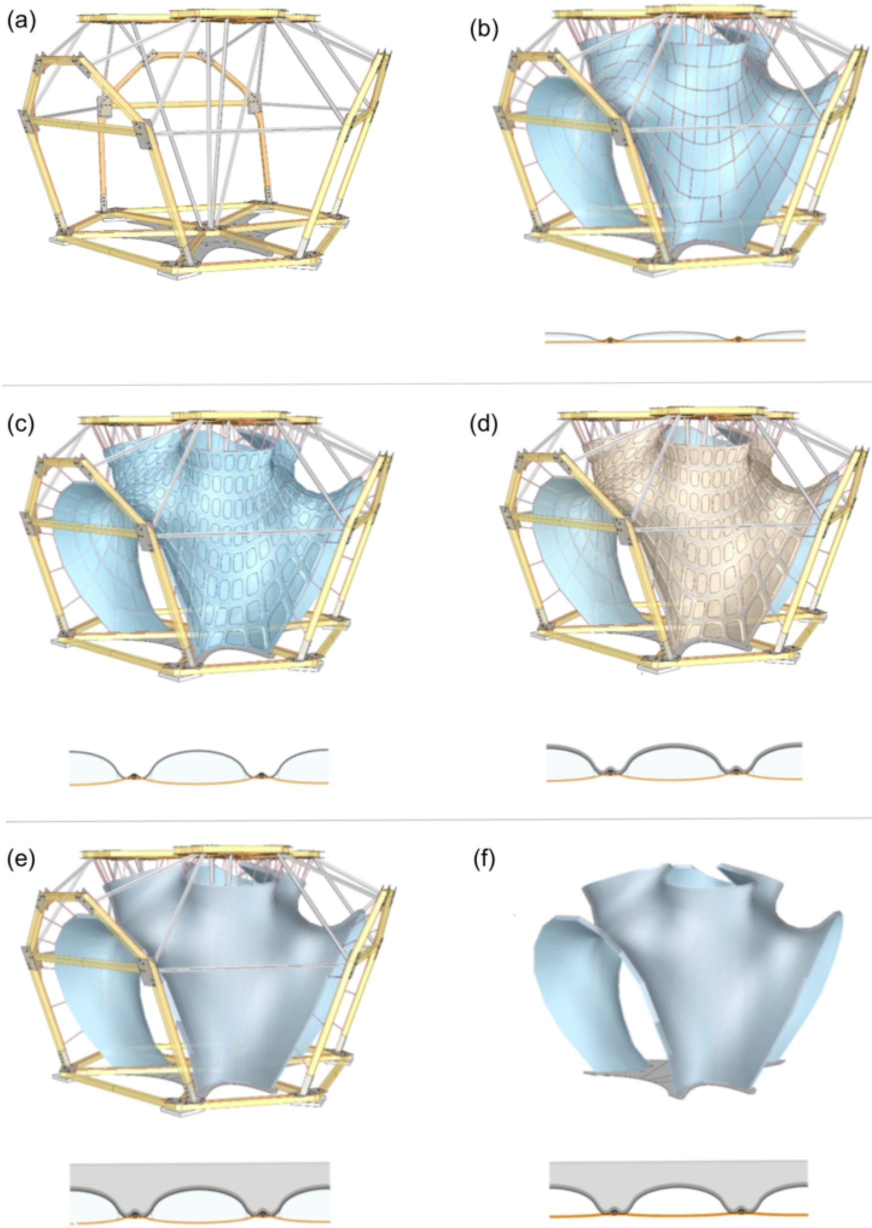


Figure 7.38: Construction sequence of KnitCandela: (a) external tensioning frame; (b) tensioned cable-net and knitted textile; (c) inflated pockets to form cavities; (d) fast-setting cement paste coating; (e) concrete; (f) finished structure after decentering.

Finally, all hooks needed for hanging the cable-net and fabric formwork were fixed to the frame in their correct positions.

Formwork assembly

The formwork consisted of two elements, a cable-net falsework and a knitted textile shuttering. To assemble the formwork, the four strips of textile were sewn together into a long strip (Figure 7.39), and the cables inserted in the corresponding channels of the textile. The long loop cables were inserted first, followed by the short cables. Then, loops were formed on the ends of the short cables and turnbuckles attached to each one. Finally, all nodes were temporarily fixed in place with plastic zip ties (Figures 7.40b).

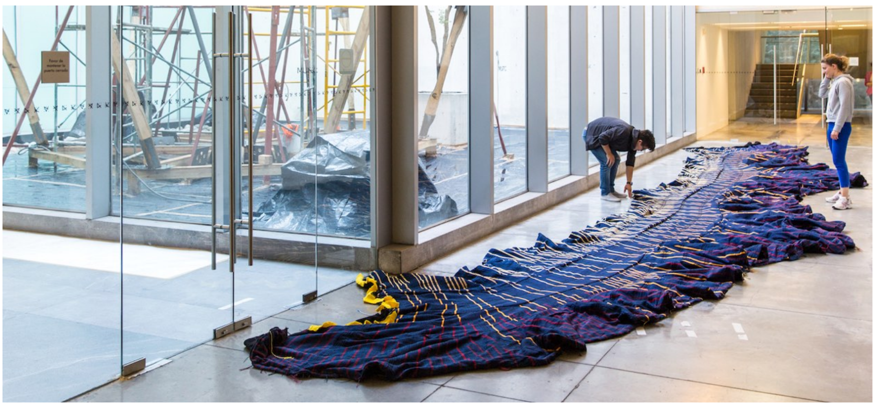
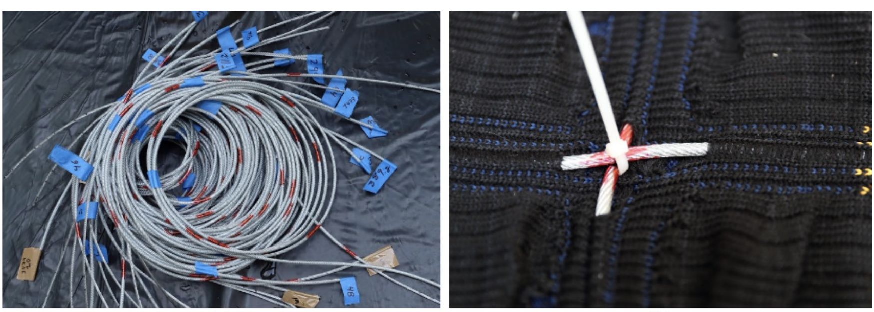


Figure 7.39: Textile shuttering layer was sewn into one long strip (photo credit: Lex Riter).



(a) (b)

Figure 7.40: Steel cables of the falsework: (a) marked cables; (b) node connection with cables inserted in the textile.

Figure 7.41: Tensioning the hybrid cable-net and knitted textile formwork in the timber frame: (a) formwork around middle frame support; (b) hoisting formwork; (c) connected cables to the frame; (d) tensioned formwork (photo credit: (a)-(c) Lex Reiter, (d) Maria Verhulst).

Tensioning

The assembled cable net and textile were laid out around the central poles of the timber frame (Figure 7.41a). The last vertical seam was sewn and the ends of the loop cables were connected using standard cable connectors. This package was then hoisted up by ropes tied to the top most nodes and the cable ends were connected to the corresponding hooks on the frame. Figure 7.41b and c show the textile hanging from the top of the frame and the cables connected to their corresponding hooks. After securing the textile to the top of the frame, the ropes were removed and the opposite end of each cable was connected to the corresponding hooks on the frame arches. The cable-net nodes were secured in place with rebar wires to ensure their position remained correct during tensioning. The tensioning was performed by gradually tightening the turnbuckles around the outer perimeter.

Figure 7.41d shows the formwork secured to the frame and tensioned. Once tensioned, modelling balloons were inserted into the textile's pockets to form the cavities within the concrete. Finally, the edge profiles (Figure 7.30) were attached and the edge detail was fixed in position.

Figure 7.42: Concreting steps: (a) spraying; (b) coated structure; (c) first concrete layer; (d), finishing (photo credits: (d) Alicia Nahmad).

Coating and concrete

Once fully assembled, the textile was coated with a thin fast-setting cement-paste coating developed at the Chair of Physical Chemistry of Building Materials, at ETH Zurich. The coating is a Calcium Aluminate Cement (CAC) formulation designed to harden within two hours in ambient conditions. A standard Bolero mortar pump and air compressor were used as the material delivery system to the spraying nozzle. The coating was sprayed as a light mist (Figure 7.43a) onto the entire textile forming a layer approximately 1-1.5mm thick (Figure 7.43b)[11]. Glass-fibre-reinforced concrete was applied onto the coated formwork in three layers. First, all the ribs were filled in and then a second layer built up the thickness of the shell (Figure 7.43c). Finally, a third, finishing layer was applied and hand rendered smooth (Figure 7.43d).

[11]The spraying setup and fast-setting cement paste coating was developed within a jointly supervised bachelor thesis project presented in Appendix B.

Decentering

Ten days after casting, the shell was decoupled from the frame to stand unsupported, referred to as decentered. First, the tension in all cables was released by gradually untightening the turnbuckles. Then, the cables were unhooked from the timber frame in two groups. The shell was visually inspected for cracks at every step to make sure the structure was sound. Once decoupled, the frame could be dismantled and removed.

Figure 7.43: KnitCandela finished shell structure (photo credits: Angelica Ibarra).

7.3.6 Time, cost and transportation

The shell was designed, fabricated and constructed over a period of three and a half months, of which one and a half months were dedicated to the fabrication and on-site construction. The timber and steel frame was fabricated and assembled by construction workers in two weeks. In the meantime, the knitted textile took 36 hours of machine time to produce and was transported easily to the worksite due to its low weight and compactness. Table 7.1 shows an overview of the weight and cost of and production time needed for the fabrication of hybrid cable-net and knitted fabric formwork, cement-paste coating and concreting.

Assembling the textile shuttering and cable-net scaffold on-site took approximately one week. Once assembled, three more days were dedicated to the preparing of the formwork for coating and concrete casting. This preparation included:

- tensioning of the cable net,
- inserting and inflating balloons, and
- inserting and fixing edge detail.

The special cement-paste coating was sprayed onto the textile in two sessions of four hours over the course of two days. Finally, three layers of fibre-reinforced concrete were applied over the course of three days.

Table 7.1: Weight, cost and production/assembly time of KnitCandela's fabric formwork and concrete.

	Material	Mass kg	Cost EUR	Production/ assembly time
Knitted textile	PES dtex 167x 30x 8	25	230	36 hours
Cable net and connectors	Stainless stell 3mm	30	1.200	4 days
Balloons	4-5cm diameter	N/A	230	1-2 days
Cement-paste coating	CAC based	200	220	2 days
Concrete (including labour)	Fibre reinforced	5000	5.300	2-3 days
Tensioning frame (including CNC and labour	Wood and steel	N/A	21.560	10-14 days

7.3.7 Discussion

The KnitCandela prototype demonstrated that with an appropriate computational design and digital fabrication pipeline knitted textiles can be easily produced. When coupled with other load-bearing elements, knitted textiles can be used to shape complex geometries at an architectural scale.

Tensioning the cable-net and textile formwork in a timber frame removes the need for dense scaffolding to support heavy moulds. Figure 7.44 shows the sparseness of the employed systems by comparison to a traditional rigid one. The minimal foundations and scaffolding required to realise the formwork give a glimpse into how such forms can be realised with a minimal falsework and need for material. The frame used for tensioning was custom-designed and fabricated for this project. However, a system relying on standard scaffolding elements could be developed, making the tensioning frame a reconfigurable and reusable part.

Additionally, the use of a knitted textile offers advantages with respect to integrating features such as channels for guiding other structural elements and changing the surface texture, all in a single fabrication process. The inclusion of features such as guiding channels and pockets makes it possible not only to shape a mould that would otherwise require extensive milling but also to guide and place elements for construction without the need for complicated logistics and labelling of custom elements.

Figure 7.44: Tensioned cable-net and knitted textile formwork and the minimal scaffolding needed by comparison to a traditional rigid system (photo credit: Maria Verhulst).

An example of the simplified logistics are the pockets of the textile, which helped shape individual cavities of different shapes and sizes using the same standard element (balloon). In this case, the standard balloons produced varied solutions through the embedded properties of the textile. This means custom solutions can be created with standard elements. The design and construction was carried out by multiple teams in Europe and Mexico over a period of 3.5 months. The intense development cycles, collaboration between multiple teams in different locations and numerous structural and constructional iterations were realised with a building information modeling (BIM) approach using the open-source computational framework COMPAS. This made the structural design, engineering, digital fabrication, and construction of KnitCandela efficient. The design-to-production process, made possible by the streamlined computational strategy, presents an outlook toward a more integrated, research-driven architectural and engineering practice with increased productivity. As an ecologically conscious construction system, KnitCandela utilises a stay-in-place mould that is practically zero-waste as the formwork becomes part of the structure and the tensioning frame could be reused. Because of the structural geometry, a doubly-curved 3 cm-thick shell with stiffening ribs with a depth of 4cm running in both directions, fewer materials were required overall, making the project economical both in terms of financial costs and material or construction waste. Finally, rather than shipping heavy and high-volume formwork parts to site, the lightweight knit significantly reduces the carbon emissions from transport. This could be further improved by only delivering the needed fabrication data and manufacturing the textile locally.

Given the tight schedule of the project and fabrication limitations, the frame used for tensioning was custom-designed and fabricated for this project. It was designed to be easily manufactured with traditional methods using standardly available timber and steel profiles, which could be effortlessly assembled into a self-contained frame. However, a system relying on standard scaffolding elements could be developed, making the tensioning frame a reconfigurable and reusable part. The NEST HiLo roof is an example of a flexible fabric formwork system using standard scaffolding and reusable elements that can serve as a model for further development of standard solutions. The full-scale prototype of the concrete shell roof and the final structure are built using the same scaffolding, frame and cable elements (Echenagucia et al., 2019).

Tensile structures are ideal for creating fluid doubly-curved geometries, but need higher prestress or stronger coating for geometries with less curvature. Though the cavities of the waffle shell were easy to build using standard balloons, the geometry of the larger cavities, which were 0.5m - 0.75m in size, were more difficult to control. Having large flat areas, these larger pockets were not stiff enough after coating to support the casting of concrete. In the future, to prevent the pockets from collapsing during casting, other geometries or other coating materials should be explored.

Using a flexible formwork system and textiles has some implications for the construction site and general handling. While the system is lighter, to avoid tears, it needs to be handled with particular care. During the assembly of the textile, a dry and relatively clean environment is preferable, especially if the textile is exposed as an aesthetic face layer in the finished structure.

7.4 Summary

This chapter presented experiments and prototypes built using weft-knitted textiles as mould within flexible fabric formwork systems. The prototypes investigated the process from the design and fabrication of the knitted textile through to the tensioning, coating and concreting to create the final structure. The component-scale prototypes were used to develop the fabrication pipeline and explore the possibilities offered by using weft-knitted textiles. The features investigated within these prototypes were used in the larger prototypes. With the KnitCrete bridge prototype, the possibilities of building with a hybrid system consisting of bending-active elements and a knitted textile were discussed and the possibility of gradually building strength in layers to minimise deformations during casting investigated. This prototype hints at the possibility of building without the need for scaffolding. It presents an approach that could be used at scale as prefabricated formwork components. Finally, KnitCandela showed the possibilities of using the system at an architectural scale and discusses the needed fabrication pipeline to fabricate knitted textiles at mould at this scale. When scaled-up, the implications of this approach are far-reaching in contrast with many traditional formwork systems. Other than significant waste reduction, this construction method grants increased site accessibility, reduced labour and fewer or lighter foundations. The system has several potential benefits over traditional approaches to concrete formwork, as it is lightweight, easy to manufacture, highly transportable and quick to assemble. Additionally, the use of a knitted textile offers extended advantages with respect to integrating features such as channels for guiding other structural elements and changing the surface texture, all in a single fabrication process.

Part IV

Reflection

Chapter 8

Conclusions

This dissertation has presented a novel approach to produce formwork moulds for concrete structures, rooted in the global need to increase the material efficiency of buildings. The various chapters provided the context, problem statement, and literature review supporting the stated need for an alternative approach to concrete formwork. Chapter 4 and Chapter 5 gave a description of the proposed forming system, and an overview of the characteristics required of the moulds, followed by the presentation of fabrication strategies for achieving those characteristics using weft-knitted textiles. Chapter 6 presented the computational algorithms and tool developed for generating knitting patterns in an automated way for doubly curved and non-developable 3D geometries. The workflow employed to transfer the generated knitting patterns to machine code for fabrication was also detailed and explained in the same chapter. Finally, Chapter 7 presented the various prototypes built with the proposed forming system and employing the developed computational tools and fabrication workflow. This chapter summarises the contributions made by this thesis, discusses the advantages of the proposed moulding approach, complemented by an overview of the limitations, as well as outlining possible future work.

8.1 Contributions

The thesis contributes to the field of architecture and concrete construction through the development of a novel forming system using stay-in-place knitted moulds. Aligned with the objective of creating a feasible and efficient approach to the construction of bespoke concrete structures, the main contributions of the thesis are: conceptualisation of the moulding system using weft-knitted fabrics at a component and structural level; development of necessary computational tools and workflows for translating a designed 3D geometry to a streamlined textile fabrication process. The following sections will expand and detail on these contributions.

8.1.1 Forming system - Proof of concept

Various prototypes were built to demonstrate the feasibility of using the proposed forming system for building bespoke concrete structures. The prototypes showed that the approach may be used at a component or a structural scale when combined with a falsework of other flexible systems such as bending-active elements or prestressed cable nets. The prototypes showed that a gradual approach to stiffening the knitted textiles is beneficial for controlling local deformations when casting and, depending on the scale, allows for a lower prestress in the textile, which could result in lighter supports. The KnitCandela prototype showed that weft-knitting could be used on an architectural scale and underlines the implications of the approach in terms of formal expression, lightness, labour, waste, cost and productivity.

8.1.2 Forming system - Feature development

Weft knitting is at the core of the proposed system due to the ease with which shaped geometries and features may be created in a single production process. While the knitting process offers a multitude of possibilities, the types of features and geometries needed for moulds had to be investigated and production strategies outlined. The component-scale prototypes in Chapter 7.1 presented the different types of geometries and features needed specifically in the context of moulding of architectural geometries. Knitting strategies for shaped geometries and multidirectional nodes were developed alongside strategies for one-step manufacturing of rib-stiffened surface configurations.

8.1.3 Knitting and digital fabrication

A computational approach was developed for the automatic generation of knitting patterns for 3D-shaped or doubly curved geometries (Chapter 6). Flexibly generating knitting patterns for large, non-repetitive geometries is an important step for knitted textiles to be used in an architectural context. Furthermore, a workflow for translating the generated patterns to industrial knitting machine code was proposed in Chapter 6 and used in the fabrication of the KnitCandela prototype. The computational tool and workflow bridge the gap between digital design and the bespoke fabrication process, which would otherwise require time-consuming and tedious pattern design.

8.2 Advantages

The research presented in this thesis addresses the need to reduce costly and/or materially inefficient formworks. The thesis described the approach to building concrete structures using a lightweight, weft-knitted fabric as standalone mould or as part of a flexible formwork system. The system relies on tensioning a prefabricated textile to produce the desired 3D geometry, coating it with a stiffening material and using it as stay-in-place mould, thus removing the need for traditional timber formworks. The approach has several potential benefits over traditional approaches to concrete formwork, as it is lightweight, easy to manufacture, highly transportable and quick to assemble. It enables the construction of bespoke geometries cheaper than standard systems, wasting less material and thus creating efficient prefabrication solutions.

Geometrical freedom

Traditional rigid formwork systems need extensive milling or carpentry to produce doubly curved formwork geometries. By contrast, flexible membranes or fabrics can be shaped into doubly curved geometries easily through tailoring and tensioning. Furthermore, knitted textiles can be produced directly in three-dimensional shapes without the need to rely on the assembly of several flat sheets of material. This implies that the range of doubly curved geometries can be extended to non-developable geometries, omitting or significantly reducing the need for cutting patterns.

Custom functional integration

Using a weft-knitted textile allows for customisation and conforming to predefined geometrical and structural needs. Knitting allows for custom placement of material and surface texturing, which offer increased control over the performance of the formwork and control during concrete construction. Furthermore, features such as channels, holes, spacers, branching, ribs, inserts, etc. can be integrated without the need for extensive patterning, cutting, sewing, glueing or joining.

Reliable and fast digital fabrication

The CNC manufacturing of weft-knitted textiles is a well developed industrial process. 3D-knitted geometries are easy to produce on existing knitting machines with little or no alteration. Coupled with a computational approach to generating knitting patterns and a pipeline to go from digital design to fabrication files, the production of geometrically complex shapes becomes easier, faster and less wasteful. The production speed compared to traditional milling processes is best illustrated with the knitted shuttering of the KnitCandela prototype, which took 36 hours of machine working time to produce 50 m^2. That amounts to less than a third of the time needed to mill the same surface area out of EPS (roughly 750 hours)

Lightness and compactness

Fabric formwork systems are inherently lighter than traditional timber moulds. Knitted textiles are no exception; they are lightweight, compact and easy to transport. The implications of a lighter mould are not restricted to transportation but also to the amount of scaffolding or temporary support needed during construction. Lighter moulds mean lighter supports, which translates into reduced and lighter foundations. Finally, by offering a forming system for complex geometries, lighter, more materially efficient structures can be built despite their intricate forms.

Easy construction

Other than significant waste reduction, this construction approach grants increased site accessibility, reduced labour and fewer or lighter foundations. Owing to the geometric possibilities of knitting, provisions for assembly and control over construction detailing can be included in the knitting process. On-site handling is expected to be less complex or requiring less expert knowledge compared to similar bespoke building techniques without traditional formwork as most of the formwork logistics are embedded in the knit.

Economy

The system has the potential of greatly reducing the cost and waste typically associated with building bespoke concrete structures. Its reliance on cheaper and lighter mould materials makes it an economical solution. In terms of material costs, these can be as low as 50 CHF/m^2 (based on the KnitCandela prototype), depending on the chosen materials and excluding temporary supports, which may be reused. However, the system is not only economical strictly in terms of materials, but has economical influences on the entire construction process. Being lightweight and compact the moulds can be transported more economically. Moreover, on site, heavy, specialised, and expensive machinery is not needed for hoisting or fixing the moulds in place. Finally, the fewer and lighter foundations needed for such a system also reduce the overall construction cost.

Direct technology transfer

The proposed forming system is among the first technologies in the realm of digital fabrication in construction where the technologically difficult step can be substantially delocalised from the application because these textiles are lightweight, easily packable and transportable. As the system does not directly affect concreting processes, mix designs, standards and regulations, but is used as a lost formwork, the transfer to industry would be rather straightforward. Moreover, the system relies on well developed industrial machines and fabrication processes.

8.3 Limitations

The forming system presented in this thesis relies on the use of tensioned weft-knitted textiles as part of a flexible formwork. While flexible systems present several benefits, their flexibility also poses some challenges and limitations.

Geometry

Tensile structures are ideal for creating fluid doubly curved geometries. To ensure that the constructed geometry is the designed one, the prestress in the flexible system needs to be high enough to withstand the loading of casting concrete. Lesser doubly curved geometries need higher prestress, which translates into larger and heavier supporting frames for tensioning. Therefore, the approach is not ideal, infeasible, in fact, for moulding flat or standard geometries with sharp corners. Furthermore, if disregarding inflatables, synclastic geometries are very difficult to build with the system.

Size

At an architectural scale, the knitted textile is too flexible to act as a formwork on its own and needs support. This can be provided by other lightweight, flexible falsework systems such as bending-active elements or cable nets. Therefore, the scaling of the proposed approach is highly dependent on the scaling possibilities of the supporting structure.

Support structure

The tensioning approaches used for the prototypes built during this thesis relied mostly on rigid, external frames. These frames are custom designs and are discarded after single use. Better approaches, where the tensioning frame is based on standard reusable elements, can be developed. Alternately, deployable systems that are fully self-supporting, could also be investigated to bypass the need for an external tensioning frame.

Geometric and material control

The behaviour of flexible systems, particularly with knitted textiles, is harder to predict than rigid systems. Reaching the target geometry implies that there should be good control over the tensioning and understanding of the material behaviour. When hybrid flexible systems are used, predicting the interaction between the textile and the supporting flexible system is important. However, knitting is a very flexible and heterogeneous material, the behaviour of which is hard to predict. Within this thesis, iterative empirical tests informed the fabrication and construction of prototypes to a satisfactory target geometry. Simulation, prediction and control tools have not been developed or provided within the scope of this research, but are necessary for accurate construction of flexible structures for architectural applications.

Concrete casting

The system presented in this thesis has been tested for open surface moulds that are used to produce thin shell-like structures through spraying or trowelling. Filled moulds would need to withstand higher pressures and may be more difficult to build with the proposed approach. Flexible systems are more sensitive to deformation and damage on the construction site, which means they cannot be used to support workers during construction. Applying the cement-paste coating or concrete layer on flexible systems requires a rethinking of the construction workflow. With the current approach of manual spraying or troweling, size and reachability limitations can arise.

Computational design

The tool developed within this thesis makes it possible to create automated patterns for given complex 3D geometries. It is intended to be used within a research environment and still relies on some manual operations and user experience and knowledge. The initial patching of the geometry, for instance, could be approached in an automated and informed manner. Furthermore, the knitted textile patterns generated so far are relatively homogeneous for each patch. To take full advantage of the flexibility that knitting has to offer, strategies for designing, generating and simulating varied and heterogeneous topologies would be desirable. Pattern generation for large geometries is computationally intensive because of the small size of the knitted loops in relation to the surface area of the structure, e.g. 2-5mm versus 50m^2 for KnitCandela. If strategies that allow for a computationally less intensive process, are not developed, this could become a bottleneck.

Machine knitting

While knitting offers various opportunities related to geometry and fabrication of textiles with integrated features, it is limited in size by the width of the machine. Depending on the chosen characteristics, and the size of the structure, the textile may still need to be produced in a large number of elements. To produce geometrically complex elements, various machine operations are needed (e.g. loop transfers, needle-bed racking). These operations can slow down the production process and may introduce defects in the produced piece. Some of the mechanical properties of the knitting machine (such as the takedown system) can also influence or limit the possibilities to produce extremely shaped geometries.

8.4 Future work

Transforming the tensioned knitted formwork into a load-bearing concrete structure represents an innovative and exciting challenge. The opportunities and limitations discussed in Section 8.2 and Section 8.3 point towards the following avenues of future research:

- development of automated concrete application techniques,
- investigation of mechanical properties of (concrete reinforced with) knitted textiles,
- development of deployable support structures for tensioning,
- development of tools for predicting and controlling the behaviour of flexible formwork systems, and
- development of strategies to use the knitted textiles as reinforcement.

Some of the research avenues outlined above will be taken up in the collaborative research project "Flexible formworks for concrete" in the second phase of the NCCR Digital Fabrication. Collaborators from the fields of architecture, structural design, structural/concrete mechanics, material science, computer science and robotics will work on:

- developing the necessary computational and fabrication methods for bespoke, structurally informed knitted textiles for construction-scale;
- developing material formulations and a responsive curing system for the cement-paste coating to be applied outdoor;
- investigating the mechanical aspects of using a knitted membrane as a structural element;
- developing a reinforcement strategy for a novel integrated textile-concrete-composite material;
- developing approaches for robotic manipulation of structures consisting of flexible surfaces;
- modelling of deformation under prestress; and,
- developing unmanned aerial vehicles (UAVs) that can accurately apply material onto the flexible tensioned formwork.

8.5 Final remarks

At the heart of this research is the premise that employing knitted textiles in architectural applications can cut down on material, labour, and waste, while simultaneously simplifying the construction process for sophisticated shapes. It combines traditional established production techniques with digital and computational advances in design and fabrication. In doing so it addresses several challenges currently faced by the building industry: the need to reduce construction waste and use fewer materials while increasing the structure's efficiency without increasing cost and labour. By deploying a custom-designed, knitted textile as formwork for the KnitCandela pavilion, the efficiency of the entire construction process was increased exponentially. This demonstrated that the system targets areas such as speed of production, transportation, on-site logistics, manual labour, handling and installation costs without sacrificing structural elegance and architectural aesthetics.

While the system is developed with concrete structures in mind, it can also be applied in the moulding composite elements within other fields of construction. The system could be used for shaping lightweight composite membrane structures and is not dependent on a being coated with a cement paste. Moreover, the textile remains embedded in the structure, opening up possibilities for it to perform structurally as reinforcement. Furthermore, there is a great potential of using performance textiles to enhance built structures which become customisable as a result of new digital systems and tools (e.g. using embedded sensors for monitoring and responsive design).

Finally, such an approach is an innovative way of constructing optimal and doubly curved geometries while addressing the consumption of resources and sustainability in construction. The advantages of the approach lie not only in its geometrical freedom when it comes to doubly curved surfaces but in the possibility of integrating a large variety of features and properties in one simple production process. The combination of reliable production and simple construction make it a system not confined to niche high-tech or expensive iconic projects, but accessible in a wide range of areas including deployable and temporary structures. It may be used to build in environmentally or structurally sensitive conditions, in areas with low accessibility or to retrofit structures.

Appendices

Appendix A

Knitted geometries

A.1 Non-orientable surface

Research at the University of Florida looked into the digital form finding and fabrication of a complex non-orientable surface for curved concrete (Belton, 2012). The formwork for this surface was a prestressed membrane made by sewing together several patches of flat textiles (Figure A.1a). To illustrate the potential of knitting for fabric formwork, a topologically identical was modelled and subsequently knit in one piece (Figure A.1b). The knitting was done on an electronic Brother KH-970 knitting equipped with a second needle-bed called a ribber (Figure A.2).

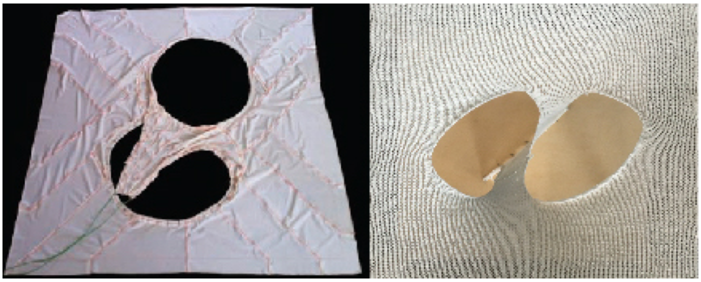


Figure A.1: Fabric formwork for non-orientable surface: (a) geometry made by tailoring flat pieces of material (Belton, 2012); (b) knitted textile geometry

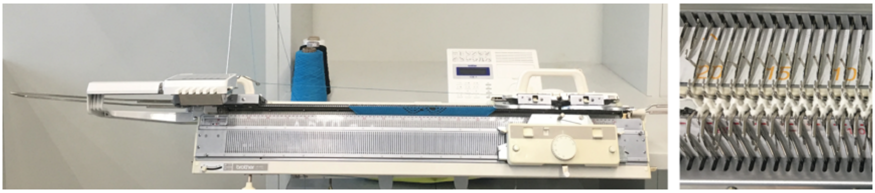


Figure A.2: Brother KH-970 knitting machine with ribber

The machine knitting process is as follows:

Yarn is cast on both needle beds for 100 needles. Separate strands are knitted over the front and back needle bed to form 40 courses. From this point on, alternation in needle use is necessary. Partial knitting, where only sections are knit instead of the whole needle bed, is employed in order to avoid the creation of chords over the area of a formed gap. The following steps are used (Figure A.3):

1. needles on the right side of both beds are set to holding position; in this position loops are held on the needles but no new loops are formed
2. left side is shaped through consecutive decreases over 30 courses for the main bed and 15 for the ribber
3. the 20 left most loops on both beds are cast off through grafting; this creates a seamless connection between the loops on both beds
4. steps 1-3 are repeated for the right side
5. 15 courses are knit separately over the remaining needless on both beds
6. the 15 loops on the ribber are transferred to the main bed
7. 20 courses are knitted and the loops are cast off

By transferring loops from the ribber bed to the main bed and continuing the courses on a single bed the twist of the surface is generated. The only telltale sign of this twist is the line where the technical back and front face of the fabric meet (Figure A.4). This is a consequence of the surface non-orientability. However, this visual discontinuity in the fabric can be avoided through the use of a pattern that is identical for the front and back face. This requires both needle beds to be used for the alternation of purl and plain loops. If we were to employ the same procedure as described above, we would need a total of four needle beds. Figure A.5 shows the result.

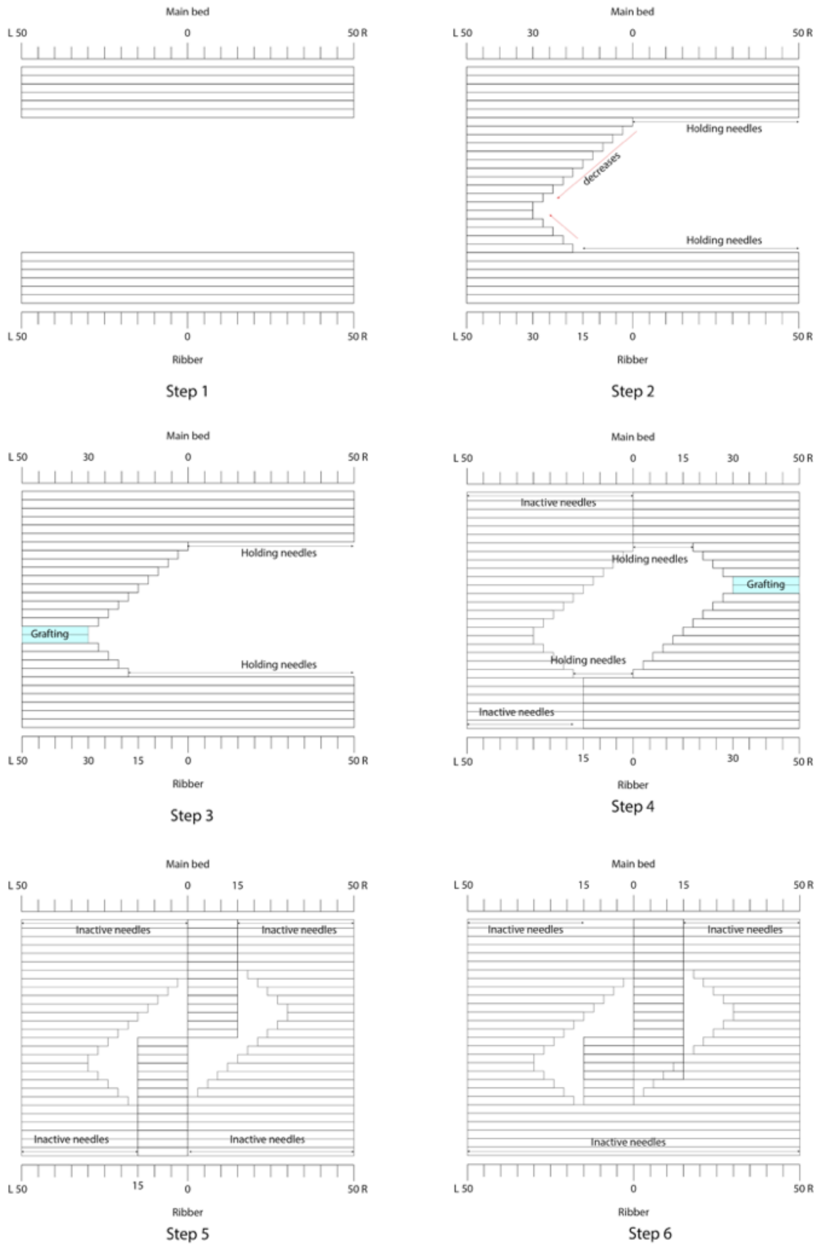


Figure A.3: Sequence for knitting the non-orientable surface

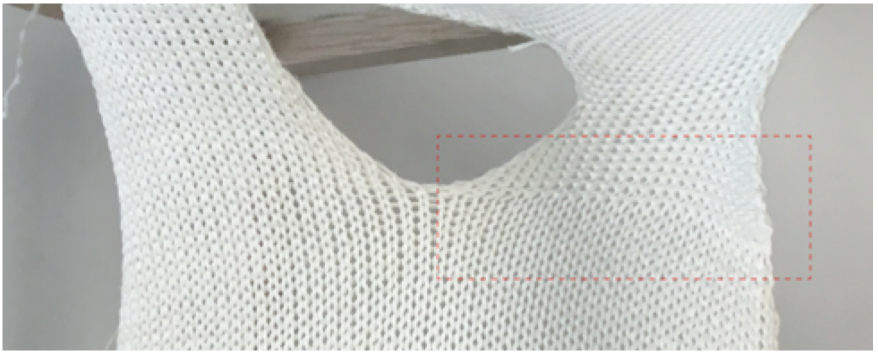


Figure A.4: Front and back face interchange in the knitted textile

Figure A.5: Knitted non-orientable surface

A.2 Six-directional node

The following case study shows the fabrication of a six-directional node (Figure A.6 (3) Node). This example illustrates the versatile geometric possibilities offered by knitting and the process needed to achieve such geometries. Figure A.6(3) shows the tensioned six-directional node knitted using the same Brother KH-970 knitting machine.

The knitting techniques needed for knitting three-dimensional geometries are as follows:

1. increases and decreases for varying the fabric width;
2. short rows for shaping a three-dimensional geometry: in this case for the out-of-plane shaping of elements
3. alternation between the two needle beds: in this case for the vertical and horizontal cylindrical elements.

The steps for making the node are as follows: (Figure A.6 steps 1-6):

1. yarn is cast on 40 needles and 20 circular courses are knit; by alternatively knitting on the two beds and connecting only the last loops of both beds. (Figure A.6 Step 1; (1) Circular knitting)
2. 15 extra needles activated both left and right; we now have a total of 70 loops (Figure A.6 Step 2)
3. 5 courses with separate strands of yarn are knit over both beds (Figure A.6 Step 3)
4. shaping of out of plane nodes through short rows: needles on the left or right side of the bed are set to holding position, meaning no additional loops are formed on those needles (Figure A.6 Step 4; (2) Cast off)
5. 15 loops to left and right on both beds are cast off through grafting, this creates a seamless connection between the loops on the two needle beds (Figure A.6 Step 5)
6. step 1 is repeated for 20 courses (Figure A.6 Step 6)

Irregularities in the textile can be observed on the node. These irregularities, where loops are slightly bigger, are a result of the process described in step 4. The material is still created in one process and seamless.

The approach to creating this complex node could be expanded to create a node with more connections. The limitations in terms of possible angles and number of nodes needs to be further investigated.

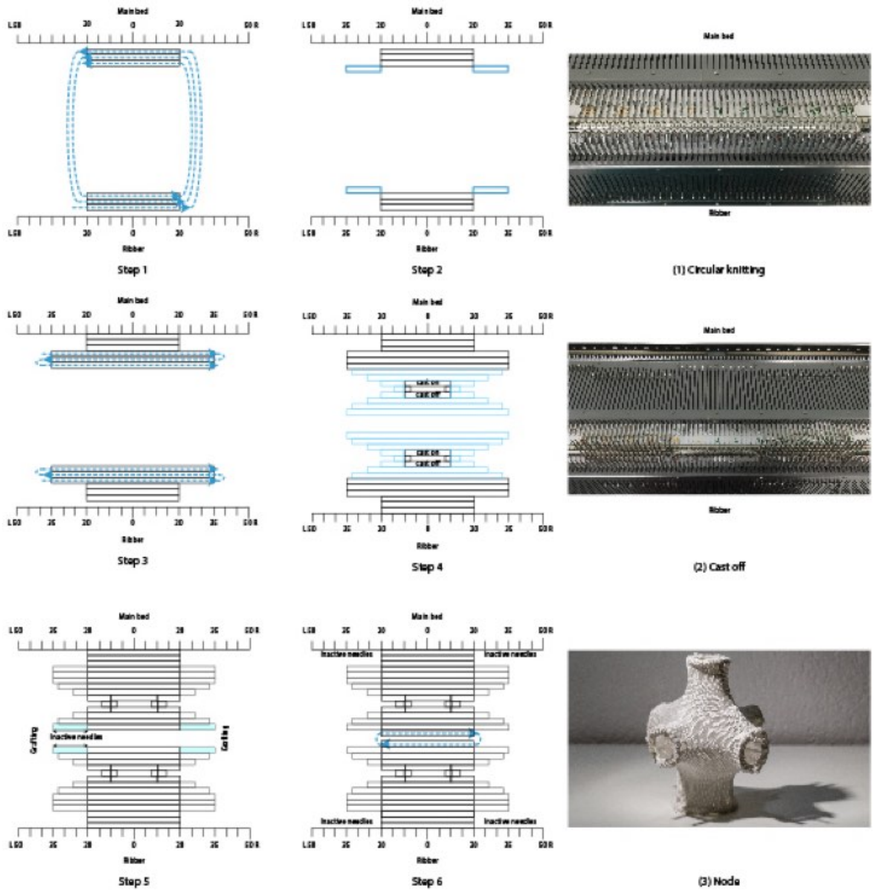


Figure A.6: Six-directional node geometry created as a seamless knitted textile on an electronic Brother KH-970 knitting machine

A.3 Non-manifold joint configurations

In existing strategies, joints are generally fabricated as single elements and not as compound surface-rib structures. Recent developments at the Technische Universität Dresden have shown the possibilities to create surface-rib formations with multiple ribs of varied geometries aggregated onto a surface (Bollengier et al., 2017). These types of skin-rib formations are always manufactured in the course direction (weft).

With the goal of creating complex architectural rib-stiffened geometries in a single process, these experiments investigates the possibility of aggregating multiple joints in varied configurations. This requires the possibility to create ribs on a surface structure not only in course direction (weft), but also perpendicular to it (warp).

Methods

Investigations into the manufacturing of varied surface-rib configurations are done through a sequential series of tests of consistent size. We start from known strategies for creating such configurations and gradually increase in complexity. This is done in terms of number of ribs, their orientation, geometry and features to be integrated into the ribs. A log off all strategies and the machining time needed to produce the pieces was also kept.

Setup

The experiments were carried out at the Institute for Textile Machinery and High Performance Textiles, TU Dresden, on a 15 gauge Shima Seiki SWG 091N WholeGarnment flat knitting machine. All samples are of constant width and height for comparability reasons and for evaluating the relationship between features and machining time. Samples are plain knit as 400 courses long and 300 needles wide in a 1-1 pattern (= 150 loops).

Experimental parameters

Experiments were divided into three categories based on rib orientation in relationship to the knitting direction (weft, warp and combines). Within the weft category all ribs are formed parallel to the knitting direction, while in the warp they are formed perpendicular to it. For the third category, the

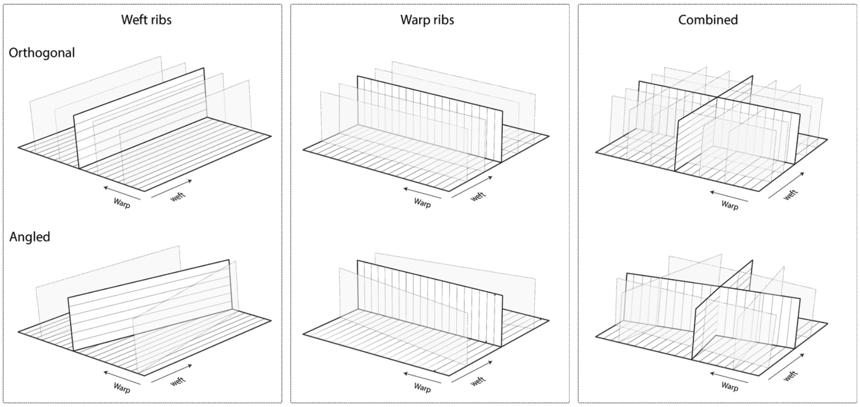


Figure A.7: Category overview of the types of ribs and orientations to test.

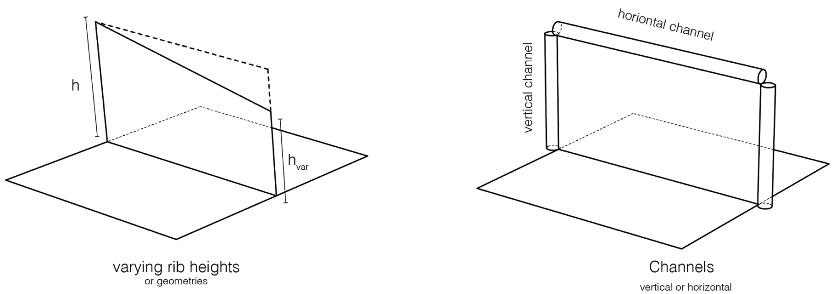


Figure A.8: Types of functional integration to be investigated (varying heights, channels along warp and weft directions.

first two are combined to produce rib formations in both directions within one piece.

Within each category the following rib characteristics are investigated:

1. Parameters: repetitions, heights, spacing (Figure A.7)
2. Orientation: orthogonal or angled (Figure A.7)
3. Features: channels, varying heights and shapes (Figure A.8)

Pattern generation

Shima Seiki's SDS-One software (ShimaSeiki 2018) was used for developing knitting patterns and generating the machine code.

For the orthogonal weft and warp experiments, patterns were designed directly within the software by using repetitions of 10 row pattern packages for the ribs and the skin.

For more varied parts, knitting patterns with increases, decreases and short rows are necessary. Designing such non-repetitive patterns within the machine software can be a tedious and time-consuming task.

Therefore, the automated pattern generation algorithm described in Chapter 6 was used to derive these varied patterns.

The pixel image generated by the algorithm is imported into the machine software through built-in functions. Subsequently, the needed machining settings are applied and the custom code can be exported to the knitting machine.

Weft direction ribs

Ribs in course direction can be formed by alternating the needle bed on which the fabric is knit or by selective transfer of loops between the beds. The chosen sequence for knitting one rib is as follows:

- 200 courses are knit on the back needle bed
- every second loop is transferred to the front bed
- 100 courses are knit on the back needle bed
- loops held on the front bed are transferred back
- 200 courses are knit on the back needle bed

Using the same technique, possible repetitions, spacing, height, orientation and of ribs within one piece was investigated.

Repetitions were tested using the same rib height and even spacing. Samples with 1,2 and 5 ribs were created. Varying rib heights were tested by keeping an even spacing and incrementing the heights in sets of 50 courses. Then, experiments were carried out with the same rib height and varying spacing. The spacing between ribs was varied ranging between 2 and 50 courses (Figure A.9).

The integration of vertical and horizontal channels within ribs was also investigated. Channels in course direction (along the length of the rib) can be created by alternating the transfer of loops to the other bed and back.

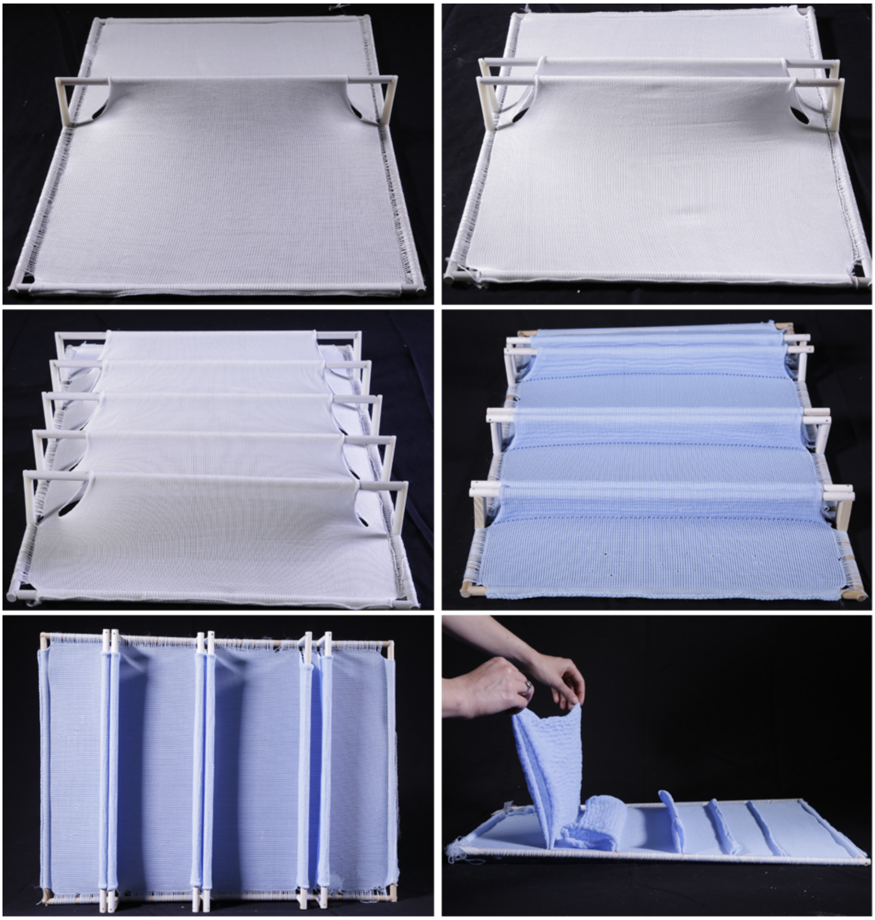


Figure A.9: Selection of various weft ribs

Along the height of the rib (in warp direction), channels are created by knitting a local tubular structure through alternately knitting on the front and back needle bed.

Angling of ribs in weft direction can be achieved by using short rows in the knitting of the surface. Their orientation can be easily varied by orienting the weft direction to the ribs.

A quarter of a ribbed floor slab geometry was chosen for the experiment, where ribs are oriented in various directions on a rectangular surface. compas_knit was to generate the appropriate knitting pattern and import it into

Figure A.10: Knitted textile with multiple weft direction ribs oriented in various angles and having varying heights

the machine software for production. The ribs are have multiple orientations on the surface and have varying heights.

Figure A.10 shows the resulting knitted textile repeated four times and assembled to form a ribbed floor fabric.

Warp direction ribs

The strategy for making warp direction ribs is shown in Chapter 5. Below is a brief recap of the main considerations regarding limitations and the possibility of including additional functional elements within the geometry of the ribs.

Ribs in warp direction can be created by alternately knitting between the front and back needle bed. A connection is formed only where the yarn switches between the two beds. Strategies for creating warp direction ribs can differ depending on the number of yarn guides used. In our experiments, a single system machine was used and a single yarn guide.

Because these ribs are knit folded over the needle bed, their height is dependent on the needle bed width. Furthermore, the height and spacing of ribs created in warp direction are interdependent.

In contrast to ribs in weft direction, the angling in warp direction is not done

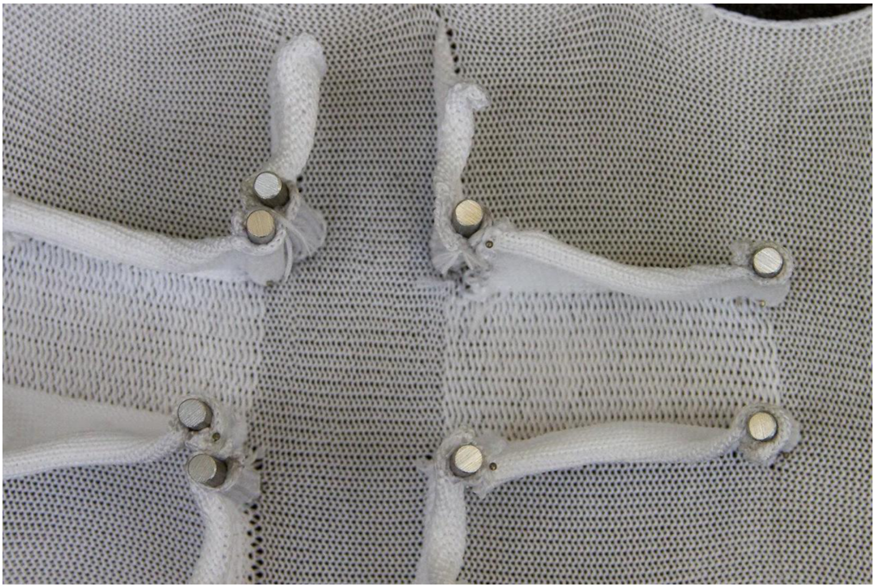


Figure A.11: Orthogonal cross knitted in one piece with ribs in both warp and weft direction

by short rows but by gradually shifting the point at which the yarn changes between the two beds.

Channels within the rib structure can be created along the height of the rib (in weft direction) using principles described above. Channels along the length of the rib (in warp direction), require tubular knitting, meaning they can only be easily created if the rib exceeds the width of the skin.

Multidirectional ribs

Having created ribs in both weft and warp direction, the combining of the two within one piece is tested. A cross with orthogonal ribs in both directions is created by combining the techniques described above.

Figure A.11 shows the resulting geometry with integrated channels.

It is to be noted that the vertical connection between ribs in weft and warp direction cannot be achieved in this process. The ribs must be connected manually. To avoid sowing, further functionalization using connecting channels could be envisioned.

Appendix B

Lounge chair - spraying setup development

A fast setting cement-paste coating and praying setup was investigated within a thesis project at the Chair of Physical Chemistry of Building Materials (IfB), ETH Zurich (Prof. Dr. Robert J. Flatt) Students: Patrick Felder and Nino Biasotto; Supervisors: Lex Reiter (IfB) and Mariana Popescu (BRG)

The project investigated ways to tackle the problem of evaporation (outside humidity chamber) and coating application with the following goals:

- leave climate chamber for cement-paste coating by using a fast-reacting cement
- reduce the cement loss and simplifying the coating process by developing a spraying setup.

To test this a lounge chair prototype was built. This appendix gives a brief overview of the developments

Cement paste

The cement paste consists of a calcium aluminate cement (CAC) from Kerneos Aluminate Technologies (Kerneos, 2019), water, a set retarder, a set accelerator and a viscosity modifying admixture (VMA). Figure B.1 shows the typical minerealogical composition of the calcium aluminate.

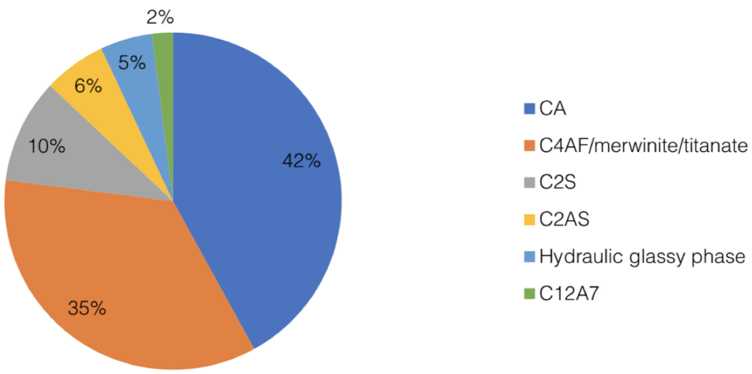


Figure B.1: Typical mineralogical distribution of a calcium aluminate cement (image from Nino Biasotto and Patrick Felder)

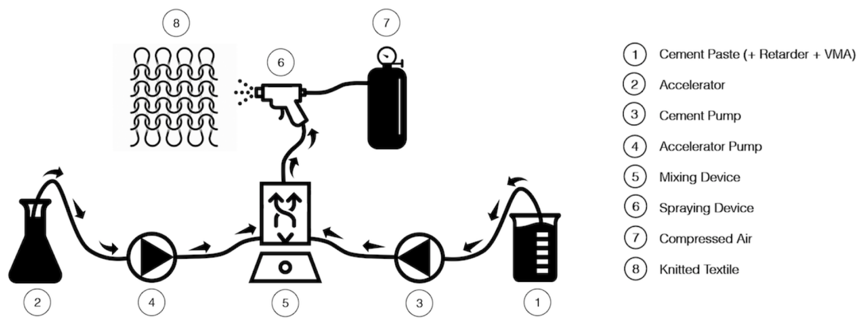


Figure B.2: Spraying setup showing the cement-paste and accelerator being pumped separately into a mixing device and then to a spray gun (image from Nino Biasotto and Patrick Felder)

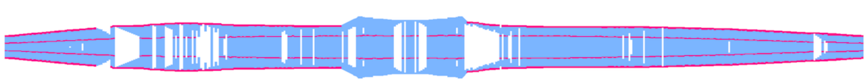


Figure B.3: Generated knitting pattern with channels marked in magenta

Spraying setup

The general operating principle is that of mixing a retarded cement-paste with an accelerator dose right before spraying. Figure B.2 shows the general spraying setup. On the one hand the cement paste, including the retarder and the VMA, is pumped to the mixing device using a progressive cavity pump (PFT Swing M). On the other hand a peristaltic pump (REGLO Digital MS-2/6 from Ismatec) delivers the accelerator solution to the mixing device (custom built based on a Chandler Engineering 3260 mixer). The mixed (accelerated) cement-paste flows to the spray pistol (A28 HPA from Sames Kremlin), which is connected to compressed air.

Knitted textile

The geometry of the lounge chair is obtained by tensioning a knitted textile using bending active GFRP rods and cables (a similar approach to the KnitCrete Bridge prototype presented in Chapter 7.2) The pattern for the lounge chair was generated using compas_knit (described in Chapter 6) based on the model designed by the students. Figure B.3 shows the generated pattern, where channels for inserting the GFRP rods and cables are shown in magenta and Figure B.4 shows the pattern in the machine software. Figures B.5 to B.10 show the construction and spraying of the lounge chair.

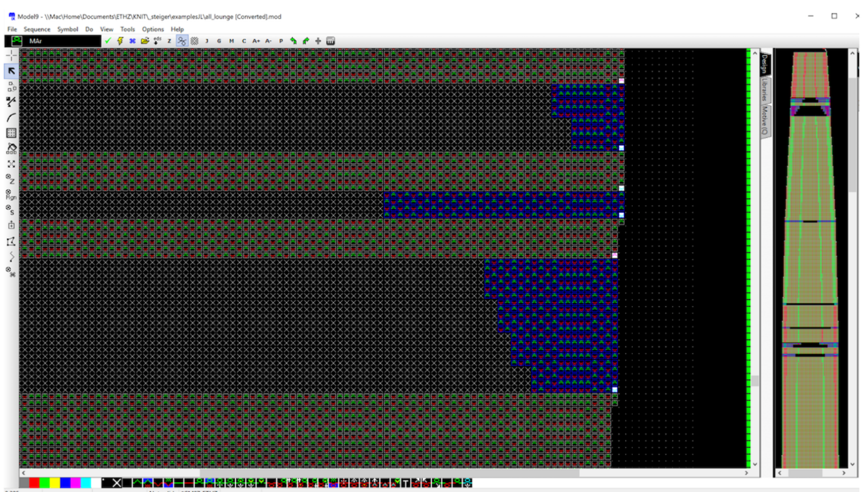


Figure B.4: Knitting pattern details in the machine software Model 9

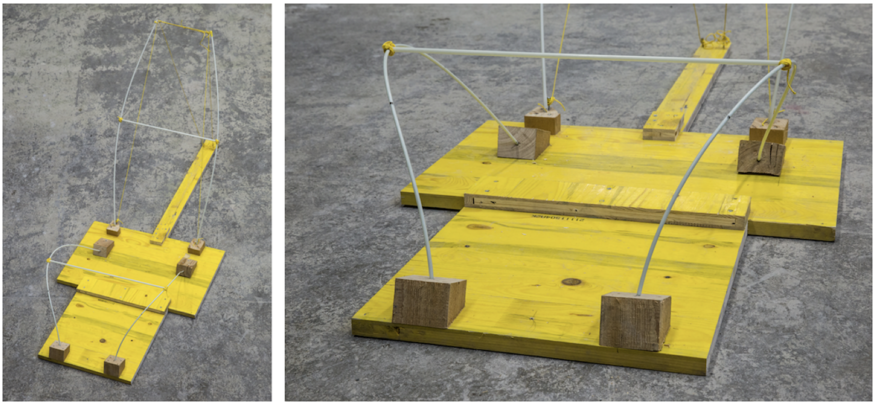


Figure B.5: Tensioning GFRP rod setup test before assembly with textile

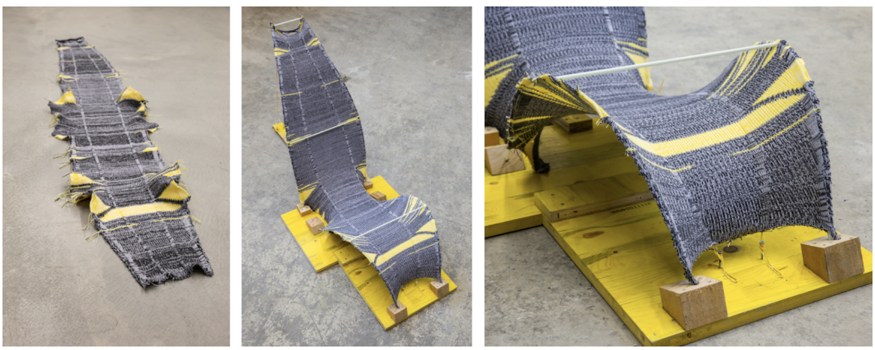


Figure B.6: Untensioned and tensioned knitted textile textile

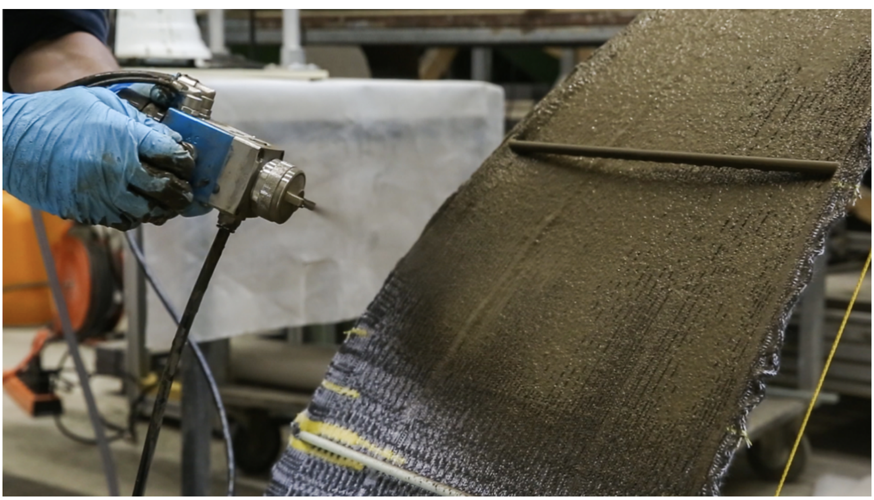


Figure B.7: Spraying CAC coating

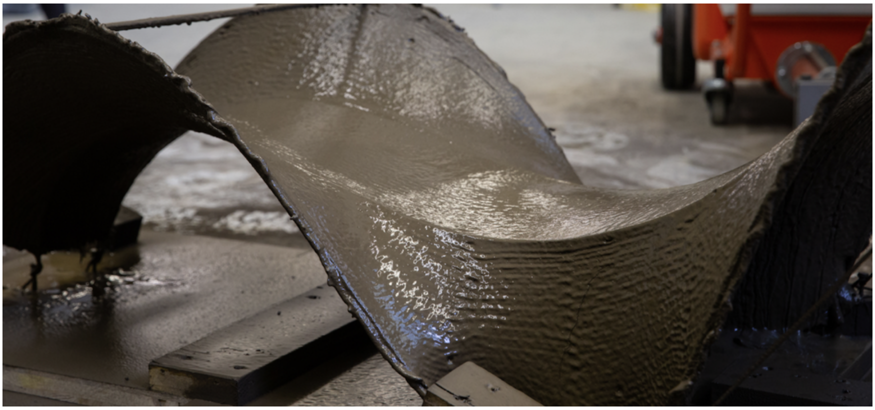


Figure B.8: Lounge chair shortly after spraying

Figure B.9: Hardened lounge chair removed from the tensioning rig

Figure B.10: Finished lounge chair with Nino Biasotto sitting on the thin chair and Patrick Felder demonstrating the lightness of the chair

Appendix C

KnitCandela knitting patterns

The patterns for KnitCandela were generated in four strips. Because the geometry is radially symmetrical only a sixth of the pattern needed to be generated for each strip. This appendix shows the generated patterns for the four strips as used in the machine software.

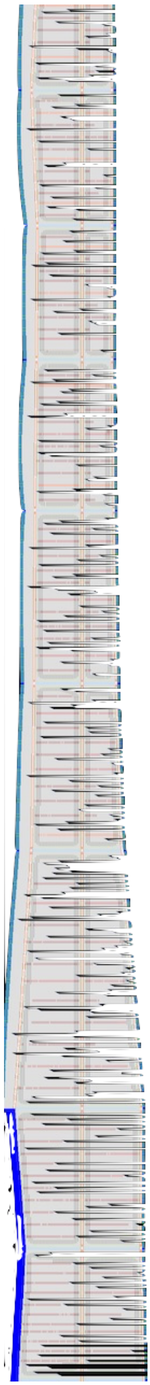


Figure C.1: Repeating pattern for Strip 1

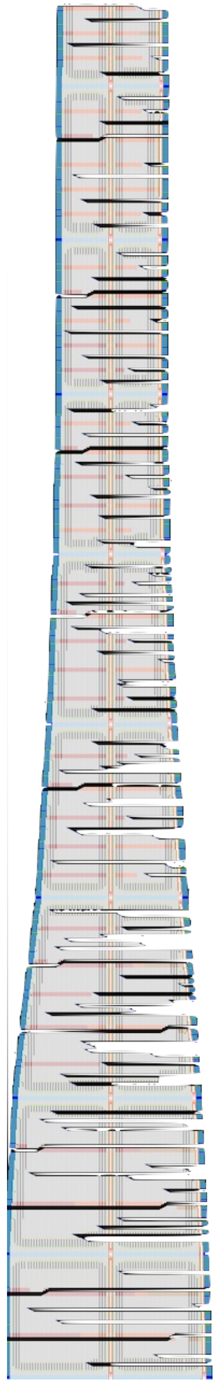


Figure C.2: Repeating pattern for Strip 2

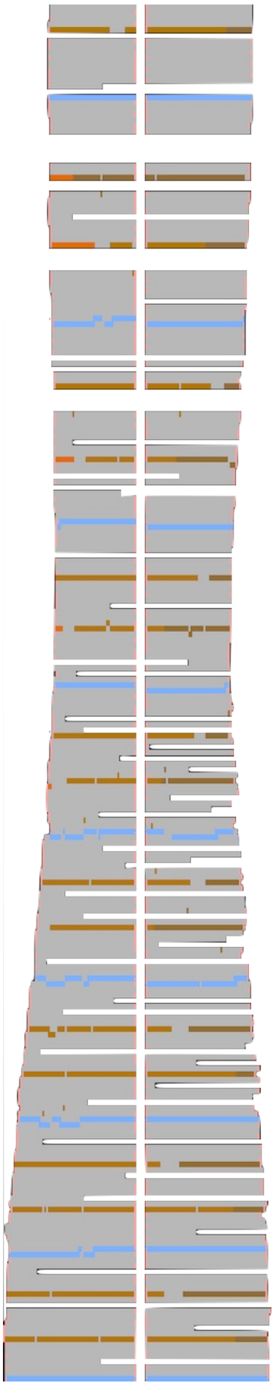


Figure C.3: Repeating pattern for Strip 3

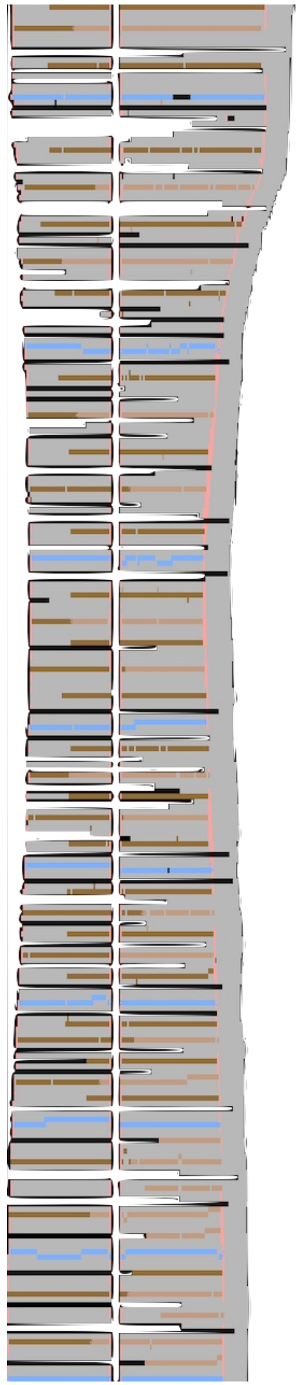


Figure C.4: Repeating pattern for Strip 4

Appendix D

Textile stretch tests

Table D.1: Biaxial tensioning tests to determine loop size

Weights						Load (Kg)	Load (N)	Length (mm)		Length (m)	Stress N/mmq	Strain	Loop	
Frame	1x90x150	2x90x150	5x30x150	5x60x150	10x80x150								Vert	Horiz
0.155	0.109	0.213	0.183	0.352	0.941									
						0	0	110		0.11	0			
1						0.155	1.55	111.38		0.11138	1.139705882	0.012545455	4.62	3.5
1	1					0.264	2.64	111.33		0.11133	1.941176471	0.012090909	4.88	3.3
1	1	1				0.477	4.77	112.36		0.11236	3.507352941	0.021454545	4.91	2.94
1	1	1	1			0.66	6.6	113.36		0.11336	4.852941176	0.030545455	4.98	2.91
1	1	1		1		0.829	8.29	114.06		0.11406	6.095588235	0.036909091	5.04	2.69
1	1	2		1		1.042	10.42	115.1		0.1151	7.661764706	0.046363636	5.18	2.44
1			1		1	1.279	12.79	116.63		0.11663	9.404411765	0.060272727	5.27	2.39
1		1	1		1	1.492	14.92	117.4		0.1174	10.97058824	0.067272727	5.39	2.33
1		1	1	1	1	1.844	18.44	119.1		0.1191	13.55882353	0.082727273	5.42	2.3
1					2	2.037	20.37	120		0.12	14.97794118	0.090909091		
1		1			2	2.25	22.5	120.35		0.12035	16.54411765	0.094090909		
1			1	1	2	2.572	25.72	121.93		0.12193	18.91176471	0.108454545		
1		1	1	1	2	2.785	27.85	122.89		0.12289	20.47794118	0.117181818		
1	1				3	3.087	30.87	123.49		0.12349	22.69852941	0.122636364		
1		1		1	3	3.543	35.43	123.65		0.12365	26.05147059	0.124090909		
1		2		1	3	3.756	37.56	123.84		0.12384	27.61764706	0.125818182		
1	1				4	4.028	40.28	124.72		0.12472	29.61764706	0.133818182		
1	1	1			4	4.241	42.41	125.13		0.12513	31.18382353	0.137545455		
1	1	1		1	4	4.593	45.93	125.62		0.12562	33.77205882	0.142		
1	1	1	1	1	4	4.776	47.76	126.03		0.12603	35.11764706	0.145727273		
1			1		5	5.043	50.43	126.39		0.12639	37.08088235	0.149		
1			1	2	5	5.747	57.47	126.74		0.12674	42.25735294	0.152181818	5.63	1.96
1			1	3	5	6.099	60.99	129.54		0.12954	44.84558824	0.177636364	5.75	2.12
1				2	6	6.505	65.05	129.74		0.12974	47.83088235	0.179454545	5.92	2.07
1		1		2	6	6.718	67.18	129.14		0.12914	49.39705882	0.174	6.11	2
						0		27						
						0		28						
						0		29						

Table D.2: Biaxial tensioning tests to determine loop size

Weights						Load (Kg)	Load (N)	Tot Length (mm)	Length (mm)	Length (m)	Stress N/mmq	Strain	Loop	
Frame	1x90x150	2x90x150	5x30x150	5x60x150	10x80x150								Vert	Horiz
0.252	0.109	0.213	0.183	0.352	0.941									
						0	0	335	50	0.335	0			
1						0.252	2.52	339.98	51.6	0.33998	1.852941176	0.014865672		
1	1					0.361	3.61	346.86	53.25	0.34686	2.654411765	0.035402985		
1	1	1				0.574	5.74	359.13	56.01	0.35913	4.220588235	0.072029851		
1	1	1	1			0.757	7.57	369.23	58.01	0.36923	5.566176471	0.102179104		
1	2	2	1			1.079	10.79	380.45	59.96	0.38045	7.933823529	0.135671642		
1	1				1	1.302	13.02	386.31	60.98	0.38631	9.573529412	0.153164179		
1				1	1	1.545	15.45	388.72	61.76	0.38872	11.36029412	0.160358209		
1		1		1	1	1.758	17.58	389.28	62.08	0.38928	12.92647059	0.162029851		
1	1			2	1	2.006	20.06	390.22	62.12	0.39022	14.75	0.164835821		
1	1				2	2.243	22.43	395.63	63.3	0.39563	16.49264706	0.180985075		
1				1	2	2.486	24.86	396.06	63.92	0.39606	18.27941176	0.182268657		
1	1		1	1	2	2.778	27.78	397.25	64.03	0.39725	20.42647059	0.185820896		
1					3	3.075	30.75	399.2	64.1	0.3992	22.61029412	0.191641791		
1			1		3	3.258	32.58	400.05	64.45	0.40005	23.95588235	0.194179104		
1	1			1	3	3.536	35.36	400.66	64.54	0.40066	26	0.196		
1				2	3	3.779	37.79	401.31	64.83	0.40131	27.78676471	0.197940299		
1					4	4.016	40.16	401.92	65.58	0.40192	29.52941176	0.199761194		
1		1			4	4.229	42.29	402.59	65.75	0.40259	31.09558824	0.201761194		
1			1	1	4	4.551	45.51	403.18	65.77	0.40318	33.46323529	0.203522388		
1		1	1	1	4	4.764	47.64	403.94	65.82	0.40394	35.02941176	0.205791045		
1	1				5	5.066	50.66	404.68	65.99		37.25	0.208		
1	1	1			5	5.279	52.79	405.51	66.02	0.40551	38.81617647	0.210477612		
1			1	1	5	5.492	54.92	405.98	66.48	0.40598	40.38235294	0.211880597		
1	1			2	5	5.77	57.7	406.57	66.7	0.40657	42.42647059	0.213641791		
1	1				6	6.007	60.07	407.3	66.68	0.4073	44.16911765	0.215820896		
1				1	6	6.25	62.5	407.54	67.05	0.40754	45.95588235	0.216537313		
1		2	1		6	6.507	65.07	407.88	67.4	0.40788	47.84558824	0.217552239		
1	1	2		1	6	6.785	67.85	408.58	67.32	0.40858	49.88970588	0.219641791		
1			1		7	7.022	70.22	409.14		0.40914		0.221313433		
1		1	1		7	7.235	72.35	409.26		0.40926		0.221671642		
1	3	1	1		7	7.562	75.62	410.16		0.41016		0.224358209		
1	2			2	7	7.761	77.61	410.47		0.41047		0.225283582		
1		1			8	7.993	79.93	410.99		0.41099		0.226835821		
1	1			1	8	8.241	82.41	411.53		0.41153		0.228447761		
1	1	2	1		8	8.498	84.98	411.7		0.4117		0.228955224		
1					9	8.721	87.21	412.01		0.41201		0.229880597		
1				1	9	9.073	90.73	412.41		0.41241		0.231074627		
1	1	1	1		9	9.226	92.26	412.88		0.41288		0.232477612		
1		4			9	9.573	95.73	412.94		0.41294		0.232656716		
1	1				10	9.771	97.71	413.37		0.41337		0.233940299		
1		2			10	10.088	100.88	414.11		0.41411		0.236149254		
1	2			1	10	10.232	102.32					-1		
1	2	1		1	10	10.445	104.45					-1		
1	3	2		1	10	10.767	107.67					-1		

List of Figures

List of Tables

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