Smart Dynamic Casting

A digital fabrication method for non-standard concrete structures

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Zusammenfassung


Der experimentelle Schwerpunkt liegt folglich auf einem speziell entwickelten roboterbasierten Gleitschalungsprozess. Wesentlicher Vorteil ist nicht nur, dass die verwendete Gleitschalung wesentlich kleiner als die resultierenden Objekte ist und somit größere bauliche Strukturen hergestellt werden können. Hinzu kommt ebenso, dass keine zusätzlichen Schalungssysteme erforderlich sind und freigeformte Betonstrukturen gewissermassen abfallfrei hergestellt werden können. Die Arbeit legt somit eine wichtige Grundlage für ein vollkommen neues, ökologisch aber auch ökonomisch effizientes Herstellungsverfahren im Bereich des digitalen Betonbaus.

Zu Beginn der Arbeit werden aktuelle Fertigungsansätze für nicht-standardisierte Betonstrukturen aufgezeigt. Hiernach folgt die Erläuterung der wichtigsten Grundsätze und
Anwendungsbeispiele des industriellen Gleitbauverfahrens. Im Anschluss werden die experimentellen Grundlagen der Arbeit dargelegt und vier unterschiedliche Experimentzyklen diskutiert, die ausschlaggebend für die Entwicklung dieses neuen roboterbasierten Gleitbauverfahrens namens "Smart Dynamic Casting" (SDC) waren. Die Arbeit schließt mit einer Zusammenfassung der Ergebnisse und weiterer zukünftiger Schritt ab.
Abstract

Reinforced concrete has been one of the great technological enablers of modern architecture, and remains one of the most common materials for enabling non-standard concrete structures in the building industry today. However, in particular when bringing this initially fluid material into a complex shape, a bespoke formwork is commonly required, which – because it is only used once – contributes to higher construction costs and increased waste.

This thesis combines digital fabrication methods and new developments in concrete material science with the well-established construction technique known as slipforming – commonly used to efficiently construct tall monolithic structures – to investigate whether this novel combination yields a resource-efficient approach for building non-standard (reinforced) concrete structures.

The main challenge consists in developing methods and techniques that enable concrete to be shaped during the delicate phase when it changes from a soft to a hard material. This thesis investigates a robotic slipforming process, where a formwork that is substantively smaller than the resulting structure is used to shape the concrete during this phase – eliminating the need for custom-made formwork and laying the basis for an ecologically and economically sustainable fabrication method for non-standard concrete construction. The thesis begins by presenting existing casting techniques for non-standard concrete structures, and giving insight into the slipforming casting method (which is at present mainly used for in situ fabrication of tall structures). It then describes in detail four cycles of experimentation that were used to explore new production methods for shaping concrete as it changes from a soft to a hard material.
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1. Introduction
1.1. Introduction

Concrete is a versatile material that can be transported in a fluid state, cast into a formwork of almost any desired shape, and hardened without any external action. Over the course of the 20th century, rapid innovation in the material science of concrete (in particular in regards to its strength properties\(^1\) and its processing\(^2\)) have given engineers and architects unprecedented abilities to construct both standard and non-standard structures,\(^3\) and in 2014 alone, 4.3 billion tonnes of cement were produced worldwide to make concrete.\(^4\) Innovations in concrete technology and construction have also brought about increased specialization, particularly in concrete material science, structural engineering, formwork technology, and architecture. As a result, these fields are generally treated as separate endeavours.

This decoupling of the design and construction processes is to some extent intensifying as rapid development in Computer-Aided Design (CAD) enables architects to design and realise non-standard, highly complex geometries and structures.\(^5,6\) Today it is common practice to test such complex designs by 3D printing them at model scale, for example. However model-sized structures generated with advanced CAD tools give little information about the 1:1 behaviour of the material and construction process needed.\(^7,8\) Therefore, such formal explorations often lead to architectural designs that are very complex to construct and therefore costly to build.\(^9\)

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3 In this context, non-standard is defined as having a large number of distinct parts with little or no repetition among them. It not only refers to a structure’s formal qualities, but also to the intention of creating structurally optimized and unique projects that are in direct contrast to ‘standard’ industrial projects. ‘Complex’ was essentially defined in the exhibition at Centre Pompidou, Paris by F. Migayrou in 2003, though was later referred as ‘non-standard’ in: F. Migayrou, Architecture Non-Standard (Paris: Centre George Pompidou, 2003).
6 Here is it important to emphasize that, when constructing buildings out of standard modular systems, this separation occurs less often. This is mainly because the building industry has (since the beginning of industrial revolution) aimed to develop efficient modular building systems. A comprehensive overview of this development is given in: U. Hassler, Was der Architect vom Stahlbeton wissen sollte (Zurich: gta Verlag 2010).
Often, when realising non-standard, formally complex building structures, concrete is chosen as the main building material as it can yield a broad range of shapes when poured into a formwork. Yet while this is true, it only displaces the problem to the formwork. Consequently, most non-standard structures require bespoke formwork solutions that are complex to build, and this causes the overall construction costs to rise significantly.\(^{10}\)

To overcome these limitations, various research institutions and industry have investigated a number of flexible or reusable formwork typologies, or have tried to eliminate the need for formwork altogether by developing additive manufacturing methods like the 3D printing of layered concrete.\(^{11}\) In fact, new methods for non-standard concrete construction are constantly evolving, but today the fastest and most cost-efficient way to produce non-standard concrete structures is still to mill formwork inlays out of wood or foam and insert these in standard formwork scaffold systems. However, this is an economically and ecologically inefficient technique because the formwork inlays are only used once.\(^{12}\) Consequently, new solutions for producing complex concrete constructions are needed.

This thesis departs from a more than 100-year-old in situ construction technique known as vertical slipforming (or simply, slipforming). Today, slipforming is used extensively in the building industry in the construction of monolithic large-scale structures (such as structural cores and façades for high-rise buildings, silos and brigade pillars\(^{13}\)) as it enables a fast rate of construction and requires little formwork.\(^{14}\) While slipforming yields a limited variety of shapes, there is theoretically no limit to the height and size of the structures it can produce. However, due to the relatively high setup cost of the formwork, slipformed structures tend to be tall (not less than 20 m\(^{15}\)) and may reach heights of up to 450 m, with footprint diameters ranging from 5 m to 60 m or more. Typical examples include monolithic cooling towers and silos,\(^{16}\) or structures for oil rig platforms, such as the 450-m tall legs of Norway’s Troll A oil-rig platform\(^{17}\) – one of the tallest

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\(^{11}\) Various methods that enable the production of non-standard concrete structures have been investigated to date. An overview of some of these is given in Section 2.3 and 2.4.


\(^{15}\) Ibid.


slipformed structures currently in existence. While this construction technique clearly proves its efficiency in large-scale construction, it has yet to be exploited at the component scale or for prefabrication. This thesis aims to: 1) use the principles of this robust concrete construction technique and merge it with digital fabrication; 2) transform slipforming from an in situ large-scale construction technique to a component-scale prefabrication system for bespoke vertical building elements; and 3) investigate methods and techniques for shaping concrete in its early hydration phase by employing a robotic slipforming process, in order to eliminate the need for excessive material usage for the production of a custom formwork.
1.2. Thesis

This thesis for the first time combines slipforming, robotic fabrication processes, and concrete material science to enable a new concrete construction technique called Smart Dynamic Casting (SDC). In this research, a formwork that is significantly smaller than the final structure is moved by a six-axis robotic arm, replacing the hydraulic jacks commonly used in large-scale slipforming and enhancing the ability to control the velocity and trajectory of the formwork in space. The thesis investigates whether this precise control allows concrete to be shaped during the delicate phase when it changes from a soft to a hard material. Specifically, it tests a concept whereby a large retarded batch of concrete is sub-divided into individually accelerated portions and subsequently placed into the formwork, which is then moved by the robot according to a specific trajectory and velocity.

![Figure 1: Schematic illustration of robotic slipforming setup.](image)

Three major aspects of the problem must be addressed simultaneously in order to empirically test this thesis on a real scale prototype.

The first aspect addresses the mechanical properties of the material system (in this case, a fibre reinforced, Self-Compacting Concrete, or SCC). The research aims at identifying if, under what specific conditions, and after how much time a given amount of SCC is able to sustain its own weight, in order to know when the formwork can be removed or slipped forward. Understanding
and being able to monitor the evolution of the material’s strength properties over time is critical to this work.

The second aspect focus on identifying a processing method capable of producing columns with varying cross sections, where the main challenge was to overcome inherent material limitations, such as cracking (due to excessive stiffness) or shape loss (due to excessive fluidity). To overcome these challenges, three distinct slipforming techniques – discontinuous, semi-continuous, and continuous – were developed and tested for their specific process parameters, such as the ideal batch size, when to add the accelerator, when to pour it in the formwork, and finally, to determine when to regulate velocity while shaping.

The third aspect focused on determining the hardware and control system best suited for the robotic fabrication process. This included the development of different formwork systems to empirically explore and validate specific constraints and possibilities of both material and process. The initial focus was set on rigid formwork cross sections that can be rotated along vertical trajectories, whereas the final experiment of this thesis investigated a flexible formwork system that can change its cross section during the slipping process. This part of the thesis also focused on characterising and implementing digital design tools capable of defining the intended geometries, as well as developing a custom control system that enabled the fabrication process to be synchronised with the evolving material properties.

Vertical columns were chosen as the prototypical architectural typology to test the fabrication process throughout the experiments. There are various reasons for this. First, there is a long history of producing vertical structures with slipforming. This conceptual affinity per se makes the column the logical typology for the development of such a novel fabrication process. Second, the column is one of the basic structural elements in architecture for transmitting vertical loads. Finally, the column’s simplicity allows all the fundamental aspects of the process to be tested in a relatively controlled manner, thus enabling short development cycles.

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18 The manifestation of the column as an important structural element dates back to ancient Greece when temples dominated the architectural landscape. The temples’ prominence was in part due to the height of their columns, and according to Vitruvius, the relationship between the columns and beams. For further information, see: J. Rykwert, The Dancing Column: On Order in Architecture (Cambridge, Massachusetts, MIT Press, 1996): 171.

1.3. Methodology

The research method used in this thesis is empirical, and largely based on physical experiments. As such, the research required full-scale iterative testing and validation of prototypes in order to develop an in-depth understanding of the specific limitations and possibilities of SDC with respect to real-world material and fabrication constraints. For example, the synchronisation of the robotic movement with the time-based evolution of the material properties could not be developed just through analysis, but required extensive empirical testing and observation. In consequence, this thesis could not be developed based on theoretical knowledge alone.

The empirical experimental setup included the exploration and validation of five major aspects. The first was the material itself: a fibre-reinforced self-compacting concrete (SCC) that was adjusted throughout the project with chemical admixtures described in Section 3.1.1., 3.1.2. and 3.1.3.

The second aspect was the custom material monitoring system, which principally consisted of a digitally controlled penetrometer. The material monitoring system was used to guide the overall robotic slipforming process by measuring the strength properties of the SCC during production.

The third aspect was the formwork system (or simply, the formwork), which was essentially the robot’s end-effector. For this research, two formwork systems were developed: one with a static cross section, and another flexible one that could dynamically change its cross section during production.

The fourth aspect was the development of a custom digital design tool that enabled a specific vertical column geometry to be parametrically defined based on the chosen formwork; the design tool can be operated within a standard CAD environment (McNeel Grasshopper20) and is able to translate design parameters into robotic fabrication code for the robot.

The fifth component was the concrete processing system, which had to be developed in a step-by-step process – first with a discontinuous material processing method, then with a semi-continuous process, and finally with a continuous concrete processing method. The experiments were developed and adjusted iteratively in sequential steps (summarised conceptually in Figure 2) in order to yield a non-standard column structure without cracks or flow of material.

Overall, this thesis describes a selection of experiments\textsuperscript{21} that illustrate all the major developments and findings of SDC. It is structured in seven main sections. Section 1., provides an introduction, and presents the topic of research and contextualises it within the field of concrete construction technology for non-standard structures. Section 2., covers the state of the art, providing an overview of slipforming as it is today and describing additional methods for the construction of non-standard concrete structures that are currently in use. Section 3., discusses the materials and methods developed in this thesis, including an initial exploratory study that was crucial in laying the groundwork for this research. Section 4., describes the experiments using discontinuous, semi-continuous, and continuous processing methods, and discusses their validation and specific findings. Section 5., discusses the overall results of this thesis, while Section 6., provides concluding remarks, and Section 7., outlines potential next steps for this research and suggests future perspectives for SDC.

\textsuperscript{21} More than 80 robotic experiment were conducted throughout this thesis. Additionally, countless laboratory experiments were needed to define the material and processing systems and to validate the monitoring system.
2. State of the art
2.1. Standard formwork

A formwork is typically required to build concrete elements or structures, and generally comes in the form of a pre-engineered temporary structure. Engineering work is required to ensure that the formwork can resist the loads of the uncured concrete and, if needed, the loads of working platforms and other equipment needed during the construction process.\textsuperscript{22}

![Formwork Diagram]

Figure 3: Typically, all standard formworks consist of a sheeting that is stiffened by studs and wales, and held together with ties, clamps or similar.

Over the course of the 20\textsuperscript{th} century, a large variation of standard\textsuperscript{23} formwork systems and typologies (Figure 3) have been developed for prefabrication and in situ construction of standard architectural structures.

These include:

- Static formworks systems with fixed dimensions, used to cast a single element such as a wall, slab, or column.

- Reconfigurable formwork systems for casting walls or slabs, such as modular standard formwork panelling systems.\textsuperscript{24} With relative ease\textsuperscript{25} these can be adjusted to cast structures with different wall thicknesses, articulated corner conditions, or curvatures.\textsuperscript{26}

- Reconfigurable formwork systems for casting columns, which also enables to adjust the dimensions.\textsuperscript{27}

\textsuperscript{22} The dimensioning of formwork is highly dependent on the requirements of the structure. Detailed information can be read in: D.W. Johnston, "Design and Construction of Concrete Formwork". 7.5-7.15. Or in: A. S. Hanna, Concrete Formwork Systems (New York: Marcel Dekker 1999).

\textsuperscript{23} 'Standard' refers to structures that can be mass processed within standard norms defined in the territory of execution of the structure, or a series of equal products. Standard generally means that it is accepted by a greater audience, and can used as a basis for comparison; an approved model.

\textsuperscript{24} Several examples exist for modular formwork systems for columns, walls or slabs. Leading formwork companies such as PERI offer several industrial solutions, for example: PERI, "Schalung Gerüst Engineering". Accessed 01.03.2016, http://peri.ch/ww/de/produkte.cfm?Fuseaction=anwendungen&Subaction=anwendung&ID/2.cfm. Other similar solutions are exemplified under: PASCHAL, "Products". Accessed 01.03.2016, http://www.paschal.de/english/products/index_wall_formwork_others.php.

\textsuperscript{25} Over the past decades, multiple assembly systems have been developed to enable unskilled workers to easily and precisely assemble modular formworks. A particular simplification has been conducted on wale and stud systems that, using holes or interlocking systems, ensures the precise assembly of the modular formwork panels. In addition, advanced connection solutions have emerged for joining panels, making the assembly of formwork panels more precise and efficient. Examples are clamp systems and hand sets for quick wall assembly. See: PERI, "Handset: Handset Panel Wall Formwork". Accessed 01.03.2016, http://www.peri.ltd.uk/products.cfm?Fuseaction=showproduct&product_ID/29&app_id/2.cfm.


\textsuperscript{27} Detailed information can be read in: D.W. Johnston, "Design and Construction of Concrete Formwork". 7.5-7.15.
The logical consequence of using a standard static or reconfigurable formwork system is that the formwork is occupied until the concrete has hardened enough to sustain itself under its own weight. The conventional process for constructing a reinforced concrete wall can be described as 1) assembling the formwork and inserting the reinforcement, 2) casting the concrete inside the formwork and leaving it in place for 24 to 48 h (depending on the structural requirements and the desired surface quality) while the concrete cures, and 3) removing the formwork once the curing is complete.

Normally, such processes comprise up to 47% of the cost of standard concrete structures and involve mostly labour, including the planning, installation and disassembly of the formwork. In order to rationalise this process, the building industry has made a great effort to develop modular standardised formwork systems that are cost-effective, in comparison to a fully customised formwork. These flexible standardised system offer a certain degree of customization while meeting the requirements of precision, quality, low waste, and safety during construction. In contrast, custom formwork solutions are usually more expensive and significantly increase the costs of the overall structure. Hence, to keep safety and productivity high and cost low, most architectural structures are built using standard modular formwork elements.

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29 D.W. Johnston, "Design and Construction of Concrete Formwork". 7.5-7.15.
2.2. Slipforming

Slipforming is a standard formwork system commonly used in the building industry as an efficient method for fabricating tall vertical monolithic concrete structures such as structural cores, chimneys, pillars, and cooling towers, to name a few. This section gives a short historical overview of the technique, followed by a description of how standard slipforming systems (known as standard\textsuperscript{30} and conical formwork systems) are employed in the construction industry today.\textsuperscript{31}

History

Slipforming\textsuperscript{32} is a process for fabricating tall structures invented in 1899 by the engineer Charles F. Haglin in collaboration with grain company owner Frank Peavey.\textsuperscript{33} Their original method has remained in practice until today: it is a process in which concrete is continuously poured into a formwork that is moved upwards by the means of hydraulic jacks at a speed set according to the rate of the hydration of the concrete,\textsuperscript{34} so that the material is already self-supporting after being slipped out of the formwork.\textsuperscript{35} In an efficient slipforming production, the velocity of slipping can range from 40 to 60 cm/hour. However, the rate of production is highly dependent on the complexity of the structure, ambient conditions, and concrete type. Generally, slipforming is used for the construction of simple monolithic structures, as this is where the construction method proves to be most efficient.\textsuperscript{36}

\textsuperscript{30} Also referred to as traditional.
\textsuperscript{32} Slipforming and jump-forming both enable the construction of a seamless structure. However, a jump form is not moved (or jumped) before after the concrete has fully hydrated. Because the jump form must be attached to the previously cast structure, this process is discontinuous. Jump-forming is a costly construction process that is primarily used for building standard forms featuring as towers and skyscrapers. See: D.W. Johnston, “Design and Construction of Concrete Formwork”. 7.13-7.14.
\textsuperscript{34} In general, the velocity is empirically adjusted in accordance to a test that involves sticking a metal rod into the formwork. The test is commonly done by an experienced worker who evaluates the strength properties of the concrete and adjusts the slipping velocity accordingly.
\textsuperscript{35} S.W. McConnell, “Structural Concrete Systems”, 10.33.
\textsuperscript{36} J.F. Camellerie, Vertical slipforming as a construction tool in Concrete Construction (1978). Accessed 01.03.2016, http://www.concreteconstruction.net/construction/vertical-slipforming-as-a-construction-tool.aspx. Though this source is more than 30 years old, it is still applicable because slipforming techniques have remained largely unchanged.
One of the first known structures erected with this technique is the 38-m high reinforced concrete grain elevator\(^\text{37}\) in Minnesota, USA\(^\text{38}\) known as the Peavey-Haglin Experimental Concrete Grain Elevator (see Figure 5, left). This elevator was constructed in two phases (from 1899 to 1900) using round wood formworks braced with steel studs. As the concrete hardened, the form was...
moved upwards by hand\textsuperscript{39} in discrete steps. Due to uncertainties regarding the grain elevator’s structural properties, the first slipforming construction cycle was stopped at a height of 20 m so that the grain elevator could be empirically tested by filling it with corn and then emptying it again.

After the structure successfully withstood the test, a second slipforming construction cycle started the following year, allowing the structure to reach its final height of 38 m\textsuperscript{40}. While one may not associate this particular structure with the pinnacle of modern architecture, it was nonetheless prominently considered to be a symbol of the new industrial age by modernist architect Le Corbusier who, according to M. Bacon, stated that this vertically slipformed structure represented "the magnificent first fruits of the new age".\textsuperscript{41}

During the 1930s, one of the first slipformed silos was erected on the European continent – in Baar, Switzerland\textsuperscript{42} – and from then on slipforming was quickly taken up by the construction industry as a standard technique for producing tall concrete structures. Its use accelerated after 1944, when the invention of centrally controlled hydraulic jacks transformed slipforming into an almost automated casting system\textsuperscript{43} that enabled the fast and cost effective construction of tall

\textsuperscript{38} M. S. Ketchum, The Design of Walls, Bins and Grain Elevators (The Engineering News Publishing Company 2011): 262-263. This book comprehensively describes how to construct reinforced concrete sand bins in a continuous process as follows: "[...] The concrete was poured in and tamped inside the forms, which were raised in 45° Sections 28 inches high, every 24 hours. The work was carried on by day and night so as to prevent any setting between the layers of concrete [...]".


\textsuperscript{41} As quoted in: M. Bacon, Le Corbusier in America, Travels in the Land of the Timid (Cambridge, Massachusetts: MIT Press. 2001) 114.

\textsuperscript{42} C. Jegher, Die Gleitschalung im Silobau". In Schweizerische Bauzeitung, 95/96, 7, (1930): 86-93.

building structures. Notable examples of this development include the CN tower in Toronto in 1974\textsuperscript{44} and the concrete apartment tower in Havana\textsuperscript{45} in the 1960s.

![Construction of the CN tower in Toronto, (1973-1975).](image)

Today, slipforming remains an efficient and commonly used concrete construction technique for tall, monolithic building structures such as tower cores, bridge piers, power plant cooling towers, chimney shafts, pylons, the legs of oil-rig platforms, and structural façades of high-rise buildings. Notably, the technique has been used to produce some of the tallest free standing structures in the world.\textsuperscript{46} Recent examples include the construction of the core of the Shard Tower in London, UK, erected from 2011-2013,\textsuperscript{47} or the recently slipformed corn silo in Zurich Switzerland.\textsuperscript{48} Yet though it is a fast and efficient construction process, it has still not significantly impacted the construction of smaller scale structures, nor has it been used for prefabrication or bespoke concrete elements.

**Industrial application**

Two types of slipforming exist in conventional large-scale concrete construction: horizontal and vertical. Horizontal slipforming is a method used extensively in the infrastructure sector, for example to build curb stones and separation walls on highways. This method involves extruding

\textsuperscript{44} An overview regarding the construction of the CN tower can be found on: Concrete Contractor, "The CN Tower - Toronto, Canada, 1974". Accessed 01.03.2016, http://www.concretecontractor.com/concrete-construction-projects/cn-tower/.


\textsuperscript{46} More information regarding structures erected with slipforming can be found in: S.W. McConnell, "Structural Concrete Systems", 10.33. Or see the article by: J. A. Bickley, "Concrete Technology Aspects of CN Tower". In Journal of the Construction Division-ASCE 101, (1975).

\textsuperscript{47} J. Parker, "Building the Shard". In Ingeni, 52 (2012): 24-30.

a dry mortar or concrete with mechanical force using single-task automated machinery that moves along a specific trajectory.49

In contrast, vertical slipforming (or simply, slipforming) uses hydraulic jacks to move a formwork vertically while reinforcement is inserted on the fly from the top.50 The formwork is moved at a constant velocity that ensures that the fresh concrete being slipped out of the form can sustain its own weight, plus the weight of the formwork and concrete above it.

Two types of formwork systems are commonly used in slipforming today: standard and conical. A standard formwork system has a constant geometry throughout the entire slipforming process. In contrast, a conical formwork can change its dimensions – for example, its diameter (in the case of a chimney or bridge pillar) or its thickness (in the case of a wall) – and even its geometrical shape during the slipforming process. This dimensional adaptation is done manually by following a "spindle list" that defines the point at which the spindle should be turned to expand or contract the formwork cross section.51 Regardless of their type, all slipformwork systems consist of lifting jacks, rods, yokes, wales sheathing, formwork panels and working platforms (Figure 7). The assembled components slide continuously upwards as the structure emerges.52

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49 Horizontal slipforming is similar to an extruding process. Extrusion is a method of using mechanical force to protrude a material through a formwork or die. For further information, see: M. Walter, Extrusion Dies for Plastic and Rubber: Design and Engineering Computations (3rd Edition, Munich: Hanser Fachbuchverlag, 2008). Because vertical slipforming is the focus of this thesis, horizontal slipforming will not be discussed further. Information on extrusion can be found on: The Concrete Society, "Horizontal slipforming". Accessed 01.03.2016, http://www.concrete.org.uk/fingertips-nuggets.asp?cmd=display&id=395.

50 S.W. McConnell, "Structural Concrete Systems". 10.33. Or in R.G. Batterham, Slipform Concrete, (New York: Construction Press): 27-38. In slipforming construction, the premixed concrete is brought to the site in sequential truck loads. The concrete is placed in batches up to a height that prevents cold joints by ensuring that the formwork is full at all times. The filling height of the batches is typically 10 cm. The setting time of the concrete layers depends on the mixture, but generally varies between 2 - 4 h. This means that a slip velocity can vary between 3 to 6 m over 24 h, or 20 to 60 cm/h, see: S.W. McConnell, "Structural Concrete Systems". 10.33-10.37. Theoretically, slipping velocities up to 30 and 40 cm/h are possible, but are seldom achieved, however, since the velocity is highly dependent on a number of factors such as: the formwork height, concrete mixture, temperature, delivery of concrete, speed of insertion of reinforcement, and the experience of the crew. In practice, therefore, slip rates are usually limited to not more than 20 cm/h according to Gleitbau. Information regarding slipping velocity is also extracted from a mail interview from the 30.08.2011, with B. Reitmaier of Gleitbau Austria.

51 According to the interview with B. Reitmaier, Gleitbau Austria: To change the diameter or wall thickness of a structure using conical formwork, a so-called "spindle list" is prepared. The diameter is changed by manually turning a spindle attached to each yoke. The list is prepared in a custom program that subdivides the vertical structure into segments that are all the same height. The program generates a list that describes how many times the spindle must be turned, and at what specific height, to achieve the correct geometry. The turning is done manually, which is said to be advantageous as this allows the crew to feel whether the concrete is too soft or too hard. For making a rotation-symmetric structure (e.g. conical chimney) this is a rather easy task, as every yoke is manipulated in the same way. For complex asymmetric structures, however, this task becomes rather complicated, as every yoke must be treated differently.

52 Here, a comparison can be derived to the automated SMART system described in Section 2.3.
Three major components are required to fabricate a standard slipformwork (Figure 7): 1) horizontal yokes (Figure 7, A.), onto which 2) the formwork panels (Figure 7, B.) and 3) the hydraulic jacks (Figure 7, C.) are installed. These are controlled via a central control unit, which makes the jacks climb on a rod mounted in the centre of the formwork (Figure 7, D., E). For a formwork with a particular geometry, multiple yokes are set up and the additional components are assembled in an array that envelopes the desired geometrical shape – usually a circle, square, or triangle. An example of such an assembly can be seen in Figure 8.53

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53 S.W. McConnell, "Structural Concrete Systems”. 10.34.
The formwork panels are stiffened by the upper and lower wailings (see Figure 7, G.) that are held in place by the yokes. The dimensions of the panels are generally 7-8 mm in thickness, but can vary in height from 1000 mm to 1500 mm, and in width from 1250 mm to 3000 mm. The panels can be made of wood, steel or hard polymeric material, depending on specific application and construction requirements.\textsuperscript{55}

The moving jacks are installed at the upper horizontal yoke beam, and climb on smooth centrally placed steel rods, also known as climbing tubes. The tubes have a length of 4 m, a diameter of 42 mm, and a wall thickness of 3 mm. Threaded pins at the end of the tube (Figure 7, C., D., E.) are used as connection points. The yokes hold a two-level working platform (Figure 7, L.). The upper level is used to cast, place reinforcement, vibrate, and control the slipform operation. The lower platform gives access to the concrete as it emerges from the underside of the formwork. At this point, the still-soft concrete surface is usually polished smooth and damaged areas repaired.\textsuperscript{56}

In principle, the components of a conical slipformwork system are the same as the standard slipformwork setup illustrated in Figure 7. The difference is that, in the conical system, the upper and lower yokes can be adjusted by moving them on a rail (see Figure 9, A), thus allowing the wall thickness and/or diameter of the structure to be adjusted. The adjustment is done via a spindle that can be controlled manually or from a central control unit.


\textsuperscript{55} Wood is generally used for simple geometries, whereas steel and polymeric material are used for more complex geometries and structures. S.W. McConnell, "Structural Concrete Systems", 10.34.

\textsuperscript{56} This information is extracted from an interview on a site visit at, GBG Gleitbau, Austria, with: B. Reitmeier., at the "Shaft for Sankt Pölten Tunnel", in Sankt Pölten, Austria 07.03.2012.
Spindles (Figure 9, C, E) are used to adjust the distance between the inner and outer yoke legs, which are in turn connected to the upper and lower yokes (Figure 9, A). Hence, the wall thickness can be adjusted.

To change the diameter or to slipform inclined walls, the upper and lower yokes are connected to an overhanging lattice girder structure (Figure 9, B). By using the spindles to taper, the yokes along the lattice girder structure inwards or outwards, the cross sectional area can be changed. Simultaneously, formwork panels varying in width from 25 cm to 50 cm are inserted or removed manually to increase or decrease the cross sectional area.

Prior to forming a structure with a varying wall or cross section, a custom CAD program is used to generate a spindle list. The spindle list contains information such as the changes in circumference or wall thickness over the height of the structure. During production, skilled workers control the central unit, changing the circumference or wall thickness of the formwork in accordance with the spindle list. In general, this process is done manually so that the crew can empirically determine whether the material is getting too hard or too soft inside the formwork. Though it enables the construction of complex geometries, custom conical formwork is generally considered to be a difficult and costly endeavour, in part because skilled workers must constantly adjust and recalculate the indentation in an ad hoc manner in order to change the spindle list.  

Conical formwork is typically used for the construction of hyperbolic structures (such as cooling towers or chimneys with a changing cross section – see Figure 10) and for, in special cases, the construction of asymmetric structures.

The type of conical formwork system illustrated in Figure 9 and Figure 11 was also used in 2005 to construct the Sakhalin II project in Russia (see Figure 11) – two offshore oil and gas platforms that were submerged into the sea after the construction was finished. Each structure consists of four asymmetrical support structures (see Figure 12) designed specifically to resist the ocean current, seasonal icepack, and seismic activity at the location in which they were placed. The support structures incline up to 20° from the vertical axis, and the wall thickness varies from 75 cm to 50 cm. The tower’s overall height is more than 50 m.
Overall, slipforming represents a highly efficient in situ concrete construction approach for tall structures, in particular for structures with a simple geometry. Additionally, when using conical systems, slipforming allows for the (semi-automated) construction of tall symmetric structures with a changing cross section or hyperbolic shape.
However, substantial challenges emerge when the geometry becomes more complex (for example, in the Sakhalin II project, see Figure 12) because such construction relies on manual control and implementation of mechanically complex custom slipformwork. Thus, concrete structures such as these remain difficult to produce. Additionally, the application of slipforming is generally limited to the construction of tall structures (over 10 m) because the formwork assembly is labour intensive and thus costly to set up. As a result, slipforming is not yet used for prefabrication or for the production of discrete concrete building components.

This thesis aims to re-conceptualise this robust and efficient construction technique by merging it with new insights in material science, digital technology, and robotic fabrication. The goal is not to reinvent slipforming, but to investigate whether this construction and production method can be transferred to and expanded through a robotic prefabrication process, and whether this can help to produce bespoke vertical building elements in a more efficient way. Prior to this thesis, slipforming has never been used in combination with robotic fabrication. Should the transfer prove successful, this thesis will lay the groundwork for a new construction technique for bespoke vertical concrete structures.

58 No examples exist of slipformed structures below 10 m (R.G. Batterham, Slipform Concrete, 27-38, or in S.W. McConnell, "Structural Concrete Systems": 10.33.). Additionally in a site visit it was confirmed that structures below 10 m are not feasible due to the high initial setup cost of the formwork (B. Reitmaier, 2012).

2.3 Automation and digital technology in construction

4.1.1. Robots in construction

Employing an industrial robot\(^{60}\) for the movement of the formwork in slipforming is new. However, implementing robotic processes for bespoke fabrication of architectural elements is not. For example, in 2005 Gramazio Kohler Research at ETH Zurich pioneered the use of industrial robots for the construction of bespoke façades elements made of bricks, and other research institutions across the globe have since launched research and development projects to investigate the potential of industrial robots for the field of architecture. However, until now this research has only just touched the surface of what is possible.\(^{61}\) This section does not aim to give a detailed historic account of the use of industrial robots in construction,\(^{62}\) but rather it aims to give a brief overview of how robots have been introduced into the construction industry over the past decade.

Since its invention in 1956, the main purposes of the industrial robot have been to improve productivity and to perform hazardous or monotonous tasks,\(^{63}\) in particular in the automotive industry. For similar reasons, research and development in Japan during the 1990s aimed to bring robotic technology to the construction sector.\(^{64}\) In contrast to today’s R&D efforts, however, the development of robots in construction at that time did not target the implementation of a generic industrial robot that could be used for various construction tasks, but rather focused on the development of specialized automated devices. These machines were designed to improve

\(^{60}\) According to: ISO 8373:2012, “Robots and robotic devices – Vocabulary,” an industrial robot is defined as “automatically controlled, reprogrammable, multipurpose manipulator[s]. In other words, an industrial robot is a machine that can be reprogrammed to conduct a variation of specific tasks. However, to do a task it must be equipped with specific end-effectors that vary depending on application.


\(^{62}\) The first official research in the field of robotics in construction dates back to 1978 in Japan. An outline of some of the main efforts can be found in: Y. Hasegawa, “A new Wave of Construction Automation and Robotics in Japan”. In the proceeding of the 17th International Symposium, Automation and Robotics in Construction (ISARC) (Taipei, Taiwan, 2000). A comprehensive discussion of robotics in construction history is described in: T. Bock, S. Langenberg, “Changing Building Sites: Industrialization and Automation of the Building Process”. In AD: Made by Robots: Challenging Architecture at a larger Scale, 05, 06 (2014): 88-89. Here, the first automated/industrialized construction processes are considered as forerunners for the robotic boom in the 1990s.

\(^{63}\) The first industrial robot (Unimate) was invented in 1956 by George Devol and Joseph Engelberger. In 1961 it was installed at the assembly line for General Motors for extracting and separating parts of a die-casting machine. Later the same machine was used for spot welding. J. F. Engelberger, “Historical Perspective and Role in Automation”. In Handbook of Industrial Robotics, ed., Y. N. Shimon, (2nd edition, New York.: John Wiley & Sons, 2007): 3-10. The primary application for industrial robots continues to be the automobile industry according to: T. Bonwetch, “Robotically assembled brickwork”. (PhD, Diss., ETH Zurich, Switzerland, 2016): 16-21. The implementation of Unimate was only a few years after the first computer from Remington Rand (UNIXAC) and IBM had been launched on the market. More information in: L. R. Johnson, “Coming to Grips with Univac”. In, IEEE Annals of the History of Computing, 04 (2006): 32-42.

efficiency by automating a particular construction process such as,\textsuperscript{65} for example, bricklaying
masonry,\textsuperscript{66} welding, positioning of modular steel elements, concrete slab shedding and
finishing,\textsuperscript{67} fire resistance, and paint spraying.\textsuperscript{68} In parallel, industry driven research projects
investigated the fully or semi-automated construction of high-rise buildings, which (similar to
slipforming) used hydraulic systems to lift complete platforms containing factory-like
environments for the automatic construction of entire floors directly on the construction site.
These onsite factories featured a temporarily covered working platform that automatically moved
at the speed of construction progress (see Figure 13).\textsuperscript{69} In the weather-protected construction
areas, material handling systems (in form of fully or semi-automated cranes) and various single-
task robots operated on diverse jobs, such as welding, concrete finishing, and the placement of
prefabricated concrete floor slabs, to name a few.\textsuperscript{70} In 1991, Shimizu Construction Company
developed a real scale prototype of such a system for the construction of a high-rise
building.\textsuperscript{71, 72}

These integrated systems did not make it beyond prototypical applications, however. This was
due largely to limitations related to the software and the control systems available at that time.\textsuperscript{73}
To increase productivity and automation, these systems also required special prefabricated
elements (for example, the SMART system required special joint systems for the assembly of
wall elements) that, in turn, constrained the freedom of the architectural design.\textsuperscript{74} Ultimately,
these systems were also not able to construct beyond the footprint of the moving platform,

\textsuperscript{65} B. Balaguer, "Nowadays Trend in Robotics and Automation in Construction Industry: Transition from hard to Soft Robotics". In
conference proceedings, 21st ISARC (Jeju, South Korea, 2004): 32-42.
\textsuperscript{66} The most advanced construction robots in the 1990s were the ROCCO and the BRONCO industrial robotic arm projects. These
projects presented prototypes for in situ robotic brick laying, however none of the projects made it beyond the prototype stage. One
reason was their lack of flexibility; another was their size, which prevented them from passing through the door openings of the
building site. For further information, see: J. Andres, T. Bock, F. Gebhart, "First Results of the development of the masonry robot
system ROCCO". In conference proceedings, 11th ISARC International Symposium on Automation and Robotic in Construction
(ISARC), (Brighton, England 1994).
\textsuperscript{67} Concrete screeding machines have been developed by several corporations, such as Takenka, Obayashi Shimizu. For further
information, an outline is given in: M. J. Skibniewski, R. Kunigahalli, "Automation in Concrete Construction". In Concrete
\textsuperscript{69} Parallel is drawn between the semi-automated construction sites and slipforming in: T. Linner, "Automated and Robotic
\textsuperscript{70} Y. Miyatake, Y. Yamazaki, and R. Kangari, "The SMART System Project: A strategy for Management of Information and Automation
Technology in Computer Integrated Construction". In conference proceedings, 1st International conference, Management of
information technology for construction (Singapore, 1993). A comprehensive overview of robots in construction can be found in:
T. Bonwetch, "Robotically assembled brickwork"(2016): 14-34.
\textsuperscript{72} Similar systems were developed by several construction companies, such as Obayashi: K. Hameda, N. Furuya, Y. Inoue, T.
Wakisaka, "Development of automated construction systems for high-rise reinforced concrete buildings". In IEEE International
Salmi, "Bringing an old concept into the future: The Maeda MCCS Analysis". In conference proceedings, CIB IAARC W 179
(Munich, Germany, 2012).
\textsuperscript{73} T. Yoshida, "A short History of Construction Robots Research & Development in a Japanese Company". In conference
proceedings, ISARC (Tokyo, Japan 2006): 188-193.
\textsuperscript{74} Y. Yamazaki, J. Maeda, "The SMART System: an integrated application of automation and information technology in production
meaning that the dimensions of the moving platform defined and thus constrained the possible footprint of the building.

Figure 13: SMART-System developed by Shimizu Corporation (1978). Left to right: Assembly of a movable structure, assembly of a working platform, construction process, construction of upper story and completion of construction.

More advanced examples of industrial robot applications in architectural construction were not seen until 2006, when Gramazio Kohler Research\(^{75}\) introduced industrial robots for the additive fabrication of non-standard architectural constructions.\(^{76}\) This research views the robot not as a tool for replicating or automating a specific manual task, but rather as a generic digital fabrication machine that can be custom programmed with algorithms to yield components and structures that are highly complex or impossible to construct manually. A pioneering example is the brick façade of the Gantenbein Vineyard, in which the robot was programmed to lay bricks in a specific configuration to produce a large-scale pixilated image (see Figure 14). This robotic brick laying method has since been adopted by industry.\(^{77}\)

Figure 14: Gantenbein Façade, Gramazio Kohler Research 2006.

Today, however, the industrial robot is still not widely used in concrete construction. The only known examples are semi-autonomous devices that are either remotely controlled or

\(^{75}\) F. Gramazio, M. Kohler, Digital Materiality in Architecture, (Baden, Lars Müller Publishers, 2008).


programmed to do a specific task on site, such as device tested for the demolition of concrete structures (see Figure 15) or the shotcrete devices typically used in tunnelling.  

![Figure 15: Left; ERO concrete design study for demolition robot. Right: example of a shotcrete device. Meyco’s shotcreting robot uses a robotic arm mounted onto a truck base.](image)

In prefabrication, industrial robots are mainly used to conduct repetitive tasks, such as moving heavy concrete components, preparing formwork components, or drilling holes in half-hardened concrete prefabricated elements, as was done at CreaBeton in Brugg, Switzerland (see Figure 16). With the exception of the complex construction of the Gantenbein Vineyard façade by Gramazio Kohler Research, all these cases make it reasonable to conclude that the concrete construction industry uses robots primarily to increase productivity, and not to conduct complex tasks that would otherwise be difficult or impossible to do using human labour alone.

![Figure 16: Left: a six-axis robotic arm being used to mill holes in semi-hydrated concrete elements. Right: a detail of the holes positioned at different heights.](image)

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4.1.2. Non-standard formwork systems

Despite the limited use of industrial robots in concrete construction, a boom in CAD technology in the last decade has significantly impacted architectural research and construction. This technological development has enabled architects and engineers to design geometrically complex structures. However, these structures are generally non-standard (meaning non-planar and non-repetitive) and thus require large amounts of custom formwork. Concrete is often the material of choice for these structures, as this versatile material can be formed into almost any shape. To erect structures such as these, inlays are often inserted into standard formwork scaffolding systems. A pioneering example using this technique is the Nationale-Nederlanden Building in Prague by Frank O. Gehry, or more recently the Spencer Dock Bridge in Dublin by Amanda Levete Architects (see Figure 17).

![Figure 17: Left: Milled formwork inserts in preparation for the casting of the Spencer Dock Bridge. Right: Final structure of the Spencer Dock Bridge.](image)

The formwork inlays are generally fabricated using a CNC-mill to carve material out of a homogenous block of expanded polystyrene foam (EPS) or wood. Though this production method allows almost any form to be made, it is very cost intensive and unsustainable because the milling process produces a large amount of waste, is very slow, and consumes a great deal of energy. This method also generally leaves the formwork with a grooved surface, which then

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82 It is important to mention the possibilities CAD technology provide, such as the ability to program with algorithmic tools, and to visualise the results in a CAD environment such as the R. McNeel & Associates, “Rhinoceros”. Accessed 01.03.2016, http://www.rhino3d.com/.
85 A comprehensive overview of energy consumption related to milling is given in the article of: L. Li, J. Yan and Z. Xing, "Energy requirements evaluation of milling machines based on thermal equilibrium and empirical modelling". In Journal of Cleaner Production, 52 (2013): 113-121.
requires manual fairing and (often toxic) epoxy-based coatings and post-treatments. These formwork inlays are frequently discarded after a single use. Nevertheless, this wasteful and expensive production process has until now been one of the most efficient techniques available for making custom formwork for concrete constructions with non-standard geometries.

To overcome these problems, a number of companies and research institutions have invested in the development of new fabrication approaches. The aim is to develop CAD tools and formwork systems that integrate the construction constraints in the early design phase, thus optimising the construction of bespoke concrete structures. Some solutions are being developed by leading formwork companies such as PERI. Other approaches have been explored by research projects such as ADAPA, TailorCrete, and MeshMould.

PERI, a leading formwork company, has introduced a flexible formwork system for the construction of cylindrical or double curved wall elements that can be cast up to a height of 14 m. The system is re-adjustable, beginning with a minimal radius of 1 m. The system has been successfully used for the construction of silos, water tanks, and pipes, as well as for the erection of buildings such as ADAC Headquarters in Munich, which consists of a curved 5-storey plinth with an 18-storey curved tower. For the construction and planning of such geometries, PERI has developed software that automatically determines the optimal formwork subdivision. However, both PERI's software and its flexible formwork system are limited when it comes to constructing buildings with extreme double curved surfaces, such as the Mercedes Benz Museum in Stuttgart. For this building, for example, external specialists developed a custom

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87 An example for this process is the construction of the "EPFL Rolex Learning Center" in Lausanne, Switzerland in 2008, for which 7,500 m² concrete surfaces were constructed using conventional scaffolding components onto which 1,500 individual wooden formwork panels were mounted. For more information see: Design to Production, 2008, "EPFL Rolex Learning Center". Accessed 01.03.2016, http://www.designtoproduction.com/projects.en?epfl_learning_center.
96 The company, Design to Production, was involved as a specialist for the development of the formwork system of the Mercedes Benz Museum. Design to Production is an interdisciplinary team with architects and computer scientists which have "[...] specialized in supporting architects, designers, engineers, and manufacturers bridge the gap between idea and realization when it comes to so-called 'Non-Standard-Architecture' [...]" For more information see: Design to Production, "Mercedes Benz Museum". Accessed on 01.03.2016, http://www.designtoproduction.com/projects.en?mercedes_benz_museum and http://www.designtoproduction.com/company.en.
algorithm that allowed the double curved geometry to be tessellated into discrete single curved panels. These panels were individually bent and attached onto 3D formwork systems by PERI in situ.\(^7\) This example illustrates the architectural potential of digital technology to provide solutions where the state of the art in the construction industry (despite attempts at flexibility) falls short of viable solutions.

![Figure 18: Tessellated formwork panels for the construction of the double curved surface of the Mercedes Benz Museum, Stuttgart, (2005).](image)

ADAPA,\(^8\) a spin-off company specialised in producing double curved panels of concrete, has developed a digitally controlled formwork system that should enable the efficient production of double curved non-structural panels of concrete, gypsum or thermoplastic (see Fig 19). Here, a digitally controlled flexible formwork is automatically deformed to custom double curved surfaces onto which concrete is cast or thermoplastic is deformed. The size and curvature of the panels is limited by the physical constraints of the formwork, which consist of a membrane deformed by digitally controlled pistons. Despite the non-structural nature of the final panels, this system clearly demonstrates the potential of an integrated design and production system for fabricating non-standard concrete building elements without the need for a custom formwork.

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\(^8\) ADAPA, "Adaptive Moulds".
In academic research, a similar approach has been pursued by the TailorCrete\textsuperscript{99} project, for which a digitally controlled flexible formwork system has also been developed. However, in this process, the concrete is not cast directly onto the flexible membrane. Wax, which can be fully recycled, is instead used to produce double-curved formwork elements (see Figure 20). These elements are then used as inlays in standard formwork systems on site, similar to what has been done for the Spencer Dock Bridge with EPS elements.\textsuperscript{100} This innovative system combines the advantages of standardized modular in situ formwork technology with the efficient and waste-free production of recyclable wax formwork inlays.\textsuperscript{101}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{tailorcrete_production.png}
\caption{The production process of TailorCrete. First the mould is configured. Then the wax is cast, brought on site, and placed in a standard formwork. Finally, after stripping the formwork, the wax is melted and reused for new inlay elements.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure19.png}
\caption{Flexible formwork developed by ADAPA.}
\end{figure}

\textsuperscript{99} Gramazio Kohler Research, "TailorCrete".
\textsuperscript{100} Note that this system is constrained by the fact that the wax formwork inlays tend to lose their precisely defined shape due to temperature variations.
\textsuperscript{101} S. Oesterle, A. Vansteenkiste, A. Mirjan, "Zero Waste Free-Form Formwork". In conference proceedings, CICM, University of Bath (Claverton Down, BA 2 7 AY, United Kingdom, 2011): 258-267.
A final example is the research project Mesh Mould, also conducted at Gramazio Kohler Research at ETH Zurich. In this project, the investigation focuses on combining formwork and reinforcement into one single robotically fabricated construction system for complex concrete structures. Overall, these approaches demonstrate how contemporary digital design and fabrication can integrate standard casting and/or formwork techniques to yield economically and ecologically sustainable fabrication systems and processes for making double curved surfaces for concrete structures.

4.1.3. 3D printing

A different approach to efficiently fabricating concrete structures is 3D printing. 3D printing is a digitally controlled process in which successive layers of material are deposited in order to additively construct three-dimensional structures. Until recently, this technique was mainly used to produce non-functional prototypes for development purposes. However, 3D printing has made rapid inroads into industry and is presently a common manufacturing system in various sectors, including aeronautics, medicine, fashion, and the furniture industry, to produce anything from pills, textiles, and chairs to functional mechanical components such as body and car parts, to name a few.

In parallel to this rapid industrial development, several research institutions and companies have explored 3D printing of concrete for the prefabrication of architectural elements. Here the focus varies from the mass production of housing units to the fabrication of non-standard...
concrete structures. One example is the company Winsun in Shanghai,\(^\text{108}\) who recently succeeded in 3D printing full-scale houses in less than 24 h (see Figure 21). The same company has also assembled a six-story house at the Suzhou industrial park, China that was 3D printed offsite piece by piece.\(^\text{109}\) The machine was able to print concrete in a building volume with a ground surface of 10 m by 40 m and a height of 7 m.

Another recent example is the Philippine-based company, Total Custom,\(^\text{110}\) which uses 3D concrete printing technology to erect one-story houses. The company claims to specialise in custom-made houses with standard façades, but which can contain special features on customer demand, such as the twisted columns or bathtubs with curve walls illustrated in Figure 22.

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However, the pioneer of concrete 3D printing technology is Prof. Khoshnevis from the University of Southern California, who developed a process called *Contour Crafting* as early as 2009.\(^{111}\)

The project’s marketing material claims that they will be able to 3D print high-rise buildings and even houses on the moon within the next 10 years.\(^{112, 113}\) However, their short term vision is to 3D print inexpensive, standard houses with low environmental impact on site (see Figure 23).\(^{114}\)

Independent of scale, the system requires a modular, transportable 3D printer that must be as large as the structure produced. Once assembled on site, a digitally controlled nozzle extrudes a rather dry cement-like material in a layer-by-layer process. The layers vary in thickness depending on application, but are generally up to 10 cm thick.\(^{115}\) This project has thus far only succeeded in producing a number of prototypes, including one that is 2 m long and 60 cm tall, and was produced in approximately 10 h.\(^{116}\)

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116 ibid.
A similar approach is taken in the Free Form Construction research project developed at Loughborough University in 2010. However, unlike Contour Crafting, this technology uses a wet concrete mixture applied in layers ranging from 6–24 mm. Here the goal is presumably to achieve higher resolution and geometrical control; its downside is that it is almost 50% slower than Contour Crafting. As a proof of concept, a curved bench (2 m long, 0.9 m wide, and 0.8 m tall) consisting of 128 layers of concrete was printed with a velocity of approximately 20 min/layer. This resulted in a production time of 41 h (see Figure 24).

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118 In accordance to the data received in the paper of: B. Khoshnevis, et al., “Mega Scale Fabrication by Contour Crafting”, 301-320, this project was able to produce 60 cm in 10 h, (layer = 10 cm). This theoretically equals 1.5 layers (15 cm) in 1 h. In contrast, Free Form Construction can produce 7.2 cm in 1 hr when the layers are 2.4 cm; see: S. Lim, R.A Buswell, T.T Le, S.A. Austin, A.G.F. Gibb, and A. Thorpe, "Development in construction-scale additive manufacturing processes”. In Automation in Construction, 21, 1 (2012): 262-268. This means that Free Form Construction is up to 50% slower. One can thus conclude that the geometric resolution has a direct impact on the production speed. Note that this might not be the most recent development of the respective research institutions: due to rapid development in the field of concrete printing, material is selectively published.

119 S. Lim et al "Development in construction-scale additive manufacturing processes", 262-268.
The projects discussed herein demonstrate that research on 3D printing of concrete has already affected the industrial production of standard housing projects, as exemplified in the Winsun project. However, 3D printing of concrete faces one major technical challenge relating to the hydration time of the material and the speed of the deposition process. While a layer of material needs to harden enough in order to be able to sustain the weight of the next layer without deforming, the stiffer the lower layer has become the weaker the bonding to the next layer will be. This bonding problem is a well known issue referred to as the "cold-joint". Consequently, an optimal production velocity mediating between these diverging parameters must be found. Finally, the layer height of the printed structures has a direct impact on the surface resolution, and thus on the geometrical freedom (which until now has been limited to double curved surfaces with limited inclinations).

Despite these major challenges, concrete structures have already been successfully 3D printed by industry at an architectural scale, showing the undeniable progress of this potentially influential construction technique. However, 3D printing cannot cover the entire spectrum of bespoke concrete construction. Thus, new solutions for producing complex concrete constructions are needed.

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121 Note that while scaled up 3D printing is often compared with the research conducted in this thesis, it is in fact a radically different layer-based technique based on concrete extrusion. Extrusion as a technology is further defined in: Walter, Extrusion Dies for Plastic and Rubber, 2008.
3. Materials, methods and preliminary trials

This thesis aims to investigate whether slipforming can be combined with robotic fabrication to produce an efficient technique for the construction of bespoke vertical concrete structures. Consequently, this section describes the various material components and methods that were required to realize this.

The critical components of this research was concrete, and certainly its development goes hand in hand with the development of the formwork systems described in Section 2. Also relevant to the discussion is the development of self-compacting concrete, which make it possible to cast concrete into a formwork of almost any desired shape, without the use of vibration.122 Furthermore, progress in modelling the flow of self-compacting concrete has offered new possibilities for planning the best possible casting strategies for this material.123 This development is often ignored in architectural design processes because, in architecture, the interest in concrete often targets the final aesthetic124 and the final strength properties of the structure.125

This thesis applies a high performance self-compacting mortar, which, for the sake of simplicity, will hereafter be referred to as either SCC or concrete. SCC has an initial low yield stress, which is good for casting. The basic mix also has a high final strength quotient, which makes it suitable for structural elements. Finally, this material has (in earlier studies) proven to have good formability in the early hydration phase. In contrast to standard casting techniques, this thesis focuses on the early hydration phase126 of concrete, when it has the greatest potential to be shaped with a robotic slipforming process, and thus used for bespoke concrete structures that might one day be used in exposed concrete structures.

122 Self-compacting concrete was first developed in Japan in 1988. Since then various investigations on this material have been carried out. For more information see: H. Okamura, M. Ouchi, "Self-Compacting Concrete". In journal of Advanced Concrete Technology, 1 (2003): 5-15.


124 The paper discusses the fact that common architectural construction fabrication and production methods are only considered in the final state of the design. This can, at times, be an obstacle in reaching the intended geometry or structure: N. Williams et al., "A Case Study of a Collaborative Digital Workflow in the Design and Production of Formwork for 'Non-Standard' Concrete Structures". 223-240.

125 The German association for concrete (DBV) publishes comprehensive guidelines for exposed concrete, also referred to as "Sichtbeton" in German speaking countries. The guidelines divide exposed concrete into four main classes of texture, porosity, homogeneity of the colour tone, evenness, construction/panel joints and formwork sheet, beginning from low to very high aesthetic and technical requirements. For more information see: K. R. Goldammer, "Sichtbeton". In DBV/VÖZ-Merkblatt, Berlin, Germany, (Deutscher Beton- und Bautechnik-Verein E.V. 2015).

126 Hydration refers to the reaction that occurs after water has been added to cement or concrete mix until it has reached the properties of a rock-like material, referred to as concrete. More detailed information can be found in: N.W. Winter, Understanding Cement (Great Britain: WDH Microanalysis Consultants Ltd. 2008): 63-82.
The following Section gives an overview of the material components used in this thesis, followed by a short description of the hydration of cement. It also includes a description of the mixing method used in this research, with an emphasis on the fact that coherency of mixing is crucial for the success of the experiments described in Section 4. Part of this section briefly describes the hydration of cement, as this gives a good indication of the time-based challenges when shaping concrete in an early hydration phase. This is followed by an overview of the testing methods. Finally, it describes the experiments that were needed to prove whether concrete can be shaped in the short period of time in which it transforms from a soft to a hard material – also referred to as the early hydration phase.
3.1. Material components

The material used throughout this thesis had to fulfil three main requirements. First, it had to be fluid enough to be self-consolidating, to allow for fast and efficient placement in the formwork without the need of vibration. Second, it had to maintain good workability\textsuperscript{127} throughout the entire processing. Third, the material had to reach a self-supporting capacity relatively quickly after placement, while still being formable. A self-compacting fibre reinforced mortar (referred to as SCC or concrete) was chosen for its ability to meet these criteria.\textsuperscript{128} Throughout the thesis, various adjustments (in particular, to the hydration time) were made to suit the changing processing methods considered and presented in Section 4. The mix designs are listed in APPENDIX 1.

This section describes the materials used in this research. The first part describes the binders, which are the core of the concrete mixture. The next part describes the aggregates (stone in the form of gravel and sand) that principally function to reduce the amount of cement required and thus to lower the cost, but also to reduce cracking from shrinkage and thermal gradients. The following part describes the chemical admixtures, which were essential for controlling the rheological properties and the hydration rate. The final part describes the materials, used to reinforce the material in tension.

3.1.1. Binders

Cement

The cement used is a CEM I 52.5R Portland cement, Normo 5R from Holcim AG. It contains 95-100% clinker. This type of cement is characterized by a fast hydration, early strength development, and high final compressive strength.\textsuperscript{129}

\textsuperscript{127} Workability properties of concrete or mortars is highly dependent on the application. More can be read regarding this issue in: D. Bapat, Mineral Admixtures in Cement and Concrete. (New York: Tailor & Francis Group, 2013), 124.

\textsuperscript{128} The material composition used and adjusted throughout this thesis was initially based on the material composition developed by P. Stähli. See P. Stähli, "Ultra-Fluid, Oriented Hybrid-Fibre-Concrete". (PhD Diss., ETH, Institute for Building Materials (IBB), ETH Zurich, Switzerland, 2008): 23-40. Or in: J. Pauli, "Biegen von Betonstreifen in halbharten Zustand". (Bachelor Thesis, Zurich, Switzerland: Institute for Building Materials (IBB), ETH Zurich, Switzerland, 2007): 14.

\textsuperscript{129} Holcim, "Betonpaxis: Der Weg zum Dauerhaften Beton" (Manual, Switzerland: Holcim, Germany AG, 2008)
Fly ash

A Class F pozzolanic coal fly ash, named Hydrolent from Holcim AG, is used throughout the experiments in this thesis. Fly ash is residue from coal combustion that is most often a by-product from thermal power plants. The particle size is comparable with that of cement and has a smooth spherical surface, which is beneficial to flow properties. This fly ash allows mixtures to be prepared with low water content while keeping a good workability. Fly ash can be used to replace cement, which reduces the heat release and can (at a later phase of hydration) reduce thermally induced cracking.

Silica fume

The silica fume used in these experiments is a micro silica named Elkem Microsilica 971-U (18.9m²/g) from BASF. Silica fume (or micro silica) is a by-product of silicon alloy production. It has a smaller particle size than that of cement and fly ash, and can therefore pack the interstices between the cement particles, enhancing the final strength of the mixture. Additionally, the filler effect of silica fume contributes to the bonding between the fibres and the cement paste.

3.1.2. Aggregates

Sand

Due to the scale of fabrication equipment, and in particular the pump, the experiments in this thesis used a standard river sand with a diameter up to 4 mm. Note that, the due to the size of the sand particles, the material used throughout this thesis is categorised as mortar.

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2.38.
135 L. Reiter, "Mechanical Aspects of Smart Dynamic Casting".
136 Mortar can be considered a fresh concrete without large aggregates. Several divisions of mortar exist depending of the size fraction of the aggregates included in the mix. For more information, see: P.F.G. Banfill, "Rheology of Fresh Cement and Concrete". In Rheology Reviews (2006): 61-130.
137 This does not exclude the use of larger grain sizes for the future. In fact, when bringing SDC to an industrial application, it will be necessary to increase the grain size and the amount of aggregate while reducing the amount of cement.
3.1.3. Chemical admixture

Superplasticiser

During this thesis a Glenium ACE 30 from BASF\textsuperscript{138} was used. This superplasticiser allows one to reduce the use of water while maintaining good workability. For the hydration of Portland cement, the minimum water to binder (w/b) ratio is approximately 0.25. Standard concrete has a w/b from 0.4 to 0.6, which is required to allow the material to flow, but water not involved in cement hydration results in capillary porosity. Less water (towards w/b of 0.25) results in a concrete or cement with a higher strength, longer durability, and lower shrinkage,\textsuperscript{139} but with the disadvantage of a higher yield stress, which in concrete processing is referred to as lower workability. Adding small amounts of superplasticiser allows the w/b to be decreased while maintaining good workability.

Retarder

In this project, sucrose (with a purity of >99\%) from Sigma-Aldrich is used as a solution for delaying the early setting of the material. This delay is referred to as retardation. The retarder is prepared as a solution with 30\% solid content and 70\% purified water. The solution is used to ensure a homogeneous distribution of the retarder.\textsuperscript{140}

Accelerator

The accelerator used in the material mix is X-SEED 100, from BASF. For this project, it is used to overcome the retardation effects from other admixtures, in this case the sucrose solution. X-Seed consists of a suspension of synthetic crystal nuclei that favour the growth of calcium silicate hydrate (C-S-H) particles. Accelerators are commonly used to speed up the setting time, for example to speed up construction in colder climates.\textsuperscript{141} The effect of accelerator on hardened concrete is not considered in this thesis.

\textsuperscript{138} BASF, "Glenium ACE 30" Data Sheet, BASF (Zurich, Switzerland, 2013).
\textsuperscript{140} Ibid, 3.2. Note that the solution and material composition using retarder was initially developed during the Bachelor thesis "Formwork Free Concrete" see: A. Alberti et al, "Formwork Free Concrete".
3.1.4. Reinforcement

**Fibres**

Two different lengths of poly vinyl alcohol fibres (PVA) were added to the mix: 6 mm (KURALON RF 400) and 12 mm (KURALON RF 350). The main purpose of the fibres is to improve tensile strength and the ductility when shaping the concrete, as the fibres increase cohesion in the material.\(^{142}\)

*Steel reinforcement*

It is well known that, when no reinforcement is used, concrete is weak in tension and strong in compression. A general rule is that concrete is generally ten times stronger in compression than in tension.\(^{143}\) Therefore, concrete is generally reinforced with materials of high tensile strength, which is why steel bars are commonly used.

The resulting demonstrators in Section 4. are reinforced up to 1 m. This is because inserting reinforcement during production over the full height of a demonstrator would have required positioning the formwork cross section in a way that would either reduce the kinematic movement of the robot in the rotational direction, or significantly reduce the possible height of the demonstrators. Yet even though the rebar only reaches a height of 1m, this height is sufficient for demonstrating that it is possible to slipform and shape around steel rebar. Figure 25 illustrates how the rebar is positioned. To mount the rebar, a column is slipformed onto a concrete base with an inner dimension of 73x73x10 cm (volume 62 l). Before casting concrete into the base, six steel pieces of rebar with a diameter of 0.6 cm and a height of 1.20 cm were prepared. The pieces of rebar were each bent 90°, and then equally distributed around a wooden template in order to form a cage that reflected the shape of the formwork. In Figure 25, the template is an ellipse with the dimension 5x3 cm. The dimensions ensure a minimum distance of 5 cm\(^{144}\) from the rebar cage to the outer surface of the structure. The ‘cage’ is mounted in the centre of the formwork base, and then concrete is cast into the base.\(^{145}\) After the concrete has cured, the

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\(^{142}\) A study on the influence of the PVA fibres was conducted by: L. Reiter, "Mechanical Aspects of Smart Dynamic Casting". In addition, a comprehensive study conducted on the mechanical properties of columns produces similar to the ones in this thesis. The results of the studies proved that a reinforced twisted column had high strength properties. The studies are reported in: M. Schultheiss, "Reinforcing SDC", (Master Thesis, ETH, Institute for Building Materials (IB), ETH Zurich, Switzerland, 2015).


\(^{144}\) The distance from the rebar to the surface of the concrete can theoretically be less, depending on the building norm. A larger distance was used to avoid material collapse. Further it must be noted that this rebar system only functions as a joint between the column and the base, and can therefore not be compared with a conventional rebar.

\(^{145}\) The material mix design for the base is listed in APPENDIX 1, Table 11.
wooden formwork is removed and the base is brought to the robotic fabrication laboratory. Prior to production, the robot is jogged into its start position, which is done by cantilevering the formwork around the rebar and lowering the bottom of the formwork onto the concrete base.

Figure 25: Illustration of the rebars inside the base. 1) is the base with concrete. 2) By bending each piece of rebar 90°, they can easily be mounted to the wooden base. 3) Each piece of rebar is 0.6 cm thick, reaching a height of 1 m after being bent. 4) A template dimensioning 3x5 cm is used to position the rebar in equal distances around a template 1.5 times smaller than the actual formwork.

Note that a parallel study was conducted in which the rebar was inserted over the full height of the column. The study was done by conventionally casting SDC-like columns. The results of this study indicated that columns similar to the ones produced in section 4.2. and 4.3. had a superior mechanical behaviour in terms of buckling load, bending moment, and toughness when reinforced with rebar over the full height.146

3.2. Material composition

During this thesis, four different concrete mix designs were developed, referred to as Mix A, B, C, D (see APPENDIX 1 for details). The compositions were developed as an evolutionary part of this thesis to suit the increasing scale and speed of the slipforming. Mix A was used for the preliminary studies described in Section 3.7. Mix B was used only for the systematic testing of the rheological properties of the material, and formed the basis for Mix C, the first retarded mix. Mix C was composed to maintain a good workability of the material for up to 3 h by adding small amounts of retarder. The retardation was overcome at specific time intervals by adding small doses of X-Seed to smaller batches of material. The large retarded batch is referred to as ‘B’ 1, 2, 3 etc. The extracted portions of material are referred to as B1.1, B1.2 etc. However, with the integration of an automated feeding system described in Section 4.3, the short workability time of the material became an obstacle. Therefore, a fourth mix was developed, which had a workability time of 7 h. This material had the added value that it hydrated faster after being placed in the formwork, a phenomenon that increased the slipforming rate up to 50%. Table 1 gives an overview of the amounts of all the components used for the preparations of a mixture. The values refer to one litre of concrete.

<table>
<thead>
<tr>
<th>Component</th>
<th>Name</th>
<th>Amount [g]</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand (&lt; 4 mm)</td>
<td>No name</td>
<td>740.34</td>
<td>37.4 % of dry</td>
</tr>
<tr>
<td>Cement</td>
<td>Holcim Normo 5</td>
<td>981.73</td>
<td>49.6 % of dry</td>
</tr>
<tr>
<td>Fly ash</td>
<td>Hydrolent Holcim</td>
<td>164.67</td>
<td>4.7 % of dry</td>
</tr>
<tr>
<td>Silica fume</td>
<td>Micro Silica Elkem 940 BASF</td>
<td>92.89</td>
<td>8.3 % of dry materials</td>
</tr>
<tr>
<td>Water</td>
<td>No name</td>
<td>371.79</td>
<td>0.3 w/b</td>
</tr>
<tr>
<td>Superplasticiser</td>
<td>Glenium ACE 30</td>
<td>7.84</td>
<td>1.5 % of active bwc</td>
</tr>
<tr>
<td>Retarder</td>
<td>Sigma – Aldrie;</td>
<td>0.98</td>
<td></td>
</tr>
<tr>
<td>PVA Fibres 6 mm</td>
<td>Kuraray RF 400</td>
<td>13.00</td>
<td>1 % Volume of cement</td>
</tr>
<tr>
<td>PVA Fibres 12 mm</td>
<td>Kuraray RF 350</td>
<td>13.00</td>
<td>1% Volume of cement</td>
</tr>
<tr>
<td>Accelerator</td>
<td>BASF X-Seed 100</td>
<td>24.54</td>
<td></td>
</tr>
</tbody>
</table>

Table 1: Mix C, with a retardation of 3 h.

147 A. Alberti et al, "Formwork Free Concrete".
148 Material Mix D, was developed on the side with support from Sara Mantelatto and Tim Wangler, and refined as an integrated part of: S. R. Garcia, D. Mijailovic and N. Vassic, "Smart Dynamic Casting, Optimierung des Misch- und Betoniervorgangs bei der Herstellung von frei geformten 3D-Betonelementen", Bachelor Thesis, Institute for Building Materials (IB), ETH Zurich, Zurich Switzerland (2013).
3.3. Material mixing procedure

To avoid variations in the material properties, a strictly defined mixing procedure must be followed. This includes taking particular care of the order in which the dry and liquid components are added to the mixing pot. The order in which the ingredients are listed in Table 1 represents the order in which they should be added to the mixing pot. In particular, this means that sand, cement, fly ash, and silica fume are added first in the written order, after which the material is dry mixed. After dry mixing, the water, superplasticizer and retarder are first mixed in a separate jug before they are added to the dry mix. The first chemical reactions occur when the water and chemicals are added to the dry mix, and so the timer is started at this point in the process. The material is mixed until lumps of aggregate can no longer be detected, and then the fibres are loosely added and mixed in until no fibre lumps can be detected.

After mixing the large retarded batch, it is sub-divided into smaller batches. The batches are divided by weight, where the weight of the batch is defined by the processes described in Section 4. The batches are each accelerated with BASF X-Seed, after which they are placed in the robotic slipformwork or pump. During the course of the thesis a number of mixing procedures were developed and a number of mixing devices were used in parallel to the evolution of the material and the processing methods described throughout Section 4. The mixing protocol in Table 2 represents the standard mixing procedure for a large retarded batch mixed with the Collomatic 65/2 K-3 force action mixer. Table 3 lists the last acceleration procedure developed for this thesis.
### Table 2: Standard mixing procedure for Mix C or D, with Collomatic 65/2 K-3.

<table>
<thead>
<tr>
<th>Time: Start - end [min]</th>
<th>Action</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Dry Material is mixed for 5 min at speed: 40% to achieve a good homogeneity</td>
</tr>
<tr>
<td>0 – 5</td>
<td>Addition of water (and if used, superplasticizer and retarder); Speed: 40%</td>
</tr>
<tr>
<td>5 – 6</td>
<td>Mix speed: 80%</td>
</tr>
<tr>
<td>6 – 8</td>
<td>Stop mixing, clean edges</td>
</tr>
<tr>
<td>8 – 9</td>
<td>Mix speed: 40%</td>
</tr>
<tr>
<td>9 – 11</td>
<td>Stop mixing, clean edges, add fibres</td>
</tr>
<tr>
<td>11 – 12</td>
<td>Mix speed: 40%</td>
</tr>
<tr>
<td>12 – 14</td>
<td>Stop mixing, clean edges, add fibres</td>
</tr>
<tr>
<td>14 – 16</td>
<td>Mix speed: 80%</td>
</tr>
<tr>
<td>16</td>
<td>Divide batch in defined portions</td>
</tr>
</tbody>
</table>

### Table 3: Standard acceleration process with Hobart A200-N.

<table>
<thead>
<tr>
<th>Time: Start - end [min]</th>
<th>Action</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-3</td>
<td>Add accelerator to batch and start mix, speed 1</td>
</tr>
<tr>
<td>3-4</td>
<td>Stop, clean edges</td>
</tr>
<tr>
<td>4-5</td>
<td>Mix, speed 2</td>
</tr>
<tr>
<td>5</td>
<td>Stop, bring batch # to robot</td>
</tr>
</tbody>
</table>
3.4. Material properties

3.4.1. Yield stress

In the case of concrete, yield stress is a parameter defining the stress at which a material starts to or maintains flow. When yield stress is measured over time, it provides information about the material’s setting properties, where setting refers to the gradual transformation of concrete from a fluid (soft) to a solid (hard) state.

Two types of yield stress are commonly defined: static and dynamic. These can be determined using mechanical tests that evaluate the shear rate of the material. With static yield stress, the shear stress increases approximately linearly with the shear rate. Figure 26 (left) illustrates how the static yield stress can be used to determine the minimum stress level required to initiate flow, as it corresponds to the minimum level of structural breakdown in the fluid. With dynamic yield stress, the shear stress slows to a relatively low constant as the shear rate increases. Figure 26 (right) illustrates how the dynamic yield stress can be used to define the material behaviour at a moderate level of structural breakdown, but not at the onset of flow.

Thus, static or dynamic, the yield stress is affected by reversible and irreversible phenomena. The reversible part is due to flocculation and is termed thixotropy.\textsuperscript{149} The irreversible part is crucial for SDC production and comes from the ongoing hydration, which produces more hydrates and possible contact points between particles. Thus the latter ultimately provides the strength necessary to construct taller elements.

\textsuperscript{149} Thixotropy is a phenomenon exhibited when certain materials become fluid when stirred or shaken and return to the semisolid state upon standing. For more information, see: J. Mewis, N. J. Wagner, Colloidal Suspension Rheology (Cambridge: Cambridge University Press, 2011): 228-251.
In SDC, the shaping takes place early in the setting phase, when the concrete yield stress can be quantitatively measured. Various test methods exist for this.\textsuperscript{150} This thesis employs three such methods – slump flow, compression load test, and penetration test – which are described in Section 3.5.

### 3.4.2. Hydration of Portland cement

The SCC used in this thesis contains Portland cement, of which the hydration plays a crucial role in the critical operation window of SDC.\textsuperscript{151} In the following section, the intention is not to give an in-depth explanation of this, but rather to emphasise the hydration period during which the concrete can be shaped by a robotic slipforming process. It is well known that when water is added to Portland cement it turns into a paste.\textsuperscript{152} This cement paste is used to bind various aggregates together. When water is added to the material, an exothermic reaction occurs,\textsuperscript{153} marking the beginning of a heat release process. The rate of heat release then evolves as shown schematically in Figure 27. As this occurs, hydration progresses and the strength develops. In a common construction process the formwork is removed after at least one day (or more), when the concrete is considered to be strong enough and well-cured.

Figure 27 divides the heat release into five phases.\textsuperscript{154} The first phase is the "pre-induction phase", which occurs after water has been added to the Portland cement. A rapid heat evolution occurs due to dissolution and the reaction of the clinker (tricalcium aluminate (C\textsubscript{3}A). This period stops after 15-20 min. The second phase is the "induction (dormant) phase", where a constant low heat release can be measured and no significant reaction occurs. At this stage, the material is still workable. The third phase is the period of "acceleration"; in this phase alite (C\textsubscript{3}S) starts to react and calcium silicate hydrate (C-S-H) and portlandit (CH) deposit into any available water-filled spaces. Two phenomena occur in the early phase of the acceleration period. The first is the

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\textsuperscript{151} Portland cement is generally composed of four different clinker minerals. The first is tricalcium silicate (alite) (C\textsubscript{3}S), which is the main strength-giving clinker of most Portland cements, hence hydraulic. Second is belite (C\textsubscript{2}S), which is less reactive and hydraulic than alite. Third is aluminate (C\textsubscript{3}A), which has a strong influence on the early setting of the cement as it produces a lot of heat. Fourth is ferrite, (C\textsubscript{4}A), which is mainly responsible for the initial reaction when water is added. This clinker is moderately reactive, and weakly hydraulic. For more information, see: Dr. X. Li. Advanced Concrete Technology (Hoboken New Jersey: John Wiley & Sons 2011): 38-42.

\textsuperscript{152} Ibid.

\textsuperscript{153} In thermodynamics, the term \textit{exothermic process} describes a process that releases energy from a system. P. Perrot, A to Z of Thermodynamics (Oxford: Oxford University Press, 1998).

thixotropic build-up due to colloidal forces, which is easily broken down by stirring or vibrating the material. The second phenomenon is due to the C-S-H bridge formation, in which the material gains ultimate cohesion, while turning into a clay-like substance that can be shaped. This short period lasts for approximately 10 min, and is the crucial period in which concrete has the potential to be shaped. Note that after this time, which occurs well before the end of the acceleration period, the material can no longer be shaped. The fourth phase is the period of "deceleration", in which the hydration and liquid-solid interphase decreases (and there are fewer un-hydrated cement particles). During this period, a decrease in heat release can be measured, and the material can definitely no longer be shaped – this phase is therefore not considered further in this thesis. The fifth phase is the "diffusion controlled process". Here the heat gradually tails off as there are fewer and fewer un-hydrated cement particles remaining. The formwork is commonly removed during this period in traditional concrete construction processes.

Figure 27: Typical plot showing the heat evolution of hydrating Portland cement. The y-axis shows the rate of the heat evolution, measured in watts per kg of cement. The x-axis shows the stages 1-5, which are described in the text. The red dotted lines indicate the approximate time during which the concrete can be shaped.

This thesis does not intend to provide a deep understanding of the specific heat evolution properties of concrete, but rather to emphasise the short period of time (10 min) in which the material can be shaped. That said, it is critical to understand the material’s strength properties (static yield stress) in this short time period, as this is crucial for developing concepts of how to

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155 Thixotropy is a time-dependent shear thinning property. Certain viscous materials such as yogurt, ketchup or (in this case) concrete, will flow or become less viscous when shaken, agitated, or otherwise stressed; when resting, these fluids will build up a gel-like structure returning to a more viscous state. In concrete, thixotropy is a time-dependent property. For further information, see: L.J. Struble, W.G. Lei, "Rheological changes associated with setting of cement paste". In Advanced Cement Based Materials, 2, 6, (1995): 224-230. And also: K. H. Khayat, A. F. Omran, T.V. Pavate, "Inclined Plane Test to Evaluate Structural Buildup at Rest of Self-Consolidating Concrete". In Materials Journal, 107, 5, (2010): 515-522. As well as in; N. Roussel, Understanding the rheology of concrete (Oxford, Woodhead Publishing, 2012).

156 Colloidal refers to the particles sticking together, and is well defined in: J.-J. Butt, M. Kappl. Surface and Interfacial Forces (United Kingdom: Wiley Verlag, 2010): 1-3. Thixotropic build-up can occur even in the induction period, but it is easily broken down in this early phase.
process the material and to exploit the forming capabilities. It is also crucial to understand that after shaping, the layers enter the acceleration period and develop substantial strength. This is also essential to SDC as it makes it possible to produce tall structures in a short period of time.
3.5. Testing and validation methods

To analyse the properties of the mixtures both during the development of the mixtures and during the production process (described in Section 3.7. and throughout 4., respectively), various test methods were used. These are described in the following section.

3.5.1. Mini slump flow test

To analyse the dynamic yield stress of the material, a mini slump flow test is used. The test provides information about the flow properties (rheology) of the liquid material, and hence it provides information about the workability. The dynamic yield stress can be calculated using the results of the slump flow test, by using the following formula (reported in literature\textsuperscript{157}), in which the density, \( \rho \), the acceleration due to gravity, \( g \), is the volume of the cone, and \( R \) is the radius of the spread flow after the cone is pulled up.

\[
\tau_0 = \frac{225 \rho g V^2}{128 \pi^2 R^5}
\]

In other words, to calculate the dynamic yield stress of the material it is only necessary to measure the radius of the spread flow and insert it into the formula. The slump flow test is performed after the accelerator is added to a batch. A Haegermann Minicone (see Figure 28), is used.

To perform the test, a clean glass plate (300 x 300 mm) is moistened with a sponge, after which the cone is place on the plate and filled with accelerated material until it reaches the top edge of the cone. The cone is lifted after resting for 10-15 sec, and once the flow has stopped, the flow diameter is measured. The optimal diameter can range from 18-22 cm, corresponding to a yield

\textsuperscript{157} N. Roussel, P. Coussot, "Fifty-cent rheometer"-for yield stress measurement: From slump to spreading flow". In Journal of rheology, 49, 6 (2005).

\textsuperscript{158} A. Alberti et al, "Formwork Free Concrete", 53.
stress of between 50 Pa and 21.5 respectively. In the rare case that the slump flow is too low, the workability of the material is adjusted by adding small amounts of superplasticiser to the accelerated batch. Thus, the slump flows of the individual batches were an important proof in ensuring that the material had been mixed correctly.

3.5.2. Calorimetry test

An isothermal conduction calorimeter (type: I-Cal 800 by Calmetrix Inc.) was used for the development of the various mixtures used in the experiments described in Section 3.7. and throughout Section 4. The calorimeter is a device that measures heat released from cement hydration, and is used determine the onset of the acceleration period, which is the critical phase for SDC (here also referred to as setting for convenience). This allowed an efficient optimization of the material composition, in particular to balance the retarder and accelerator dosages. During experiments, the calorimeter was set to 20° C. The fresh material samples, weighing around 100 g, were placed for a minimum of 24 h in the calorimeter.

3.5.3. Uni-axial compression test

A compression test is commonly used to evaluate the compressive strength of a hardened specimen of concrete. In this case, however, it is used to test a still-formable SCC specimen. The uni-axial compression tests are performed on a Zwick Machine (see Figure 29), after the Swiss codes SIA 162/1. The cylindrical specimens have a height of 200-300 mm and a diameter of 200 mm. The compressive yield stress is calculated by dividing the maximum force by the area of the cross section, in which $f_c$ is the compressive strength.

\[ f_c = \frac{F}{A} \]

The tests were used to evaluate when a column section could self-sustain and how much weight could be loaded onto a column section once the formwork had been removed. The tests used one batch of material (the mixtures used for these tests were Mix A and Mix C). After the material had been mixed it was placed in a cylindrical PVC formwork with a diameter of 200 mm and a

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160 The test performed based on the Swisscodes SIA 162/1, with a cubical edge length also reported in: A. Alberi et al, "Formwork Free Concrete". Or in E. Lloret, L.K. Mettler, A.R. Shahab, F. Gramazio, M. Kohler, R.J. Flatt, Smart Dynamic Casting: A robotic fabrication system for complex structures, 1st Concrete Innovation Conference, Oslo (2014).
variable height of 200-300 mm. The inner side of the formwork was coated with 0.5 mm Polypropylene film (PP). The PP was oiled prior to casting the material in order to ensure that the formwork would slide off without friction force. Once the material could self-sustain, the formwork was removed, the sample was placed in the centre of the Zwick, and a load with a velocity of 1 mm/sec was applied to the sample until the maximum force was reached. The measurement stopped when the maximum force was obtained. This was registered by observing either a decrease in the measured force or by the appearance of visible cracks on the sample.

Figure 29: A) Zwick Universal testing Machine; Type B) compression plate (diameter 20 cm); C) Column Section; D) Base plate.

### 3.5.4. Penetrometer (force sensor)

The penetrometer is principally a scaled down version of the uni-axial compression tests, except that the loading geometry (or just penetrometer needle, see Figure 30) pushes into a material sample much larger that itself. The scaling down was possible due to additional systematic experiments that correlate the measuring techniques.\(^{161}\)

A penetrometer test is designed to measure the force exerted onto an intruding needle tip that penetrates the material with a given force. The measurements give results regarding the strength properties during the transition from liquid to solid state. In this thesis they were used to quantify the mechanical properties in relation to the fabrication process. This meant that the penetrometer

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161 Systematic studies of the transfer from uni-axial compression test to measurement conducted with the penetrometer test can be found in: A. Alberti et al, “Formwork Free Concrete”, 53.
was used to determine when to add accelerator, when to place a respective batch, and when to start the slipping. A Mecmesin AFG 1000 N penetrometer\textsuperscript{162} with a measuring range from 0-1000 N and a resolution of 0.2 N was used throughout this thesis. The needle tip mounted to the tip of the penetrometer was a cylindrical needle head with a diameter of 19.4 mm and a height 4.1 mm (Figure 31).

![Figure 30: needle tip for the penetrometer.](image)

The tests conducted in this thesis were performed by submerging the needle tip into a still-mouldable material sample with a slow velocity, until the maximum force was reached.\textsuperscript{163}

![Figure 31: Penetrometer, used for the inline measuring system.](image)

The penetrometer tests conducted in the initial part of this thesis were handheld. However, due to large deviations in the measurements, two automated measurement techniques were developed.

The first used a table sized robotic arm, a Universal Robots UR5 industrial manipulator (see Figure 32).\textsuperscript{164} The second used a tri-axial table. In the first setup the robot was controlled via a custom Rhinoceros Python script, which allows commands to be manually executed in predefined time intervals. After execution, the robot submerges the needle head into the material with a predefined velocity of 2 mm/sec. This setup was used in the experiments described in Section 4.2., where it is referred to as a material monitoring system.

\textsuperscript{162} For more information on Mecmesin devise see: Mecmesin, "Shot-crete Penetrometer". Accessed on 01.03.2016, http://www.mecmesin.de/spritzbeton-penetrometer.

\textsuperscript{163} The test is conducted in accordance the standard test method reported in: Standard Test Method for Time of Setting of Concrete Mixtures by Penetration Resistance, ASTM C403/C403M-08 (2008).

A predefined pattern was prepared, in which the measurement points were positioned at an equal distance (20 mm) from each other, to ensure that the structural build-up in the surrounding material was disturbed as little as possible. The pattern was based on two major factors. First, the two measuring points must not be taken too close to each other; for instance, point 1 and point 2 are not placed next to each other. Second, it indicates that two measuring points must have a minimum distance of 20 mm. Following the pattern, these should ensure that the structural build-up of the material is disturbed as little as possible, and hence, the measurement should deviate as little as possible.

A second setup was prepared, using a three-axis table onto which the penetrometer was attached. This setup was developed into a feedback measuring system, which will be further described in Section 4.3.

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165 Systematic experiments were done on the side, in which the pattern was defined. Here it was detected that the robotic arm was shaking slightly when penetrating the material. This was initially not a problem, however, the second system used a tri-axial table, which ensure that the measurement deviated less, as the geometry of the table ensured that the penetrometer did not vibrate when penetrating.
3.5.4.1. Evaluating results

The penetrometer is principally a scaled down version of the uni-axial compression test. A set of systematic experiments correlates the relationship between the two measuring techniques.

The systematic experiments, conducted during the bachelor thesis Formwork Free Concrete\textsuperscript{166}, concluded that the penetrometer test can only be performed after the material has rested for a while. This time is needed for the material to build up a certain strength, from which the yield stress ($\tau$) of the material can be approximated. The calculation is done analogue to the uni-axial compression test by dividing the measured force $F$ by the surface area $A$ of the needle tip.\textsuperscript{167}

\[ \tau = \frac{F}{A} \]

\textsuperscript{166} Systematic studies of the transfer from uni-axial compression test to measurement conducted with the penetrometer test can be found in: A. Alberti et al, "Formwork Free Concrete", 53.

\textsuperscript{167} Here it is important to emphasize that this calculation might not be correct, but it did enable the strength properties to be successfully correlated throughout this thesis. In the article of: Mettler, L.K., F. K. Wittel, R. J. Flatt, H. J. Hermann, "Evolution of Strength of Failure of SCC during Early Hydration". \textit{In Press}, 2016. A method is described that should comprehensively enable the correlation of the material’s strength properties with the uni-axial test.
3.6. Robotic setup

Robots have been explored in construction for the past several decades (see Section 2.3.1.). However, robots and slipforming have never been combined prior to this research. Slipforming is a construction process that is indeed already automated. Yet though it is being used to construct rather complex structures (such as the underwater Sakhalin II project\(^{168}\)), requiring a team of trained and skilled workers who must rely on empirical evaluation and labour to manually adapt the formwork. Secondly, due to the high cost of setting up a slipform, this construction method has never been considered feasible for the production of structural building elements below 10 m.

The experiments conducted in this thesis do not aim to compete with the slipforming industry for tall building structures, but rather, they intend to explore the potential of a robotic slipforming process for shaping concrete at the building component scale. This could open up a new avenue for slipforming in which the process is not only fully automated, but which (by exploiting the robots’ ability to respond to real time data input\(^{169}\) and move freely in space) can be used to efficiently prefabricate non-standard concrete structures without the need of a custom formwork.

A multi-purpose robotic work cell was used for the 1:1 experiments conducted throughout this thesis. The cell contains a six-axis industrial robot – a KUKA KR 150-110 – installed on an 8-m long linear axis. The robot has a maximum reach of 3 m and a payload of 150 kg.\(^{170}\) The robot has a work area of 6 m x 8 m and 3 m in height. The robot can be equipped with various end-effectors to conduct numerous fabrication processes. A standard end-effector with a gripping function was used in this research for mounting the slipformwork.\(^{171}\) In this particular project, the maximum slipping height is 1.9 m, due to the height of the formworks applied (see Section 3.6.1.).

This generic robotic setup was expanded for the SDC research to include custom end-effectors and inline measurement systems that allowed exploration of the robotic slipforming process. Note

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\(^{168}\) As discussed in the Section 2.4, slipforming as it is practiced today depends on manual labour and empirical evaluations; such was the case in the Sakhalin II project.

\(^{169}\) The KUKA system can be equipped with electronic and sensing devices. Serial connection can send feedback regarding the robotic position in space or material properties.


\(^{171}\) This particular robotic cell has been used to develop multiple prototypical structures for Gramazio Kohler Research at ETH Zurich. A comprehensive overview of the processes conducted can be found in: F. Gramazio, M. Kohler, J. Willmann, *The Robotic Touch: How Robots Change Architecture*, (Zurich: Park Books, 2014): 486-487.
that any change in the setup of the robotic equipment has a direct impact on the physical boundaries of the design space, and these constraints must be considered in the digital design.

### 3.6.1. Formwork

The generic robotic cell combined with the gripping end-effector allowed custom-made formwork systems to be mounted, and over the course of the project a variety of formwork geometries and systems were developed. Two customizable formwork systems were developed for this purpose: a rigid formwork system, and a flexible one (see Figure 36).

![Formwork systems](image)

*Figure 36: Left: The six-axis robotic arm with a mounted rigid formwork. Upper right: Schematic illustration of rigid formwork geometries. Lower right: Schematic illustration of the flexible formwork system and its possible morphologies.*

In the experiments described in Section 3.7. (Initial studies) and in 4.1., the formwork inlays were made of steel, however it was time consuming to produce the steel shapes. The formworks used in Section 4.2. onwards were therefore all milled out of polyurethane foam (density $0.24 \text{ g/cm}^3$)$^{172}$ – a hard foam appropriate for tooling. The rigid formworks were coated on the inner side with a $0.5 \text{ mm}$ polypropylene foil, while the flexible formwork applied various flexible membranes further discussed in Section 4.5. Both the rigid and flexible formwork systems were inserted into a generic frame made of Mecano profiles (Type F-30x30).$^{173}$ The frame was attached to the robot’s standard gripping tool. For the sake of comparison, the formwork cross sections all had the area $(314 \text{ m}^2)$. However, the height of the formworks changed over the course of the project, starting with $1000 \text{ mm}$ and decreasing to $400 \text{ mm}$.

The rigid formworks consisted of four different formwork cross sections: a circle, an ellipse, a square with varied radii in the corners, and a star shape (See Figure 36). The round formwork

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was used in the initial studies to test curvatures, described further in Section 3.7. The ellipse formwork was used to prove that concrete could be shaped, in a rotational trajectory. Using, the ellipse was likely to pose major challenges connected with shaping concrete in its early hydration phase. Thus, the ellipse is used throughout the experiments (described in Sections 4.1. to 4.3.).

Four different radii of the square formwork were tested to gain insight into the limitations of corner geometry (specifically, how small the radii in a formwork can be before a corner causes the concrete to rip or crack at the edge). This formwork was used in experiments described in Section 4.2. The last of the rigid formwork types was the star shape, which is considered an extreme geometry and therefore a first proof of concept towards a flexible formwork system.

The flexible formwork was designed so that the cross section could be changed on the fly during the slipforming process. The intention here was to investigate if a single formwork has the potential of being used to shape the material in the third dimension while the concrete is being slipped in either a straight or rotated trajectory.

### 3.6.2. Sensor system for height of material

In the experiments described in Section 4.2. onwards, the height of the material in the slipform was measured with a laser distance sensor from Baumer (PA210.009AX01). The laser was mounted to the top of the formwork frame to send on-line information regarding the height of the material in the formwork. Further information regarding the laser distance sensor is described in Section 4.2.

### 3.6.3. Robotic control (code)

The possible formal and structural spectrum of the fabricated elements in SDC is theoretically defined by the trajectory of the robotically controlled formwork. The design space of the intended vertical structures is unknown prior to production, as these are constrained by the gravitational force and the shapeability of the material in relation its hydration rate.

Therefore, to develop a suitable robotic control system, it was first necessary to conduct a series of experiments to analyse the hydration rate in relation the robotic slipforming process. These enabled the development of rules for a robotic control system (in form of a script) in which a particular target was set on precise real time velocity control of the slipforming.
The control script was developed in two steps. The first script used pre-determined velocities that were assigned over the height of the column, a conditional flexible control, that allowed the velocities to be over-ruled via the hand held robotic controller. This setup is further described in Section 4.1. The second control system, discarded the idea of velocities assigned to a specific height. Instead, a custom control system that featured a Graphical User Interphase (GUI) on one hand enabled to receive real time information regarding the production process and the material properties and above all to control the velocity in precise steps in real time via serial connection. Thus, this system, enabled to collect data regarding the production process and quantify the results of the experiments.

The latter system could be controlled based on manual velocity adjustment or theoretically, it could be calculated to run in a fully automated mode. The manual mode was crucial though, as little knowledge regarding the material properties in regards to the slipping and shaping velocity was known prior to the experiments. Therefore, the program was designed so that the velocity can be changed gradually, based on empirical evaluations done during production. The fully automated mode functioned by sending data regarding material properties, which were measured with the digital penetrometer via Transmission Control Protocol/Internet Protocol (TCP/IP) to the robotic control GUI (which used the data to automatically adjust the slip velocity). Again, the rules were defined based on empirical knowledge gathered throughout the experiments.

To transfer a design to the robotic system or define a trajectory, a Rhinoceros Grasshopper tool\(^{174}\) was prepared. This tool was based on the only design constraints known prior to production: the geometrical shape of the formwork, the height of the robotic cell, and the kinematic constraints given by the robotic setup prepared. In other words, the tools did not inform whether or not the material could be shaped. The tool was prepared for the rigid and the flexible formworks, respectively.

Both tools sub-divided the vertical structure into horizontal segments (frames) that comprised the coordinates needed for the robotic trajectory. Detailed descriptions of the design tools are given in Section 4.1. (rigid) and Section 4.5. (flexible formwork), respectively. Regardless of the velocity-control system used, the design made in the Rhinoceros Grasshopper tool comprised

\(^{174}\)Grasshopper is a visual programming environment used for algorithmic design, developed by David Rutten at Robert McNeel & Associates. For general reference see: http://www.grasshopper3d.com/. Accessed on 01.03.2016.
the coordinates needed for the robotic trajectory.\textsuperscript{175} These were exported via a custom Python
script. The script translated the coordinates into the KUKA Robotic Language (KRL)\textsuperscript{176} along with
the assigned velocity control system (specific or global velocity control).

\textsuperscript{175} Rhinoceros (typically Rhino, or Rhino3D) is a commercial 3D computer graphics and Computer-Aided Design (CAD) software

3.7. Initial studies

To prove the fundamental feasibility of the SDC process and to collect first insights into the material’s behaviour, an initial feasibility study was conducted prior to the official start of this thesis. The experiments of the feasibility study focused on the curing time needed for any column section of fibre-reinforced self-compacting concrete (SCC) to support itself, as well as the additional load-bearing capacity of a column section once the formwork was removed. In the second stage, a series of curved column sections were robotically fabricated using a cylindrical rigid formwork in order to validate the process at a prototypical scale.

Compression tests

The uni-axial compression load tests were performed on a Zwick machine (see Section 3.5.2), with specimens produced using a cylindrical PVC formwork (d=200 mm, h=200 mm) with a lubricated inlay. After mixing, the fresh SCC was placed into eight individual cylindrical formworks. The first formwork was removed from the specimen after the material had hydrated just enough to self-sustain. The specimen was placed centrally in the Zwick machine, where vertical pressure was used to the column with a constant velocity of 5 mm/min. The test ran until either a decrease in the force resistance was observed, or visible cracks appeared. This test sequence was repeated on all eight specimens at intervals of 5 min.

Figure 37: From left to right. Step 1: the material rests; Step 2: the formwork is removed; Step 3: force is used in the Zwick.

The results allowed three distinct periods and material states to be identified, all of which are summarized in Figure 38.
Velocity of the slipping formwork

The first experiment determined the time period in which the material could support its own weight without formwork, as well as its load capacity during this time. A second series of experiments was then conducted, the goal of which was to understand the overall formability of the concrete and assess the ideal velocity of the slipping formwork.

For these experiments, a cylindrical steel formwork with a diameter of 200 mm and a height of 1000 mm was coated with a lubricant foil of polypropylene and attached to the six-axis robotic arm shown in Figure 39. The formwork was moved along a curved trajectory at a variable velocity. While the geometry of the trajectory was drawn as a curve in the CAD program, the velocity was programmed based on the following rules: slow in the beginning while the material gained strength, then accelerating once the material was able to carry more than its own weight. Empirical measurements allowed the fine-tuning of these parameters over successive iterations.
A batch of 30 l of fibre-reinforced SCC was then mixed and placed to a height of 600mm in the formwork. After a resting time of approximately 130 min, it was possible to begin the slipforming process. Based on the initial velocity principle, a sequence of experiments was conducted. The trajectory and a discussion of the tested velocity sequences are shown in Figure 40.

The following conclusions could be drawn from the second experiment:

- **Velocity A**: When the velocity is too high in the initial phase, the material creeps (collapses).
- **Velocity B**: When the velocity is too low in the initial phase, hydration occurs in the formwork, which generates too much friction and thus causes breakage.
- **Velocity C**: The optimal velocity is slow in the beginning (to allow the material to obtain strength) and increases exponentially, adjusting as the mixture sets.
Despite the discrete curvatures in the columns and the occurrence of creep and cracks, these experiments were still considered to be successful as proof of concept studies, since they identified the narrow timeframe during which a fibre-reinforced self-compacting concrete is both formable and self-supporting. The results revealed an ideal velocity distribution along the slipforming trajectory (see Figure 40 C a), which enabled the fabrication of a 650-mm tall column in 19 min. This is more than 100 times faster than other layer-based techniques. Experiments also revealed that the SCC is only in an optimally formable state for approximately 15 min after the early acceleration phase\textsuperscript{178} has started. After this period, friction in the formwork begins to produce cracks. Hence, these experiments showed that – in order to maintain optimal formability – it is critical to use and to develop concrete for which hydration can be controlled over time.

\textsuperscript{177} Note, however, the fold on the right hand side of the column’s base (caused by the material being too soft to carry the weight of the entire section) and the cracking at the most extreme curved point (caused by the material being too hard to shape).

4. Robotic slipforming

The short period of time in which a single batch of non-retarded SCC is self-sustaining and can be shaped was detected in the initial studies described in Section 3.7. This non-retarded batch had a limited workability, which required the material to be placed into the form within 10 min after mixing. After this period of time the material lost it workability, and was hence no longer self-consolidating. This directly constrained the scalability and the shaping; it was only possible to slipform column sections that were a maximum of 600 mm in height. The goal of this next phase of the study was to scale up the process, and to further explore the potential of shaping concrete during the short period of time in which the material changes from a soft to a hard material.

In these experiments, a large batch (referred to as B1, B2 etc.) of heavily retarded fibre-reinforced SCC was mixed\textsuperscript{179} and then sub-divided into smaller batches.\textsuperscript{180} The accelerated batch (referred to as B1.1, B1.2 etc.) was sequentially placed into the formwork. Concurrent with this step, corresponding batches were placed into separate containers so that the material properties of the batches could be observed outside the formwork. A custom feedback system was used to monitor the strength evolution (yield stress) of the material. The measurements from this system reflected the properties of the material in the formwork,\textsuperscript{181} and were used to define the slipping velocity, the time of shaping, and when to add accelerator to the subsequent batch.

The 1:1 experiments described in the following sections tested the overall concept. However, several iterations of experiments had to be conducted to reach the goal of scaling the process up. Each of the first three sets of experiments explored a different processing strategy, while employing the rigid formwork system described in Section 3.6.

- The first set of experiments used a discontinuous batch process in which the batch sizes were up to 30 cm in height.

- The second set of experiments used a semi-continuous batch process. Here, the batches were intermixed to attempt a gradual transition from one batch to the next.

\textsuperscript{179} In the experiments described throughout Section 4., the large batches are referred to as B1, B2 etc. The sub-divided batches are referred to as B1.1, B1.2 etc.

\textsuperscript{180} This is further described in Section 3., Materials and Methods and preliminary trials.

\textsuperscript{181} Systematic tests were used to establish a correlation between the measurements from the uni-axial test and the penetration test, which in this case is concurrent with the penetrometer. See Section 3.7. for further information.
• The third set of experiments used a pump system to enable a continuous feeding process in which the batches were placed in layers 2-5 cm thick. The goal here was to pursue a proof of concept towards an industrially applicable fabrication method for non-standard structures.

• The fourth set of experiments used a flexible formwork system employing the semi-continuous processing method. The goal here was to explore whether SCC can be shaped by dynamically changing the cross section of the formwork as the slipping is progressing.

Several key components of the overall experimental setup had to be adjusted and further developed as the project evolved. These were: A) the material mix design, with a particular focus on balancing the retarder and accelerator dosages; B) the inline monitoring system; C) the algorithmic design tool and robotic control system; and D) the formwork and measuring sensors.

![Diagram](image)

*Figure 42: A) Retarded material. B) Chemical admixtures for accelerations. C) Inline measurement system. D) Algorithmic tool and robotic control.*
Two major challenges were encountered while attempting to realise a batch-by-batch production process that was independent of whether it was dis-, semi-, or continuous. The first challenge was to ensure that the individual batches were well bonded. This challenge is directly related to time. The second essential challenge was to define the height and time of placement for each subsequent batch. A major constraint is that it must not lead to an excess load that cannot be sustained by the previously placed batches. The two constraints (bonding and time of placement) have contrasting requirements in terms of addition time. The first requires adding layers quickly, so that the lower batch is still workable enough to guarantee good bonding. The second requires waiting as long as possible for the same batch to have a load bearing capacity, to ensure that the already placed batch does not collapse while being slipped.\textsuperscript{182} The schematic diagram in Figure 43 illustrates how the forming time is determined in relation to the time at which a layer is placed.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{schematic_diagram.png}
\caption{The height of the layer ($h_i$) in the $y$-axis, together with the strength evolution curve, determines the time at which a layer of that height can be shaped ($t_i$).\textsuperscript{183}}
\end{figure}

The height of the layer ($h_i$) in the $y$-axis, together with the strength evolution curve, determines the time at which a layer of that height can be shaped ($t_i$). The interval between this time and the time at which the material becomes too stiff to be shaped is $t_{\text{max}}$. The time interval available to shape a layer of height $h_i$ is therefore $\Delta t_i = t_{\text{max}} - t_i$. If a batch is slipped out of the formwork before it has reached the yield stress needed to carry its own weight and that of subsequent batches, it

\textsuperscript{182} Collapse in this context refers to: 1) the break down of the thixotropic build-up, and 2) the additional load from the subsequent batch, which can cause the already slipped batches to collapse. L.K. Mettler et al., "Evolution of Strength of Failure of SCC during Early Hydration".

will flow or lose its shape (as exemplified in the experiments described in Section 3.7.). On the other hand, if the material is slipped out too late it will rip or crack (as also exemplified in Section 3.7.).

An additional challenge was the fact that these times can be modified by variations in the material composition, a change of room temperature, the mixing process, or the cement, and this can make a difference in whether a layer will fail or flow. However, the feedback system developed for this project allows the loads to be quantitatively defined, and the 2nd and 3rd cycles of experiments suggest that it is indeed possible to repeatedly shape successive concrete layers during their respective transitions from a soft to a hard material.
4.2. Discontinuous slipforming

4.2.1. Concept and goal of experiments

The 1:1 experiments described in Section 4.1. were conducted in order to prove the overall concept of SDC described in Section 4. As such these experiments aimed to produce prototypes where large batches 300 mm or 12 litres (l) of retarded SCC were discontinuously placed into formwork at time intervals ranging from 50 to 90 min and subsequently accelerated over time (the batch sizes are illustrated in Figure 44). Note that a large retarded batch is referred to as B1, B2 etc. and the sub-divided batches referred to as B1.1, B1.2, etc.

One challenge with the discontinuous process is to ensure that each batch of material being slipped has reached the strength properties needed to support its own weight, while at the same time remaining shapeable. Second, the batch must have reached a static yield stress that enables it to carry the weight of the subsequently placed batch. Additionally, the lower layers that are already shaped must be able to support the accumulated weight of the layers above. To detect the material strength evolution, a digital penetrometer is employed and later (in Experiment B and C) mounted to a table-sized robot (see Section 3.5.).

In this discontinuous approach, a subsequent batch is placed while the previously placed batch is being slipped and shaped. In this process, the velocity of slipping should theoretically be set at a rate that allows the subsequently placed batch to reach the strength it requires to be slipped. However, experiments have proven that slipping too slowly causes excessive friction, resulting in cracks (see Section 3.7.). The strategy employed in this approach is to slip the main part of the batch at an estimated ideal velocity, but to use a stop-go method while slipping in the

![Figure 44: Schematic illustration of the discontinuous process in which large accelerated batches B1.1, B1.2, etc. of material are sequentially placed.](image-url)
transition zone between one batch and the next. This empirically ensures that the material in the subsequent batch has reached the strength it needs to be slipped.

The overall goal of the experiments in Section 4.1. was to produce an elliptical column with a rotation of 180° over its full height (1800 mm), without significant cracks or flow of material. Several iterations of experiments were conducted in order to define the optimal placement rate of the batches in relation to the robotic slipping velocity, and to explore whether the batch-by-batch production process is suitable for shaping and scaling up the SDC process. Finally, the experiments evaluated the potential of employing a digital penetrometer (see Section 3.5.) as an integrated feedback system that can be used to define when to add the accelerator, when to start the slipping, and when to place the subsequent batch.

### 4.2.2. Material processing method

In all experiments described in Section 4.1., Mix C was used (see Section 3.2.). The mixing procedure is described in Section 3.3.

Mix C has a workability time of 3 h, which is more than is needed to produce a tall column.\(^{184}\) It is known from previous experiments that the column production takes between 6 and 7 h.\(^{185}\) To ensure that workable material was at hand throughout the entire production period, two large batches of retarded Mix C were mixed with an offset in time ranging from 90-100 min, yielding workable material for up to 7 h at a time.

After the large batch was mixed, the material was sub-divided and accelerated in 11.5 l portions. 10 l of the accelerated material were then placed in the formwork, while the remaining 1.5 l were placed aside in a metal container to be used as a mirror sample from which to measure the material hydration during production. A custom monitoring system (from here on referred to as the inline measuring system) was used to monitor the material. This consisted of a penetrometer mounted to a six-axis robotic arm that was controlled via a custom software script. The results from the measurements were used to dictate when to add accelerator to a subsequent batch, when to start the slipping, and – theoretically – how fast to slip (see Section 3.5.).

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\(^{184}\) Experiment A showed that it takes approximately 3 h to produce a 900 mm column.

\(^{185}\) A. Alberti et al, "Formwork Free Concrete".
**Production rules**

The batches in the experiment described in Section 4.1. were 10 l; this is equal to 21 kg or 300 mm in the selected formwork, further described in Section 4.1.3. Previous studies showed that a batch with a height of 300 mm and a diameter of 200 mm can self-sustain (carry its own weight) at 4-5 N (see Section 3.7.) of force, and is hence the point at which slipping can start. It was also known that a batch with these dimensions can sustain the weight of a subsequent batch at 7-8 N; hence at 7-8 N, a subsequent batch can be placed.

![Figure 45: Schematic graph of the correlation of the support height and the penetration force measured.](image)

Apart from measuring the batch strength, it was also critical to consider the time it takes for a batch to reach the strength needed to self-sustain and carry the weight of a subsequent batch on top, because this decreases as the retarded batch ages over time. In the context of the slipping process, this means that the velocity of the slipping must progressively increase as the batch is slipped and shaped. The velocity control (described in Section 4.1.5.) aims to compensate for this.

### 4.2.3. Experiment setup

The following experiments employ the full-scale robotic fabrication setup described in Section 3.6. The end-effector of the robot consisted of a custom elliptical formwork made of 2 mm stainless steel plate. For the sake of comparison, and to be able to use the data gathered from

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186 Density of material is 2100 kg/m³.
187 Systematic studies have correlated the strength properties of the column section with the penetrometer. This was initially done by correlating the uni-axial compression test with the penetrometer as described in Section 3.5 and 3.7. The study is also reported in A. Alberti et al, "Formwork Free Concrete."
the experiments in initial studies described in Section 3.7., the axis radius \( r \) of the elliptical cross section were \( r_1=125 \text{ mm}, \ r_2=80 \text{ mm} \). This corresponded to the area of the cylindrical formwork in the experiments described in Section 3.7. The height of the formwork was reduced as the experiments evolved. In Experiment A, the height was 1000 \text{ mm}; in Experiments B and C, the formwork height was reduced to 600 \text{ mm}, as this height turned out to be sufficient to subsequently slip two batches. The formwork was mounted in the centre of a generic formwork frame, which was attached to the end-effector of the KUKA-KR150-110. The outer frame had the following dimensions: width 430 mm x length 430 mm x height 1200 mm. The elliptical formwork was inserted with an offset of 200 mm from the top of the frame to ease the placement of the material during production.

![Figure 46 Left: Illustration of the elliptical formwork attached to the robotic arm. Right: Top view of the elliptical formwork.](image)

### 4.2.4. Inline measurement

To guide production, the batch system relies on continuous measurement of the material’s strength as it evolves. With these measurements, it was possible to determine when to shape (i.e. start slipping) each batch, when to add accelerator, and when to place material in the formwork.

The used UR5 robot was controlled via custom software written in Python. The robot was connected to the program via TCP/IP. The measurements were executed in predefined time intervals throughout the production. The program was set to measure specific predefined points in the measuring container featured in Section 3.4.3., into which a sample of each accelerated batch was placed. The measurements were conducted as described in Section 3.4.3.
4.2.5. Algorithmic tools

**Design tool**

In order to define a particular robotic path curve, which in this case is always vertical with an optional rotation degree or displacement in the horizontal direction, a custom design tool was developed in Grasshopper, a visual programming plug-in for McNeel's Rhinoceros CAD-environment. The Grasshopper included a set of variables that in theory allowed various slipping path curves to be algorithmically generated. These path curves were featured in Rhinoceros as geometry, in this case a column (see Figure 48), and were designed within a set of known physical boundaries given by the physical fabrication setup (such as the geometry of the formwork, a maximum slipping height of 1900 mm, and a maximum rotation of 180°). The custom design tool was also used to define the height at which a rotation or curvature begins and ends.

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188 "Grasshopper, algorithmic modeling for Rhino".
189 Note that the tool did not simulate the constraints of the material behaviour, as this was not within the scope of this research.
In order to generate the path curve required to produce a column, a specific formwork geometry (e.g. elliptical, square or star) reflecting the physical formwork mounted on the robot was drawn in 2D in McNeel’s Rhinoceros CAD-environment. The formwork geometry was then linked to the Grasshopper tool, where the robotic path curve (e.g. rotation degree, curvature and height of structure) was defined.

Then the structure was converted into curves, along with the coordinates describing the geometry. The resulting geometry served as a preview of the intended structure, but by no means ensured that the structure could be produced, as the tool did not include simulations of the material properties in the early hydration phase. In a final step the coordinates were exported via a custom Python script that converted the coordinates into robotic control code (KUKA KRL), hence generating the robotic path curve.
Velocity control

Ideally, the velocity should be programmed to slip at a velocity that would allow the next batch to gain the strength needed to self-support, while remaining shapeable. This means that the slipping rate should ideally be programmed to slip at a rate that follows the hydration rate of the material. Based on systematic studies conducted prior to the experiment, it was known that the time needed to reach this strength varied from 50-90 min after placing the batch in the formwork, depending on the age of the material.\textsuperscript{190} Hence, to slip according to each batch’s hydration rate required that the batches were slipped with a velocity ranging from 0.3-1.6 cm/min, respectively. However, slow slipping causes excessive friction to occur.\textsuperscript{191} Therefore, instead of slipping slowly over the full height of the batch, the first 250 mm of the batch were slipped with an approximate ideal velocity ranging from 1.5-3.5 cm/min, which was defined in the Python export code prior to production (also discussed in Section 3.6.3.).

This velocity control method takes three major factors into account. First, to prevent friction from occurring, each batch must be slipped with a velocity adjusted to the hydration rate of the material (i.e. the velocity must increase as the batch ages). Second, the hydration rate of the batches can vary from experiment to experiment (i.e. the material can hydrate more quickly or slowly depending on ambient temperature or mixing variability). Third, to allow the subsequent batch to gain enough strength to self-support and to avoid friction, a ‘manual’ stop and slip should be possible in the transition zone from one batch to the next. To accommodate these factors, the velocity was programmed in a way that allowed the predefined velocity to be interrupted and manually changed during production using the robot’s control panel. The variables of the velocity, however, were by default constrained to seven steps defined as percentages, with 100%, 75%, 50%, 30%, 10%, 3%, 1% of the programmed velocity.

\textsuperscript{190} A. Alberti et al, “Formwork Free Concrete”.
\textsuperscript{191} The friction measurements were based only on empirical evaluations. However, it is well known in literature that two major effects can be observed when concrete hydrates: First, water content (hydration) is reduced as the concrete ages, which decreases the natural lubrication effect given by the water. Second, the material expands during hydration. For further information on the expansion of concrete in its hydration phase see: J. D. Bapat, Mineral Admixtures in Cement and Concrete, 127-128.
In the experiments described in the following Section, the ideal velocity of each accelerated batch (referred to as B1.1 etc.) was estimated to be 1.5 cm/min for B1.1, 2 cm/min for B1.2, and 1.3 cm/min for B1.3. These velocities were repeated for B2.1, B2.2 and B3.1, respectively, and were equal to the velocities listed under 75% in Table 4. To achieve flexibility in the velocity controls, however, the velocities were programmed in the export code with what equals 100% in the table. This gave some flexibility during production as it enabled the velocity to be reduced or increased in steps, as listed in Table 4.

Table 4: The second vertical row (75%) shows the programmed velocity. The subsequent rows are the variable velocities that can be manually changed during production.

<table>
<thead>
<tr>
<th>Robot velocity [%]</th>
<th>100</th>
<th>75 (estimated optimal velocity for batches)</th>
<th>50 (estimated optimal velocity for the intersection)</th>
<th>30</th>
<th>10</th>
<th>3</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Velocity [cm/min]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B1.1</td>
<td>2</td>
<td>1.5</td>
<td>0.75</td>
<td>0.45</td>
<td>0.15</td>
<td>0.045</td>
<td>0.015</td>
</tr>
<tr>
<td>B1.2</td>
<td>2.67</td>
<td>2</td>
<td>1</td>
<td>0.6</td>
<td>0.2</td>
<td>0.06</td>
<td>0.02</td>
</tr>
<tr>
<td>B1.3</td>
<td>4</td>
<td>3</td>
<td>1.5</td>
<td>0.9</td>
<td>0.3</td>
<td>0.09</td>
<td>0.03</td>
</tr>
</tbody>
</table>
4.2.6. Experiment A: Validation of batch system

The goal of the first experiment was to evaluate the batch-by-batch production method by placing 300-mm thick batches in time intervals based on the evolution of the material’s static yield stress. To evaluate the strength gain of the individual batches, a second goal was to evaluate whether the penetrometer described in Section 3.5.4. was suitable for guiding production (at this point, the penetrometer was not yet attached to the table-sized robotic arm, as described in Section 3.5.3.). To simplify the challenge, this experiment aimed only to produce a section of a column (900 mm) with a straight trajectory, applying the robotic setup described in 4.2.3. The following experiment therefore only used one 35-l batch of Mix C (see Section 3.2.). The mixing and acceleration method used in this experiment is described in Section 3.3.

![Figure 51: Elliptical steel formwork attached from the top to the robotic arm.](image)

The measurements conducted with the handheld penetrometer dictated three major rules. First, the penetrometer must measure 3 N in the previous accelerated batch before the subsequent batch is accelerated. Second, when this measures 4-5 N (an indication that the material in the formwork can carry its own weight – about 23-30 kg), the slipping should begin. Third, when the sample measures 7-8 N (41-47 kg), the subsequent batch should be placed in the formwork and a sample should be extracted. The whole process is then repeated.
**Experimental process**

Production began by mixing a large 35 l batch of Mix C. Immediately after mixing, the batch was sub-divided into three 11.5 l portions. The sub-divided accelerated batches (referred to as B1.1, B1.2, and B1.3. B1.1) was accelerated 20 min after water was added to the main batch. Next, 10 l (20.7 kg) of accelerated B1.1 was placed in the formwork, filling up to 300 mm, and a 1.5 l sample was placed in the measuring container. After 60 min, the first measurement was conducted with the handheld penetrometer. This was done as slowly as possible; when the penetrometer measured 3 N, B1.2 was accelerated. The slipping process for B1.1 began when this batch measured 6 N. B1.2 was placed when B1.1 measured 7 N. At this point the formwork had been slipped to 200 mm. This process was repeated for B1.3.

![Slipping process, with three subsequent accelerated batches, applying the elliptical formwork. Note the scant evidence of the transition from one batch to the next.](image)

The result of the measurement in Figure 53 shows that the slipping of B1.1 started at 110 min, and the slipping of B1.2 at 165 min. When slipping began for B1.1, its strength properties were 6 N – too late to achieve a successful column. It was determined that the late start was due to inconsistency in the measurement method and time intervals. A new measuring process –

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192 In the initial experiments, an attempt to ensure that the material height of the batch was correct was made by measuring with a ruler inside the formwork. This method turned out to be rather complicated and imprecise when it came time to scale up the process, as was done in Experiment B and C. Therefore, a laser (described in Section 4.2) was eventually installed on the upper part of the formwork.

193 Note that various persons executed the measurement until it was discovered that this was causing deviations in measurements. It was therefore decided that only one person should conduct the measurement.
where a single person was responsible for measuring and executing the process – was thus developed, and allowed B1.3 to be correctly slipped when the batch measured 4.7 N.

The measurement results (Figure 53) clearly show that B1.3 reached the strength required to self-sustain only 25 min after acceleration. This was approximately 30 min earlier than expected. The early strength gain was due to the fact that the accelerator had been mixed earlier than planned.\textsuperscript{194}

![Experiment A, penetrometer results.](image)

\textbf{Figure 53:} The lower red line shows the time when the slipping can begin. The upper line shows the time period when the material’s shapeability is ending. The three curves show the strength evolution, starting from the left with B1.1, B1.2, and finally B1.3. The slip start of B1.1 was at 6 N, 110 min; B1.2 was at 6 N, 165 min; and finally B1.3 was slipped at 4.7 N, 195 min.

Despite the deviation in the first measurement, it could be concluded from the experiment that the batch-by-batch system is generally suitable for SDC production. In addition, it could be concluded that the penetrometer has potential to be used as a production guide – if used in a precise and systematic fashion. The deviations of the measurements were not critical at this phase since the column was being slipped in a straight trajectory. However, if the penetrometer is to be used as a production guide to qualitatively evaluate the process, the measurements must be automated.

With respect to the slipping velocity, it was not possible determine a precise sequence. However, it was possible to confirm that the range in which each batch must be slipped is between 1.5 - 3

\textsuperscript{194} A mismatch in the communication was caused by the fact that the acceleration was conducted in a different space from the slipping and measuring.
86 cm/min. This rate became the basis for the production and algorithmic tools developed for the experiments discussed in Section 4.2.

4.2.7. Experiment B: Time-based production guide

The aim of the following experiment was to test the overall formability of the material by producing a 1800-mm tall column, rotated 180° around its central axis, using a time-based production guide. Overall, the time-based production guide aimed to test and put into practice the conclusions from a set of systematic studies in the Bachelor Thesis "Formwork Free Concrete".\textsuperscript{195} namely, that it was possible to predetermine the time needed for a batch to be shaped. This was crucial to test because developing a practical method for implementing a time-based system would make the inline measurement redundant and radically simplify the production process. Thus, unlike Experiment A, the production in this experiment was not guided by measurements taken with the digital penetrometer, but by a predefined production sequence.

To compare the two processing strategies with each other, this experiment continued to extract samples of each batch to evaluate its material properties. The robot-mounted penetrometer was used to evaluate the material as described in Section 4.1.2. The goals of this second experiment were therefore to test the formability of the material in a rotational trajectory, while determining whether the production could rely on a purely time-based production guide.

The experiment setup remained the same as described Section 4.2.3. In this experiment, however, the elliptical formwork was reduced from 1000 mm to 600 mm because the batch process never required more than two batches in the formwork at once. The material system and mixing method remained the same as in Experiment A.

The experiment followed a time guide based on conclusions made from previous laboratory experiments, which showed that the individual batches can self-sustain, be shaped, and carry the next batch after resting in the formwork for a specific amount of time. Based on these assumptions, a production guide was developed, in which a buffer time was included to avoid delays. The production guide is shown in Table 5.

\textsuperscript{195} A. Alberti et al, "Formwork Free Concrete", 56-57.
Table 5: Time-based production guide for Experiment B.

<table>
<thead>
<tr>
<th>Time [min]</th>
<th>Mix retarded Batch #</th>
<th>Accelerate Batch #</th>
<th>Place Batch #</th>
<th>Start slip Batch #</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-15</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>1.1</td>
<td>1.1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>75</td>
<td>1.2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>110</td>
<td>2</td>
<td>1.1</td>
<td></td>
<td>B1.1 must rest in form for approx. 90 min.</td>
<td></td>
</tr>
<tr>
<td>120</td>
<td>1.3</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>130</td>
<td>2.1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>150</td>
<td></td>
<td>1.2</td>
<td></td>
<td>B1.2 must rest in form for approx. 70 min.</td>
<td></td>
</tr>
<tr>
<td>160</td>
<td>2.2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>175</td>
<td></td>
<td>1.3</td>
<td></td>
<td>B1.3 must rest in form for approx. 50 min.</td>
<td></td>
</tr>
<tr>
<td>210</td>
<td>2.3</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>225</td>
<td></td>
<td>2.1</td>
<td></td>
<td>B2.1 must rest in form for approx. 90 min.</td>
<td></td>
</tr>
<tr>
<td>235</td>
<td></td>
<td>2.2</td>
<td></td>
<td>B2.2 must rest in form for approx. 70 min.</td>
<td></td>
</tr>
<tr>
<td>245</td>
<td></td>
<td>2.3</td>
<td></td>
<td>B2.3 must rest in form for approx. 35 min. No additional batch.</td>
<td></td>
</tr>
</tbody>
</table>

In this experiment (Figure 54), the upper part of the column was sheared off by the rotation of the formwork. The later analysis of the measurements showed that the failure was due to the initial decision predefining the time in which the first batch should be slipped. This assumption resulted in a chain reaction of several delays during production, which in turn caused the material to lose 1) its workability (or self-consolidating properties) when placing, and 2) its formability, due to the fact that by following the time-based system the material had surpassed its optimal yield stress for shaping.
The first problem occurred at the beginning of the experiment. Here, the slipping time was started correctly at 110 min, according to the time-based production guide. However, the penetration result of the material at this point was 11.9 N (see Figure 55) — the material had already exceeded
the yield stress needed for shaping (4-5 N). The high measurement did not cause friction to occur due to the fact that the formwork was well lubricated prior to placing the first batch, and because the first 300 mm of the column were straight.

When the formwork bottom reached 200 mm, however, it was detected that the material in B1.1 had not self-levelled when placed. This was because material from B1.2 started to flow out while B1.1 was being slipped (see Figure 56). Hence, the slipping of B1.1 had to be stopped at 200 mm. As shown in Figure 55, the result was that each batch had surpassed its ideal strength properties (4-5 N) by the time slipping was begun. In addition to the fast hydration, it was visually detected that the bonding between the batches was very weak. This was particularly visible in the interphase between B1.3 and B2.1 (see Figure 56). Overall, these results suggested that the digital penetrometer would be crucial for detecting the material properties over time, and for successfully guiding the production in future experiments.

![Figure 55: Measurements from Experiment B. The lower red line shows the time when the slipping can start. The upper red line shows the time when the shaping capability of the material is ending. The six curves show the strength evolution starting from left with B1.1, B1.2 and finally B1.3, etc. The slip start of B1.1 was at 110 min, where the material measured 11 N. The slip start of B1.2 was at 155 min, where the material was 9 N. B1.3 was slipped at 272 min, when the material was 12.5 N. Batch B2.2 was slipped at 304 min, when the material was 8.6 N. Finally B2.3 was slipped at 340 min when the material was 10 N.](image-url)
The experiment clearly showed that the resting time of the batch could not be precisely predicted prior to the physical production, as least at this experimental stage. However, the experiment made evident that a digital penetrometer would be crucial to guide the discontinuous process of applying a batch-by-batch system, as without one it would be impossible to precisely and systematically evaluate the material’s properties. Hence, it was determined that the inline system must be re-introduced to predict when to start the slipping and when to add accelerator to the next batch.

Further, the experiment revealed that the transition and bonding between the batches is an additional critical issue for SDC, and that processing methods that improve the bonding between batches would be required in future experiments.

4.2.8. Experiment C: Robotic material monitoring

The overall goal of Experiment C was to improve on Experiment B by testing the formability of the material. The goal was thus to produce a 1800-mm-tall column, rotated 180° around its central axis. Because Experiment B clearly concluded that a time-based system was not suitable

As a follow up to the critical issue of bonding, the Master Thesis of L. Reiter, "Mechanical Aspects of Smart Dynamic Casting", reports a systematic study that investigated methods of how to strengthen the intersection between the layers.
for the SDC process, this experiment used a robotically controlled measurement system to guide production (see Section 4.2.3.). The experiment also introduced a gradual placing method (referred to as poking\textsuperscript{197}), with the aim of improving the bonding between the batches. As such, the experimental setup remained the same as the one used in Experiment B, except that the production was guided by measurements received from the accelerated material samples.

Measurements were crucial to this experiment, and were used to define the time sequencing in five major steps: 1) when to mix the second large batch (B2); 2) when to poke and place the batch; 3) when to accelerate the subsequent batch; 4) when to add accelerator; and 5) when to add the remaining batch and start slipping.

The only predetermined action was when to add accelerator to the first batch, which was exactly 30 min after adding water to the first retarded batch (B1). Overall, the measurement results dictated that:

- At 0.5 - 1 N, the subsequent batch should be accelerated.
- At 2 N in B1.1, B2 should be mixed (35 l); simultaneously, the upper surface of material in the form should be poked and a thin layer (approximately 30 mm) of the next batch should be placed.
- At 4-5 N, slipping should begin, the surface of the batch in the form should be poked, and the rest of the batch should be placed.

\textsuperscript{197} The gradual placing method uses a stirring tool comprising a wood stick with three 30 mm nails. During production, but before a layer of an accelerated batch is placed (layer = 40-50 mm), the stirring tool is used to break down the built up structure of the previous batch. This is done by stirring the upper surface (approx. 30-50 mm) of the previously placed batch. This action is repeated three times in intervals of 5 min, or until the previous batch in the form has reached 4 N.
The results of the measurement were crucial for the success of the experiment. The measurements in Figure 58 show that the slipping of all the batches was started when the material measured 4-6 N.

Additionally image d) in Figure 57 shows the shaping of five batches that were considered successful, as no significant cracks or flow of material could be detected. Hence, it was
concluded that the measurement taken with the inline monitoring system reflected the material properties of the material in the respective batch. The figure also shows that the hydration rate of the batches deviates in time from Experiment A and B. This deviation clearly shows that the hydration rate of the material is variable from production to production, and that the process is highly sensitive to small variations in the processing and fabrication sequence.

Thanks to the real-time monitoring of the material’s strength evolution with a precise and systematic measurement system, the variation of hydration rate did not cause any failures in this experiment. However, production challenges still occurred in the transition zone from one batch to the next despite the introduction of a gradual placing technique. It was once again necessary to use a stop-go method of slipping in order to allow the subsequent batch to become strong enough to be slipped. Despite introducing the poke and place method, shear forces still caused cracks to appear on the lower material batch (which had surpassed its optimal shaping time) while the material in the upper batch was still too soft to be shaped. In other words, the poking method used to achieve a gradual transition from one batch to the next was indeed not gradual enough. Thought the resulting columns featured horizontal cracks, these did not cause the overall experiment to fail. Ultimately, a column with a final height of 1800 mm rotated around its central axis was successfully produced in 405 min (see Figure 59).

Overall, Experiment C showed that it is possible to form concrete in its early hydration when it changes from soft to hard. It also clearly showed that discontinuous batch-by-batch production of a geometrically differentiated SDC column requires real-time monitoring to quantitatively determine the material processing and the gradual transition from one batch to the next.
Figure 59: Left: the 1800 mm elliptical column with a rotation of 180°, produced with six batches of accelerated material over a period of 6 h.
4.2.9. Conclusions about the discontinuous process

The overall result of these experiments was successful as a first proof of concept that concrete can be shaped at the time when it changes from a soft to a hard material. The experiments also proved that the batch-by-batch system is well suited for scaling up the SDC process to a building component scale. Finally, the experiments clearly show that the robotically controlled digital penetrometer is a well suited and crucial component to dictate the batch-by-batch production method. Despite these conclusions, however, the discontinuous processing method was questionable. This is because the method of processing and shaping large batches clearly created obstacles for both the shaping and bonding thanks to the long resting time from one batch to the next. Additionally, this resting time made it challenging to define the right slipping velocity, especially in the transition zone from one batch to the next.

The predetermined velocity programmed in the Python code prior to production was limiting because the maximum velocity programmed for a certain height could not be exceeded during production. First, this was an overall limiting factor in the transition zone from one batch to the next, where a stop-go method was used because the optimal velocity was not known prior to production (again, the hydration rate of the batch is not predictable at this stage with this processing method). Second, the inflexibility of the velocity control was a particularly limiting factor in Experiment B, where the material hydrated faster than expected. Here it would have been beneficial if the slipping could have been set faster. These limitations with respect to velocity clearly indicated that to proceed, a code and control system that allowed for flexible velocity control would have to be developed.

The faulty production in Experiment B, however, was due not only to the inflexible velocity control, but also to the predetermined production process. The results of Experiment B clearly showed that the rate of hydration could not be fully predicted based on time factors. In turn, the experiment proved that the material system is sensitive to variations in the mixing, processing, and temperature.

In contrast to the time-based production strategy in Experiments A and B, Experiment C proved that precise robotically conducted measurements could be used to guide production, as they made it possible to determine when to slip, when to accelerate, and when to place the next batch. This method resulted in the first full-scale robotically slipformed rotated column, which was constructed in 405 min. The down side of the material monitoring system was its disconnection
from the robotic fabrication system. If this automated system was connected to the robotic fabrication setup, it could have the potential of running a fully automated slipping process, in which the shaping and slipping is done in line with the evolving material properties.

Despite the success of Experiment C, however, a major challenge continued to be the transition between the batches. This was not evident in Experiment A, as the trajectory was straight and no shear forces were used to the material. However, in Experiment B the shaping in the transition zone clearly caused a chain of problems, such as loss of shapeability, friction occurrence, and a lack of bonding between layers.

In Experiment C, an attempt was made to solve this issue by ‘poking’ the previous batch and gradually placing three layers of material in the transition zone from one batch to the next. However, during production it was still possible to detect friction and cracking due to slow slipping in the transition zone. These problems were to a large extent caused by the fact that the upper part (50 mm) of the previously placed batch had surpassed the optimal shaping moment, while the newly placed batch was too soft to be shaped. As the rotational slipping progressed, shear forces caused the lower material to crack. This is particularly evident in Experiment B.

The overall results suggest that a new processing method that can successfully transition between one batch and the next will be required. One solution to this problem would be to ensure a continuous gradual hydration throughout the entire column. This could be achieved by either continuously processing the batches in small portions, or by combining this method with a sophisticated automated feeding system – a topic that is beyond scope of this thesis. A second method would be to intermix the individual batches gradually on the fly. This method will be further investigated in Section 4.2.
4.3. Semi-continuous slipforming: Intermixing batches

4.3.1. Concept and goals of experiments

In order to respond to the limitations in the discontinuous processing method, in particular in regards to the forming of the material in the transition zone between the batches, a semi-continuous processing method is defined. This method maintains the batch-by-batch approach, in which a large retarded batch is sub-divided and accelerated over time. Instead of sequentially placing large ‘pure’ accelerated batches\(^{198}\) in the formwork over longer time periods (50-90 min), this new processing method subdivides the batches in smaller portions, where the individual batches are intermixed gradually and then placed in the formwork at much shorter time intervals (3-5 min). This processing method aims to ensure optimal formability throughout the entire slipping process.

![Figure 60: Schematic illustration of the column section showing how the batches gradually intermix from one batch to the next.](image)

Furthermore, in order to respond to the limitation of the predefined velocity used in the experiments described in Section 4.1., a new fabrication control system was developed and integrated. The system enhances three major functions. First, it enables the x-y-z position of the formwork to be monitored, and it displays the height of the material in the formwork. The latter enables the slipping and filling to be synchronized – a crucial function when applying a semi-continuous processing method. Second, it allows the slipping velocity to be controlled relative to the evolution of the material strength properties. Finally, it allows the robotic control to be interlinked with the material monitoring system, which now is able to send strength data to the

\(^{198}\) Pure in this context refers to an accelerated batch, which is not mixed with another batch.
robotic control system, thereby enabling an automatic control of the slipping velocity relative to the strength evolution of the material. Finally, this experiment cycle introduces a new modular formwork system that enables a variety of geometries to be tested.

The goals of the experiment in this section were to test the new control system, and to enable a gradual hydration of the material by defining an optimal acceleration, placement, and slipping rate for this semi-continuous production system. The ultimate motivation was to produce an elliptical column without flow of material or cracks in the transition from one batch to the next.

### 4.3.2. Material and processing method

**Material and processing method**

The material system and overall mixing of the retarded batch remained the same as in the previous experiments described in Section 4.1. However, as it was observed in previous experiments that the material lost its workability towards the end of the production time, large batches were increased from two to three batches (B1, B2, B3) of 25 l each in order to ensure good workability of the material throughout the slipping and filling process. These were mixed in an offset time period of 20 and 60 min, counting from zero min, which is the time water is added to the first batch (see Figure 61). This offset ensured that the material had an optimal workability for a minimum of 4 h.

![Figure 61: Mixing and acceleration plan for the intermixing process used in the intermixing experiment.](image)

The process for this experiment was as follows: First, the first large batch (B1) was sub-divided in two equal portions of 12.5 l. After 30 min, the first sub-divided batch (B1.1) was accelerated.

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199 Mix C has a workability time of approximately 3 h (180 min). However, in previous experiments it was observed that the workability reached a critical state at approximate 140 min. Three batches were therefore mixed in order to ensure that the material had optimal workability throughout the entire production process. This ensured that the material was accelerated and placed at a time when the workability was optimal.
Thereafter, subsequent batches were accelerated in time intervals ranging from 17 to 25 min (see Figure 61). The acceleration time was defined on the fly, as the time of acceleration depends on the hydration rate of the material. Before placing the material in the formwork, a sample of the pure (non-intermixed batch) was extracted and placed in the container of the inline material monitoring system. The remainder of the batch was placed in layers ranging from 2-5 cm thick at time intervals defined during the production. After reaching a specific height (in these experiments, ranging from 10 to 28 cm) the intermixing was begun. As identified in Section 4.1., the acceleration time varied from production to production, depending on the hydration rate of the material.

Differences in hydration rates can be caused by various factors, such as minimal changes in the mixing process, variations in the cement, and/or temperature variations. These undetermined factors can cause the chemical admixtures to react differently than expected and, ultimately, to considerably influence the experiments. Thus, in an effort to reduce the hydration rate variability, a system of pre-mixing several bags of dry cement in large barrels prior to final mixing was introduced.

**Production rules**

The intermixing system used the general principles of the batch system described in Section 4.1., in which large batches of retarded material were mixed, sub-divided, and accelerated at specific times. However, instead of sequentially placing the pure batches at time intervals ranging from 50-90 min, this semi-continuous production method intermixed the respective accelerated batches gradually, and placed them in small layers at much shorter time intervals ranging from 2-8 min.

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200 An internal parallel study reported that variations were observed from one bag of cement to the other. These could be caused by several factors such as: pre-hydration and/or carbonation of cement, different grain size, content and type of calcium sulphate, and content of aluminates. For further information, see the appendix of S. Garcia et al., “Smart Dynamic Casting: Optimierung des Misch- und Betoniervorgangs bei der Herstellung von frei geformten 3D-Betonelementen”.

201 A set of side experiments proved that if two respective batches were accelerated at 15 min time intervals, and the respective batches were thereafter systematically intermixed, a gradual transition from one batch to the next could be achieved.
A schematic graph of the intermixing concepts is illustrated in Figure 62 in which the colour changes gradually from black (Pure batch 1) to green (Pure batch 2). First, a layer of a pure batch (dark red) was placed. Then a second batch was prepared, consisting of 75% of the first accelerated batch and 25% of the subsequently accelerated batch. Consequently, the resulting third batch consisted of 50% of each and finally the last batch was 100%. The intermixing procedure process was repeated throughout the entire slipforming process, until the last batch was reached. This system reduced or eliminated the resting time between the single batches. The goal of the intermixing is therefore to approach a continuous system, as doing so considerably opens up the design space of SDC (see, for example, the experiments described in Section 4.3. and 4.4.202).

### 4.3.3. Experimental setup

In this experiment series, a new material concept for the customizable formwork system was introduced, in which the formworks were milled out of a number of polyurethane modules featuring an outer dimension of 300x300x100 mm. After milling, the modules were manually assembled into the required height (400-600 mm) and coated on the inner side with a 0.5 mm polypropylene foil. The formwork modules were held in place by a generic aluminium scaffold, and mounted from the top to the six-axis robotic arm (see Figure 63). Three formwork cross sections were prepared. To transfer the processing method developed during the experiments, the formworks’ cross sections all had the same inner volume, identical to the previous experiments (also discussed in Section 4.1.3.).

202 This principle has also been reported in the Bachelor Thesis Project of: S. Garcia et al., "Smart Dynamic Casting: Optimierung des Misch- und Betoniervorgangs bei der Herstellung von frei geformten 3D-Betonelementen"
The first was a formwork inlay that featured an elliptical cross section (with the dimension \( r_1=125 \text{ mm}, r_2=80 \text{ mm} \)). The second formwork inlay had a square cross with four different edge radii \( r\) (10, 20, 30, 40 mm), and aimed to overcome the limitations of corner geometry by exploring the minimum corner radius that can be achieved before the concrete rips or cracks at the edge. The third was a star shape, and was used to characterize the overall geometric flexibility. The formwork inlays were used to produce three full-scale columns.

![Formwork inlays](image)

Figure 63: The formwork used during the experiment is the same as was used in the Intermix experiment.

### 4.2.4. Inline material monitoring system and robotic control

The experiments conducted in Section 4.1. proved that the digital penetrometer was well suited as a material monitoring system, as long as it is used precisely and systematically. The results from those experiments were used to determine when to slip, when to add accelerator, and when to add a batch into the formwork. Should it have been possible to send these measurements to the robotic control system, these measurements could have also been used to determine the slipping velocity. In the previous experiment, however, the monitoring system was a separate system that was not connected to the robotic control system (see Section 3.6.). Additionally, because the control system from the previous experiment required programming, it was rather constrained in terms of velocity control.

For the following set of experiments, an integrated control system was developed in order to extend flexibility to the velocity control, and ultimately to control the robotic fabrication system via measurements received from the digital penetrometer. In this setup, the digital penetrometer was mounted on a three-axis table device (see Section 3.4.3.), replacing the function of UR5 robotic arm.
This new control system consisted of three systems running in parallel. The first system was written in Python code, and was used to evaluate the material with the digital penetrometer. This control system featured a graphical user interface (GUI), hereafter referred to as the material monitoring unit (MMU). The second system, also written in Python code, was used for inline control and monitoring of the robotic fabrication process, and is hereafter referred to as the robotic control unit (RCU). Finally, the third system was the robotic export code (or KRL export), which contained the trajectory and inline functions needed to monitor and control the production.

The robotic control unit was the main control unit of the fabrication process and had three major functions. The first function received information regarding the formwork position. This was enabled via a function defined in the robotic export code, which was programmed to send the position via serial intervals of 600 ms. The second function measured the height of the material inside the formwork with a sensor that was installed on the upper part of the formwork frame. The sensor was connected to the digital input/out (I/O) of the robotic control system. Here again, a function defined in the robotic export code enabled the height of the material in the formwork to be sent via serial port to the robotic control unit. Tracking the height enabled the controller to signal when the next material layer should be filled. This function was crucial, as it enabled the filling and the slipping velocity to be synchronized. The third function was velocity control, which was divided in three subsections. The first subsection defined the global velocity: in this case, this global velocity was sent to the robotic control unit via serial port at the beginning of production; in the following experiment, the global velocity was set to 12 cm/min. The second subfunction enabled the fabrication to be run in a fully automatic mode, by receiving measurements from the material monitoring unit. The new setup of the material monitoring unit enabled the values of the measurements to be stored, and the results of the measurement to be sent to the robotic control unit via TCP/IP. In such cases, the robotic control unit received the measurements and synchronised them with a list of possible velocities in order to determine at which velocity the robot should slip when receiving a particular measurement result. Thereafter, the robotic control unit could automatically set the slipping velocity in relation to the force.

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203 The control system of the penetrometer was developed by Oliver Glauser, Institute for Building Materials (IfB), ETH Zurich, Zurich, Switzerland, while the implementation and GUI were developed in sequential steps in collaboration with support from Dr. Ralph Rütschi, Beat Lüdi, and Maryam Tayebani (see APPENDIX 6).

204 Baumer OADM 1216460/S35A, output signal 4-20 mA.

205 The global velocity in this case refers to the maximum velocity at which the robot can slip. Based on the previous experiment conducted in Section 4.1., it was concluded that the maximum velocity needed did not exceed 12 cm/min.

206 The principal function of the DP GUI has remained the same as described in Section 4.2.5., which is to measure the material samples in a predefined pattern, with a velocity of 1 mm/sec with the cylindrical needle head described in Section 3.5.
measured on a respective batch. However, as the material sample measured in the semi-continuous process did not reflect the intermixed batches, a third subfunction was built to enable the velocity to be overwritten based on empirical evaluations done directly on the material being slipped. In the case of the following experiment, in which the global velocity was set to 12 cm/min, the velocity can be overwritten in 100 steps, of which one step is 0.12 cm/min. A flow chart (see Figure 64) gives a comprehensive overview of the control system.

Figure 64: The diagram shows the entire digital control system, which is controlled via the robotic control unit (RCU). During production, the RCU is able to receive data via TCP/IP from the material monitoring unit (MMU) regarding the material properties. The RCU can theoretically synchronise the force values with the velocity, which is sent via serial port. During production the graphical user interface (GUI) of the RCU displays real time information regarding the position of the formwork. Additionally, a sensor attached to the upper part of the formwork sends inline information regarding the height of the material in the formwork.
4.2.5. Experiment D: Processing system 1

The first experiment conducted with the intermixing process aimed to improve the delicate transition from one batch to the next. It also aimed to test the new control system’s ability to perform gradual velocity control, as described in Section 4.2.4. and 4.2.5. Further, the experiment implemented the new elliptical formwork system described in Section 4.2.3. The overall goal was to test the formability of the SDC by producing a full-scale elliptical column with 180° of rotation — without cracks — and to collect data regarding the slipping velocity. For the sake of comparison, the trajectory remained the same as in the batch experiment described in Section 4. In these experiments, three batches of Mix C (see Section 3.3) were mixed using the mixing process described in Section 3.4. The first batch (B1) was 30 l and the following two batches (B2, B3) were 25 l each. The timing of the mixes was offset, as described in Section 4.2.2.3.

This first full-scale intermix experiment used 20-30 mm thick layers of material, with the exception of the first 100 mm, which were placed in a single portion. The intermixing followed a recipe that was defined prior to production (see APPENDIX 3: Intermixing Strategy 1).

The first batch of material was accelerated 35 min after water was added to B1. The batch was then divided into portions of 17.5 l (B1.1) and 12.5 l (B1.2). The subsequent batches were divided into two equal portions of 12.5 l and were accelerated in time intervals ranging from 15-20 min.

The production began by placing 100 mm of pure B.1.1 in the formwork; a sample was simultaneously extracted and placed for measurements (executed with the MMU). Thereafter, layers 20-30 mm thick were placed at time intervals ranging from 6-8 min. The filling was done slightly too fast, which resulted in the formwork filling up before the material in B1.1 had gained the strength needed to be slipped. To compensate for the overly fast fill rate, the filling was stopped for 10 min. During this period the slipping continued.

Slipping should begin when the material monitoring system measures 4 N in the first batch; in this case, this occurred 100 min after water was added to B1 (see Figure 65). Once slipping has

207 The first experiment aimed to collect data regarding the velocity of the production. This data was used because it was not possible to run the production in a fully automated mode.

208 The first batch is larger because 1.5 l is needed for the inline measurement system and 3.5 l are needed for the base of the column, which is placed before the intermixing begins.

209 The concept of initially placing 100 mm ‘pure’ material is to ensure that the first part of the material in the formwork reflects the material measured with the MMU.
begun, the challenge was to keep the filling and the slipping synchronised. In this case, this meant keeping the height of the material in the formwork at a constant height of 50 mm to allow for a continuous slipping velocity. Because of the break described in the previous paragraph, however, the velocity fluctuated constantly (see Figure 67). This was because it had to be slowed down to ensure that the material in the area between 50-60 mm had gained the required strength. Inconsistency in the filling and slipping remained an issue throughout the entire process. At times this resulted in the material being too soft, resulting in bulks or wrinkles. At other times, the material became too hard and friction developed. A manual tapping method was used to release friction, but this had the downside of re-fluidifying the material and creating wrinkles on the surface of the column (see Figure 66).

The final result of the column can nonetheless be considered successful; the target column (total height of 1800 mm and a rotation of 180°) was achieved without cracks or any visual trace of the transition from one batch to the next.
The experiments also showed that the semi-continuous process (red line, figure 67) was on average 0.3 cm/min faster than the discontinuous process (grey line) described in Section 4.1. This resulted in a reduction of the total slipping time to 95 min. Furthermore, despite the fluctuation, the slipping was fairly continuous as compared to the discontinuous process, where the slipping had to be completely stopped.

By approximating a continuous process, Experiment D clearly showed (despite the slightly wrinkled surface) that SDC provides an important step towards the possibility of shaping concrete as it transitions from soft to hard without cracks, and without visual traces of the transition from one batch to the next. This set of experiments showed that the challenge of the process is to keep the filling synchronised with the slipping. Thus, subsequent experiments (see Experiment E) focused on optimizing some of the processing steps to enable the further evaluation of the
discontinuous SDC technique. This included a) increasing the height of the layers to ease the processing and to eliminate intermixing errors, b) using additional and systematic material vibration to avoid crack occurrence or wrinkles, and c) to further elaborate on the geometric design and fabrication space.

4.2.6. Experiment E: Processing system 2

The second experiment conducted with the intermixing process aimed to increase the height of the intermixed material and thereby reduce the total number of intermixed layers needed, with the goal of being able to synchronise the slipping and filling velocity. Furthermore, the experiment introduced a battery-driven low frequency vibration tool. The formwork and the trajectory remained the same as in the previous Experiment D, as well as the material system, which was also accelerated and divided as described in Experiment D. The intermixing layers now ranged from 30 to 50 mm (APPENDIX 4: Intermix strategy 2). Furthermore, the initial 100 mm pure layer was eliminated and replaced by 34 mm layers that were placed at time intervals ranging from 4-8 min. The overall goal was once again to test material formability by producing a full-scale elliptical column with 180° of rotation, without substantial cracks or wrinkles.
After the first batch was accelerated, 34 mm layers were placed at intervals of 4 min. When the column reached a height of 28 mm, however, it was evident that the strength gain of B1.2 was slower than expected (see Figure 69). Therefore, the filling intervals were gradually decreased to 8 min.

To ensure good bonding between the layers, the vibration tool was once again used to re-fluidify the upper part of the material in the formwork. The gradual change in the filling intervals directly affected the velocity (as was also the case in Experiment D), which resulted in an inconsistent
slipping process (see Figure 67). Friction also developed as a result, however the vibration tool turned out to be suitable as it did not cause the material to flow.

The result of the second intermixing experiment was a considerable improvement over results from Experiment D. First, the surface of the column was smoother and the intersection from one batch to the next was not visually traceable. This was helped by vibrating the top layer prior to placing a new layer. Secondly, because the intermixing process was simplified, it was possible to slip at a faster velocity than in Experiment D (despite the slow strength gain of B1.2). This, in turn, resulted in less friction. Additionally, decreasing the number of intermixing layers made it easier to synchronise the slipping with the filling. As such, when the column height was between 1000-1300 mm, the filling was done at 3 min intervals — a filling and intermixing velocity that would not be possible if more intermixed layers were made.

Overall, the experiment showed that the process of production relies on continuous monitoring of the material properties.

Experiment E revealed promising results. The intermixing strategy used in this experiment significantly reduced the problems of poor bonding in the transition zone between the batches; this reduction in turn allowed the column to be rotated 180° without any cracks caused by shear...
forces, as was the case in the experiment described in Section 4.1. Furthermore, the integration of the handheld vibration tool ensured that the bonding between the subsequently added layers were well intermixed, and in case of friction, allowed the material to re-fluidify at the exit of the formwork without leaving any visual traces (wrinkles). In fact, the prototype produced in this experiment shows little evidence of the transition from one batch to the next.
Figure 71: Result of second column produced with Intermix System 2.
4.2.7. Experiment F: Square cross section

Experiment F aimed to test formability by introducing a square formwork with four different radii (r 10, 20, 20, 40 mm), described in Section 3.6. The overall goal was to gain initial insight into the constraints of the corner geometries for SDC; more specifically, the goal was to understand whether the chosen radius will cause the material to rip or crack when the formwork is rotated 180° around the central axis. Secondly, the experiment evaluated the production process in terms of its ability to perform continuous filling and slipping. The experiment used the same material system and acceleration process as in Experiments D and E. The intermixing process was the same as in Experiment E, further described in APPENDIX 4. As in Experiment D, the first pure layers of material were placed in layers 34 mm thick. The placement intervals were in this case set to 5 min, with the goal of aiming for consistent slipping and placing. In this experiment, the vibration tool was used from the start to re-fluidify the upper part of the material in the formwork.

The slipping started when the material monitoring system measured 4 N in the sample of the first batch. After this point, the velocity was gradually increased from 0 to 1.5 cm/min (see Figure 72). The result of the velocity data shows that the velocity started to fluctuate after 20 min. In the time between 20-40 min, the transition from the pure layers to the intermixed layers began, for which no data regarding the material properties existed. Therefore, two empirical operations were done to ensure that the material was neither too soft nor too hard: The first one empirically estimated the material properties by manually sensing its properties as it was slipped out of the formwork. This, in turn, allowed for the second one to empirically adjust the slipping velocity in accordance to the actual material properties. After 60 min of slipping and filling, these actions became synchronized, and as a result, the slipping became almost constant.
Figure 72: Velocity diagram: average velocity 1.2 cm/min

Figure 73: Upper left: manual filling of layers at the start of production. Right: rotation of square formwork. Lower image: tapping to empirically evaluate the evolving material properties.
The initial assumptions concerning this new geometry was that the small radii in the corner of the formwork would cause the material to rip. However, this did not occur. Instead, the result was a smooth rotation in which no visible cracks or rips could be detected. The lines featured in the prototype depicted in Figure 75 are traces of the digital code (the robot is programmed to interpolate the rotation every 10 mm). All in all, the experiment was clear evidence that if the filling and the slipping are synchronised, new possibilities for producing and designing concrete structures can be explored.
Figure 74: A close-up of the final part of the column, where the digital interpolation of the code are evident.

Figure 75: Result of square column.
4.2.8. Experiment H: Star-shaped formwork

The last experiment described in this section once again aimed to test formability – this time with the star-shaped formwork described in Section 3.6. The goal of this experiment was to push the geometrical possibilities of robotic slipforming to its limits. A particular goal was to learn whether the cross section of the star would cause additional challenges when shaping a column with 180° of rotation over a height of 1800 mm. The experiment used the same material system and acceleration process as in Experiments D, E, and F. The intermixing process was the same as in Experiment E and F, also described in detail in APPENDIX 4:. The filling process remained the same as the one used in Experiment F, where the first pure layers of material were placed in layers of 34 mm at 5 min time intervals. Once again, the goal was to have a consistent filling and placing method.

The slipping began when the B1.1 material sample measured 4.4 N. After this point, the velocity was gradually increased from 0 to 2.4 cm/min (see Figure 76). Once again, the velocity fluctuated in the beginning due to lack of data regarding the material properties. The material began to collapse 60 min into the process, causing a full stop that can be observed in the velocity diagram. Evidence of the full stop can also be observed in the finished column in the form of a bulky feature at approximately 700 mm height (Figure 77). The collapse was due to the layers being filled slightly faster than the slipping, causing the load of the material in the formwork to exceed the load capacity of the already shaped material.

![Figure 76: Velocity graph of experiment H. The y-axis shows the velocity in cm/min, and the x-axis shows the time of slipping in min. Note the initial fluctuation, and also the full stop at 60 min, which resulted in the bulky formation on the column depicted in Figure 73.](image-url)
Figure 77: The column shaped with the star-shaped formwork. At 700 mm, a small bulky feature can be seen. This is the result of the material being filled too quickly in relation to the slipping.
Despite this minor imperfection, the experiment nonetheless showed that the robotic slipforming process is suitable for forming complex geometries such as the one generated by the star-shaped formwork. The experiment also reconfirmed that a continuous slipping and filling process must be pursued if the robotic slipforming system is to be used efficiently at an industrial scale.

4.2.9. Conclusion about the semi-continuous process

The semi-continuous experiments clearly developed the SDC technique further, eliminating the problems in the transition zone between batches (Section 4.2). These experiments also proved that it is generally feasible to robotically shape concrete in 1:1 rotated SDC columns using a variety of geometrical cross sections.

By applying non-circular geometries (ellipse, square, and star geometry) in a 180° rotational trajectory, it was possible to detect some of the major challenges connected to the SDC process. First, the friction force increased over time in all three formwork types due to the loss of lubricant (oil) inside the formwork. However, it was shown in experiments that the friction force could be eliminated by the use of local vibration, and by ensuring that material residue from previously placed batches was well intermixed with the subsequent batch (also by means of vibration). The second challenge – shear force – became evident in the rotational trajectory with the non-circular geometries. It was concluded that if the material was shaped too late, significant shear forces caused by the hardening material would result in horizontal cracks. To prevent this, the slipping was started at 4 N, which is slightly earlier than in the experiment discussed in Section 4.1. (where the slipping was started between 5-6 N). This approach appeared to reduce friction and shear forces on the material, and resulted in smoother surfaces on the finished structures. The early slipping technique was used effectively with both the star-shaped and the square formworks – the latter resulting in a smooth column with no visual cracks or bulky features whatsoever.

A second key to successful shaping is to ensure that the material being filled does not exceed the load capacities of the material being shaped. This was evident in Experiment F, where a bulky feature emerged because more material was filled into the form than could be carried by the previous batch. It was also found that if the acceleration intervals of the individual batches deviated more than 2-3 min within a single production cycle, the velocity of the robot had to be change significantly. This had direct consequences for the overall filling-slipping-acceleration process, which had to be adjusted ad hoc to account for the changes during production.
Inconsistencies in the process resulted in the material being either too soft or too hard to be shaped, and was particularly evident in Experiment D, where both wrinkles and bulky features emerged due to unsynchronised filling and slipping.

The discontinuous system would not have been possible without the robotic control unit. This unit was used to: 1) continuously monitor the height of the material in the formwork (a crucial function for the success of the semi-continuous system, since it ensured that the material in the formwork remained within certain height bounds); and 2) precisely control the slipping velocity, which through inline control could be set in accordance to the material properties. This replaced the rough and predefined velocity used in the experiments described in Section 4.1.

The robotic control unit was additionally able to run the process in a fully automated mode based on measurements from the material monitoring unit about the material properties of the batches. However, this function was not used in the semi-continuous process, as it would have required a sample of each intermixed batch to be extracted. The system was used to 1) dictate when to start the production, and 2) to ensure that the subsequently accelerated batches hydrated as expected. In the intermediate period when the batches were intermixed, the system relied on real-time empirical monitoring and on synchronised filling and slipping process.

Overall, the prototypes produced in this set of experiments were considered successful as they proved that by ensuring a gradual hydration of the material in line with the shaping, columns can be produced without cracks or flow of material. In particular, this allowed the production of columns with relatively good surface quality and no visual evidence of the transition from one batch to the next. Thus, the semi-continuous processing system successfully proved the overall architectural potential of SDC as a design and fabrication system that is capable of producing non-standard concrete columns without the use of excessive formwork material.

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210 Extracting a sample of each intermixed batch would require extracting more than 60 samples during production – a task that would be a significant logistical undertaking.

211 A reasonable way to automate the system would be to develop a reliable simulation tool that could, in real time, interpolate the material properties based on a single sample extracted from the first accelerated batch. Another possibility would be to introduce a non-destructible measuring technique directly mounted on the formwork, for which parallel studies have been conducted in collaboration with the former ETH-group of Chiara Daraio, at the Chair of Mechanics and Material. These studies tested a device that has the potential of measuring the non-linear behaviour of the material over time. For further information: C. Beck, M. S. Garcia, T. Reuter, C. Daraio, L. Bonanomi, D. Eggenspieler, “Devise and Method for a Non-Destructive Measurement of Mechanical Properties”. Patent No. EP15193239.9. (Zurich, Switzerland, 2015).
4.3. Continuous slipforming: Pump integration

4.3.1. Concepts and goals of experiments

Based on the findings from the intermixing process, where it was concluded that an automated filling system would be advantageous for SDC, the goal of the next set of experiments was to implement a continuous feeding system. This was explored by applying a standard pump system that was empirically known\textsuperscript{212} to be appropriate for the SDC production process.\textsuperscript{213} Key objectives were to: 1) refine the formability of the material during the slipping process; and 2) simplify the overall production by automating the filling process. To ensure that the results would be comparable to previous experiments, the focus remained on producing full-scale prototypes – specifically, with a height of 1800 mm and a rotation of 180° around the central axis.

The main challenge in implementing the pump turned out to be synchronising the pumping rate with the slipping rate. It was discovered after the accelerated material was placed in the pump that a thixotropic build-up caused it to lose its self-consolidating properties by the time it exited the pipe. Several solutions were developed to compensate for this effect, including shortening the pipe and using vibration tools to improve the workability of the material. Though these mechanical actions were not optimal, they were sufficient enough to enable the experiments to proceed.

Results from the first test suggested that the pumping could be approximately 50% faster than the semi-continuous process described in Section 4.2., so long as the logistics of mixing could be simplified. However, this would require that the retardation of Mix C to be extended from 3 to 7 h. As such only one large batch of material was required for the production. An outline of this adjustment is described in APPENDIX 2: and is referred to as Mix D.

\textsuperscript{212}A set of experiments were conducted with the pump. These experiments ensured that the concrete mix design used in this thesis could be pushed through the pump without losing a significant amounts of aggregate. This was tested by running the material through the pump and visually evaluating if a substantial amount of stone or fibre was left behind in the pump container after all the material had been pumped through. This was not the case, and as such, the pump was initially validated as a suitable processing devise.

\textsuperscript{213}The integration of the pump into the SDC system was done in a bachelor thesis project by S. Garcia et al., "Optimierung des Misch- und Betoniervorgangs bei der Herstellung von frei geformten 3D-Betonelementen", jointly supervised by Robert J. Flatt, Heinz Richner, Linus Mettler and the author of this thesis. The main goal of the studies was to define a method and technique in which the pump could be used in the SDC process.
4.3.2. Material and processing method

4.3.2.1. Material and processing method

In the first experiment with the pump, described in Section 0, the number of retarded batches of Mix C was increased from 3 to 4 (18 l). The large batches were mixed at 30 min time intervals. After each large batch was mixed, it was brought to the robotic laboratory for acceleration, which was done at 17-20 min intervals. The first batch was 10 l, and subsequent batches were 6 l, for reasons described in Section 4.3.2.2.

The goal of simultaneously increasing the number of retarded batches while decreasing their size was to ensure that the material retains workability and is not caught in the pump system during pumping and production.

Results from the first experiment with the pump indicated that the logistical effort of mixing large batches was causing time delays that directly affected the production process. Thus the material mix design was changed to give a workability time of 7 h, (see Mix D, APPENDIX 1, Table 10.). The experiments from 4.3.5. onwards use the new Mix D. The process therefore required mixing only one 80 l batch of Mix D using the mixing method described in Table 13 of APPENDIX 1. After mixing, the large batch was accelerated. In this case, the first batch was 10 l (23.35 kg), and was processed as described in Section 4.3.2.2. The subsequent 11 batches were 6 l (14.10 kg) each. After the material was accelerated, it was placed in the pump according to a set of rules described in the Section 4.3.2.2 "Pump processing rules".

4.3.2.2. Pump processing rules

The rules proposed for processing the material with a concrete pump are based on systematic studies that analysed how the material flows inside the pump container. In these studies, a division plate was inserted into the pump (see Figure 78) to ensure that the material remained in the intended position inside the pump. Pigments were added to the respective batches to help

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214 In the experiments in Section 4.2., the large retarded batch was 25 l, while the accelerated batches were 12.5 l.
215 Further, a strategy was developed that theoretically simplified the process of mixing the large batches; however, this method required that two large batches were mixed within 8 min. This was not possible without automating the entire process. Further descriptions of this theory can be found in: S. Garcia et al., “Optimierung des Misch- und Betoniervorgangs bei der Herstellung von frei geformten 3D-Betonelementen”, 33-34.
216 These rules are valid for material Mixes C and D, as both mixes have approximately the same rheological properties after the accelerator has been added to the retarded mix.
visually detect the transition from one batch to the next. Results showed that when a batch was placed at the back of the pump container (see Figure 78, left), the material would gradually intermix. By contrast, when the material was placed at the front of the pump container, it would remain on the upper level of the already placed material, and would therefore not gradually intermix (see Figure 78, right). Hence, one rule developed in this study is to place new material at the back of the pump container.

![Figure 78: A schematic of the pump intermixing process. A) shows the gradual intermix of the material when a batch is placed at the back. By contrast, B) shows that when a batch is placed at the front of the pump, it does not intermix.](image)

The division plate was not used during production because, ultimately, it complicated the process: material residue tended to attach to the plate, which then required further cleaning. To ensure that the material was gradually intermixed required that the batch in the pump container had reached an inclined position (illustrated on the right in Figure 79) before a subsequent batch was placed.217

At the start of production, the first accelerated batch (10 l) was placed in the pump. The first 3 l of this material were discarded, as it generally contained water remains (from previous cleaning) that could change the material’s water-to-binder ratio, resulting substantial changes in the

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217 Prior to placing a batch, the pump should be turned off, and residue from previous batches removed.
strength properties. To ensure that water residues were no longer present, a slump flow test was conducted using the method described in Section 3.5.1. Once the slump flow test confirmed the quality of the material, the pumping could begin. First, a 1 l sample of material was pumped into the measuring container for the inline measurement system, while 10 cm of material were simultaneously pumped into the formwork (which was not yet moving). Then 20 mm layers were pumped into the formwork at (approximately) 3 min time intervals until a predefined height of 450 mm was reached. When the inline measurement results of B1.2 showed 4.5-5 N, the robotic slipping began.

Figure 79: A schematic of the pump filling process, showing how batches of material move through the pump. Left: A first batch (red) is placed at the back of the pump container. Right: The subsequent batch (grey) is placed when the red batch has reached an inclined position.

4.3.3. Experimental setup

4.3.3.1. Robotic equipment and formwork

In this experiment series, the robotic set up and formwork system remained the same as described in Section 4.2.3., in which the formwork consisted of a modular system milled out of polyurethane foam. Unlike the first experiment, which used the star-shaped formwork, the following experiments employed the elliptical formwork to enable comparison between the changes in the individual experiments. This was particularly important with respect to the mechanical vibrations tools, which had to be inserted to regain the workability of the material after pumping. Also new was the pump system, which was mechanically attached to the upper part of the formwork frame (see Figure 77).

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218 Note that the material in the formwork must remain at a constant height, which must be defined prior to production (e.g. 450 mm). This height can indeed vary slightly from production to production, but should remain constant within one production cycle. The predefined height has a direct impact on the production rate.
4.3.3.2. Pump system

The initial challenge of automating the system turned out to be finding a pump that was both slow enough to synchronise the pumping rate with the slipping rate and powerful enough to pump a real scale building material with aggregate sizes up to 4 mm and fibre lengths ranging from 6-12 mm.

Research on various pump systems revealed that pumps that were slow enough for the SDC process were not able to deal with the required aggregate sizes. Likewise, pumps that could handle the aggregate sizes were too fast, unless a stop-go mode was employed. Ultimately a PFT SWING L 400 pump was selected (Figure 81) as a compromise. This type of pump is generally used for mortar and plastering material with aggregate sizes up to 8 mm, and turned out to be a feasible solution for the experimental sequence. The pump was, in theory, too fast.

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219 The filling rate should be 1 cm/min, which corresponds to 0.3 l/min. Standard mortar pumps, such as the type selected for this experiment, have a minimum pumping rate of 6 l/min. This is extensively faster than needed; therefore, a start/stop modus had to be used.

220 Here the real scale building material refers interchangeably to Mix C and Mix D, which both have the same rheological properties after accelerating.

221 Press hose pumps are generally able to pump very slow, however a set of tests showed that the aggregates were not able to pass though the pump and caused it to break down. A series of pumps were tested from the company Watson-Marlow, and can be found in: Watson-Marlow Pumps Group, catalogue. "Problemlosung Verdrängerpumpen." (Wilmington, Massachusetts: Watson Marlow, 2015).


223 The pump was systematically tested analysed in order to define an appropriate method for implementing the pump in SDC. The studies can be found in: Bachelor Thesis: S. Garcia et al., "Optimierung des Misch- und Betontervorgangs bei der Herstellung von frei geformten 3D-Betonelementen".
However, it could be operated in a stop-go mode, and more importantly, it was able to process the material without significant loss of aggregate and fibre.224

Figure 81: Pump type. Left: PFT SWING L 400 with a) the standard rotor, b) connection point for pipe, and c) pump container. Right: The view inside pump container, with the arrow indicating flow direction.

In addition to the pump’s standard components (rotor, pump connection point, and container, illustrated in Figure 81) a 5-m long pipe with an inner diameter of 35 mm (total volume = 1.95 l) was needed to reach from the floor up to the maximum building height of the robot. For reasons discussed in Section 4.4.6., the pipe was eventually shortened to 3 m, reducing the volume to 1.15 l.225

A remote control for starting and stopping the pump was also added, as this allowed the robotic controller to coordinate the pumping with the slipping. A set of studies determined that the minimum flow rate of the pump was 5.21 l/min when using the standard rotor226 – far faster than the target filling rate of 1-2 cm/min, corresponding to 0.3 to 0.6 l/min.227 To compensate for this, a strategy that involved starting and stopping the pump at specific time intervals was developed. For instance, the pump would be turned on for 10 sec to fill the formwork up 20 mm, and then stopped for a specific time to adjust to the slipping speed, which can range from 1-5 min, depending on the hydration rate of the material being slipped.

4.3.3.3. Inline material monitoring system and robotic control

The robotic control system was significantly expanded upon for the experiments conducted in Section 4.2. Because these developments are also applicable to the continuous system, the

224 A comparative study of potential fibre loss was analysed. This was done by filtering equal amounts of material through a bucket before and after pumping. The studies concluded that the fibre loss was not significantly high (approx. 2%). S. Garcia et al., "Optimierung des Misch- und Betoniervorgangs bei der Herstellung von frei geformten 3D-Betonelementen", 32.

225 Note that if the cross section of the formwork is scaled up to a radius of 200 mm, the pump could be used for a continuous filling process, where layers of 50 mm would be filled every minute. The studies are reported in: S. Garcia et al., "Optimierung des Misch- und Betoniervorgangs bei der Herstellung von frei geformten 3D-Betonelementen", 30.

226 The rates of the pump are reported in: S. Garcia et al., "Optimierung des Misch- und Betoniervorgangs bei der Herstellung von frei geformten 3D-Betonelementen", 30-32.
control system remained the same. The system allows the height of the material in the formwork to be detected, and can therefore be used to precisely determine when to fill material – information that is highly relevant when determining the pumping rate. Second, the robotic control unit precisely controlled and recorded the velocity, gradually in accordance with the material properties. Furthermore, the control system was developed to automatically control the entire process of slipping based on the measurements received from the inline material monitoring system. The fully automated system was not used because the semi-continuous experiments indicated that it would be necessary to extract a sample of each intermixed batch, and this was both logistically difficult and likely to cause delays. However, the semi-continuous experiments also showed that the process could function without continuous measurements as long as the slipping and filling are synchronised and the material state can be manually verified as the slipping progresses. It was therefore concluded that it was not necessary to extract material samples from each batch (even though a sample of the first pumped material was still extracted to help decide when to initiate the start of production).

4.3.4. Experiment H: Pump without pipe

The first experiment conducted with the pump system aimed to produce an 1800 mm column with a rotated trajectory of 180° using the square formwork described in Section 4.3.3. This initial experiment used Mix C. 228 As described in Section 4.3.2.1, this particular experiment increased the number of retarded batches from 3 to 4 x 18 l of Mix C. 229 These were mixed in 30 min intervals. Furthermore, the accelerated batches decreased in size, from 12.5 l (as in the previous experiment in Section 4.2.) to 6 l. Increasing the number of retarded batches while decreasing the size of each batch helped to keep the material workable throughout the entire pumping and production process. This experiment also used the material monitoring system to evaluate the hydration rate of the first accelerated batch of each mix. The goal here was to evaluate the hydration rate of each batch (B1.1, B2.1, B3.1, B4.1), in order to ensure that they behaved similarly.

A pipe is normally attached to the pump (see Section 4.3.3.2), but it was not used in this experiment because it was not known at this point exactly where in the pumping process the

228 At this point it was not yet known that Mix C was causing significant delays in the process.
229 In the experiments in Section 4.2., the large retarded batch was 25 l, while the accelerated batches were 12.5 l.
material loses its self-consolidating properties. To evaluate the process, the pipe was initially replaced with 10 cups with a volume of 0.5 l each (see Figure 82). The cups were subsequently filled and placed at sequential time intervals during production. In theory, the amount of material placed in the cups reflected the amount of material that would be pumped through the pipe during production.

Figure 82: Schematic illustration of the production setup. The material is pumped into 1 l cups at 3-5 min intervals. The amount of material in the cups reflected the amount of material that would be in the pipe. Thus by replacing the pipe with cups it was possible to empirically evaluate at which point the material might lose its workability to such an extent that it was no longer self-consolidating.

After the first batch (B.1.1) was accelerated, the processing rules described in Section 4.3.2. were followed. Production began 95 min after water was added. At this point, the material in the monitoring system measured 4.5 N and the material in the formwork had reached a filling height of 400 mm. The goal from here on was to maintain a filling rate that kept the material in the formwork at a constant height of 400 mm. As expected, the material in the cups lost its workability as the filling progressed. To manage this problem, a two-step process was introduced ad hoc, in which the material in the cup was stirred and the material at the surface of the formwork was vibrated (a similar strategy was used in the semi-continuous process Section 4.2.).

Aside from this issue, the first part of the production proceeded as expected, meaning that no cracks or flow of material occurred. However, the overall process turned out to be logistically challenging. Mixing four large batches in 30 min time intervals was not possible, as it turned out that transporting the material and cleaning the equipment was significantly more time consuming than expected. The additional stirring contributed to this logistical challenge. This resulted in the

230 In the semi-continuous experiments described in Section 4.2, the material was stirred before it was placed in the formwork, allowing the thixotropic build-up to be broken down and ensuring that the material was self-consolidated as it was being placed. This is not possible when using a pipe.
third batch being mixed 10 min later than planned (see Figure 83). This delay alone was long enough to cause a chain reaction of delays and major problems such as material inconsistency and the loss of workability in the material in the cups, which then required further processing (stirring).

This required the slipping to be slowed significantly after 78 min (see Figure 84), which meant that the pumping rate had to be slowed down as well. This in turn caused the material to stiffen and clog the inside of the pump container and especially around the pump exit, preventing the correct amount of material from exiting the pipe. In the end, the last batch had to be manually filled into the formwork to complete the experiment. Bulks were apparent on the final column because the overly fast filling rate caused excessive loads on the lower layers (see Figure 85).
Figure 84: Slipping velocity over production time. The grey line shows the velocity changing during production. The red line indicates an average velocity of 1.09 cm/min. The graph shows that the velocity had to be reduced significantly after having slipped for 78 min. This drop in velocity occurred in the area where batch B2.3 and batch B3.1 intersect. It was here that a sudden change in strength properties occurred when the delayed mixing of B3 prevented a gradual transition between the batches.

Figure 85: Result of Experiment H, which was produced using four subsequently mixed batches of Mix C. The column has bulky features at the transition between B2.3 and B1.3.

As such, despite having produced a column with a height of 1800 mm in only 2 h and 22 min, the experiment clearly showed that material and mixing logistics must be radically simplified if a pump system is to be used for SDC; after all, the overall aim of implementing the pump was to significantly simplify the production. The results of the experiment indicated that a radical approach would be to extend the workability of the material, and fully automate the acceleration.

231 This production speed is on average 40 min faster than producing a similar column with the semi-continuous process described in Section 4.2., and more than two times faster than the discontinuous process described in Section 4.1.
A first step for further experiments would therefore be to develop a material with an extended workability time. This, in turn, would eliminate delays caused by mixing large batches in sequence. In such a process, the acceleration could be done ad hoc, according to the pumping and slipping rate.

### 4.3.5. Experiment I: Pump with pipe

Experiment I used a new Mix D (see Table 10, APPENDIX 1.), which has an extended workability time of 7 h. This meant it was no longer necessary to mix subsequent retarded batches to extend the workability of the large retarded batch. Instead, one large batch was mixed prior to production, and was subsequently accelerated in 6 l portions at time intervals defined by the process (see Section 4.3.2.2). The overall goal was to prove that the SDC process could be radically simplified to continuously produce columns without bulky features or cracks – ideally, with a perfect surface. Practically speaking, this meant being able to process the new material with the pump into the formwork at 15 min intervals. For the purpose of comparison this experiment once again aimed to produce an elliptical column of 1800 mm, rotated 180°, using the elliptical formwork described in Section 4.2.3. This enabled the process and final structure to be compared with the previous experiments described in Section 4.1. and 4.3.

A 5-m long pipe with a volume of 1.95 l (see 4.3.3.2) was used in this experiment. Because Mix D has similar rheological properties as Mix C, it was anticipated that, after accelerating and being placed in the pump for a given time, the material would once again lose its self-consolidating properties. An electronic mixing device in the form of a paddle stirrer onto which a custom flexible rubber was attached (see Figure 86) was therefore used to continuously stir the upper 50 mm of the material in the formwork, and thereby break down any thixotropic build-up that might prevent the pumped material from self-consolidating. The goal of using the mixer was to replace the manual vibration employed in the previous Section and further automate the process. Note that, due to the simplified production, the material monitoring system is only used to detect the moment at which the material in the first batch is ready to be shaped.

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232 An outline of the material adaptation is given in APPENDIX 2:

233 Here it is important to distinguish between the workability of the retarded batch and the accelerated batch. Mix D has a workability time of 7 h, and during this period has low viscosity. However, with the addition of retarders, the material is chemically kept in a 'dormant phase'. After the accelerator is added, the material goes into its acceleration phase. SDC exploits the early part of the acceleration phase for shaping. This period lasts approximately 10 min, after which the material loses its shapeability unless the material is stirred or vibrated (see Section 3.4.1).

234 When the material was processed through the pipe without a pump, it lost its self-consolidating properties after resting in the cups for a certain amount of time. This is further described in 4.3.4.
Prior to production, a large batch of Material Mix D was prepared according to the mixing process described in APPENDIX 1, Table 13. Once the mixing was finished, the large 80 l batch was brought to the robotic fabrication laboratory. Exactly 60 min after the water was added to the large retarded batch, the first 10 l batch was accelerated and further processed, as described in Section 4.3.2. The subsequent four batches were accelerated in 20 min intervals and subsequently poured into the pump container just as the previously placed batch reached the inclined position. Small portions of material were simultaneously pumped into the formwork (approximately 2 cm in time intervals of 5 min). At 90 min, batch B1.1 had reached 5 N and production began. At this point, the material in the form had reached 500 mm. From this point on, the acceleration intervals were reduced to 15 min for the first 40 min (see Figure 88). However, at a height of 1200 mm, the velocity was reduced (see Figure 88) because material had accumulated on the stirring tool and at the exit point of the pipe. The velocity was slowed and the acceleration intervals of (B1.6 and B1.7) were reduced ad hoc to 25 min while the material was cleaned off the stirrer and the pipe exit point. This resulted in a fraction on the surface of the column, which featured as holes (see Figure 87, left). The acceleration time of the remaining five batches was gradually decreased to 20 min, and the velocity was also increased. However, after this point it was necessary to continuously clean the upper edge of the formwork, the exit of the pipe, and the stirrer to prevent material from accumulating.

\[235\] Note that to obtain a gradual transition from one batch to the next, the material must reach an inclined position in the pipe before a subsequent batch is placed.
The resulting column was produced within two hours (see Figure 88) using a single material mix. The experiment was considered to be a partial success, as the inconsistencies in material hydration observed in all previous experiments were eliminated.

However, the goal of fully automating the process was not completely achieved, in part because the material (as suspected) lost its self-consolidating properties while in the pipe. Material continued to accumulate around the pipe exit (despite continuous stirring), causing fractures to
emerge on the surface of the column. Ultimately, it would not have been possible to complete the experiment without manually cleaning the pipe exit and the stirrer.

The loss of self-consolidating properties could be solved by developing a new mix that is better able to maintain a state of self-consolidation after it has been accelerated, or by developing a processing method that automatically accelerates smaller doses of retarded material. However, both solutions would require extensive investigation into the material and processing system. Another solution would be to further investigate mechanical methods, such as vibration, for re-fluidifying the material. Finally, an ad hoc solution would be to shorten the pipe and thus reduce the amount of material processed in it. The latter two options were explored in the subsequent experiment, as it did not require reformulating the material or the pumping system.

4.3.6. Experiment J: Exploring vibration tools

The objective of the three experiments described in this section was to reduce the manual intervention needed to ensure that the material remains self-consolidating.

These experiments replaced the rotating mixing device used in the previous experiment with a vibration device (Type: Vibro Mixer E 1, see Figure 89, left). Three custom vibration end-effectors (see Figure 89, right) were developed and tested in the order in which they are presented. The first end-effector A) was a 2 mm aluminium cross with an elliptical border. The intention of this shape was to scatter the vibration from the centre to the border of the formwork. The cross shape should vibrate the upper 5 cm of the material in the form, while still enabling the material to flow through the shape. The second end-effector B) was made of a 2 cm x 2 cm prefabricated mesh diagonally connected to a rod. Once again, the goal was to distribute the vibration in the upper material of the formwork, while allowing the fibres to flow through. The final end-effector C) was a radical reduction of the star shape (A), and consisted of a bent rod with a diameter of 0.5 cm. The round profile of the rod was intended to ensure that no material or fibres would accumulate on the tool while it vibrated on the upper surface of the material.

The pipe was also reduced in these experiments from 5 m to 3 m, decreasing the volume of the pipe by 0.77 l.\textsuperscript{236} Reducing the length of the pipe by 2 m also reduced the time in which a portion

\textsuperscript{236} One consequence of shortening the pipe was that the pipe became elevated 60 cm from the floor. The ad hoc solution of shorting the pipe is thus not an adequate solution for future production, as the intention of SDC is to provide a flexible fabrication system for non-standard structures of architectural dimensions, which indeed refer to structures beyond 1800 mm.
of a batch (approximate 0.5 l) is inside the pipe by an average of 50%.

Indeed this was not sufficient for solving the problem of losing the self-consolidating properties of the material. However, the aim of this experiment was to determine the mechanical interventions (i.e., vibration) that might enable an elliptical rotated column without cracks or surface fractures to be produced using a fully automated filling process.

Figure 89: Various vibration tools. Left: Vibro Mixer E 1. Right: A) flat aluminium profile with wholes allowing material to flow through, while intending to distribute the frequency of the vibration. B) Diagonal assembled mesh, intending to distribute the vibration deeper into the cross section of the formwork while aligning the fibres. C) Bent rod, intending to distribute the vibration over the entire surface. The round profile of the rod is intended to ensure that no material would be caught on the tool.

Apart from changing the vibration device and shortening the pipe, the three experiments all used 80 l of material Mix D and employed the same elliptical formwork as the previous experiment described in Section 4.4.6. The processing also remained the same as the previous experiment, described in Section 4.3.5. This meant that the first 10 l batch of B1.1 was accelerated exactly 60 min after water was added to the large accelerated batch. The subsequent batches were then accelerated at 20 min intervals at the beginning of production, and thereafter accelerated at 17 min intervals.

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237 When assuming an average pumping rate of 0.5 l / 1.5 min, it takes 6 min for 0.5 of material to travel through the 5 m pipe, while it takes 3 min for 0.5 litre of the same amount of material when the pipe is 3 m. This means that for a 3 m pipe, the last material of the 6 l batch comes through after 18 min, if one includes the time during which the material is in the pump container and accounts for the fact that the last material pumped of a single batch is 36 min. Hence, the only possible way to regain the self-consolidating properties in this particular setup is by vibrating or stirring the material.

238 In the previous experiment, the intervals after the production was started were 15 min. However, this caused the material to further lose its self-consolidating properties. Hence reducing the time intervals also reduces the time during which the batches are left standing before being pumped.
Cross-shaped vibration tool

The cross-shaped vibration tool (Figure 86 A) was used in the first experiment in this set. In the initial experiment, the process proceeded as intended, and the material re-fluidified when the vibration tool was used. However, halfway through the production (at approximately 110 cm), the material began to accumulate on the border of the tool. In this case, the material was not removed so as to further explore the consequences of the build-up. This, indeed, resulted in accumulated material that eventually hardened and closed off the material flow in certain areas. The consequence of this can be seen in Figure 90, which shows that material is completely missing on one side of the column. Furthermore, towards the end of the production when the pumped material had accumulated all the way to upper part of the vibration tool, the upper part of the column was ripped off. Results from this experiment clearly indicate that the cross-shaped vibration tool was not appropriate as the flat surface of the vibration device caused the material to accumulate on the tool and eventually created a nest that prevented the material from flowing though.

![Image of experimental results using the cross-shaped vibration tool](image)

Figure 90: Experimental results using the cross-shaped vibration tool (see Figure 89 A). Left: a full view of the resulting columns. Right: a close-up of the column surface. The missing material is due to the fact that some of it had hardened on the edge surface of the vibration tool.

Mesh-based vibration tool

The mesh-based vibration tool (Figure 89 B) was used in the second experiment in this set. Like the other vibration tools, this one was developed to help maintain the self-consolidating
properties of the material inside the formwork. In this case, however, the geometry of the tool was intended to prevent material accumulation by helping the fibres to align with the flow direction.

Once again, this experiment initially advanced without problem, however the experiment began to fail when it reached a height of around 1 m, when excessive amounts of material had accumulated inside the mesh and had begun to harden. The experiment was stopped at this point as the tool had completely failed its purpose. In fact, the mesh had the complete opposite effect as intended: instead of aligning the fibres, it caused the fibres to nest further, completely blocking the flow of material, and eventually causing the material to be ripped off while still in the formwork (see Figure 91). Results from the experiment indicated that the mesh size should be increased by a factor of 3. However, due to the scale of the formwork and experiment, this option was excluded.

![Figure 91: Experimental results using the mesh-based vibration tool (see Figure 89 B). Left: a full view of the resulting column. Right: a close-up of the last slipformed part, in which the material had hardened completely. As a consequence, the material began to rip apart.](image)

**Coil-shaped vibration tool**

A coil-shaped vibration tool (Figure 86 C) was tested in the final experiment in this set. The bent elliptical spiral was a radical simplification of the two previously tested vibration tools. The goals of this minimal tool were to prevent fibres from accumulating and to test whether it could
sufficiently vibrate the material to maintain self-consolidation. It was also hoped that vibrating the edges might reduce friction while at the same time ensuring that material does not accumulate in the formwork edges, as was the case in the first experiment with the cross-shaped tool.

Figure 92: Experimental results using the coil-shaped vibration tool (see Figure 89 C). Left: a full view of the resulting column. Right: a close-up showing the wrinkles that occurred as an effect of the vibration tool moving itself out of its center position.

Overall, the vibration tool functioned well (see Figure 92) and no material accumulated on it, as was the case in the previous vibration experiments. The new vibration tool ensured good material workability, and it was possible to produce a full-scale column. This is particularly evident in the first 120 cm, in which the column was slipped without wrinkles or flow of material. Up until this point, the feeding process had been autonomous and the surface of the column was therefore smooth (see Figure 92). However, after this point the tool had vibrated itself out of the centre position and touched the inner side of the formwork edge. The result was that the entire formwork vibrated slightly, which made the material at the bottom of the formwork fluid, resulting in wrinkles on the surface of the column (see Figure 92, right). To prevent collapse, the vibration tool was turned off at 140 cm. After this point, the slipping velocity was kept constant (see Figure 93), and the last part of the column was slipped in a completely autonomous process, without any manual interference whatsoever.
Figure 93: Slipping velocity over production time. The grey line shows the velocity changes during production. The red line shows the average velocity (0.24 mm/sec = 1.48 cm/min).

The column reached 180 cm and was slipped in 100 min, which was on average 50% faster than the columns produced in Section 4.2. Apart from the occurrence of wrinkles, the tool principally showed that constantly vibrating the material on the upper section inside the formwork can ensure that the material self-consolidates after being pumped.

This explorative study was another important step in showing that SDC can become a fully automated and efficient production process for non-standard concrete structures. However, the goal of producing a column without trace of batches, wrinkles, surface fractions, or cracks remained – at this point – elusive.

4.3.7. Experiment K: Testing optimal shaping

The final experiment conducted in Section 4.3.6. showed that the self-consolidating properties of the material can be maintained after pumping, and thus proved SDC’s potential to become an efficient production method for non-standard structures. However, up to this point, the automated pumping process had still not been able to produce a single column without surface imperfections or wrinkles. Hence, the goal of the next experiment was to use the automated processing method (from Section 4.3.5.) with a pipe length of 3 m (as in 4.3.6.) to produce an elliptical rotated column with a smooth surface. The experiments on automated vibration tools were unable to address surface quality, and so the following experiment discarded this option and instead returned to the manual vibration tool as an aid to maintain workability after pumping (see Section 4.2.).

The material process remained the same as in previous experiments, described in Section 4.3.5. and Section 4.3.6. Hence, the process began by mixing 80 l of retarded Mix D. The first batch
B1.1 was accelerated 60 min after adding water to Mix D. Thereafter, the batches were accelerated at 20 min intervals. Production began when the material measured 4.5 N; at this point the formwork was filled to 45 cm. The slipping was done at a velocity ranging from 1.32 cm/min to 2 cm/min (see Figure 94). The pumping was done in time intervals that ensured that the material in the form remained a constant height of 45 cm. Before material was pumped into the form, the upper edge of the formwork (2-3 cm) was cleaned off and oiled, and the pipe exit was cleaned off with a cloth. At every second filling, the material surface was vibrated using the manually held vibration tool (see Section 4.2.).

![Figure 94: Slipping velocity over production time. The grey line shows the velocity changes during production. The red line shows the average velocity (0.25 mm/sec = 1.49 cm/min)](image)

The result was successful. For the first time it was possible to produce a smoothly shaped column without visual cracks or bulks (Figure 95). The images show that the column has a smooth surface without traces of the transition from one batch to the next. The rotational shaping did not cause horizontal cracking in the transition zones between the batches because the transition was gradual. However, despite the fact that the acceleration was done at precise intervals, the slipping velocity could not be kept constant. To ensure that the surface was smooth, it was necessary to constantly adjust the velocity during production based on empirical evaluation of the material properties, which during the slipping, had slightly different hardening properties around the cross section of the column. In other words, even though most of the process can be run autonomously, it is still necessary to have a human in the loop to evaluate the material properties and set the velocity accordingly.
The experiment was nevertheless considered successful as it showed that by automating the feeding process, a gradual transition can be achieved from one batch to the next.

![Image](image.png)

**Figure 95:** Right: the result of the column produced with an automated pumping process and a manually controlled vibration. Left: a close-up of the column. Note that the surface is smooth and shows no trace of the individual batches.

### 4.3.8. Conclusions about the continuous process

This experiment series proved that a pump system can be used to ensure a continuous and gradual intermixing and filling of multiple accelerated batches. This enabled the production of smooth columns without traces of the individual batches, and without substantial cracks or material flow. This was particularly evident in the final experiment in this section (Section 4.3.7.), in which a full-scale column with a smooth surface was produced.

Furthermore, the experiments conducted with the pump could, on average, be processed 50% faster than the previous experiment (Section 4.2.), which used a semi-continuous production method. This is also shown in Figure 96, which compares the slipping velocity of the third experiment in Section 4.3.6. with the slipping velocity of the semi-continuous production process described in Section 4.2.6. As compared to the discontinuous process described in Section 4.1., this new automated process is simpler, uses significantly smaller batches, shapes the material smoothly, and does so 75% faster than the initial SDC batch production.
The fast production was due to two major factors: 1) the pump-based continuous process had eliminated the need to stop slipping in the transition zone from one batch to the next; and 2) in comparison to material Mix C, Mix D hydrated faster once it had been accelerated (see Figure 133, APPENDIX 2:).

Despite these successes, one problem remained unsolved: namely, that the material tends to lose its self-consolidating properties in the time that it takes a batch to reach the formwork after being accelerated. To shorten this time, the pipe length was decreased. Also, various vibration end-effectors were developed and tested to see if they could help maintain the material’s self-consolidation properties.

The experiments yielded two main conclusions. First, the frequency of vibration must be precisely controlled since an overly high vibration force can affect the structural build-up of the material to a point where the material collapses or wrinkles. The latter was the case in the third experiment described in Section 4.3.6. Second, the geometry of the vibration tool must be simple enough to ensure that fibres do not accumulate and block the flow of the material. Even though a final solution for an automated vibration tool was not obtained, it could be concluded that the material could regain its self-consolidating properties after being pumped. In the case of the final experiment conducted in this section (see 4.3.7.), a perfectly shaped column was produced with the help of a manually held vibration tool. These experiments proved that – as long as the
material is self-consolidating inside the formwork – an automated feeding system is not only faster, but it also enables smooth shaping of concrete in its early transition phase.\textsuperscript{239}

\textsuperscript{239}In future research, a processing and material system could be developed that enables smaller batches of material to be accelerated. This could be a viable solution for maintaining the self-consolidating properties of the material throughout the entire feeding process.
4.4. Flexible formwork for robotic slipforming

4.4.1. Concept and goals

The experiments in the following section focused on implementing a flexible formwork into the SDC robotic fabrication process. The goals were to be able to dynamically change its cross section during the slipping process and to further explore geometrical possibilities and constraints when shaping concrete in its early hydration phase. Here, changing the cross section yields the potential to open up an expanded design space for SDC, enabling the production of more complex column designs and allowing for specific structural optimisation. To prove that the SDC system can be expanded beyond rigid formwork, however, a number of challenges (in particular, those related to friction forces) had to be addressed. Experiments with the flexible formwork must be seen as a key step in this research, as they further our basic understanding of how concrete can be shaped in its early transition from soft to a hard material.

Flexible formwork has been used by the construction industry to produce non-standard or geometrically differentiated concrete structures for centuries. An early example of an adaptable formwork system was developed in the 1960s for the construction of the Olympic Hall in Rome. This was an assembly of various modules produced with the same formwork.240 Other examples of flexible formwork systems are described in Section 2.3. and 2.5., and include both manually and digitally adaptable formwork systems. These systems rely on reconfiguring the formwork prior to the casting, however, and hence they do not dynamically shape the concrete during the phase when it changes from a soft to a hard material.

The experiments described in the following section were aimed to develop a flexible formwork system that allows 3D shaping of concrete during the slipping process by applying a digitally-controlled formwork that can change its geometry into specific configurations as the casting progresses. The overall formwork shape is in this case cylindrical, but can be manipulated by means of digitally controlled actuators that indent onto a flexible membrane while the formwork...

240 Pier Luigi Nervi, mainly known for his innovations in structural design, introduced what he named "structural prefabrication" for the construction of a large number of differently shaped structural building elements. His system allowed a radical reduction in the use of wood and steel reinforcement (today well known as Ferror Cementi) in a time of material shortage. Structural prefabrication was the result of empirical studies, integrating material and structural properties with fabrication logics. Further described in, P. L. Nervi, Aesthetics and Technology in Building by Pier Luigi Nervi, (Cambridge, Massachusetts: Harvard University Press, 1965) 106-107. The system was used for the construction of some dome structures for the 1960 Rome Olympics, including the spherical vault of the Sports Palace, a structure composed of 19 different kinds of prefabricated elements. Further described in: T. Iori, S. Poretti, "Pier Luigi Nervi's Works for the 1960 Rome Olympics." In conference proceedings, Actas del Cuarto Congreso Nacional de Historia de la Construcción, (Cádiz: COAAT Cádiz, 2005): 605-613.
is being moved by the robot during the slipping process. To shape an initially incompressible self-compacting concrete in three dimensions required the development of specific shaping techniques and systems that minimize inner friction generated during shaping and slipping.

The experiments described here are divided into three sections. The first explored the formwork configuration and material shaping devices. The second set of experiments tested various trajectories to gain insight into the shapeability of the material. The last experiment explored a technique to significantly reduce the inner friction force and thus address a number of the constraints inherent in this shaping process.

4.4.2. Material and processing rules

Mix D (See APPENDIX 1; Table 10) was used once again for the experiments conducted with the flexible formwork. For the 900 mm columns, 25 l of Mix D was needed, and was mixed with the process described Section 3.3., Table 2. For the tall demonstrators reaching 1800 mm in height, 60 l of Mix D was needed, and was mixed with the process described in, APPENDIX 1.; Table 13.

Independent of mixing size, the accelerated batches were each 12 l and were mixed using the method described in Section 3.3, Table 3. The batches were accelerated at 17-20 min intervals. The pump system was not used in this set of experiments because it had not yet been resolved how to prevent the material from losing its self-consolidating properties after exiting the pipe of the pump. Thus the intermixing strategy (defined in detail in APPENDIX 4:) was employed instead. In every experiment, the first batch was accelerated after 60 min. Then a sample was placed in the material monitoring system while 20-mm thick layers of material were simultaneously placed inside the formwork at 3-4 min intervals. The production started when 4.5 N was measured, continuing with the 20 mm layers and filling at intervals that ensured that the height of the material inside the formwork remained relatively constant (heights ranged from 350-450 mm).

4.4.3. Experimental setup

The following experiments also employ the full-scale robotic fabrication setup described in Section 3.6. and the overall research setup described in Section 4. However, in this case the end-effector of the robot used a custom digitally controlled flexible formwork system (see Figure
The formwork was controlled in line with the robotic control system via an application incorporated in the ONLINE GUI described in Section 4.2.4. The application will be further described in Section 4.5.4.1.

![Figure 97: The final setup of the flexible formwork, showing four actuators mounted to the bottom of the formwork (right).](image)

Experiment 4.2., proved that the star shaped formwork (which at that time was considered a complex shape) could be used to shape the material in a rotational trajectory. Thus the flexible formwork was configured with four actuators in such a fashion that the formwork could transform from a circular to a star shape by indenting the actuators up to a maximum of 50 mm.

However, the final configuration (and calibration) of the flexible formwork described in this section was determined through several iterations of experiments (described in Section 4.4.5.). These were used to define the final position of the actuators, the size of the end-effector on the actuator, the material system of the flexible membrane, the maximum indentation, and the material volume that can be shaped with this particular setup.

Based on these studies, the final setup of the flexible formwork was tailored to explore the possibilities of shaping this initial incompressible but soft material in three dimensions, not only using rotation, but also by indenting the material. The formwork consisted of polyurethane foam into which a cylindrical cross section (diameter = 214 mm and height = 400 mm) is milled. This main formwork was then assembled into a formwork frame mounted to the sixth axis of the robotic arm. A 2 mm flexible PVC membrane (inner diameter = 212 mm and height = 500 mm) was attached on the inner side of the formwork cylinder, and an inner core was mounted to the centre.

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241 In this case the formwork was also milled into cassettes of polyurethane foam with an outer dimension of 300 x 300 mm.
of the flexible formwork. The upper part of the core was rigid, while the lower 100 mm was flexible. The flexible part served as a inner support for the material while it was shaped.242

![Figure 98: Illustration of the flexible formwork end-effector: A) the formwork; B) the formwork frame; C) actuators; D) end-effector of actuator; E) membrane; F) inner-core with 80 mm in diameter.](image)

On the lower part of the formwork frame, four digitally controlled actuators were mounted at an equal distance around the cylinder.243 An end-effector in form of a half-spherical shape (diameter = 50 mm) was mounted at the end of each actuator. During production, the four actuators could either simultaneously or individually indent up to 50 mm into the flexible formwork membrane and thereby precisely change the shape of the formwork from its initial cylindrical form.244

![Figure 99: Schematic of overview of the indenting actuators. Left: view of the flexible formwork. Four actuators were mounted in equal distance around the formwork. The outer dimension of the formwork is 300x300 mm. Right: Schematic illustration of the three possible actuator configurations.](image)

242 The formwork frame was in this case also made of 300 x 300 mm Phoenix Mecano profiles, as described in Section 4.1. and 4.2.
243 The actuators refer to the electro cylinder from Festo, type EPCO-16-100-3P-ST-E-D+G+C5 DIOP. A comprehensive description of the electro cylinder and its control system can be found on: FESTO, 2015, “Support Portal”. Accessed, 01.03.2016.
244 Theoretically, the actuators can indent up to 80 mm; however, as the inner diameter of the formwork had a diameter of 210 mm and the outer dimension of the inner core had a diameter of 80 mm, this resulted in an initial material thickness of 65 mm before the material has been shaped. Hence, if the material was indented up to 80 mm, the membrane would press into the remaining material to such an extent that friction would rip the material apart.
4.4.4. Inline material monitoring system and robotic control

The robotic control unit was significantly developed for the experiments conducted in Section 4.2. and was also used in the experiments described in Section 4.3. As this had proven advantageous, a custom application was developed and implemented in the existing robotic control unit to enable the flexible formwork system to be controlled inline with the robotic fabrication system. The material monitoring unit was not further developed, as it was once again used only to dictate the start of the production.

4.4.4.1. Custom control of the flexible formwork

The Festo actuators used on the flexible formwork could not be synchronised with the KUKA control system. It was therefore necessary to write a custom control program that enabled the Festo actuators to be controlled in line with the KUKA control system.245 The custom program was written in Python, and controlled the actuators via Ethernet (CVE). The control of each actuator was done via individual CMMO-ST (control box). To control the individual actuators via the ONLINE GUI (via Python) the actuators were connect via a switch to the Ethernet port of the PC using the "Control via Ethernet" (CVE) function.246 As such, the respective control boxes were controlled via the Ethernet interface of a PC program, receiving data from the KUKA and sending it on to the actuators.247

Two files were generated to control the production process. The first file defines the movement of the robot (straight, rotational, or curved) and was generated with the Python export code to the robotic export code as described in Section 4.1.5. The second file, referred to as the design curve (see Figure 100), defined the indentation of the individual actuators at a specific height. The design curve was generated in the McNeel Rhinoceros CAD-platform and exported via the Grasshopper graphical programming interface as a list of coordinates, further described in Section 4.4.5.

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246 A switch in this context refers a box or “central hub” into which every CMMO box is wired. The box is connected to the Ethernet port of the PC.
247 The integration and development of the flexible formwork was done in collaboration with electrical engineer Maryam Tayeban and Student Assistant, Andreas Thoma. For further information, APPENDIX 6.
At start-up, the program loads a file containing the design curve (Figure 100) stored as a table that maps the height of the robotic arm along the z-axis to the positions of the actuators. The robot starts as soon as a velocity of a value of one or more was entered into the robot control unit. Once the fabrication begins, data regarding the position of the formwork is sent to the application at 60 millisecond intervals. The program then reads the updates about the position of the robot via serial port. The program searches for a corresponding actuator position in the second file containing the design curve for each robot position it receives, and moves the actuators accordingly using the CVE API over Ethernet.

Figure 100: Illustration of a design curve. The dark black line represents the design curve; the dotted line with a point at the end represents the actuator.
Figure 101: A flow chart diagram of the robotic control unit. The KUKA sends information via serial to the robotic control unit, which analyses the position and sends a signal to the respective actuators. In this example the actuators work in pairs opposite to each other (2+4 and 1+3).

The process could, as in the case of the experiment described in Section 4.2. and 4.3., be monitored during production via the robotic control unit’s GUI, which in this case was both connected to the robotic control system via serial interface and the actuators via Ethernet. The custom GUI (illustrated in Figure 102) provided control over various parameters and settings. The most important functions during production were the velocity of slipping (A) and the speed and position of the actuators (G).
4.5.4.2 Algorithmic design tool

The tool described in the following section is an extension of the algorithmic design tool developed for the rigid formwork (described in Section 4.1.5). Up until this point in the research, the tool had been developed to define the trajectory of a rigid formwork, and was hence used only to define the robot trajectory and give a preview of the intended structure. However, the next set of experiments employed a flexible formwork and involved four actuators, and thus a new function was added to the Grasshopper tool to define the trajectory of each actuator while generating a quasi-preview of what this would mean in terms of design. This meant that, in addition to defining the robot trajectory, the tool would now be used to define the indentation of the actuators at a specific height.

A rendering of the physical formwork was first drawn in Rhinoceros 2D to generate the design curve for production. The physical formwork was reflected as a cylindrical cross section with an inner membrane diameter of (d=212). The formwork was then linked to the Grasshopper tool,
where the number of actuators needed for the design curve were selected. These were represented as points and were parametrically linked both to the curve representing the formwork and to an individual curve. The curve represented the design curve (example in Figure 104) and could be manipulated. After the indentation of each actuator was defined, a robotic trajectory and fabrication height was selected, and a quasi-preview of the intended structure was generated. The parametricised curve enabled the respective actuator curves to be adjusted; however a warning was given if the indentors went beyond 50 mm. Assuming that the final trajectories were defined, a two-step process was then begun. The first step used a function in Grasshopper to convert the parametric geometry into a list of coordinates. As in the previous experiments, the coordinates were exported via the Phyton export script, which converted the coordinates into KRL code. The second step exported the movement of the respective actuators as a list of x, z values via Grasshopper; these values represented the design curve (see Figure 100). During production, the ONLINE GUI program read the position of the KUKA via a serial port, and for each robot position received, the program searched for the corresponding actuator positions in the table and moved the actuators according to the list using the CVE API over Ethernet.

![Figure 104: Left to right: Basic geometry of formwork arrows representing the actuators. Curves drawn in Rhinoceros representing the path curve of the actuator over the height of the column. Right: Basic settings for generating robotic paths A – D followed by Actuator Settings.](image)

### 4.4.5. Experiment A: Formwork calibration

Three experiment sequences are described in this section. The main objective of these experiments was to calibrate the specific components of the flexible formwork. Specifically, the experiments focused on: 1) the actuators and the effect of shaping in a one- or two-step process; 2) the effects of introducing a hollow core inside the formwork to reduce the volume of the material and to enable this incompressible material to be shaped in three dimensions; and finally 3) evaluating the effect of a flexible silicone membrane.
All these experiments all used 36 l of material Mix D (APPENDIX 1: Table 10), mixed according to the process described in Section 3.3., Table 2. The semi-continuous process (already validated in Section 4.2.) was once again used. In all cases, the formwork membrane was lubricated with a standard formwork oil prior to production in order to reduce friction. In all experiments, the first batch was accelerated after 60 min, and a sample of the accelerated batch was placed in the material monitoring system. Then 12 l batches were accelerated at 20 min intervals. The formwork initially differed from the final setup described in Section 4.5.3. in several ways. First, the basic formwork was 600 mm high (whereas later experiments were reduced to 300 mm; this was because later experiments showed that by reducing the height of the material in the form a better formability could be obtained). Second, the four actuators were mounted in two levels opposite each other. Finally, the membrane in this case consisted of a 2-mm thick silicone membrane that was 700 mm long (see Figure 105). The formwork was gradually adapted over the course of these experiments until it reached a final state, described in Section 4.4.3. All the experiments initially aimed to indent the material up to 50 mm by applying the design curve illustrated in Figure 106.

Figure 105: Two levels of actuators are mounted opposite each other. During the production, the upper actuators A2 and A4 indent first, followed by actuators A1 and A3.
Figure 106: The diagram illustrates the indentation of the actuator. During the process the upper actuators first indent the intended trajectory -5 mm. Then the lower actuators indent the entire intended trajectory. The intention is to disturb the structural build-up of the material as little as possible by indenting in two sequential steps.

A1: Actuator position

The initial exploration of the flexible formwork was intended to shape the material in a two-step process. The first mechanical setup of the flexible formwork thus consisted of two layers of actuators aligned on top of each other at a defined distance of 100 mm (see Figure 105).

The goal was for the upper actuators to continuously shape 50% of the intended design trajectory, while the lower actuators would follow, continuously indenting the remaining 50% of the trajectory. The goal of this two-step shaping process was to prevent any significant disturbance to the structural build-up of the material during the shaping.

Once the first batch was accelerated, 20 mm layers of material were placed inside the formwork at 3-4 min intervals. The production began when 4.5 N was measured; at this point the formwork was filled up to 460 mm. The filling continued at a pace that ensured that the height of the material inside the formwork was kept constant; in this case, the filling was incrementally increased by intervals of 2 cm every 1-1.5 min. The indentation began at a height of 100 mm, and the first 300 mm of the shaping and slipping were slipped without significant problems. However, at 400 mm – the point at which the lower actuator indented 50 mm – the material collapsed (see Figure 107).
It was suspected that the collapse had been caused by transitioning the filling rate too quickly after slipping. A second experiment thus repeated the process, this time ensuring that the filling rate after slipping was increased in precise increments of 0.5 min. The result was the same, however: this time the material collapsed at around 450 mm.

![Figure 107: Result of shaping with two levels of indentation. The image to the left shows the first part of the production, where the indentation was successfully achieved. The image on the right shows the material collapsing; this occurred at approximately the same time as when the lower actuators reached the maximum (50 mm) indentation.]

**A2: Implementing a hollow core**

Until this point, it had not been possible to prove that the actuated formwork could be used with SDC to shape concrete in three dimensions during the fabrication process. An excursus of experiments (described in APPENDIX 5) concluded that when slipping with the flexible formwork, constant friction caused tension forces at the surface of the material. It was also concluded that when indenting the flexible membrane, the compression force from the actuators caused the material to be pushed excessively downwards. Consequently, the two opposite forces tended to break down the structural build-up of the material, making it impossible to detect the right moment for shaping with the method used in the previous experiments. Two possible solutions to this problem were explored, both of which had potential to reduce the stresses used to the material during shaping. The first was to continuously pre-shape the formwork in the indented geometry, similar to a jump-form technique;\(^{248}\) this would require placing more actuators in the z-direction. The second was to create a void space in the centre of the formwork, into which the material could be displaced. The latter option was tested in the following experiment.

\(^{248}\) For more information on jump form systems, see: A. S. Hanna, *Concrete Formwork Systems* (New York: Marcel Dekker, 1999), 179-185.
Based on the conclusions of the excursus (described in APPENDIX 5) and the results of the first experiments described in this section, three major changes were made to the formwork. First, a rigid PVC core with a diameter of 80 mm was mounted to its centre (see Figure 108). The core reduced the material volume while providing space to displace the material being shaped with the actuators. Second, this experiment used only the two lower actuators for shaping, with the intention of reducing stress on the material. Third, the height of the rigid formwork part was reduced by 100 mm. While this had no significant effect, reducing the height showed just how little formwork is needed for the SDC process. The design curve of the actuators remained the same as in the previous experiment, and so a maximum indentation of 50 mm (see Figure 100) was retained. The material processing also remained the same as described the previous experiment.

The experiment resulted in a first intact column prototype that was 900 mm tall, proving that it was possible to shape the material in three dimensions by integrating a hollow space into which a single row of actuators could displace material. The indentation in this experiment was, however, limited to 40 mm (Figure 109, lower right) due to two major problems that occurred during production. The first problem was caused by the membrane being too elastic: this was obvious because the membrane extended and contracted up to 50 mm during production, causing horizontal cracks to occur on the column (see Figure 109, upper left). This phenomenon was further exaggerated as the indentation reached its maximum, resulting in a visual gape in the column. To prevent the entire upper part of the column from being ripped off, the indentation was stopped at 40 mm. The combination of the elastic membrane and the indentation resulted
in an extreme “slip-stick effect”. Another unexpected material effect was that the material collapsed inside the void space towards the end of the production when the slipping velocity was increased, likely because the material being shaped was too soft in relation to slipping velocity. Because the hollow core was 100 mm above the shaping point, there was no support on the inside of the formwork to prevent the material from collapsing.

See APPENDIX 5, in which the phenomena of slip-stick effect is also shown in Figure 139.
Figure 109: Results of the hollow-core experiment. Upper left: production begins. Note that friction force has caused a horizontal crack to occur. Upper right: the crack is no longer evident. However, the surface is wrinkled as a result of a constant slip-stick effect caused by the friction force of the membrane. Lower left: the first successful indentation. Lower right: the final column section, and the start of the second indentation.

Figure 110: Results of the hollow-core experiment. The view from the top of the column shows the material that collapsed to the inside.
The following experiment remained focused on the calibration of the formwork, and three changes were made based on the findings of the previous experiment. First, as the previous experiment had proven that a single level of actuators could be used to shape the material, all four actuators were now placed at the lower level of the formwork in an equal distance around the rigid form (see Figure 99). Consequently, this allowed the height of the rigid formwork part to be reduced another 100 mm, bringing the total height of the rigid formwork to 300 mm. Second, the silicone membrane was exchanged for non-elastic (but bendable) 2 mm PVC membrane. The membrane hung 100 mm below the rigid formwork part, making the total length of the formwork 400 mm. Finally, a flexible 1 mm PVC membrane was wound around the inner core. The lower part of the core was thus now flexible enough to enable the material to be displaced as the actuators indented, while still being able to support the still soft material. The design curve of the actuators remained principally as illustrated in Figure 100. As a result of the previous experiment, however, the maximum indentation was reduced to 40 mm. For comparability, the indentation was once again done from two sides, as in the previous experiments. The material processing remained principally the same as described the initial part of this section, however due to the reduction of the formwork, the constant filling height was reduced to 350 mm.

The production began at 4.5 N. At this point the formwork was filled up to 400 mm, but was gradually reduced to 350 mm. This height was then kept constant during production. During shaping, the actuators were able to smoothly shape the column with an indentation of 40 mm, while the slipping and filling was done at an average velocity of 1.5 cm/min.
The experiment resulted in an intact 900 mm 1:1 column prototype, without any collapse of the inner core and with a simultaneous indentation from two sides (see Figure 112). Changing the formwork membrane to PVC radically reduced the friction and the “slip-stick effect”. This reduction meant that the slipping process was kept constant, resulting in a significantly smoother surface without substantial cracks or failures. Moreover, the extension of the inner core by 100 mm also prevented material from collapsing inside the void of the column.\textsuperscript{250} The result of the experiment was considered the final set up for further experimentation, as it had proven that it was possible to shape the concrete in three dimensions using a flexible formwork.

\textbf{Figure 112:} A) Production of column after it has been indented 30 mm, and B) close-up of the indentation showing horizontal lines as an artefact of the indentation process.

\subsection*{4.4.6. Experiment B: Indenting with a straight trajectory}

Building upon the successfully realised prototype in described in Section 4.4.5., A3, this experiment further tested the three-dimensional formability of the material using the final formwork setup described in 4.3.3.1. The first experiment used a design curve in which two opposite actuators indented the material gradually up to a maximum of 40 mm in a “shift indent”\textsuperscript{250}

\textsuperscript{250} However, it was necessary to clean accumulated material from the inner core and from the flexible membrane at every filling.
process (see Figure 113) while the robot moved the formwork along a straight trajectory. The second experiment also used a straight trajectory, but this time all four actuators gradually indented up to 30 mm simultaneously. The third experiments demonstrated the shift indent trajectory at full scale.

The material processing remained as described in the initial part of Section 4.4.6. (with the exception of the last experiment, which used 60 l of Mix D), and was mixed according to the process described in APPENDIX 1:, Table 12. As was the case in experiment A3 (in Section 4.4.5.), the formwork filling height was aimed to be 350 mm once production had begun (as a result of the overall reduction in formwork height).

**B1: Shift indent**

The following experiment aimed to shape a 900 mm column section using a shift indent trajectory. This meant that two oppositely placed actuators (2 and 4) indented simultaneously; as the maximum indentation was reached, the actuators gradually moved back to their start positions. Simultaneously, the two other actuators (1 and 3) gradually began to indent (see Figure 113).

![Figure 113](image)

*Figure 113: Left: the trajectory of actuator 1 and 3 (1/3). Right: the design trajectory used for actuator 2 and 4 (2/4). Note that as one set of actuators reach the maximum point of indentation, the second set of actuators begin their gradual indentation. Hence the term 'shift indent'.*

Overall, the experiment proved successful, and enabled the material to be indented up to 40 mm. It was the first prototype where all four actuators were used to shape the material, and is a clear proof of concept that a flexible formwork that dynamically changes its cross section can be used to further investigate new geometries. Note that this experiment went beyond the rotational trajectories explored with the rigid formwork in Sections 4.1. and 4.3. (see Figure 114).
Figure 114: Production of the first demonstrator in which four actuators indent on shift.

_B2: Indent simultaneously_

The following experiment further explored the formability of the material by indenting all four actuators simultaneously along the full height of the column. Identical to the previous
experiments, the target for the prototype was 900 mm. The trajectory aimed at indenting the material up to 40 mm from four sides using the design trajectory illustrated in Figure 115.

![Design Curve Illustration](image)

*Figure 115: Illustrates the design curve used simultaneously for all four actuators.*

The indentation reached 35 mm during production, causing minor horizontal cracks (see Figure 116). At the slipping height of 250 mm, the indentation was paused while the slipping continued. After slipping 300 mm, the actuators began to move outwards again. Thus the maximum indentation of 40 mm was not reached, as this would have caused the column to fail. As such, it can be concluded that when indenting all four actuators, the maximum possible indentation is 35 mm, since indenting further will cause significant horizontal cracks.
Despite the indentation limits, the overall result still shows that it is generally possible to three-dimensionally shape a vertical concrete object with a variable cross section. Moreover, the experiment made evident that this can be achieved from all four sides by the flexible formwork’s actuation system, and can feature a wall thickness of 35 mm. The prototype was ultimately 1000 mm tall and was produced without substantial material collapse or cracks.

**B3: Tall demonstrator**

The target of this experiment was to produce a tall demonstrator with a total height of 1800 mm using the shift-indent trajectory described Experiment B1, in which the actuators indented a maximum of 40 mm from two sides (see Figure 113). The material processing remained the same as described in Section 4.3.2. However, the impossibility of lubricating the lower part of the formwork membrane as the slipping progressed remained an issue at this stage. Therefore, special attention was given to cleaning the upper section of the inner and outer membranes before adding layers of material. Further, a syringe was used ad hoc to inject lubrication oil from the lower part of the membrane; this oiling functioned partly to release friction.

The production began at 4.5 N. However, in contrast to the initial experiment described in “B1: Shift indent”, horizontal cracks (see Figure 117) began to appear after slipping for 400 mm. This was a result of the slip stick-effect, and occurred at the point when the second indentation began. Fortunately, this did not cause the production to fail. It clearly shows, however, that the lubrication
oil wears off after a certain slipping height (in this case 400 mm) and causes additional friction\textsuperscript{251} to occur on the membrane. To reduce the friction, local vibration was used to the membrane with the hand held vibration tool\textsuperscript{252} This, combined with the systematic injections of oil described above, sufficiently reduced friction so that it was possible to slipform a full-scale demonstration column. The final column featured a curved surface as a result of the indentations up to 40 mm.

\textsuperscript{251} As described in APPENDIX 5: a constant friction is always applied to the material while slipping. The friction referred to here is additional, as a consequence of the lubrication oil wearing off.

\textsuperscript{252} The vibration tool in this case is the battery-driven vibration tool used throughout the experiments in Sections 4.2. and 4.3. to intermix the material when placing.
The cracks indeed invalidated this column as a structural element. However, this final demonstrator still served as a proof of concept that the geometry of a simple formwork shape
(in this case, a circle) can be transformed dynamically during the slipping process to achieve columns with complex geometries, featuring curved surfaces. While this does not show the full potential of SDC system, it is a key step in showing the flexibility of this process.

4.4.7. Experiment C: Indenting with a rotational trajectory

The experiment in the previous section focused on exploring the limits of indentation when moving the flexible formwork along a straight trajectory. To explore further geometrical constraints and possibilities, the following experiments focused on rotating the formwork while indenting (see Figure 119). Thus, the initial goal of the experiments was to produce a tall column in which the robotic trajectory rotated 180° while applying the shift-indent design curve of Experiment B1 and B3 (Section 4.4.6.). It was already known that the slipping process itself puts stress on the material,253 and that simultaneously rotating and indenting magnifies this significantly, resulting in cracks. Lack of lubrication was also a known issue, as discussed in 4.4.6. To address this problem, a capillary oiling system254 was used in the next set of experiments to produce a tall demonstrator with a 120° rotation and a shift indent trajectory up to 30 mm.

This section describes three experiment cycles: C1) was used to validate the initial intended robotic trajectory and design curve of the actuators illustrated in Figure 119; C2) used this design trajectory on a tall structure (though this was not successful for reasons described later); and C3) was used to develop a capillary oiling system, which was ultimately used to enable the production of a 1800 mm column with a rotation of 120°.

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253 An exploratory study outlining this issue is described in APPENDIX 5.
254 A capillary system (sometimes referred to as capillary action, capillary motion, or wicking) is characterised by the ability of liquid to flow into narrow spaces without the assistance of external forces.
C1: Shift indent rotate

The goal of the first experiment in this cycle was to validate the intended rotational trajectory in which the actuators apply the design curve that gradually indents the formwork up to 40 mm (see Figure 119). The material processing remained as described in the initial part of Section 4.4.2.; the formwork filling height was kept at a constant 350 mm once production began. To help with friction, the manual vibration tool was used, and oil was locally injected into friction-prone areas with a syringe.

The process began as planned when the material monitoring system measured 4.5 N, after which the formwork was filled with material at a rate that maintained a constant height. The experiment produced a 900 mm column with a rotation characterized by the shift-indent design curve. Two notable phenomenon were detected during the process. First, fine ridges formed on the column’s surface as a result of the sharp edge of the membrane, which cut into the material. The ridges (which can be observed as horizontal lines in Figure 120) occurred systematically every 5 mm – a result of the actuators receiving data regarding the height of the robot every 600 ms. Second, a slip-stick effect appeared during the process as the actuators reached their maximum limit of 40 mm. This can be observed as horizontal cracks on the upper part of the column in Figure 121.
Overall, the experiment validated that it was possible to apply a rotational trajectory while indenting up to 40 mm with the actuators.
Figure 120: Results from Experiment C1. Note that horizontal ridge lines occur systematically every 5 mm – a result of the actuators receiving data regarding the height of the robot every 600 mm.
C2: Aiming for a tall demonstrator of C1

The goal of the following experiments was to produce a full-scale, 1800-mm tall column as depicted in Figure 119, using the trajectory validated on the previous experiment (C1). The attempt failed, however, for several reasons described below.

Before production, two minor changes were made to the membrane in order to prevent it from cutting into the material and to reduce the slip-stick effect that occurred in C1. First, the membrane was shortened 20 mm to ensure that the shaping was done as close to the edge as possible in hopes that this would reduce the slip-stick effect in the areas of extreme indentation. Second, it was sanded down from the outside to make the edge thinner and softer.

The following two experiments are referred to as C2.1 and C2.2. Each of these experiments used 60 l of Mix D prepared according to the processing method described in Section 4.5.2. The formwork filling height was kept at a constant 350 mm once production began. The manual vibration tool and the syringe-injected oil were once again used to prevent friction.

The first experiment (C2.1) proceeded almost perfectly up to 1000 mm. At this point one of the actuators stopped indenting due to a simple technical failure, and the slipping was paused for 3-4 min while the system was re-started. This caused the material inside the formwork to stiffen, as the optimal shaping phase had expired. To overcome this problem, the actuators were moved...
back to their initial position, and an attempt was made to slip along a straight trajectory for a section before restarting the shaping process. However, as the indentation process was restarted, a large horizontal crack began to emerge (see Figure 122) due to excessive friction. At this point, the experiment was stopped and declared a failure due to technical problems.

The second experiment, C2.2, again attempted to produce a full-scale demonstrator with the trajectory validated in Experiment C1. However, a crack appeared at 300 mm – exactly the point at which the indentation reached its maximum. Continuous vibration was used to the membrane to release the friction, but this caused ridges to emerge as the material became fluid. This can be observed as roughness (Figure 123) on the surface of the column, also referred to as the "sharkskin" effect.255

255The shark skin effect is well known especially in the polymer extrusion industry. The cause of the phenomenon is described further in: B. Douglas, “The sharkskin effect in polymer extrusion” (Master Thesis in Mechanical Engineering, Graduate School of The Ohio State University, Ohio State University, 2011).
As the crack and shark skin effect did not lead to critical failure (complete collapse), the experiment proceeded. At the second point of indentation, however, horizontal cracks emerged once again. At this point, the acute area was overcome by injecting oil into the lower part of the formwork membrane. This helped to reduce the severity of the cracks, however the column had been destabilized by the first crack and the experiment was stopped at 1200 mm.

While the experiment did not yield the tall demonstrator as hoped, it showed that vibration on the outer membrane causes the material to become fluid to the extent that it effects the surface quality (this was also detected during the experiments described in 4.3.6. and featured in Figure 92, and in the continuous process described in Section 4.2.). It also indicated that if lubrication is continuously added to the inside of the membrane, it might be able to reduce friction significantly.
Figure 124: Results from Experiment C2, showing the rotational indentation, and showing the initial crack, which caused severe instability in the process.

The experiments clearly demonstrate that friction is a problem that is significantly magnified when rotating and after slipping and shaping a certain height of the column – an issue that may not have become evident without having attempted a full-scale demonstrator.

**C3: Tall demonstrator with capillary oiling system**

The next experiment introduced a new technique for lubricating the formwork to deal with the friction issues identified in previous experiments. In the previous experiment, when oil was injected with a syringe into the thin slot between the membrane and the material, it was observed that the pressure from the material on the membrane caused the oil to distribute automatically without requiring the application of additional force, similarly to how a capillary system works.
A capillary oiling system was thus developed in which three layers of 0.5 mm polypropylene foil were arranged in a feathered layering system and folded into a cylindrical shape. The system was mounted around the inner formwork core and around the inner side of the flexible membrane (see Figure 126). During production, syringes were used to systematically inject oil from the upper part of the formwork. The pressure applied to the feathered layers of polypropylene was amplified by the pressure from the material inside the formwork, causing the oil to be distributed into the entire inner side of the membranes. This new oiling system was tested by producing a full-scale 1800 mm concrete column using the previously used flexible multi-actuated formwork. This experiment reduced the rotation to 60° and the maximum indentation to 30 mm, as the major objective was to first prove the new system’s ability to continuously lubricate the formwork during slipping and shaping.

The material processing was done as described in Section 4.4.6, and the process began when 4.5 N was measured. The material in the formwork was kept at a constant height of roughly 350 mm. Between every second material placement, oil was injected into the upper part of the oiling
system in a quasi-equal distance around the oiling membrane of the inner core and around the oiling membrane of the flexible membrane.

The slipping was done at an average velocity of 1.5 cm/min. The added task of injecting oil made it challenging to maintain a constant height in the formwork. This caused some inconsistency in the slipping and filling, which in turn caused horizontal cracks to appear at 1200 mm when the slipping got too slow (see Figure 127). Aside from this minor issue, however, the slipping and shaping proceeded effortlessly in comparison to experiments C2 and C3.

While the system was only tested with this setup once, the experiment clearly serves as a proof of concept that the capillary oiling system can effectively distribute oil throughout the entire formwork (evidence of which is the column’s shiny surface in Figure 127) and thus significantly reduce friction.
Figure 127: Results of Experiment C3, showing the final result of a tall demonstrator, with an indentation of 35 mm and a rotation of 60° over the height of 1800 mm. The shiny surface is a result of the oiling process.
4.4.8. Conclusions about the flexible formwork

From the outset, the goal of testing a flexible formwork was to investigate additional geometrical possibilities for the SDC process. Because this incompressible material had never before been shaped in this way (i.e. indented by a formwork moved along a rotational trajectory), the viability of the flexible formwork tool had to be investigated before it could be fully employed.

A particular initial challenge was to understand the point at which – and how – the material could be shaped without breaking down its delicate structural build-up. A second major challenge was to find a method to reduce friction, which is significantly increased when using a flexible formwork system.

The experiments started by shaping the material in a two-step process, with the goal of gradually shaping the material into an intended geometry. However, the first physical experiments (Section 4.4.5. A) were characterised by material collapse caused by multiple stresses when the material was being simultaneously pushed upwards and downwards by the indentation process. This, in effect, made it impossible to determine the best moment for shaping.

Various experiments were then conducted to explore different means of reducing material stress including: 1) the addition of a hollow core to allow displaced material to move into; 2) reducing the number of actuators working on the material at one time; 3) adding lubrication through various means to reduce surface friction; 4) improving the structure of the flexible formwork by switching from silicone to PVC; and 5) using manual vibration to liquefy the material and thus release friction.

The main conclusion from these experiments is clear: to shape the material in the third dimension by indenting the formwork, it was necessary to insert a hollow core that enabled the material to be radially displaced without resistance, otherwise compressive loads were transferred to the lower layers and caused them to fluidity. The experiments also showed that by increasing complexity in the robotic trajectory, friction increased. This had to be eliminated by continuously applying oil to the inner side of the membrane, which was done with the introduction of the capillary oiling system. It was also clear that indenting at two levels simultaneously did not

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256 This was also proven in the experiments described in APPENDIX 5:
257 The capillary oiling system was later used in the Bachelor thesis, by: L. Fuhrimann, C. Graffè, M. Hächler, "Betonkanu: Smart Dynamic Casting." (Bachelor Thesis, Institute for Building Materials (IfB), ETH Zurich, Switzerland, 2015). In this thesis, it turned out to be impossible to slipform the thin wall structure beyond 100 mm, however, in this case the capillary oiling system turned out to be the success making factor once again.
work, as this caused excessive stresses upon the material, thus collapse. It can also be concluded that the membrane used in a flexible formwork should not be elastic (as the case of the silicone membrane) as this caused additional friction and slip-stick effect on the material. It was also discovered that when pausing the control system of the actuators during production, the port connection was lost and a rebooting of the system was required. Finally, it was concluded that the maximum indentation possible when all four actuators were indenting simultaneously was 30 mm. However, this value could be increased up to 45 mm by applying the shift indent trajectory (see example of shift indent Figure 114).

Yet despite the various limitations, these experiments were more than mere shaping exercises. They were crucial in identifying the major challenges inherent in flexible formwork systems for slipforming. Moreover, the experiments significantly fostered the technology and the process to the point of identifying the key constraints, parameters, and structural considerations needed to ultimately formalise rules for robotically slipforming structural elements.
5. Summary and discussion

The goal of this thesis was to investigate if an enhanced robotic slipforming process has the potential of becoming a novel technique for non-standard slipforming of vertical concrete structures at an architectural component scale.

Seen in relation to the state of the art of non-standard concrete construction (discussed in Section 2.3.) the results of this thesis demonstrated that bespoke vertical structures can be produced by precisely manipulating the material in its early hydration phase, using a formwork which is considerably smaller that the structures produced. Through a series of iterative experiments, a number of physical demonstrators supporting the thesis and demonstrating both its potential and limits, were produced. All together, these must be considered as proof that by enhancing material control with a robotic fabrication process and corresponding digital tools, slipforming can be used to efficiently produce bespoke vertical concrete components for architectural construction.

Reaching this goal essentially required investigating the potential to shape concrete as it transforms from a soft to a hard material. In turn, this implied the parallel development of three major process components: 1) a sophisticated “batch-by-batch” material processing system allowing for the sequential placement of the material in the formwork and the control of the
hydration of the material (see Section 4.3.); 2) custom digital tools for monitoring material properties, controlling the robot movement throughout the fabrication process, and designing the specimens; and 3) two different formwork systems (rigid and flexible) for the physical shaping of the concrete. All these methods and tools were developed and optimised in an iterative process during the entire period of experimentation. The final iteration – a prototypical Smart Dynamic Casting system capable of producing a series of bespoke concrete structures – synthetizes the interaction of all the tools developed in the experiments. Depending on the formwork selected, the prototypical system can produce rotated columns with a variety of cross sections, as well as columns with undulated surfaces of various degrees.

This section is divided in four subsections. The first subsection summarises the findings of the material processing system, the second focuses on the control and material monitoring systems that were developed in the course of this thesis, the third section discusses the achievements of the formwork system, and the final section explores SDC’s potential as a digital tool, along with its constraints.
5.1. Material processing system

Robotic slipforming of bespoke concrete structures requires shaping the material in its early hydration phase. In order to do so, a specialised material processing method, referred to as the batch-by-batch system, had to be developed.

A prerequisite for this investigation was the selection of an adequate concrete material mix design and the analysis of the key mechanical characteristics of this material in its early hydration phase. For this, a set of preliminary studies analysed the load capacities of a number of concrete specimens (without a formwork) over a specific period of time in their early hydration phase. These tests made it possible to define how much material could be filled into the robotic slipform, and when the slipforming process could be started.

Following these first studies, a number of both straight and curved columns sections were produced (max height 600 mm), helping to characterise the key aspects of the process – most notably, speed and timing. First, the material can only be shaped for a short period (about 10 min) starting at the point in time when it becomes able to carry its own weight. Second, if the slipping is done too fast the material collapses. The opposite is true if the slipping is too slow, as excessive friction between the formwork and the material causes the material to crack. Third, the studies clearly showed that the possible shapes of the columns are constrained in terms of curvature and scale.

As such, the results demonstrated that 1) concrete has the potential of being shaped in its early hydration phase, and 2) that to further scale up the Smart Dynamic Casting process, it is critical to have an enhanced material processing system and the ability to monitor the material properties during production.

Batch-by-batch system

To enhance the process and increase the height of the prototypes, a specific material processing system, called “batch-by-batch” had to be introduced. Essentially this system functions as follows. First, a large quantity of heavily retarded fibre-reinforced SCC is mixed. During production, batches of the retarded material are individually accelerated. Then they are sequentially placed into the formwork at specific time intervals. In parallel, a sample of each batch is placed in a custom material monitoring system, which measures its evolving strength...
properties. The measurement dictates when to accelerate the next batch, when to start the slipping, and in due course, with which rate the slipping process should be best performed.

To develop such a batch-by-batch system, however, required defining specific placement methodologies, batch sizes, and time sequences for the acceleration and placement of the batches. Three different methods, characterised by the way the material was brought into the formwork, were sequentially developed and tested: first a discontinuous process, then a semi-continuous one, and finally a continuous process. Each of the methods was evaluated on its potential to enable the shaping of the concrete while slipforming.

In the discontinuous processing method (see Section 4.1.), individual batches were sequentially accelerated and placed into the formwork, filling up to 30% of its height. In contrast to this, the second method (based on intermixing single sequential batches) resulted in a semi-continuous material processing (see Section 4.2.2.). This allowed thin layers of material to be placed down to 5 cm height, and to achieve a gradual workability of the material. This also ensured an improved bonding in the transition from batch to batch. The third processing method (described in Section 4.3.) focused on a semi-automated feeding system, which allowed for an almost continuous process through the placement of thin material layers of only 2% of the total formwork height, ensuring a gradual distribution of the strength properties of the material along the slipping path.

**Conclusion**

The refinement from a discontinuous to an almost continuous material processing method was clearly crucial to ensure optimal bonding between single layers of material, and thus to reduce friction occurrence and cracks. This correlation was proved by the experiments described in Section 4.3. Here, the prototypes were produced using a pump, which enabled a radical simplification of the processing system, assuring precise timing of the acceleration, filling and slipping, and allowing for the production of a column with no visual traces of the batch transition.

Overall, both the results of the experiments in which the concrete batches were intermixed (see Section 4.2.) and the results of the continuous material processing (see Section 4.3.) exemplified that concrete shaping can be significantly optimised by employing a continuous filling and slipping process. However, despite several mix design adjustments, the continuous pumping
process primarily showed that slow pumping caused the material to lose its self-consolidating properties when it exited the pump; an issue that was solved by applying mechanical vibration.

Figure 129: Result of using the flexible formwork with an alternating indentation in a straight trajectory.
5.2. Monitoring and control system

Introduction
The first experimental iterations with the batch-by-batch system led to the conclusion that the Smart Dynamic Casting process would need both a material monitoring system and a robotic control system running in parallel in order to synchronize the evolving strength properties of the material with the movement of the formwork in space (see 4.1.). In this scheme, the material monitoring unit (MMU) would inform the robotic control unit (RCU) in real time about ideal velocity of the slipforming relative to the evolution of the hydration process of the material.

Material monitoring unit (MMU)
The MMU essentially consisted of a digital penetrometer (see Section 3.4.3.) that measured the strength properties of the material. In the beginning, the digital penetrometer was evaluated and identified as being an adequate tool in manual modus (as discussed in Section 3.5.4. and further in 4.1.4.). However, as the goal was to synchronise the measurement with the actual robotic slipforming process, the penetrometer was mounted onto a tri-axial table, which enabled the data collection from the samples of the accelerated batch to be automated.

As the samples directly reflected the properties of the material inside the formwork, the results of the measurements could be used to determine when to add accelerator to the next batch, when to fill it into the formwork, and when to start the slipping. Ultimately, the MMU could be synchronised with the RCU allowing the automatic control of the slipping velocity in accordance to the evolution of the material properties (see Section 4.2.4.). The fact that the MMU was only able to measure the material properties off line, in a separate sample and not in the formwork itself, was unproblematic as long as the batch processing system was discontinuous and individual batches were not intermixed with one another (see Section 4.1.). However, with the implementation of a continuous slipping and feeding process (described in Section 4.2. and 4.3.), the MMU lost most of its function as it was impossible to extract individual material samples of the intermixed batches for offline measurement. Ultimately, the function of the MMU was limited to dictating when to start the overall production process and to observe at which rate the material gained its strength properties.
**Robotic control unit (RCU)**

The second component, the RCU, has been designed to be driven by the data transmitted from the MMU, thus enabling the real-time adjustment of the velocity of the robotic movement of the formwork according to the current hydration rate of the material.

However, it soon became clear that in the semi-continuous and continuous batch-by-batch processes, the slipping velocity could not be controlled by the data collected from the MMU alone. Therefore, the RCU has been equipped from the onset with a user-friendly interface (GUI) allowing the manual override of the data received from the MMU. Consequently, the RCU enabled the manual real-time control of velocity in very precise steps. Additionally, the RCU displayed real-time information about the position of the formwork, the position of the actuators (when using the flexible formwork), as well as the amount of material inside the formwork.

**Conclusion**

Although the direct control of the RCU by the MMU and the consequent automatic synchronization of hydration and formwork movement proved to be limited to the discontinuous process, the RCU turned out to be the key process control tool. By providing both flexible velocity control and precise real-time process information to the operator, the RCU made it possible to react on insights provided by on-line manual material evaluations as well as visual assessments gathered directly on the column. As such, the RCU made it possible to ensure that the concrete filling was perfectly coordinated with the robotic slipping velocity, and thus to prove that by precisely synchronising the slipping and the filling, almost perfectly shaped columns could be produced.
5.3. Formwork systems

Introduction
Alongside the material processing system and the digital control tools, the formwork system developed in this thesis represents a critical component of the Smart Dynamic Casting process as it defines the range of possible cross sections and, as such, the formal design space. In order to develop a basic understanding of the fundamental formwork constraints, various cross sections were first tested. Starting with a simple circular steel pipe (see Section 3.7.), a reconfigurable formwork system was used to test various different cross sections (see Section 4.6.1.). This eventually led to the development of a digitally controlled flexible formwork system that could change its cross section dynamically during production (as described in Section 4.5.3.).

Rigid formwork system
The initial circular cross section formwork had exactly the same circumference as the specimens produced for the preliminary uni-axial load tests and was moved in a straight trajectory, thus validating the results of the load tests.

In order to be able to experiment with different cross sections, a reconfigurable rigid formwork system (consisting of a generic frame into which a cross section geometry of choice could be inserted) was then developed. In the scope of this thesis, three different rigid cross sections were tested: an elliptical shape, a square, and a star shape (see Section 3.6.1.). These formworks were all moved in a straight vertical trajectory, but in contrast to the round formwork, they were simultaneously rotated around the central slipping vector. This rotation additionally caused strong shear forces and thus stress upon the material, and helped to identify and understand the limits of the shaping process. While the elliptical formwork was used throughout all the experiments as a validation method allowing the different processing methods to be compared, the square and the star shaped formworks were only used to explore extreme situations.

The tests with the square formwork (featuring four different radii) revealed that even the smallest radius (10 mm) did not cause any crack or ripping in the material. Surprisingly, the star shape (which was at the time considered an extreme geometry and therefore a first proof of concept towards a flexible formwork system) also did not pose any challenges and allowed the slipforming of columns with an overall smooth surface (see Section 4.2.8.). Overall, the experiments with
these three very different formworks proved that the Smart Dynamic Casting process could work with a large variation of cross sections and thus suggested that the potential of a flexible formwork should indeed be explored.

Flexible formwork system

In order to significantly expand the design space, a flexible formwork system that can dynamically change its cross section while slipforming and thus produce a larger variation of geometries, was developed (see Section 4.4.3.). It consisted of a circular formwork into which a flexible membrane was inserted. Four digitally controlled actuators could influence the geometry of the cross section by individually pushing the membrane inwards (see Section 4.4.3.).

The initial setup consisted of several actuators arranged over the height of the formwork’s cross section (see Section 4.5.5., Experiment A1). However, the first experiments showed that, in order to work, this configuration had to be modified. First, a hollow core in the centre of the column, which would allow the displaced material to move inwards and thus reduce vertical stresses, had to be implemented in the formwork. Secondly, to reduce stresses and avoid destruction of the structure build of the material (see APPENDIX 5), the actuators had to be positioned at the bottom of the flexible formwork. Finally, to further reduce stresses, in particular in regards to slip-stick (pull-slip) effect upon the material, the membrane was changed from an elastic silicon membrane to a non-elastic but bendable PVC membrane. The final design of the flexible formwork is described in detail in Section 4.4.5., Experiment A3.

In the first experiment, all four actuators indented simultaneously, but gradually in and out over the height of the column. The results showed that if the indentation was bigger than 35mm, the friction between the membrane and the material would cause the material to crack or rip (see Section 4.5.6.). In the second experiment, the two opposite actuators indented alternately in and out over the height of the column. Due to the reduced deformation of the cross section, with this method it was possible to indent 40 mm into the material (see Section 4.5.6.). The final experiment used the same alternate indent of the actuators as in the second experiment, but with an additional rotation of the formwork by 180° over the height of the column. The initial results eventually showed that the rotation caused excessive friction to occur, which made it impossible to produce the column in its full height. To reduce friction between the membrane and the
material, a custom capillary oiling system was developed, enabling the production of a tall column with a 60° rotation (see Section 4.4.7.).

**Conclusion**

The experiments demonstrated that, although the formwork cross section has a huge impact on the addressable design space, a proper understanding of the constraints and limiting factors of flexible formworks can considerably expand the possible formal repertoire of Smart Dynamic Casting.

The experiments also exemplify that, like in the traditional slipforming techniques, the formwork cannot be conceived as a generic tool, but will always be specifically designed to manipulate the material within a definite geometrical domain. In these terms, the design of the formwork itself becomes part of the overall design process.
5.4. Design and simulation tool

Introduction
While the structural geometries that can be produced with Smart Dynamic Casting are constrained by the shape of the slipping formwork, the SDC design space can be considerably expanded by changing the trajectory of the robotic arm that moves the formwork. A parametric design and simulation tool was thus developed to facilitate the design process and to generate the trajectories for the robotic arm. While this tool could be used to visualise a column’s geometry, it was not able to simulate the structure’s material properties and thus could not be used to determine whether it was in fact possible to build.

Digital design and simulation tool
The parametric design and simulation tool was developed in two stages: first for the rigid formwork; and next for the flexible formwork, which was considerably more complex.

The initial rigid formwork implementation made it possible to: a) define the geometry of the rigid formwork; b) set up the main fabrication parameters, such as the formwork’s trajectory (curvature, height) and its rotation around this vector throughout the slipping process; and c) visualise the physical structure that would result from these parameters. An export function would then automatically generate the data needed by the robotic control unit (RCU).

The introduction of the flexible formwork added a great deal of complexity to the design and simulation tool. To maintain the ability to parametrically define and visualise the geometry of the column, four curves defining the indentation of the material inside the flexible formwork were added as inputs to the design tool. These curves represented the path of the respective actuators relative to the trajectory of the formwork, and as such described the geometrical changes to the formwork cross section. Again, the export function would generate the data for the RCU, which this time consisted of the robotic trajectory for the formwork as well as the relative movement of the actuators.

Conclusion
The development of the parametric design and simulation tool showed that the visualisation of SDC geometries produced with the rigid formwork did not divert significantly from the physical result – despite the fact that the design tool was not directly informed by any material properties.
However, in the case of the flexible formwork, the visualisation did not correspond at all to the results of the initial physical experiments. This manifests the necessity of conducting empirical physical experimentation, as the formwork systems’ constraints along with the material processing must be well understood if they are to be implemented into the digital design tool. Though the digital design tool did not enable a visualisation of the material constraints, it was successful in parameterising the trajectories and enabling a preview of possible results.
6. Conclusion

A new industrial approach to additive manufacturing

The main contribution of this thesis was to successfully scale down and automate the already established construction technique of slipforming in a process called Smart Dynamic Casting (SDC). This was achieved by using an industrial robot to move the formwork instead of hydraulic jacks, and by introducing a material monitoring system to provide data for precisely controlling the movement of the formwork in space. In proving that it is possible to precisely manipulate concrete in its early hydration phase, this thesis lays the basis for a new additive manufacturing process for bespoke concrete construction.

From the outset, Smart Dynamic Casting was deliberately designed as an industrial prefabrication system – a system primarily intended to efficiently produce non-standard architectural elements that can be transported and assembled into a larger whole. In general, prefabricated building elements are constrained in size as they must remain small enough to be efficiently transported from the shop to the construction site, but they offer several advantages, including: integrated planning and fabrication, lower overall construction cost, higher quality, improved durability, less construction-site waste, and a general reduction of energy consumption. Indeed, SDC is particularly well suited to prefabrication construction methods because the controlled environment of the shop makes it possible to keep the materials and processes as constant as possible from one production to the next.

The SDC construction system is embedded in a technological paradigm shift that in the recent years has already seen robots become an integral part of most production lines across many industries in an effort to reduce costs and make processes more efficient. Should SDC prove to be an efficient means for flexibly manufacturing for both simple and complex bespoke concrete building elements, it is reasonable to expect that it will become a standard manufacturing tool for

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concrete prefabrication. Especially given the improved sustainability it offers over conventional concrete casting techniques for bespoke concrete elements, which require full size formworks that are discarded after a single use.

Until this point, the focus of this thesis has been to realise vertical bespoke prototypes of a size of up to 2 m. While these prototypes do not yet address the full potential of SDC, they do illustrate the geometric variability that can be achieved by shaping the concrete in its early hydration phase, and they provide a general understanding of the process constraints. The thesis results thus lay the conceptual basis for a future industrial prefabrication system for the additive manufacturing of mass-customised concrete elements.

The architecture of Smart Dynamic Casting

While SDC has conceptually demonstrated the potential to produce load bearing columns, it digitally controlled fabrication method also fosters the potential for structural optimisation, for example by changing the section of columns throughout their height. Further, beyond these functional roles, the variable geometry enabled by SDC has the potential to contribute to the character of an architectural space, and therefore reintroduce the column as a central element in architectural design. On that scope, the columns produced with the flexible formwork (see Section 4.4.) represent a key step in exploring the overall design space of SDC, and, ultimately, its architectural potential for a radically expanded notion of bespoke vertical concrete construction.

260 SDC like columns were produced with conventional formwork and structurally tested. The results can be found in the thesis of: M. Schultheiss, "Reinforcing SDC", 58.
261 Optimising structures while articulating their geometry is nothing new. This is particularly known in the work of Pier Luigi Nervi, who cultivated the possibilities of structural columns throughout his entire career. Examples of such columns are erected in the Palazzo del Lavoro, Turin, Italy, 1961. These are featured in: P. L. Nervi, Aesthetics and Technology in Building by Pier Luigi Nervi. According to Vitruvius, a column should exhibit three qualities: it must be solid (firmitas), functional (utilitas), and beautiful (venustas). See: M. Gelernter, Sources of Architectural Form: A Critical History of Western Design Theory (Manchester University Press 1995). Or in: Vitruvius. translated by: M. H. Morgan, The Ten Books On Architecture (New York: Harvard University Press, 1914).
Figure 130: A) examples of columns produced with a formwork that can change shape, such as from a triangle to a hexagon. B) conceptual illustration of columns produced with a circular formwork that can change volume during the slipping process.

The research has also proven that the SDC system can be used to produce folded architectural structures. This potential was tested in the Bachelor Thesis “Betonkanu”-project, which used a custom flexible formwork to automatically change the cross section of a thin folded concrete element (20 mm) during production. This eventually resulted in the slipforming of a 4-m long canoe, demonstrating that thin folded concrete elements can be produced using the SDC approach. Such bespoke elements can then be assembled into larger differentiated architectural structures, for example consisting of horizontal elements for roofs or canopies, or vertical elements for walls or façades (see Figure 131). A geometrical differentiation of the single elements can articulate a spatial sequence while at the same time informing the structural performance of the structure.

263 Again, this statement is based on the success of the concrete canoe (produced with the SDC technique developed during this thesis), which proved the concept that structures with changing volume and cross section can be produced with the SDC technique. For more information see: L. Fuhrimann et al., “Betonkanu: Smart Dynamic Casting”.

264 The upper and lower point of the canoe was made with a conventional casting process. Including the end parts of the canoe, the total length was 4.4 m. For further information, see: L. Fuhrimann et al., “Betonkanu: Smart Dynamic Casting”.

265 The possible design space within SDC for the production of folded structures remains to be defined, and would certainly require further research into the shapeability of the material – in particular, the constraints of the inclination in line with the formwork system. From a material point of view, decreasing the thickness of such elements raises the requirements on the self-compacting quality of the concrete and the ability to deliver it homogeneously throughout the cross section. Such geometries would also require innovation in terms of the reinforcement, which should ultimately be incorporated during the fabrication process. This could be solved by integrating posttension systems or by inserting conventional steel reinforcement sequentially during production.
Towards a new material awareness in digital fabrication

SDC contributes to the ongoing discussion about the potential of digital manufacturing processes for architecture and the construction industry. In this context, SDC is challenging the assumption that mass production should enable individual variation, but of a different kind to that of handcraft. This raises questions about the relationship between humans and their technological capabilities, about how architectural elements are tailored for specific functionalities (structure, context, light etc.) and indeed about how such processes can be controlled and authored by designers. As such, digital fabrication processes like SDC are developed through human skill, judgement, and interpretation.

As already outlined by Axel Kilian, such fabrication processes are often triggered by the need to work within the constraints given by the design and fabrication context. This was shown to be true in context of this research, especially with respect to material and process constraints. It was found, for example, that the material can only be slippable at a certain velocity and shaped within certain geometries before it collapses, cracks, or loses its ability to transfer loads. In other words, the constraints of both fabrication and material must ultimately be incorporated in the design process and become one of its main drivers.

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266 The process embeds itself within a paradigm shift, which according to Mario Carpo, blurs the lines of the author. See: M. Carpo, *The Alphabet and the Algorithm* (Cambridge, Massachusetts: MIT Press 2012). Carpo argues that times have changed since Leon Battista Alberti (1404-1472), who established a (modern) distinction between the thinker and the maker, and that now, the architect, the engineer, the material scientist, and the robotic specialist all become the makers and designers of a new building system — a position that is supported by the results of this thesis. This shift is in accordance to McCullough, who argues that as a medium, computers have largely replaced many of the manual labour task of makers (workmen). See: M. McCullough, *Abstracting craft: the practiced digital hand* (Cambridge, Massachusetts: MIT Press, 1998).

Viewed in this framework, the goal of this research was not the formal expression of the end product, but rather the development an understanding for the specific material behaviour inherent to SDC in order to characterise the architectural design space that can be explored with this process. This clearly means that the design process in SDC is driven by material constraints, and that the velocity, trajectory, formwork, load capacity, and geometry are all functions that must be 1) in symbiosis with each other, 2) defined in line with the material properties, and consequently 3) defined in the design space of SDC.

Ultimately, this thesis has shown that material behaviour and processing in line with digital technology can both enhance the architectural design and become a constituent driver for it. As such, it establishes the basis for a new material-driven design methodology in which automated fabrication and material control are an integral part.
7. Future research and outlook

This thesis has developed new methods and techniques for shaping concrete into non-standard vertical elements through the use of a formwork that is significantly smaller than the structures produced. While the limited scope of the doctoral thesis could not fully explore its architectural potential, the resulting experimental specimens revealed the fundamental constraints and the formal and functional opportunities of this integrated design and fabrication method. In order to unlock the full potential of the SDC method, further research must be conducted, specifically toward the development of: 1) full automation of the material processing system, including material design optimisation; 2) design tools that simulate the constraints of the material in line with a selected formwork system; 3) formwork systems that expand the design space; and finally, 4) additional reinforcement systems.

Automated material processing system

To dictate the timing of the production process, a remote material monitoring system was developed over the course of this thesis (see Section 3.4.3.). As the SDC process became continuous, this monitoring system turned out to be partly redundant and had to be replaced by a manual evaluation of the material strength properties throughout the process. This became a challenging factor, as the slipping velocity has a direct impact on the acceleration of the material as well as on its pumping rate.

Consequently, to fully automate the SDC process, a new material monitoring system suitable for continuous processing must be developed. This would require a sensing strategy that allows the mechanical properties of the concrete to be measured in its early hydration phase, directly on the material released at the bottom of the formwork. One possible solution is to use a tap-tool—a sensing device for the non-destructive measurement of mechanical properties developed by the group for Mechanic and Materials of Prof. C. Daraio at ETH Zurich. A first study by the group of Prof. C. Daraio has demonstrated this tool’s general potential as a feedback system for controlling the SDC process.

Although an “on the fly” measurement would reveal only a second order estimate of the strength properties of the material, and not the real strength properties of the material itself, this is still

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268 The tap-tool device has been developed by the group of Prof. C. Daraio. Also see: C. Beck et al., “Devise and Method for a Non-Destructive Measurement of Mechanical Properties”.
269 These studies were focused on the implementation of the tap-tool device of Prof. C. Daraio. Ibid.
sufficient for dictating the overall fabrication process, including the automation of material acceleration and pumping.

Experiments showed that continuous filling and slipping must be further pursued given the importance of maintaining good concrete shapeability in SDC, and fully automating the SDC process will require optimising the material mix design. This could include reducing the cement and increasing the aggregates while maintaining material pumpability. Along this line it would be necessary to develop a continuous and adaptable material acceleration system that allows the batches of material to be adjusted while maintaining its self-consolidating properties until it has reached the formwork. Both topics are currently being investigated by the research group of Prof. Robert Flatt. Ultimately, the “on the fly” monitoring system described above, which measures the material properties directly on the formwork, could automatically adjust the pumping (including acceleration) and slipping rate in accordance to the real time measurements.

Enhanced design tool
This thesis implemented a custom digital design and simulation tool\textsuperscript{270} to define the vertical trajectory of the formwork as well as to provide the designer with a visual approximation of the structure to be produced. However, the tool did not directly integrate the evolving material properties as a parameter. While, with the rigid formwork, the design and simulation tool still delivered congruent results, this limitation became fully evident with the use of the flexible formwork (see Section 4.4). A more advanced design and simulation tool should therefore be able to model the main physical parameters of the material process and, ultimately, to produce direct visual feedback that will enable the designer to assess the both formal outcome and its technical feasibility prior to production.

Formwork
Until now, both the rigid and the flexible formwork developed in this thesis have mainly focused on shaping the material by deformation – either through the trajectory of the formwork itself (see Section 4.1.- 4.3.) or by manipulating the cross section of the formwork through the use of mechanical actuators (see Section 4.4.). While these experiments have improved the

\footnote{\textsuperscript{270} "Grasshopper: Algorithmic modelling for Rhino".}
understanding of the interaction between material and formwork and can be used to assess the material stresses generated in relation to the evolving state of hydration, new formwork systems must be developed in order to expand the design space addressable by SDC. These should feature the ability to change their cross section in terms of both size and geometry in a more significant manner.\textsuperscript{271} As the experiments with thin folded structures conducted for the production of the canoe project\textsuperscript{272} have already demonstrated, such concepts would enable the geometrical (and thus potentially the structural) optimisation of structures produced with SDC, and would radically enlarge its theoretical design space and its significance to the architectural discipline.

*Structural advancements and reinforcement*

Another open question needing further investigation is the enhancement of the load-bearing characteristics of SDC structures, as loose fibres provide only limited tensile strength to the material. Four basic strategies (which have in part already been pursued by the research group of Prof. Robert J. Flatt, at ETH Zurich) can be addressed. The first option is to use conventional steel reinforcement, which is sequentially placed into the formwork during production. As the Master Thesis project of Marc Schulthess, “Reinforcing SDC” has shown,\textsuperscript{273} this procedure allows the load-bearing capacities of the columns to be significantly augmented, but it also creates challenging limitations to the SDC process and hence to the design space.\textsuperscript{274} The second alternative consists in the use of textile fibres (i.e. carbon or aramid filaments) for the reinforcement of the concrete.\textsuperscript{275} Because they are flexible, these filaments could be continuously embedded into the material during the slipping process without interfering with the changing shape of the formwork or its trajectory in space. This approach has already been tested in the SDC canoe project, where long string fibres were vertically embedded throughout the elements while a secondary system weaved fibres in the horizontal direction.\textsuperscript{276} Here, further research into the filament processing method would be required in order to identify processing methods that enable interweaving of the fibres inside the material. A third alternative would be to slipform...
structures with hollow cores into which post-tension cables could be inserted after production.\textsuperscript{277} Finally, a last option would be to concentrate on the production of compression-only structures in which the need for reinforcement could be minimized or even eliminated.\textsuperscript{278}

Each of these limitations and open-ended concepts clearly show that this thesis is only a first step and that SDC is still in its infancy. To reach the goal of seamlessly integrating design and fabrication, and ultimately, to automatically produce mass-customised SDC concrete structures with design freedom at the component scale will clearly require significant follow-up experimental investigation.

\textsuperscript{277} A. Bommer, B. Aalami, \textit{Design Fundamentals of Post-Tensioned Concrete Slabs} (State of Washington, USA: Adapt Corporation, 1999). This issue is also discussed in the paper by: E. Lloret et al., “Smart Dynamic Casting: A Robotic Fabrication System for Complex Structures”.

\textsuperscript{278} According to: L. Lachauer, P. Block, “Compression Support Structures for Slabs”. In conference proceedings, \textit{Advances in Architectural Geometry}, (Paris, France, 2012): 135-146. Compression-only structures offer a rich variety of formal expressions that can take form as inclined columns, branching structures, double-curved walls, or shell surfaces.
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APPENDIX 1: MATERIAL MIX DESIGN AND MIXING

For the success of the experiment described throughout Section 4 and 5, it was necessary to adjust the material formulation. This was done in close collaboration with the Institute for Building Materials and was integrated into two different thesis projects.279

Table 6: Initial Material Mix based on Jacqueline Pauli280 and Patrick Stähli281

<table>
<thead>
<tr>
<th>Component</th>
<th>Name</th>
<th>Amount [g] for 1 litre</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement</td>
<td>Holcim Normo 5</td>
<td>981.73</td>
<td>49.6 % of dry material</td>
</tr>
<tr>
<td>Fly ash</td>
<td>Hydrocement Holcim</td>
<td>92.89</td>
<td>4.7 % of dry materials</td>
</tr>
<tr>
<td>Silica fume</td>
<td>Micro Silica Elkem 940</td>
<td>164.67</td>
<td>8.3 % of dry materials</td>
</tr>
<tr>
<td></td>
<td>BASF</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sand (&lt; 4 mm)</td>
<td>No name</td>
<td>740.34</td>
<td>37.4 % of dry materials</td>
</tr>
<tr>
<td>PVA Fibres 6 mm</td>
<td>Kuraray RF 400</td>
<td>13.00</td>
<td>1 % Volume of cement</td>
</tr>
<tr>
<td>PVA fibres 12 mm</td>
<td>Kuraray RF 350</td>
<td>13.00</td>
<td>1 % Volume of cement</td>
</tr>
<tr>
<td>Main water</td>
<td>No name</td>
<td>247.86</td>
<td>w/b282 variable</td>
</tr>
<tr>
<td>Correction water</td>
<td>No name</td>
<td>640</td>
<td>w/b variable</td>
</tr>
<tr>
<td>Superplasticiser</td>
<td>Glenium ACE 30</td>
<td>14.72</td>
<td>1.5 % of active bwc</td>
</tr>
</tbody>
</table>

279 In A. Alberti et al., "Formwork Free Concrete", and in S. Garcia et al., "Smart Dynamic Casting, Optimierung des Misch-und Betoniervorgangs bei der Herstellung von frei geformten 3D-Betonelementen".

280 J. Pauli, "Biegen von Betonstreifen in halbbarem Zustand".

281 P. Stähli, "Ultra-Fluid, Oriented Hybrid-Fibre-Concrete".

282 w/b = water to binder. Means the ratio of the weight of water to the weight of cement used in a concrete mix. The w/b has a great impact on the quality of a mix. For example, a lower water-cement ratio leads to higher strength and durability, but may make the mix more difficult to place. Placement difficulties can be resolved by using plasticizers or superplasticizers.
### Table 7: Material Mix A

<table>
<thead>
<tr>
<th>Component</th>
<th>Name</th>
<th>Amount [g] for 1 litre</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement</td>
<td>Holcim Normo 5</td>
<td>981.73</td>
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</tr>
<tr>
<td>Fly ash</td>
<td>Holcim Normo 5</td>
<td>92.89</td>
<td>4.7 % of dry materials</td>
</tr>
<tr>
<td>Silica fume</td>
<td>Micro Silica Elkem 940</td>
<td>164.67</td>
<td>8.3 % of dry materials</td>
</tr>
<tr>
<td>Sand (&lt; 4 mm)</td>
<td>No name</td>
<td>740.34</td>
<td>37.4 % of dry materials</td>
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<tr>
<td>PVA Fibres 6 mm</td>
<td>Kuraray RF 400</td>
<td>13.00</td>
<td>1 % Volume of cement</td>
</tr>
<tr>
<td>PVA Fibres 12 mm</td>
<td>Kuraray RF 350</td>
<td>13.00</td>
<td>1% Volume of cement</td>
</tr>
<tr>
<td>Water</td>
<td>No name</td>
<td>304.5</td>
<td>w/b = 0.245</td>
</tr>
<tr>
<td>Superplasticiser</td>
<td>Glenium ACE 30</td>
<td>14.72</td>
<td>1.5 % of active bwc</td>
</tr>
</tbody>
</table>

### Table 8: Material Mix B

<table>
<thead>
<tr>
<th>Component</th>
<th>Name</th>
<th>Amount [g] for 1 litre</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement</td>
<td>Holcim Normo 5</td>
<td>981.73</td>
<td>49.6 % of dry material</td>
</tr>
<tr>
<td>Fly ash</td>
<td>Holcim Normo 5</td>
<td>164.67</td>
<td>4.7 % of dry materials</td>
</tr>
<tr>
<td>Silica fume</td>
<td>Micro Silica Elkem 940</td>
<td>92.9</td>
<td>8.3 % of dry materials</td>
</tr>
<tr>
<td>Sand (&lt; 4 mm)</td>
<td>No name</td>
<td>740.34</td>
<td>37.4 % of dry materials</td>
</tr>
<tr>
<td>PVA Fibres 6 mm</td>
<td>Kuraray RF 400</td>
<td>13.00</td>
<td>1 % Volume of cement</td>
</tr>
<tr>
<td>PVA Fibres 12 mm</td>
<td>Kuraray RF 350</td>
<td>13.00</td>
<td>1% Volume of cement</td>
</tr>
<tr>
<td>Water</td>
<td>No name</td>
<td>304.5</td>
<td>w/b = 0.245</td>
</tr>
<tr>
<td>Superplasticiser</td>
<td>Glenium ACE 30</td>
<td>14.72</td>
<td>1.5 % of active bwc</td>
</tr>
</tbody>
</table>
Table 9: Material Mix C. Workability ~ 3 h

<table>
<thead>
<tr>
<th>Component</th>
<th>Name</th>
<th>Amount [g] for 1 litre</th>
<th>Comment</th>
</tr>
</thead>
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</tr>
<tr>
<td>Fly ash</td>
<td>Hydrolent Holcim</td>
<td>164.67</td>
<td>4.7 % of dry materials</td>
</tr>
<tr>
<td>Silica fume</td>
<td>Micro Silica Elkem 940 BASF</td>
<td>92.89</td>
<td>8.3 % of dry materials</td>
</tr>
<tr>
<td>Sand (&lt; 4 mm)</td>
<td>No name</td>
<td>740.34</td>
<td>37.4 % of dry materials</td>
</tr>
<tr>
<td>PVA Fibres 6 mm</td>
<td>Kuraray RF 400</td>
<td>13.00</td>
<td>1% Volume of cement</td>
</tr>
<tr>
<td>PVA Fibres 12 mm</td>
<td>Kuraray RF 350</td>
<td>13.00</td>
<td>1% Volume of cement</td>
</tr>
<tr>
<td>Water</td>
<td>No name</td>
<td>371.79</td>
<td>0.3 w/b</td>
</tr>
<tr>
<td>Superplasticiser</td>
<td>Glenium ACE 30</td>
<td>7.84</td>
<td>1.5 % of active bwc</td>
</tr>
<tr>
<td>Retarder</td>
<td>Sigma – Aldric, Purity &gt; 99%</td>
<td>0.98</td>
<td></td>
</tr>
<tr>
<td>Accelerator</td>
<td>BASF X-Seed 100</td>
<td>24.54</td>
<td></td>
</tr>
</tbody>
</table>

Table 10: Material Mix D. Workability ~ 7 h.

<table>
<thead>
<tr>
<th>Component</th>
<th>Name</th>
<th>Amount [g] for 1 litre</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement</td>
<td>Holcim Normo 5</td>
<td>982.0</td>
<td>49.6 % of dry material</td>
</tr>
<tr>
<td>Fly ash</td>
<td>Hydrolent Holcim</td>
<td>165.0</td>
<td>4.7 % of dry materials</td>
</tr>
<tr>
<td>Silica fume</td>
<td>Micro Silica Elkem 940 BASF</td>
<td>93.0</td>
<td>8.3 % of dry materials</td>
</tr>
<tr>
<td>Sand (&lt; 4 mm)</td>
<td>No name</td>
<td>740.0</td>
<td>37.4 % of dry materials</td>
</tr>
<tr>
<td>PVA Fibres 6 mm</td>
<td>Kuraray RF 400</td>
<td>13.00</td>
<td>1% Volume of cement</td>
</tr>
<tr>
<td>PVA Fibres 12 mm</td>
<td>Kuraray RF 350</td>
<td>13.00</td>
<td>1% Volume of cement</td>
</tr>
<tr>
<td>Water</td>
<td>No name</td>
<td>370.0</td>
<td>0.3 w/b</td>
</tr>
<tr>
<td>Superplasticiser</td>
<td>Glenium ACE 30</td>
<td>4.0</td>
<td>1.5 % of active bwc</td>
</tr>
<tr>
<td>Retarder</td>
<td>Sigma – Aldric, Purity &gt; 99%</td>
<td>2.70</td>
<td></td>
</tr>
<tr>
<td>Accelerator</td>
<td>BASF X-Seed 100</td>
<td>60.0</td>
<td></td>
</tr>
</tbody>
</table>
Table 11: Material Mix for base (see Section 3.1.4)

<table>
<thead>
<tr>
<th>Component</th>
<th>Name</th>
<th>Amount [kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand &lt;4 mm</td>
<td>&lt;4 mm</td>
<td>50.00</td>
</tr>
<tr>
<td>Gravel</td>
<td>4-8 mm</td>
<td>30.00</td>
</tr>
<tr>
<td>Cement</td>
<td>Holcim Normo 4</td>
<td>16</td>
</tr>
<tr>
<td>Water</td>
<td>No name</td>
<td>8.00</td>
</tr>
</tbody>
</table>

**Mixing equipment**

Four different mixers were used throughout this thesis. These are listed in
Table 9.

Table 12: Mixer Specifications

<table>
<thead>
<tr>
<th>MIXER TYPE</th>
<th>Low rotation speed</th>
<th>Medium rotation speed</th>
<th>Maximum rotation speed</th>
<th>Max capacity of dry mix</th>
<th>Max capacity of wet mix</th>
</tr>
</thead>
<tbody>
<tr>
<td>Collomatic 65/2 K-3 (vol. of drum 65 L )</td>
<td>40% (16 rpm)</td>
<td>-</td>
<td>80% (32 rpm)</td>
<td>20 L</td>
<td>30 L</td>
</tr>
<tr>
<td>Zyklos Rotating Pan Mixer ZK 50 HE</td>
<td>27.8rpm</td>
<td>60 rpm</td>
<td>83.5 rpm</td>
<td>38 L</td>
<td>-</td>
</tr>
<tr>
<td>Hobart A200-N (vol. bowl 20 L)</td>
<td>1 (107 rpm)</td>
<td>2 (285 rpm)</td>
<td></td>
<td>6 L</td>
<td>12 L</td>
</tr>
<tr>
<td>Zyklos Zwangsmischer</td>
<td>Only speed</td>
<td>1</td>
<td></td>
<td>40 L</td>
<td>I</td>
</tr>
</tbody>
</table>
Mixing procedure for Mix D

It was necessary to prepare Mix D in a two step process due to the limitations of the mixing equipment. As listed in Table 12, the largest mixer available during this thesis could only mix 40 l of dry mix. The following procedure was therefore developed:

Table 13: Mixing procedure for 80 l of Mix D

<table>
<thead>
<tr>
<th>Time [Min]</th>
<th>Action</th>
</tr>
</thead>
</table>
| Preparation, dry mix for 5 min. | 2x20 l in the Collomatic Mixer  
1x40 l in the Zyklos |
| 0-2 | Add water to the first 20 l in the Collomatic |
| 2-4 | Add water to the 40 kg mix in the Zyklos |
| 4-6 | Stop the Collomatic mixer, clean edges of mixing container, and put it aside. Place the second dry mix in the Collomatic Mixer and add water. |
| 6-10 | Mix the second 20 l mix. |
| 10-13 | Stop Zyklos and Collomatic, clean edges of mixing containers. Add the 2x20 l wet mixes to the mix in the Zyklos; add fibres. |
| 13-15 | Mix. |
| 15-18 | Stop; clean edges and add fibres. |
| 18-20 | Mix. |
| 20-23 | Stop; clean edges. |
| 23-25 | Mix. |

Note that the large mix had to be removed with a pallet wagon and driven to the robotic laboratory; this process took approximately 15 min.
Due to constraints related to the mixing logistics, an effort was made to expand the workability of Mix C from 3 to 7 h. This change significantly simplified the mixing process, making it no longer necessary to offset the mixing of several batches of retarded material in order to maintain an appropriate level of workability. The new material mix (Mix D) was developed in four steps. The first step analysed the amount of sucrose needed to extend the retardation up to 7 h. The second adjusted the superplasticiser dosage, which had to be decreased due to the higher amount of sucrose solution. The third step adjusted the accelerator dosage, which was used to eliminate the retardation and thereby start the hydration on demand (see Section 3.1). In the final step, the hydration rates of the respective batches were analysed using the digitally controlled penetrometer described in Section 3.4.3.

To adjust the sucrose solution, five individual portions of 0.5 l of Mix C were prepared at 15 min intervals (See Section 3.2, Table 1). Each mix was prepared with 0, 2, 3, 4, 5 g/l of retarder (sucrose solution), respectively. After mixing the material, a 100 g sample of material was extracted and placed in the Isothermal Calorimetry device (See Section 3.4.1), which was set to a constant temperature of 20° C. After 30 h, the samples were removed. The results (see Figure 132) show how much the hydration gets delayed by increasing sucrose dosages. Based on systematic studies, it was concluded that 2.7 g/l of sucrose had to be added in order to maintain a workability of 7 h.

283 An extensive listing of the studies is also reported in the Bachelor Thesis of: Garcia et al (2014): 34-35.
In a second step, the superplasticiser dosage was adjusted. More specifically, it had to be reduced from 7.84 g/l to 4 g/l in order to compensate for the added sucrose solution (sucrose itself can contribute to fluidification and water is introduced with the solution). The third step analysed the accelerated batches and adjusted them accordingly to meet two basic requirements: 1) a slump flow test of the accelerated material should result in a slump flow of 21 cm, and the material should have self-consolidating properties without sedimentation; and 2) the material should accelerate similarly to the previous Mix C.

To meet these two requirements, the accelerator was increased from 24.54 g/l to 60 g/l. The new material Mix D (see Table 10) resulted in an optimal workability time of approximately 7 h, and was considered to be an adequate material solution for the pump system process.
mixing and placed them directly in the material monitoring system described in Section 3.4.3. In this analysis, the first six batches were accelerated in sequential 15 min intervals. The remaining three batches were accelerated in 30 min intervals. The results show a constant homogeneous shift in the hydration curves (see Figure 134).

Half portions from each batch were simultaneously intermixed and driven through the pump. The results in Figure 135 show the hydration of the intermixed batches. Starting on the left, the curves show the sequentially intermixed batches, which hydrate gradually. First, the hydration curve of a pure batch (red curve) is shown. Next is the intermixed batch (a dark orange curve), followed by a pure batch (light yellow curve). Then comes a pure batch again (light green), etc.
APPENDIX 3: INTERMIXING STRATEGY 1

The first intermixed plan aimed to place subsequent layers of approximately 2-3 cm each. This required a mixing process in which 16 portions of material were placed and intermixed at 2-3 minute intervals (Figure 136).

Table 14: The following tables show the volume of the cups used for the intermixing of Mix C (density of 2200 kg/m³).

<table>
<thead>
<tr>
<th>Cup</th>
<th>Cup B</th>
<th>Cup C</th>
<th>Cup D</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.4 cm</td>
<td>2.46 cm</td>
<td>1.4 cm</td>
<td>0.4 cm</td>
</tr>
<tr>
<td>1.05 L (2.3kg)</td>
<td>0.77 L (1.7 kg)</td>
<td>0.43 L (1 kg)</td>
<td>0.12 L (0.3 kg)</td>
</tr>
</tbody>
</table>

In this plan, the first three layers were 3.4 cm each, and were placed in one go. After these were placed, a sample was placed in the feedback system container. The pure batch was used to ensure that the initial material in the form reflected the material in the feedback system, since it would have been logistically difficult to extract samples of every intermixed batch.

Figure 136: Overview of intermixing plan. A, B, C, D corresponds to the sizes of the cups used for the process.
APPENDIX 4: INTERMIX STRATEGY 2

The second intermix plan increased the layers to 3-5 cm. This required a mixing plan in which 12 portions of material were placed and intermixed. Again, the goal was to place the material at 2-3 min intervals. Figure 136 shows the intermixing plan. A, B, C, D again refer to the cups sizes used for the production, however in this case cup B was increased to 1.57 l (5 cm). The volume of the cups are listed in Table 15.

Table 15: The following table shows the content of the cups used for the intermixing. Mix C (density of 2200 kg/m) was used.

<table>
<thead>
<tr>
<th>Cup A</th>
<th>Cup B</th>
<th>Cup C</th>
<th>Cup D</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.4 cm</td>
<td>5 cm</td>
<td>1.4 cm</td>
<td>0.4 cm</td>
</tr>
<tr>
<td>1.05 l (2.3kg)</td>
<td>1.57 l (3.5 kg)</td>
<td>0.43 l (1 kg)</td>
<td>0.12 l (0.3 kg)</td>
</tr>
</tbody>
</table>

Figure 137: Overview of intermixing plan. A, B, C, D corresponds to the sizes of the cups used for the process.
APPENDIX 5: WEIGHING EXPERIMENTS

The experiments in the following appendix must be seen as an excursus, as they loosely contributed to generating a better understanding of how concrete is shaped in three dimensions inside the formwork during slipping.

As self-compacting concrete is an incompressible fluid, it was suspected that the collapse of the material in the experiment described in Section 4.4.5., A was due to a combination of tension stress (caused by the friction forces on the membrane while slipping) and compression stress (caused by the indentation of the actuators). This would put more load on the previously released material and cause its collapse. To test this "overload" hypothesis, the column base and actuated formwork were placed on a scale (as shown in Figure 138) so that it was possible to record the loading of the released material as it was being displaced by the actuators.

In the first experiment, one batch of 12 l (= 25 kg on the scale) was filled into the formwork. After 6 N was reached, the experiment began. For the first 100 mm, the slipping was done slowly (0.5 cm/min). After 100 mm were slipped, the actuators began to continuously indent. As the slipping process began, the weight of the material on the scale began to fluctuate (see Figure 139). This was due to the friction pulling the material upwards and causing the weight on the scale to be reduced. At 100 mm the slipping was stopped, but the actuators continued to indent; as this
happened, the weight on the scale increased as material was pushed downwards. At the moment the actuators were moved back to their initial position, the weight of the material returned to 25 kg.

Figure 139: Result of the first experiment showing indentation without moving. The y-axis shows the weight of the material in kg as indicated on the scale. The x-axis shows the time in min. The blue line connects the data point of the weight change over the course of the experiment. The graph is divided into four segments indicated by red discontinuous lines. The first segment shows a constant weight of 25 kg, when the formwork was not moving. In the second segment, the formwork was moved 100 mm with a velocity of 5 mm/min, resulting in a 10 kg reduction in the graph. In the third section, the indentation was begun and the actuator positions were at 150 mm (in the middle of the material). Here the blue line first shows a constant weight. As the indentation increases, however, the graph shows the weight of the material on the scale increasing up to almost 25 kg, indicating that the material was being pushed forcefully downwards as a result of the indentation. The peak of the blue line indicates the maximum indentation. At this point the actuator reached its maximum force (125 N) and automatically moved back to its zero position.

In the second experiment, 12 l of material were once again placed in single batch. At 6 N the formwork began to move. This time, however, 20 mm layers were filled at intervals of 12 mm/min in an attempt to simulate the production process.

Slipping was once again started at 6 N; as it began (at a rate of 5 mm/min), the weight again dropped to almost 50% (see Figure 139) due to friction pulling the material upwards. Indentation began at 100 mm, and the velocity was increased to 12 mm/min. From here on, material was filled at 1.2 min intervals. In this case, however, the moving of the formwork and the weight of the material caused the weight to remain fairly constant. This suggested that two opposite effects were occurring: the slipping was pulling the material up, while the actuators were pulling the material down.
Figure 140: Result of the second scale experiment, showing indentation while moving. The y-axis shows the weight of the material in kg. The x-axis shows the time. The blue line shows the weight of the material on the scale over time. The graph is divided in four segments indicated by a red discontinuous line. The light blue colour in the background shows the weight of the material. The first segment shows a constant weight of 22 kg, indicating that the robot is not moving. In the second section, the blue line fluctuates as a result of the formwork moving. In the third segment, the robotic velocity increases to 12 mm/min and the indentation begins while material is filled 1.2 min intervals. The dark blue line shows that the indentation is causing the material weight to increase. In this case, however, the increase is almost parallel to the weight of the material and the movement of the robot.

The scale experiments showed two clear results. First, slipping using the flexible formwork caused constant friction, which created tension forces at the surface of the material. Second, when indenting the inner membrane, the compression force from the actuators caused the material to be pushed downwards.

Figure 141: Schematic illustration of the force flow occurring while indenting and slipping.

The two opposite forces made it impossible to detect the right moment for slipping and shaping, as discussed in the experiments. One possible solution to this problem is to add more actuators, which, similar to a jump-form technique, would continuously pre-shape the formwork in the indented geometry. Another solution would be to create a void space in the column into which
the material could be displaced to reduce the stresses used during shaping. Ultimately this latter solution was used in experiments described from 4.5.6.-4.5.7.
APPENDIX 6: EXPERIMENTAL PROJECT CREDITS

Based on the first experiments discussed in this thesis, in which it was proven that concrete has the potential of being shaped in its early hydration phase, this project received an ETH Research Grant ETH-13 12-1 under the name \textit{Smart Dynamic Casting}.

The grant supported an interdisciplinary research set up within the ETH Zurich between: (PI) Prof. Dr. Robert J. Flatt (Institute for Building Materials, Physical Chemistry of Building Materials); Prof. Erich Windhab (Laboratory of Food Process Engineering); Prof. Hans Herrmann (Institute for Building Materials, Computational Physics for Engineering Materials) and Prof. Fabio Gramazio and Prof. Matthias Kohler (Gramazio Kohler Research, Chair of Architecture and Digital Fabrication)

The experiments and projects discussed in this thesis have been conducted within the interdisciplinary research setup between the named groups, under the main guidance of Prof. Fabio Gramazio, Prof. Matthias Kohler and Prof. Robert J. Flatt.

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- Orkun Kasap

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- Maryam Tayebni
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