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SMART DYNAMIC CASTING

SLIPFORMING WITH FLEXIBLE FORMWORK - INLINE MEASUREMENT AND CONTROL

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ABSTRACT

Smart Dynamic Casting (SDC) – a robotic prefabrication method for non-standard structures – has emerged from shaping concrete with a rigid formwork into an almost fully automated system enabling the production of concrete structures with variable cross-section and geometries using flexible actuated formworks. The flexible formwork systems have yielded full scale prototypes (up to 3 meters in height) that vary in shape, volume, thickness and geometry (or a combination of these), and show that the SDC design space can be significantly expanded, far beyond what has been achieved in previous studies.

Two different shaping methods were applied. The first method shapes the material locally, at the exit of the formwork, only allowing a minimal gradient of deformation. The second method shapes the material globally, across the whole height of formwork, allowing for significant variation in cross section.

Regardless of whether the deformation occurs locally or globally, any deformation modifies the load on the concrete at the exit of the formwork, thus requiring continuous inline measurements and automated feedback loops. A recent successful approach combines formwork pressure and friction measurements to define the lower and upper strength limits of the shaping window, thereby enabling more robust control of the process.

This paper presents the current SDC process, with a particular emphasis on how the experimental setup has changed from previous studies. This includes descriptions of new flexible formwork typologies, followed by a description of the novel inline measurement technique. Together, these advances bring the SDC system another step closer to the main objective of the research, which is to develop a fully automated system that enables efficient production of load bearing structures in a continuous digital chain.

Keywords: *Architecture, non-standard, flexible formwork, inline control system, automated continuous production system, concrete, digital fabrication*

1. INTRODUCTION

Advances in digital fabrication over the past ten years have promised to revolutionise the field of architecture by enabling design of complex and optimized structures. The application of digital fabrication to concrete technology has been of particular interest to researchers, as the material’s versatility lends itself well to freeform design [1]. Over the past few years, a number of studies have used digital fabrication methods in the design and implementation of freeform concrete structures. However, these have been focused primarily on using CNC milled formwork [2], which has the downside of being a wasteful process as the custom formwork is used only once. Another new method is to 3D print via layered extrusion processes, such as Contour Crafting [3]. However, this method requires the addition of reinforcement after the structure is printed, a limiting factor in particular for double curved shapes. More recently, the Mesh Mould process [4] has been used to 3D print a functional stay-in-place formwork, with single as well as double curvature, by robotically fabricating a steel wire mesh that would act both as a formwork as well as the structural reinforcement. While this method is still in development, it nonetheless promises to become an efficient technique for the construction of nonstandard, freeform concrete structures.

Smart Dynamic Casting (SDC), presented here, is an alternative digital fabrication process for prefabricating custom elements [5-6]. The process takes its inspiration from slipforming, a well-known concrete technology for on-site construction of structural elements such as cores and pillars. In SDC, fresh concrete is poured into the top of a formwork that is much smaller than the final element, and comes out the bottom in a partially hardened state – with enough strength to support its own weight and the weight of what is in the formwork, but still soft enough that it can be shaped. This process requires control of the hydration kinetics, as flocculation alone is insufficient for the structure to support its own weight once it grows beyond half meter in height [1]. In SDC, hydration is controlled via a novel set-on-demand system, where a batch of massively retarded concrete is incrementally activated with accelerators before being placed in the formwork [7-9]. The background and development of this process are described in the following section.

2. OVERALL SDC SETUP

In the early stage of development, the SDC process was guided by a feedback system consisting of a digital controlled penetrometer measuring the strength evolution of the material, remote from the formwork [5-6, 8]. Batches of concrete in this early stage were sequentially accelerated and manually placed in a pump which fed the material into the formwork. Now, however, SDC is managed by a digitally controlled feeding system that automatically accelerates and places the material into the formwork. The remote feedback system is now used simply to indicate when to initiate slipping. To gain information regarding the strength evolution of the material in the formwork, our new feedback system measures the material directly in the formwork, a necessary step towards fully automating the process and assuring robustness when dynamically changing the formwork cross section.

The new process for the production is illustrated in Figure 1, and can be described as follows: Prior to production, a large batch of retarded concrete is prepared (a). As production begins, small amounts of accelerator (b) are pumped into the retarded material, which is then placed into a central mixing chamber above the formwork (c). A small amount of the mixed material is reserved for the remote feedback system (d). The formwork is then filled. The robotically controlled slipping (g) begins when the remote feedback system (d) indicates that the material's strength properties are adequate. As slipping begins, the inline feedback system in the formwork (e) sends information about the properties of the material in the formwork. The accelerator dosage and pumping rate are adjusted accordingly.

2.1. Material

The mortar used in this study consists of 52% volume fraction of primarily siliceous aggregate (grain size 0-4 mm). A commercial Portland cement (CEM I 52.5R, according to the European standard EN 197-1:2000) is blended with 8% undensified silica fume by mass of binder. The water to binder ratio is 0.38, taking into account the water contained in the admixtures. 0.103 % D (+)-sucrose (99.5%, Acros Organics) by weight of binder is used as a retarding admixture along with 0.8% commercial weight by binder of a commercial polycarboxylate ether superplasticiser used for precast applications. A 4 % weight by binder of a commercial calcium nitrate based solution is used as an activating/accelerating admixture. The retarding and superplasticising admixtures are added to the mixing water, which is mixed with the aggregates and binder for 8 minutes, creating the sleeping mortar. The activating agent is mixed into the sleeping mortar shortly before the mortar is placed into the formwork.

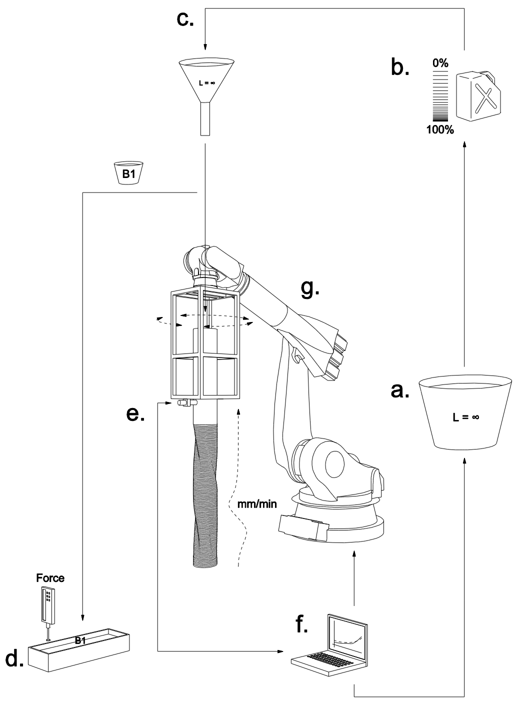

Figure 1: Conceptual diagram showing the production process of SDC. Starting with: a. large retarded batch of concrete; b. accelerator; c. mixing chamber; d. remote feedback system; e. formwork with in-line feedback system; f. control system; g. 6-axis robotic arm conducting the vertical movement.

2.2. Formwork systems

When using any rigid formwork cross section (as was done in SDC until now), the possible geometrical range is restricted to a variation of rotational or curved structures [6, 8]. In order to expand the design space of SDC, a natural next step is to explore using a formwork that can transform its geometry and/ or volume during the slipping process. This study used flexible formwork systems to explore two different shaping methods. First, the material shaping was done locally, at the exit of the formwork. Next, the material shaping was done globally over the entire cross section of the formwork. The limitations of the two approaches are briefly described below.

Local deformation at the exit

The goal of these experiments was to assess the method of indenting the material at the exit of the formwork in a straight or rotated trajectory [10]. Here, a flexible membrane was mounted into a circular formwork with a diameter of 200 mm and a height of 400 mm (Figure 2, left). An 80-mm diameter hollow core was inserted into the centre of the formwork to allow space for the material to displace. Four digitally controlled actuators (mounted at the lowest part of the flexible membrane) were used to indent the membrane and deform the concrete, thereby changing the cross section geometry. To reduce friction, a capillary oiling system was used to inject oil into the membrane layers.

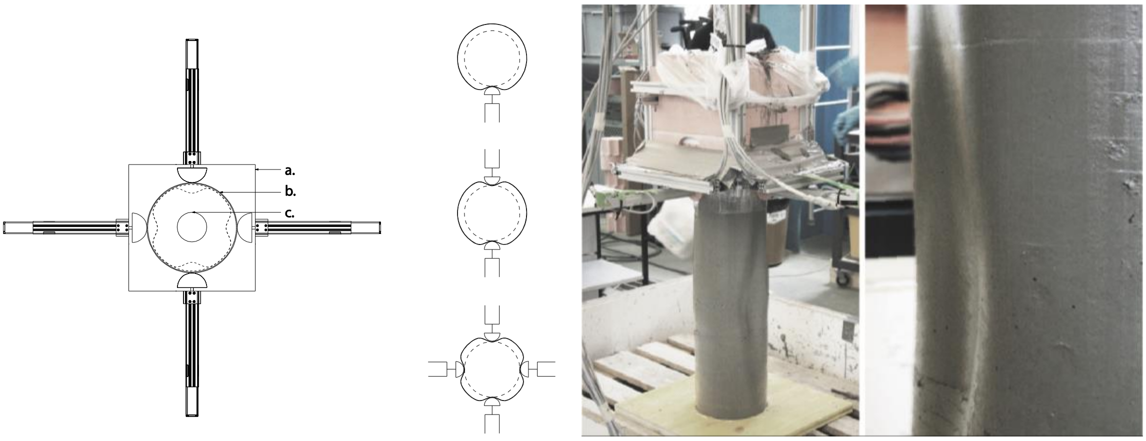

Figure 2: Left: Schematic view of the flexible formwork; four actuators were mounted in equal distance around the formwork, with three diagrams showing the possible configurations. Right: production with flexible formwork [10]

Several prototypes varying from 1.2 – 2 m in height were produced with this formwork, and two major conclusions could be made from these experiments: first, the maximum material indentation was limited to 40 mm (1/5 of the initial diameter) in a straight trajectory; second, friction increases substantially during simultaneous indentation and rotation, thereby reducing the design space. It was also shown that a lack of lubrication resulted in horizontal micro cracks (Figure 2) due to a stick-slip effect [10]. While these experiments demonstrated that concrete can be shaped at the formwork exit in a rotational or straight trajectory, this formwork did not explore the possibility of changing the cross sectional area. However, this topic was explored in the production of a canoe for the Concrete Canoe Regatta of the German Civil Engineering Student Association [11].

The overall goal of producing a canoe with the SDC process was to assess three major aspects. First, if it was possible to change volume and angle of the formwork while slipping. Second, if it was possible to slipform extremely thin structures, and third, to explore the important question of whether or not reinforcement in the form of long bundles of carbon fibres could be integrated into the structure while slipping. The flexible formwork for the production of this canoe is illustrated in plan view (Figure 3, left). The base geometry was a V-shape that could change angle and volume by the means of stepper motors while slipforming [12]. During the canoe production, the formwork was translated from narrow (dashed lines, Figure 3, left) to wide (full lines, Figure 3, left) and back to narrow. To control the height of the canoe, hence the volume of the formwork cross-section, indenters left and right (Lv, Rv, Figure 3, left) could change the cross-sectional area.

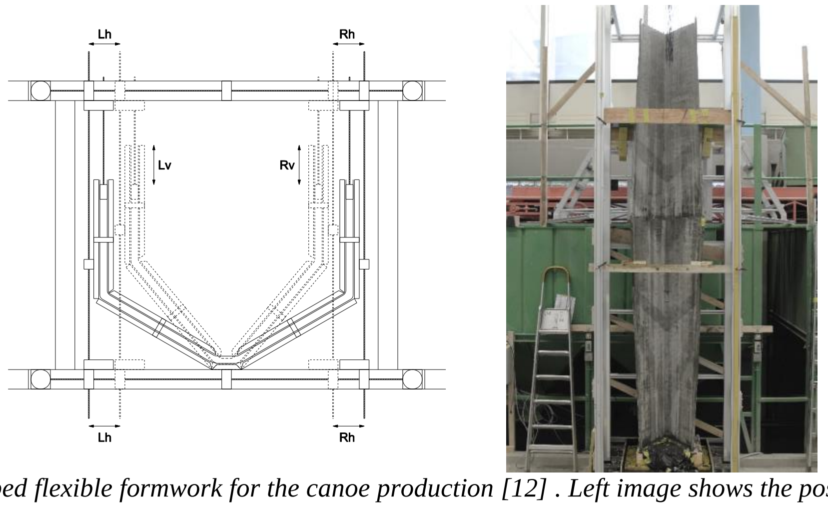

Figure 3: V-Shaped flexible formwork for the canoe production [12] . Left image shows the possible translation of the formwork. The angle could be changed by moving sliders indicated (Lh, Rh). The volume could be changed by "indenters" pressing into the inner cross section of the formwork, indicated as (Lv, Rv). Right, shows the result of the 4-m-tall structure.

Due to the fact that the shaping was done locally at the formwork exit, it turned out not to be possible to translate the formwork to the planned width. During production it became clear that significant shear stress due to the local deformation caused minor cracks to occur, limiting the range of deformation to 0.45 mm per centimetre of height. Despite the limited shaping it was nevertheless possible to produce a final prototype with a total height of 4 m, with a wall thickness of 1.8 cm with integrated carbon fibre treads from base to top. The result was considered a radical step in the SDC process and demonstrated, for the first time in the history of a digital fabrication with concrete, that it is possible to dynamically shape concrete in a slipforming process while integrating reinforcement. In fact, recent experiments not reported in this paper have successfully integrated conventional steel reinforcement into SDC, thus moving SDC a step closer to its ultimate goal of a process enabling efficient production of structural non-standard construction elements.

The experiment conducted with both the membrane flexible formwork and the V-shaped flexible formwork showed that the SDC design space can be further expanded, depending on the configuration of the formwork used. However, the maximum deformation in both systems was constrained in scale. It was therefore assumed that a global material shaping process (across the entire height of the formwork) would be needed to produce structures with greater deformation-to-height ratios.

Global shaping across the formwork height

The goal of this set of experiments was to significantly change the cross sectional area of the elements to access the possibilities of producing structures with a higher degree of deformation over the height of the structure. To achieve this, a flexible formwork was developed which could shape the material over the entire formwork height [13]. The formwork consisted of a rigid box into which two flexible metal plates were mounted; these were manipulated by actuators following a predefined digital trajectory, and synchronised with the system's vertical movement (see Figure 4).

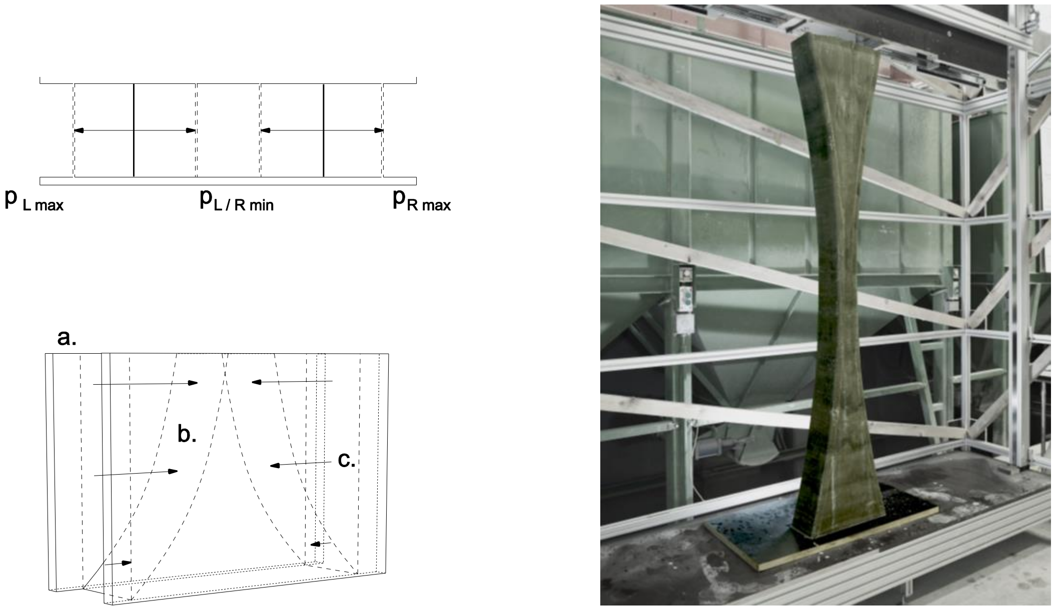

Figure 4: Upper left, schematic top view of flexible formwork. $P_{L/R\ max}$, is the maximum volume increase, while $P_{L/R\ min}$, indicates the minimum volume decrease. P_L and P_R are controlled individually, thus the design space is not constrained to a symmetric structure. Lower left: a schematic illustration of the formwork; a) rigid box; b) flexible metal; c) arrows indicate position of actuators manipulating the flexible metal globally over the height of the formwork. Right: a 2-meter tall structure produced with the flexible formwork [13].

A number of prototypes were produced with this formwork, the most successful of which was a 2-m tall column with a cross section area that varied by more than 50% over its height (Figure 4). During the production of another prototype, the mortar weight increased the load at the exit point as the formwork widened, causing the structure to fail. This failure led to the development and implementation of an inline monitoring system that would enable feedback control to avoid such failures in the future.

2.3. Inline feedback control

Variable cross sectional area changes resulted in the need for better process control – SDC requires the material exiting the formwork to support the weight of material in the formwork, but it must not be so stiff that it cannot be shaped, otherwise friction between the formwork and the material leads to fracture. Previous reliance on offline penetration measurements to monitor strength build-up presented a logistical problem in continuous production, and with global deformation formworks with variable cross section, the stress at the formwork exit varies with constant filling height. Consequently, the balance of self-weight and cohesion may change as an object is shaped, and monitoring of material structural build-up in the formwork was the next natural and necessary step. Thus sensors were implemented to measure the pressure and friction inside the formwork, and used to define a processing range.

Figure 5 illustrates the inline feedback system that was implemented. First, to measure the vertical cumulative contribution of friction F_{fr} along the formwork surface, load cells were mounted between the robot lifting system and the formwork – a method of which initial steps were described in [14]. Secondly, the formwork pressure σ_{h_M} was measured by the displacement w of a thin foil at a point M shortly before the exit of the material (point E).

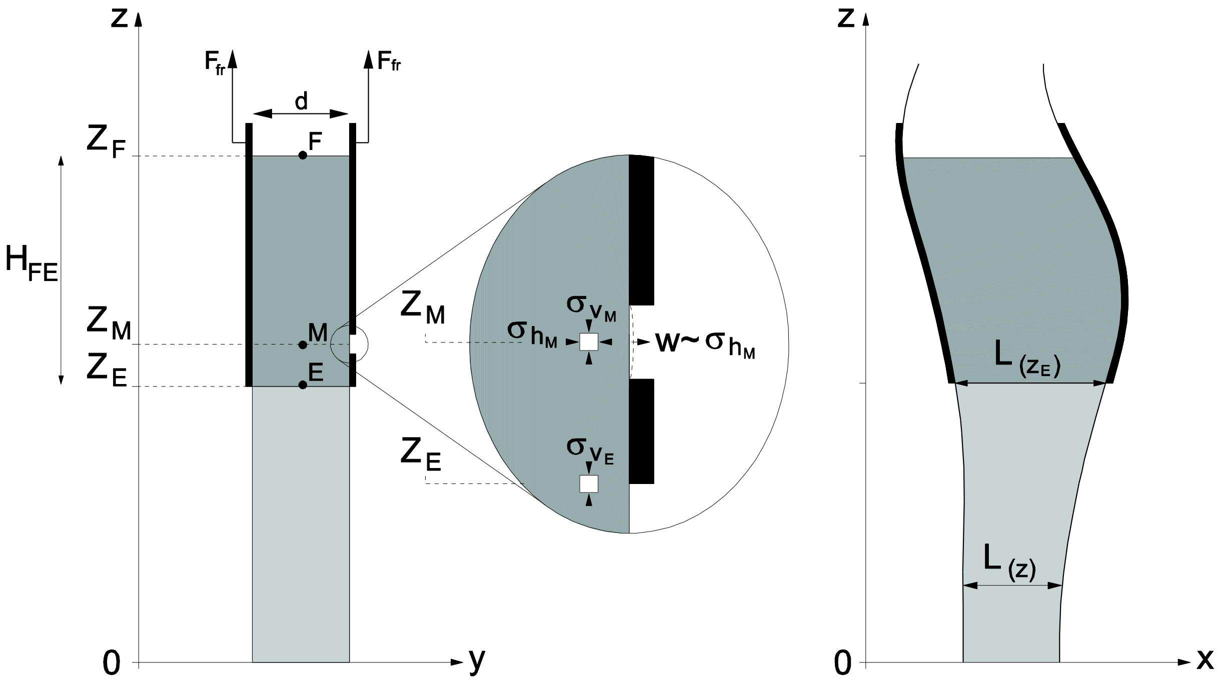

Figure 5: SDC filling and slipping process and inline feedback system: The mortar is filled up to the filling point F (at z_F) and exits the formwork at the exit point E (at z_E). The yield stress τ_{f_M} is estimated at the measurement point M (at z_M) using the formwork pressure σ_{h_M}. The vertical load at the exit point E is calculated using the filling level H_{FE}, cross-section geometry L(z), d and friction force F_{fr}

The friction measurement can give an indication if the material at the exit point E is in compression or tension and used to assess the risk of fracture. The vertical stress σ_{v_E} at the exit point depends on the mortar's density ρ, the gravity constant g, the dimensions of the product's cross section $L(z)$ and d, the filling height H_{FE} from the filling point F to the exit point E, as well as the friction force F_{fr}:

$$\sigma_{v_E} = \int_{z_E}^{z_F} \frac{\rho \cdot g \cdot L(z)}{L(z_E)} dz - \frac{F_{fr}}{d \cdot L(z_E)} \tag{1}$$

Conservatively, there is a risk of fracture if the material at the exit point is subjected to tension, therefore a processing limit of the vertical stress at the exit point can be defined:

$$\sigma_{v_E} > 0 \tag{2}$$

which also gives the following process criterion

$$F_{fr} < d \cdot \rho \cdot g \int_{z_E}^{z_F} L(z)dz \tag{3}$$

Assessing the risk of material collapse from inadequate strength build-up requires knowledge of the shear strength in the formwork and at the exit point. The inner friction angle of the material is 0° [15] between the formwork pressure measuring point M and the exit point E. Consequently, the Tresca failure criterion gives the shear strength τ_f as a function of horizontal and vertical stress σ_h, σ_v:

$$\tau_f = \frac{\sigma_v - \sigma_h}{2} \tag{4}$$

At the exit point E, the horizontal stress is zero. Therefore the shear strength of the material τ_{f_E}, which defines a minimum yield stress necessary for the material to support itself at the formwork exit, can be calculated:

$$\tau_{f_E} > \tau_{f_{E,min}} = \frac{\sigma_{v_E}}{2} \tag{5}$$

The mortar shear strength τ_{f_M} at the measurement point M can be estimated by the formwork pressure measurement σ_{h_M} and an estimation of the vertical stress σ_{v_M}:

$$\tau_{fM} = \frac{\sigma_{vM} - \sigma_{hM}}{2} \tag{6}$$

The shear strength evolution between points E and M must be captured. For this we rely on empirical knowledge from past penetrometer measurements showing that the yield stress – equivalent to shear strength – of our mortar increases exponentially with resting time *t*: $\tau_f(t) = \alpha \cdot e^{\beta t}$, with $\beta \approx 0.08$ min^{-1}. Therefore the ratio τ_{f_E}/τ_{f_M}describing the mortar's relative yield stress increase while it is conveyed from the measurement to the exit point and be related to the instantaneous slipping rate v_s:

$$\frac{\tau_{f_E}}{\tau_{f_M}} = e^{\beta \frac{z_M - z_E}{v_s}} \tag{7}$$

Substituting (5) and (6) into (7), we obtain a second process criterion:

$$e^{\beta \frac{z_M - z_E}{v_s}} > \frac{\sigma_{v_E}}{\sigma_{v_M} - \sigma_{h_M}} \tag{8}$$

Which can be reformulated to a more useful form, directly giving the maximum slipping rate v_{max} on the basis of the inline measurements:

$$v_s < v_{max} = \frac{\beta \, (z_M - z_E)}{\ln \frac{\sigma_{v_E}}{\sigma_{v_M} - \sigma_{h_M}}} \tag{9}$$

This relation is conservative as the material can be considered at least partially confined at the exit point because of the continued hardening of the previously extruded mortar below. A shortcoming of this relation, however, is that it requires an empirical estimation of the self-weight stress σ_{v_M} at z_M as the distribution of friction in the formwork is unknown. So far, we assume that friction stress is proportional to the mortar depth.

The processing criteria in (2) and (9) were tested directly in three experiments. In all experiments, samples with a fixed cross section $L(z)=d=15$ cm were produced. The formwork pressure measurement was positioned 43 mm above the exit point of the formwork. Slipping was initiated based upon penetrometer results and different slipping rates were chosen, including typical (Case 1), slower (Case 2) and faster (Case 3) rates, with Cases 2 and 3 intended to cause failures at both process boundaries.

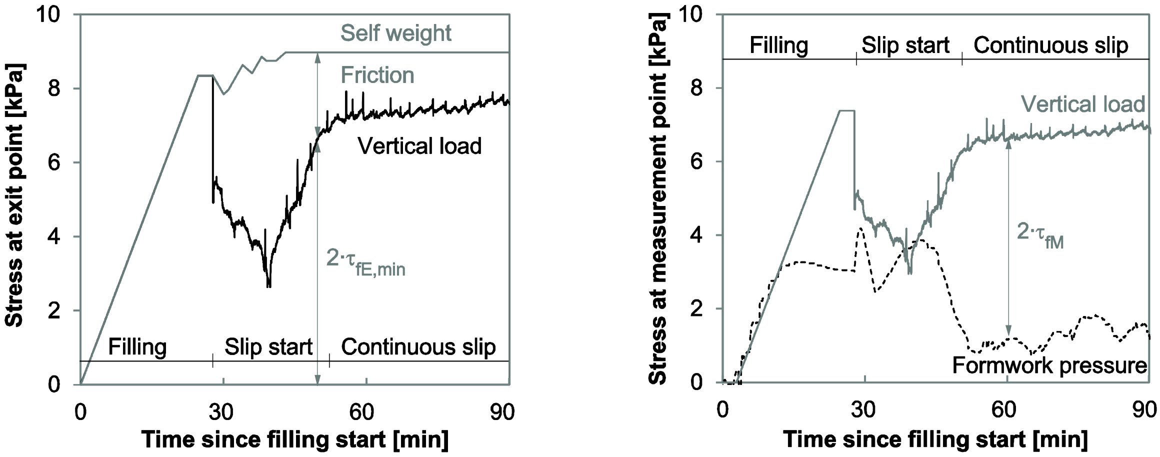

Figure 6: Measurement results from a typical SDC process (Case 1). (left) Subtracting friction from the mortar self-weight gives the load σ_{v_E} at the exit point E. σ_{v_E} is positive throughout, so the process condition (2) is fulfilled. (right) The difference of formwork pressure σ_{h_M} to vertical load σ_{v_M} at the measurement point M allows yield stress estimation. The strong friction in the slip start range may interfere with the yield stress estimation τ_{f_M} and lead to very low estimations.

The results for Case 1 are seen in Figure 6. Results show that as the formwork was filled stepwise with mortar, formwork pressure increases and reaches a steady state despite additional filling. This measurement could serve to indicate whether sufficient strength has been reached for slipping, but it was not used in this study. At the exit point, the vertical load σ_{v_E} is positive throughout the experiment, which fulfills process criterion (2). The estimated yield stress at the formwork pressure measuring point τ_{f_M} can be calculated based on (6) with the results seen in the right side of Figure 6. While this value is positive most of the time, friction in the slipping startup phase strongly reduces the estimated value, which is probably a model limitation associated to the estimation of friction distribution.

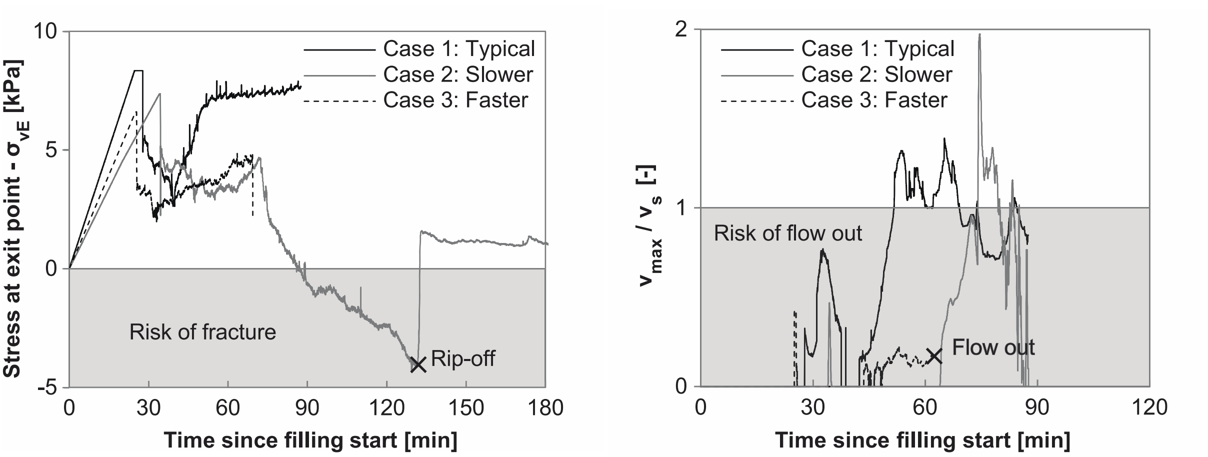

Figure 7: Process criteria (2) and (9). (left) With respect to criterion (2) only case 2 turns to tension from 90 min onwards and rip-off failure is observed at 130 min. (right) After the slipping start-up period, process criterion (9) is fulfilled in cases 1 and 2 in the continuous phase and as long as (2) is also fulfilled, but it suggests that the effective slipping rate in case 3 is substantially too high. Indeed, the mortar flows out in case 3 at 70 min.

In Figure 7, all three cases are depicted. Friction measurements show only Case 2 entering the range of tensile stress at the exit, and indeed fracture was eventually observed. Formwork pressure measurements, expressed in terms of the slipping rate process criterion in (9), were more ambiguous. Only in Case 3 did the mortar flow out of the formwork, and the model is confirmed by a $^{v_{max}}/_{v_s}$ ratio substantially below 1. However, the results show that the criterion is only fulfilled in the continuous slipping phase for a prolonged time in Case 1. In fact, during the slip start phase in Cases 1 and 2 friction strongly reduces the vertical load (compare to Figure 6), which strongly reduces the estimated yield stress at point M and in turn reduces the allowed slipping rate. It appears that with strong friction, the unknown distribution of friction inside the formwork is the determining factor for the yield stress determination at point M. Consequently, the proposed model appears to only allow relevant estimations if friction is low compared to the vertical load. For large objects, the friction distribution is a less significant factor (lower formwork surface to volume ratio), and confinement should be stronger. These factors should ultimately increase the reliability of the proposed process control. Alternatively, friction could be considered concentrated in the formwork between measurement and exit point, but this would overestimate v_{max} and lead to an unsafe process criterion.

3. CONCLUSION

The structures resulting from experiments using different flexible formwork systems demonstrate that SDC can significantly expand the design space: it is now possible to produce custom columns with changing cross sections, as well as structures with thin shell-like components. The shaping method directly impacts the design space by altering the resolution of the deformation. Local deformation at the exit primarily changes the shape of the surface rather than the cross sectional area, as was demonstrated with the concrete canoe. This can be extended further to thin, shell-like components. Global shaping within the formwork, on the other hand, enables radical changes in cross sectional area, a key requirement for producing structurally optimised prefabricated elements.

Radical changes in cross sectional area required a new and more precise inline feedback control system. Knowledge of the filling level combined with friction measurements can quantify vertical stress at the exit point and inform the process about the occurrence of tension and the risk of fracture. Inline measurement of formwork pressure near the exit of the formwork can inform the process about the risk of insufficient structural build up and material outflow failure so that the slipping speed can be adjusted accordingly.

Overall, the results presented in this paper demonstrate how flexible formwork systems and an inline feedback control system can be used to expand the SDC design space. While this is significant, it is merely a prerequisite for fully exploring the possibilities of this prefabrication system. Future developments will focus on a completely automated system to explore the design space more fully with respect to structural optimisation and thin shell elements.

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