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In-Crease: Less Concrete More Paper

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Abstract

Concrete is one of the most used materials after water. Largely owing to this, its environmental impact is substantial, although its embodied carbon per unit volume or mass is low when compared to most alternatives. This, along with the broad availability, good strength, durability and versatility of concrete means that it will remain a material of choice, although more efficient ways of using it must be found.

Structurally optimized building components are a means to do this as they can save about 50% material. Unfortunately, however, such elements are presently too expensive to produce owing to them requiring non-standard formwork. It is an objective of digital fabrication to propose solutions to this issue. In this con-text, Digital Casting Systems (DCS) have advanced material control strategies for setting-on-demand in digital concrete processing. Thereby, the formwork pressure is reduced to a minimum, which opens possibilities of rethinking formworks as systems that are dynamically shaping, millimetre thin or weakly supporting the material cast inside.

In this paper we present a brief overview of millimetre thin formworks and summarize the first realization of concrete elements that utilizes the mechanics of paper folding to make millimetre thin formworks up to 2.5 meters high. Such formworks could initially be flat packed, erected into shape, and eventually peeled-off and recycled in established material streams. This would reduce waste and transport cost, while offering a surface finish that meets the expectations for exposed concrete surfaces.

Keywords: Robotics; Automation; Digital cutting; Digital concrete; Sustainability; Formworks; Bi-stable structures; Origami

1 Introduction

1.1 Room for improvement

The construction sector is responsible for 40% of natural resource consumption and 50% of global energy use, making it a major societal objective to build or renew our homes and infrastructure using less materials. Reducing the consumption of concrete, which after water is the most used material worldwide, would make major contributions to this objective. Among the different approaches to achieve this, one option with great potential is smart structural design in which form-finding is used to design structurally optimized and material-lean structures [1-4]. Specifically, advanced CAD software and form-finding algorithms, along with advances in structural mechanics, are facilitating major advances in efficiency [1]. Unfortunately, most of the optimised structures that have been proposed are non-standard shaped elements, which generally require custom formworks that are costly and wasteful to produce when produced with the state-of-the-art technologies for concrete casting [5,6].

Digital fabrication with concrete, however, could potentially reduce the economic barrier for producing such structures, facilitating their realization and enabling substantial material savings in the construction sector [7]. In part due to this promise, the field of digital fabrication has seen major growth in the number of projects and in investment in new technologies, many of which focus on 3D concrete extrusion [8]. However, to date most novel concrete processes fall short of credibly demonstrating true cost-effectiveness, ease of application and adoption by industry. This is often due to the added complexity of the processes and the need for introducing alternative reinforcement systems that may not be compatible with current construction norms [9], as well as a lack of knowledge of the long-term durability of these structures.

1.2 Motivation

In contrast to the current trend of 3D concrete printing, the focus of this article lies on casting systems with set-on-demand concrete called Digital Casting Systems (DCS) [10]. DCS allows for control of the hydration of a self-compacting concrete on the fly of production, thus reducing formwork pressure to a state that eliminates the need for heavy-duty formworks for concrete while also allowing for the inclusion

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*Corresponding author: Ena Lloret-Fritschi, E-mail: ena.lloret.fritschi@usi.ch of standard reinforcement systems that comply with norms. Over the past decade, the different DCS processes have used different formworks starting with dynamic slipforming known as Smart Dynamic Casting (SDC) [11], Eggshell, using ultra-thin fused deposition modelling (FDM) formworks [12], and lightweight formworks made from foil, textile or paper for Admixture Controlled Digital Casting (ACDC) [13]. Overall, these formworks show that a well-focused combination of traditionally disconnected fields can open new and simple ways to realize material-lean structural concrete elements. Recently, the boundaries of millimetre thin formwork were pushed by combining the mechanics of paper folding with another DCS process, which will be introduced in this paper.

Compared to SDC formworks, which requires a rather complex formwork with actuators to increase the geometric flexibility [14], a paper formwork uses an initially flat paper and folds it into 3D formwork, which is light-weight, cost-efficient and easy to recycle. This formwork is filled with set-on-demand concretes typically used in industry, with the inclusion fibres and aggregates up to 8 mm. The particular combination of using millimetre thin formwork with paper formworks shows the potential of surpassing the challenges that most digital concrete technologies currently face [15-17]. This includes issues of cold joint formation between layers (known from 3D printing) and marks of the layer deposition, which do not match the standard architectural finish required for most buildings. Most importantly, the system presented can incorporate standard, normed reinforcement into architectural elements.

2 State of the art

2.1 Digital fabrication with concrete

3D concrete printing (3DCP). 3DCP today aims at providing a more sustainable construction method with concrete, by eliminating the need for traditional heavy-duty formworks, while placing material exactly where it is needed and offering more freedom of shape. The process however presents several downsides: cold-joint formation may compromise mechanical integrity and/or durability [18,19], placing reinforcement is difficult [20]. Also, large amounts of cement are typically used (up to 620 kg/m^3 of ordinary Portland cement) to meet the requirements of pumpability and rapid acquisition of strength (buildability) [21,22]. Thus, the environmental footprint of 3D printed concrete is most often substantially higher than that of normal concrete, which typically uses 350-400 kg/m^3 of Portland cement). Development of blended cements in digital concrete processes are promising though—for example, recent studies have reduced the cement content to 305 kg/m^3 [23], roughly half the content generally used in 3DCP processes. However, even if such advances in the mix designs are achieved, 3DCP elements still not match the standard norms required for structural concrete, reducing the printed elements to lost formwork and makes them too expensive for most construction. In addition, using 3D printed structures as formworks presents new challenges for casting logistics, as these formworks are typically not designed to take the hydrostatic pressure from the cast material inside.

Stay in place formworks. Alternative methods to 3DCP unify structural function and formwork, making reinforcement an integral part of the form. A pioneering example of this is Mesh Mould [24], today further developed through the spin-off Mesh [25]. Here, an industrial robot with a customized end effector bends and welds metal wires into a 3D mesh structure, which acts as a porous formwork during the concreting process and serves as reinforcement upon setting. Other approaches use lost knitted formworks to fabricate slender concrete structures [26]. Still others shotcrete horizontal layers around a rebar cage [27] for more bulky, structurally-optimized building elements. While some approaches have successfully demonstrated the true potential for real-scale construction such as Mesh Mould [28] and KnitCandela [29], they generally still remain specialized and require skilled personnel to apply the cover layer, although efficient processes are being developed for the spraying of millimetre thin moulds [30] and for automating the cover layer spraying [31].

Digital Casting Systems (DCS). In contrast to printing and spraying, DCS show another approach, which uses a digital casting process coupled with the concept of set-on-demand to control the hydration rate and fluidity of the concrete during fabrication [32-35]. Smart Dynamic Casting (SDC), a robotic slipforming process [30,31], was the first DCS process which could produce reinforced standard and non-standard columns with an excellent surface quality. The surface quality can be categorised under the Swiss Norm SIA 118/662, BOK 2 to 3 [36], while the conventional reinforcement, complies with existing norms [14] (Figure 1a, b). The process has been applied to a real world architectural project known as DFAB HOUSE [37]. With SDC formwork, however, the degree of freedom of shapes is limited owing to the complex mechanical actuation of the slipping formwork section.

The more recent examples of the DCS include digital casting control which regulates the vertical building rate to reduce the formwork pressure to almost zero, revealing new opportunities of using millimetre thin formworks of almost any material (e.g. polymer, textile, concrete, or clay, to mention a few) [38]. Thus, casting control of a self-compacting concrete significantly widened the possible geometrical spectrum for concrete structures compared to SDC.

This led to formwork systems called Eggshell (Figure 1d, e) that use a thin formwork shell produced with Fused Deposition Modelling (FDM) [12]. These are then filled with the digital casting system which, thanks to the rapid strength gain of digitally processed self-compacting material, does not exert significant pressure on the formwork. Eggshell has amongst others, also made it into a real-world construction scenario where again a reinforced concrete column was produced for an exterior office landscape (Figure 1d).

Figure 1. a) Smart Dynamic Casting, 2012 [11]. b) Mullions in the Dfab House, Empa Dübendorf, CH [37], c) Admixture Controlled Digital Casting, with weakly supported formwork with foil, 2018 [13]. d) demoulding of Future Tree column, e) close-up of column for the Future Tree, at the premises of Basler Hoffman Engineering, Esslingen, CH, 2018 [12].

Further concepts of using thin formworks were investigated by Szabo [13], where weakly supported formworks made of suspended foil (Figure 1c), textiles, rammed boards or paper were filled with a digital casting process called ACDC to fabricate post-tensioned thin folded members [13,39]. The results demonstrate one of the most economically feasible ways to produce formwork for non-standard shapes for thin folded and reinforced plate structures.

In this article, we show how these millimetre thin formworks can be pushed to the extreme, applying the concept toward replacing normal heavy-duty formwork with folded millimetre thin paper. This should not be confused with existing commercial cardboard formwork systems [40,41], which are either limited to simple cylinder or quare shapes or require the use of additional custom-made inserts placed within a cardboard cylinder which are typically made of expanded polystyrene foam (EPS). Thus, while those commercial solutions allow for inclusion of reinforcement and achieve a good surface finish, they remain inefficient and wasteful to produce complex bespoke structures.

2.2 Paper Folding

Millimetre thin paper folding with curved creases where diamond-like “cells” pop inward and appear to look like a folded column was first described in 1930 by Joseph Albers [42] (Figure 2). In the late seventies, the mathematician, David A. Huffman, investigated the mathematical rules of origami and brought the curved creases folding technique well beyond the prior work of Albers. Figure 2b, shows Huffman’s piece, *Horizontally Fluted Column*, alongside Albers’s original versions Figure 2a [43].

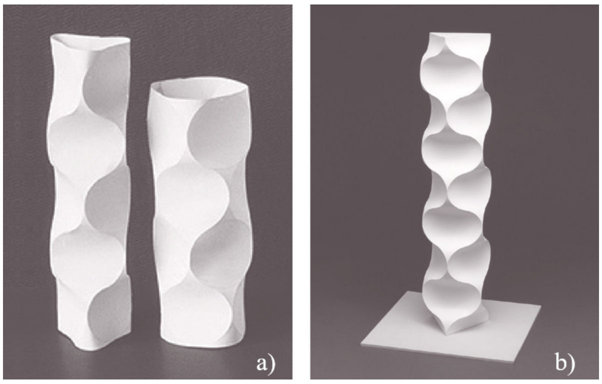

Figure 2. a) student work by Josef Albers in 1936-37, b) a model by David A. Huffman in 1977.

The physical behaviour of these folded columns pertains to that of the elastic buckling of a circular tube [44]. Indeed, there are many similarities between the “natural deformed shape of a buckled cylinder, namely the diamond mode” with that of Albers’ crease pattern [44]. In short, their work found increased control in the overall buckling geometry of a cylinder when using curved creases. While the buckling of thin-walled tubes has been explored for decades [45], mainly in the effort to create lightweight structural elements for building applications, such as stainless-steel hollow sections [46], such structures, to the authors knowledge, have not yet been explored as formworks for concrete.

The work presented in this article seeks to utilize such controlled buckling to create an thin, self-standing formwork for use with the digital casting process with set-on-demand concrete [22]. The following studies show that the buckling inward helps to build non-standard millimetre thin formworks that can resist the relatively small amount of hydrostatic pressure coming from the concrete pushing outward. As the objective of this article is to demonstrate the potential of this approach, we do not develop novel crease patterns, but rather calibrate established folding patterns for a specific formwork geometry. While the folds in the upcoming results mainly provide stiffness to the paper - thus no functionality to the structures produced - such folded formworks could potentially enable an easy way to produce non-standard formwork for structurally optimised concrete elements that use significantly less materials thanks to DCS.

3 Process and results

In the following section we present three distinct experiments that highlight the potential of using paper as a formwork for concrete casting, starting with folded elements and moving to columned sections to ultimately end up with a 2.5-meter-tall columned structure. The study first focused on empirically determining the right type of paper for the process, with materials being evaluated in terms of thickness, foldability, hydrophobic behaviour, and demoulding ability. Next, we tested global geometries and strategies for crease patterns and assembly.

Two types of paper were explored. First, was a museum backing board in thicknesses of 1 and 2 mm. This board is typically used for mounting and matting fine archival works of art and is specially treated with acid-free 100% cotton fibres which work well as a hydrophobic buffering agent from the water and base in the concrete. In addition, this paper was easy to connect into larger pieces, using off-the-shelve tape or glue, a good property when scaling up the formwork. The second type of paper tested was a wax-coated paper with a thickness of 0.4 mm. [47]. This was easy to crease and fold, and because the wax coating is hydrophobic, it was also easy to demould and resulted in a smooth surface quality. However, the challenge of this paper was to find a good bonding agent due to the waxy surface. Therefore, it was eventually excluded from the large-scale experiments, as it was neither available in single large pieces nor suitable to connect multiple pieces.

The experiments presented here consist of three primary operations: 1) the design of the folding patterns, 2) the fabrication of the formwork, and 3) the casting, for which two different digital casting techniques were used. One is the Admixture Controlled Digital Casting (ACDC) described in [13], which uses a self-compacting fast setting mortar. The aggregate content (sand 0-4 mm) for this mix was 52% by volume of concrete. Microsilica (Elkem 940U, BASF) was also used to replace a part of the cement (5% by weight of cement). The water to binder ratio for this mix was 0.39. Superplasticizer ACE30 and a 30% sucrose solution as retarder were also used (0.84% and 0.37% by weight of cement respectively). For the mortar used in ACDC, the hardening is accelerated with an aluminium sulphate solution, while the fluidity for assuring self-consolidation of the material during the casting is controlled with the addition of flow enhancer [13]. This mix allows for demoulding after 1.5 hours, when the material has reached a strength of 15MPa. The second mix design, a fast setting self-compacting concrete, was developed to implement in Digital Casting for a Swiss industrial prefabrication plant [48]. It is the first digital casting mix with aggregate sizes up to 8 mm and contains polypropylene fibres for fire resistance. The aggregate content of this mix was 40% by volume of concrete. The sand (0-4 mm) to gravel (4-8 mm) ratio was 4:1. Supplementary cementitious materials, fly ash and limestone filler were used to replace a part of the cement (28% and 49% by weight of the cement). The water to binder ratio was 0.4. Superplasticizer ACE30 and a 30% sucrose solution as retarder were also used (3.2% and 0.35% by weight of cement respectively). The hardening is accelerated using calcium aluminate cement (CAC) [49] and the mix reaches a strength of 15MPa (needed for demoulding) within 4 hours and 85MPa after 28 days [48]. The mix and process will be referred to as DC-industry-mix from hereon.

For both mixes, we prepare a retarded base mix and place it in a conveyer pump. The material is pumped into a mixer, into which precise dosages of admixtures are added in a continuous process as the mix is cast into the formwork [11,48]. A custom control software regulates the dosing of the accelerator and flow enhancer to match the flowrate of the retarded concrete. By controlling the hydration and casting speed on the fly of production, we drastically reduce the hydrostatic pressure acting on the walls of the formwork. Prior tests on the subject of thin formwork deformation were studied by Szabo et al [13], where a series of tests using thin suspended foils showed the correlation between formwork deformation and hydration and casting speed. To minimise the deformation a calibration between hydration and casting speed were found and further used in the following studies. For the initial experiments described in section 3.1 and 3.2, the casting was done using the ACDC mix design and setup. In this case the inline mixing devise is mounted to a 6-axis robotic arm that moves in a specific trajectory above the paper formwork depositing the fast setting mortar [13]. In the experiment described in section 3.3 we used the processing and DC-industry-mix developed for the industry partner [48], mimicking the industrial casting process developed for a Swiss prefabrication plant, where a crane is used to hover the digital concrete casting hose above the concrete during the casting.

3.1 Thin folded member: unstable to bistable

The column formwork design began by testing a simple hinge or linear crease with the goal of producing a thin folded element of concrete [39]. Typically, a single crease on a sheet of paper behaves like a hinge, such that the fold is never fixed at any angle (see Figure 3a). However, by incorporating curved creases that “kiss” and mirror along the vertical axis, it is possible to create bistable structures. By calibrating the arc of the curved creases, it is possible to control the maximum angle at which it can be folded. Thus, a sharper curved crease will be able to fold at a shallower angle than an elongated curved crease. As the curved creases are folded, the inner “cell” defined by the creases will “pop” inward (see Figure 3b), similar to controlled buckling [44] and a curved tape spring [50]. The method transforms the simple hinge at a corner into a bistable structure, and this was used to design a formwork for a thin folded member.

The formwork shown in Figure 4c is 1000 mm-tall, with an inner width of 70 mm. The formwork was made with 2 mm museum board, which is moderately hydrophobic, and a horizontal collar was added to the upper part to increase resistance to deformations that could occur during casting. The crease lines were designed in 2D in a CAD software and processed with a 3-axis CNC machine, after which the formwork was manually folded. The formwork was filled in 21 minutes using the ACDC mix [13] with the digital casting process, and it was easily removed 1.5 hours after production. The demoulded result depicted in Figure 4d shows the first element cast with paper formwork. With the naked eye, we could not detect major deformations in the global geometry, and the collar attached to the upper part of the paper formwork assured that the global geometry remained as designed during the building process [39].

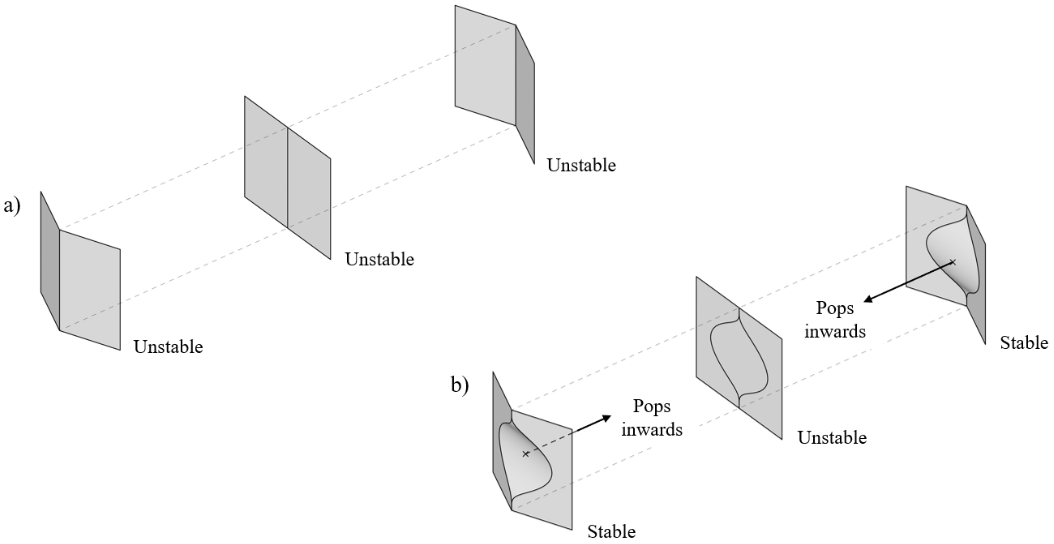

Figure 3. a) illustrates a simple hinge, where the folded geometry is unstable, b) shows a bistable structure, where the arc of the curved creases “lock” the geometry at a particular angle.

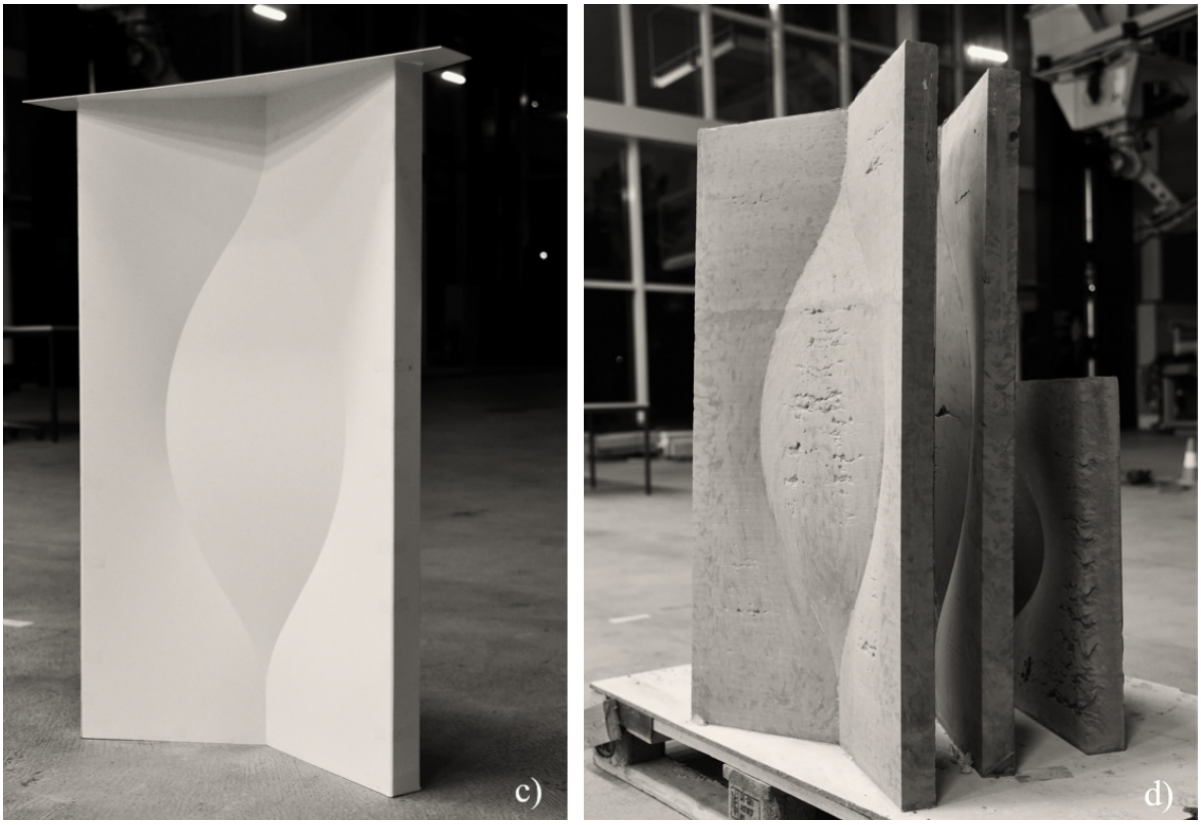

Figure 4. c) formwork made of 2mm Museum board. d) demoulded results in concrete [39].

3.2 Nested creases

In the next series of experiments, the goal was to reduce from 2 mm to the 0.4 mm thick wax paper. This required developing a formwork with increased rigidity, which can be achieved through an array of nested of creases that alternate between mountain and valley folds (see Figure 5). The nested creases provide increased surface area around the formwork. This can contribute to the structural performance of the millimetre thin formwork, but it needs to be carefully calibrated for certain designs and geometries as the incorporation of a valley fold can make the formwork weaker. For example, for a very elongated curved crease, it will be easy to pop the valley fold outward and for a very firm curved crease, it proved to be almost impossible to fold the initial valley fold. Future research should explore the exact proportions and geometric ratios that are ideal for such applications of curved creases.

The formwork paper used was 0.4 mm wax coated paper (Figure 5a), the lines were designed in 2D and again creased with a 3-axis CNC machine and manually folded into a formwork with dimensions of 150 × 150 × 1000 mm (Figure 5b, c). The ACDC system was again used to fill the formwork [13] (Figure 5d).

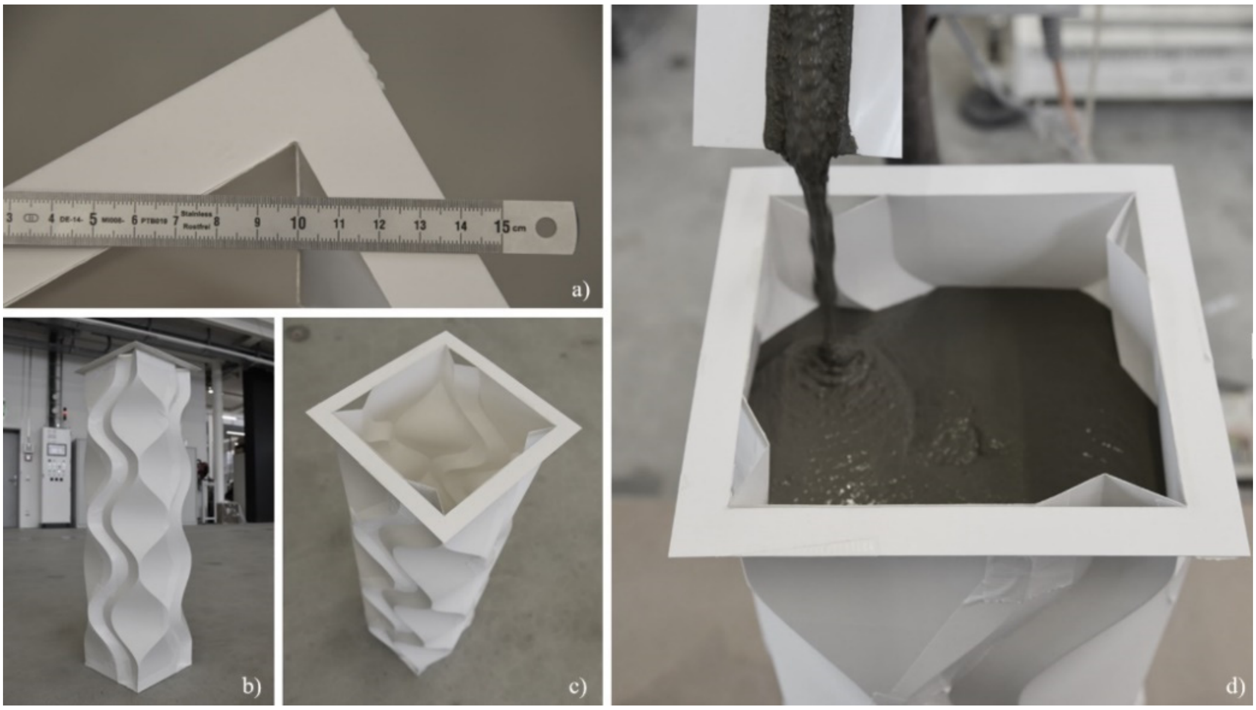

Figure 5. a-c) the 0.4 mm paper formwork. d) digital casting into the formwork at 1-meter showing its ability to resist the hydrostatic pressure of the concrete.

After 1.5 hours the formwork was again easily peeled-off. Figure 6a, b shows the result of a relatively smooth surface quality with some air voids and minor defects resulting in some inconsistency in the rheology during casting (Figure 6c). Such defects could for instance be avoided by adding viscosity modifying admixtures to the mix, which could provide a more robust rheology. Although the formwork produced with the 2 mm paper in the initial experiment was quite successful, the folding possibilities were limited due to the thickness of the paper. Further, studies not reported here showed that using the 0.4 mm wax-coated paper was easier to handle in terms of folding and assembly, with the downside of not being able to scale up, as we could not find a good method to connect the wax paper into larger pieces.

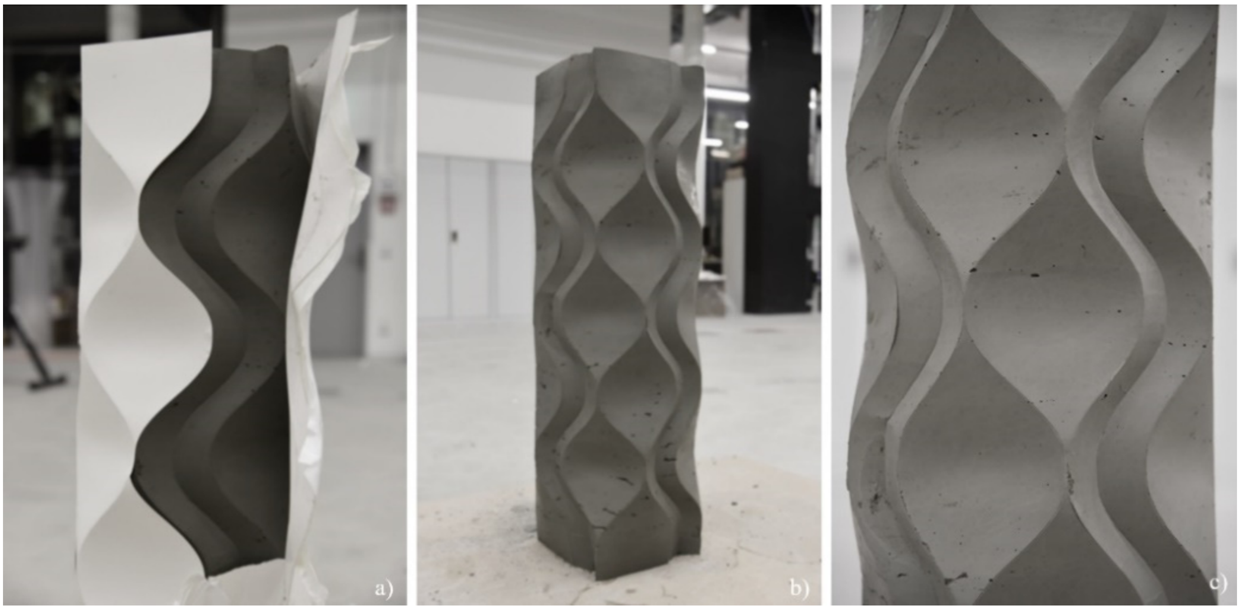

Figure 6. a) demoulding the 1-meter-tall concrete column prototype after 4 hours. b) demoulded column. c) close-up showing the suboptimal surface quality.

3.3 Scaling up

The next goal was to tackle a full-scale prototype with varying cross sections translating from 300 mm to 800 mm, with the height of 2500 mm, which combined the efficiency of the curved creased paper formwork with the DC-industry-mix and process [48]. For the sake of simplicity, the column was reinforced with an industrially produced rectangular reinforcement cage (dimension 150 mm × 150 mm). Building a suitable cage with the exact dimensions of the columns was not the goal of the experiment. Such a cage would resemble the same type as used in the Eggshell project Future Tree [51], further described in [52]. The rebar cage was placed into the paper formwork prior to casting. The material processing was digitally controlled, but instead of using a robotic arm to hold the digital casting mixer, a hose was extended from the mixing funnel to hover with a crane over the formwork, thus mimicking the intended industrial process [48]. Due to the changing cross section, the casting flow rates varied from 1.5 to 3.0 litres/minute. The total casting time was approximately 100 minutes, although this may vary +/- 20 minutes with the behaviour of the concrete hydration.

As the goal for this experiment was to scale up, the wax paper was not considered owing to its connection issue. Instead, we used 1 mm museum board, as a series of studies not reported here showed good results for folding and rigidity of the overall formwork, in addition to being easily taped into larger pieces. Also, the museum board did not require any sealant to join the edges of the creased patterns and had also shown good hydrophobic behaviour in the initial experiment described in 3.1. The paper formwork was made in three sections, according to the dimension constraints of the paper sheets available on the market. Each sheet was 800 mm × 1100 mm, and these were connected at the height of 1 meter with a collar (see formwork illustrated in Figure 7a). This final prototype successfully combines research on controlled concrete hydration and alternative formwork systems to showcase a novel option of shaping concrete for non-standard structures. It lays the basis for a systematic rethinking of the design and performance of concrete formwork, providing an innovative solution for future manufacturing options.

Figure 7. a), the 1 mm-thin formwork formed out of three pieces of museum board approximately 800 mm each. The resulting structure b), a tapering concrete column with a height of 2.5 -meters.

4 Conclusions

DCS processes offer additional possibilities for producing structurally informed elements with non-standard shapes. In contrast to 3DCP, it still relies on separately produced formworks, but avoids various shortcomings of 3DCP. It facilitates the incorporation of standard reinforcement systems, making it less cumbersome to certify load bearing structures. It also eliminates cold joints, reducing durability concerns and, when paper is used, provides an excellent surface finish.

The use of paper is enabled by the mechanics of folding. However, while paper folding shows potential and a large range of options exist [53], we have still not fully explored the possibilities and constraints. Further, to set the upper and lower bounds of the casting speed and hydrostatic pressure on the folded formwork, more information is needed on how specific folds in the formworks are influenced by the pressure. Therefore, further research is required for truly enabling the production of material-lean structures in the future with paper formworks. This can include considerations on thickness, folding properties, resistance to hydrostatic pressure, but also further materials solutions as fiberglass that could be reused. Beyond this, the simple fact that concrete can be successfully cast into paper formworks should question the current “taken for granted concepts” on bulky formworks and point us towards affordable production of material-lean elements of non-standard shapes.

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Authorship statement (CRediT)

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Fabio Scotto: Conceptualization, Methodology, Investigation, Formal analysis, Writing – Original Draft.

Anna Szabo: Conceptualization, Investigation, formal analysis, editing of original draft.

Robert J. Flatt: Supervision cconceptualization, Writing - Review & Editing.

Fabio Gramazio: Supervision, Review & Editing.

Matthias Kohler: Supervision, Review & Editing.

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