SCRIM – Sparse Concrete Reinforcement in Meshworks

Ayres, Phil; da Silva, Wilson; Nicholas, Paul; Andersen, Thomas; Greisen, Johannes Rauff

Published in:
Robotic Fabrication in Architecture, Art and Design 2018

DOI:
10.1007/978-3-319-92294-2

Publication date:
2018

Document Version:
Early version, also known as pre-print

SCRIM – Sparse Concrete Reinforcement in Meshworks

Chapter · January 2019

DOI: 10.1007/978-3-319-92294-2_16

5 authors, including:

Phil Ayres
Royal Danish Academy of Fine Arts, Schools of Architecture, Design and Conservat…

Paul Nicholas
Royal Danish Academy of Fine Arts, Schools of Architecture, Design and Conservat…

SCRIM – Sparse Concrete Reinforcement In Meshworks

Phil Ayres[1], Wilson Ricardo Leal da Silva[2], Paul Nicholas[1], Thomas Juul Andersen[2] and Johannes Portielje Rauff Greisen[2]

[1] Centre for Information Technology and Architecture, The Royal Danish Academy of Fine Arts, School of Architecture, 1435 Copenhagen, Denmark

[2] The Danish Technological Institute, Gregersensvej, 2630 Taastrup, Denmark

phil.ayres@kadk.dk

Abstract. This paper introduces a novel hybrid construction concept, namely *Sparse Concrete Reinforcement In Meshworks* (SCRIM), that intersects robot-based 3D Concrete Printing (3DCP) and textile reinforcement meshes to produce lightweight elements. In contrast to existing 3DCP approaches, which often stack material vertically, the SCRIM approach permits full exploitation of 6-axis robotic control by utilising supportive meshes to define 3D surfaces onto which concrete is selectively deposited at various orientation angles. Also, instead of fully encapsulating the textile in a cementitious matrix using formworks or spraying concrete, SCRIM relies on sparsely depositing concrete to achieve structural, tectonic and aesthetic design goals, minimising material use. The motivation behind this novel concept is to fully engage the 3D control capabilities of conventional robotics in concrete use, offering an enriched spatial potential extending beyond extruded geometries prevalent in 3DCP, and diversifying the existing spectrum of digital construction approaches. The SCRIM concept is demonstrated through a small-scale proof-of-concept and a larger-scale experiment, described in this paper. Based on the results, we draw a critical review on the limitations and potentials of the approach.

Keywords: 3D Concrete Printing, Textile Reinforcement, Robotic Fabrication.

1 Introduction

1.1 Context and Motivation

Concrete continues to be the most used material within the construction industry, with use predicted to increase dramatically over the coming years [1]. Despite its relatively low impact compared to many other construction materials, the extent of global consumption has made concrete use a primary contributor to CO_2 production [2]. Coupling increased scrutiny of environmental credentials with the prospect of escalating use creates a high-impact arena for research efforts directed at improvements, advancements and innovation within all concrete fabrication aspects.

Over the last 40 yrs., the associated fields of digital practice and digital fabrication have matured as potent sources of innovation - advancing, evolving or introducing novel design and construction practices. Within the context of concrete fabrication, the literature evidences modern digital approaches having contributed to: a) Formwork strategies supporting free-form geometry, e.g. single use moulds [3]; adaptive formwork [4, 5]; b) Stay-in-place formworks [6]; fabric formworks [7]; c) Formwork-free strategies, e.g. 3D Concrete Printing [8, 9] and robot-assisted generative manufacturing [10]; d) Tailored reinforcement strategies, e.g. MeshMould and integrated thin-shell roof [11, 12]; e) Adapted slip-forming approach, e.g. Smart Dynamic Casting [13].

Yet, whilst the targeting of concrete fabrication through the optic of digital-design research has enriched and diversified the landscape of approaches, the transfer to high-impact and disruptive changes within industry remains nascent; and 3DCP is a particular case. Despite 3DCP garnering substantial research interest over the last decade, and having been demonstrated at various scales, key challenges remain that hinder its broader acceptance. A recent [accepted] publication by Buswell et al. [14] offers examples of application and identifies the spectrum of research prospects.

1.2 Scope

This paper presents an approach to 3DCP that takes point of departure in layer deposition based on extrusion, but critically intersects the method with aspects of textile/fabric formwork and tailored reinforcement techniques. This hybrid approach offers advantages that overcome key challenges facing layer extrusion, namely restrictions on build orientation and incorporation of reinforcement. The approach also articulates a distinct architectural expression. To start, we contextualise our approach to relevant technologies and research work. Next, we describe our methodology, experimental setups and results. Then, we examine key implications and identify principle contributions and limits of the approach, particularly those related to imprecision due to dynamics of the meshwork. Finally, we outline future development work that could contribute to improve our approach.

2 State-of-the-Art

The SCRIM approach combines 3DCP and integrated reinforcement technologies. As such, we dedicate this section to a review on 3DCP, while highlighting the latest digital fabrication process with integrated reinforcement strategies.

In a nutshell, 3DCP technology uses computer-controlled placement of material to build a concrete component without formwork. As such, it enables the production of complex geometries in a fully-automated setup, while featuring material savings, faster production time for complex products, and new architectural insights and design strategies. The fundamentals of the process comprise (a) mixing, (b) pumping, (c) controlling and (d) extrusion. These basic steps are combined to configure a 3DCP setup, and the construction application lends itself in categories such as off-site factory-based production of components and on-site, large-scale automated construction. Notice, however, that the existing 3DCP demonstrations (see examples in [14]) are followed by time-consuming processes and/or costly full-scale testing, obstructing general uptake by industry. Besides the absence of technical standards or specification, the main obstacles preventing 3DCP from moving ahead to the market include: the process robustness and reinforcement strategies. The SCRIM approach represents an innovation towards the latter barrier as well as an attempt to overcome limitations in relation to build orientation, which is primarily vertical.

As for integrated reinforcement strategies, MeshMould [11] is one of the latest technologies that provides means to robotically fabricate spatial meshes that compose reinforced concrete without formwork. Likewise, a generative approach for manufacturing of complex concrete structures without formwork and using robotic spray technology is proposed in [10]. In essence, SCRIM could be interpreted as a variation of the above mentioned approaches, since they rely on a spatial reinforcement as the support base for concrete. Nonetheless, in the SCRIM approach we selectively deposit concrete by 3D printing rather than spraying and/or pouring and vibrating it. Besides these technologies, the formwork system technology for shell construction developed for the NEST HiLo [12] represents an innovative solution that uses integrated fabric formwork for modern constructions. This technology offers a degree of control over the shape such that it can be easily optimised for improved structural behaviour and other criteria compared to traditional geometries [12]. Similar to SCRIM and MeshMould, it is the textile material serving as basis for supporting concrete, except a cable-net falsework provides additional support.

3 Methodology and Experimental Setups

The SCRIM approach combines selected aspects of the methods outlined in the previous section. In principle, we employ commercially available Carbon-Fibre Reinforced Polymer (CFRP) meshes to define a target geometry that acts as a combined stay-in-place-formwork and reinforcement. The textile basis of the mesh requires the use of boundary restraints and adequate tension to resist applied loads (mostly self-weight) when robotically printing cementitious material. The material is selectively deposited to achieve specific design goals. In this light, we invert the conventional understanding of ‘adding’ tensile capabilities to concrete through the introduction of continuous (rebar) or discrete (fibre) ductile reinforcement; rather, we sparsely ‘add’ compressive capabilities to the CFRP meshwork. In this section, we provide details of the general setup and describe two experiments showcasing the SCRIM approach.

3.1 Process Setup

The installations from the High-Tech Concrete Lab, at The Danish Technological Institute, served as basis for the two SCRIM experiments. The 3DCP setup comprises a 6-axis industrial robot (Fanuc R-2000iC/165F), a progressive cavity pump (NETZSCH with flow rate up to 100 dm^3/h), a 3.0m long steel-wire concrete rubber hose (Ø32mm), and custom-design nozzles produced with ABS plastic and metal parts. Additional details are described in [15]. For this setup, we set a robot work volume of 2000 x 1000 x 2000 mm (length x width x height). In Experiment 1, we used a rectangular nozzle with cross-section of 40x10mm; in Experiment 2 we used a round nozzle with Ø26mm.

The design-to-production framework relies on a custom algorithm developed in Rhino/Grasshopper that translates toolpath designs in to Gcode files. This algorithm generates point coordinates and associated orientation vectors; the information required for the end-effector to follow a specified path. The generated files are then sent to the robot using RoboDK, which computes optimal toolpath through inverse-kinematics.

3.2 Cementitious Material Setup

A batch of 36 dm^3 was used in each experiment. In Experiment 1, the mix design comprises a binder system with CEM I 52.5N and fly ash mixed with fine sand (max. particle size: 1.0 mm), water (water/binder ratio: 0.38), a retarder admixture (0.5% by wt. of cement) to maintain a long open time, and a high-range water reducer admixture (0.1% by wt. of binder). All materials were kept the same in Experiment 2, except for the binder system - now composed of CEM I 52.5R (White Cement) and limestone filler (water/binder ratio: 0.36) as well as a Viscosity-Modifying Agent (0.1-0.05% by wt. of cement). A paste composed of limestone filler, red pigment and water was added to modify the concrete colour.

3.3 Setup for Experiment 1 - testing the SCRIM concept

Experiment 1 aimed to test the production viability of the SCRIM concept. A carbon-fibre reinforced polymer textile with open-mesh grid of 30x30mm was used to construct two meshworks with curved geometry – a tapered half-cone and a ¼ pipe as shown in Fig.1. The ¼ pipe (with 500mm radius) was divided in two sections (P_1 and P_2). In section P_1, the mesh was tied back to a support surface with an 18mm offset. While in P_2, two layers of mesh were overlapped with a translational offset to double the mesh-grid density, i.e. the final grid is 15x15mm. The two layers were intermittently tied to prevent separation. The mesh spanned to the boundary of the formwork frame, with tension wires used to pull the mesh surface into a closer cca. of the target surface. Next, clamping rails were applied to both the top and bottom edges of the mesh. To systematically test the adhesion of deposited material in non-horizontal orientations, a linear ‘square-wave’ toolpath with increasing vertical travel was defined and repeated for each section.

The same mesh was used to prepare a tapered half-cone with 920mm edge length and respective diameters 200mm/100 mm. The mesh was free-spanning with boundary restraints cut from 15mm shuttering plywood. The mesh-grid configuration is similar to that used on section P_2. The continuous toolpath for this target was defined as cca. sinusoidal pattern with 3.5 ‘waves’ bilaterally mirrored.

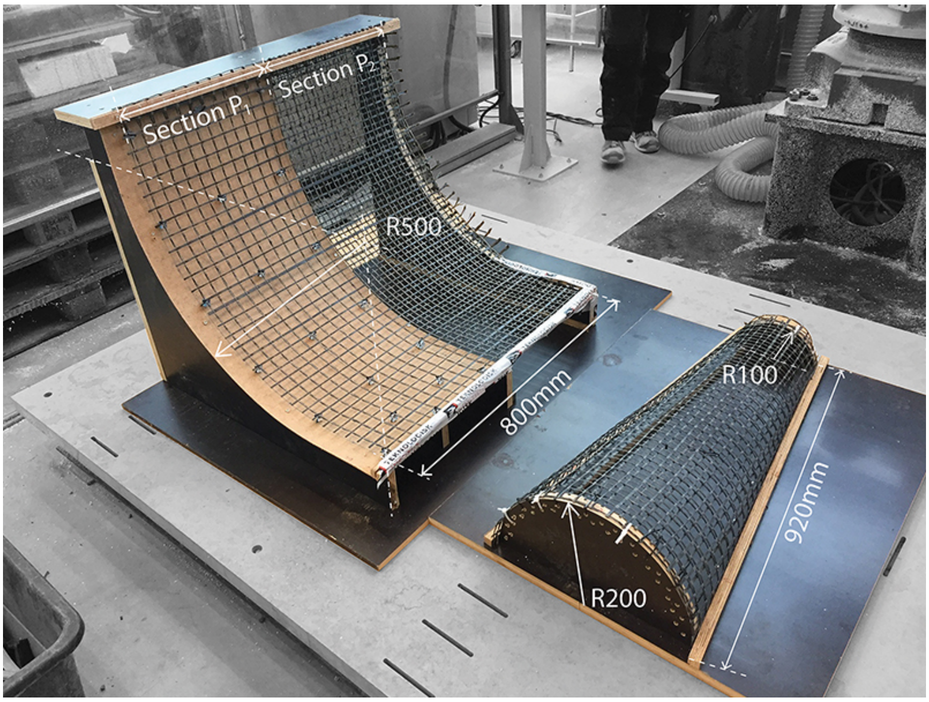

Fig. 1. Meshwork setups for Experiment 1.

3.4 Setup for Experiment 2: Scaling up

Experiment 2 aimed at scaling up the SCRIM concept. The goals for this experiment were to: a) address a larger-scale mesh target, b) increase spatial complexity by combining two CFRP meshes, c) demonstrate the use of applied material as a permanent junction mechanism between discrete meshes, and d) test the effect of an intersecting toolpath on deposition and adhesion performance.

In this experiment, a CFRP mesh with grid size of 14x7 mm was used in combination with a Ø26mm nozzle. The target meshwork comprised two CFRP planes (1800x1000mm each) intersecting with an angle of 103° and a 74° inclination from horizontal, giving a 2nd-order rotational symmetry in plan and bilateral symmetry in elevation. One of the CFRP meshes was cut along the intersection line and re-joined with ties. The assembly is shown in Fig. 2. The CFRP meshes were held top and bottom using aluminium Keder rails (40x10mm), with aluminium plates holding the rails at the prescribed intersection angle.

This assembly was attached to a support superstructure to tension the mesh and transfer loads during construction and curing. The superstructure was made up of Ø34mm steel tubes held with Kee-klamp connections and screwed into the build base. With the exception of cross-bracing and 'outrigger' supports, its configuration approximated the boundaries of the mesh planes to minimise obstacles for the robot.

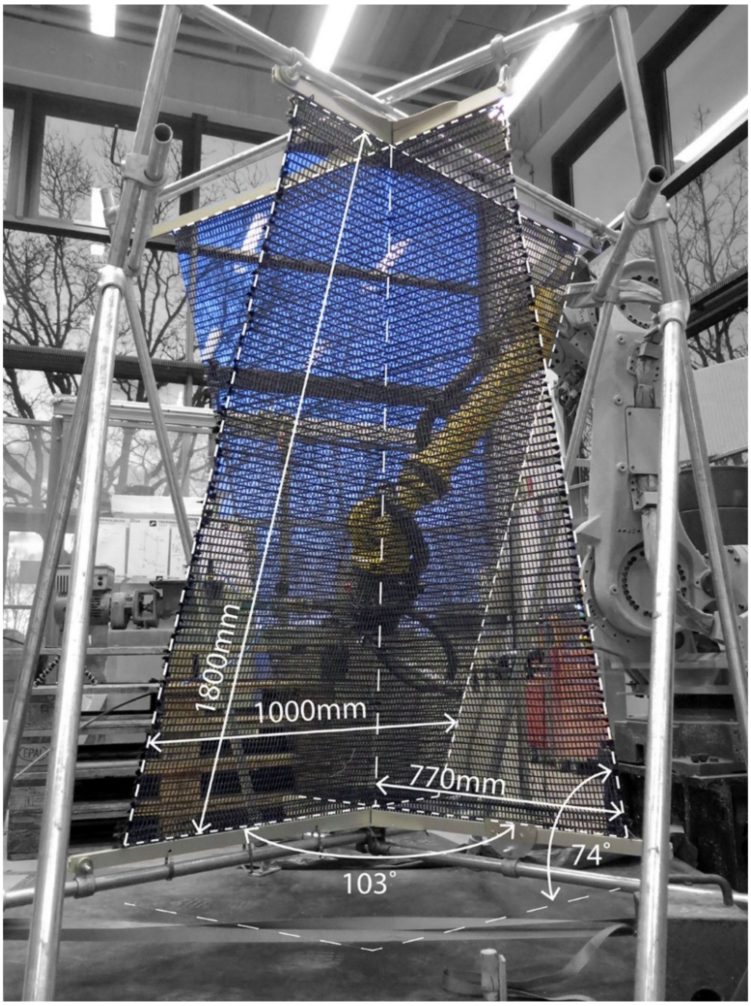

Fig. 2. Meshwork setup for Experiment 2.

The toolpath for this experiment was developed from a knit-like pattern to test intersection conditions. The total toolpath length was 38.0 m, yielding a concrete consumption of cca. 20.2 dm^3. This pattern was projected onto the 'open' face of the mesh assembly to define a toolpath, modified at the boundary conditions to ensure continuity. This strategy prevented start-stop in the pumping process.

4 Results

4.1 Experiment 1

The open cell size in section P1 was similar to the nozzle width (40mm); thus, a slight amount of material fell through the mesh. This falling effect in P1 was more pronounced in the vertical parts of the mesh (Fig. 3a). This effect indicates that the fresh concrete mix cannot cope with the bending moment and shear stresses in the open cell. Alternatives to tackle this effect include the use of fibers in the mix design, and production of a stiffer mixture – with the drawback that these yield greater challenges to 3DCP; namely, stiff mixtures are prone to filament tearing and/or splitting during extrusion [16]. Also, the use of a denser mesh (as in P2) provides better support – minimizing the falling effect as shown in Fig. 3b. Notice, however, that due to the deviation of meshwork from the assembly in P2, this resulted in a mismatch between the CAD model and toolpath; specifically, the curvature in the model was greater than that of the assembly, hampering the maintenance of a regular tool offset during printing. Thus, in certain areas, the extruded material was excessively pushed through the mesh as can be seen in Fig. 3c. In the cone section, a greater distance between the nozzle and mesh was noticed (Fig. 4a); as a result, the material-mesh connection was apparently weaker than that observed in the deposition areas in P1 and P2, though the push effect was eliminated (Fig. 4b, c).

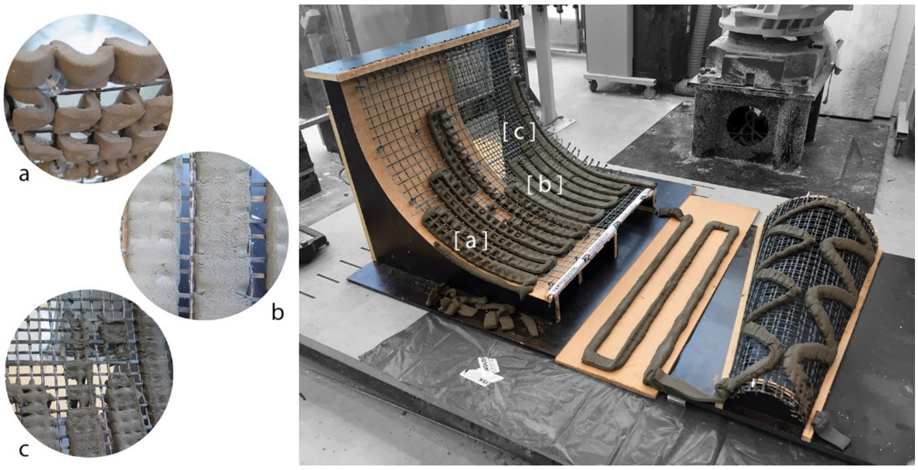

Fig. 3. SCRIM results of ¼ pipe in Experiment 1.

In general, Experiment 1 showed that, despite localised challenges, there was a good integration of the mesh within the concrete and that printing in vertical conditions is plausible.

Fig. 4. SCRIM results of tapered cone in Experiment 1. Released free-standing assembly (right), with details of deposition process and results (left).

4.2 Experiment 2

The 3DCP started at the top of the mesh with a nozzle travel speed of 30mm/s. Good adherence and encapsulation was observed on the first two rows (Fig. 5a), but, as further material was added, the distance between nozzle and mesh increased due to mesh deflection under the applied self-weight. This reduced the filament adhesion (and sometimes direct contact) to the mesh. After cca. 20 kg of deposition, material sheared down the 74° mesh inclination. In a second attempt, we reduced the pattern length to 16 m (Fig. 6), corresponding to 18 kg material. The nozzle travel speed was increased to 60mm/s, thus decreasing the linear material deposition rate by half. In this case, we achieved markedly better material adhesion and encapsulation to the mesh, with only localised sections of material collapse due to mesh dynamics, as detailed on Fig. 5b.

Fig. 5. SCRIM results in Experiment 2. a) First deposition attempt; b) second deposition attempt

In general, Experiment 2 showed that heavy deposition of material in partially supported meshes causes sufficient deflection to impact consistency in “layer height”. Also, the use of a slow travel speed and dense toolpath intersections contributed to failure in adhesion. By reducing the amount of deposited material and increasing travel speeds, we succeeded in demonstrating: a) increased complexity of the toolpath, b) deposited material acting as a bonding mechanism between discrete meshes, and c) adhesion of material even with toolpath intersection in non-horizontal conditions.

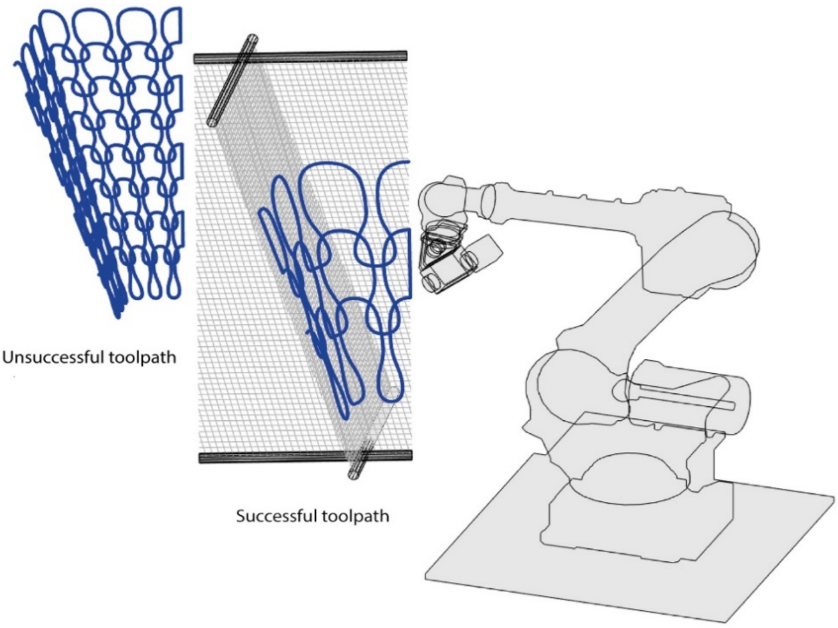

Fig. 6. Toolpaths for Experiment 2.

5 Discussion and Further Work

Having demonstrated the plausibility of the SCRIM concept through two experiments, we now outline key contributions, implications and limits of the approach as well as prospective developments.

5.1 Contributions and Implications

The SCRIM concept offers three main contributions: a) fully exploiting 3D spatial capabilities of conventional robotics, allowing greater freedom in build orientation that includes near-vertical material deposition; b) resolution of the challenge to integrate reinforcement by inverting the conventional concept of ‘adding’ reinforcement to concrete, to printing on CFRP meshes that act as reinforcement; and c) decoupling the printing process from a time-critical dependency on very-early age properties of previously extruded layers. These contributions imply that the SCRIM approach a) supports greater geometric freedom in design targets, extending beyond extruded geometries prevalent in existing 3DCP approaches; b) supports intricate optimised geometries that selectively place material to achieve design aims, further reducing material use; c) introduces a novel tectonic language that diversifies the existing spectrum of digital construction approaches.

5.2 Limits

Limits of the method. A principle challenge in the SCRIM approach is that the meshworks require tensioning and exhibit dynamics when load (mostly from the material self-weight) is applied during printing. This can result in layer height irregularities, with consequences on mesh encapsulation and adequate adhesion as witnessed in the first print attempt of Experiment 2. Although SCRIM offers greater freedom in build orientation and the geometry of design targets, the mesh deformation places additional emphasis on tool path verification, which can be more complex in comparison to 2D layered approaches.

Limits in exploration. To date, the SCRIM experiments have focused on developing the production processes and exploring deposition of cementitious material in non-horizontal conditions; production of designed components is yet to be explored, and, by extension, a study of their cured performance and tectonics in the context of larger assemblies.

5.3 Further Work

In the short-term, incremental advances shall focus on applying the SCRIM concept to the production of indicative building elements with determined performance demands, so that measures of success can be established through testing. Lightweight building elements fulfilling a range of roles can be envisaged, such as load bearing partitions

(Fig. 7) or suspended ceiling elements, with each element being individually graded in porosity to accommodate multi-criteria design demands and being produced either through off-site factory-based production, or by on-site automated construction. A further potential use could be as prefabricated stiffened reinforcement elements, marking an interim step towards massive concrete casting. An interim casting process utilising knitted textiles in combination with cement pastes to produce stay-in-place formwork has been recently demonstrated [17]. The use of SCRIM could mark a hybrid approach combining reinforcement and stay-in-place formwork. Partial, or localised, massive casting would extend this idea further, with compelling architectural potential.

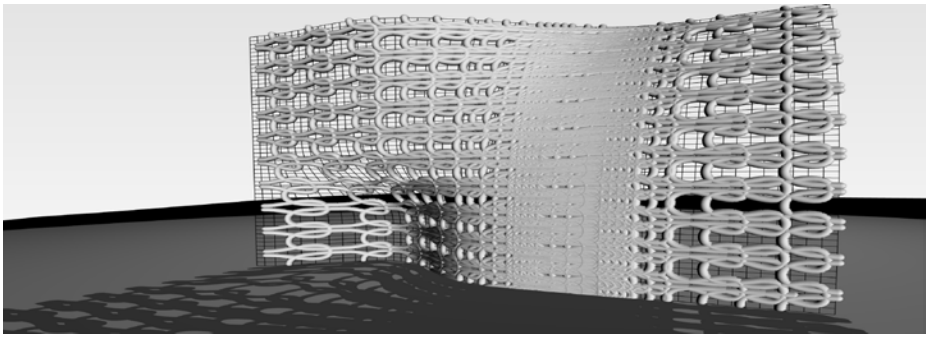

Fig. 7. Speculative visualisation of an envisaged building element - a graded internal partition.

In the longer-term, further development shall focus on refining and advancing the potentials of SCRIM by means of the following:

a) 3DCP material: investigating a1) the effect of 3D printed concrete rheology on the encapsulation between mixture and mesh, a2) the use of accelerators to control the concrete setting time on demand, and a3) the effect of fibres on the early age mechanical properties of 3D printed concrete. The goal in this investigation would be to optimise the mix design to achieve an optimal material deposition on CFRP meshes, preventing the falling and/or sliding effect noticed in our experiments.
b) CFRP mesh design and production: investigating the production of bespoke meshes will allow for refined tailoring of structural performance (during and post-printing), provide optimised cell sizing in areas of deposition and support customised incorporation of other architectural elements.
c) Adaptive robotic control: two complementary approaches can be considered: c1) scanning and registering of constructed meshes to provide ‘as-built’ data and generate the deposition path; and c2) online toolpath adaptation through real-time scanning to enable optimised layer height in response to mesh dynamics.
d) Integrated design environment: simulation and analysis of fabrication, in concert with post-fabrication performance, will be used to inform and optimise deposition pattern in relation to design goals. Strategies such as stress-line additive manufacturing (SLAM) [18] could be productively combined with the current aesthetically oriented patterning approaches.

6 Conclusion

This paper has introduced a novel hybrid construction concept that intersects robot-based 3D Concrete Printing and textile reinforcement meshes to produce lightweight elements, namely, *Sparse Concrete Reinforcement In Meshworks*. We have described the process setup and results of two experiments that demonstrate how the SCRIM concept offers advantages that tackle key challenges facing conventional 3DCP based on vertical layer extrusion, i.e. restrictions on build orientation and incorporation of reinforcement. In addition, SCRIM supports subsequent processes of element addition and embellishment as well as articulates a distinct architectural expression in contrast to the approaches reviewed in the literature. We have examined key implications of SCRIM, identified principle contributions, stated limits of the approach, outlined future development work that could contribute to further improvements during and post-production and suggested two application scenarios that we envision as uses for the method.

Acknowledgements

Danish Agency for Science and Higher Education for funding the project "3D Printet Byggeri" at the Danish Technological Institute. The authors gratefully acknowledge the assistance of Stian Vestly Holte, Kit Wai Chan, Alma Bangsgaard Svendsen and Suna Ezra Petersen, enrolled at the Master of Architecture programme *CITAstudio: Computation in Architecture*, KADK. The authors also wish to thank the anonymous reviewers for their comments and suggestions to improve the quality of the paper.

References

[1] P. Wray and K. Scrivener, “Straight talk with Karen Scrivener on cements, CO2 and sustainable development,” *American Ceramic Society Bulletin*, vol. 91, 2012.

[2] H. Ritchie and M. Roser, “CO_2 and other Greenhouse Gas Emissions,” 2017. [Online]. Available: https://ourworldindata.org/co2-and-other-greenhouse-gas-emissions. [Accessed 28 02 2018].

[3] H. Pottmann and J. Wallner, “Geometry and Freeform Architecture,” 2010. [Online]. Available: http://www.geometrie.tugraz.at/wallner/matharch.pdf. [Accessed 28 02 2018].

[4] S. Hickert, “Evaluation of free-form concrete architecture, moulding systems and their technical potentials,” *Journal of Facade Design and Engineering*, vol. 3, no. 3-4, pp. 273-288, 2015.

[5] C. B. Costanzi, “3D Printing Concrete Onto Flexible Surfaces,” Delft University of Technology, 2016. [Online]. Available: https://repository.tudelft.nl/islandora/object/uuid%3A84d36c2e-8969-4432-b1a5-c9c02e6304f6 [Accessed 08 05 2018]

[6] M. S. Nelson, A. Z. Fam, J. P. Busel, C. E. Bakis, A. Nanni, L. C. Bank, M. Henderson and J. Hanus, “Fiber-Reinforced Polymer Stay-in-Place Structural Forms for Concrete Bridge Decks: State-of-the-Art Review,” *ACI Structural Journal,* vol. 111, no. 5, pp. 1069-1079, 2014.

[7] D. Veenendaal, M. West and P. Block, “History and overview of fabric formwork: using fabrics for concrete casting,” *Structural Concrete,* vol. 12, no. 3, pp. 164-177, 2011.

[8] J. Pegna, “Exploratory investigation of solid freeform construction,” *Automation in Construction,* vol. 5, pp. 427-437, 1997.

[9] B. Khoshnevis, “Automated construction by contour crafting related robotics and information technologies,” *Automation in Construction,* vol. 13, pp. 5-19, 2004.

[10] S. Neudecker, C. Bruns, R. Gerbers, J. Heyn, F. Dietrich, K. Dröder, A. Raatz and H. Kloft, “A New Robotic Spray Technology for Generative Manufacturing of Complex Concrete Structures Without Formwork,” in *Procedia CIRP*, 2016.

[11] N. Hack and W. V. Lauer, “Mesh-Mould: Robotically Fabricated Spatial Meshes as Reinforced Concrete Formwork,” *Architectural Design,* vol. 84, no. 3, pp. 44-53, 2014.

[12] P. Block, A. Schlueter, D. Veenendaal, J. Bakker, M. Begle, I. Hischier, J. Hofer, P. Jayathissa, I. Maxwell, T. Mendez Echenagucia, Z. Nagy, D. Pigram, B. Svetozarevic, R. Torsing, J. Verbeek, A. Willmann and G. P. Lydon, “NEST HiLo: Investigating lightweight construction and adaptive energy systems,” *Journal of Building Engineering,* vol. 12, pp. 332-341, 2017.

[13] E. Lloret, A. R. Shahab, M. Linus, R. J. Flatt, F. Gramazio, M. Kohler and S. Langenberg, “Complex concrete structures Merging existing casting techniques with digital fabrication,” *Computer-Aided Design,* vol. 60, pp. 40-49, 2015.

[14] R. Buswell, W. R. Leal da Silva, S. Z. Jones and J. Dirrenberger, “3D printing using concrete extrusion: a roadmap for research,” *Cement and Concrete Research,* 2018. (Accepted for publication.)

[15] W. R. Leal da Silva, “3D Printed Constructions - Engineering perspective (Presentation Slides),” in *3D Printet Byggeri Conference*, Denmark, 2017. [Online]. Available: https://www.dti.dk/_/media/67675_3DPrintetByggeri_Konference_TeknologiskInstitute.pdf [Accessed 28 02 2018].

[16] F. Bos, R. Wolfs, Z. Ahmed and T. Salet, “Additive manufacturing of concrete in construction: potentials and challenges of 3D concrete printing,” *Virtual and Physical Prototyping,* vol. 11, no. 3, pp. 209-225, 2016.

[17] M. Popescua, L. Reiter, A. Liew, T. Van Mele, R. J. Flatt and P. Block, “Building in Concrete with an Ultra-lightweight Knitted Stay-in-place Formwork: Prototype of a Concrete Shell Bridge,” *Structures,* vol. 14, pp. 322-332, 2018.

[18] K. M. M. Tam, J. R. Coleman, N. W. Fine and C. T. Mueller, “Robotics-enabled stress line additive manufacturing,” in *Robotic Fabrication in Architecture, Art and Design 2016*, Springer, Cham, 2016.