Potential Approaches for Reinforcing Complex Concrete Structures with Integrated Flexible Formwork

Conference Paper

Author(s):
Lee, Minu; Mata Falcón, Jaime; Popescu, Mariana; Block, Philippe; Kaufmann, Walter

Publication date:
2020

Permanent link:
https://doi.org/10.3929/ethz-b-000425528

Originally published in:
RILEM Bookseries 28, https://doi.org/10.1007/978-3-030-49916-7_67

Potential Approaches for Reinforcing Complex Concrete Structures with Integrated Flexible Formwork

Minu Lee[1] (✉) [0000-0002-6489-8310], Jaime Mata-Falcón[1] [0000-0001-8701-4410], Mariana Popescu[2] [0000-0001-5524-852X], Philippe Block[2] and Walter Kaufmann[1] [0000-0002-8415-4896]

[1] Institute of Structural Engineering, Swiss Federal Institute of Technology Zurich (ETHZ)
lee@ibk.baug.ethz.ch
[2] Institute of Technology in Architecture, Swiss Federal Institute of Technology Zurich (ETHZ)

Abstract. Conventional construction of doubly-curved concrete structures is a time-, labour- and cost-intensive process. Flexible formworks have already been identified as a possible solution to produce such structures more efficiently. The KnitCrete technology developed at ETH Zurich uses 3D weft-knitted fabrics as stay-in-place formwork, which deliver multiple advantages over woven textiles due to their wider range of feasible geometries and possibility to include features and local material properties. The textile is initially coated with a fast-setting high-strength cement paste. The stiffened membrane is stable enough to serve as formwork for the final concrete layer. This paper discusses potential reinforcing strategies to guarantee structural safety and serviceability in KnitCrete structures. Possible approaches range from the use of the textile as a stay-in-place formwork as well as final reinforcement (by utilising high-strength fibrous materials such as aramid, glass or carbon fibre) to the implementation of geometric features, such as channels within the textile to guide conventional reinforcement or post-tensioning tendons. The feasibility and efficiency of the proposed reinforcement strategies have to be experimentally verified, for which a systematic methodology is proposed. Preliminary analyses of the experimental campaign show the beneficial effect of the knitted reinforcement on the cracking behaviour of the textile-concrete composite material. Additional research is needed to exploit the potential of possible hybrid solutions using short steel fibres, post-tensioning or linear steel or glass fibre reinforcement.

Keywords: concrete structures, textile reinforcement, high-strength fibres, KnitCrete, digital fabrication

1 Introduction

Computer-aided design and digital fabrication have enabled a greater freedom for the definition of complex spatial geometry, for which concrete is the predominantly used building material. Due to its capability to be cast in any shape given by the formwork, concrete is highly favourable for the construction of bespoke and efficient structures. Flexible formworks have an advantage over traditional milled and cut formworks due to their low amount of waste and reduced manual labour in the production and assembly, eventually leading to lower cost. Fabric formworks for building construction were introduced on a larger scale in the 20th century, when several patents for floor and wall systems using fabrics as main surface shaping elements were filed, e.g. [1,2]. However, their importance in structural applications in practice is rather limited, as they are mostly used for aesthetic and non-structural purposes such as fair-faced concrete facades. Recently, researchers started again to examine the potential for larger-scale structures. West [3] investigated beams, trusses and slabs where the use of fabric formwork allowed varying shapes following the force flow. The fabric defined the closed outer shell of the structure where the concrete would inflate the formwork due to the pressure from injection. Similar work was accomplished by Orr et al. [4] and Brennan et al. [5]. Veenendaal et al. [6] developed a hybrid cable-net and fabric formwork system. The textile serves as shuttering that is placed on a tensioned cable grid and the concrete is poured directly onto this layer. This technique has been further developed and used for the production of the NEST HiLo roof prototype [7].

The KnitCrete technology [8], which has been developed at ETH Zürich within the National Centre of Competence in Research in Digital Fabrication in Switzerland, uses pre-stressed knitted textiles that are tensioned in a scaffolding frame or supported by elements such as bending-active rods or inflatables. The textile is initially coated with a high-strength cement paste, which – after hardening – serves as formwork for the following layers of concrete. Knitted textiles allow for great flexibility in the definition of spatial geometry due to their capability to vary both width and length by adding or removing loops along their internal structure to create curved and spatial geometries, whereas woven textiles are limited to single-curved patches. The technology has proven to be applicable for larger structures with the construction of KnitCandela – a pavilion that has a surface area of approximately 50 m^2 – in collaboration with Zaha Hadid Architects in Mexico City [9].

However, the addition of reinforcement within the construction process of such structures has not been sufficiently explored yet. Conventional steel reinforcing bars require a lot of time and manual labour for bending and installation [10] since for complex geometries, each rebar has to be placed in its unique position and orientation. This paper describes potential approaches for reinforcement strategies of concrete structures with flexible formwork, focusing on opportunities arising from knitted textiles.

2 From formwork to reinforcement

The approach of combining formwork and reinforcement to an integrated stay-in-place-system offers great potential to deliver a more efficient construction process with low waste and a minimum amount of temporary support elements. This section revises the possibilities that knitted textiles provide to integrate reinforcement into the formwork.

2.1 Knitted textiles as flexible formworks

Knitted textiles have various advantages over conventionally woven fabrics in the definition of complex geometries. Curved spatial surfaces can be created by locally varying the length and width of the textile during production [11]. The mechanical properties of the knitted textile depend on various parameters such as the diameter and material of the used yarn, loop size, tension in the yarn during fabrication or degree of prestress in its final state. Those parameters can be continuously varied over the fabric allowing a specifically tailored distribution of properties. Modern CNC knitting machines are able to include straight rovings within the knitted textile (known as inlays), which significantly increase stiffness and introduce a more defined directionality to the fabric. Other features include ribs and channels as shown in Figure 1. Spacer fabrics are also possible by introducing stiffer materials for the connection between two membranes.

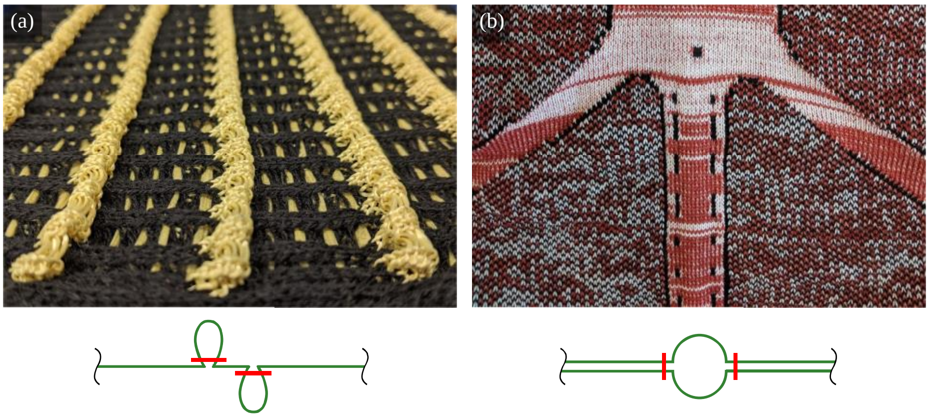

Figure 1. Weft-knitted textiles with (a) ribs and (b) channels.

The KnitCrete technology developed at ETH Zürich makes use of the knitting features in multiple aspects. Loops or channels within the textile allow the introduction of elements such as bending-active rods [8] or cables [9] that can be used to actively shape the formwork and support the membrane during construction. Therefore, the range of possible geometries extends from the simple full section (Figure 2a) that is supported from underneath during casting to a variety of new shapes (Figure 2b-e). Ribbed sections, which significantly reduce the volume and thus, the self-weight while maintaining high stiffness through geometry, can be formed by inflating hollow pockets between two connected knitted membranes (Figure 3a) or by creating a folded spatial fabric (Figure 3b).

Variable thicknesses in the shell section can be controlled by implementing sandwich elements with two membranes that are connected by couplers of variable length (Figure 2c). Openings in the top layer may be used for concrete filling and to let air escape for preventing voids. Furthermore, linear elements such as beams or grid shells are possible by directly filling concrete into channels within the textile, which (for vertically oriented channels) creates a circular tube section due to the hydrostatic pressure against the formwork (Figure 2d). Any polygonal shape might be created by introducing cables or bending-active rods defining the vertices of the cross section (Figure 2e).

Besides integrated support structures, a key aspect in the KnitCrete technology to guarantee form stability during casting and hardening of the concrete is the initial stiffening of the fabric by means of applying a thin layer of high-strength cement paste or a fluid resin (e.g. epoxy). The textile-cement-composite displays a much higher stiffness than the bare textile, which significantly reduces deformations during construction and allows partly straight surfaces.

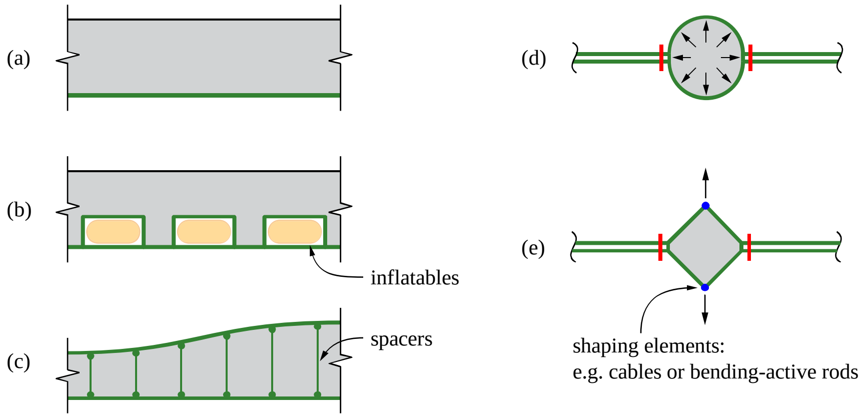

Figure 2. Schematic overview of possible cross sections with flexible formwork.

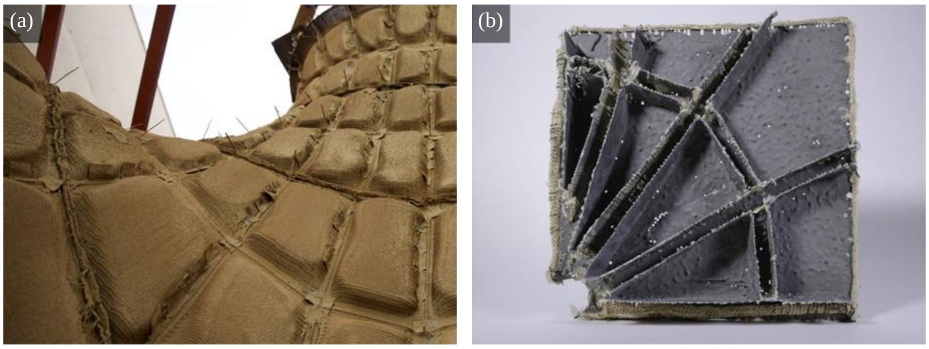

Figure 3. Ribbed cross sections from (a) inflating hollow pockets and (b) folding.

2.2 Requirements on reinforcement in cementitious composite materials

Concrete is a quasi-brittle material that displays high compressive strength but very low tensile capacity. It shows a brittle failure mode upon reaching its tensile strength and thus, reinforcement is necessary to ensure an adequate ultimate and serviceability behaviour. Most design approaches rely on the ductility of the material, which (i) allows the redistribution of internal forces to compensate for unknown initial stress states and (ii) prevents brittle failure modes upon reaching the ultimate load. To this end, a ductile reinforcement must be able to resist the cracking load of the concrete.

The most commonly used type of reinforcement in conventional construction are straight reinforcing bars, which are aligned in a bi-directional grid. For standard geometries such as slabs or walls, this reinforcement layout is easy to place on site and its structural performance – in terms of ultimate strength, serviceability and ductility – as well as its workability are unparalleled. However, curved geometries significantly increase the complexity of the reinforcement requiring steel bars to be bent into the right shape and placed at the correct position with little tolerances, which increases manual labour. Furthermore, steel reinforcement demands a minimal concrete cover thickness (usually between 20 and 50 mm depending on structure type and exposition) to guarantee an adequate protection against corrosion, which limits the slenderness of thin shell structures.

2.3 Integrating reinforcement

Asprone et al. [12] group possible approaches to address reinforcement integration in digitally fabricated concrete either by structural principle – ductile printing material, digitally fabricated composite, compression loaded structures or hybrid solutions – or by the stage of the manufacturing process – before, during and after manufacturing. The present paper mostly revises possible approaches for integrating the reinforcement into the formwork, which classifies as 'before manufacturing' and as a 'digitally fabricated composite'. Moreover, a hybrid solution that uses fibre reinforced concrete for casting the element is studied.

Stay-in-place formworks. Flat composite slab systems offer great flexibility where construction needs to be fast and there is only limited space for additional scaffolding (e.g. industrial buildings or bridge decks). During construction, the formwork has enough bearing capacity to carry its self-weight and the load of the wet concrete. After hardening, the formwork acts as bottom reinforcement resisting sagging bending moments. Various material combinations exist, including precast concrete slabs using either short fibres [13] or steel reinforcement [14], corrugated steel sheets [15] or beech-laminated timber [16]. These are mostly suitable for applications with simple geometry due to their high potential for prefabrication of standardised element shapes and sizes. The major challenge is the proper stress transfer at the interface between the stay-in-place formwork and the concrete. The bond stress capacity typically needs to be increased by introducing mechanical shear coupling elements such as embossments in steel sheets, notches in timber plates or dowels, since friction and adhesion alone are not sufficient and thus, delamination would occur.

Textile reinforced concrete. By using high-strength fibrous materials for knitted textiles, the formwork can act as a reinforcement in the final state. Textile reinforced concrete (TRC) has gained much interest in academia in recent years. The fibre material ranges from metal, natural fibres such as basalt, synthetic polymers to inorganic materials [17]. The use of non-corrosive materials not only allows the fabrication of much thinner concrete elements since there is no lower limit for the concrete cover to protect the reinforcement, but can also reduce the amount of clinker (required to obtain a high pH-value to passivate steel reinforcement) and thus, decrease CO_2 emissions. Carbon or glass fibre-based textiles are among the most commonly applied materials in practice as they exhibit very high tensile strength (around 3'000 – 4'000 MPa) and stiffness (glass fibre: ca. 70 GPa, carbon fibre: ca. 240 GPa). However, they tend to be sensitive to lateral loading and exhibit no ductility at all (perfectly brittle materials). Most research and design approaches cover commercially available textile reinforcement by means of bi-directional grids of bundled fibre rovings that are usually impregnated with a resin coating (e.g. epoxy) [18,19]. Only little literature covers knitted textile reinforcement and no proper mechanical model exists up to date. Due to its dense interlocked structure (Figure 4a), the tensile capacity of the yarn is reduced. Moreover, many types of fibres are not suitable for direct use as knitting yarn since they often only allow rather large bending radii and thus, would break when knitted. However, as mentioned in Section 2.1, it is possible to integrate straight rovings as inlays into the base textile (Figure 4b). This allows the use of thicker yarns and the fabrication of "quasi-woven" grids of inlays that can follow defined paths (e.g. according to the principal stresses) within the knitted textile.

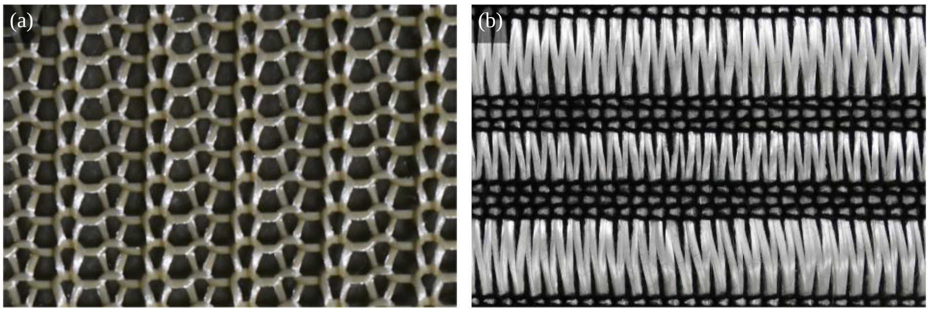

Figure 4. Flat weft-knitted textile with (a) aramid yarn and (b) glass fibre inlays (white rovings) within base pattern made out of acrylic yarn.

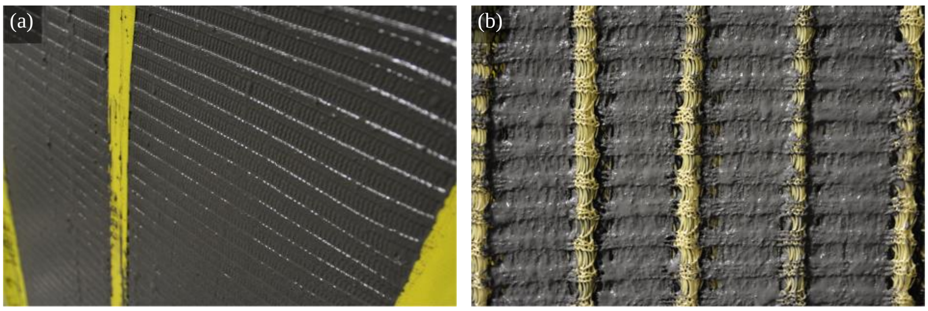

Figure 5. Knitted textile after application of cement paste coating (fresh state): (a) flat textile; (b) textile with ribs for bond enhancement.

Besides the performance of the reinforcement as a tensile element, its connection to the concrete brings up another major challenge. In conventional reinforcing bars, bond stresses between reinforcing bar and concrete primarily result from mechanical interlock of the profiled bar [20]. Flat sheets of knitted textiles do not have a pronounced surface profile. Furthermore, the cement paste coating creates a cold joint that significantly lowers the bond stress capacity [21]. Ribs in the textile (see Figure 5) can create a mechanical connection between the reinforcement and the concrete, which leads to enhanced bond conditions and counteracts delamination and spalling.

Linear reinforcement. Placing steel reinforcing bars in spatial doubly curved structures requires more time and, eventually, cost for manual labour due to greater complexity and lesser geometric tolerances compared to simple slabs or walls. However, implementing defined guiding features into the textile can significantly simplify this procedure. Reinforcing bars, cables or sheaths for pre-tensioning tendons (e.g. mono strands) can be threaded through loops or channels and might even act as additional support structure for the flexible formwork as bending-active or hanging elements, minimising temporary support structures during construction. Due to the fixed positions within the textile, there is no need for tedious measuring and arranging work on site. Figure 6 shows two possible concepts for the implementation of linear reinforcement into the textile. The flexible formwork can be suspended from a centred reinforcement layer (Figure 6a). Alternatively, sandwich elements that consist of two external layers of formwork can carry the reinforcement in the top and bottom faces of the shell section (Figure 6b). Additional coupling elements between the two layers might be needed to ensure the proper connection of the reinforcement to the concrete and to prevent a breakout of the bars. Such a layout results in very low to no reinforcement covers, which demands the use of non-corrosive materials such as glass fibre reinforcing bars or steel with increased corrosion resistance.

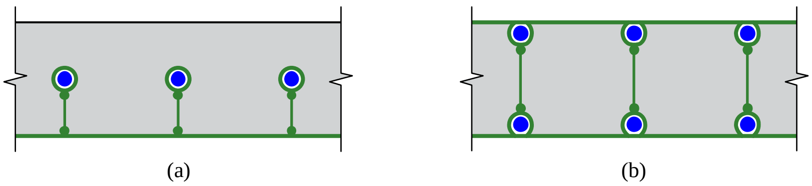

Figure 6. Concepts for integrating linear reinforcement into knitted formwork: (a) bottom layer suspended from reinforcement and (b) sandwich-elements with top and bottom layer.

Fibre reinforced concrete. As a combination or alternative to the previously presented reinforcing approaches, which are installed before concrete placement, fibre reinforced concrete can be used to cast the structural elements in order to improve strength and serviceability. According to Du et al. [22], steel fibres mainly improve the interfacial bonding between textile reinforcement and concrete as well as the shear resistance of textile reinforced concrete specimens, which is especially beneficial for curved structural members as it impedes delamination caused by deviation forces. The influence on the deformation capacity, which might partially compensate for the lack of ductility in the textile material, still needs to be addressed. Existing models for conventionally reinforced concrete members [23] might be adapted for textile reinforcement but more experimental investigations are required.

3 Experimental investigations

Proper characterisation of the aforementioned reinforcement strategies demands an extensive experimental investigation to assess structural performance and validate the feasibility of critical construction details. The development of a constitutive model for the mechanical behaviour is paramount for implementing stable numerical simulation methods that are required for modelling and designing concrete structures with complex geometries.

So far, the authors' investigations concentrated on the structural testing of weft-knitted textile reinforcement, focusing on (i) various knitting patterns; (ii) fibres (aramid, carbon and glass fibres); (iii) coating type (cement paste and epoxy); and (iv) spatial features to enhance the bond between reinforcement and concrete. The experimental campaign consists of uniaxial tension tests on flat tension ties as well as 4-point-bending beams as shown in Figure 7.

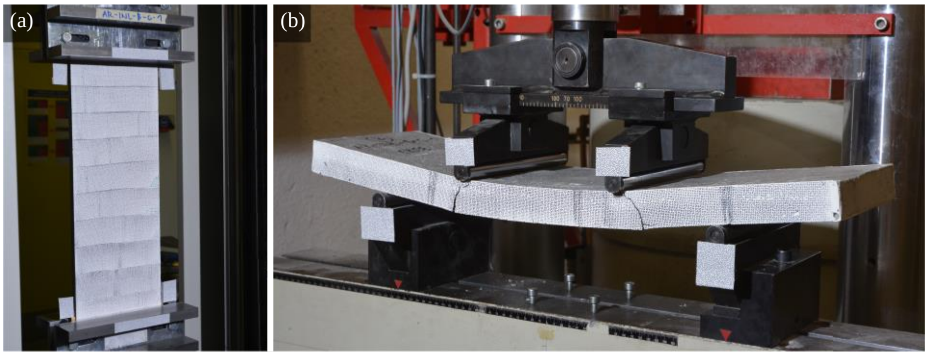

Figure 7. Textile reinforced concrete specimens (a) in uniaxial tension and (b) in bending.

Preliminary results show that the textile reinforcement considerably increases the post-cracking strength of the concrete although the specimens fail before reaching the nominal ultimate load derived from the textile reinforcement tensile strength and content. The interaction between reinforcement and concrete results in tension stiffening; the average strains in the reinforcement are lower compared to the bare textile. The Tension Chord Model [24] can be used to describe the load-deformation behaviour. First approaches show a pronounced effect of tension stiffening in the experimental data as shown in Figure 8, but more test data and analyses – currently in progress – are required to assess the mechanical properties and the interaction between materials to characterise the composite behaviour. Furthermore, the results from the uniaxial tension tests may be used to predict the behaviour of the reinforcement as a tension chord in bending beams.

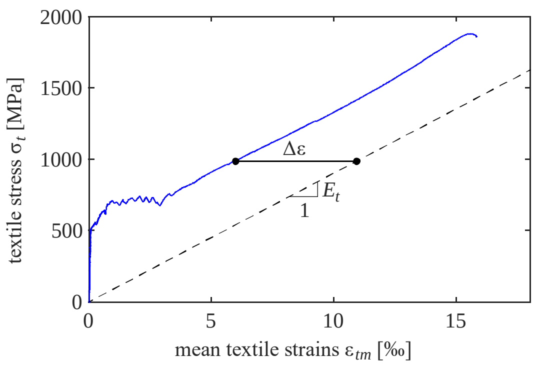

Figure 8. Load-deformation behaviour of tension ties with textile reinforcement.

The testing scheme for integrated linear reinforcement may follow the same principles and generally, similar experiments may be suitable. Since the bond capacity between the reinforcement and the concrete, considering the low cover thicknesses and potential deviation forces in curved members, is critical for the structural feasibility, the experimental campaign needs to address these challenges with special care and attention.

4 Conclusion

Flexible formworks have shown their potential to significantly increase the efficiency of the fabrication of doubly curved concrete structures by reducing manual labour and material waste. Reinforcement, which ensures structural safety, serviceability and robustness for multiple load cases, is still a major challenge in complex geometries. This paper revised several approaches to integrate reinforcement into weft-knitted textile formwork, decreasing construction time and simplifying construction processes on site.

The use of high-strength fibrous materials for stay-in-place fabric formworks offers the possibility to combine the installation of formwork and reinforcement in a single step. Knitted textiles enable many possibilities to create geometric features without cutting and connecting multiple patches together. Loops and channels within the fabric can guide linear reinforcement in the form of bars or cables for post-tensioning, which might serve for the erection of the formwork and as support structures during construction. For the proper activation of reinforcement of any kind, the bond conditions at the interface between reinforcement and concrete are the governing parameter, for which mechanical interlock has the biggest influence. Preliminary experimental investigations on concrete tension ties and beams with weft-knitted textile reinforcement show promising results but further research – including large-scale experiments – is needed to validate the feasibility of the proposed reinforcement approaches and identify further challenges for improving structural performance as well as workability during construction.

Current research of the authors focuses on the adaptation and refinement of existing mechanical models to describe the load-deformation behaviour of concrete elements with weft-knitted textile reinforcement and on the further development towards an integral formwork-reinforcement system, considering the potential of linear reinforcement, the addition of short fibres or combinations thereof.

Acknowledgements. The authors gratefully acknowledge Dr. Lex Reiter from the Institute for Building Materials (ETHZ) as well as the students Seraina Buholzer and Salome Geiser for their valuable support during preparation and testing of specimens shown in Section 3. This research is supported by the National Centre for Competence in Research in Digital Fabrication, funded by the Swiss National Science Foundation (project number 51NF40-141853).

References

[1] Lilienthal LWG. Fireproof Ceiling. US619769, 1899.
[2] Farrar D. Construction of Roofs, Floors, Ceilings, and the Like. US2096629, 1937.
[3] West M. The fabric formwork book: methods for building new architectural and structural forms in concrete. London ; New York: Routledge; 2017.
[4] Orr JJ, Darby A, Ibell TJ, Evernden M, Otlet M. Concrete structures using fabric formwork 2017. https://doi.org/10.17863/cam.17019.
[5] Brennan J, Pedreschi R, Walker P, Ansell M. The potential of advanced textiles for fabric formwork. Proc Inst Civ Eng - Constr Mater 2013;166:229–37. https://doi.org/10.1680/coma.12.00052.
[6] Veenendaal D, Block P. Design process for prototype concrete shells using a hybrid cable-net and fabric formwork. Eng Struct 2014;75:39–50. https://doi.org/10.1016/j.engstruct.2014.05.036.
[7] Veenendaal D, Bakker J, Block P. Structural Design of the Flexibly Formed, Mesh-Reinforced Concrete Sandwich Shell Roof of NEST HiLo. J Int Assoc Shell Spat Struct 2017;58:23–38. https://doi.org/10.20898/j.iass.2017.191.847.
[8] Popescu M, Reiter L, Liew A, Van Mele T, Flatt RJ, Block P. Building in Concrete with an Ultra-lightweight Knitted Stay-in-place Formwork: Prototype of a Concrete Shell Bridge. Structures 2018;14:322–32. https://doi.org/10.1016/j.istruc.2018.03.001.
[9] Popescu M, Rippmann M, Liew A, Reiter L, Flatt RJ, Van Mele T, et al. Structural design, digital fabrication and construction of the cable-net and knitted formwork of the KnitCandela concrete shell. Structures 2020. https://doi.org/10.1016/j.istruc.2020.02.013.
[10] Wangler T, Lloret E, Reiter L, Hack N, Gramazio F, Kohler M, et al. Digital concrete: opportunities and challenges. RILEM Tech Lett 2016;1:67–75.
[11] Popescu M, Rippmann M, Van Mele T, Block P. Automated Generation of Knit Patterns for Non-developable Surfaces. In: De Rycke K, Gengnagel C, Baverel O, Burry J, Mueller C, Nguyen MM, et al., editors. Humaniz. Digit. Real., Singapore: Springer Singapore; 2018, p. 271–84. https://doi.org/10.1007/978-981-10-6611-5_24.
[12] Asprone D, Menna C, Bos FP, Salet TAM, Mata-Falcón J, Kaufmann W. Rethinking reinforcement for digital fabrication with concrete. Cem Concr Res 2018;112:111–21. https://doi.org/10.1016/j.cemconres.2018.05.020.

[13] Martens R. Zum Tragverhalten von Betonplatten mit integrierten Schalungselementen. Doctoral dissertation. Institut für Baustatik und Konstruktion, ETH Zürich, 1997. https://doi.org/10.3929/ethz-a-001853800.

[14] Steinle A, Bachmann H, Tillmann M. Bauen mit Betonfertigteilen im Hochbau. In: Bergmeister K, Fingerloos F, Wörner J-D, editors. Beton-Kal. 2016, Berlin, Germany: Wilhelm Ernst & Sohn, Verlag für Architektur und technische Wissenschaften GmbH & Co. KG; 2016, p. 237–467. https://doi.org/10.1002/9783433603413.ch3.

[15] Kurz W, Mensinger M, Sauerborn I, Sauerborn N, Claßen M. Verbundträger und Deckensysteme. In: Kuhlmann U, editor. Stahlbau Kal. 2018. 1st ed., Wiley; 2018, p. 435–522. https://doi.org/10.1002/9783433607701.ch4.

[16] Boccadoro L, Frangi A. Experimental Analysis of the Structural Behavior of Timber-Concrete Composite Slabs made of Beech-Laminated Veneer Lumber. J Perform Constr Facil 2014;28:A4014006. https://doi.org/10.1061/(ASCE)CF.1943-5509.0000552.

[17] Peled A, Mobasher B, Bentur A. Textile reinforced concrete. Boca Raton, FL: CRC Press, Taylor & Francis Group; 2017.

[18] Hegger J, Horstmann M, Voss S, Will N. Textilbewehrter Beton: Tragverhalten, Bemessung und Anwendung. Beton- Stahlbetonbau 2007;102:362–70. https://doi.org/10.1002/best.200700552.

[19] Fernàndez Ruiz M, Muttoni A. Building in a lighter and more sustainable manner: textile reinforced concrete for thin structural elements. cemsuisse; 2017.

[20] Alvarez M. Einfluss des Verbundverhaltens auf das Verformungsvermögen von Stahlbeton. vol. 236. Basel, Switzerland: Birkhäuser; 1998.

[21] Mata-Falcón J, Bischof P, Kaufmann W. Exploiting the Potential of Digital Fabrication for Sustainable and Economic Concrete Structures. In: Wangler T, Flatt RJ, editors. First RILEM Int. Conf. Concr. Digit. Fabr. – Digit. Concr. 2018, vol. 19, Cham: Springer International Publishing; 2019, p. 157–66. https://doi.org/10.1007/978-3-319-99519-9_14.

[22] Du Y, Zhang X, Liu L, Zhou F, Zhu D, Pan W. Flexural Behaviour of Carbon Textile-Reinforced Concrete with Prestress and Steel Fibres. Polymers 2018;10:98. https://doi.org/10.3390/polym10010098.

[23] Markic T, Amin A, Kaufmann W, Pfyl T. Strength and deformation capacity of tension and flexural RC members containing steel fibres. ASCE J Struct Eng 2020;in print. https://doi.org/10.1061/(ASCE)ST.1943-541X.0002614.

[24] Marti P, Alvarez M, Kaufmann W, Sigrist V. Tension chord model for structural concrete. Struct Eng Int 1998;8:287–298.