le:	The potential of textile reinforced concrete for design of innovative structures
thors:	Valeri P, Guaita P., Baur R., Fernández Ruiz M., Muttoni A.
blished in:	Proc. of the International fib Symposium on Conceptual Design of Structures
ges:	8 p.
y, country:	Madrid, Spain
ar of publication:	2019
pe of publication:	Peer reviewed conference paper

ase quote as:	Valeri P, Guaita P., Baur R., Fernández Ruiz M., Muttoni A., *The potential of textile reinforced concrete for design of innovative structures*, Proc. of the International fib Symposium on Conceptual Design of Structures, Madrid, Spa 2019, 8 p..

The potential of Textile Reinforced Concrete for design of innovative structures

Patrick Valeri, Patricia Guaita, Raffael Baur, Miguel Fernández Ruiz and Aurelio Muttoni

IBETON & ALICE
École Polytechnique Fédérale de Lausanne
Route de la Sorge, Lausanne (CH-1015), Switzerland

Abstract

Textile Reinforced Concrete (TRC) is a recent evolution of ordinary reinforced concrete. This relatively new construction material replaces steel reinforcement with high-strength, non-corrosive textile fabrics in order to reduce cover requirements to minimum static values. This allows to cast thin and durable members with a thickness of 10 – 20 mm.

To encourage the use in practice of TRC, several researches are focussing on its material and structural response. Within this frame, a number of prototypes have been built to explore the potential application of TRC. In the present research, the material and structural response of TRC are investigated as well as its application on full-scale elements. In this paper, the main results of this investigation are shown to highlight the potential of this material.

1 Introduction

First patents for reinforced concrete were registered at the beginning of the XXth century [1]. At that time, the availability of raw materials was relatively limited and, consequently, construction oriented to material savings and low thickness of the structural elements. Later in that century, the cost of concrete dropped significantly with respect to labour wages. In addition, codes of practice prescribed increasingly larger cover requirements (typically 20 – 55 mm depending on the exposure class) in order to ensure the durability of concrete works. As a consequence, casting concrete elements below 10 cm has become currently almost not feasible and concrete construction is nowadays associated to a robust, but massive, construction technique.

Within this frame, a new perspective is offered by Textile Reinforced Concrete (TRC), where conventional rebars are replaced by a non-corrosive, high-strength fabric reinforcement [2]. This allows to drastically reduce cover requirements and to cast significantly thinner components with repect to ordinary concrete ($t \approx 10 – 25$ mm [3]). Taking advantage of this solution, the architecture can be combined with a lightweight load-bearing structure opening new possibilities for designers (architects and engineers).

In the following, the collaborative work of architects, engineers, students and researchers exploring the application potential of the new material is presented [4]. After a short introduction of the material behaviour and the structural response, a specific case study is illustrated showing the re-interpretation of existing ferrocement elements [5] with TRC. On this basis, the potential use of the material for a precast floor system, as a synthesis of statics and architecture needs, is discussed in the second half of this article.

2 TRC: material and potential

TRC is composed of several fabric layers embedded in a fine-grained matrix (Fig. 1a). To penetrate in the fabric layers, the matrix typically consists of a grout or high-performance mortar with small aggregates and superplasticizer. The resulting mortar, with a low water-to-cement ratio, leads thus to relatively high compressive strengths and enhanced compacity. In addition, low-clinker content cements can be used since no passivation of the reinforcewment is required. Consequently, the environmental footprint associated to cement production can be significantly reduced. The mortar used in the present research has a maximum aggregate size of $d_{g,max} = 1.60$ mm, a compressive strength of $f_c = 120$ MPa, a tensile strength of $f_{ct} = 4.25$ MPa at 28 days (see Fig. 2) and a water-to-cement ratio of $w/c = 0.25$.

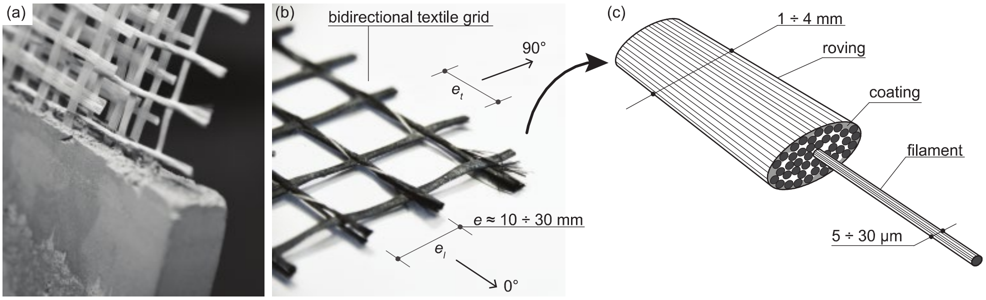

Fig. 1 Structure of TRC: (a) composite; (b) carbon textile fabric; (c) roving structure.

The fabric reinforcement is usually made of a bi-directional grid composed of rovings, which are bundles of filaments (see Fig. 1). The mechanical properties of the fabric are strongly influenced by the coating and impregnation of the rovings [6]. In this research, sand-coated carbon fabrics were mainly used, since these have particularly good bond properties [7]. The mechanical properties of the rovings were determined by simple tensile tests and are reported in Table 1. As shown in Fig. 2, when rovings are subjected to tension, they are characterised by a straightening phase (which can be neglected for the composite [8]) followed by a linear elastic behaviour until their tensile strength is reached.

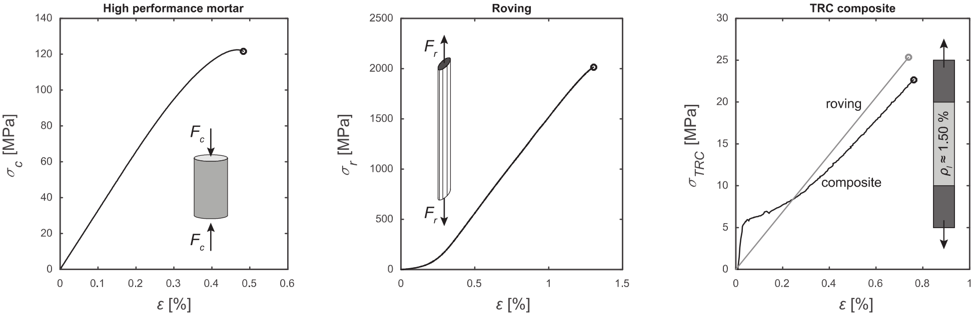

Fig. 2 Compressive behaviour of HP-mortar, tensile behaviour of rovings and of the composite.

Similarly, also the tensile response of the composite was investigated on TRC ties. As shown in Fig. 2, their response can be divided into three stages: uncracked response (stage I); crack development phase (stage II) and stabilized cracking (stage III). Failure in tension occurrs in a brittle manner during stage III, where the failure load and the cracked stiffness are governed by the fabric reinforcement. Since the filaments of the rovings are not uniformly activated, the rigidity and the failure load can be lower with respect to the bare reinforcent (see Fig. 2). The degree of activation can vary significantly according to the impregnation, coating and undulation of the rovings [9]. For the cases investigated, excellent serviceability behaviour was observed, with a uniformly distributed cracking pattern and low crack openings. Typically, the crack spacing coincides with the spacing of transverse rovings and crack opening remain below 0.3 mm at failure [10].

The structural response of the material was investigated in three-point bending tests. Fig. 3 presents three of the tested members: beams BV1 and BV2 present an I-shaped cross-section with a maximum wall-thickness of 20 mm whereas the plate PV1 consists of a slender unidirectional slab (45 mm of thickness). The members BV1 and PV1 were reinforced with several layers of carbon fabrics, while beam BV2 presented an additional concentrated reinforcement made of high strength stainless steel, arranged in the bottom (tension) flange. The arrangement and details of the reinforcement are shown in Fig. 3 and complete details can be found in [8] (see [11,16] for mechanical modelling and design formulations).

Table 1 Mechanical properties of sand coated carbon fabric (λ_r: linear density; a_r: area of roving; e_r: roving spacing; E_r: modulus of elasticity of roving; f_r: strength of roving).

Direction	λ_r [tex]	a_r [mm^2]	e_r [mm]	E_r [GPa]	f_r [MPa]
Dir. 0°	2 × 800	0.85	20	230	1700
Dir. 90°	1600	0.85	20	200	2000

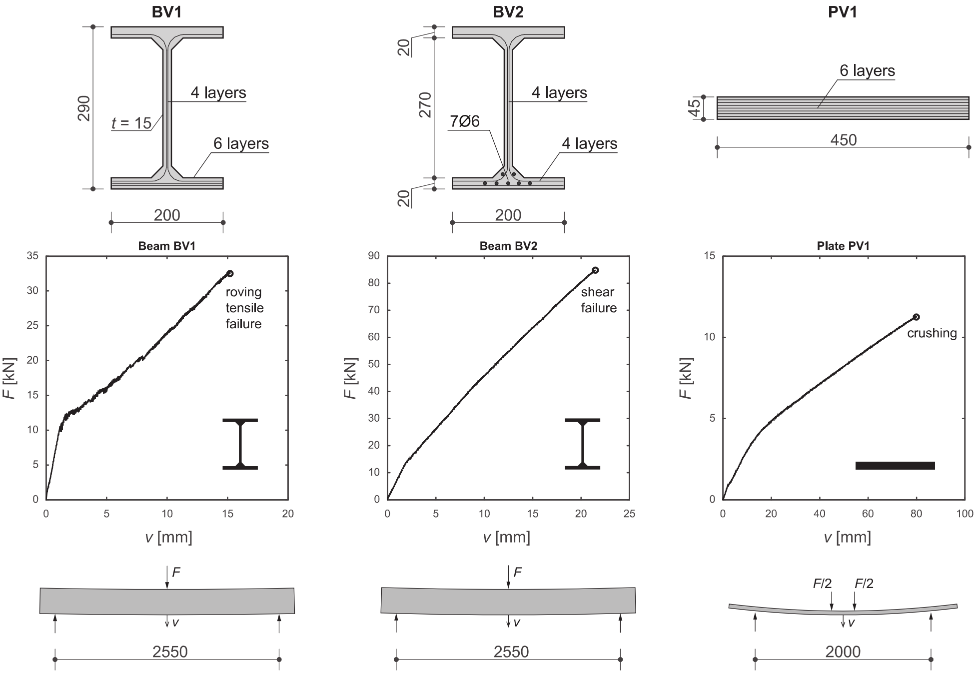

Fig. 3 Flexural response of TRC. All dimensions in [mm].

The structural response of the tested TRC members (Fig. 3) can be summarized as follows:

- Linear members reinforced only with carbon fabric fail in a brittle manner and have low to moderate bending capacities (BV1);
- The bending capacity can be significantly increased by adding a concentrated reinforcement (e.g. stainless steel bars) in the tension chord (BV2). In the present case, the stainless steel rebars had a significant deformation capacity, so that the transverse fabric reinforcement was governing at failure (brittle shear failure due to the delamination of the top flange from the web [8]);
- When the slenderness is drastically increased (PV1), the flexural response is softer giving the structure a quite large deformation capacity.

3 Argamassa Armada in TRC: a case study

The probably most famous thin-walled concrete structures were built by Pier Luigi Nervi between the 1930's and 1960's in Italy [12]. A fine-grain mortar reinforced with several layers of micro-reinforcement [13] was implemented in a systematic manner under the name *Ferrocement*. An evolution of that construction technology was conceived and implemented by João Filgueiras Lima (Lelé) in Latin America between the 1970's and 1990's [14]. *Argamassa Armada* [15] was mainly produced in large factories, but the elements were kept light enough to be carried by few persons so to be assembled on site. The largest application of this technology consists of severals structures (mainly schools, buildings and small infrastructures) built in areas of difficult acces (e.g. favelas, where roads are too narrow for cranes). To reduce costs associated to formworks, structures were designed with the least possible components, yielding that each member had to fullfil a series of functions (as water tightness and assemblies).

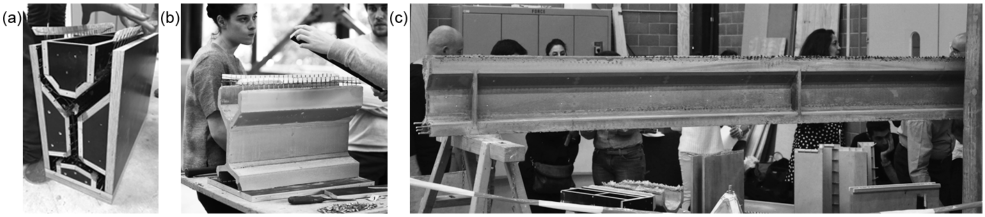

Fig. 4 X-beam: (a) timber formwork; (b) segment; (c) full-scale member.

In the frame of this study, some elements designed by Lele were re-interpreted with TRC. To investigate on different formworking materials and pouring methods, 35 segments and 16 full-scale members were cast by students during a practical course in the last four years [4]. The element studied in most detail is Lele's X-beam from his school system (Abadiânia, Brazil and other projects). At first, two segments were build in TRC using timber formworks. Therafter, a full-size element was cast, using a larger timber mould (Fig. 4). After these first experiences, the authors undertook a site visit of the precast factories in Salvador de Bahia (Brazil). It was observed that stiff steel formworks ensured an enhanced surface quality of the elements and simpler demoulding with respect to the tested timber prototypes. As a synthesis of both technologies, a similar methodology was implemented, combining thin folded metal sheets with timber stiffeners (Fig. 5). This concept was found to ensure fast assembly, very simple demoulding, and is adequate to build linear folded members and barrel-shell vaults [3].

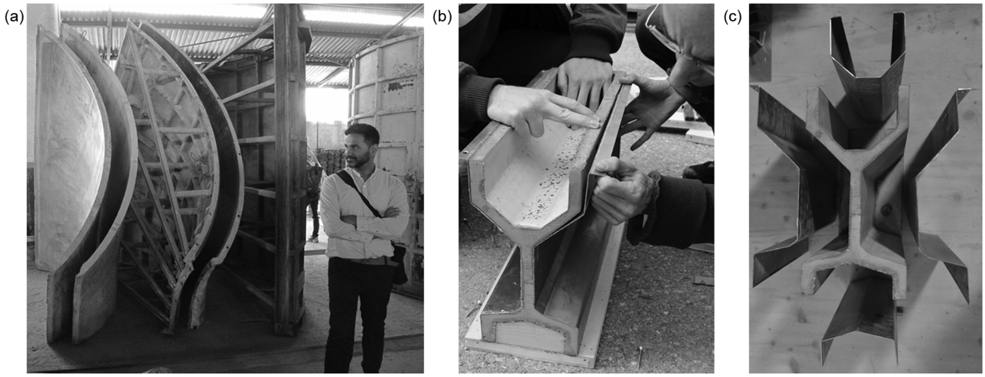

Fig. 5 Steel formworking: (a) Brazilian precast plant; (b) X-beam segment; (c) principle.

4 New materials, new shapes and tailored structural systems

As described earlier, TRC linear members have relatively limited bearing capacity. To increase the flexural capacity, one possibility is to add some concentrated reinforcement (e.g. stainless steel, carbon- or glass-fibre bars). Another option is to increase the width of the tensile flange in order to accommodate a larger number of rovings. These two aspects were explored within the following project to design a lightweight, modular floor system. The developed concept consists of a series of parallel box girders with sufficient torsional stiffness (longitudinal direction in Fig. 6) placed on a series of supports (columns or walls).

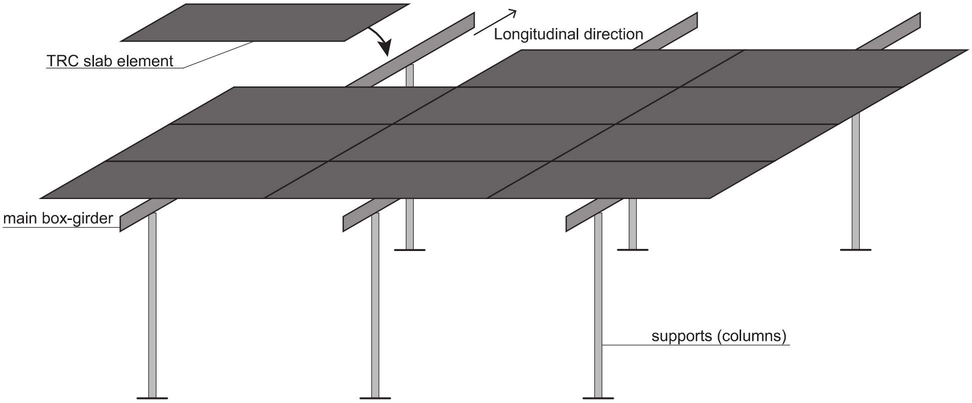

Fig. 6 Basic concept of modular TRC flooring system.

The transverse members, consisting of flanged TRC slabs are placed on top of the main girders and the constructions joints are filled with grout so to result in a monolythic system (see Fig. 7 illustrating the construction sequence).

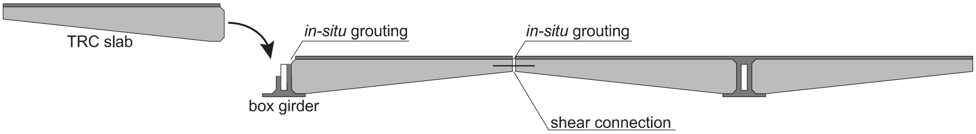

Fig. 7 View of floor system concept.

The proposed concept presents a series of advantages for the statics and use of the elements:

- The system minimizes the weight of the structural elements which are consequently very slender (maximum wall thickness $t = 20$ mm);
- Longitudinal and transverse bending moments acting in the slab can be controlled by its span and width so to maximize the efficiency of the bi-directional reinforcement;
- The width of the upper tension flange can be maximized and constitute the deck;
- The core of the main box-girders can be used for installations (e.g. drainage pipes).

A fragment of the system has been build and tested in full-scale with a span of $L = 3$ m and a width of $b = 1$ m. The element was designed to withstand a permanent load of $g = 2$ kN/m^2 and a variable load of $q = 5$ kN/m^2 (selfweight of 0.6 kN/m^2 neglected).

The flexural reinforcement was designed to withstand these actions and with failure to occur on the concrete side (designed according to [16]). Shear was not found to be governing and thus only a minimal shear-reinforcement was placed in the web. The arrangement of the reinforcement is illustrated schematically in Fig. 8. Fig. 9b shows the density of the textile in the most critical zone (connection between slab and box-girder).

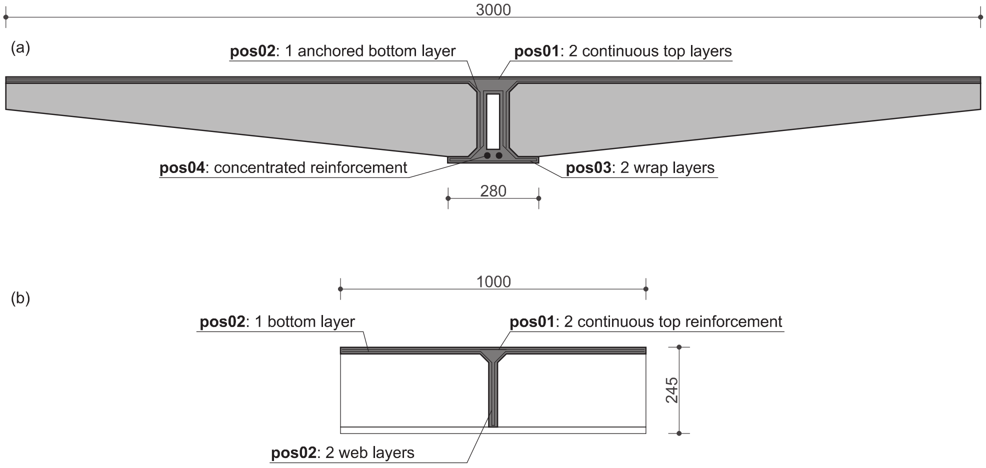

Fig. 8 Dimensions and reinforcement arrangement of the test element: (a) transversal direction (b) longitudinal section. All dimensions in [mm].

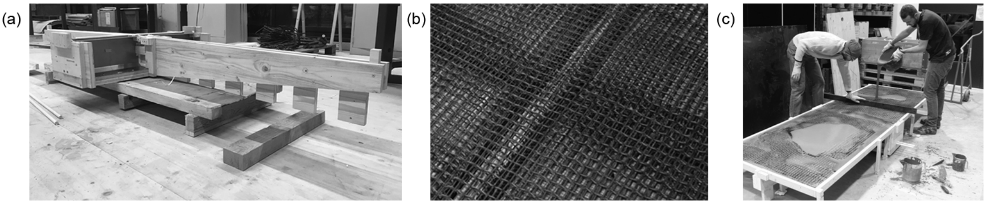

Fig. 9 Construction: (a) formwork; (b) reinforcement; (d) casting.

The prototype was cast with one batch (without any construction-joint). The formwork of the box-girder was made with folded metal sheets, whereas the flanged slab was moulded with a timber formwork (see Fig. 9). The mortar was fluid enough to penetrate between all fabric layers whose position was ensured with small plastic washers (black spots in Fig. 10).

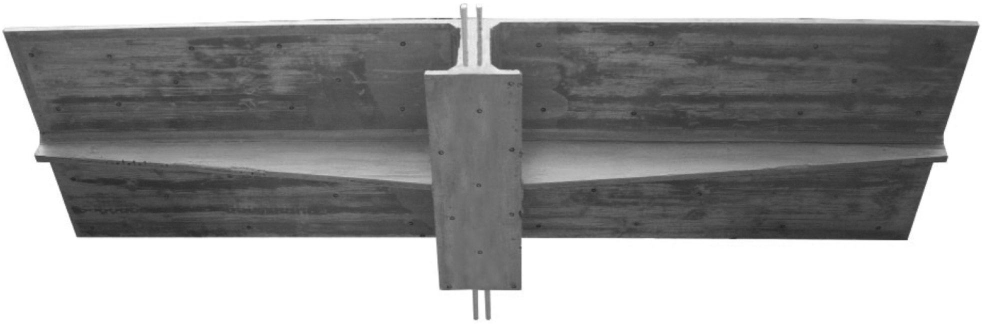

Fig. 10 Test element. View from underneath showing the web.

After 28 days, the element was subjected to a load test in a three-point bending configuration. The member was turned up-side down, so that only one jack had to be piloted. The test was carried out in displacement control with a rate of 1mm/min.

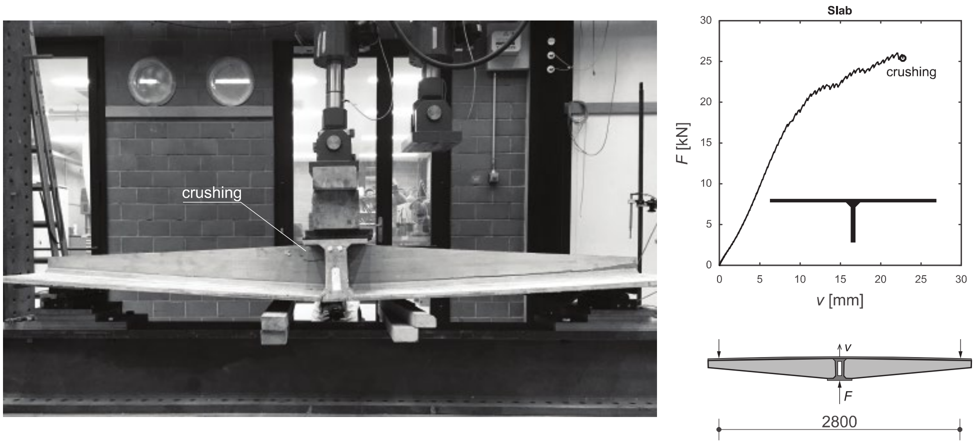

Fig. 11 Structural load test and failure of the slab-element.

At first, the structre responded in a linear-elastic manner, until the cracking moment was reached. Thereafter, the rigidity of the structure continuously decreased, until a stable crack-pattern was reached. Eventually, the cracked rigidity was governing the force-deflection response until the failure load was reached. As predicted, failure occurred in the compression zone, associated to a deflection of $v_u = 22.7$ mm (clearly visible at bare eye). It can be noted that the failure governed by crushing of the concrete significantly enhanced the deformation capacity of the element with respect to members governed by rupture of the textile (refer to Fig. 3).

5 Conclusions and outlook

Textile Reinforced Concrete is a new construction material with several promising characteristics. Despite the large interest of the construction industry, designers (engineers and architects) are still not confident to systematically apply the material due to the lack of code prescriptions and construction experience. Both aspects are addressed in this article and its main conclusions can be summarized as follows:

- Textile Reinforced Concrete alone can achieve a low to moderate resistance in tension. When combined with stainless steel reinforcement, its bending and tension capacity can be significantly enhanced;
- At serviceability, distributed cracking ensures satisfactory behaviour with low crack-openings hardly visible at bare eye;
- Due to the brittle nature of the fabric reinforcement, TRC subjected to tension failes in a sudden manner. However, slender structures can achieve a relatively high deformation capacity so to show sufficient premonitory signs of failure;
- As for the formworking, thin folded metal sheets combined with timber stiffeners seem a very promising method especially for thinwalled members;
- Such concepts can be integrated in a smart manner for the design of modular, light-weight slab elements with a tailored static system.
- Further research is still required to accommodate other issues as phonic insulation or thermal consideration (thermal inertia).

Acknowledgements

The authors would like to sincerely acknowledge the support given by the association of the swiss cement producers *cemsuisse* (research project nr.201407) for their financial support, providing the concrete mix and technical discussions.

References

[1] Simmonet, Cyrille. 2005. *Le béton. Histoire d'un matériau*. Marseille : Parenthèses.

[2] Scholzen, Alexander, and Chudoba, Rostislav, and Hegger, Josef. 2015. "Thin-walled shell structures made of textile-reinforced concrete." *Structural Concrete* (2015) No.1:106–114.

[3] Scholzen, Alexander, and Chudoba, Rostislav, and Hegger, Josef, and Wil, Norbert. 2016. "Leichte Dachschalen aus Carbonbeton." *Beton- und Stahlbetonbau 111 (2016)*. Heft 10:663–675.

[4] Valeri, Patrick, and Guaita, Patricia, and Baur, Raffael, and Fernández Ruiz, Miguel. 2018. "Pedagogy through artisanal construction of thin-walled concrete elements: a dialogue between engineering and architecture." Proceedings of the IV Int. Conference on Structural Engineering Education , Madrid, Spain, June 20–22.

[5] Vilela, Adalberto. 2018. "Architecture without Applause: The Manufactured Work of João Filgueiras Lima, Lelé". PhD diss., ETH Zurich.

[6] Lorenz, Enrico. 2014. "Endverankerung und Übergreifung textiler Bewehrungen in Betonmatrices. " PhD diss., Technische Universität Dresden.

[7] Donnini, Jacopo, and Corinaldesi, Valeria, and Nanni, Antonio. 2016. "Mechanical properties of FRCM using carbon fabrics with different coating treatments." *Composites Part B* 88:220–228.

[8] Valeri, Patrick, and Fernández Ruiz, Miguel, and Muttoni, Aurelio. 2017. *Building in a lighter and more sustainable manner: textile reinforced concrete for thin structural elements.* semsuisse.

[9] Bertolesi, Elisa, and Carozzi, Francesca, and Milani, Gabriele, and Poggi, Carlo. 2014. "Numerical modeling of Fabric Reinforce Cementitious Matrix composites (FRCM) in tension." *Construction and Building Materials* 70:531–548.

[10] Voss, Stefan. 2008. "Ingenieurmodelle zum Tragverhalten von textilbewehrtem Beton." PhD diss., RWTH Aachen.

[11] Josef, Hegger, and Wil, Norbert, and Bruckermann, Oliver, and Voss, Stefan. 2006. "Load–bearing behaviour and simulation of textile reinforced concrete." *Materials and Structures* 39:765–776.

[12] Gargiani, Roberto. 2016. *The rhetoric of Pier Luigi Nervi. Concrete and ferrocement forms*. Lausanne, EPFL Press.

[13] Busse, Daniel, and Empelmann, Martin. 2018. "Shear strength of thin-walled concrete members with micro-reinforcement" Proceedings of The 12th International PhD Symposium in Civil Engineering, Prague, Czech Republic, August 29–31.

[14] Giongo, José, S. 1990. "Argamassa Armada: Dimensionamento de prefis submetidos à flexao." PhD diss., Universidade de Sao Paolo.

[15] Lina, Bo, and Bardi, P. M.. *João Filgueiras Lima Lelé*. Lisboa: Editorial Blau; 2000

[16] Valeri, Patrick, and Fernández Ruiz, Miguel, and Muttoni, Aurelio. 2018. "Experimental research on Textile Reinforced Concrete for the development of design tools" Proceedings of The 12th International PhD Symposium in Civil Engineering, Prague, Czech Republic, August 29–31.