Prestressed ultra-high performance concrete (UHPC) beams for reusable structural systems: design and testing

D Redaelli[1], J Moix[1], A Muresan[1,2], J Brütting[2] and C Fivet[2]

[1] Institute of Construction and Environmental Technologies, University of Applied Sciences Western Switzerland (HES-SO), Fribourg, Switzerland
[2] Structural Xploration Lab, Swiss Federal Institute of Technology (EPFL), Fribourg, Switzerland

dario.redaelli@hefr.ch

Abstract. With the aim to reduce the environmental footprint of buildings, this paper presents an original structural system concept for two-way slabs in residential and office buildings. The proposed system extends the best practice in terms of modularity, versatility, demountability, reusability, and durability. A finite set of elements can be used to form the main load-bearing system of multiple successively constructed buildings having different and unpredicted layouts and static systems. Ultra-High Performance Concrete (UHPC) was identified as one of the most promising materials for this application because of its high strength, extreme durability and the opportunities it opens for shape optimization and material consumption reduction. In the first part of this contribution, the main features of the new structural system and preliminary design assumptions for UHPC modules are briefly outlined. Then, the authors present and discuss the results of an experimental campaign on prestressed UHPC beams that were tested in bending and shear, under service and ultimate load conditions. Beams with transversal openings in the web were also tested to assess the influence of these openings on the cracking behavior and shear strength of the beams. Experimental results provide useful information for the subsequent modeling of the structural system. Thanks to the presence of fibers, transversal openings in the web only have a limited influence on the response of the beams, thus allowing horizontal technical shafts to pass through the structural thickness of the slab.

1. Introduction

Today, the global resource consumption is 1.7 times higher than what the planet can sustain [1]. The construction industry alone is responsible for approximatively one third of material usage [2], energy consumption [3] and waste production [4] worldwide, with load-bearing systems (e.g. slabs) contributing the major share of these impacts. Existing strategies to face these issues are mainly based on the use of construction materials with a low environmental impact (e.g. natural, locally available, or recycled materials) or on the design of material-efficient systems (e.g. weight minimization). These approaches, however, do not provide a long-term solution since they are not addressing in a decisive way the building's end-of-life: costs and energy required to demolish, transport and transform materials to be recycled, and the inevitable degradation (down-cycling) of their properties.

An alternative strategy to reduce environmental impacts [5, 6] consists in conceiving building's components in order to allow their reuse with minimal interventions in successive buildings and for multiple building lifetimes. This strategy, even though not yet widely established from a technological point of view, has the potential to radically transform the construction industry towards a more sustainable circular economy.

2. A reusable structural system for two-way slabs

The fundamental requirements that a building system must fulfil in order to ensure open-ended reusability are: durability, versatility, modularity, reversibility and adaptability [5].

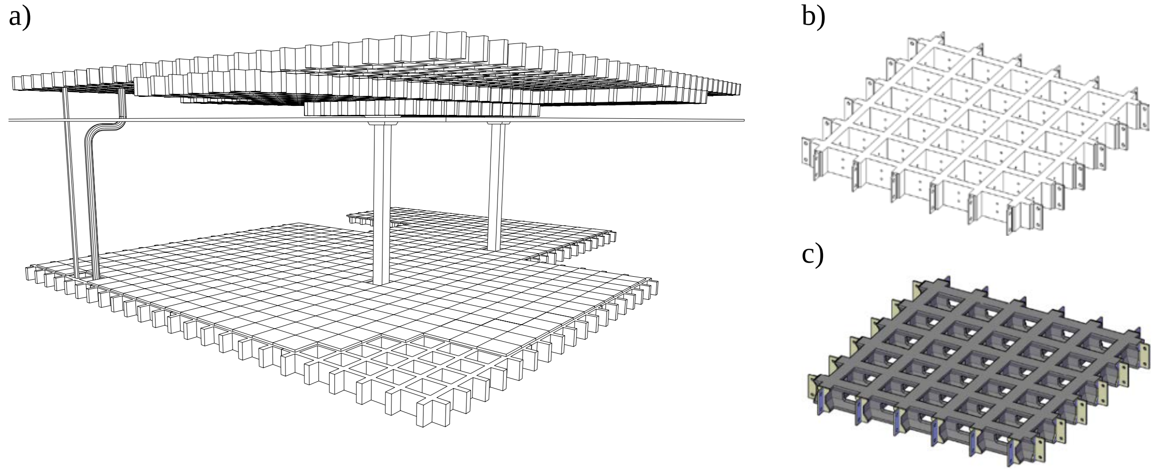

Figure 1. Schematic representation of the structural system (a) and of individual modules realized with glue-laminated timber (b) or UHPC (c)

A new type of structural system for two-way slabs, which complies with all the above requirements, has been conceived within the framework of a collaborative research project between the Swiss Federal Institute of Technology (EPFL) and the University of Applied Sciences Western Switzerland (HES-SO). The system (figure 1.a) consists of quadrilateral slab modules that can be interconnected in a plane to create slabs with different ground plans. Each module (figure 1, right) is conceived as a grid of orthogonal and regularly spaced beams, creating an array of transversal openings that define possible locations both for columns (with the addition of a head capital to support the slab) and for vertical technical shafts. Slab modules can also be stacked vertically to locally increase the static height of the system, thus allowing to tailor the strength and stiffness distribution of the slab to meet specific static requirements [7]. Extremely versatile, the proposed structural system allows for multiple re-adaptations in successive buildings with unpredicted uses, geometries and support positions.

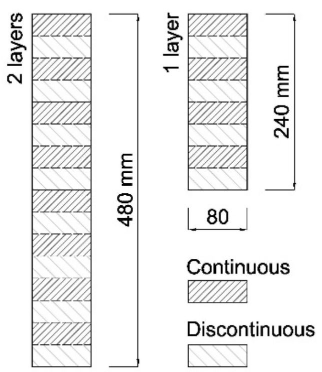

Table 1. Geometric and mechanical properties of glue-laminated timber beams

	Shear strength[1] V_{Rd} [kN]	Bending strength[1] M_{Rd} [kNm]	Stiffness EI [kNm^2]	Weight [kg/m]
1 layer	11.5	8.8	719	8.7
2 layers	23.1	34.0	5750	17.3

1 : ultimate limit state (ULS) design values

For practical applications, the system was designed to resist vertical loads of residential and office buildings with spans varying between 4 and 12 meters (with multiple layers). A first implementation is presented here as a reference and was designed in GL32h glue-laminated timber. Bolted steel plates fixed to the ends of the beams with epoxy glued steel rods were chosen as connections between modules (figure 1.b). The geometric and mechanical properties of timber beams are given in table 1 for one-layer and two-layer configurations. Each beam is made of eight 80×30 mm laths. Due to the crossing of orthogonal beams, however, only half of the laths are continuous in each direction (figure in table 1, left), which limits the structural performance of this solution. Shear strength, bending strength and bending stiffness given in table 1 were calculated according to Swiss standards [8] by assuming that only continuous laths contribute, which was confirmed by laboratory experimental tests.

Despite the lightness, the positive environmental properties and the good mechanical strength of timber, stronger and stiffer alternative solutions were searched. Ultra-High Performance fiber-reinforced Concrete (UHPC) was identified as a promising alternative due to its very high strength, extreme durability and the opportunities it opens for shape optimization and material consumption reduction. The rest of the paper focuses on design, testing and preliminary modeling of the UHPC implementation.

3. Conceptual and detailed design of the UHPC implementation

With respect to timber, UHPC is heavier, more expensive and its production requires more energy and non-renewable materials. To provide a competitive solution with respect to timber, the following criteria were set as basis of UHPC modules design:

- provide with a single UHPC layer (24 cm height) strength and stiffness equal or higher than two layers of glue-laminated timber (48 cm, see table 1)
- optimize the geometry of the cross-section to reduce self-weight and material consumption
- explore the potential to create transversal openings in the webs for horizontal technical shafts, which is not possible for glue-laminated timber beams

Detailed design of the beams was carried out according to Swiss Standard SIA 2052 [9] assuming the mechanical properties of a relatively common tensile-hardening UHPC mixture (class UA, [9]): compressive strength f_{Uck} = 150 N/mm^2, elastic limit in tension f_{Utek} = 7.5 N/mm^2, maximal tensile strength provided by the fibres f_{Utuk} = 9.5 N/mm^2 and modulus of elasticity E_U = 55'000 N/mm^2. Table 2 gives the calculated ULS design values of shear and bending strength, as well as the corresponding average values (that might be expected in case of testing). Also given are the estimated average values of shear and bending strength required in case of testing so that the corresponding design values (ULS) are at least equal to those of two layers of timber (see table 1 for comparison).

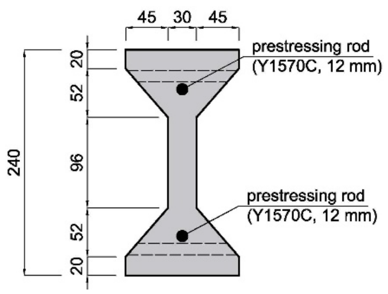

Table 2. Geometric and mechanical properties of UHPC beams

	V_R [kN]	M_R [kNm]	EI [kNm^2]	Weight [kg/m]
ULS Design values	46.5	36.2		
Expected average values	69.7	46.3	6105	41.8
Required average values	34.7	43.5		

UHPC beams are pre-tensioned with 12 mm diameter Y1570C pre-stressing wires directly fixed to steel plates at the extremities of the beams (figure 1.c). Since the position of a specific slab module within the structural systems is *a priori* unknown, each module must be able to resist both positive and negative moments. Consequently, symmetrically prestress was designed, with one prestressing wire per flange. Flanges were sized to resist the compressive force generated by bending moments at ultimate, while their shape was chosen to allow placing longitudinal and transversal prestressing wires with a minimal cover according to [9]. A web thickness of 30 mm was chosen to facilitate the casting of UHPC and to obtain a design value of the shear strength (V_{Rd} = 46.5 kN, table 2) significantly higher than the target design value corresponding to two layers of glue-laminated timber beams (V_{Rd} = 23.1 kN, table 1).

Thanks to this shear strength surplus, the creation of transversal openings in the web of UHPC beams can be explored. Despite the presence of few experimental and modeling approaches in the literature [10-13], no recognized design approach exist to the authors' knowledge for the shear strength of UHPC beams with transversal web openings.

4. Experimental campaign on pre-stressed UHPC beams with or without web openings

To acquire a better knowledge on the influence of web openings on the behavior of the studied system and to provide basic information for further analytical and numerical modeling, an experimental campaign on prestressed UHPC beams with and without web openings was carried out.

4.1. Description of the test series

Four beams were fabricated for testing (figure 2). Beams S1 and B1 have no web openings, while beams S2 and S3 have openings with different geometries. Beams S1, S2 and S3 were designed to fail in shear and were tested in three-point bending with 1.5 m span. These beams were fabricated with a length of 1.5 times the test span, two test regions in the outer thirds and a strong region in the central part. By changing the position of load and supports (black and red configurations, figure 2), it was possible to carry out two tests per beam, named "side a" and "side b" hereafter. To avoid any risk of bending failure, the central part of these beams was reinforced with an additional ϕ20 B500B steel rebar. Beam B1 was designed to fail in bending and was tested in four-point bending with 3.0 m span.

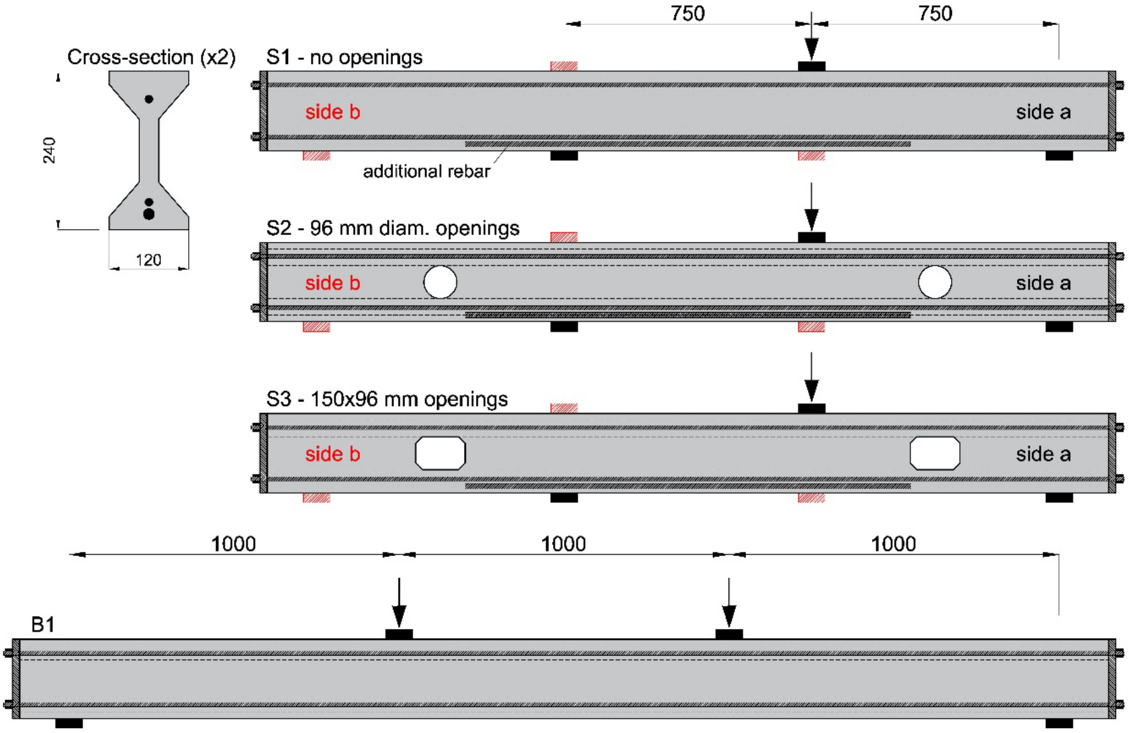

Figure 2. Geometry of the four tested beams

Each beam was fabricated with a separate UHPC batch. Prestress forces of 115 kN per wire were freed three days after casting. Instantaneous and delayed shortening of the beams were monitored until the day of testing for a precise evaluation of prestress losses. For "S" elements, longitudinal strains on "sides b" were monitored while testing "sides a": strains very close to zero were detected, showing that the prestressing level on "sides b" was not influenced by cracking and failure that occurred on sides "a".

Tests on "side a" were stopped relatively early after the peak force, while tests on "side b" were pursued much further in the post-peak to verify the ductility of the beams.

4.2. Materials

The commercial product Ductal FM was used as UHPC mixture for the test series, with self-compacting consistency and 270 kg/m^3 (3.4% in vol.) high-strength straight steel fibers (length l_f = 14 mm, diameter d_f = 0.2 mm). Table 3 summarizes the average 28 days mechanical properties for each batch. Measured values are comparable but slightly higher than those assumed for preliminary design. However, relatively low values of the elastic limit in tension, f_{Ute}, were measured for some specimen. This could be partly explained by the surface grinding procedure which was applied to 30 mm thick plates according to [9], which may have damaged these specimens.

Table 3. Measures mechanical properties for UHPC at 28 days

Beam/ Batch	Compressive Strength f_{Ucm} (*) [N/mm^2]	Elastic modulus E_{Ucm} (*) [N/mm^2]	Elastic limit in tension f_{Utem} (**) [N/mm^2]	Tensile Strength f_{Utum} (**) [N/mm^2]	Hardening strain in tension ε_{Utum} (**) [‰]
B1	177.2 (3)	60’100 (3)	8.25 (6)	8.90 (4)	1.87 (4)
S1	167.2 (3)	55´300 (3)	6.97 (3)	9.82 (2)	5.21 (2)
S2	169.1 (3)	56’567 (3)	6.17 (6)	13.53 (6)	3.08 (6)
S3	177.1 (3)	58’900 (3)	6.48 (6)	10.83 (6)	2.30 (6)

(*) Measured on 70×140 mm cylinders

(**) Calculated by inverse analysis of bending tests on 30 mm thick plates according to [9]

(2), (3), (4), (6) indicate the number of tests used to calculate the average value

4.3. Test results

All load tests were carried out at an age of UHPC comprised between 28 and 34 days. Table 4 summarizes the maximal applied force and the corresponding maximal shear force and bending moment for each test. These values are compared to expected and required average strength values according to preliminary design (see table 2) and to strength predictions obtained with non-linear numerical modeling (see section 5). Figures 3, 5, 6 and 7 present force versus mid-span displacement curves (at two different displacements scales) and pictures of the crack patterns at failure for each beam.

Table 4. Summary of test results

Beam/ Batch	Web opening	Maximal measured force	Numerically predicted max. force	Maximal measured shear	Maximal measured moment	Expected strength (see tab. 2)	Required strength (see tab. 2)	Shear/moment at 1st detectable[1] crack
B1	No	86.4 kN	-	-	43.2 kNm	46.3 kNm	43.5 kNm	39.0 kNm
S1-a	No	146.3 kN	158.8 kN	73.2 kN	-	69.7 kN	34.7 kN	54.9 kN
S1-b		174.3 kN		87.2 kN	-	69.7 kN	34.7 kN	75.2 kN
S2-a	ϕ96	149.6 kN	151.0 kN	74.8 kN	-	-	34.7 kN	35.0 kN
S2-b		151.3 kN		75.7 kN	-	-	34.7 kN	44.9 kN
S3-a	96x150	139.7 kN	127.8 kN	69.9 kN	-	-	34.7 kN	40.1 kN
S3-b		135.4 kN		67.7 kN	-	-	34.7 kN	45.2 kN

1. Cracks detected either by visual inspection or by digital image correlation

Based on observations and measured values data, the main experimental findings are summarized:

- all beams showed the expected failure mode
- for all beams, including beams with web openings, the measured strength is equal or higher than the required values (see tables 1 and 2). For beams “S”, the location of the critical shear crack was strongly influenced by the position where the additional ϕ 20 rebar ends

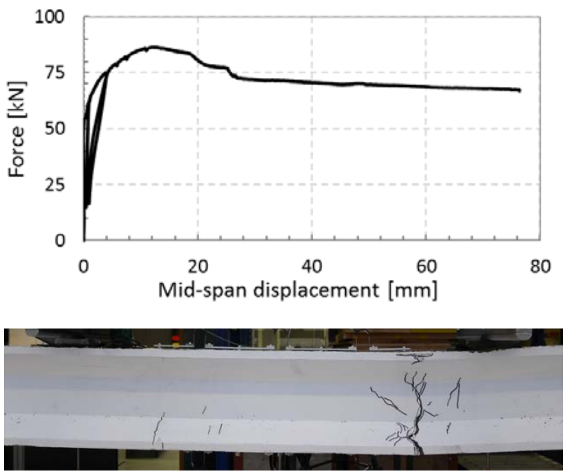

Figure 3. Measured force-displacement curve and crack pattern at failure for beam B1

• test results of sides "a" and "b" are practically identical for beams S2 and S3, but show a significant difference for beam S1 (figure 5). This difference could be explained by the accidental presence of a failure plane with particularly poor number or orientation of fibers on side "a". More detailed analyses are however required to explain this behavior

• by taking as a reference the average strength of beams S1-a and S1-b, the reduction of shear strength due to presence of transversal web openings is in any case less than 20%

• for all beams, ultimate behavior is extremely ductile, with the progressive formation of a collapse mechanism showing very significant post-peak residual strength

• cracks were only detected (table 4, note 1) at relatively high load levels, indicating that UHPC beams will be uncracked or micro-cracked in service.

5. Non-linear finite element modeling

To gain a deeper understanding on test results and to carry out further parametric analyses, the structural behavior of type "S" beams was modeled with a non-linear finite element software [14]. The software solution implements a coupled tensile fracture, compressive plasticity model and allows to define strain hardening/strain softening constitutive laws within a smeared crack modeling approach. For the sake of simplicity, a unique strain-hardening tensile law was used for all the beams, with f_{Ute}, f_{Utm} and ε_{Utu} calculated as the average of all the bending tests carried out for batches S1, S2, S3 and B1 (figure 4, black). For the softening part, a stress-crack opening softening law according to [15] was assumed, with zero stress for a crack opening equal to $l_f/2$. To consider the less favorable alignment of fibers in beams than in thin bending plates, the post-cracking part of the tensile law was scaled on the stress axis by a factor 0.8 (figure 4, red). Young's modulus and compressive strength were set according to values given in table 3, while other parameters of the three-dimensional mechanical model were set according to state-of-the-art knowledge and are not detailed here.

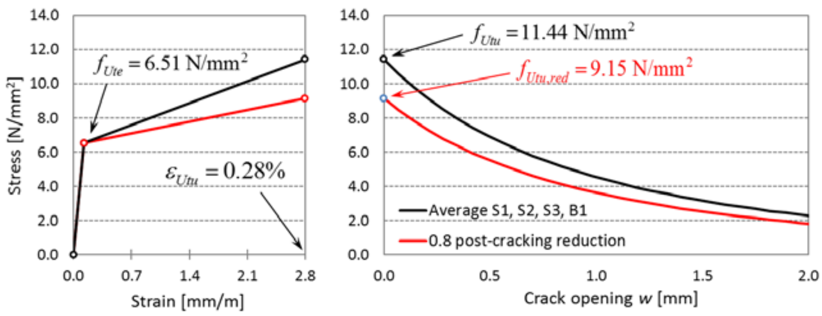

Figure 4. Tensile stress-strain and stress-crack opening laws for modeling

Numerical solutions are compared to experimental ones in figures 5 to 7: despite some numerical instabilities in the post-peak and the need to validate the sensitivity of the numerical solution to variations in the numerous mechanical parameters, the experimental response is quite well reproduced both in terms of crack pattern and forces vs mid-span displacements.

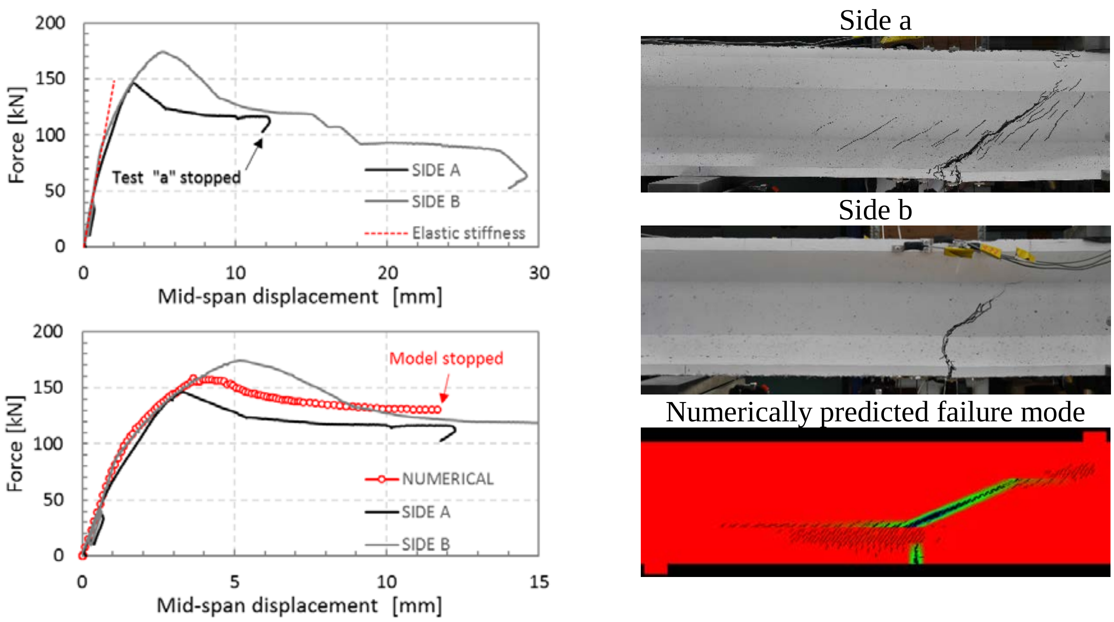

Figure 5. Measured vs simulated force-displacement curve and crack pattern at failure for beam S1

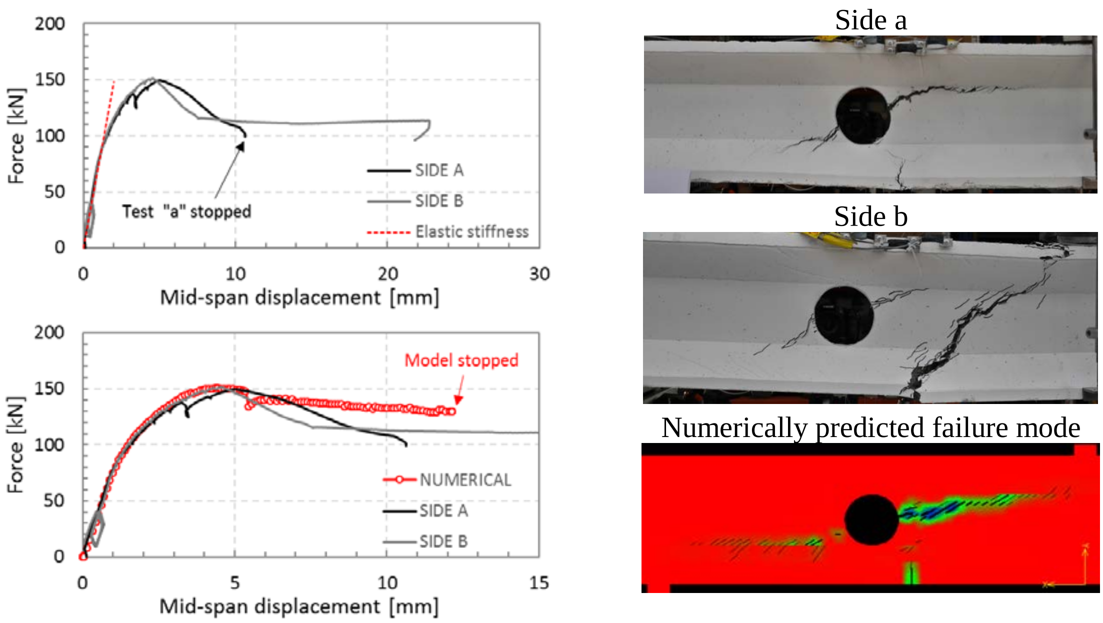

Figure 6. Measured vs simulated force-displacement curve and crack pattern at failure for beam S2

6. Conclusions and future work

This paper presented the design, testing and preliminary modeling of UHPC beams that were conceived as a possible technical implementation of a new modular, reusable and extremely versatile structural system for two-way slabs of residential and office buildings.

Experimental and modeling results demonstrate that UHPC beams can be designed to meet the strength and serviceability requirement of the new modular structural system with the imposed limitations of height and with a relatively light cross-section.

Thanks to the tensile contribution of the fibers, the presence of web openings of significant size only has a limited influence on the mechanical performances of the beams, thus allowing horizontal technical shafts to pass through the structural thickness of the slab.

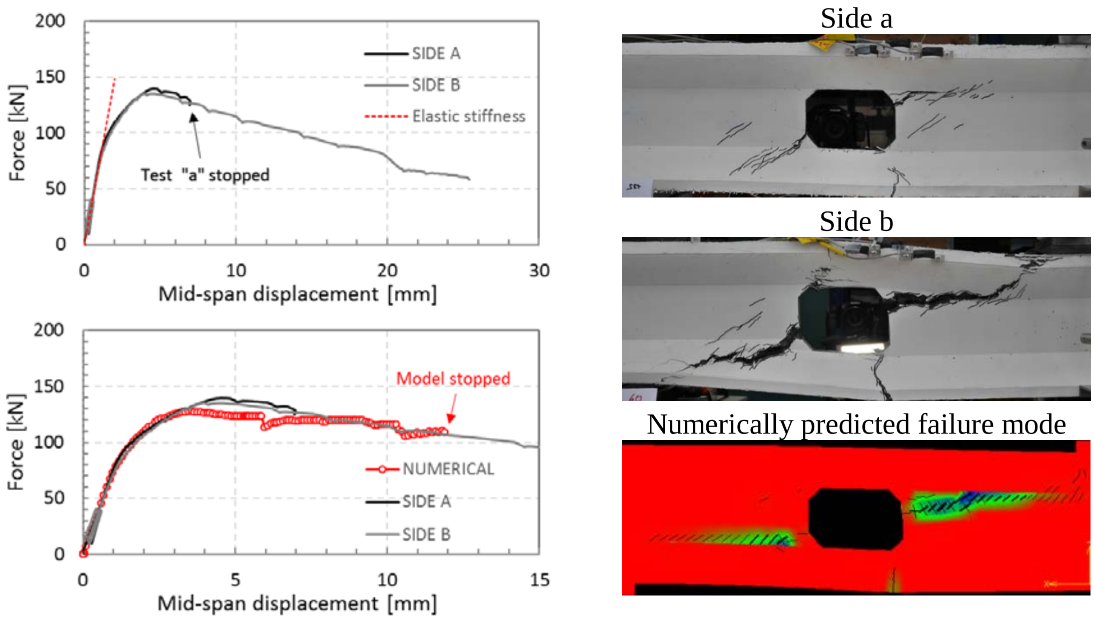

Figure 7. Measured vs simulated force-displacement curve and crack pattern at failure for beam S3

In the next steps of the research program, the economic and environmental impact of the system will be evaluated and compared to other possible implementations of the new modular system (e.g. timber, steel or mixed-construction) and to traditional, non-reusable constructive systems for two-way slabs.

The sensitivity of finite element modeling with respect to variation of the input mechanical parameters will be checked, then the model will be used as a tool for parametric analysis and for further optimization of the proposed concept.

7. References

[1] European Environmental Agency 2018 *National Footprint Accounts*

[2] Danish Environmental Protection Agency 2018 *Building a Circular Future, 3rd edition*

[3] Pérez-Lombard L Ortiz J Pout C 2008 *Energy and buildings* **40** 3 pp 394-398

[4] Becqué R et al. 2016 *Accelerating Building Efficiency* (Washington: World Resources Institute)

[5] Fivet C 2019 *IOP Conf. Ser.: Earth Environ. Sci.* **225** 012031

[6] Fivet C and Brütting J 2020 *The Structural Engineer* **98** 1 pp 74-81

[7] Muresan A, Brütting J, Canada J, Redaelli D and Fivet C 2018 *Proc. of the IASS Symp. Creativity in Structural Design* ed C Mueller and S Adriaenssens (Boston: MIT)

[8] Swiss Society of Engineers and Architects 2012 *SIA 265 - Timber construction*

[9] Swiss Society of Engineers and Architects 2016 *SIA 2052 - Ultra-High Performance Concrete (UHPC) - Materials, design and construction*

[10] Hegger J Bertram G 2008 *Tailor Made Concrete Structures: New Solutions for our Society* ed J C Walraven and D Stoelhorst (CRC Press) p 96

[11] Zagon R, Matthys S and Kiss Z 2016 *Construction and Building Materials* **124** pp 258-268

[12] Moreillon L Nseir J Tomas J and Suter R 2013 *RILEM-fib-AFGC Int. Sym. on Ultra-High Performance Fibre-Reinforced Concrete* ed F Toutlemonde and J. Resplendino pp 549-556

[13] Redaelli D and Nseir J 2020 *Fibre Reinforced Concrete. From Design to Structural Applications, fib Bulletin No. 95* pp 474-483

[14] Cervenka V Jendele L and Cervenka J 2018 *ATENA Program Documentation – Theory*

[15] Redaelli D 2009 Thèse n° 4290 École Polytechnique Fédérale de Lausanne