FLEXURAL AND SHEAR BEHAVIOUR OF STRUCTURAL ELEMENTS IN UHPFRC

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Abstract

Ultra-high performance fibre reinforced concrete (UHPFRC) has an important potential to allow innovative design due to its high mechanical properties and its durability. This paper reports some results of a theoretical and experimental research carried out at the University of Applied Sciences (UAS) Fribourg/CH, on UHPFRC structural elements. The experimental studies included load tests on beams, slab stripes and slabs. In a first study, consisting of 25 beams, the behaviour of linear elements subjected to bending and shear stresses was analysed. A second study dealt with the behaviour of 38 thin slabs strips in uniaxial bending. The third study was dedicated to the behaviour of 22 thin slabs subjected to concentrated loading. Finally, in a fourth study, the behaviour of 16 thin slabs exposed to biaxial bending stresses was analysed. The results of these studies contribute to the development of a recommendation of the Swiss Society of Engineers and Architects (SIA) for the design and the construction of UHPFRC structures.

Résumé

Les bétons fibrés ultra-performants (BFUP) ont un potentiel indéniable pour réaliser des structures plus élancées et innovantes en raison de leurs propriétés mécaniques élevées et de leur durabilité. Cette contribution présente les résultats d'une importante recherche théorique et expérimentale menée à l'Ecole d'ingénieurs et d'architectes (EIA) de Fribourg/CH sur des éléments de structure en BFUP. Dans une première étude, comprenant 25 poutres, était analysé le comportement flexionnel et la résistance au cisaillement. Une deuxième étude, comprenant 38 bandes de dalles minces, traitait le comportement flexionnel. Une troisième étude, comprenant 22 dalles carrées, était analysé la résistance au poinçonnement. Finalement, dans une quatrième étude, comprenant 16 dalles octogonales, était analysé le comportement sous des sollicitations de flexion bi-axiale. Les résultats de ces études théoriques et expérimentales contribuent à l'élaboration d'une directive de la Société Suisse des Ingénieurs et Architectes (SIA) pour le dimensionnement et la réalisation de structures en BFUP.

1.   INTRODUCTION

Since the beginning of the 20th century, reinforced concrete structures experienced a fast development, becoming an indispensable building technology in our modern society. The concrete technology has continuously evolved, due to active research in this field. Particularly, advanced knowledge in cementitious materials has led to the development of concrete having particular properties and increasingly high performances. In parallel, the progress in steel fibre reinforced concrete has led to the development of ultra-high performance fibre reinforced concrete (UHPFRC) which is characterized by its high tensile toughness and high compressive strength. Since 2000, UHPFRC knew several structural applications and highlighted the numerous advantages of using this material. With its high tensile toughness, elements subjected to moderate stress or having complex shapes can be realized without conventional steel reinforcement. Furthermore, structural elements with less complicated shapes, such as slabs, decks or facade panels, can be achieved with a combination of UHPFRC, a lower fibre volume ratio and passive steel reinforcement. This paper aims to show the beneficial contribution of UHPFRC with reinforcement and presents some results of a theoretical and experimental research carried out at the University of Applied Sciences (UAS) Fribourg, on UHPFRC structural elements with and without passive steel reinforcement. The experimental studies included load tests on beams, slab strips and slabs. In a first experimental study, consisting of 25 beams, the behaviour of linear elements subjected to bending and shear stresses was analysed. A second study (35 slab elements) dealt with the behaviour of thin slab strips in uniaxial bending. The third study (28 square slabs) was dedicated to the behaviour of thin slabs subjected to concentrated loading (punching shear). Finally, in a fourth study (16 octagonal slabs), the behaviour of thin slabs exposed to biaxial bending stresses was analysed. This contribution will present some principal results of the research and more detailed information will be presented in the different test reports.

2.   MATERIAL PROPERTIES

The test specimens were made in Béton Composite Vicat BCV®. The BCV is developed by Vicat and belongs to the family of UHPFRC as defined in the interim recommendations of the French Civil Engineering Association (AFGC) [3]. The two following compositions with their respective denominations were analysed:
−   BCV-0   without fibres
−   BCV-1 %A   short steel fibres 13/0.18 mm, V_f = 1 % (79 kg/m^3)
−   BCV-1 %B   mix steel fibres 13/0.18 and 20/0.30 mm, V_f = 1 % (79 kg/m^3)
−   BCV-2 %   mix steel fibres 13/0.18 and 20/0.30 mm, V_f = 2 % (158 kg/m^3)
−   BCV-3 %   mix steel fibres 13/0.18 and 20/0.30 mm, V_f = 3 % (237 kg/m^3)
−   BCV-FO   synthetic fibres, V_f = 20 kg/m^3

The BCV exhibits an average compressive strength f_{cm} of 150 MPa on cylinder, produced without a heat treatment. The Young's modulus was around 45 GPa. In order to evaluate the post cracking response of the UHPFRC, bending tests on prisms (notched and unnotched) and uniaxial tensile tests were performed (Fig. 1).

Figure 1: Three-point bending test setup of UHPFRC plates and notched prisms

The three formulations BCV-1 %, 2 % and 3 % showed a hardening behaviour in bending while the BCV-FO exhibits a softening behaviour in bending. The bending stress was positively influenced by the small thickness, especially for the high fibre content. The tensile laws were identified according to AFGC inverse analysis for thick and thin elements [3].

3.   BEAM ELEMENTS

Within the scope of this study, load tests were performed on 25 beams of 100 x 150 x 1700 mm made of UHPFRC and normal strength concrete (NSC) (Fig. 2). The principal parameters were the concrete type, the amount and the type of fibres, the steel reinforcement ratio and the prestressing intensity.

Four beams were tested for the series BCV-1 %, 2 %, 3 %, FO. The four beams in each series were differentiated by their steel reinforcement ratio. The first beams of each series were without reinforcement. The next two elements were reinforced with respectively two 10 mm diameter rebars (ratio of 1.31 %) and two 16 mm diameter bars (ratio of 3.35 %). The effective depth of the reinforcement was 120 mm. The forth element of each series was without reinforcement, but prestressed by a mono-strand without bond. The prestressing force was 180 kN, which represented an initial stress $\sigma_{cp,0}$ of 12 MPa in the concrete. The concrete NSC corresponded to a normal strength concrete C30/37. The specimens were tested on four-point bending with a span of 1350 mm.
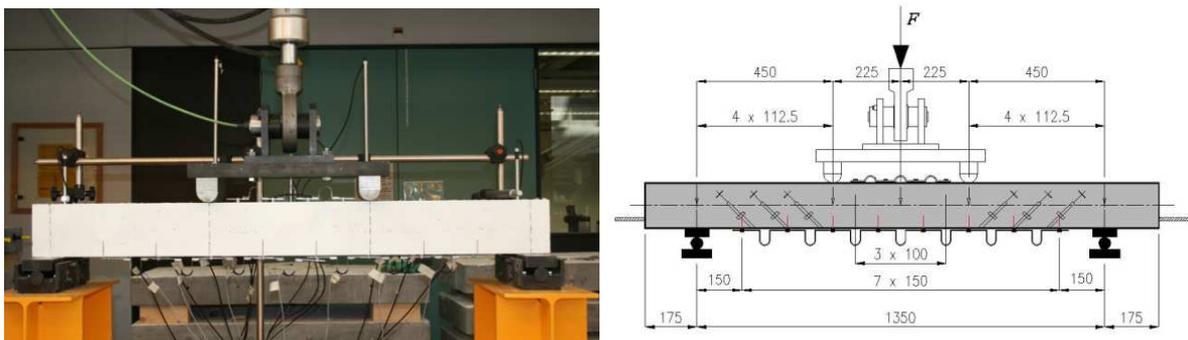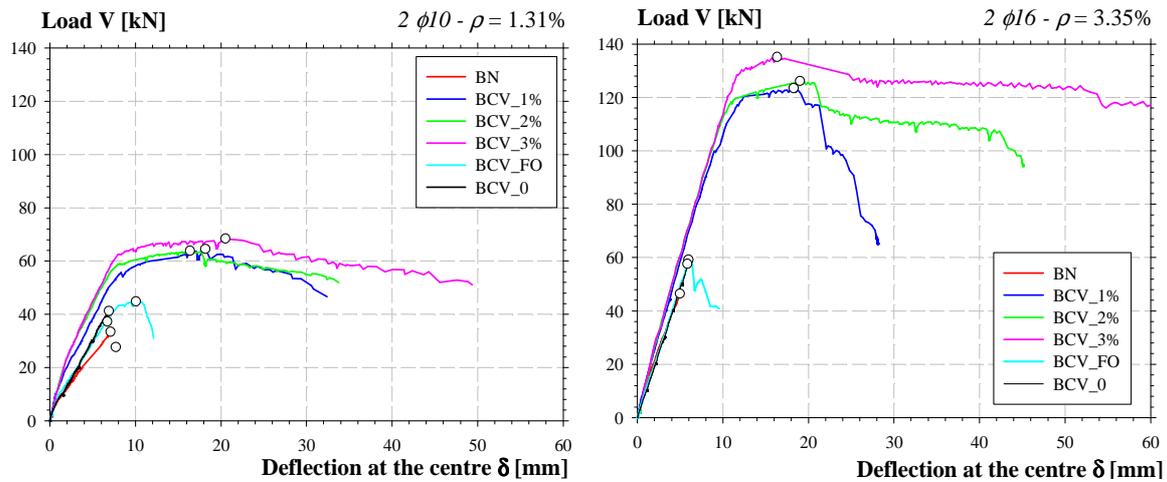

Figure 2: Test set-up and specimens' geometries

Figure 3: Shear force vs. deflection curves at the center of the specimens

The elements made of NSC, BCV-0 and BCV-FO undergo a sudden shear failure without reaching the steel reinforcement yielding. The BCV elements with steel fibres showed a flexural failure except for the BCV-1 % beam having a high reinforcement ratio. For this beam the deflection capacity after the reinforcement yielding was limited by a shear failure. Only a hardening behaviour in bending of the material can control the shear cracks and thus delay or prevent a sudden shear failure.

Figure 4: Cracking pattern at failure of the BCV 1 % / 2 % beams, with 2 ϕ16 mm rebars

4. SLAB STRIPS

The second experimental study was composed of 35 UHPFRC slab strips with and without steel reinforcement. The distinguishing parameters between the tested elements were: the thickness, the amount of fibres and the reinforcement ratio. The strips had a length of 1400 mm and a width of 400 mm. The corresponded thicknesses varied between 30 and 80 mm. Two reinforcement ratios were adopted: 1.1 % and 2.5 %. All elements were casted in the same way. The elements were tested in four-point bending loads with a span of 1200 mm. Loads were introduced at the ends of the strips through two actuators. This test configuration allowed following the evolution of the cracking in the upper side of each element.
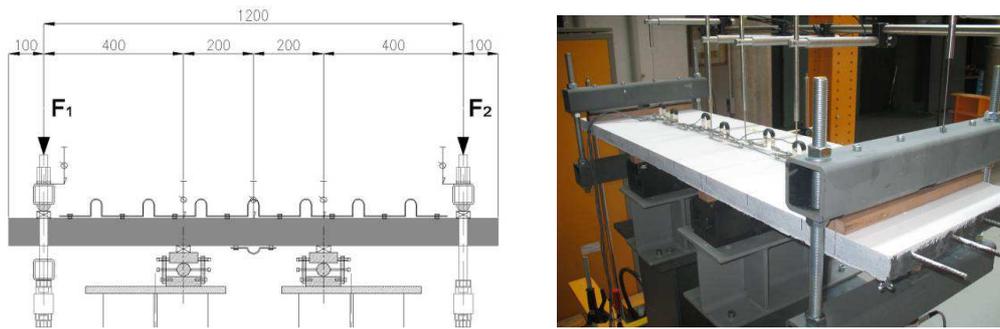
Figure 5: Test Set-up and specimens' geometries

The reinforced strips exihibited a higher stiffness after the cracking load compared to the slab without reinforcement. The cracking was well distributed and the cracks' openings were close to 0.1 mm. The steel yielding marqued an imortant decrease of the stiffness. At this point the deformation was concentraded on a single macro-crack. The maximum load was then rapidly reached. The test showed that the deflection at the peak load tended to decrease with an increasing amount of fibres. In the post-peak stage, the load decreased rapidly and was followed by the rupture of the rebars. For high reinforcement ratio, no delamination of the rebars and shear failure was observed.
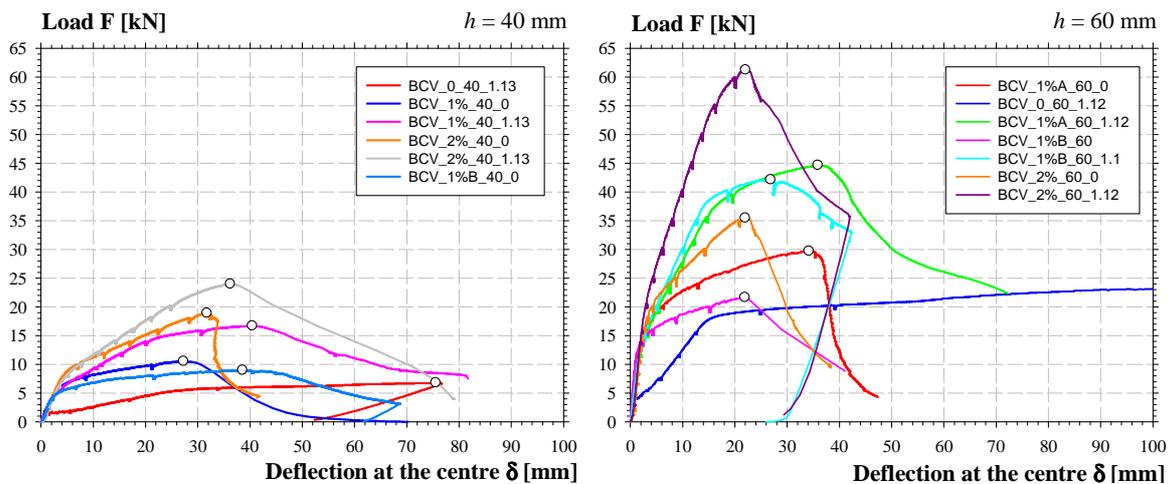

Figure 6: Load vs. deflection curves for the 40 and 60 mm BCV elements

Figure 7: Cracking pattern at failure of a 80 mm BCV element

5.   SQUARE SLABS

The third experimental study was composed of 28 UHPFRC square slabs (960 x 960 x *h* mm). The main parameters of this tested study were: the thickness, the amount of fibres and the steel reinforcement ratio. The thicknesses ranged from 30 to 80 mm. The ratio of steel reinforcement varied between 0.98 % and 2.57 %. Two compositions of steel fibres were analysed: 1 % of short fibres and 2 % of mixed short and long fibres. The load tests have been carried out on a punching test setup specially designed for this study (figure 8). The load was applied with a actuator located at the centre of the slab through a 80 mm diameter steel punch. The slab was supported by eight steel rods, anchored to a steel frame. The support system described a circle with a diameter of 878 mm and spherical plain thrust bearings allowed free rotations.
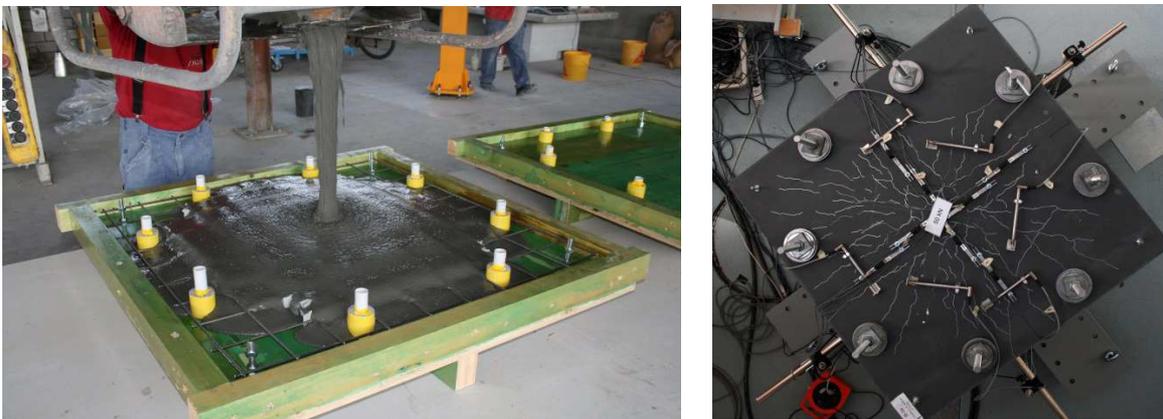

Figure 8: Slab casting and test set-up

BCV_2%_30_0   BCV_2%_40_0   BCV 2% 60 0   BCV_2%_80_0

BCV 2% 30 1.36   BCV 2% 40 1.02   BCV_2%A_60_1.00   BCV 2%A 80 1.10
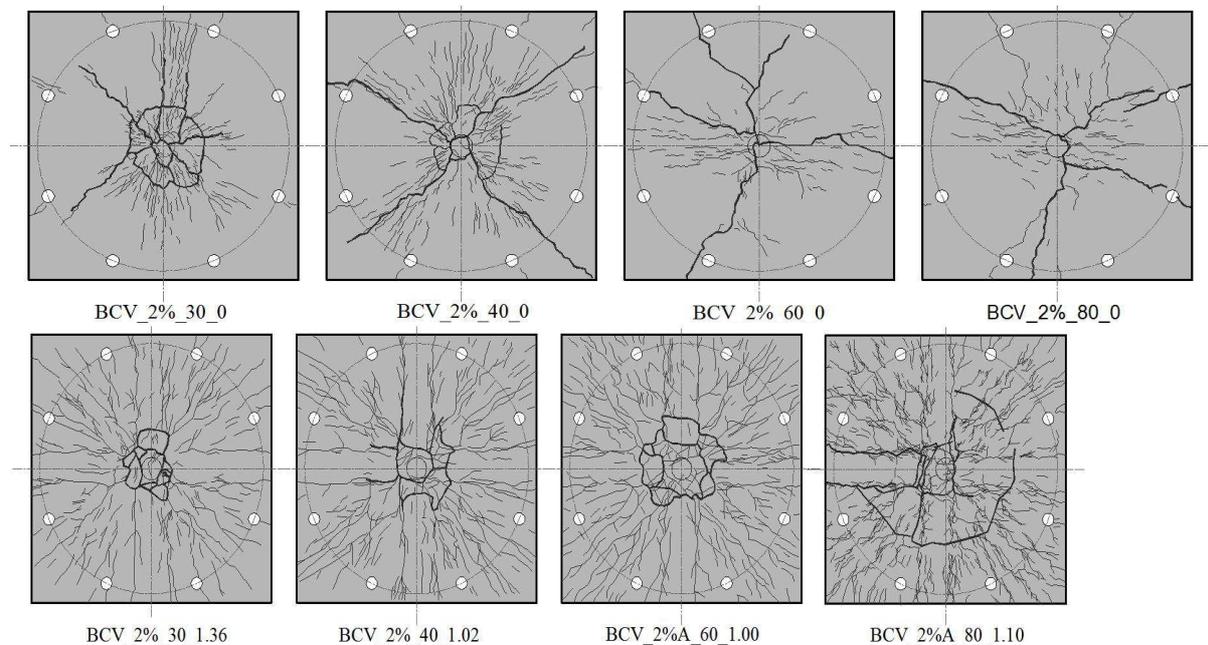
Figure 9: Cracking pattern of the 2 % slabs with and without steel reinforcement

Slabs without steel reinforcement showed a flexural failure. After the internal cracking analysis, no punching cone was developed. In the tested configuration, the flexural strength is moderate therefore the punching is not the determining criteria.

Regarding the behaviour of reinforced slabs, it is possible to draw the following comments: (i) the elastic-cracked phase resembles an almost linear behaviour (ii) for high reinforcement ratio the difference between the two fibres amount is close. Additionally, distinct failure mechanisms were observed: (i) flexural failure, characterized by large deformations with a post-peak softening behaviour; (ii) punching shear failure described by a sudden drop in the load without a significant plastic deformation and (iii) a combined flexural and shear failure, where the flexural strength was reached, but the punching shear limit restricted the plastic deformation capacity of the elements.

Moreover, it is worth noting that the combination of a fibre dosage of 2 % with a steel reinforcement ratio of 1% showed similar results, when compared to the combination of a 1 % fibre content and a 2 % reinforcement ratio. In fact, for this comparison the maximum load was only considered and, therefore, it didn't include post-peak and pre-peak phases of the constitutive behaviour.

Analogously, similar behaviour was reported for slabs with only a fibre content of 2 % and with slabs with a fibre content of 1 % comprising steel reinforcement.
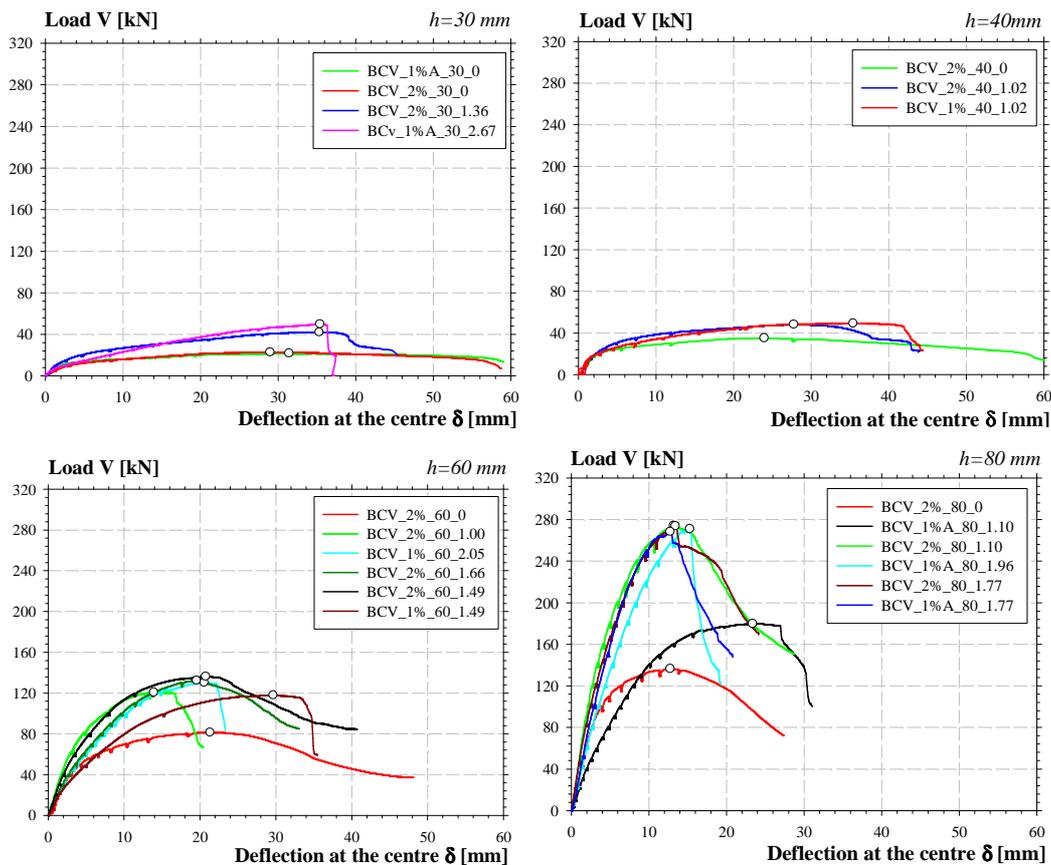

Figure 10: Load vs. deflection curves represented according to the different thicknesses

6.   OCTOGONAL SLABS

In this fourth experimental study, 16 thin UHPFRC slabs (2040 x 2040 x *h* mm) were subjected to bidirectional bending stresses. The study was divided into four series in which the variable parameters were: the slabs' thicknesses varying from 30 to 80 mm, the amount of fibres ranging from 1 to 2 % and the steel reinforcement ratio varying from 1 % to 2 %. The load tests were performed on a test setup specially designed for this study (figure 11). The load was applied at eight points located on a circle with a diameter of 1934 mm. At each load point, spherical plain thrust bearings allowed free rotations.The slabs were supported at the center by a ring having a diameter of 500 mm composed of 24 spherical nuts.
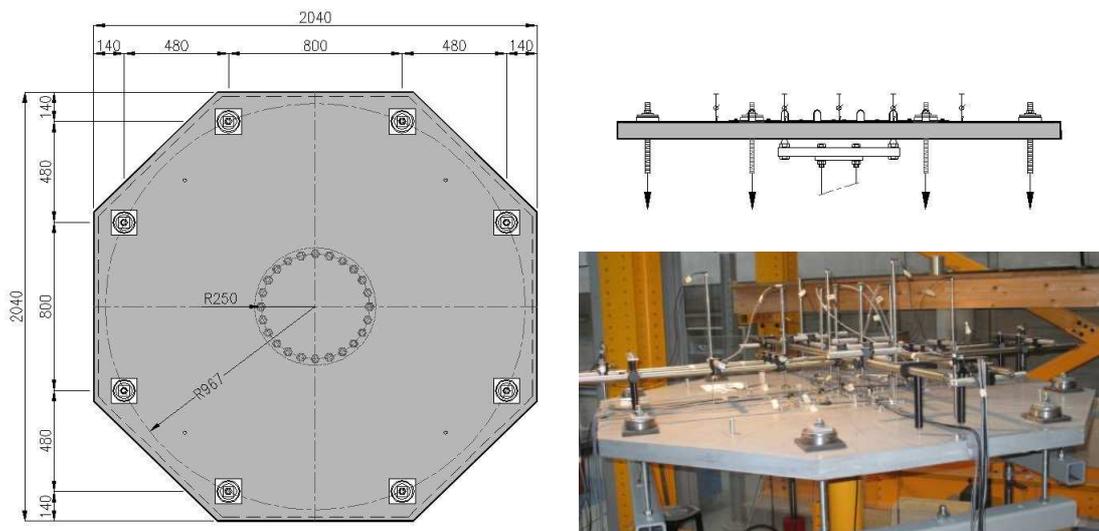

Figure 11: Specimen geometry and test setup

The macro-cracks appeared faster in the 1 % slabs than in the 2 % slabs. However, elements having 1 % of fibres and the ones with 2 % of fibres showed a more or less similar deformation capacity. Slabs with 2 % of fibres had a higher stiffness than the slabs with 1 % of fibres. All the elements had a flexural failure. The difference in stiffness and resistance between these two amounts of fibres became less pronounced in the presence of a high passive reinforcement ratio.

For slabs of low thickness (30 and 40 mm) in which the rebars were located at the neutral axis, they acted primarily by large deformations. In the first stages, the behaviour of the elements with and without steel reinforcement was almost similar. Once the crack reached the bars in the half-thickness, their effect was important despite their unfavorable location. The reinforced slabs showed a double resistance of the same slabs without reinforcement. However, it is interesting to note that their deformation capacity was similar. For slabs having larger thicknesses (60 and 80 mm), the effective height of the rebars increased. Therefore, the reinforcement contributed significantly to the structural response of the element, not only in terms of resistance but also in terms of the deformation capacity.
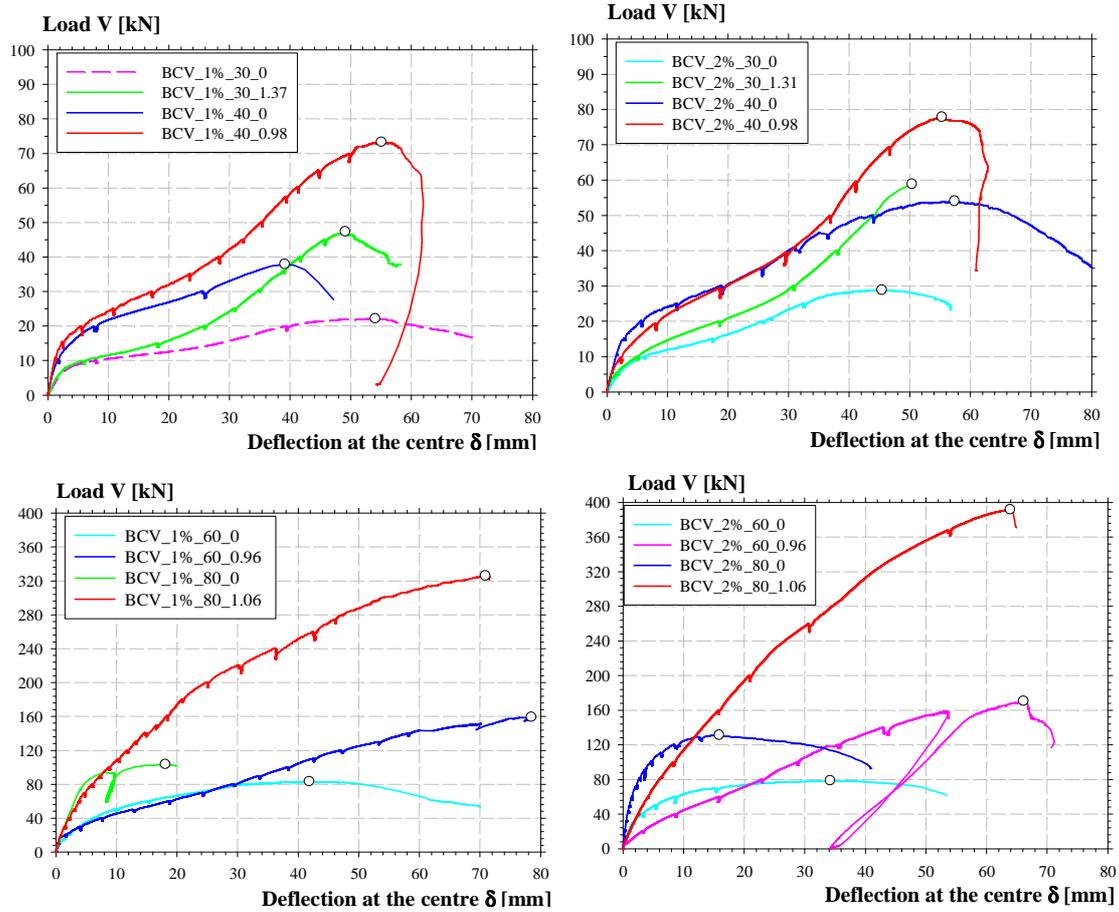
Figure 12: Load vs. deflection curves for different amounts of fibres and different steel
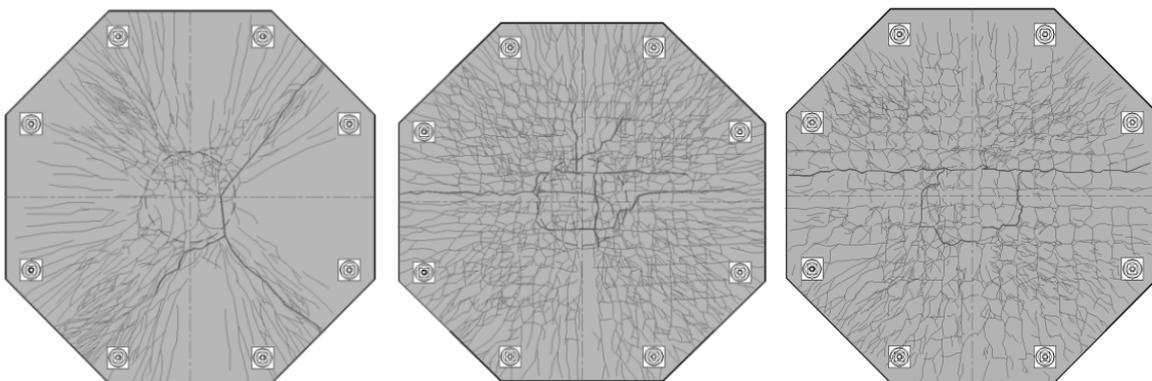reinforcement ratios

Figure 13: Cracking pattern at failure of the elements:
BCV_2 %_80_0; BCV_1 %_80_1.06; BCV_2 %_80_1.06

7.   CONCLUSIONS

Since 2007, the University of Applied Sciences Fribourg has carried out a large research program on UHPFRC structural elements. The principal aim of this project was to analyse the behaviour of UHPFRC structures with and without steel reinforcement and to propose design models. Several experimental studies on structural elements, beams slab strips and slabs, were undertaken for this purpose. The results will contribute to the development of a recommendation of the Swiss Society of Engineers and Architects (SIA) for the design and the construction of UHPFRC structures. This contribution shows the principal results of the theoretical and experimental studies.

The experimental studies performed have highlighted the following points:
- The high mechanical properties of UHPFRC allow the execution of thin elements having a high reinforcement ratio without encountering brittle failures
- The combination of a UHPFRC with steel rebars allows achieving a rather high resistance, but the deformation capacity tends to decrease with an increasing dosage of fibres.
- In a general manner, a combined reinforcement of steel rebars with an appropriate dosage of fibres could present a rather good economical solution.
- An adequate dosage of steel fibres can eliminate secondary reinforcement, enabling thus a better ability to realize different structural shapes.
- The tensile strength of UHPFRC depends on the casting method; the determination of the material's tensile law must take into account an eventual anisotropy.
- Simplified design model for bending, shear and punching shear strength of UHPFRC elements with passive steel reinforcement is still in development on the basis.

ACKNOWLEDGEMENTS

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