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Shear resistance of ultra high performance fibre-reinforced concrete I-beams

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ABSTRACT: Ultra High Performance Fibre-Reinforced Concrete (UHPFRC) refers to materials with a cement matrix and a characteristic compressive strength in excess of 150 MPa, and containing steel fibres in order to achieve ductile behaviour under tension. Thanks to these outstanding properties thin and durable structural elements can be made. Shear verifications of structures made of UHPFRC are thus often critical. The possibility to add the stirrups force at yielding and the post-cracking fibres contribution in the theoretical estimate of the ultime shear resistance requires appropriate verification. In order to quantify the safety margin of shear design provisions, an experimental campaign has been carried out at the LCPC (French Public Works Research Institute). In a Four-Point Bending configuration, shear tests have been conducted on nine 3m-long I-shaped girders with varied types of shear reinforcement (stirrups, fibers and both) combined with longitudinal prestressing or passive reinforcement.

1 INTRODUCTION

Many parameters such as the properties of concrete used, the slenderness, the presence or not of shear reinforcement, the tension reinforcement ratio and the cross section influence the shear capacity of beams. For fiber reinforced concrete properties, main parameters are the fiber content, their shape, their dimensions and the quality of cementitious matrix. Many previous programs have indicated the major positive effect of fiber content and presence of stirrups on shear behavior of beams (Mansur 1986, Narayanan 1987, Li 1992, Casanova 1995, Khuntia 1999, Noghabai 2000) and have shown the synergetic effect of both factors (beyond a minimum shear reinforcement ratio) in the case of "normal" fiber reinforced concrete (Swamy et al., 1993).

Since UHPFRC tensile post-cracking behavior and bond capacity significantly differs from fibre-reinforced conventional concrete, it is necessary to check experimentally for structures made of UHPFRC with transversal passive reinforcement, the simultaneity of fibres contribution and the stirrups effort at yielding for the ultime shear resistance. Moreover, previous research on UHPFRC (Sato et al. 2008) and High Performance Reinforced Concrete (Cucchiara et al. 2008), have shown a synergy of fibres and stirrups for shear behaviour but not at the Ultimate Limit State (ULS) due to a quite premature flexural failure of specimens with transversal passive reinforcement.

An experimental program was thus defined, within AFGC (Association Française de Génie Civil) Task group on UHPFRC, including Lafarge and Eiffage as partners, to complement the experimental background on UHPFRC shear design provisions.

2 SHEAR TESTS

2.1 *Specimens and parameters*

All specimens were fabricated in a precast factory (Veldhoven, the Netherlands) in industrial conditions, using two concrete mixes (A and B) presented in Table 1. The results of preliminary tests of material characterization are also shown. Material input data will be further identified according to the French AFGC Recommendations on UHPFRC (AFGC-Sétra 2002). The workability of these materials is close to self-compacting concrete.

During the manufacturing of beams made of concrete A, the prestressed beam with stirrups was not satisfactorily cast. An additional batching was decided for both prestressed beams. Consequently two batches exist for the first concrete mix: A and A-bis. Two days after casting, the beams made of concrete B were placed during 48 hours in a climate-conditioned box at 90°C with a relative humidity of about 100 %. The intent of this step is to increase the mechanical characteristics of concrete up to 10 % and to reach the final maturity of heat treated component: the total further shrinkage is zero and the creep is significantly reduced after the heat treatment.

Table 1. UHPFRC mix characteristics.

Concrete Mix	fc cube (*MPa*)	Steel straight fibers Lf – Φf (*mm*)	Vf (*%*)
A	195	20 - 0.3	2.5
A-bis	202	20 - 0.3	2.5
B	212	13 - 0.2	2

The main parameters studied in this experimental program were the UHPFRC mix, the active or passive longitudinal reinforcement and the presence of shear reinforcement in the specimens. Nine beams of I-shaped cross section were tested. An overview of beams characteristics is shown in Table 2.

Table 2. Parameters of the shear tests.

Specimen	Concrete Mix	Reinforced / Prestressed	Stirrups
Beam 1-A	A	Prestressed	no
Beam 1-A-bis	A-bis	Prestressed	no
Beam 1-B	B	Prestressed	no
Beam 2-A-bis	A-bis	Prestressed	yes
Beam 2-B	B	Prestressed	yes
Beam 3-A	A	Reinforced	no
Beam 3-B	B	Reinforced	no
Beam 4-A	A	Reinforced	yes
Beam 4-B	B	Reinforced	yes

The beams were 3 meters in total length having a span of 2.0 meters and a total depth of 380 mm. The effective depth was 305 mm for all beams. The web was designed as a thin membrane 65 mm-thick. The top flange was 270 mm wide and the bottom flange 230 mm.
For prestressed beams, the lower chord was pretensioned with six rectilinear T15S tendons, each with a prestressing force of 170 kN. For other specimens, the passive longitudinal reinforcement was realized with five #20 and one #25 rebar. The shear reinforcement consisted in #6 stirrups and was installed in four specimens with 75 mm spacing. The shear reinforcement ratio was 0.6 %. This value has been chosen to represent the ratio existing in real structures made of UHPFRC (in which stirrups are generally used just as a local help for shear capacity) and to produce a significant contribution of transversal steel reinforcement (approximately 20 % of the total ultime shear resistance).
Only specimens with shear reinforcement had an upper steel rebar (#10). In order to get homogeneously distribute fibers throughout the whole specimen, the distance between reinforcements or between formwork and steel reinforcing bars was fixed higher than 30 mm (= 1.5× the Maximum Fiber Length). Indeed the combination of fibres and shear reinforcement could have shown a negative effect due to fibre blockage if enough space for concrete flow into the mold could not have been provided.
The full details of dimensions and arrangement of reinforcement are shown in Figures 1 and 2.

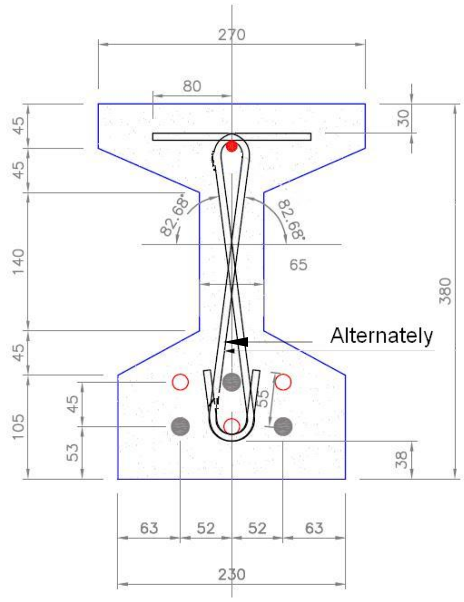

Figure 1. Cross section of prestressed beams with stirrups (Dimensions in mm).

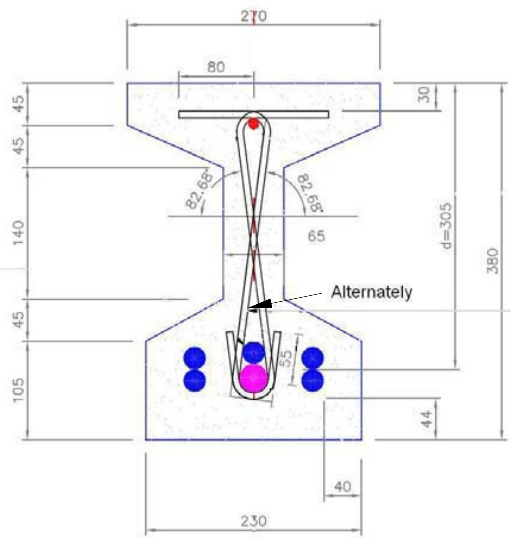

Figure 2. Cross section of reinforced beams with stirrups. (Dimensions in mm).

2.2 *Loading setup and instrumentation*

All beam specimens were tested in a four point bending configuration (Fig. 3). The span was 2 meters and the shear span ratio was 2.5 in order to avoid an important arching action.
In all tests, the load was applied in 50-kN increments until failure. After each load increase reached stabilization, the new appeared cracks were identified and the maximum of diagonal and flexural crack openings were measured thanks to a magnifying glass with micro graduation.

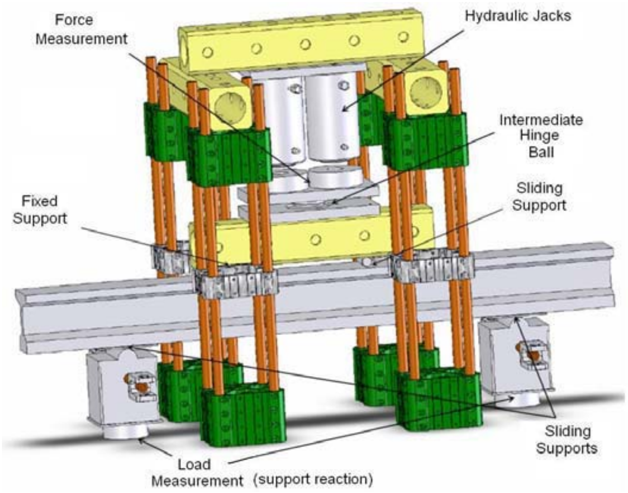

Figure 3. Overview of the specimen under four point bending test.

For all specimens, the instrumentation included fifteen LVDT sensors: five to capture the vertical deflection of the girder (two of them are used to identify the settlement on support), six to measure the diagonal cracks opening and three at midspan of the beam to identify the linear strain diagram within the constant bending Moment zone. Additionally, two rosettes (one for each shear span) were attached to obtain principal strains direction.

For beams with passive longitudinal reinforcement and with stirrups, strain gauges were attached to measure strain in every second stirrup at the center of web, in each shear span. Locations of the strain gauges and reference number of stirrups are shown in Figure 4.

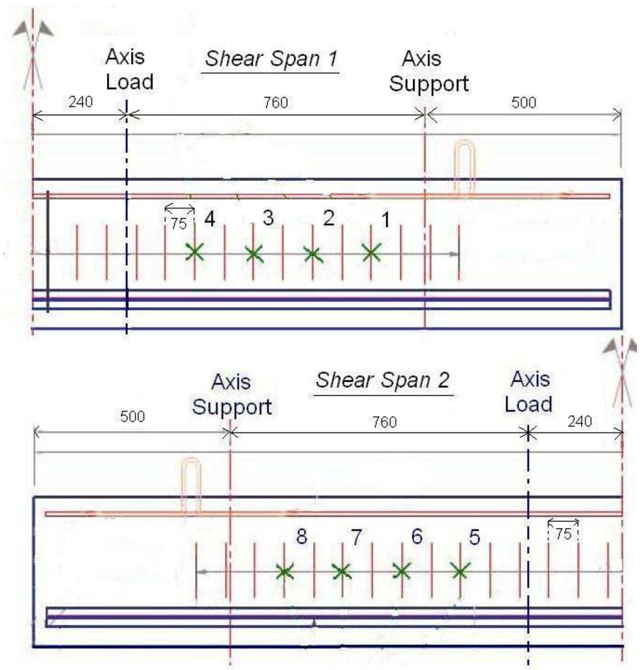

Figure 4. Locations and reference number of stirrups on which strain gauges were attached. (Dimensions in mm).

The strain gauges had been glued before casting. The Vishay AE10 type glue had been heated to ensure correct bond even after concreting and heat treatment.

3 RESULTS AND DISCUSSION

Figures 5-6 show the experimental load-deflection curves for prestressed and reinforced beams, respectively.

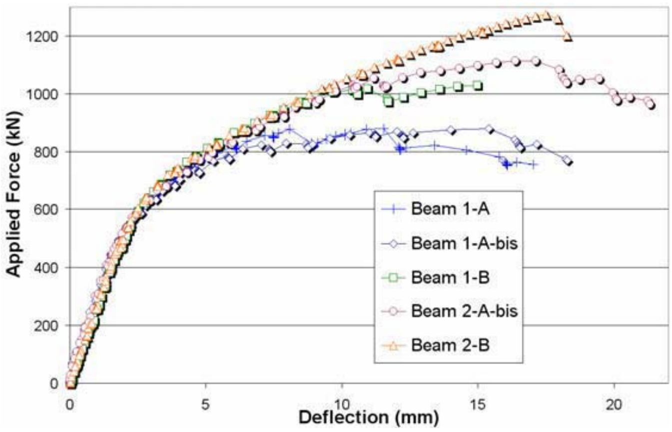

Figure 5. Load-deflection curves of prestressed beams.

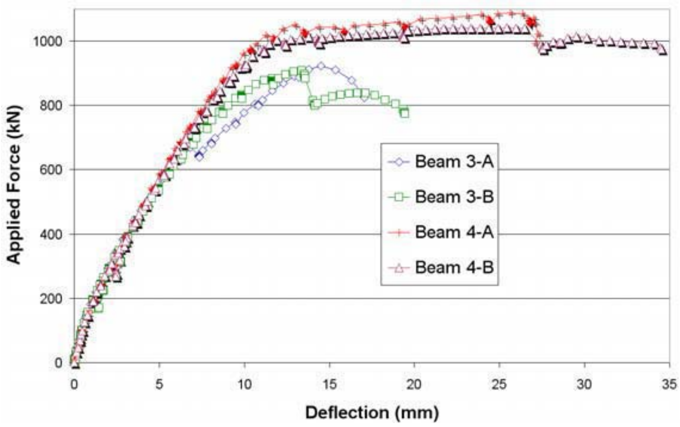

Figure 6. Load-deflection curves of reinforced beams.

Despite they were fabricated with a different batch, the behaviour of beams 1-A and 1-A-bis were very similar with approximately the same ultime load.

Except beams with passive longitudinal reinforcement and with stirrups, all specimens have failed in shear, exhibiting a largely opened diagonal tension crack (Figs 7-8-9-10).

Figure 7.Shear failure of Beam 1-B.

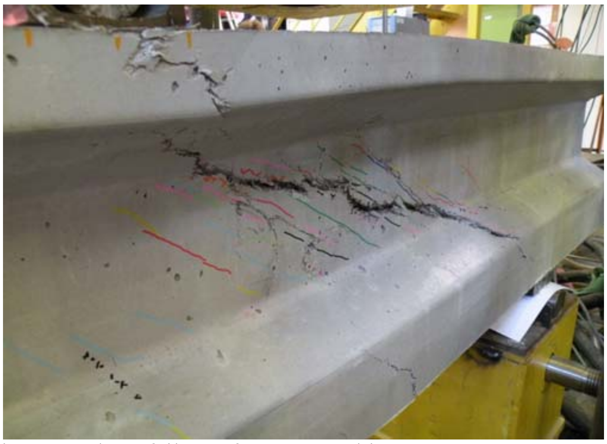

Figure 8. Shear failure of Beam 2-A-bis.

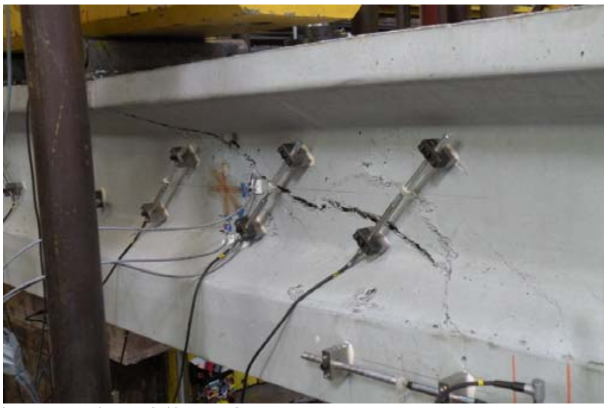

Figure 9. Shear failure of Beam 3-A.

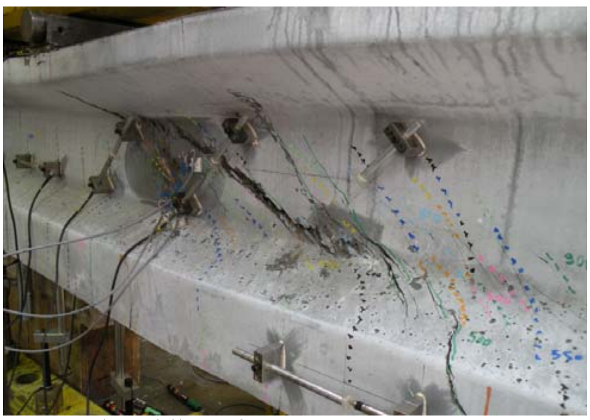

Figure 10. Shear failure of Beam 3-B.

Concerning beams 4-A and 4-B, they failed in bending but with large openings of diagonal cracks which indicate that the maximum load applied was close to the ultimate shear capacity. Figure 11 shows, for beams 4-A and 4-B, the displacements measured by LVDT sensors which were fixed at 45° on the web. The measure of stirrups strain confirms occurrence of yielding of some shear reinforcements (Figs 12-13). The maximum experimental load applied on beams 4-A and 4-B can thus be considered as a lower bound estimate of the shear resistance, with reasonably low difference.

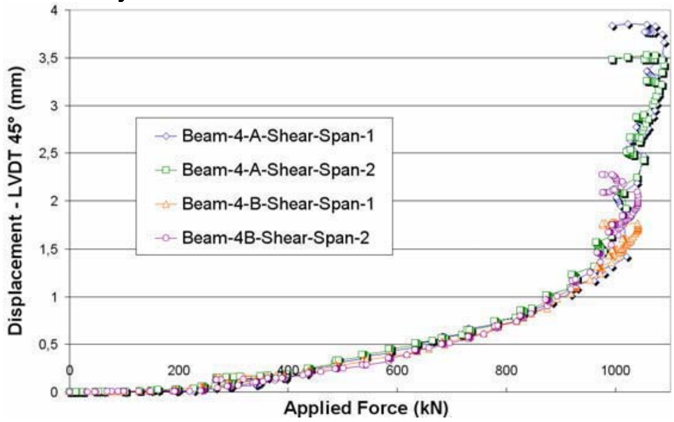

Figure 11. Displacement measured by LVDT sensors fixed at 45°- Load curves of reinforced beams with stirrups.

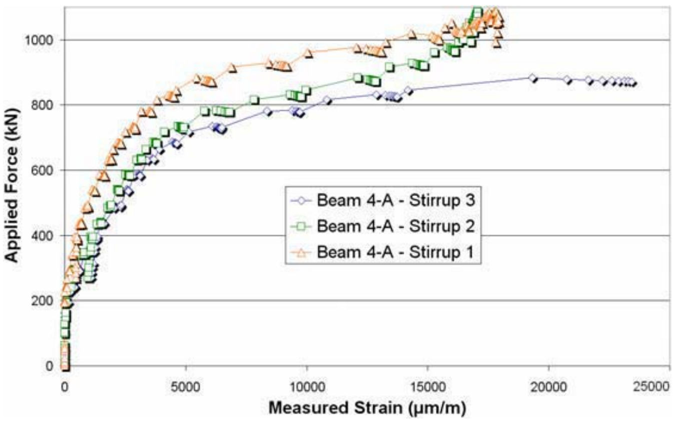

Figure 12. Strain development in stirrups for beam 4-A.

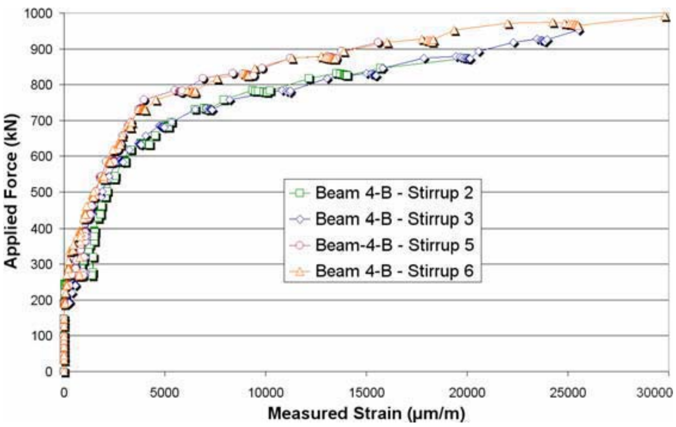

Figure 13. Strain development in stirrups for beam 4-B.

From the designer's point of view, all the results are compared (Tab. 3) with the theoretical shear strength prediction obtained with the French AFGC Recommendations on UHPFRC (1).

$$V_{ult} = V_{rb} + V_a + V_f \qquad (1)$$

V_{rb} is the term for the contribution of the concrete,

V_a is the term for the contribution of the stirrups,

V_f is the term for the contribution of the fibres.

- *For reinforced concrete:*

$$*V_{rb} = 0.21 \cdot k \cdot \sqrt{f_{cj}} \cdot b_0 \cdot d$$

$$k = 1 + \frac{3 \cdot \sigma_{cm}}{f_{tj}} \text{ in compression}$$

$$k = 1 - \frac{0.7 \cdot \sigma_{tm}}{f_{tj}} \text{ in tension}$$

$$*V_a = 0.9 \cdot d \cdot \frac{A_t}{s_t} \cdot f_y$$

$$*V_f = 0.9 \cdot d \cdot b_0 \cdot \sigma_p$$

- *For prestressed concrete:*

$$*V_{rb} = 0.24 \cdot \sqrt{f_{cj}} \cdot b_0 \cdot z$$

$$*V_a = z \times \frac{A_t}{s_t} \times f_y \times \cot an\beta_u \text{, avec } \tan \beta_u = \frac{2 \cdot \tau_u}{\sigma_{cd}}$$

$$*V_f = b_0 \cdot z \cdot \sigma_p \cdot \cot an\beta_u$$

- With :

b_0 web width

d efficient depth of the longitudinal reinforcement

z lever arm of internal forces

f_{cj} compressive strength

τ_u ultimate shear stress

σ_m mean stress in the total section of concrete under the normal design force.

σ_{cd} design value of the normal concrete stress in the centre line

σ_p concrete post cracking tensile strength

f_y yield strength of stirrups

A_t cross sectional area of the stirrups

s_t spacing of shear reinforcement

All Material Safety factors have been taken equal to 1 in equation (1) for purpose of design provision validation.

Material input data have not been again completely identified. Thus quantitative assumptions have been made for the stirrups force at yielding (f_y = 600 MPa compared with the characteristic value f_y = 500 MPa), the concrete compressive strength (f_c=185 MPa) and for the post cracking tensile strength σ_p. This latter value has been taken equal to 10 MPa for both concrete mixes, referring to previous results of characterization tests realized for concrete A and B. Concerning prestressed beams, the angle of struts (β_u) has been determined by iteration.

According to these experimental results, the approach proposed by the French recommendations is conservative in all cases. The safety factor on the maximum applied load ranges from 1.35 to 1.61 for prestressed beams and from 1.76 to 1.97 for reinforced beams.

Table 3. Comparison of experimental and theoretical results with the French AFGC Recommendations on UHPFRC (eq. 1)

Specimen	Type of failure	Maximum experimentally applied force (kN)	Maximum predicted applied force (kN)
Beam 1-A	Shear	883	651
Beam 1-A-bis	Shear	881	651
Beam 1-B	Shear	1031	651
Beam 2-A-bis	Shear	1115	790
Beam 2-B	Shear	1275	790
Beam 3-A	Shear	923	470
Beam 3-B	Shear	910	470
Beam 4-A	Flexure	1089	593
Beam 4-B	Flexure	1042	593

The comparison of ultimate applied load between beams with and without stirrups (beams 2 versus 1, 4 versus 3) shows the possibility to add the stirrups force at yielding and the post-cracking fibres contribution in the theoretical estimate of the ultime shear resistance. Namely for prestressed specimens, the contribution of shear reinforcement is approximately similar for beams fabricated with concrete mix A and B, close to 240 kN while the theoretical value is 139 kN. Concerning reinforced specimens, the experimental contribution of stirrups is equal to 166 kN and 132 kN for beams in concrete mix A and B respectively, which is close to the theoretical value 123 kN.

At serviceability limit state, stirrups contribution on the control of cracking is significant. Figures 14-15 represent the evolution of displacements measured by LVDT sensors attached at 45° versus the applied force. After the first development of diagonal cracks (at an applied force equal to 350 kN for prestressed beams and 210 kN for reinforced specimens), for the same load the cumulated crack openings are significantly less important in presence of stirrups.

This confirms a synergy of fibres and stirrups for the control of crack opening.

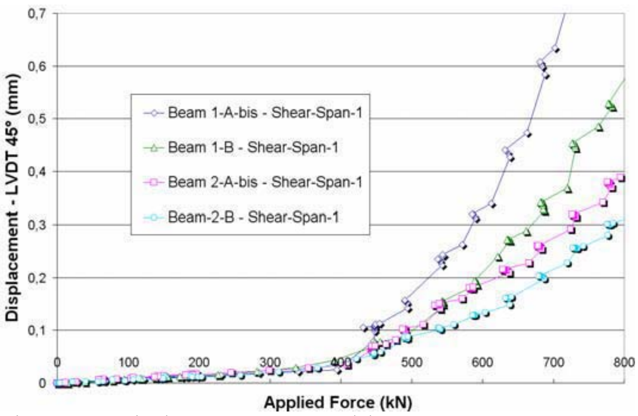

Figure 14. Displacement measured by LVDT sensors at 45°- Load curves of prestressed beams with and without stirrups.

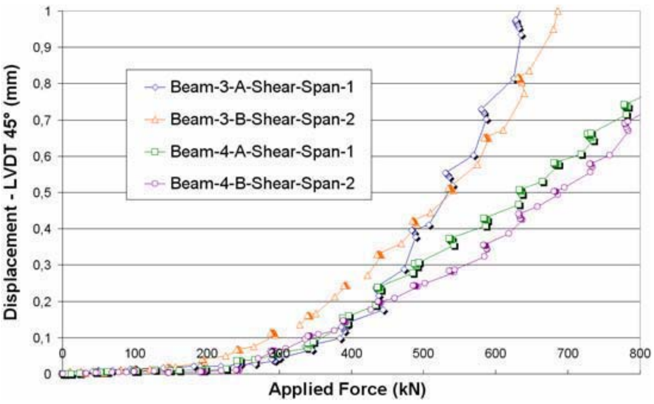

Figure 15. Displacement measured by LVDT sensors fixed at 45°- Load curves of reinforced beams with and without stirrups.

4 CONCLUSIONS AND FURTHER INVESTIGATIONS

Shear tests have been realized in a Four-Point Bending configuration on nine prestressed or reinforced UHPFRC I-shaped beams with two types of shear reinforcement: fibres and combination of stirrups and fibres.

The results of the experimental campaign help draw following conclusions:

- The presence of stirrups has increased the shear capacity of prestressed and reinforced beams.
- The possibly negative effect of combination of fibres and passive shear reinforcement due to the fibre blockage has been avoided thanks to reinforcement arrangement.
- For theoretical evaluation of ultimate shear strength, it has been demonstrated as conservative to add the stirrups force at yielding and the post-cracking fibres contribution.
- Before yielding, passive shear reinforcements can help to control the crack opening.

These shear tests will be further analyzed thanks to a complete materials characterization including following experimental investigations:

- The tensile strength of UHPFRC will be established for each batch with four point bending tests on prisms 7cm*7cm*28cm.
- The concrete post cracking tensile strength will be identified using three point bending tests on notched prisms 7cm*7cm*28cm and inverse analysis.
- The yield strength of stirrups will be determined thanks to direct tensile tests.

In order to identify the contribution of "concrete" itself and of the fibres in the ultimate shear strength as detailed in AFGC provisions, two types of complementary investigations have been undertaken:

- Two beams with the same configuration of beams 3 (similar cross-section and passive reinforcement but without steel fibres or with organic fibres) have been manufactured. These beams will be tested with the same loading setup as the other specimens in order to experimentally identify the "concrete term" in the ultimate shear strength.
- In both extremities (which have not been damaged) of the beams, prisms will be cut horizontally, vertically and at 45° to determine the real "coefficient of orientation" K, thus the "real" contribution of fibres.

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