SEISMIC DUCTILITY OF UHPFRC COLUMNS: SOME RESULTS

Pierre Marchand (1), Florent Baby (1), Grégory Généreux (2), Alain Simon (3), Wafae Mazighi (3), Jean-Paul Deveaud (2), Jean Ernult (2), Philippe Rivillon (4), François Toutlemonde (1)

(1) UPE-Ifsttar, Paris, France

(2) CEREMA, France

(3) Eiffage, France

(4) CSTB, France

Abstract

Within the French joint Research consortium BADIFOPS, nine longitudinally-reinforced UHPFRC columns with a rectangular cross-section and various ratios of transverse reinforcement were tested under combined axial and repeated or alternate transverse loading. Moreover, three composite columns consisting of UHPFRC-jacketed conventional reinforced concrete cores at their basis were tested following the same protocol, as well as a conventional reinforced concrete companion specimen. The global ductility of the columns can be derived from their bending moment vs. transverse displacement response for different applied axial loads. Details of the experimental program carried out are given.

Résumé

Dans le cadre du projet de recherche français BADIFOPS, neuf poteaux en BFUP de section rectangulaire armés longitudinalement ont été testés sous un chargement constitué d'une compression axiale et d'une flexion alternée ou répétée. En outre, trois poteaux en béton armé renforcés par un chemisage en BFUP à leur encastrement ont été testés de manière similaire et comparés avec un poteau de référence sans chemisage. La ductilité globale des poteaux peut être déduite des courbes moment – flèche obtenues pour différentes valeurs d'effort axial. L'article présente le programme d'essais réalisé et les principaux résultats.

1. INTRODUCTION

Use of UHPFRC in the context of earthquake-resistant structures deserves research efforts to demonstrate which contribution to ductility can be provided by the fibre-reinforced material, so that a safe combination of steel reinforcement and fibers is determined with respect to the ductility demand. Within the French R&D consortium BADIFOPS, this issue was addressed especially for columns, due to their critical role in the provision of possible plastic hinges at their connection to floors, deck or foundation, when designing the earthquake resistant structural frame of a structure [1].

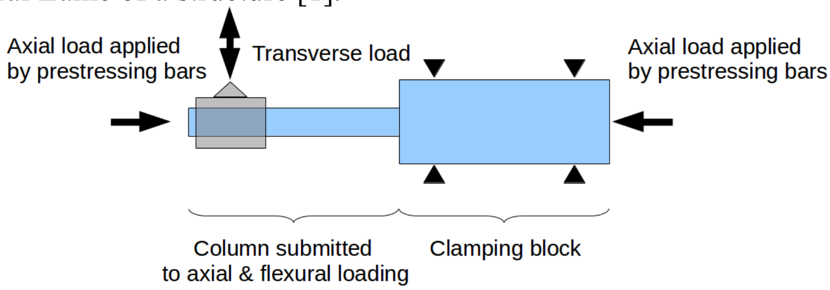

Figure 1: Test principle

Principle of the tests carried out follows the principle shown in Figure 1. The column is tested horizontally. Axial (horizontal) load is held constant while the column is submitted to flexural loading. The flexural loading is generated by a transverse (vertical) load applied in the vicinity of the top of the column. This transverse load can be applied always downward (repeated protocol) or alternatively upward and downward (alternate protocol).

2. TESTED SPECIMENS

2.1 Jacketed reinforced concrete columns

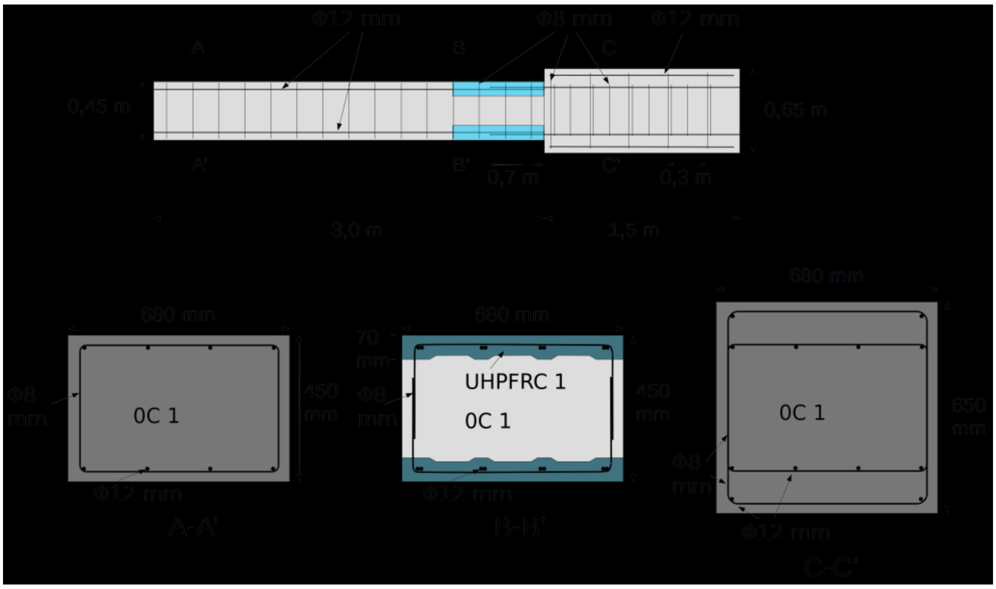

Figure 2: Longitudinal and transverse sections of jacketed columns

Table 1: Mechanical characteristics

	OC1	OC2	UHPFRC 1 (without pp fibers)	UHPFRC 2 (with pp fibers)
f_{cm} (MPa)	55,5	43,5	222,5	220,2
Poisson's ratio	0,21	/	/	0,22
f_{ctm} (MPa) – splitting tensile strength	/	3,0	/	/
$f_{ctm,el}$ (MPa)	/	/	14,5	14,0
σ(w = 0,3 mm) (MPa)	/	/	15,3	14,3

Three jacketed columns and one companion non jacketed companion column were fabricated. The columns were 3 m long and were embedded in a footing. Column and footing were cast at the same time. The specimens were designed to be representative of old French bridges with wall-shaped piers designed for non seismic areas. The design was inspired by the rules for current bridges piers from 1973 [2]. The UHPFRC jacketing could represent a strengthening technique for such columns due to consideration of an increasing seismic risk.

Used materials are ordinary concrete n°1 and UHPFRC n°1 (see Table 1 for material mechanical characteristics). Parts of columns made of ordinary concrete have been cast first. A recess for casting UHPFRC has been created using polystyrene elements. UHPFRC has been cast secondly in the lap zone between rebars of the footing and rebars of the column as described in Figure 2. Compared to ordinary concrete, the UHPFRC should enable to reduce the lap length and avoid spalling. These columns were tested with an axial load of 612 kN, corresponding to a longitudinal stress of 2 MPa (see Table 2).

2.2 UHPFRC columns with longitudinal rebars

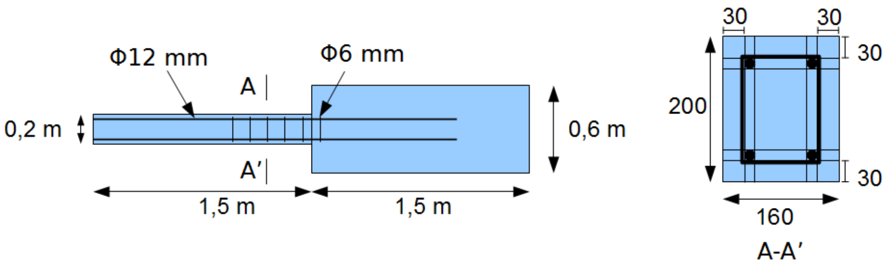

Figure 3: Longitudinal and transverse sections of UHPFRC specimens

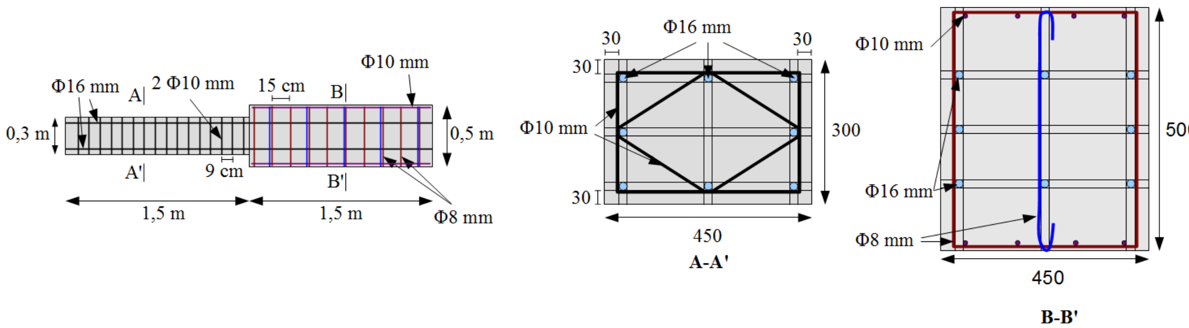

Figure 4: Longitudinal and transverse sections of RC specimen

Nine UHPFRC specimens were fabricated consisting in one column 1,50 m long embedded in a footing. Footing and column were made with UHPFRC (UHPFRC 1 or UHPFRC 2) and cast at the same time. The column is reinforced with 4 longitudinal rebars, 12 mm diameter. Some of the columns comprise shear reinforcements (squared closed link, 6 mm diameter with 12 cm spacing) or not (see Figure 3 and Table 3). One ordinary concrete (OC2) specimen was also fabricated following Eurocode 8 [3] design principle, to compare the ductility of both kinds of structures. The column length is also 1,50 m but the cross section has been enlarged to take the same axial load (see Figure 4). Columns were tested with an axial load of 640 kN or 1120 kN, corresponding to a longitudinal stress of 20 or 35 MPa for the UHPFRC specimens and 8,3 MPa for the ordinary concrete specimen.

2.3 Material mechanical characteristics

The UHPFRC mechanical characteristics were determined according to NF P 18-470 [4] or AFGC Recommendations [5] and according to EN 12390 [6] for ordinary concrete. Characterization tests were made at the same time as the test, namely 2 years and a half after casting. The Table 1 sums up the main mechanical characteristics of ordinary concrete and UHPFRC mixes used. Two kinds of UHPFRC were used, one with polypropylene (pp) fibers and one without.

3. TEST SETUP AND TESTING PROTOCOL

3.1 Test setup

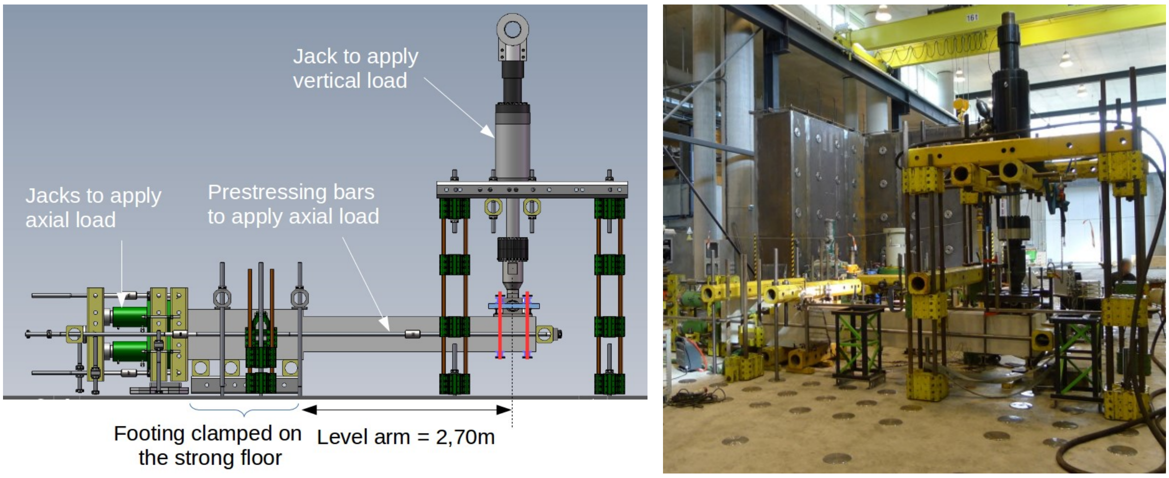

Figure 5: Scheme and picture of test rig for 3m long column specimens

Figure 5 shows a scheme and a picture of the test setup used for specimens with 3 m long column. In this latter case, the lever arm between the maximum moment section at the junction of the column with the clamping block (footing) and transversal load axis is 2,70 m. In the case of the specimens with a 1,50 m long column, the level arm is reduced to 1,20 m.

3.2 Testing protocol

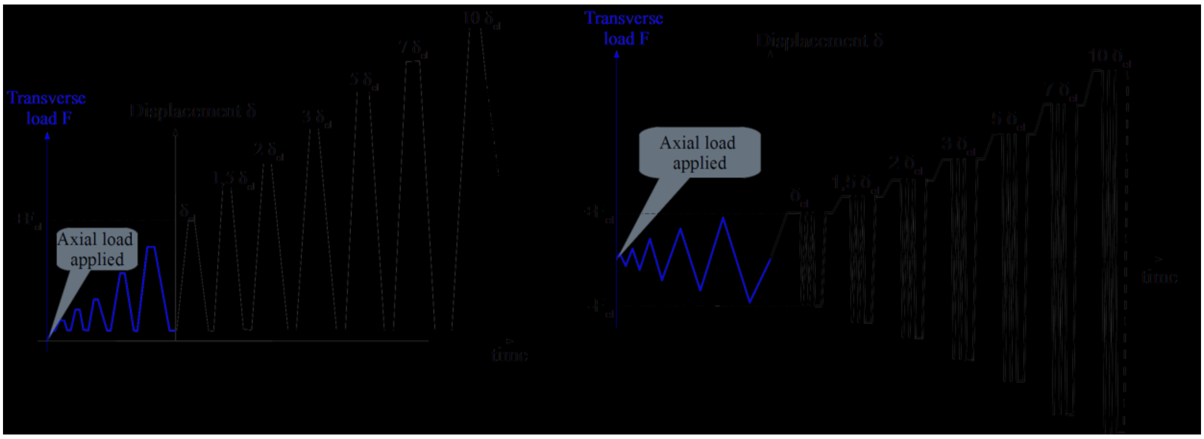

Figure 6: Loading procedure for repeated protocol (left) and alternate protocol (right)

Axial load is applied first. Then the vertical jack applies a transverse (vertical) load to create a bending moment which is maximum at the foot of the column. The vertical jack is first controlled in force until the theoretical elastic force is reached, then for safety reasons the vertical jack is controlled in displacement as shown in Figure 6.

3.3 Tested specimens

Table 2 details the tests carried out for 3 m long column specimens. The varying parameters influencing the results are the jacketing or not of the column as well as the kind of test protocol (repeated or alternate).

Table 2: Tested specimens with column length = 3 m

Specimen n°	Axial load (MN)	Shear reinf.	UHPFRC jackets	Materials used	Test protocol
1	0,612	Yes	Yes	OC1 and UHPFRC 1	Repeated
2, 3	0,612	Yes	Yes		Alternate
4	0,612	yes	No	OC1	Alternate

Table 3 sums up the tests carried out for 1,5 m long column specimens. For these kinds of specimens, the varying parameters are the axial load (0,64 MN or 1,12 MN), the presence or absence of shear reinforcement, and the test protocol (alternate or repeated).

Table 3: Tested specimens with column length = 1,5 m

Specimen n°	Axial load (MN)	Shear reinf.	Materials used	Testing protocol
Ref OC	1,12	Yes	OC 2	Alternate
2	1,12	Yes	UHPFRC2	Repeated

Specimen n°	Axial load (MN)	Shear reinf.	Materials used	Testing protocol
1, 9	1,12	Yes	UHPFRC2 (UHPFRC1 for n° 9)	Alternate
7	1,12	No	UHPFRC2	Alternate
3	0,64	Yes	UHPFRC2	Repeated
6, 10, 4	0,64	Yes	UHPFRC2 (UHPFRC1 for n° 10)	Alternate
11	0,64	Yes	UHPFRC 1	Alternate

4. RESULTS

4.1 Determination of bending moment

Since the axial force is applied at the extremity of the column through prestressing bars, bending moment at the footing-column junction depends not only on the transverse force but also on the axial force and transverse displacement as explained in Figure 7.

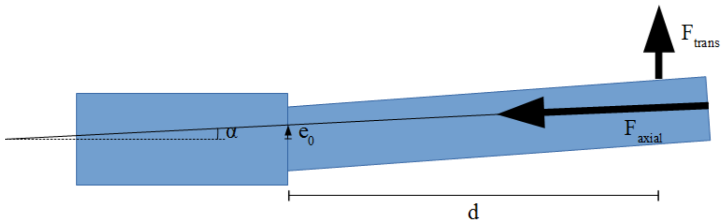

Figure 7: Forces taken into account to determine bending moment at junction footing-column

The expression of bending moment M at the footing-column junction is:

$$M = d * F_{trans} + e_0 * F_{axial} * \cos(\alpha) \approx d * F_{trans} + e_0 * F_{axial} \quad (1)$$

In equation (1), the term $\cos(\alpha)$ is approximated to 1,0. In the case of a small column (1,50 m long) with a high axial load (F_{axial} = 1,12 MN), the term coming from the eccentricity of prestressing bars can become very high and it would be significantly wrong to consider M to be $d * F_{trans}$. In this case, a displacement sensor has been used to measure as accurately as possible the eccentricity of prestressing bars e_0.

4.2 Curves "bending moment – displacement"

Figures 8, 10, 11 and 12 show the column responses in terms of bending moment – displacement curves for the different tested specimens. Whole curves are displayed on the left graphs and "envelope curves" comprising only extremum point of each loading cycle are displayed on the right graphs.

Figure 8 shows the curves for the jacketed reinforced concrete columns and companion non jacketed column (specimen n°4) and Table 4 gives some test values. The curves show that the jacket does not modify the ductility of the specimen. Conversely to [7], there is no positive influence of the UHPFRC jacket on seismic behaviour. Indeed, the longitudinal reinforcement ratio is much lower in our case than in [7]. The UHPFRC jacket improves significantly the behaviour under compression (less damage in compression for the jacketed specimens than for non jacketed specimens), but the rebars failure occurs approximately for the same load and for slightly lower displacement (see Figure 9 and Table 4). Such a retrofitting seems to be much more relevant in case of a high longitudinal reinforcement ratio.

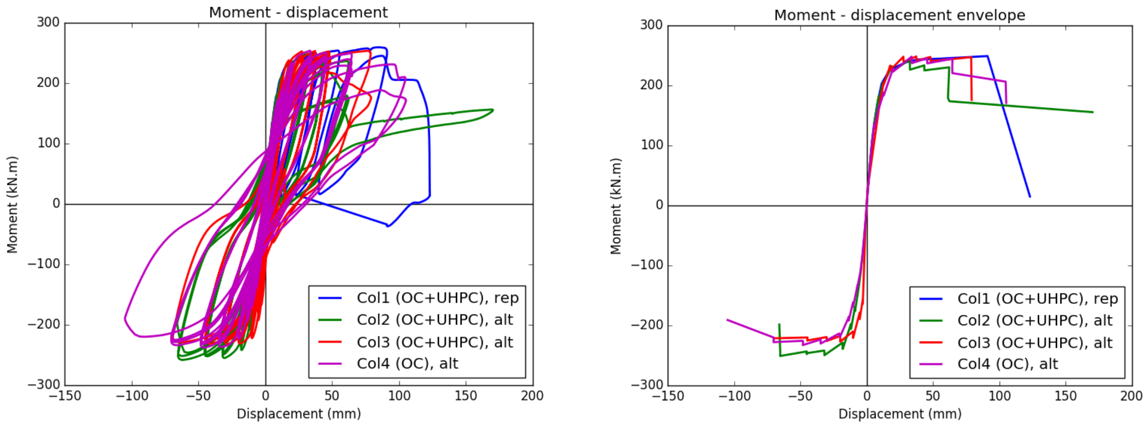

Figure 8: Moment – displacement curves for columns jacketed (1, 2, 3) or not (4)

Figure 9: View of specimens col 2 (OC + UHPFRC) and col 4 (OC) after test

Table 4: Main results for 3 m long column specimens

Specimen	Mmax* (MN.m)	δ_u (mm) at failure	Failure
Col1	85,4	123,1	Rebars failure
Col2	87,1	63,2	Rebars failure
Col3	84,9	74,1	Rebars failure
Col4	84,0	105,0	Rebars failure

* Mean value between Mmax and Mmin when alternate cycles are applied.

Figures 10 and 11 display the behaviour of UHPFRC columns under an axial load of 1,12 MN and 0,64 MN, respectively and Figure 12 displays the behaviour of the RC column under an axial load of 1,12 MN. Table 5 gives some figures of interest. We can see that UHPFRC columns can hold the load during many cycles. However the bending moment decreases significantly during the cycles, compared to the ordinary concrete specimen.

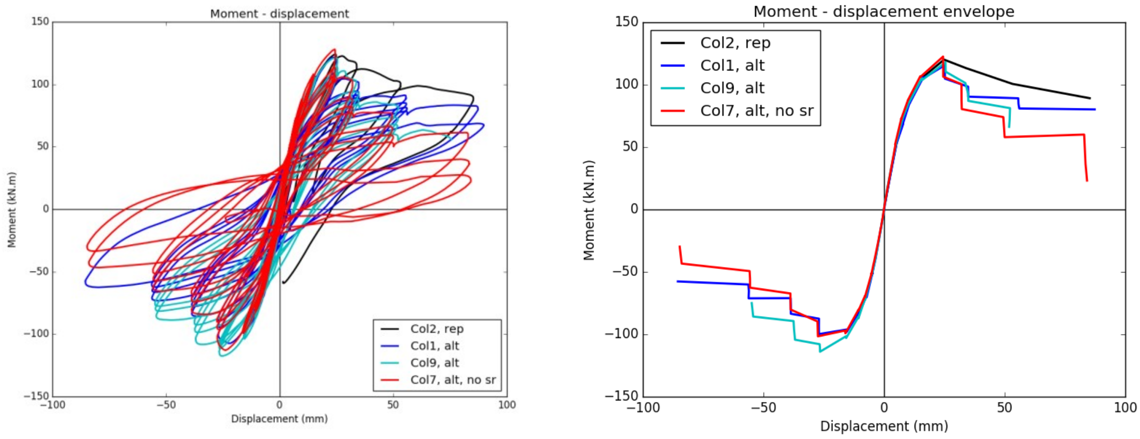

Figure 10: Moment-displacement curves for UHPFRC columns with high axial load (1,12 MN)

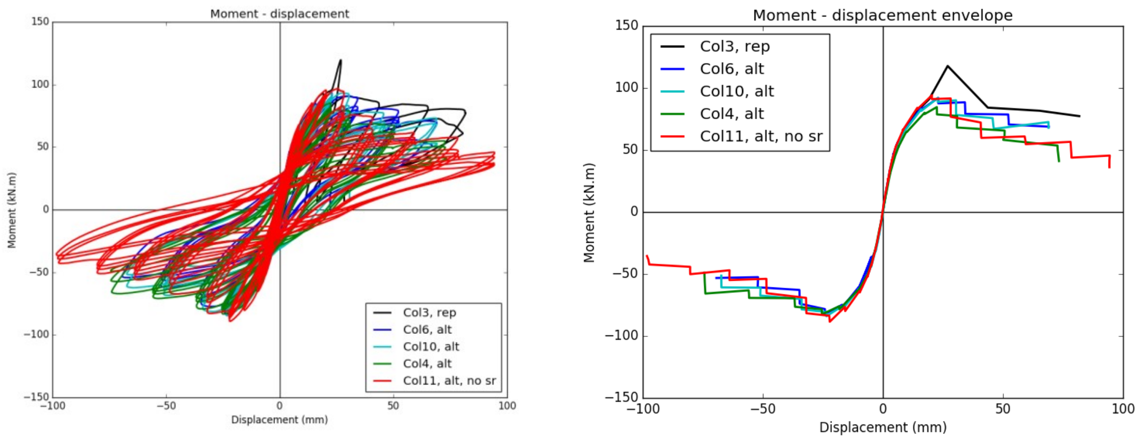

Figure 11: Moment – displacement curves for UHPFRC columns with low axial load (0,64 MN)

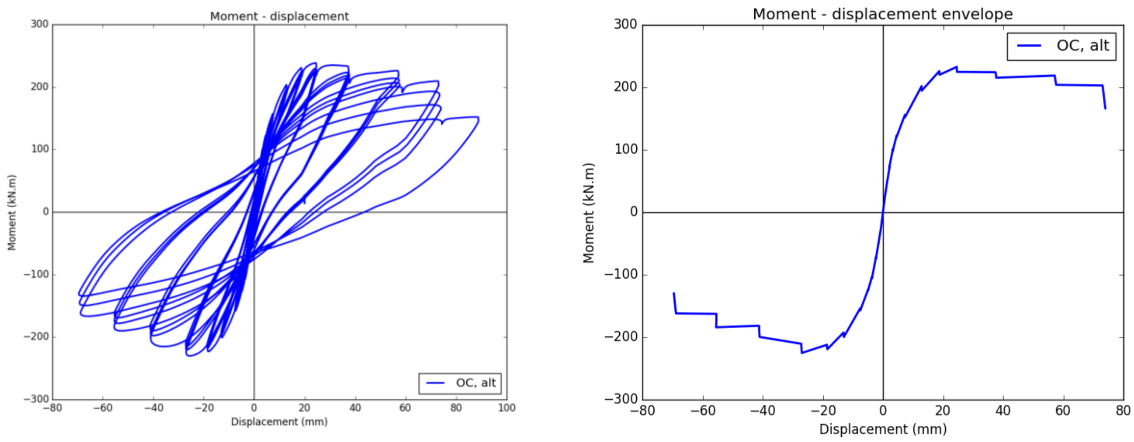

Figure 12: Moment – displacement curves for RC column (ref OC)

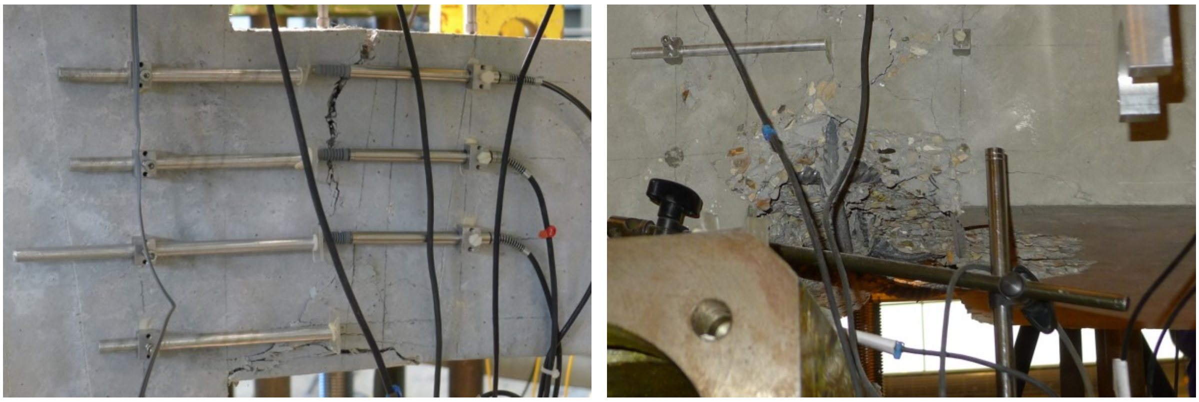

Figure 13: View of specimens col 2 (UHPFRC) and "ref OC" after test

This decrease of the resisting bending moment is due to the fibres torn-off as the cycles amplitudes increase. It is relatively lower in the case of the lower axial load (0,64 MN, that is 20 MPa average axial stress). In the case of the higher axial load, the presence of shear reinforcement seems to improve the behaviour (the decrease of bending moment is steep). As concerns the compressive behaviour, the UHPFRC behaves very good under the repetition of cycles. The loss of concrete around rebars is very limited compared to the ordinary concrete specimen (see Figure 13).

Table 5: Main results for 1,5 m long column specimens

Specimen	**Mmax* (MN.m)**	**δ_u** (mm)**	**Failure**
Col1	107,7	55,8	Stop before failure
Col2	120,1	85,3	Stop before failure
Col3	Not measured	81,8	Rebars failure
Col4	83,5	53,2	Rebars failure
Col6	87,1	52,1	Rebars failure
Col7	112,0	68,3	Compression
Col9	115,9	53,2	Compression
Col10	88,0	66,6	Compression
Col11	91,3	68,8	Rebars failure
Ref OC	229,0	70,9	Stop before failure

* Mean value between Mmax and Mmin when alternate cycles are applied.
** Mean value between δmin and δmax when M becomes ≤ 0,8 Mmax

5. CONCLUSIONS

Repeated and alternate bending tests of UHPFRC columns and RC columns strengthened with UHPFRC simultaneously subjected to axial load have been carried out, providing useful background data for improvement of UHPFRC structural seismic design (cf Annex U of [8]).

From a first analysis of these test results, it can be concluded that:

- The UHPFRC jacket improves significantly the behaviour of concrete in compression. But since the failure is governed here by the longitudinal rebars failure, the impact on seismic behaviour and ductility is relatively limited compared to non jacketed specimens. Consequently, the UHPFRC jacket is not appropriate to a seismic retrofitting of the current old French bridges with wall-shaped piers. Such a retrofitting would rather be more appropriate for columns with higher longitudinal reinforcement ratios.
- The UHPFRC columns show a good ductility in the sense that they can hold the axial load during many cycles. However, the bending moment decreases relatively quickly during the cycles due to the fibres which are torn off progressively. Nevertheless, the behaviour under compression seems to be very good under the succession of alternate cycles.

ACKNOWLEDGEMENTS

The works detailed in this paper were carried out within BADIFOPS research project, aiming at developing ductile solutions of UHPFRC structures for earthquake-resistant applications, where optical fibers for reinforcement strain monitoring has been fruitfully applied. BADIFOPS is a French-State sponsored project (2011-2014) within "Design and Build for Sustainable Growth" program of the Civil Engineering Department Unit of the Ministry in charge of Sustainable Growth (ref grant 10 MGC S010). Partners are Eiffage Company, CSTB (Research Center for Buildings), Ifsttar (Public Works Research Institute) and Sétra, now CEREMA (Highways Agency).

REFERENCES

[1] Toutlemonde F., Chenaf M., Deveaud J.-P., Genereux G., Moreira Fernades Luis N., Simon A. (2016) *UHPFRC application in plastic hinges for seismic design: three examples*, HiPerMat, 4th int. symp. on Ultra-High Performance Concrete and High Performance Construction Materials, Kassel (Germany), March 9-11, 2016

[2] Sétra, 'Piles et Palées – Appuis des tabliers continus – P. P. 73', Ministère de l'Equipement et du Logement, 1973

[3] AFNOR, NF EN 1998-1, 'Eurocode 8 - Design of structures for earthquake resistance - Part 1 : general rules, seismic actions and rules for buildings'

[4] AFNOR, NF P 18-470, 'Concrete - Ultra-high performance fibre-reinforced concrete - Specifications, performance, production and conformity', 2016

[5] AFGC, Ultra High Performance Fibre-Reinforced Concretes, recommendations, 2013

[6] EN 12390, Testing hardened concrete

[7] Massicotte B., Dagenais M.A., Lagier F. 'Performance of UHPFRC jackets for the seismic strengthening of bridge piers, in 'RILEM-fib-AFGC Int. Symposium on Ultra-High Performance Fibre-Reinforced Concrete'', UHPFRC 2013, October 1-3, 2013, Marseille, France

[8] AFNOR, NF P 18-710, 'National Addition to Eurocode 2 – Design of concrete structures : specific rules for ultra-high performance fibre reinforced concrete (UHPFRC)', 2016