PERFORMANCE OF UHPFRC JACKETS FOR THE SEISMIC STRENGTHENING OF BRIDGE PIERS

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Abstract

The paper presents the results of an experimental program aimed at developing an innovative seismic strengthening technique using UHPFRC jackets to eliminate splitting failure mode in splice regions with deficient reinforcement details. The testing program included direct tensile tests on lapped bars, monotonic and cyclic tests on beams, and cyclic tests on four large-scale rectangular bridge piers with cross-sectional aspect ratios of 2:1.

The bridge pier cyclic test results led to the following conclusions for unconfined 24 d_b long lap splices: 1) UHPFRC jackets allow eliminating the splitting failure mode; 2) drift ductility ratio up to 8 were obtained without any strength reduction for bars up to 45 mm in diameter; 3) longitudinal bar buckling failure mode was eliminated for 300 mm stirrup spacing. The results of the project also suggest that this technique could be applied at other locations where reinforcement details are inadequate. The technique allows keeping the column initial dimension and can also be used for any column shape

Résumé

Cet article présente les résultats d'un programme expérimental dont l'objectif est de développer une méthode de renforcement sismique par chemisage en BFUP afin d'éliminer la rupture par fendage de joints de chevauchement ayant des détails d'armatures déficients. Le programme expérimental inclut des essais de traction directe de joints de chevauchement, des essais monotones et cycliques sur poutres ainsi que des essais cycliques sur piliers de ponts à grande échelle dont la section est fortement rectangulaire.

Les résultats des essais cycliques sur piliers de ponts ont conduit aux conclusions suivantes pour un joint chevauchement d'une longueur de 24 d_b non confinés par étriers transversaux : 1) le chemisage en BFUP permet d'éliminer la rupture par glissement des barres d'armature chevauchées suite au fendage du béton; 2) un niveau de ductilité équivalent à 8 a été obtenu sans diminution de la résistance pour des barres d'armatures jusqu'à 45 mm de diamètre; 3) la rupture par flambement des barres longitudinales a été éliminée pour une configuration d'étriers espacés à 300 mm. Les résultats de ce projet indiquent également que la technique de renforcement proposée pourrait être utilisée à d'autres endroits dans une structure où situe un joint de chevauchement inadéquat. La technique par chemisage en BFUP n'implique pas de surépaisseur et peut être appliquée à n'importe quel type de colonnes.

1. INTRODUCTION

1.1 Vulnerability of existing bridge piers

Observations made following major earthquakes that occurred worldwide in the last four decades showed that lap splice details were often not adequately designed and contributed to the collapse of bridges. A common design practice before the 1970's was to use dowel bars in the footing that were lapped with continuing bars at the bottom of the column (Fig. 1).

Modern design recommendations prohibit lap splices where plastic hinges may form during a severe earthquake. Several solutions have been proposed and applied for strengthening bridge piers. However, most of them were developed for circular and square columns, while very few efficient solutions have been proposed for rectangular columns with a large aspect ratio. As illustrated in figure 2, conventional jacketing solutions, applicable to circular, square or slightly rectangular (b/h ≤ 2) columns, aim at increasing the confinement of the concrete core for eliminating failure modes in lap splice regions, and for providing sufficient shear capacity. However these techniques cannot be easily adapted for rectangular columns with an aspect ratio higher than 2 due to a reduced efficiency or feasibility.
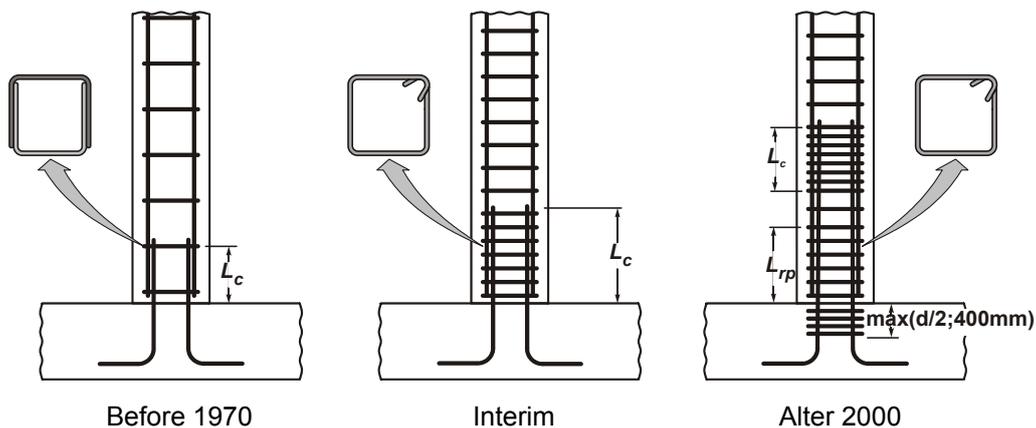

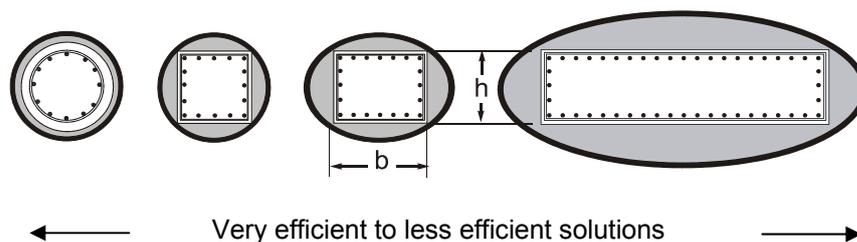Figure 1: Evolution of reinforcement detailing requirements in the Canadian Bridge Code

Figure 2: Conventional retrofitting technique with steel or FRP jackets

1.2 Elimination of splitting cracks

Figure 3 illustrates a typical splitting failure mechanism associated with inadequate lap splice detailing. Splitting cracks may form at the tensile face, as shown in figure 3a, but can also develop in the plane of the reinforcing bars, parallel to the tensile face, as illustrated in figure 3b. Confining techniques eliminate the formation of these cracks by applying compression stresses to the concrete. The approach adopted with the proposed strengthening

technique replaces the brittle concrete in the lap zone by a ductile material that mitigates splitting crack propagation, allowing the load transfer between lapped bars. The use of conventional steel fibre reinforced concrete (SFRC) and ultra high performance fibre reinforced concrete (UHPFRC) has been considered as two potential ductile materials.
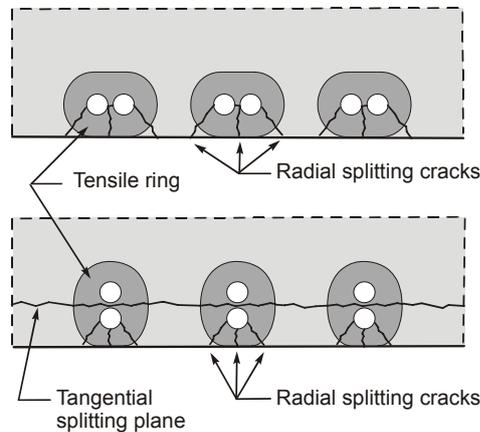
Figure 3: Splitting failure mode in inadequate detailed lap splice

1.3   Scope of the paper

The paper presents the basic principles of the proposed strengthening technique and the experimental program that has been carried out to validate this new technique. Although the main objective is to develop a new solution for strengthening the lap splice of highly rectangular columns, it also applies to any column shape and might be an alternative to conventional jacketing techniques.

2.   STRENGTHENING TECHNIQUE PRINCIPLE

2.1   Proposed retrofitting technique with UHPFRC

A research project was initiated at École Polytechnique de Montreal in 2002 to develop this retrofitting technique for highly rectangular bridge piers. In the first attempt, Vachon [1] used conventional SFRC with 30 mm long hooked-end fibres at 80 kg/m^3. Very satisfactory results were obtained. However, the size of the fibre required thick cover and deep demolition of the existing concrete to expose the lapped bars. The availability of newly developed self compacting UHPFRC by Braike [2] presenting exceptional tensile characteristics allowed further improving the strengthening technique.

The jacketing method considered by Boucher-Proulx [3, 4] was applied on a large scale column with a 4:1 cross-sectional aspect ratio as presented in figure 4. With this concept, the existing concrete cover is removed whereas the dowel bars and the continuing reinforcement are exposed in order to place the FRC cover. The adopted mix contained 240 kg/m^3 (± 3 % by volume) of 10×0.20 mm straight fibres. This mix presents a high workability with a fresh concrete spreading exceeding 700 mm, allowing casting thin elements or covers.

With the proposed strengthening technique, the concrete around the bars in lap splice region is first removed using conventional demolition methods, and is then replaced by self-levelling UHPFRC. This technique allows keeping the original column dimensions and makes it applicable to any column shape.
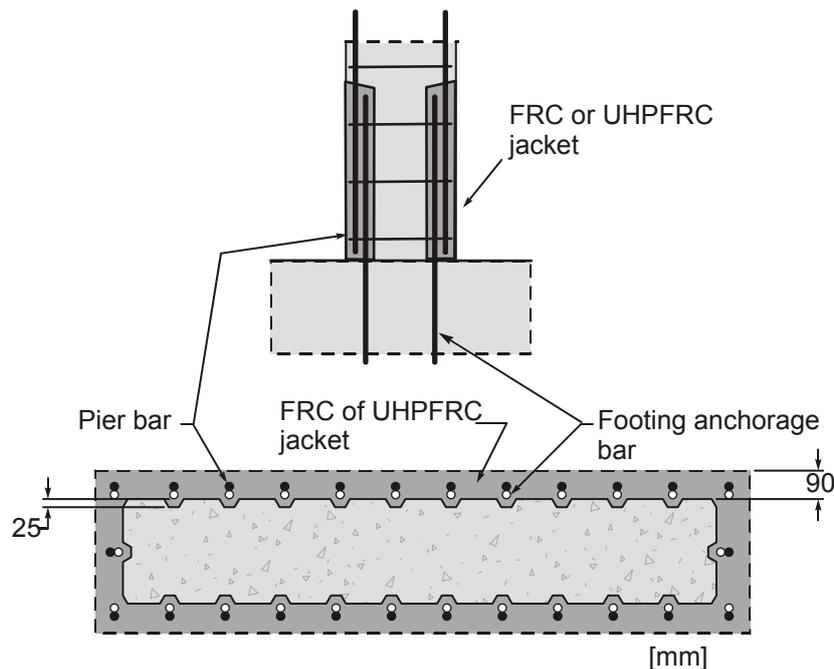
Figure 4: Fibre reinforced concrete jacket [3, 4]

2.2   UHPFRC characteristics

Direct tensile properties measured on dog-bone specimens for different UHPFRC mixes developed at École Polytechnique de Montréal for this project are shown on figure 5. These tensile properties are for well oriented fibres and represent the best expected tensile characteristics. Actual tensile properties in structural elements would necessarily be less due to fibre orientation and mix heterogeneity. For this reason, as it will be seen later, higher fibre contents are preferable in order to have adequate properties.

The selected UHPFRC mix for the columns was the same as Boucher-Proulx [3, 4] and contained 3% by volume of straight steel fibres. It presents strain hardening characteristics in direct tension measured on dog-bone test reaching up to 10 MPa at strains exceeding 2000 $\mu\varepsilon$ (figure 5). The compressive strength typically reaches 120 MPa at 28 days and exceeds 150 MPa after a few months. Preliminary tests on structural elements presented later in this paper, clearly showed the better performance of the 3% mix compared to the 2% one for providing the required performance for lapped bars subjected to cyclic tension-compression loading.

3.   EXPERIMENTAL PROGRAM

The research program included two types of approaches: laboratory testing and nonlinear finite element modeling. This paper deals only with the experimental program which was planned at two scales: the local for transfer mechanism [5] and the structural behaviour [6]. The research program comprises five types of tests:
*   direct tensile tests, for studying the local transfer mechanisms (figure 6);
*   monotonic beam tests, for determining the effect of geometrical parameters (figure 7a);
*   cyclic beam tests, for observing the behaviour without confinement (figures 7b and 8);
*   cyclic uniaxial column tests, for determining the scale effects of the technique (figure 9);
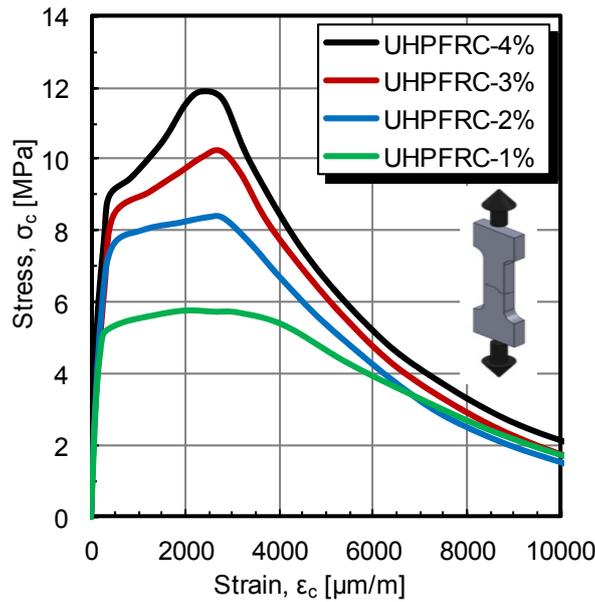*   biaxial cyclic column tests, for validating the concept on actual bridge piers.

Figure 5: UHPFRC direct tensile strength properties [5, 6]

The first 4 test series are completed whereas the last one will be carried out in 2013. Table 1 summarizes the various parameters considered in this experimental program. The direct tensile tests included UHPFRC with fibre contents of 1, 2 and 4% by volume. Most beam specimens and all column specimens were made using 3% by volume of fibres. All beams and bridge pier specimens were built in a precast plant where the UHPFRC was made using conventional mixing equipments. Due to the fluidity of the UHPFRC mix, the fibres in the repaired zone would naturally be oriented horizontally, perpendicular to the lapped bars, which is favourable regarding the strengthening of lap splice joints. Therefore, the tension and beam specimens were fabricated by orienting the fibres perpendicularly to the lap bars to reproduce the same conditions obtained in the column specimens. The results of the 4 types of tests for specimens made with the 25 mm bars are presented in figure 10.

Table 1 – Overview of the testing program

Parameters	Type of tests			
	Direct tension	**Monotonic beams**	**Cyclic beams**	**Cyclic columns**
Number of specimens	20	18	6	4
Fibre volume (%)	1, 2, 4	0, 3	1, 2, 3	3
Bar diameter d_b (mm)	25, 35	25, 35	25, 35	25, 30, 35, 45
L_s/d_b	25mm: 5, 8, 10, 12 35mm: 5, 10, 18	6, 12, 18	25mm: 12 35mm: 18	24
Splice configuration	Lateral	Radial / Lateral	Radial / Lateral	Radial
Repair depth / d_b	1.2	0, 1, 2	1	1

Figure 6: Direct tensile test series

a) Monotonic beam test series   b) Cyclic beam test series
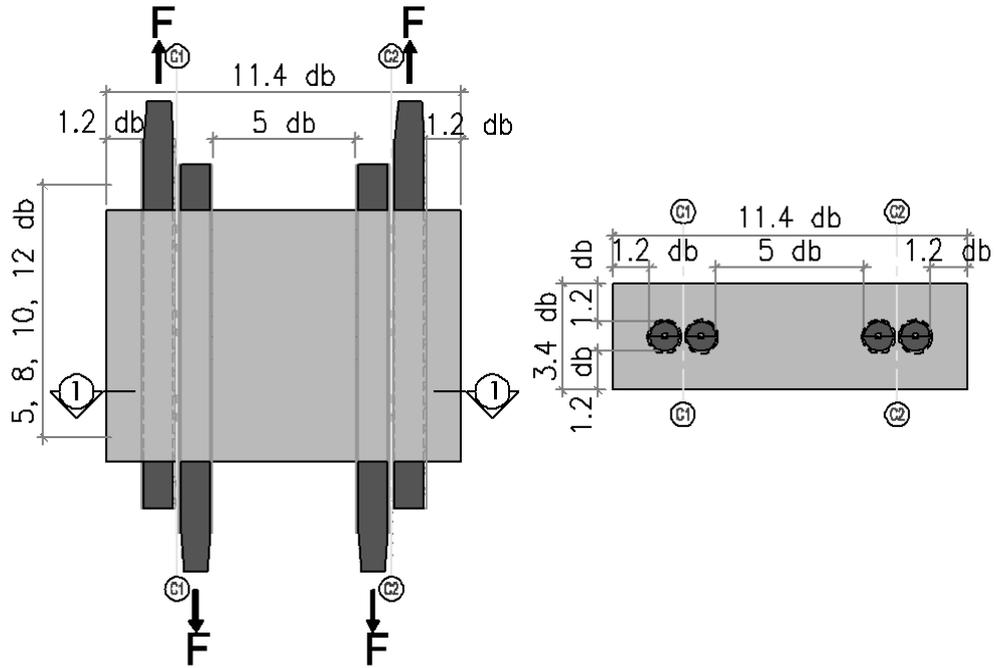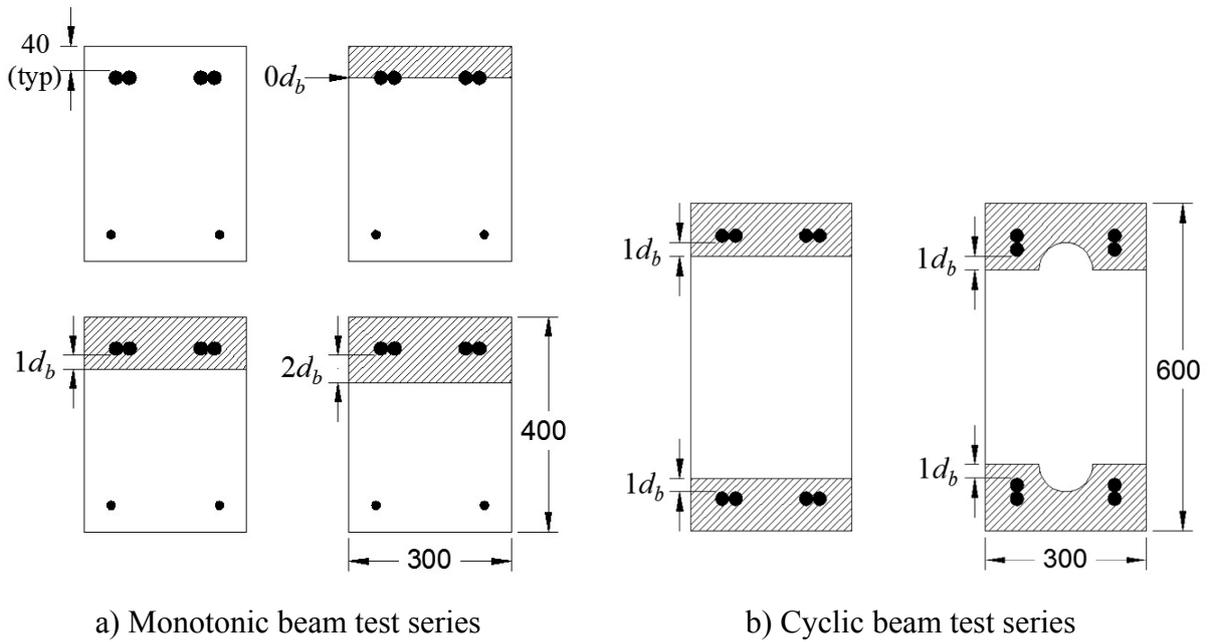
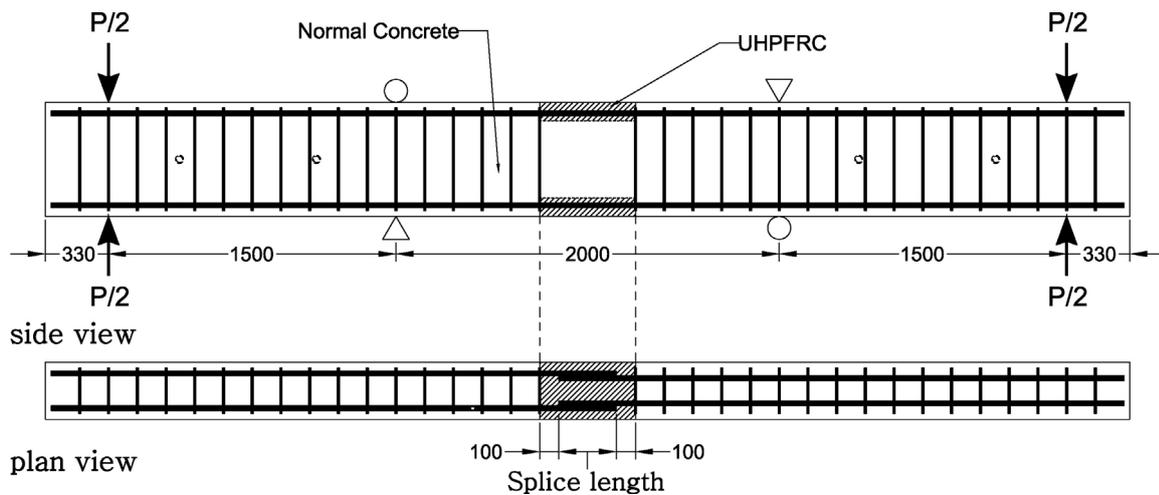Figure 7: Beam test series

Figure 8: Testing set up for the beam test series

4.   RESULTS AND DISCUSSIONS

Figure 10a illustrates the average tensile stress reached in the lapped bars as a function of the normalized lap splice length (l_s/d_b) for all direct tensile tests. The three identical specimens (UHPFRC-4%) with a splice length of 12 d_b led to very similar results, confirming the good repeatability of the experimental setup. From this test series, yielding of rebars was obtained for a lap splice length of only 12 d_b for 4% fibre volume. The influence of the fibre content on the overall strength of lap joints shows the importance of having tensile properties (strength and ductility) sufficient to adequately strengthen lap splices with inadequate lapped length and poor confinement details. Indeed, for a lap splice length of 10 d_b, it was found that the increase in the bar force, increases with the fibre content and is closely linked to the improvement of tensile properties of UHPFRC. Some of the bars had internal strain gauges. These measures enable to determine that relatively uniform bond stresses develop all along the bar [7] showing that UHPFRC behaves has a plastic ductile material.

In term of mode of failure, all specimens failed by the propagation of splitting crack over the lap length in the concrete cover, perpendicular to the axis of splices. Due to bridging effect of fibres, specimen integrity was preserved throughout during the post-peak behaviour, no sudden or brittle failure occurred.

Monotonic tests results of five beams are presented in figure 10b. The specimens had the same dimensions (figure 7a) and were tested in four point bending (figure 8). The reference specimen with normal concrete in the lap zone (R-12-25-L) failed early by splitting of the concrete surrounding the splice region. The other beams were all strengthened with a 3% UHPFRC with different repair depth as shown in figure 7a). The 0 d_b repair depth specimen (0-12-25-L) failed at a low load level with the debonding of the UHPFRC. The beams with 1 d_b and 2 d_b repair depth did not fail and were able to sustain considerable load and high curvature compared to the normal concrete specimen. The splitting failure mode was eliminated in 1-12-25-L, 1-12-25-L1 and 2-12-25-L beams. Similar results were obtained for larger size bars [8].
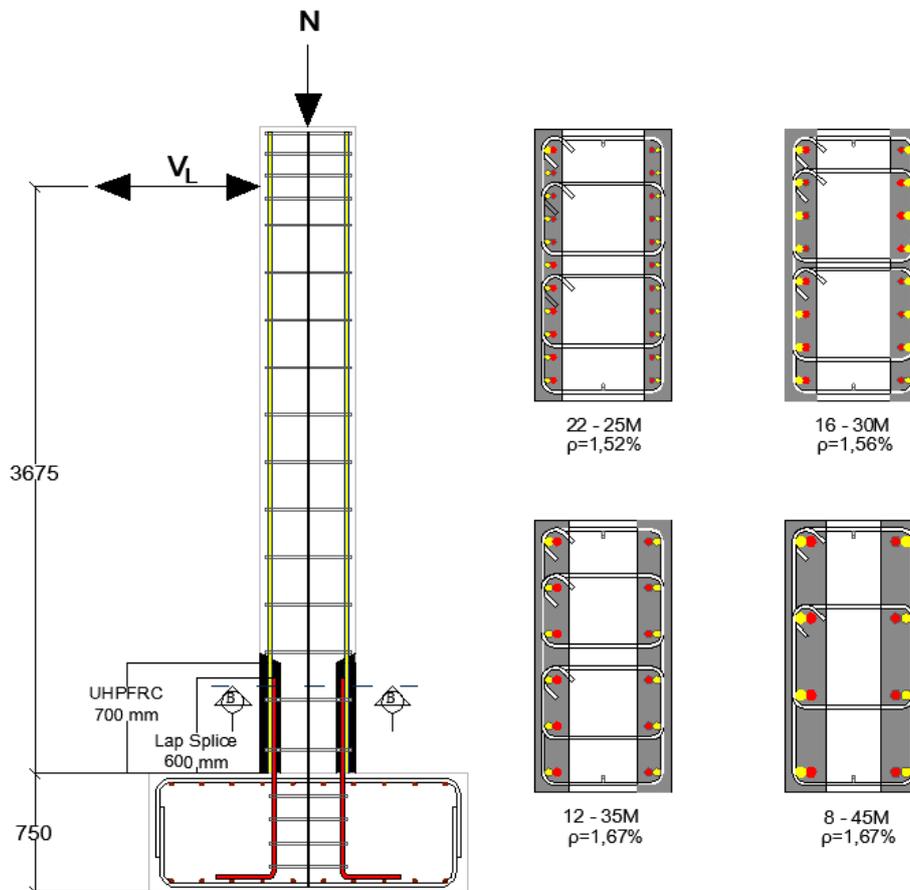
Figure 9: Column test series – Specimen and cross-section geometry

Cyclic test results of one beam are presented in figure 10c. The splice length was 12 d_b on both sides with 25 mm diameter reinforcement as showed in figure 8. The repair configuration details were chosen following the monotonic test series where a 12 d_b repaired splice length was found to be sufficient for 25 mm bars. The beam was able to sustain a total of 19 cycles and reached a ductility level of 5. Failure occurred by splitting of the UHPFRC around the spliced bars.

The repaired column showed in fig. 9 was tested in uniaxial cyclic loading. The results are presented in figure 10d. The splice length of 24 d_b was located at the bottom of the column. A 3 % UHPFRC mix was used for strengthening the lap zone. Concrete was removed 1 d_b behind dowel bars. A vertical load of 1500 kN was applied by hydraulic actuators to simulate the bridge dead load. The specimen is a half scale model of a real bridge. The specimen sustained a total of 24 cycles and reached a ductility ratio of 8. The splitting failure was completely eliminated and only little damage could be observed on the UHPFRC. The column failure occurred by the rupture of the reinforcement in the footing due to low cyclic fatigue. The same behaviour was observed for the specimens containing 30, 35 and 45 mm bars.

Although the transverse reinforcement was spaced at 300 mm, no longitudinal bar bucking was observed. Moreover, there has been no concrete cover spalling and the column integrity was maintained intact throughout the test. The failure was progressive and ductile.
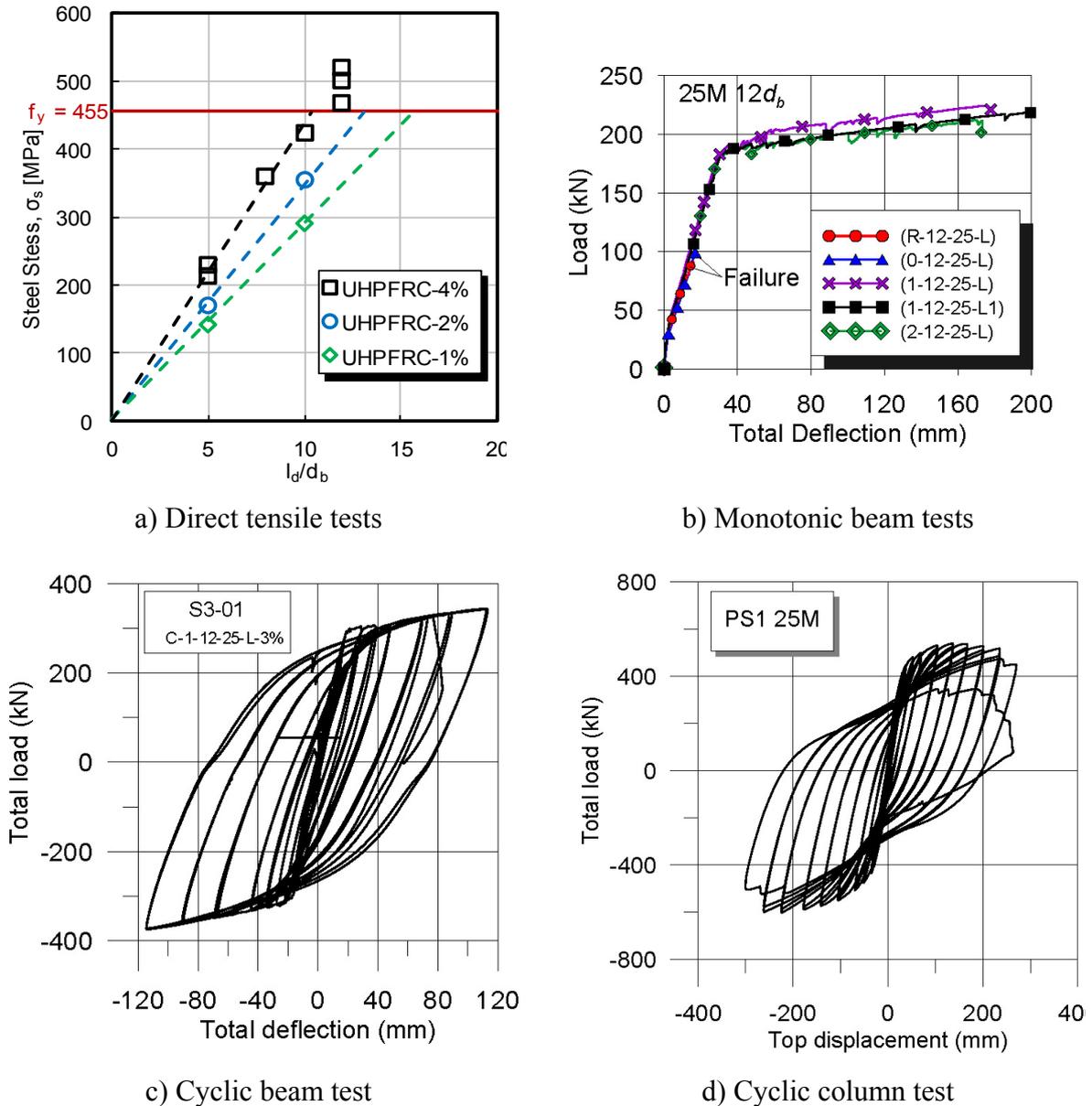
a) Direct tensile tests

b) Monotonic beam tests

c) Cyclic beam test

d) Cyclic column test

Figure 10: Test results for 25mm bar specimens (Lagier 2013 and Dagenais 2013)

5. CONCLUSION

Results of the experimental program carried out by Lagier [5] and Dagenais [6] allow drawing the following conclusions:

- UHPFRC can be used to strengthen deficiently detailed lap-splice regions;
- lap-splice failure, concrete cover spalling, and longitudinal bar buckling were eliminated;
- UHPFRC used in lap splice regions subjected to cyclic tension-compression loading must combine high strength and high ductility characteristics;

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- for 24 d_b lapped length, UHPFRC mix with 3% fibre content was sufficient for reinforcement diameter up to 45 mm;
- the fibre content of UHPFRC mixes is important and using other quantities could be possible for lapped length other than those used in the columns the present project but would require full scale testing.

The results of the project also suggest that this technique could be applied at other locations where reinforcement details are inadequate. The technique allows keeping the column initial dimension which can offer significant advantages in several applications. It can also be used for any column shape. Finally, the enhancement of the confinement provided by the UHPFRC cover and existing transverse reinforcement, and their effects of the shear strength, still remains to be studied. This is currently considered in an ongoing project at École Polytechnique de Montréal.

ACKNOWLEDGEMENTS

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