An application of high performance fiber reinforced cementitious composites for RC beam strengthening

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ABSTRACT: The possibility of using concrete materials with tensile hardening behavior (High Performance Fiber Reinforced Cementitious Composites, HPFRCC) for strengthening R/C beams is investigated. In order to verify the effectiveness of the proposed solution, full scale tests have been performed on 4.5 m long beams. A beam without any reinforcement and a beam with a low reinforcement ratio, equal to 0.03%, have been strengthened with a jacket in HPFRCC having a thickness of 40 mm. A third beam with the same low reinforcement ratio but without HPFRCC jacket, has been used as reference specimen. The obtained results show the effectiveness of the proposed technique both at ultimate and serviceability limit states.

1 INTRODUCTION

The interest for strengthening and repair applications on existing reinforced concrete structures is increased in the last few years. In addition to the well known problems of the seismic retrofitting regarding R/C structures, the strengthening of constructions can be also required by an increase of vertical loads (e.g. due to a change in the design loads or to problems in the construction phase). Moreover, it should be mentioned the urgent need of repairing structures damaged because of lack of durability. Finally, there are cases of important infrastructures, such as bridges or tunnels, that have to be necessarily repaired due to the difficulty in substituting with new structures.

Besides the traditional strengthening techniques, such as the beton-plaque or the R/C jacketing (Fib Report 1991), new solutions have been recently introduced; among these solutions, a great favor has been encountered by the application of FRP (Fiber Reinforced Polymer, Fib Bulletin 14, 2001). A new technique based on the use of high performance Fiber Reinforced Concrete (FRC) is presented herein.

In the last years the use of concretes reinforced with fibers is increased due to their enhanced properties in cracking stage (Rossi & Chanvillard, 2000, di Prisco et al., 2004). Fiber Reinforced Concrete is nowadays extensively used in applications where the fiber reinforcement is not essential for the structure safe (e.g. industrial pavements or shotcrete in tunnels). Besides these examples there are structures where the fiber reinforcement is used as total substitute of the traditional reinforcement (Falkner et al., 1997, ACI 544.4R, 1988). In particular, several studies demonstrated that fiber can be used to replace transverse reinforcement (Meda et al., 2005, Minelli et al., 2006). It has to be noticed that in all these practical applications, characterized by low fiber contents (<< 1% by volume), fiber reinforced concrete exhibits a post peak softening behavior in tension.

Recently, FRC materials having a hardening behavior in tension, usually named High Performance Fiber Reinforced Cementitious Composite (HPFRCC), are available for practical uses (Li, 1993, Rossi, 1997, Rilem-Pro 49, 2006, van Mier, 2004) and allow interesting applications. As a matter of fact, the possibility of having a hardening behavior avoids brittle collapse and, as a consequence, the traditional reinforcement can be removed (Shimoyama & Uzawa, 2002; Vicenzino et al., 2005). It is possible, in this way, to design structures with new geometries and shapes that are not any longer bounded to the reinforcement placement limitations. Unfortunately, the cost of these materials is not comparable with the traditional reinforced concrete and this is a limit to common applications. Nevertheless, particular solutions can be conveniently proposed such as suggested herein, where a HPRCC jacket is applied to existing beams.

As an example, the effectiveness of this application is studied by performing experimental flexural tests of beams with a span of 4.35 m, reinforced with a 40 mm thick jacket of a HPFRCC.

The proposed technique allows several advantages due to the easy placing procedures and due to the increased bearing capacity of the reinforced beams.

It has to be noticed that the HPFRCC jacketing is able to increase not only the ultimate bearing capacity since it remarkably enhances the behavior at serviceability limit state, increasing the stiffness of the beams. This effect is not often obtained with other solutions such as the beton-plaque or the FRP applications.

2 BEAMS GEOMETRIES

The effectiveness of the proposed strengthening technique with HPFRCC jacketing is investigated by performing full-scale experimental tests on three 4.55 mm long beams having a depth of 500 mm and a with of 300 mm (Fig. 1). One of the beams was cast without any reinforcement while, in the other two beams, a longitudinal reinforcement of 2Ø16 mm bars (with the behavior shown in Fig. 2) in the bottom part and 2 Ø 12 mm in the top part was placed. The bars ends were welded to steel plates in order to avoid any slip at the anchorage (Fig. 3). Stirrups were placed at the beams ends in order to avoid shear failure.

The beams were cast with a C20/25 concrete grade. Such low resistance, with the low reinforcement percentage (0.3%), was chosen to highlight the strengthening effectiveness.

One of the reinforced beams was used as the reference specimen while a 40 mm thick layer of HPFRCC was applied on the other two beams, as shown in Figure 4.

The strengthening material is a concrete reinforced with a volume fraction of 2.5% of straight steel fibers having a length of 12 mm and a diameter of 0.18 mm.

Direct tensile tests on dog-bone specimens and bending tests on small un-notched beams were performed in order to determine the material properties. The results of the tests together with the specimen geometries are reported in Figure 5.

The compressive strength measured on cubes having a side of 100 mm was 176.8 MPa.

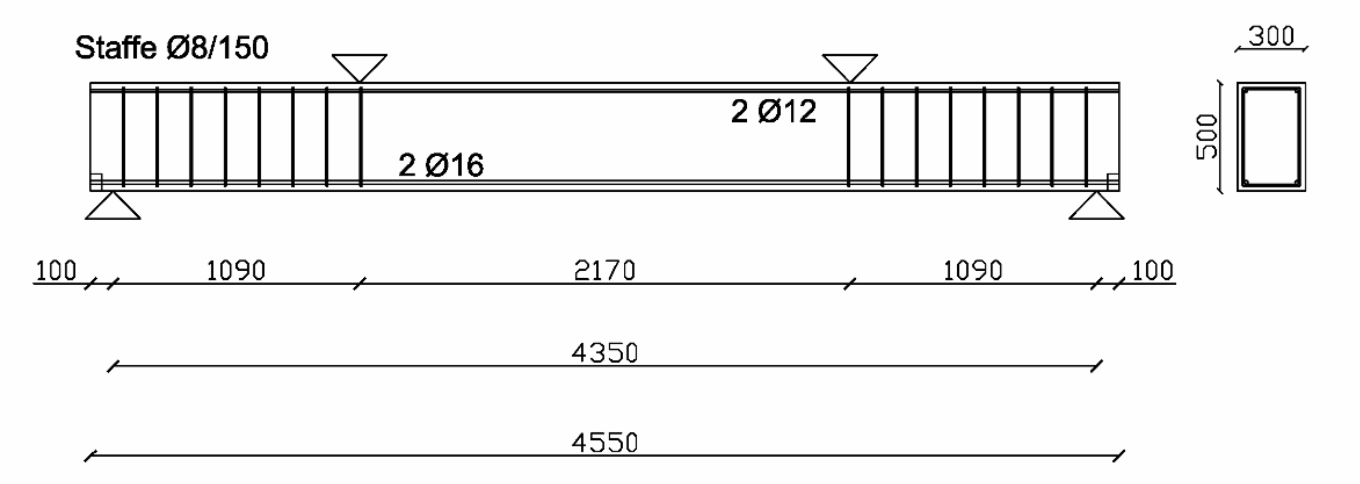


Figure 1. Geometry of the specimens.

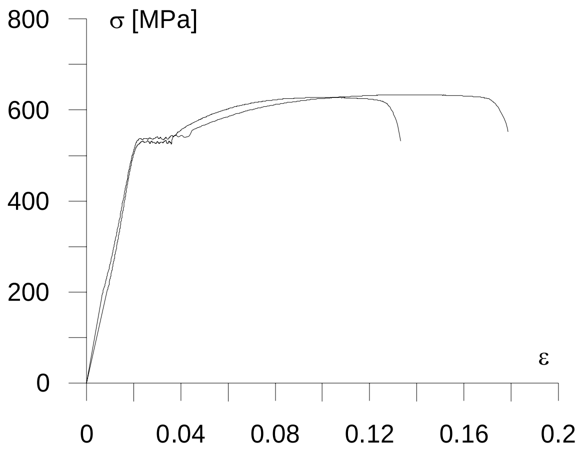


Figure 2. Constitutive relationship of the steel rebars (∅ 16).

Figure 3: Detail of the steel rebars anchorage.

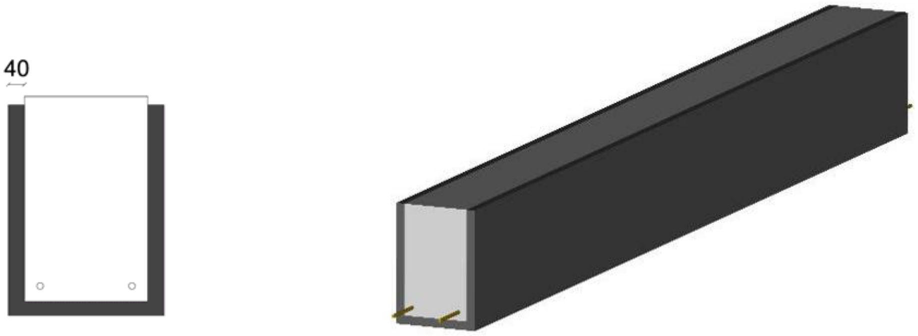


Figure 4. Strengthening scheme.

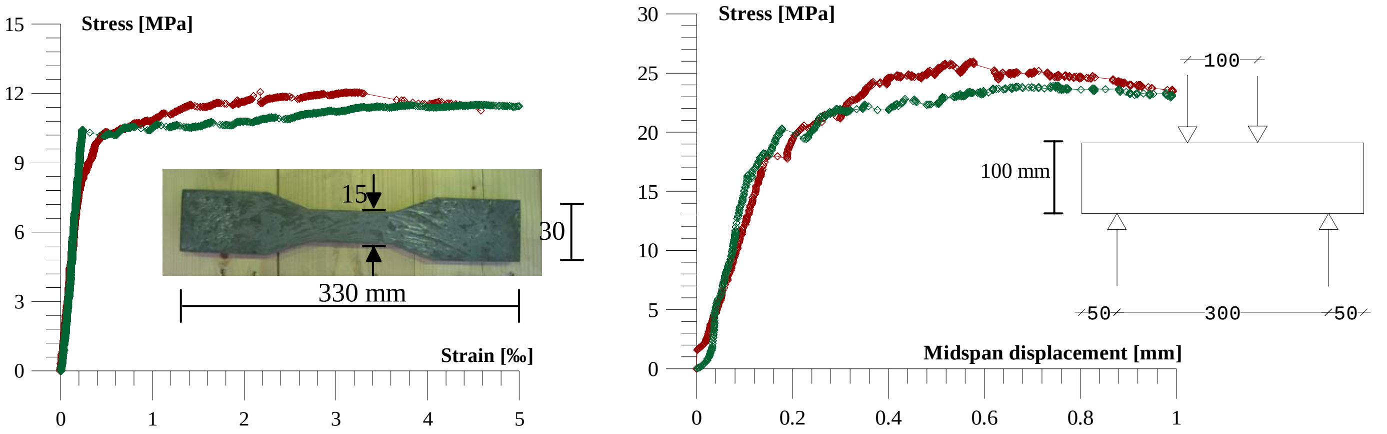


Figure 5. Material characterization: a) direct tensile test on dog-bone specimen (thickness=13mm); b) flexural test (100x100 mm cross-section).

3 JACKET APPLICATION

A preliminary investigation was carried out in order to define the procedure for the application of the HPFRCC strengthening layer. Particular attention was devoted to the optimization of the adhesion between the base concrete and the new material.

To this aim, a first series of tests was performed on 150x150x600 mm specimens made with the same concrete used for the full-scale beams. After a sandblasting of the surface, a layer of 40 mm of HPFRCC material was cast.

The adhesion between HPFRCC and existing concrete was verified by performing four point bending tests on the beam specimens (Fig. 6); after the experiments, no slip was noted between the two materials. Afterwards, the technology of the HPFRCC layer application was defined and the strengthening jacket was applied on the full scale beams after a sandblasting that allowed obtaining a roughness of 1-2 mm (Fig. 7), considered enough to avoid the use of primer products.

The HPFRCC material was prepared in mixers and placed without any vibration. After placing a plastic layer on the surface to limit the evaporation of water from the specimen, curing at ambient temperature and humidity was carried out.

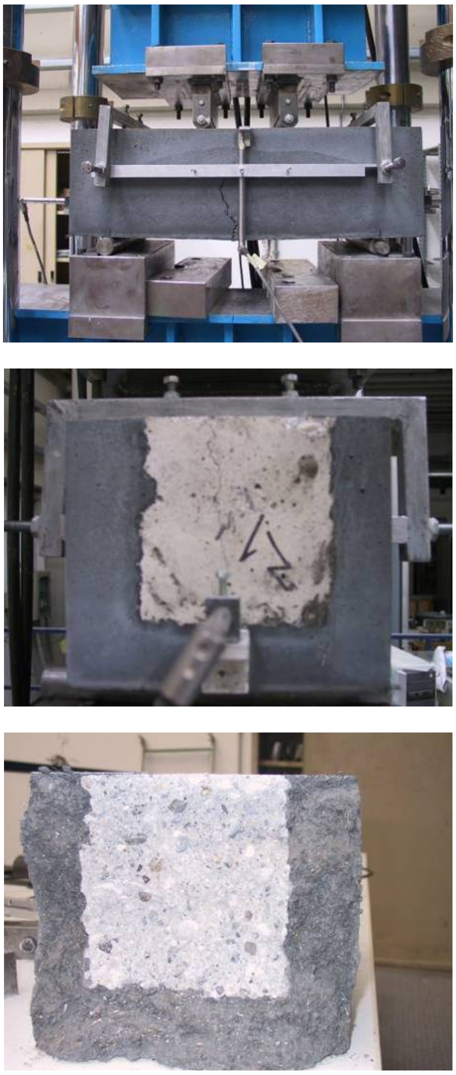


Figure 6. Preliminary tests for the evaluation of the adhesion.

Figure 7. Sandblasting of the surfaces.

Figure 8. Casting of the HPFRCC layer.

4 TESTS DESCRIPTION

The full-scale beams were tested under flexure with a four point bending set-up. The beams were placed on a 4.35 m span and loaded in two points located at a distance of 1.09 m from the supports (shear length equal to 2.4), as shown in Figures 1 and 9.

The tests were performed under displacement control by adopting a 1000 kN electromechanical jack. The jack was placed under the beam with a ties system and the applied load was measured with load cells placed on the ties (Fig. 10).

Figure 11 shows the potentiometer and LVDT transducers adopted for measuring the vertical displacement and the horizontal deformation (mainly the crack opening).

Figure 9. Testing set-up.

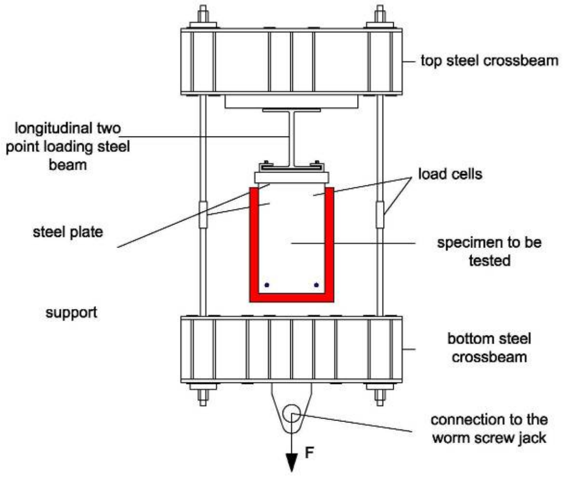


Figure 10. Loading system.

Figure 11. Transducer positions.

5 RESULTS

5.1 *R/C beam without HPFRCC jacket*

Firstly, the test on the R/C beam without the HPFRCC strengthening jacket has been carried out. Figure 12 shows the total applied load versus midspan displacement curve (the displacement does not include the support settlement as well as the contribution of the self weight of the loading frame).

When the load reached a value of 50 kN a first crack occurred. Afterwards, other cracks developed in the zone between the two point loads, with a crack spacing ranging between 300 and 400 mm. The crack depth was around 430 mm; as a consequence, the width of the compressive chord was 70 mm.

After the complete crack development the load still increased with a lower stiffness up to yielding of the longitudinal reinforcement; this occurred when the load was equal to 190 kN.

The collapse was characterized by the development of an arch mechanism. The main experimental observations are the following:

- starting from the bottom part of every crack, at reinforcement level, a splitting crack developed and led to a loss of bond between longitudinal bars and concrete (Fig. 13a);
- due to the bond failure, the stiffness of the beam remarkably decreased with great deformations;
- at the upper compressive chord, horizontal cracks developed, defining the arch mechanism geometry (Fig. 13b).

Figure 14 shows the final crack pattern at collapse.

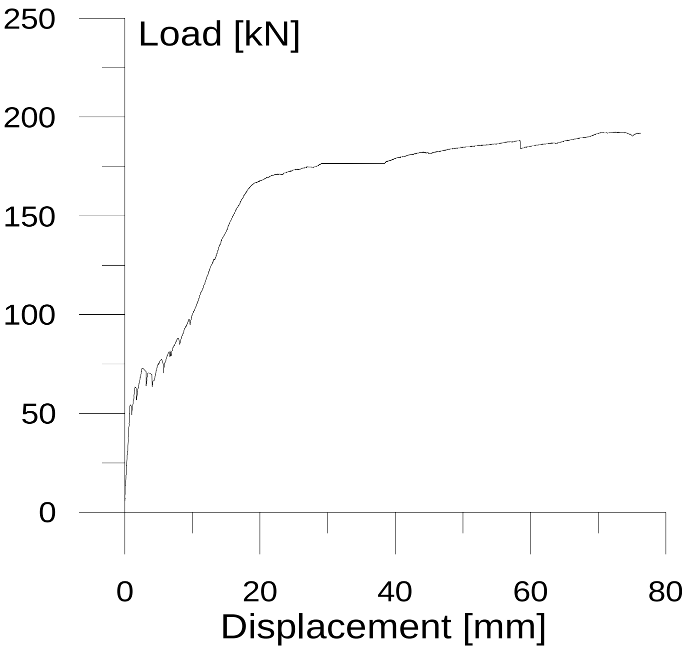
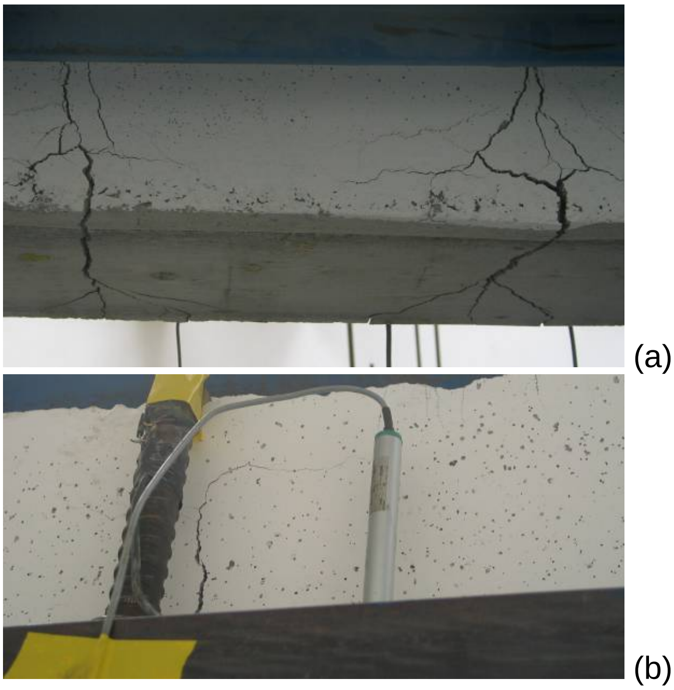


Figure 12. Reference beam (R/C): curve of the load versus midspan displacement.

5.2 *Plain beam with HPFRCC jacket*

The load versus midspan displacement curve for the beam without the longitudinal reinforcement, strengthened with the HPFRCC jacket is shown in Figure 15.


(a)

(b)

Figure 13. Un-reinforced beam: cracks distribution close to the collapse: a) bottom side; b) upper side.

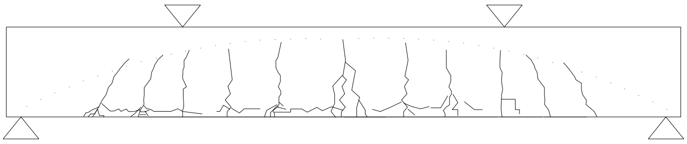


Figure 14. Final crack pattern at collapse of the reference beam (reinforced concrete) without jacket.

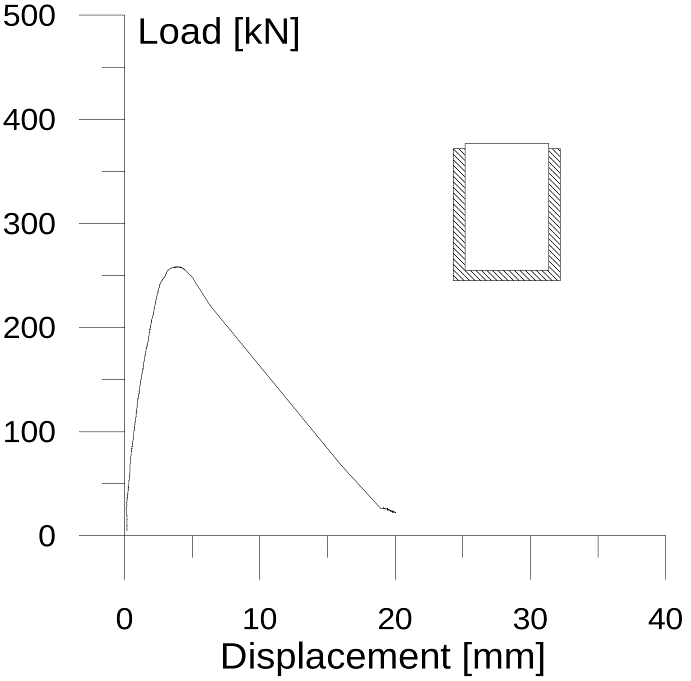


Figure 15. Plain concrete beam with HPFRCC jacket: curve of the load versus midspan displacement.

The collapse occurred with a brittle behavior when the load was equal to 258 kN. A single main crack developed close to the midspan (Figure 16).

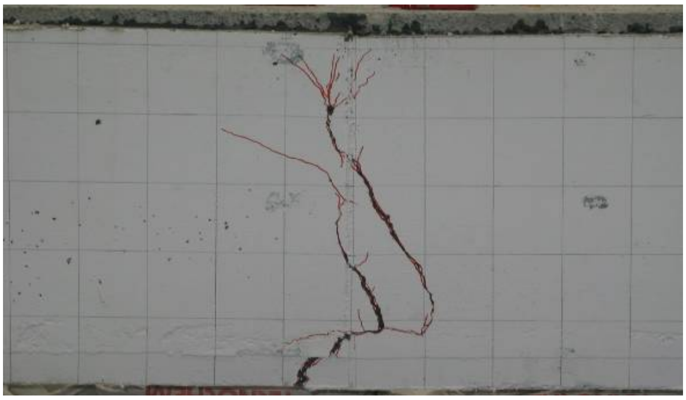


Figure 16. Plain concrete beam with HPFRCC jacket: main crack at failure.

5.3 *R/C beam with HPFRCC jacket*

The behavior of the R/C beam strengthened with the HPFRCC jacket is shown in Figure 17. The beam exhibited the same behavior of the plain beam up to a load of 250 kN. After this level, the load increased with a slight stiffness due to the development of cracks spaced at a distance of 500-600 mm.

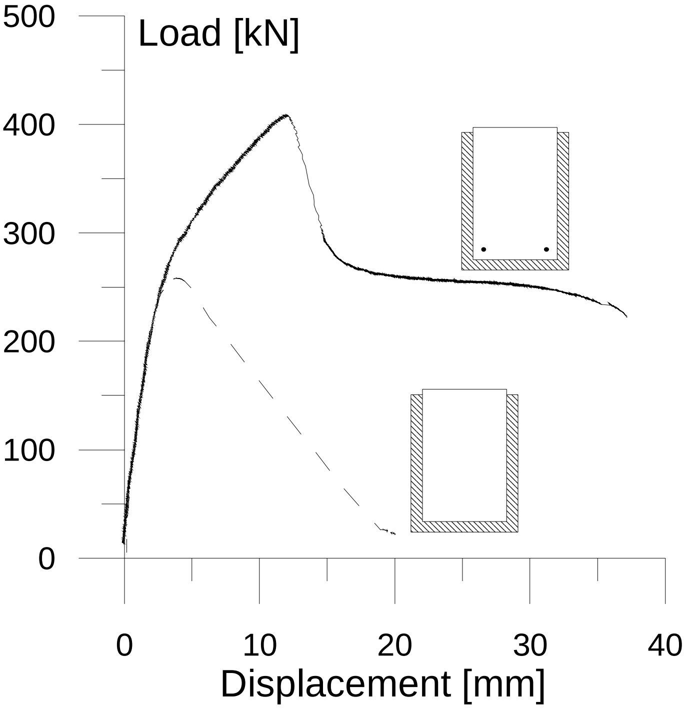


Figure 17. R/C beam with HPFRCC jacket: curve of the load versus midspan displacement.

The maximum load was equal to 410 kN; afterwards, the load decreased and stabilized at a level of 260 kN, with the development of a single crack under the point load (Fig. 18).

Beam collapse occurred because of the yielding of the longitudinal reinforcement, with the crack pattern shown in Figure 19.

Figure 18. R/C HPFRCC jacketed beam: localization of the main crack.

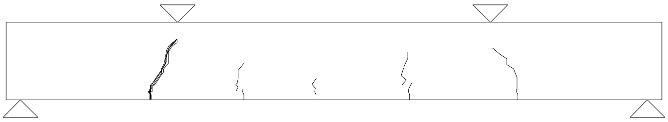


Figure 19. R/C beam with HPFRCC jacket: crack pattern at failure.

6 DISCUSSION OF THE RESULTS

The comparison between the experimental results obtained from the three full-scale beams is shown in Figure 20.

For the sake of brevity, in the following the discussion will be focalized on two R/C beams with and without strengthening jacket. It can be noticed as the HPFRCC use allows increasing the bearing capacity of the beam (2.15 times), even if the post peak behavior becomes softening. In any case, at the end of the softening branch the load stabilizes with a plastic branch, with a value higher than that obtained in the R/C beam without jacket.

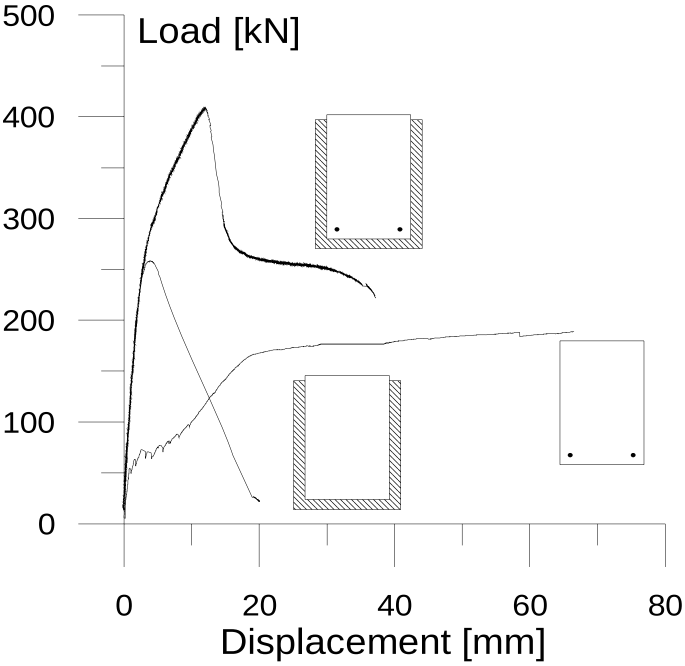


Figure 20. Comparison between the experimental results

During strengthening design of an existing structures, designers should refer to both Ultimate and Serviceability Limit States. As an example, for beam elements under flexure, an inadequate bearing capacity leads also to significant displacements and great crack openings.

As far as the service conditions are concerned, the proposed technique allows to remarkably increase the beam stiffness, with a behavior similar to the uncracked stage of the existing (before strengthening) beam (Fig. 21). Indeed, the HPFRCC jacket limits the development of macrocracking with evident advantages in terms of stiffness.

By assuming a service load of 80 kN, the use of the HPFRCC jacket leads to a decrease of the midspan displacement from 6 mm to 0.5 mm (i.e. about 12 times lower; Fig. 21). This effect is comparable to that obtained with an external prestressing, where the cracking is avoided with a fully compressed section. From the technological point of view, the use of a HPFRCC jacket can be easily proposed as a convenient alternative to the use of external prestressing cables.

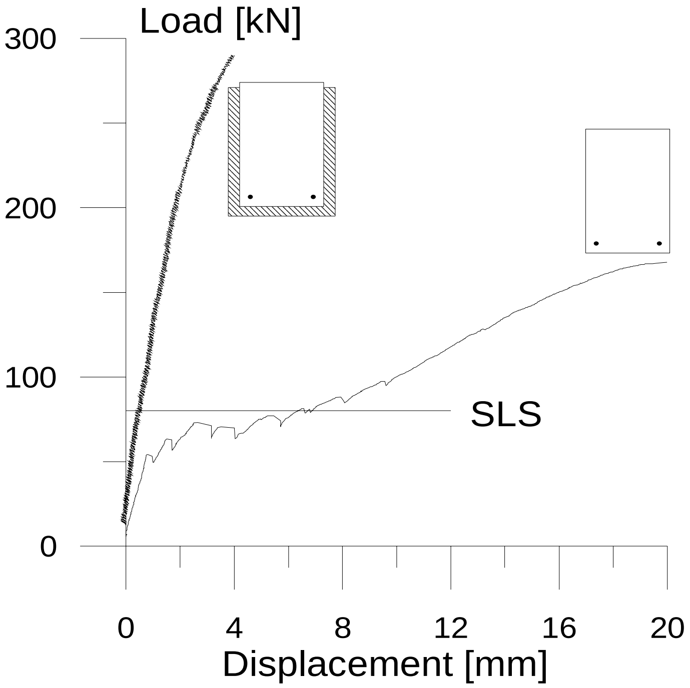


Figure 21. Serviceability limit state behavior of R/C beams with and without HPFRCC jacket.

It should also be remarked that the use of a FRP strengthening does not limit cracking phenomena and, as a consequence, it cannot increase the beam stiffness.

Furthermore, the adoption of a HPFRCC jacket enhances the durability of the structure, as it can be used as protective layer in aggressive environment.

7 CONCLUDING REMARKS

The possible use of HPFRCC materials for strengthening R/C beams has been investigated with full scale applications.

The following remarks can be drawn from the result obtained in this study:

- a simple sandblasting ensures a perfect bond between the base concrete material and the strengthening HPFRCC layer;
- the application of a layer of HPFRCC having a thickness of 40 mm remarkably increases the maximum load (more than double);
- the strengthening layer has provided a remarkable stiffness increase; as a consequence the midspan displacement at service conditions has been reduced of about 12 times. This behavior is comparable to the application of prestressing.

Finally, an interesting development of the proposed technique, now under study, concerns the possibility of the application of the strengthening material with a spray technique.

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