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# FIBER REINFORCED MORTAR AND CONCRETE FOR SEISMIC RETROFITTING OF MASONRY AND RC STRUCTURES

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## ABSTRACT

Many countries are currently facing the problem of the evaluation and retrofitting of existing buildings and infrastructures, due to structural deficiencies and durability issues. With the aim of avoiding expensive demolition and reconstruction interventions, excellent retrofitting techniques have been developed over the years, using new composite materials like fibre reinforced mortar (FRM) and ultra-high performance fibre reinforced concrete (UHPFRC).

The present paper describes the most significant experiences carried out at the University of Brescia, leading to the development of innovative retrofitting techniques for masonry buildings and RC bridges, including characterization tests of materials, tests on full-scale elements and experimental investigations performed on full-scale structures.

*Keywords: Existing structures, Seismic retrofitting, Fibre Reinforced Mortar, Ultra-High Fibre Reinforced Concrete, Masonry buildings, Reinforced concrete*

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# 1. INTRODUCTION

In recent years, many developed countries have recognized the urgent problem of adapting existing buildings and road infrastructures to renewed social and economic needs: the protection of human lives during seismic events and the preservation of road infrastructures with respect to increased loads and environmental actions are significant examples of these needs. In fact, existing buildings and infrastructures may present significant durability problems (years after their construction) or structural deficiencies (with particular reference to seismic resistance). This condition, which is quite common in many western countries, requires solutions able to prevent or limit any negative effect on people and communities. In order to solve these problems, many existing structures have to be retrofitted or, in some cases, rebuilt. As demolition and reconstruction costs is generally much higher than retrofitting costs, the latter generally represents the better solution. However, the use of new materials and techniques can be exploited to increase the effectiveness of these interventions. The continuous enhancement of mechanical and physical properties of new composite materials like fibre reinforced mortar (FRM) and fibre reinforced concrete (FRC) allowed the development of efficient construction techniques providing good structural performance and durability to existing structures.

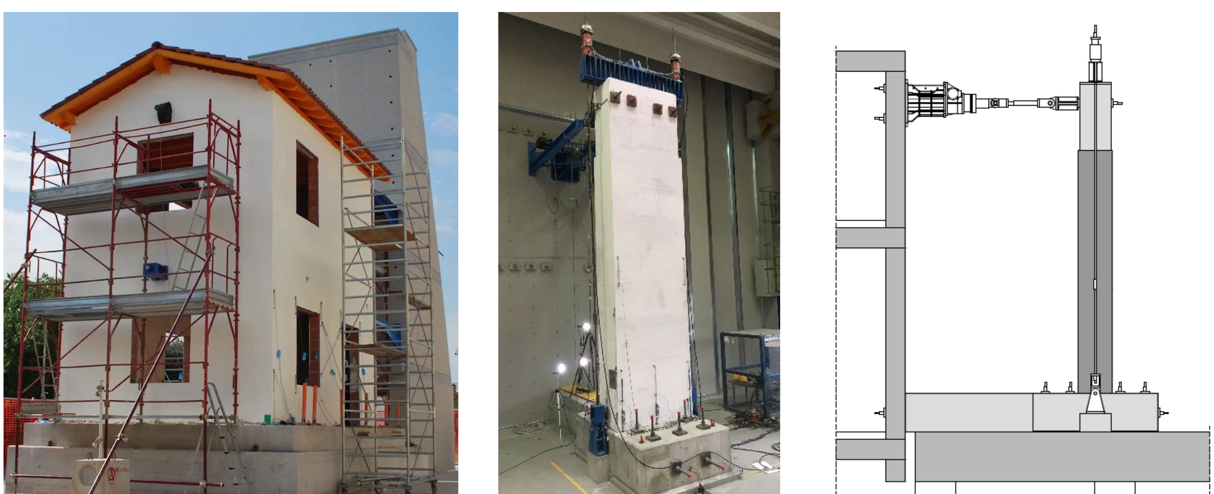
A very common type of construction for housing, frequently needing retrofitting, concerns the unreinforced masonry (URM) building which presents a considerable ability to withstand compression loads with a limited capacity to resist tensile and shear stresses. As a result, existing URM buildings are often vulnerable to seismic actions and require proper interventions to improve resistance and ductility against horizontal loads.

Literature reports several researches that proposed retrofitting methods based on advanced materials. Satisfactory results have been obtained from the application of techniques adopting FRP laminates [1,2,3], GFRP grids [4,5] or ECC [6,7] materials; as an alternative, some experimental studies carried out during the last few years proposed to retrofit URM buildings by FRM coating [8,9]. The latter proved to be an effective method for improving the in-plane resistance of masonry and for enhancing the global ductility and displacement capacity of the structure. Moreover, the lateral stiffness improvement resulting from the coating application generally provides a better structural behavior in service loading conditions since lower lateral deflections and damages are expected [10]. The improved behavior of the structure both at Serviceability (i.e., lower deflection, reduced crack widths) and Ultimate (i.e., higher shear/flexural resistance) Limit States is related to the mechanical behavior of FRM which, compared to mortar not containing fibers, typically presents a higher post-cracking tensile strength and toughness. In addition to the improved mechanical properties, the use of randomly diffused fibers in place of traditional steel reinforcing mesh allows preventing corrosion phenomena, thus leading to significant advantages in terms of durability. Finally, by considering the box behavior of the whole structure, seismic enhancement can be obtained by applying FRM coating only on the outer surface of the masonry building, thus avoiding several inconveniences including the fact that the occupants are not forced to leave the building during the strengthening intervention.

Beside masonry, a very common material for road infrastructures is reinforced concrete (RC). Many of RC infrastructures were designed and built between the 1960s and 1970s, when seismic awareness was still limited. After more than 50 years of service, these structures also need special maintenance due to the material degradation accumulated over the years. As for buildings, two solutions are feasible: the construction of new infrastructures (the demolition may cost as much as construction) or the retrofitting of existing ones. Retrofitting an existing infrastructure allows to intervene in an efficient (relatively fast), effective (with lower costs) and sustainable (reducing maintenance costs) way. As compared to competitive solutions such as wrapping with FRP, jacketing with steel elements or with ordinary RC [11], jacketing with ultra-high performance fibre reinforced concrete (UHPFRC) offers the possibility to increase not only structural performance (flexural resistance, shear resistance and ductility) of existing RC elements but also their durability (resistance to carbonation, freeze-thaw cycles and de-icing salts). This solution consists in a thin UHPFRC layer collaborating with the original structural element (which may be a beam, a pier or a bridge deck). UHPFRC is characterised by a very high mechanical compressive strength, a high toughness (given by the presence of steel fibres) and very high durability (given by the physical characteristics of the cement matrix).

High residual tensile strength can be considered in the structural calculations and allow to optimize the use of traditional steel reinforcements. Therefore, traditional steel reinforcements can integrate the retrofitting solution in the most stressed locations such as, for example, the connection of a bridge pier with the foundation. Finally, the adhesion between the UHPFRC jacketing and the existing concrete is good enough to have failure in the existing concrete and not at the interface between the two materials.

The present paper describes the most significant experiences carried out at the University of Brescia, leading to the development of new retrofitting techniques for URM buildings (Figure 1a) and RC bridge piers (Figure 1b), involving the use of innovative cement-based composites, namely FRM and UHPFRC. The most important experimental results concern the development of materials and their use on structures, verified through experimental investigations on full-scale structures representing typical applications.



(a) (b)

**Figure 1.** Views of the full-scale masonry building retrofitted with FRM (a) and 1:4 scaled bridge pier retrofitted with UHPFRC (b).

# 2. SEISMIC RETROFITTING OF MASONRY BUILDINGS

Many URM buildings worldwide were constructed on seismic areas before the publication of the modern structural codes, which include specific prescription for seismic actions. Therefore, seismic retrofitting is now necessary to reduce the vulnerability and preventing the building collapse. In addition, when earthquakes cause damages to the existing buildings, the latter may need to be repaired and strengthened with efficient techniques. One of these recently developed is based on a thin (25-30 mm thick) FRM plaster which is reinforced with short steel fibres. The use of a distributed reinforcement mixed with the plaster allows reducing the time generally required for the installation of reinforcing meshes. Moreover, as a minimum cover is not required, the coating thickness can be considerably reduced together with the construction costs.

The potentialities and the effectiveness of the proposed method is well highlighted by the experimental studies described below which are part of a broader and comprehensive research program undertook at the University of Brescia.

## 2.1. Description of the retrofitting method

The material used for coating consists of a ready-mixed cement based mortar containing nano-silica reinforced with high strength steel fibres. Mortar is based on a 20% (by weight) of water added to the premixed powder; the obtained mixture is then mixed with an electric hand-held mixer. During the mixing phase, 64 kg/m$^3$ (0.82% by volume) of hooked-end steel fibres are added to mortar. The fibres have a length of 32 mm, a diameter of 0.4 mm and a tensile strength higher than 2,800 MPa. The resulting specific unit weight of hardened mortar is usually slightly lower than 2000 kg/m$^3$.

The procedure adopted to apply the FRM coating on masonry surface can be summarized in the following few points: 1) The masonry surface must be preliminary wet by water and, when necessary, the surface of units must be properly prepared to increase the surface roughness and, as a consequence, the bond strength of the masonry-to-coating interface. 2) A very thin mortar layer (5–6 mm thick), without steel fibres, was manually spread on the wall surface to create a first substratum able to ensure a stable bond between masonry and mortar. 3) 400-500 mm spaced connectors, consisting of a steel screw provided with a 50x50x5 mm steel anchor plate, are drilled into the wall to prevent coating buckling. 4) Different layers of mortar containing steel fibres are trowelled until a total thickness of 25-30 mm is achieved. (5) In order to mitigate shrinkage cracks, the coating surface must be kept wet by spraying water for at least 3 days after completing the application. Figure 2 shows some typical details concerning the proposed retrofitting technique and the masonry-to-coating connectors.

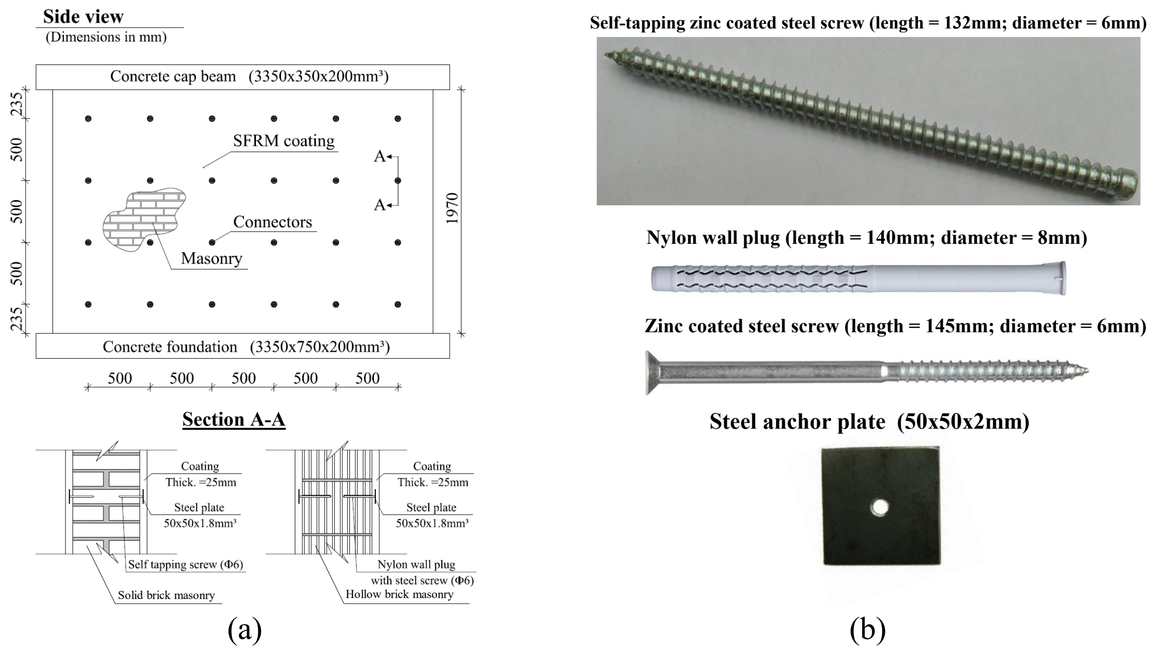



**Figure 2.** Typical details of the retrofitting technique: layout of the masonry-to-coating connectors (a) and real view of a steel connector provided with a steel anchor plate (b).

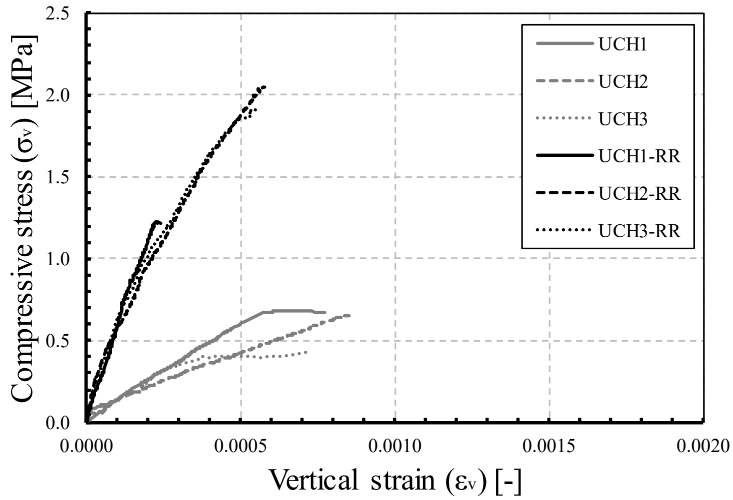
## 2.2. Characterization tests

The tests on full-scale structures were all preceded by characterization tests aiming at determining the mechanical properties of materials. Thus, mechanical tests were carried out on masonry and its components (i.e., mortar and units). In more detail, compression and flexural tests were carried out according EN 1015-11 to determine the flexural and the compressive strength of the cement based mortar used to fill the masonry joints. The compressive strength of masonry units was determined by testing unit samples according to EN 772-1. Finally, uniaxial compression tests were also performed in order to assess the compressive stress-strain response of URM wallets according to EN 1052-1. In addition to the standard compression test on URM samples, an experimental investigation was undertook to study the behaviour of masonry strengthened with coating (Figure 3a). As an example, a typical compressive stress-strain response obtained by testing a series of hollow unit masonry wallets with horizontal holes is reported in Figure 3b. The diagram compares the response of six URM samples, three of which (i.e., UHC-RR) were strengthened on both sides by a 25 mm layer of FRM coating containing 60 kg/m$^3$ of high strength steel fibres. The results highlight the ability of the strengthening technique to significantly improve the compressive strength of masonry (+270%) as well as the secant elastic modulus (+370%).

The structural performance of masonry element retrofitted with coating mainly depends on the mechanical performance of FRM in tension. The latter can be obtained by performing three-point bending tests (3PBTs) on notched beams having the same geometry (i.e., 500 mm long and 150 mm high) of that proposed by EN 14651, except for the thickness that may be reduced to 40 mm to better represent the fracture behavior of FRM coating. A typical tensile stress-Crack Mouth Opening Displacement diagram resulting from 3PBTs on FRM samples is depicted in

Figure 4a; one should note the significant tensile toughness of the material as well as the well pronounced strain-hardening response observed after first cracking.

(a)

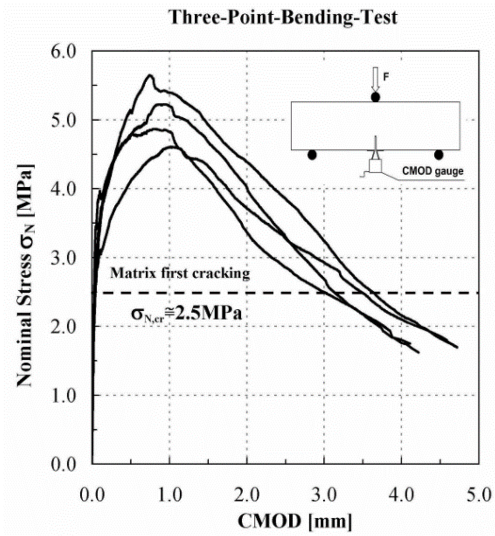



(b)

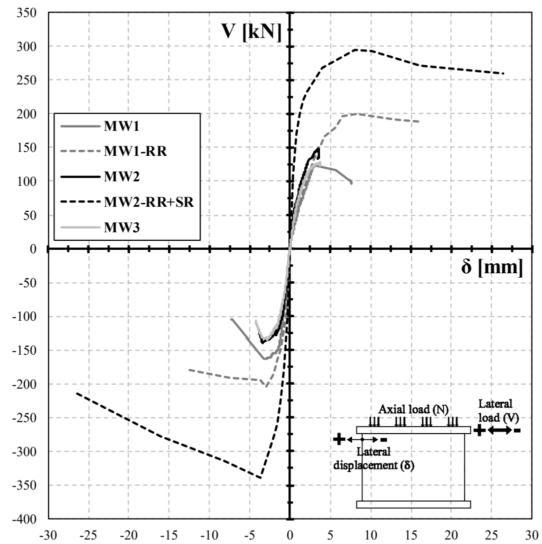
**Figure 3.** Uniaxial compression test on a hollow unit masonry wallet strengthened with FRM coating on both sides (a). Typical compressive stress-strain response of hollow unit masonry wallets with and without coating (b).

## 2.3. Tests on full-scale cantilever walls

The effectiveness of the proposed retrofitting method was first proved by the results obtained from a series of quasi-static cyclic tests on full scale cantilever walls made of either solid or hollow unit masonry [9]. The samples (see Figure 2a) were 3 m long, 2 m high and had a thickness ranging from 200 mm to 250 mm. All the cyclic tests were performed under a constant uniformly distributed vertical load of 250 kN applied on the distributor beam placed at the top of the wall. Typical envelope curves obtained from the experimental test are shown in Figure 4b. The latter compares the response of three URM walls (i.e., MW1, MW2 and MW3) with that exhibited by two specimens (i.e., MW1-RR, MW2-RR+SR) after retrofitting with 25 mm thick coating on both sides. In particular, the two retrofitted specimens were obtained by repairing the specimens MW1 and MW2, which were tested up to the formation of oriented diagonal cracks. Unlike specimens MW1-RR, the wall MW2-RR+SR was provided with vertical steel dowels to connect the coating layer to the concrete foundation of the wall. As one may observe, the wall MW1-RR presented a lateral resistance higher (25-30%) than that achieved by the un-strengthened samples and a failure mode governed by rocking. Because of the coating-to-foundation connectors, the maximum capacity of the wall MW2-RR-ST was about 2 times higher than that of the corresponding un-strengthened sample. Furthermore, its initial stiffness was significantly incremented, thus leading to an improved behavior at service loading conditions.




(a)




(b)

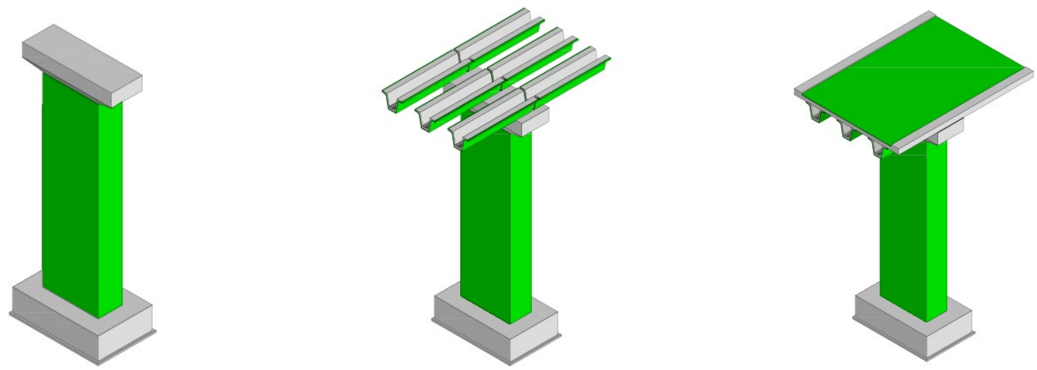
**Figure 4.** Typical nominal tensile stress-CMOD response of notched FRM beams under three point bending (a). Lateral shear vs. deflection envelops obtained by testing cantilever masonry walls with and without retrofitting (b).

## 2.4. Test on a full scale hollow clay unit masonry building

The successful results provided by the tests on full-scale walls suggested to investigate the effectiveness of the propose technique to enhance the seismic behaviour of URM buildings. Thus, a research program was carried out to perform a quasi-static cyclic test on a full-scale hollow unit masonry building by using the new test facility for large-scale testing available at the laboratory of the University of Brescia (Figure 1a). The structure represents a typical Italian building constructed during the '60s -'70s that is provided with concrete floors having a high in-plane stiffness. The two walls of the building oriented parallel to the loading direction are 5.75 m long, 6.7 m high and 200 mm thick. A preliminary test was carried out on the un-strengthened building to simulate a severe damaging condition typical of the damage grade 4 according to the European macroseismic scale (EMS-98). After having performed the pre-damaging test, the structure was retrofitted by a 30 mm thick FRM coating applied only on the outer surface of the building. The experimental test on the retrofitted specimen is still on going and the result will be available very soon. However, as observed in previous works [12], the numerical simulations predicted a surprising effectiveness of the retrofitting intervention that appeared to be able to triple the maximum resistance exhibited by the specimen before retrofitting.

## 3. STRENGTHENING OF A RC BRIDGE PIER

In many western countries, such as in Italy or in other seismic areas, a large part of the main road infrastructures was built between the 60s and the 70s, before the introduction of specific design codes for seismic actions. As a result, a large number of bridges actually in use could be considered unsafe with regards to earthquake actions. In addition, after more than 50 years from the construction, reinforced concrete bridges may have experienced structural damages (due to impacts, high temperatures, exceptional actions or lower-than-design earthquakes), and significant material degradation (due to freeze-thaw cycles, chloride and sulphate attack, or corrosion of reinforcements). The retrofitting technique hereafter described consists of a thin (30-150 mm) UHPFRC layer around (or on top of) existing RC elements such as bridge piers, bridge girders or bridge decks (see **Errore. L'origine riferimento non è stata trovata.**). The retrofitting operations are non-invasive and allow, in many cases, the infrastructure administrator not to interrupt its use. The use of traditional reinforcement can be optimized and rebars provided only in the critical sections of the element, since the repair material is fibre reinforced. Due to the fast development of strength of the UHPFRC and the reduced use of reinforcing bars, the duration of the retrofitting operations can be considerably reduced, with benefits to the road network management. The excellent mechanical properties of the material, the characteristics of the UHPFRC layer applied to small scale specimens and the structural performance obtained from a full-scale bridge pier repaired with UHPFRC are described in the following, as part of the extensive research on existing structures ongoing at the University of Brescia.



(a) (b) (c)

**Figure 5.** Schematic representation of UHPFRC retrofitting technique: strengthening of bridge pier (a), girders (b) and bridge deck (c).

### 3.1. Description of the strengthening method

The repair material consists of three components (a pre-mixed powdered part, steel fibres and a liquid part) which can be mixed on site with the help of common equipment and poured into formworks. UHPFRC is made with CEM I 52.5 R cement, a water/binder ratio 0,22, pozzolanic addition, Super Plasticizer (SP), Shrinkage Reducing Admixture (SRA). Steel fibres are added to concrete with a volume fraction of 1%. Fibres are made of stainless steel, crimped, 19 mm long, with 0.13 mm diameter. The maximum aggregate size is 4 mm to fit critical thicknesses down to

30 mm [13]. The application of UHPFRC jacketing to piers or girders is based on the following phases:
1) sandblasting of the existing RC structure to obtain a very rough surface;
2) placing of additional reinforcements in critical sections;
3) wetting of concrete surface to obtain a saturated surface dry (SSD) condition before casting;
4) mounting of formworks;
5) mixing and pouring of UHPFRC in formwork; and
6) demoulding after target strength of UHPFRC is reached.
7) water curing should be provided for 7 days after demoulding to reduce restrained shrinkage of UHPFRC. However, early age cracking is substantially prevented by the presence of fibres.

## 3.2. Characterization tests

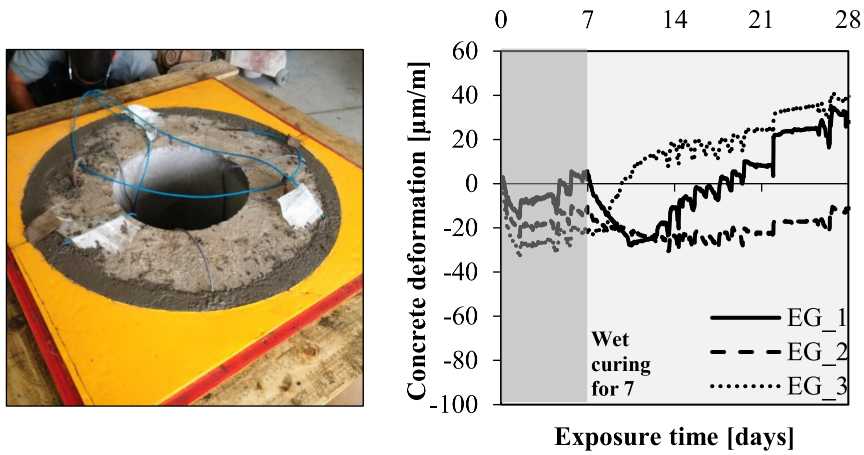
Before its final application on a real scale structure, UHPFRC has been thoroughly investigated for determining its high mechanical performance, its interaction with normal strength concrete and its high durability properties. Compressive strength (EN 12390) after 28 days was found higher than 130 MPa and direct tensile strength more than 5 MPa. Residual tensile strengths (EN 14651) were $f_{R1}$ >13 MPa, $f_{R2}$ > 10 MPa, $f_{R3}$ > 8 MPa, and $f_{R4}$ > 6 MPa. The adhesion to concrete substrate (EN 1542) was found to be higher than 2 MPa (after 28 days), leading to ruptures in the substrate. Shear bond strength was also investigated [14] with values of more about 2 MPa for concrete with a rough surface. These mechanical properties make this material a high-performance concrete.

Durability of UHPFRC is significantly improved as compared to ordinary concrete. Its application, even in thin layers, makes it possible to protect the existing concrete structure effectively. It can be assumed that, once deteriorated concrete has been removed, the durability of the retrofitted structure depends on the improved performance of UHPFRC. Resistance to accelerated carbonation (EN 13295) is complete since no carbonation (0 mm) is measured. Thermal compatibility measured as adhesion (EN 1542) is effective: no significant variation (2 MPa) is observed. Reaction to fire (EN 13501-1) class is A1. UHPFRC is water-tight, since depth of penetration (EN 12390-8) is null (0 mm).

## 3.3. Tests on reduced scale specimens

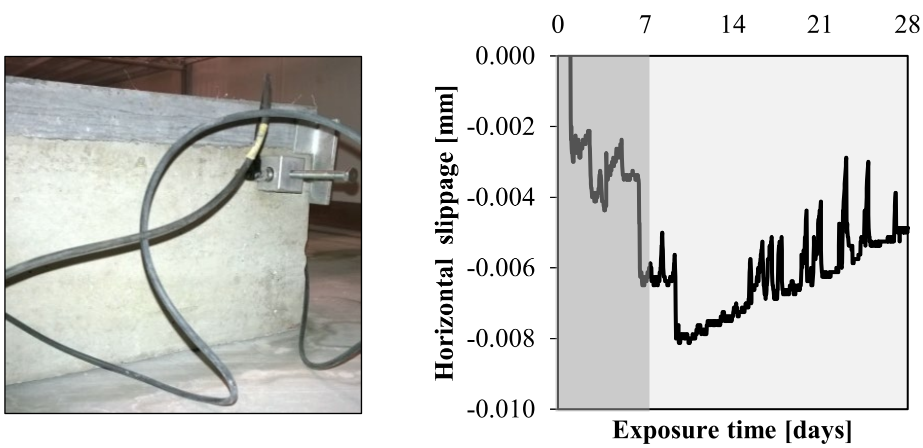
The risk of early-age cracking due to restrained shrinkage of bridge piers retrofitted with UHPFRC was experimentally and numerically investigated [15], as shown in Figure 7. This problem has been considered since its deleterious effects may affect the structural performance of the retrofitted structure and, especially, its durability. The experimental results demonstrated the development of circumferential stresses (hoop stresses) in the new repair layer due to the restrained shrinkage of UHPFRC under controlled conditions (T=20±1°C, RH=50±5%), measured by means of circumferential strains (hoop strains) with embedded strain gauges. Fibre reinforcement was found to be of fundamental importance to obtain a durable jacketing. The presence of fibres mitigates the crack development and produces a diffused distribution of micro-cracks (not visible to the naked eye) in lieu of few macro-cracks observed on specimens without fibres.

The risk of delamination of UHPFRC layer was also considered in an experimental study. The test involved the application of an UHPFRC layer on a concrete element of prismatic shape, as shown in Figure 7. The objective of the test was to monitor the deformations of the new layer subject to restrained shrinkage under controlled conditions. In particular, during the test, the relative displacement between the overlay and the substrate due to possible delamination (detachment of the new material from the substrate) or to cracking of the reinforcement itself, were monitored. At the end of the exposure period of 28 days, adhesion tests (EN 1542) were carried out on the tested specimens. The best practices for the application of UHPFRC were found to be 1) the sandblasting of the surface, 2) the wetting every day for 7 days and 3) the covering with polyethylene sheeting for 7 days. Under these conditions, the specimens did not show any delamination of the reinforcement with negligible relative displacements and a bond strength of about 2 MPa.




(a) (b)

**Figure 6.** Segment of a bridge pier after casting (a) and strain development (b).




(a) (b)

**Figure 7.** Restrained overlay test specimen (a) and slippage development (b).

## 3.4. Test a full-scale RC bridge pier

Finally, the retrofitting technique was experimentally studied by means of a laboratory specimen of a bridge pier [16], as shown in Figure 1b. The first objective of the study was the experimental evaluation of the seismic response of the strengthened element by means of a cyclic loading test, simulating the action induced by an earthquake. A further objective was the verification of feasibility of the retrofitting strategy. The laboratory specimen was tested under a constant vertical load of 1000 kN with cyclic horizontal loading following a drift-controlled protocol. UHPFRC jacketing improved the seismic response at ULS enhancing the ultimate load of more than 70% with respect to the un-strengthened element. UHPFRC jacketing also improved the structural behaviour at SLS determining a diffused pattern of micro-cracks with small values of average crack width and, thus, a lower ease of penetration of aggressive substances inside the structure for lower than design-level earthquake intensity.

# 4. CONCLUSIONS

The experimental results summarized in this paper highlight the potential of high performance fiber reinforced mortar and fiber reinforced concrete as retrofitting and repairing materials for different applications in civil engineering. In more detail, FRM coating with a small thickness (25-30 mm) appears to be effective in improving the seismic behavior of existing masonry buildings. Moreover, the use of UHPFRC appeared to be a good and versatile solution for retrofitting of RC bridge piers under seismic actions. In spite of the significant performances concerning the short-term behavior of the proposed retrofitting methods, their long-term performance deserves to be further investigated.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