SEISMIC RETROFITTING OF EXISTING SHEAR WALLS BY MEANS OF HIGH PERFORMANCE RC JACKET

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ABSTRACT :

A new technique for the strengthening of existing R/C shear walls based on the application of very thin high performance jackets is presented in this paper. The strengthening jacket is made of high performance concrete and high strength steel mesh. The experimental study on a 1:3 scale R/C wall, proportioned to resist the vertical loads only, and reinforced by means of a 15 mm thick high performance jacket is presented. The effectiveness of the technique is also verified numerically. The results show the efficiency of the proposed solution in significantly increasing the structure resistance, deformation capacity and ductility.

KEYWORDS: Seismic retrofit, shear wall, R/C jacket, high strength materials.

1. INTRODUCTION

In the restoration discipline, a growing interest is nowadays shown for the retrofit of existing R/C buildings with respect to the seismic action. In the existing buildings R/C walls are commonly located near the stair blocks and the elevator areas, or along the structure perimeter. These elements are often reinforced to resist the vertical loads only, without considering the seismic actions. In few cases, the elements may be reinforced against horizontal wind loads but may be ineffective against the design seismic actions recommended by the modern Standards.

Among all possible anti-seismic strengthening strategies, the retrofit of the existing R/C frame is hardly a viable solution provided that the strengthening of the frame nodes is difficult to pursuit and is very expensive. In this scenario, the transformation of the existing R/C walls into anti-seismic shear walls is often preferred (Fib Bulletin 24, 2003). Furthermore, it is worth noting that regardless of the strengthening strategy, the presence of the existing R/C walls should be considered anyway. As a matter of fact, even if new anti-seismic devices are adopted, the seismic action transferred to the existing R/C walls can be rather large as a result of their significant stiffness. This in turn could result in severe damage of the R/C walls, prior to the activation of the devised anti-seismic systems.

In order to transform the existing R/C walls into seismic resistant shear walls, different retrofit techniques are traditionally proposed. The retrofit can obtained by applying either reinforced concrete jackets, external post compression or externally bonded FRP (Fib Report, 1991; Fib Bulletin 24, 2003; Fib Bulletin 32, 2006; Fib Bulletin 35, 2006). However, these techniques are not always easy to apply to existing structures. For example, the strengthening of an existing R/C wall by means of traditional R/C jackets might require excessive thicknesses (about 100 mm), which could jeopardize the usage of the structure; whereas the application of FRP may be problematic because of the difficult anchorage of the fibers.

A new technique based on the use of jackets made of high performance fiber reinforced concrete was recently proposed for the strengthening of existing RC beams(Martinola et al., 2007; Maisto et al., 2006). The method resulted in a significant increase of the structure resistance; as a drawback, however, a limited ductility was observed.

The application proposed in this paper can be regarded as an enhancement of this technique. The solution is based on the use of high performance jacket made of high strength steel mesh, having a tensile resistance higher than 1200 MPa, embedded in a thin layer of high performance concrete, having a compressive strength higher than 140 MPa. By using these high performance materials, the jacket thickness can be significantly reduced with respect to a traditional solution.

In this paper, the proposed technique is validated by means of an experimental test on a 1:3 scaled shear wall. The experimental specimen was designed by reference to an existing three storey R/C building, which was proportioned to resist the vertical loads only. The high performance jacket was designed to entirely resist the seismic actions. The experimental results showed the efficiency of the proposed technique in increasing the structure bearing capacity and ductility.

A numerical study was also carried out to compare the performance of unreinforced R/C and strengthened shear walls. The numerical model was validated against the experimental results and was used to analyze the performance of a full scale strengthened shear wall.

2. EXPERIMENTAL STUDY

When performing a scaled test, special precautions must be taken for the scaled model to be effectively representative of the full scale structure. The definition of the geometry, as well as the choice of the materials and the applied loads are crucial aspects in the design of the experimental specimen. In this case, the model was built by scaling the lengths to 1:3 of their actual value.

For the construction of the R/C wall, the concrete mix design was defined by reference to a scaled aggregate grading curve, by adopting a maximum aggregate size of 15 mm. Hot rolled bars, having a diameter of 5 mm, were used for the traditional reinforcement of the R/C wall.

As for the jacketing, a high strength steel mesh was used. The mesh is made of 2 mm diameter bent wires, assembled with a spacing of 20 mm (Fig. 1a). The mesh is made of bent weaved wires. The bent prevents the unthreading of the wires from the mesh. The measured maximum strength of the single wire was always higher than 1000 MPa (Marini and Meda 2008). For the reinforcing jacket a high strength fiber concrete with a very compact matrix and with a maximum aggregate size of 2.7 mm was adopted. Given the reduced scale of the model, 6 mm fibers having a diameter of 0.16 mm were selected, with a content equal to 2.5% by volume. The resulting high performance fiber concrete exhibits a hardening behavior under tensile forces, and shows a compressive strength, measured on 100 mm cubes, higher than 140 MPa.

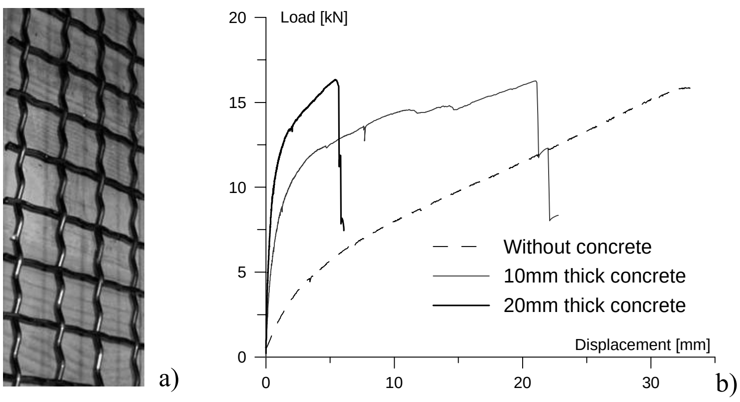


Figure 1. a) High strength steel mesh made of bent wires; b) tensile tests performed on the bare high strength steel mesh and on specimens made of high strength steel mesh embedded in 10 and 20mm high performance concrete layers.

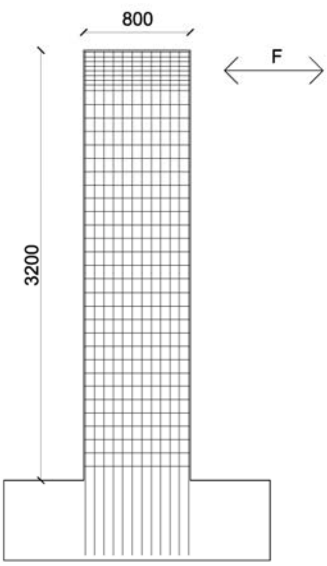
In order to assess the experimental behavior of the reinforcing jacket and in order to select the best performing jacket thickness, preliminary tests were performed on small specimens obtained with high strength steel mesh pieces embedded in a thin layer of high strength fiber concrete (Marini and Meda, 2008). As expected, the presence of the concrete layer remarkably increased the stiffness of the bare mesh wires (Fig.1b). It was observed that, in order to avoid crack localization and to guarantee larger structural ductility, the proportioning of the strengthening jacket must be carried out by controlling the ratio between the mesh diameter and the jacket thickness. Details on the experimental tests and on the material properties can be found in Marini and Meda (2008).

2.1 *Wall Specimen and Test Set-Up*

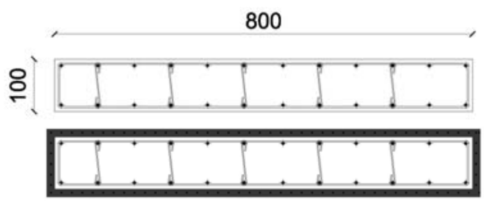
In order verify the effectiveness of the proposed strengthening technique an experimental test was carried out. Reference was made to the typical R/C wall of an existing three storey building. The R/C experimental wall was built in the reduced 1:3 scale.

The specimen, reproducing the typical stair block element of an existing building, was designed to resist the vertical loads only. The geometry of both the reference R/C wall and the scaled specimen is shown in Figure 2a-c. The scaled wall specimen has a height equal to 3.2 m (reproducing a 9.6 m real R/C wall) and a 100 mm x 800 mm cross section. The reinforcement is made of 5 mm diameter longitudinal rebars, having a spacing of 70 mm, and 4 mm diameter stirrups having a spacing of 100 mm. The R/C wall foundation block is anchored to the testing bench.

Upon completion of the R/C wall casting and curing, the reinforcing jacket was applied. In order to ensure perfect bond to the high performance jacket, the R/C wall surface was previously sandblasted in order to obtain a surface roughness of approximately 1-2 mm was obtained. This roughness was demonstrated to prevent any slip of the jacket (Martinola et al. 2007).



a)



b)

1:3 SCALE EXPERIMENTAL MODEL	REFERENCE FULL SCALE R/C WALL
Existing R/C wall	Existing R/C wall
Height 3.2m	Height 9.6m
Cross section 0.8x0.1m	Cross section 2.4x0.3m
Rebars ϕ5/70mm	Rebars ϕ16/200mm
High strength jacket	High strength jacket
Thickness 15mm	Thickness 45mm
Mesh ϕ2/20x20mm	c) Mesh ϕ5/50x50mm

Figure 2. a) Front view and b) cross section of the experimental model; c) geometric properties of the 1:3 scaled model and the full scale reference R/C wall.

After the steel mesh was fixed to the wall lateral surface, the high performance self-leveling fiber high performance concrete mix was poured into the moulds. A 15 mm jacket thickness was selected in order to obtain both a homogeneous casting and a sufficient mesh cover. The selected thickness results in a 45 mm jacket in a real scale application (Fig. 5c).

In order to properly anchor the steel mesh in the critical section at the wall footing, a 100 mm deep pocket was made in the foundation block.

The efficiency of the technique was verified by analyzing the structure performance in the critical zone, extending over the first inter-storey height, in which all the structure ductility develops. Given this foreword, the real seismic load was replaced by a point load applied to the wall top edge (F in Fig. 3a). The point load was applied by means of an electromechanical jack. Cyclic tests were carried out in displacement control. The reaction frame adopted for the experimental test is schematized in Figure 3a. The wall was fixed to the frame with eight pre-tensioned bars (P) in order to avoid significant displacements and rotations of the foundation block. A constant vertical load (N = 60 kN) was applied by means of two hydraulic jacks.

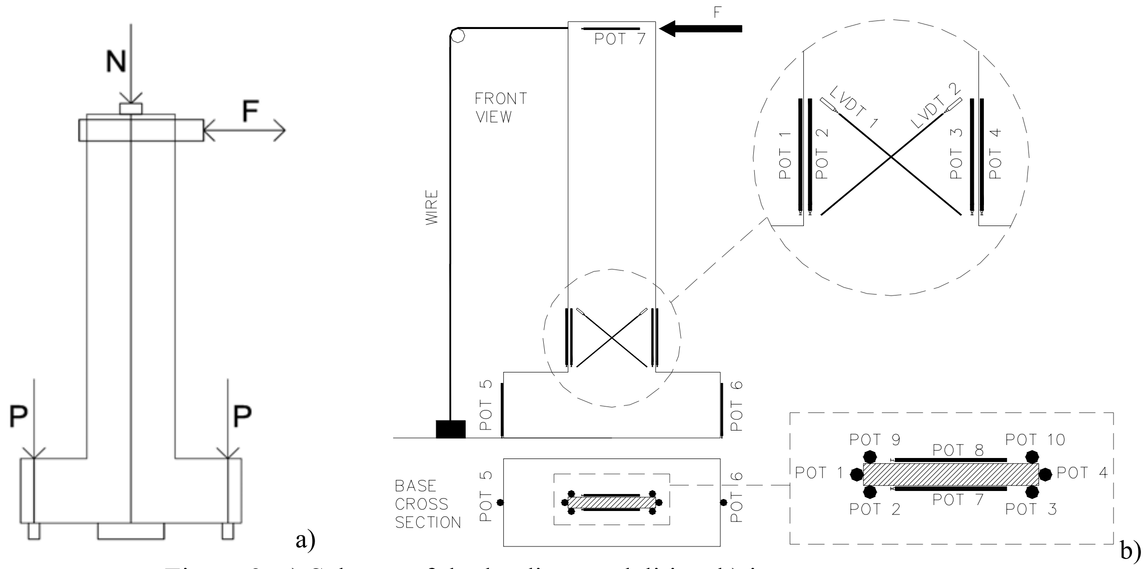


Figure 3. a) Scheme of the loading modalities; b) instrument set up.

The applied force was measured by means of a load cell placed between the electromechanical jack and the wall top edge. The top displacement was monitored by two different measurement system. By reference to Figure 3b, two linear potentiometers (one for each wall side top edge) were used to monitor the small displacements (Pot. 7-8), whereas a potenziometric wire transducer was adopted for the larger displacements. The rotation at the wall footing was measured by means of a series of linear potentiometers (Pot. 1-4, 9,10). The wall base shear deformation was surveyed by two LVDTs (LVDT 1 and 2). The rotation of the foundation block was measured by means of two linear potentiometers (Pot. 5-6).

3.2 *Experimental Test Results*

The experimental test was carried out by applying cyclic loads of increasing amplitude up to the structure collapse. Figure 4a shows the horizontal load versus top displacement curve. The behavior is almost linear up to 50 kN with a limited dissipated energy. By increasing the cycle amplitude the dissipated energy increases and the behavior becomes remarkably non linear. The structure yielding is recorded at a top displacement equal to 12 mm (δ_y); whereas the collapse is reached with a top displacement of 107 mm (δ_u) and a maximum load equal to 81 kN. The structure collapse is induced by the crushing of the strengthening jacket at the wall base (Fig. 5). The structural ductility (δ_u / δ_y) was estimated as equal to 9.

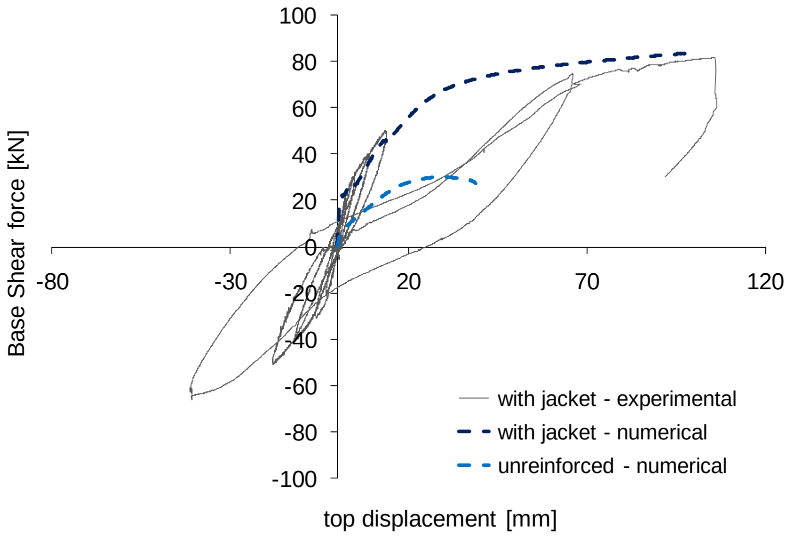


Figure 4. Applied horizontal load versus top displacement curve

a) b) c)

Figure 5. a) Side view of the deformed shear wall at collapse; b) detail of the crack pattern in the critical zone; c) collapse induced by the crushing of the jacket.

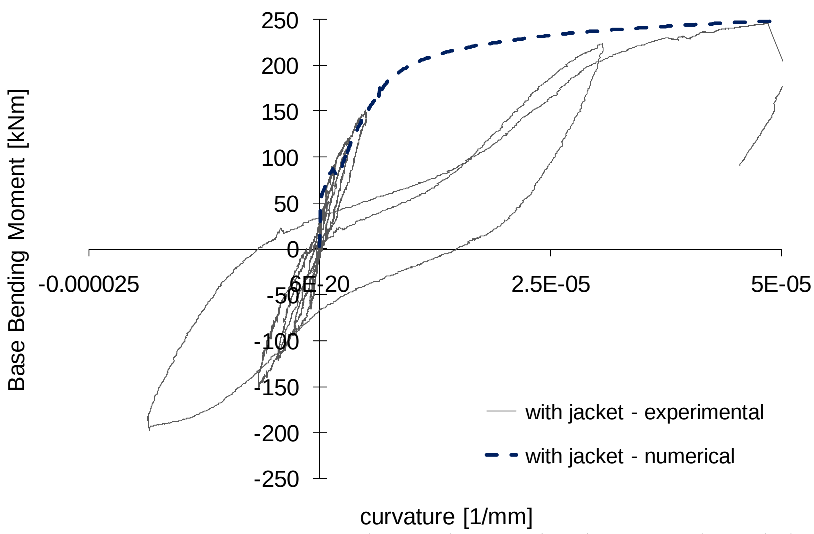


Figure 6. Bending moment versus curvature experimental curve for the strengthened shear wall and numerical response for the unreinforced R/C wall.

Figure 5a shows the pronounced deformation of the shear wall at collapse, as well as the details of both the crack pattern in the critical zone and the crushing of the jacket at the base. The cracks are almost equally spaced and have a limited opening (Fig. 5b). The cracks are mainly horizontal proving that the structure behavior is governed by the bending moment up to collapse, with no appreciable influence of the shear effects. The depth of the cracked area is almost 1.2 m (approximately equal to 1.5 times the shear wall cross section height). Neither crack localization, nor high strength mesh anchorage problems in the critical zone were observed. This way, plasticization could develop along a large portion of the shear wall throughout the test, resulting in remarkable structure deformability capacity. Unlike traditionally reinforced shear walls, a critical zone rather than a critical section was identified. Figure 6 shows the bending moment versus curvature at the base section. The experimental curvature was determined by referring to the displacement measured by the potentiometric transducers placed at the wall base edges (Pot. 1,4, Fig. 3b).

3. NUMERICAL ANALYSES

Besides the experimental investigation, the efficiency of the proposed technique was verified numerically by comparing the performance of unreinforced and strengthened shear walls. The numerical model was initially validated through comparison with the experimental results on the 1:3 scale R/C wall, previously illustrated.

Shear walls, either unreinforced or jacketed, were modeled by means of force-based fibre elements, based on the Timoshenko beam theory, implemented within the Finite Element Code FEAP (Taylor 2000). Force-based elements are computationally more demanding than displacement-based elements, but they offer the main advantage of being “exact” within the beam theory framework used for the formulation (Spacone et al. 1996). This leads to the use of one element per structural member (beam or column) in a frame analysis, thus requiring a lower number of nodal degrees of freedom. This results in the faster assembly of the numerical mesh, which might in turn be a significant advantage for practitioner engineers. Therefore, for the numerical analysis, the shear wall was modeled by means of a single element, having 5 control sections. A simple linear shear force-shear deformation law was used at the section level (Marini and Spacone 2006).

As for the materials, ordinary and high strength concrete and steel were described by Kent-Park and Menegotto-Pinto constitutive laws, respectively. The mechanical properties were obtained experimentally, by testing small specimens collected during the shear wall construction. Details can be found in Marini and Meda (2008). The material parameters are summarized in Table 1.

Table 1. Material properties

Ordinary concrete	High strength concrete	Ordinary steel	High strength steel
Kent & Park	Kent & Park + Tens	Menegotto & Pinto	Menegotto & Pinto
f_c = 17 MPa ε_{fc} = 0.002 $\varepsilon_{20\%fc}$= 0.007	f_c = 140 MPa ε_{fc} = 0.002 $\varepsilon_{20\%fc}$= 0.014 f_{ct} = 6 MPa E_{ts} = 20000 MPa	f_y = 480 MPa E_s = 200000 MPa b = 0.005 (hardening ratio) r_0 = 20.0 (exponential transition elastic-plastic) a_1 = 18.5 (coeff1 variation r_0) a_2 = 0.15 (coeff2 variation r_0)	f_y = 1000 MPa E_s = 200000 MPa b = 0.03 (hardening ratio) r_0 = 20.0 (exponential transition elastic-plastic) a_1 = 18.5 (coeff1 variation r_0) a_2 = 0.15 (coeff2 variation r_0)

In order to validate the model the experimental test was simulated. Accordingly, preliminary nonlinear pushover analyses were carried out by applying a horizontal displacement of increasing amplitude to the 1:3 scale wall top edge. The horizontal load versus top displacement curve of the strengthened shear wall is shown in Figure 4. The numerical response closely approximates the experimental curve, both in terms of initial stiffness and strength (Figure 4). In the same figure, the response curve of a 1:3 scale unreinforced R/C wall is illustrated. The remarkable stiffening and strengthening effect of the reinforcing jacket can be observed. The maximum base shear force is more than twice as large as the maximum resistance of the traditional R/C wall. More importantly, the ductility is significantly increased. The same comparison is made in terms of bending moment versus curvature at the base section in Figure 6.

Upon completion of the preliminary tests, the unreinforced and jacketed full scale shear walls were modeled. The geometry is briefly described in Figure 2c. The material properties are those of Table 1. The vertical load was amplified, to reproduce the cross section stress level of the 1:3 scaled model (N = 540kN).
The load versus top displacement curves of the full scale unreinforced R/C wall and the strengthened shear wall are shown in Figure 7. The response of the unreinforced R/C wall initially shows a piecewise linear behavior up to the yielding of the steel reinforcement (point 2' in Fig. 7). A significant reduction of the structure stiffness is observed upon overcoming the ordinary concrete tensile strength (point 1'). For increasing applied displacement the curve is nonlinear as a result of the progressive yielding of the reinforcement occurring along the element cross section. The structure capacity is reached when the rebars yield in compression (point 3'), whereas the structure failure occurs when concrete crushes in compression (point 4').
The response of the shear wall strengthened by means of high strength 45 mm jacket is shown in Figure 7. The tensile strength is first overcome in the original wall (point 1) and later in the reinforcing jacket (point 2). The stiffness reduction is observed while the ordinary reinforcement of the inner core yields (point 3). The high strength steel mesh starts yielding when the load is almost twice as large as the shear capacity of the unreinforced R/C wall (point 4). The stiffness reduces as a result of the softening of the concrete, which occurs upon overcoming the compressive resistance of the ordinary and the fiber reinforced concrete (points 5 and 6, respectively). The further increment of the structure resistance is governed by the hardening behavior of the high strength steel mesh. Unlike the experimental wall, no high strength concrete crushing was observed in the numerical model at this level of deformation. Concrete crushing was observed for a much larger drift of 5%.

The numerical results confirm the effectiveness of the proposed technique. By applying a very thin high strength jacket, R/C walls of existing buildings can be transformed into shear walls, characterized by a large stiffness and strength, as well as a pronounced deformation capacity and ductility.

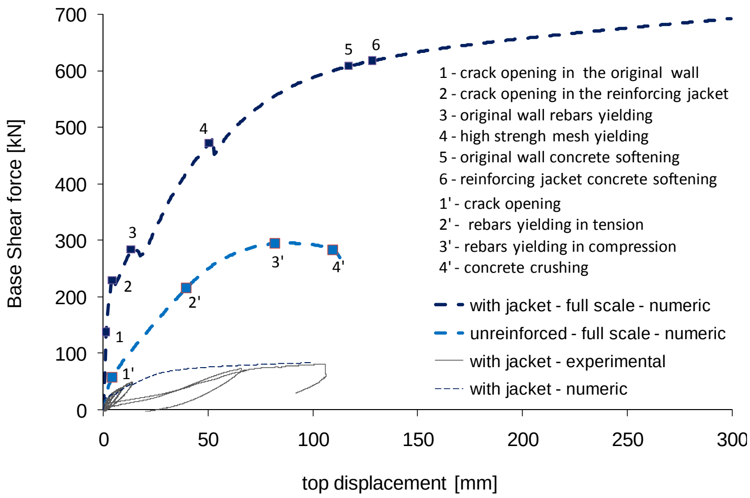


Figure 7. Full scale model: applied horizontal load versus top displacement curve.

4. CONCLUDING REMARKS

The strengthening of existing R/C walls by means of thin high performance jackets, made of high performance fiber concrete reinforced with high strength steel meshes, was presented in this paper. As a result of the strengthening, the RC walls of existing buildings, which are usually designed to resist the vertical loads only, can be transformed into shear walls effectively enduring the seismic actions.

The experimental and numerical results discussed in the paper allow drawing the following concluding remarks:

- the use of a very thin high performance jacket allows to double the structure ultimate resistance. More importantly, the proposed technique allows to largely increase the structure deformation capacity and ductility, which are the main goal of every seismic strengthening design;
- the structure failure is characterized by the wall base concrete crushing and by a crack pattern uniformly extending over a critical zone. The depth of the critical zone is approximately equal to 1.5 times the shear wall base. Unlike traditionally reinforced shear walls, no damage localization in a single critical section is observed;
- the structure behavior was governed by the bending moment up to collapse, with no appreciable influence of the shear effects;
- the proposed technique can be easily used in structural applications, provided that its construction requires neither special works or special man labor. The high strength steel meshes can be fold by the producer prior to its transfer to the construction site and the high performance concrete can be easily pumped;
- as a drawback, however, the strengthening of the existing RC walls results in significant horizontal shear forces to be transferred to the foundations, which in turn may need structural strengthening works.

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