Corroded RC columns repair and strengthening with high performance fiber reinforced concrete jacket

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Abstract

Reinforcement corrosion can induce severe damage in reinforced concrete columns leading to a relevant loss of bearing capacity. This condition can be even more critical in case of seismic events. The possibility of repairing and strengthening corrosion damaged columns by means of high performance fiber reinforced concrete jacketing is investigated herein. The main aim of the retrofit intervention is not only to restore the original bearing capacity, but also to increase the column durability. In order to investigate the effectiveness of the proposed technique, full-scale tests on reinforced concrete columns under cyclic loads have been performed. Two columns were artificially corroded and one of them was repaired with a high performance fiber reinforced concrete jacket. The obtained results are compared with those measured on a third un-corroded reinforced concrete column.

Keywords: Reinforcement Corrosion; High Performance Fiber Reinforced Concrete, Strengthening, Repair, Jacketing, Cyclic Tests.

1. Introduction

The lack of durability, typically related to reinforcement corrosion, is a cause of concern in several reinforced concrete (RC) buildings, particularly when low strength concrete is used. A retrofit intervention on these structures should have the scope not only to restore the original bearing capacity but also to ensure an adequate durability to the structure.

The feasibility of using high performance fiber reinforced concrete (HPFRC) for strengthening RC structures has been investigated by several researchers in the last few years [1-12]. In particular, the effectiveness of the adoption of a HPFRC jacket for the retrofitting of existing columns subjected to seismic action has been demonstrated in [12].

The possibility of applying this technique to corroded RC columns is investigated herein. The problem of structural element corrosion is amplified when low strength concrete is adopted (typical of the ’60 and ’70 buildings), as high carbonation or chloride penetration may accelerate the rebar chemical attack. In these structures, the lack of bearing capacity due to the use of low strength materials in combination with the possible corrosion of the reinforcement may be of serious concern. A high performance fiber reinforced concrete jacket can be adopted for repairing or strengthening corroded columns with the aim of ensuring adequate bearing capacity to the structures after the intervention. Furthermore, due to the compactness of the HPFRC concrete matrix and the reduced crack opening, the jacket can protect the existing column and increase the durability of the system, as highlighted in [13, 14].

In order to investigate the proposed solution, full-scale tests on columns subjected to cyclic loads have been performed. In particular, three specimens with the same geometry and materials are designed, cast and tested. The first one is an un-corroded reference column, the second one is corroded and the last one is firstly corroded and then repaired with a 40 mm thick HPFRC jacket. The results show the effectiveness of the proposed solution.

2. Experimental programme

Three columns have been cast for the experimental tests, named UC (Un-Corroded), C (Corroded) and CR (Corroded and Repaired). Figure 1 shows the specimens geometry and reinforcement. The columns have a 300x300 mm square section and a height of 1600 mm. The longitudinal reinforcement is made of four ϕ16 mm rebars, while the transverse reinforcement is made of ϕ8 mm closed stirrups spaced at 300 mm. The longitudinal rebars (in Tempcore steel) exhibited an average yield strength equal to 520 MPa and an average maximum strength equal to 620 MPa.

The geometry of the column foundation (1300x600x500 mm) is shown in Figure 1.

All the specimens were cast with concrete from the same batch, characterized by a mean cubic compressive strength equal to 20 MPa. The reinforcement detailing and the concrete strength are typical of structures built in Italy in the 60's and 70's, the only difference being the use of Tempcore ribbed bars instead of plain un-deformed ones.

Two of the columns (C and CR) were subjected to an artificial corrosion of the longitudinal rebars. Since the aim of the paper was the evaluation of the bending behaviour of the columns, the stirrups were coated in order to avoid their corrosion.

2.1 Corrosion process

The longitudinal reinforcement of the columns has been corroded up to a theoretical level equal to 20% in terms of mass loss. The corrosion entity was chosen on the basis of preliminary tests [15], in order to have typical longitudinal cracks, visible to the naked eye, reaching the external surface of the concrete cover. This situation is, unfortunately, very common in existing structures, when the corrosion damage is detected only when the process is in an advanced stage.

The corrosion was obtained with an accelerated process through electrolytic cells (Fig. 2b) with the columns dipped in a 3% saline solution. A preliminary survey was organized with the aim of obtaining the required corrosion entity in the rebars, to check the corrosion morphology, to evaluate the corrosion influence on the steel constitutive relationship, and the effect of the concrete in the rebar corrosion process. In particular, both bare bars and embedded bars were subjected to corrosion and eventually tested in tension. In the second case, specimens identical to those used for the cyclic tests were cast (both in terms of geometry and material properties), with the aim of calibrating the corrosion process (current intensity and time necessary for the required corrosion level). An in depth description can be found in [15].

On the basis of the obtained results, the corrosion process was assessed. The saline solution (3% NaCl), necessary for the accelerated electrolytic corrosion, was contained inside a PVC Ø500 mm pipe, placed around the column as shown in Figure 2, and fixed to the foundation through specific sealing products. The current intensity was equal to 0.5 A for each bar. The scheme of the electrolytic cell is shown in Figure 2. The four Ø16 embedded bars represent the anodes, while four Ø10 diameter steel bars, placed inside the pipe, worked as cathodes. The time necessary to obtain the desired corrosion level, (20% in mass loss), was evaluated with Faraday's law, suitably modified in order to account for the concrete presence, as shown in [15]. Figure 3 shows the effects of corrosion on the rebars obtained in the already mentioned dummy columns having the same section, concrete and rebars of the column specimens, analysed in the preliminary phase. The bars, extracted from the concrete, presented pits along their length, distributed both in the upper and bottom parts of the specimens (Fig. 3b), as often found in rebars subjected to natural corrosion. Some of the load-displacement diagrams measured during the tests [15] are briefly summarised in Figure 3c.

Finally, Figure 4 shows the columns C and CR after the corrosion. It can be noticed a typical crack pattern due to rust expansion, with longitudinal cracks close to the steel rebars, often involving the whole specimen length.

2.2 HPFRC jacket application

One of the corroded columns (specimen CR) was prepared for the HPFRC jacket application. To this aim the following steps were followed:

- the deteriorated cover in correspondence to the four longitudinal bars was removed and the reinforcement was manually brushed to eliminate the corrosion products;

- a 80 mm deep pocket was made in order to ensure the connection of the jacket with the foundation, as made in previous researches [12] (Fig. 5);

- the surface of the column was sandblasted in order to obtain a roughness of about 1 mm (Fig. 6) to ensure the adhesion between the old concrete and the HPFRC jacket (as investigated in [8]).

Finally, a jacket having a thickness of 40 mm has been cast with a self-levelling HPFRC (Fig. 6), having a maximum aggregate size of 1.3 mm and water/binder (cement + microsilica) ratio equal to 0.17 by weight. The concrete was reinforced with 1.2% (by volume) straight, 15mm long, steel micro-fibers with a diameter of 0.18 mm and an ultimate tensile strength of 2000 MPa. The average compressive strength of the material, measured on cubes after 28 days of curing, is about 130 MPa. The uniaxial tensile strength, measured on dog-bone specimen (Fig. 7a), is approximately equal to 6 MPa, while the flexural load, measured on four-point bending tests (Fig. 7b), is equal to 42 kN (nominal stress equal to 12.6MPa). As highlighted from the uniaxial tensile test (Fig. 7a), the material is characterized by a strain–hardening behaviour in tension up to 0.15% strain, followed by a stable and slightly degrading softening behaviour.

The HPFRC material was prepared in a vertical axis mixer and was cast in moulds without vibration. Since curing was carried out at ambient temperature and humidity, the column was wrapped with a plastic film in order to limit water evaporation.

3. Testing set-up

The three columns were subjected to cyclic tests in the Laboratory of the University of Bergamo.

The column foundation was anchored to the laboratory strong floor with two steel profiles and four pre-tensioned high strength rebars. An axial load of 400 kN ($\upsilon = N/f_c A_c = 0.22$, being f_c the concrete compressive strength and A_c the column section) was applied with two hydraulic jacks and monitored by a pressure transducer. A self-balanced system allowed applying the axial load to the column

(Fig. 8a). The horizontal cyclic load, applied at a height of 1.5 m from the column foundation connection, was given by means of an electro-mechanical jack fixed to the reaction wall of the laboratory. The jack was linked to the column by means of a hinged bar system along which a load cell was placed. The test set-up is shown in Figure 8a.

In order to measure the horizontal displacements, potentiometric transducers were placed on the column at the level of the load application (1.5 m from the column base; instruments 2-3 in Fig. 8b). A series of potentiometric transducers placed on one of the column faces measured the rotations at the column base. The devices 10-11 of Figure 8b measured relative displacements between the column base and the foundation, whereas devices 4-5-6-7-8-9 in the same figure measured relative displacements between points along the column. Two LVDT devices (14-15 in Fig. 8b) registered possible slip movements of the foundation. Finally, a pressure transducer was connected to the pump for the axial load monitoring. After the axial load application, the specimens were subjected to horizontal cyclic displacements of increasing amplitude, up to the failure.

The loading history was assigned according to the document [16], which defines the standard test procedure for full-scale moment-resistant elements. Once defined the drift (δ/h), as the ratio between the horizontal displacement at the load application point (δ) and the column height (h), the guide line suggests to perform three complete cycles for each drift with an intermediate unloading cycle between a triplet and the following one. The initial drift (equal to 0.15%) was chosen for capturing the elastic behaviour of the specimen. Details of the horizontal displacement history are reported in Figure 8c.

4. Results

4.1 Undamaged column (UC)

The results related to the un-corroded specimen (*UC*) are summarised in the load-drift diagram shown in Figure 9a. The first horizontal cracks appeared for a displacement of 4.50 mm (drift equal to 0.30%). The specimen behaviour was almost linear up to a drift of 0.75%. Below 1% drift, the cracks were approximately horizontal with a spacing almost coincident with the stirrup spacing. The extension of the cracked zone was about 700 mm from the column base. The maximum loads, measured for positive and negative cycles, were equal to 63 and 61 kN, respectively. The related drifts were equal to ±2%. In the cycles beyond 2% drift, a progressive strength degradation was observed, up to a value of about 40 kN (approximately 64% of the maximum load), related to a 5% drift. At this point, the test was stopped, due to the cover spalling and concrete crushing observed at the column base, involving a zone with a height approximately equal to the section side. Moreover, the buckling of one of the reinforcing bars was observed. The final state of the specimen, for a drift equal to 5%, is shown in Figure 9b.

4.2 Corroded column (C)

The results related to the corroded specimen (*C*) are summarised in the load-drift diagram shown in Figure 10a. The first cracks appeared for a displacement equal to 3.75 mm (0.25% drift). The maximum measured positive load was approximately equal to 44 kN for a drift of 1.0%, while the maximum negative one was approximately equal to 46 kN for a drift of 1.25%. A significant strength reduction was observed after the cycles at 1.5% drift. The load at 2% drift was approxiametly equal to 36 kN, (78% of the maximum measured load), while the force related to the last step (third cycle, 2.5% drift) was approximately equal to 5 kN.

Horizontal cracks located at the column base, within an extension of about 700 mm from the foundation appeared for cycles ranging from a drift of 0.25% to 1.00%, growing in number and extension. The vertical cracks, due to corrosion, visibly opened for the cycle corresponding to 1% drift; while cover spalling occurred for a 2% drift. The test was stopped at a drift equal to 2.5%, after complete concrete crushing. Buckling of all the reinforcement bars was clearly noted. The final state of the specimens, for a drift equal to 2.5%, is shown in Figure 10b.

At the end of the tests, the four steel rebars were cleaned and weighted. The measured mass losses, equal to 22.6%, 18.7%, 20.6% and 24.1% for the four bars, highlighted the effectiveness of the corrosion process in providing the foreseen corrosion level (20% mass loss).

4.3 Jacketed column (CR)

The results related to the corroded and repaired column specimen (*CR*) are summarised in the load-drift diagram shown in Figure 11. The first cracks appeared for a displacement of 4.5 mm (0.30% drift). The maximum recorded positive load was approximately equal to 86 kN at a drift of 0.75%, while the maximum negative load was approximately equal to 100 kN, at a drift of 1%. In the cycles following 1% drift, a significant strength reduction of the column was observed.

Horizontal cracks at the column base appeared for cycles ranging from a drift of 0.30% to 0.75%, within an extension of about 600 mm from the foundation (Fig. 12a). The crack patterns at drift levels of 0.75% and 2% are shown in Figure 12.

From a drift of 0.75%, the cracks development in the external jacket was stable (Figure 12a) while a local damage of the HPFRC jacket at the column-foundation interface took place at 2% drift (Figure 12b and 12c). In the case of positive drift, damage is not localized exclusively at the column-foundation interface, but there was a gradual detachment of the fiber reinforced jacket from the base foundation. The progressive pinching of the cycles for drift values higher than 1.5% is related to the detachment of the HPFRC layer at the base, whereby the contribution of the tensile strength of the jacket layer at the base is progressively lost, and a rocking mechanism takes place at the column base. The column has reached the collapse during the third cycle at 2% drift, due to the rupture of one of the longitudinal rebars during the positive drift cycle. In order to gain further knowledge of the specimen behaviour, it was decided to perform even the cycles at 2.5% drift, since for negative drifts the residual load was still high. The test was stopped at the second 2.5% drift cycle, when a second reinforcing bar failed. At the time, the load was equal to 82 kN, corresponding to 82% of the maximum strength reached for negative drift cycles.

5. Comparison of the results

The load-drift diagrams of all the specimens are compared in Figure 13. The main results, both in terms of maximum bending moments and drifts, are summarised in Table 1. The corroded column shows a decrease of the maximum strength of about 26% (rebar corrosion about 20% in weight) and a marked decrease of maximum deformation (up to 50%) with respect to the undamaged one. Furthermore, the sharp reduction of stiffness, occurring in the last two cycles of the corroded specimen test, has to be remarked.

The results obtained from the jacketed specimen showed the effectiveness of this technique for strengthening columns with corroded longitudinal rebars. The maximum load for both positive and negative drifts is higher than the peak load reached by the undamaged specimen. The maximum load measured for negative drifts, the direction in which the strengthened specimen showed a correct failure mode, is increased of about 65% and 118%, if compared to those of the undamaged and corroded columns, respectively. The shape of the envelope curve is typical of the behavior of a section characterized by a RC core with a HPFRC jacket. After reaching the maximum load, the strength of the specimen suddenly decayed because the tensile contribution of the HPFRC gradually disappeared due to the opening of a macro-crack between the column base and the foundation. In the cycles after the peak load (for negative drifts) the load was however higher than that of the un-corroded specimen for the compression contribution of the HPFRC jacket, which leads to a noticeable increase of the section internal lever arm. The specimen with HPFRC jacket did not show crushing of the concrete cover or deformation of the longitudinal rebars due to the confinement action exerted by the layer of high performance concrete.

A comparison between the experimental results of the three specimens has been further performed in terms of dissipated energy, normalized with respect to the "elastic energy", defined as the product of the maximum force (F_{max}) for the related displacement (δ_{max}), as shown in Figure 14. For the sake of comparison, the reported results are limited to a 2.5% drift (ultimate value in the *CR* specimen).

The specimen with a fiber reinforced jacket (*CR*) shows a better behavior in terms of energy dissipation. For cycles related to relatively high drifts (0.75% - 1.00%) the energy dissipated by the

CR specimen is about 50% higher than for the *UC specimen* (reference, uncorroded specimen) and 30% higher than the *C* (corroded) one. It is observed that the dissipated energy for the strengthened columns during the cycles triplets is stable, proving the validity of the proposed strengthening technique.

6. Conclusions

The influence of the rebar corrosion on the cyclic behaviour of rc columns and the effectiveness of the application of a thin HPFRC jacket as a repair technique have been discussed in the paper, on the basis of three full-scale tests. The analysis of the obtained results allows drawing the following remarks:

- the corrosion phenomenon can strongly affect the global behaviour of columns subjected to cyclic loads. In the tested case (characterized by rebar corrosion leading to approximately 20% in mass loss) a reduction of about 30% of the ultimate force and a reduction of ultimate displacement of about 50% was detected, together with a significant stiffness decrease in the last cycles. As a consequence, the corrosion phenomenon can strongly affect the local (plastic hinge properties) and global behaviour of structures under seismic actions and can significantly change their failure modes;
- by applying a high performance jacket it is possible to increase the bearing capacity of the column with corroded rebars reaching a maximum strength greater than the one of the undamaged element. This technique is suitable for strengthening existing RC structures characterized by low concrete strength, low reinforcement ratio, concrete damage and reinforcement corrosion;
- the use of a high performance concrete layer can protect the internal column and increase its durability.

Finally, the proposed technique can be easily used in structural applications as it allows strengthening R/C elements by means of a thin jacket (40 mm). Furthermore, a curing at ambient temperature and humidity is sufficient to grant the development of the full strength and a simple sandblasting ensures bond between substrate and HPFRC.

7. Acknowledgments

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8. References

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Tables

Table 1. Positive and negative bending moments and drifts

	M_{max}+ [kNm]	$(M/M_{UC})^+$	M_{max}- [kNm]	$(M/M_{UC})^-$	δ_{max}+ [%]	δ_{max}- [%]	δ_u+ [%]	δ_u- [%]
UC	92.6	1.00	89.1	1.00	2.00	1.50	5.00	5.00
C	65.0	0.70	67.3	0.76	1.00	1.25	2.5	2.5
CR	130.0	1.40	147.1	1.65	0.75	1.00	2	2.5

Figures

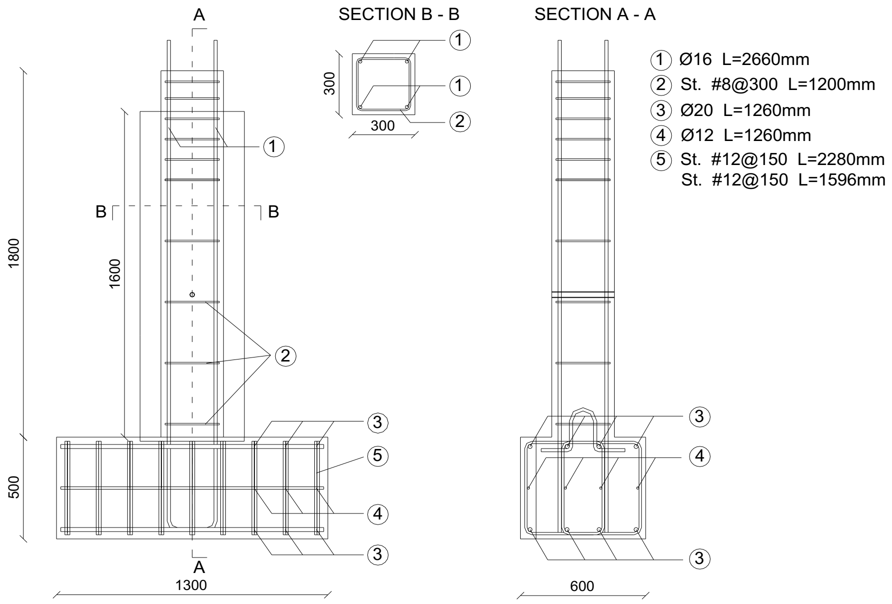


Figure 1. Geometry of the specimens

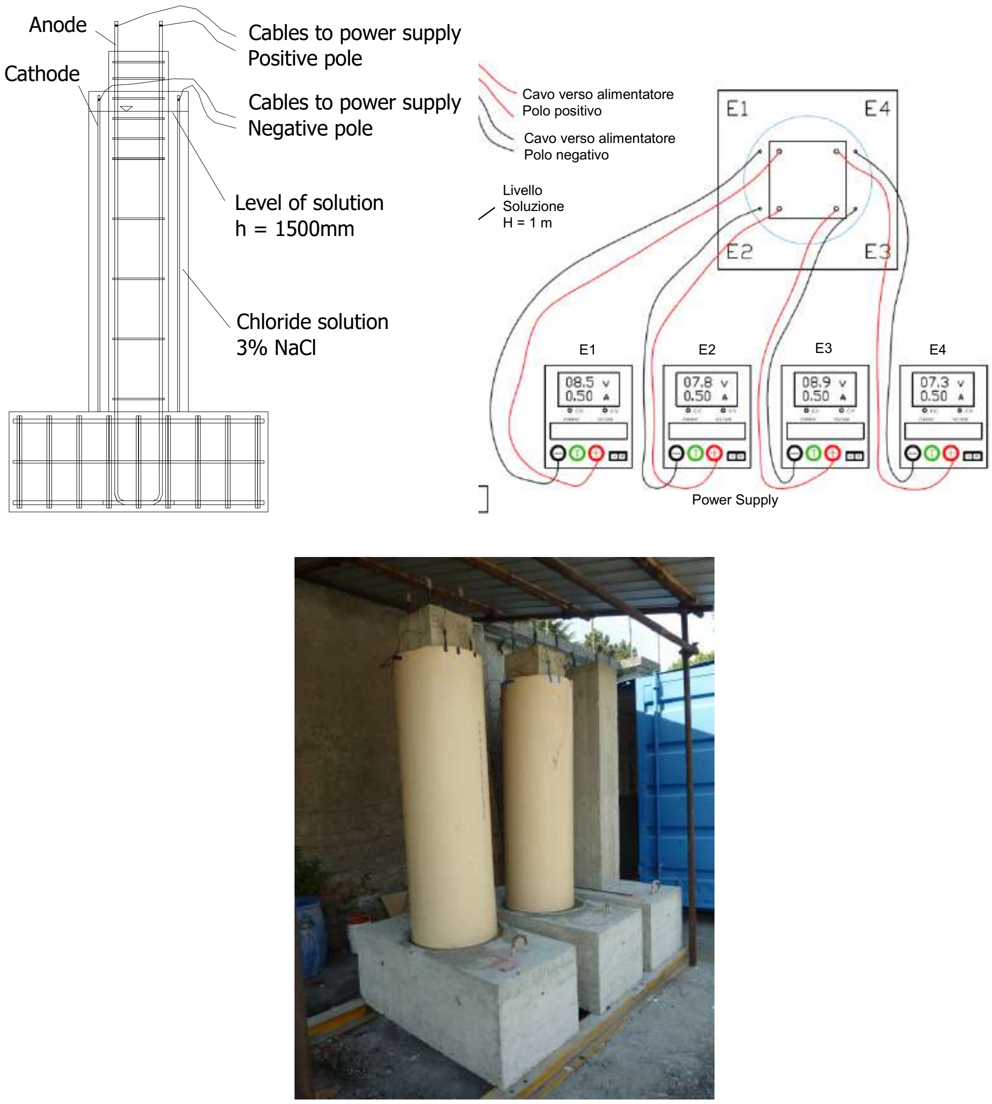


Figure 2. Accelerated corrosion process

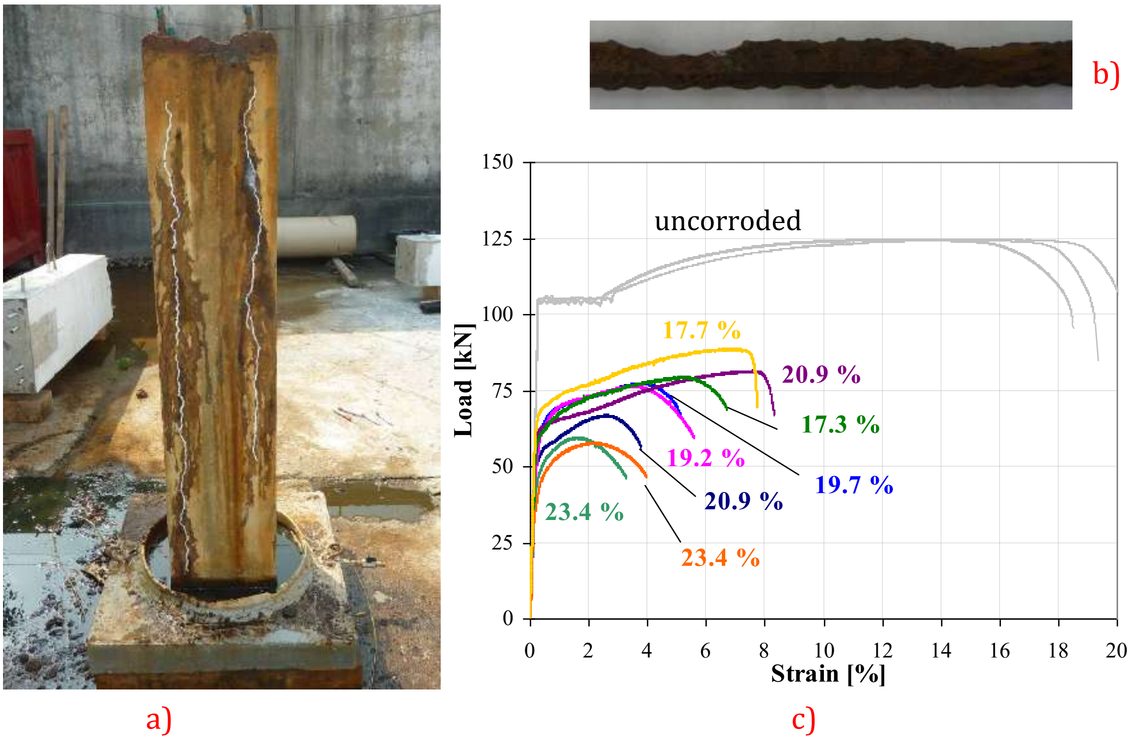
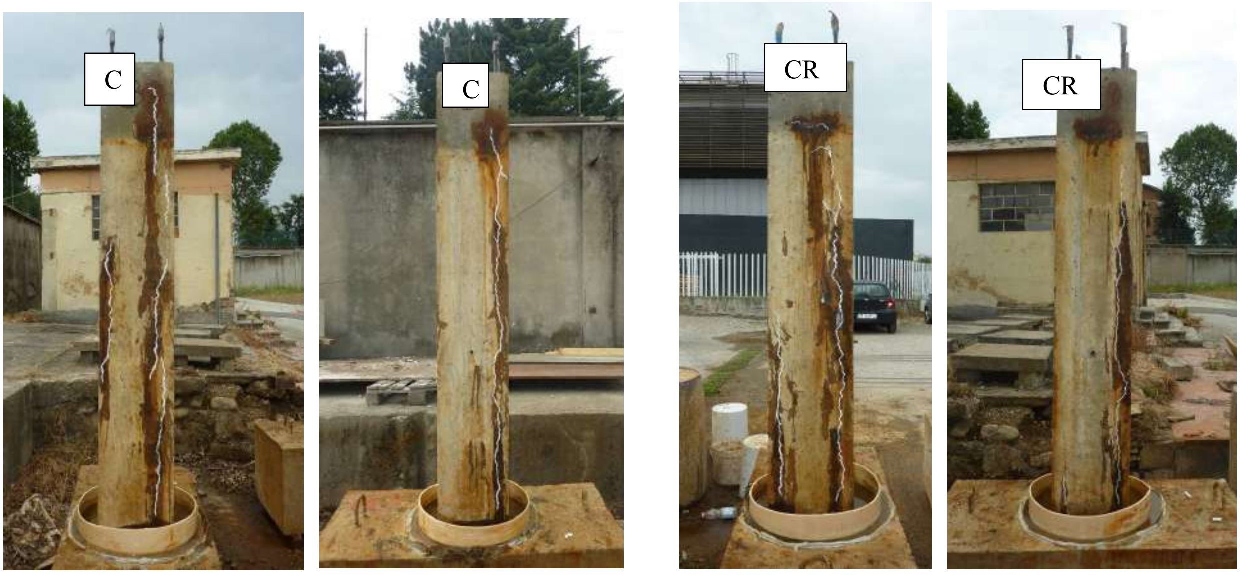


Figure 3. a) Dummy specimen after corrosion; b) state of the corroded rebar; c) Load-strain relationship of uncorroded and corroded rebars extracted from the specimen (corrosion expressed in % of mass loss marked next to each curve)



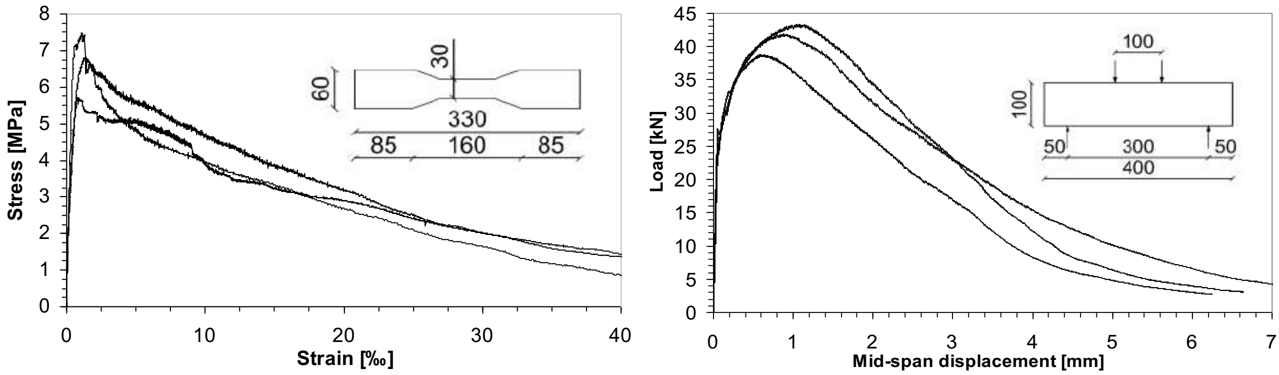
a) b)

Figure 4. Specimen after corrosion process – crack pattern; a) specimen C; b) specimens CR

Figure 5. Specimen CR: Cover removal and foundation socket, before jacket cast

(a) (b) (c)

Figure 6. Specimen CR: a); b) sandblasting; c) HPFRC jacketed column



a) b)

Figure 7. HPFRCC tensile strength; a) uniaxial test; b) 4-point bending test

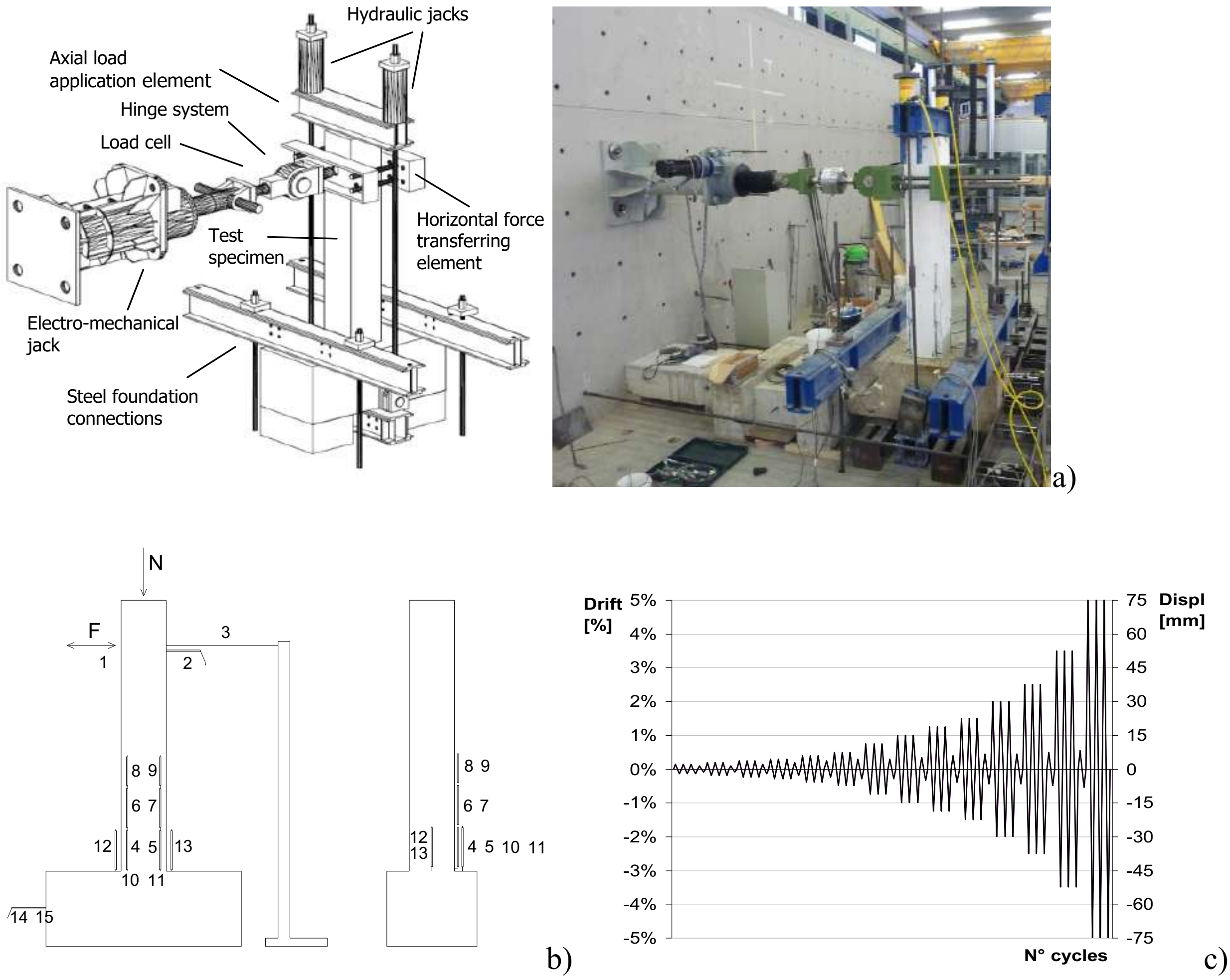


Figure 8. Test set-up for cyclic loading (a), instrument devices (b) and loading history (c)

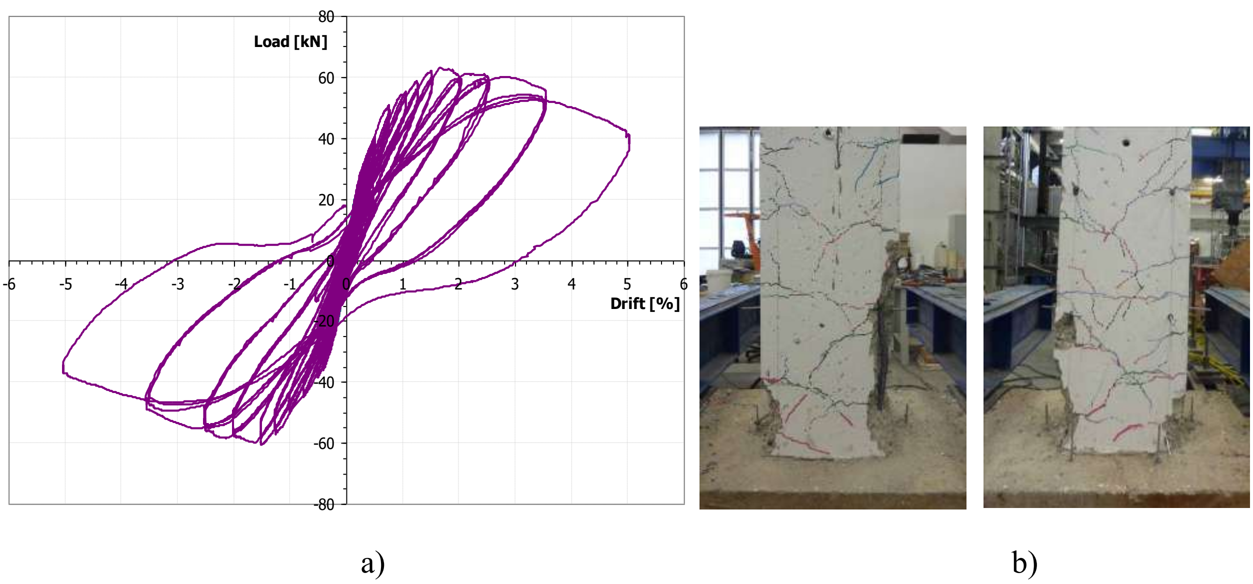
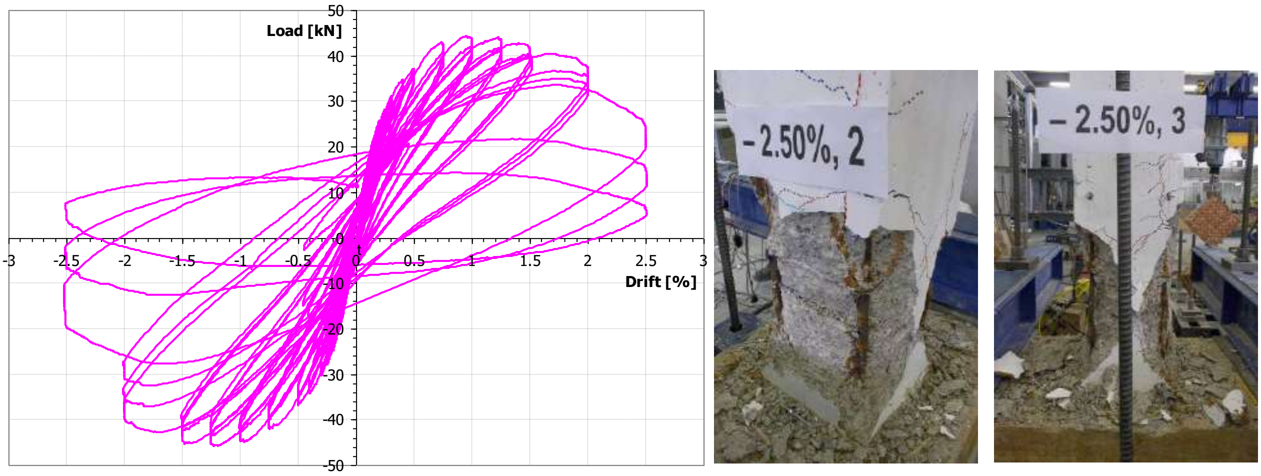


Figure 9. Reference uncorroded specimen UC: a) Horizontal load –drift; b) crack pattern at the end of the test



a) b)

Figure 10. Corroded column (C): a) Horizontal load – drift; b) crack pattern at the end of the test.

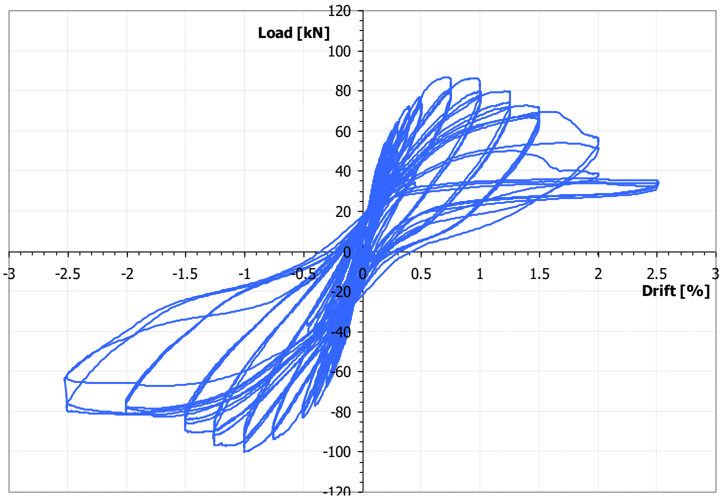
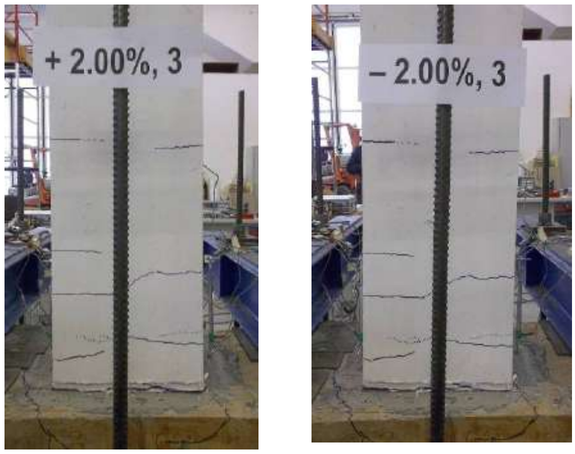


Figure 11. Corroded Reinforced column (CR): Horizontal load – drift;

a)



b)

c)

Figure 12. Corroded Reinforced column (CR): Crack pattern at a drift of 0.75% (a) and 2% (b, c)

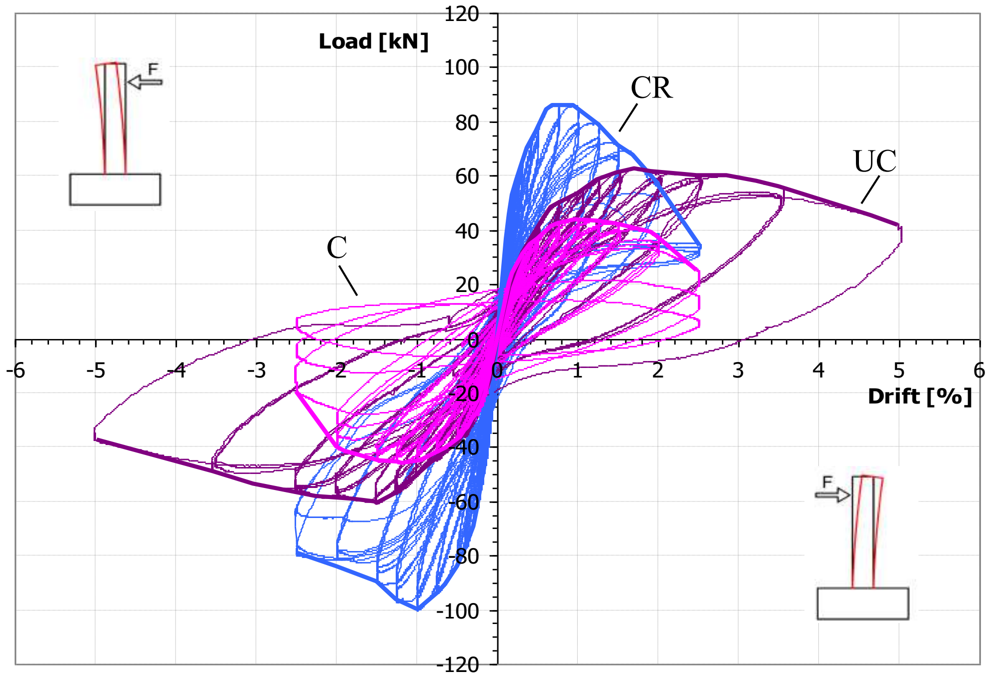


Figure 13. Load-drift relationship: comparison

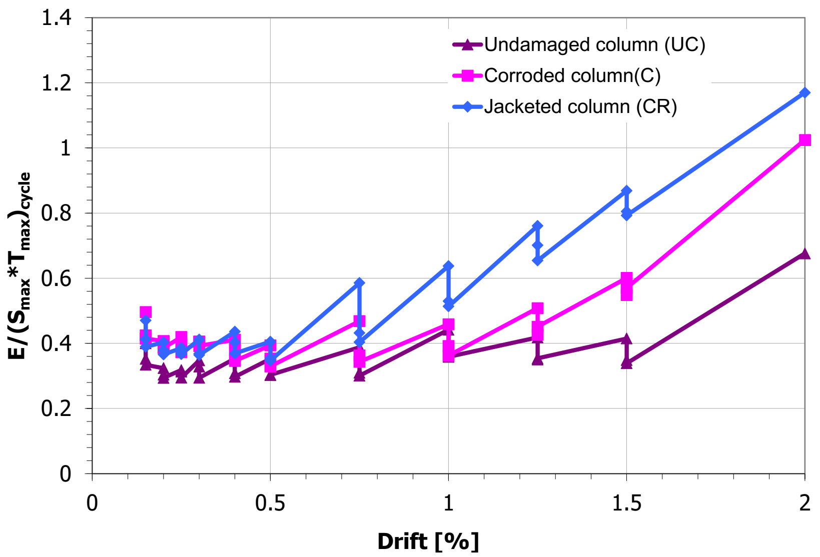


Figure 14. Dissipated Energy