

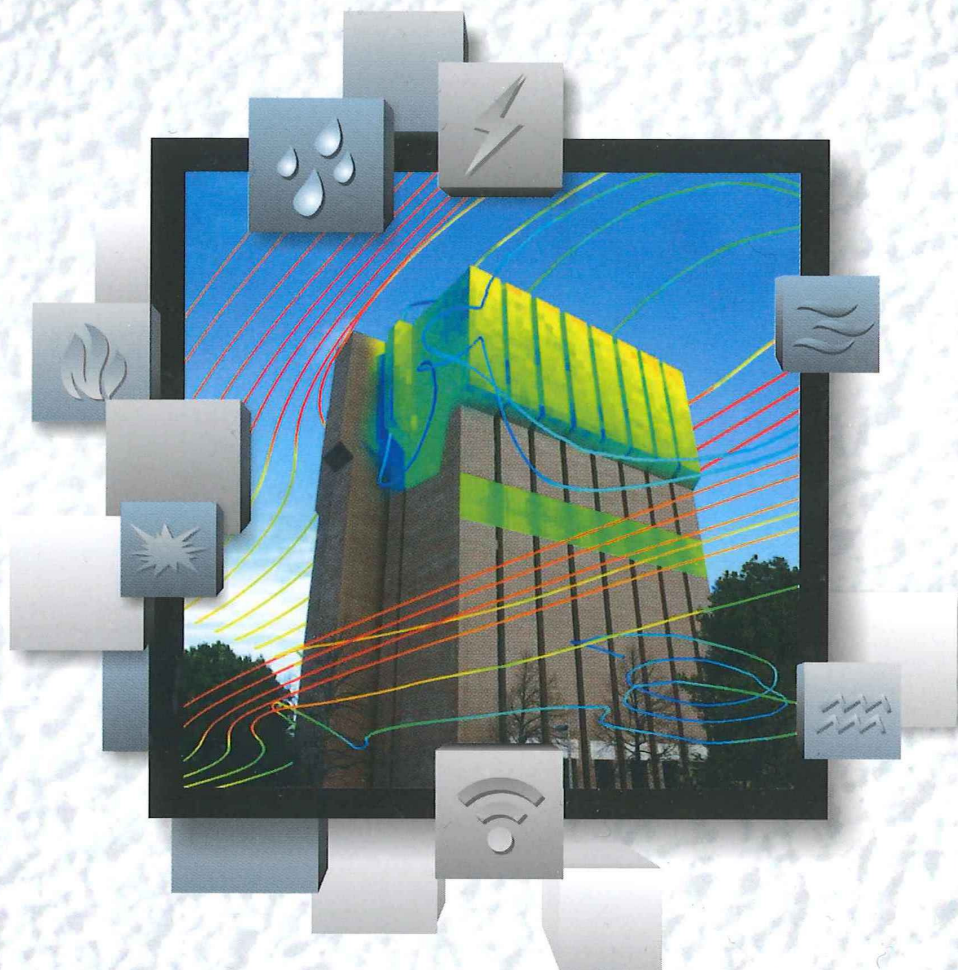
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**Proceedings**

## Performance, Protection & Strengthening of Structures Under Extreme Loading



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## **Strengthening of RC columns with corroded reinforcement by means of high performance jacket**

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### **Abstract**

Corrosion of reinforcement is one of the leading cause of the deterioration in reinforced concrete structures. Hence, in their retrofitting it is necessary to determine the corrosion damage to estimate the residual structural strength and to define strengthening techniques which allow to recover the initial capacity of the structure.

The aim of the research is to evaluate the effectiveness of a new strengthening technique based on an application of a high performance fiber reinforced jacket for the retrofitting of RC columns with problems of reinforcement corrosion.

Three full-scale experimental tests on column specimens have been performed. The first part of the study concerns the artificial corrosion of the steel bars of the specimens through the use of the electrolytic cells. In the second part of the research the specimens have been loaded with static horizontal cyclic loads with increasing amplitude, up to the failure.

The obtained results show the effectiveness of this technique in recovering the original bearing capacity of the columns, reaching also an adequate ductility level.

**Keywords:** high performance fiber reinforced concrete, seismic retrofitting, reinforcement corrosion, jacketing, cyclic test.

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## 1.0 Introduction

The reduction in the useful service-life of reinforced concrete structures, mainly due to reinforcement corrosion, is a cause of concern for several RC buildings. The structural consequences on an element affected by corrosion are multiple. The reduction of the resistant section, the decrease of the carried load of the reinforcements, the ductility reduction, the formation of corrosion products which causes cracking and high stresses in the elements, can significantly change the collapse mode of the structure. These aspects highlight the need to develop models for evaluating the corrosion damage in order to estimate the structural residual strength. Furthermore it could be necessary to define strengthening techniques which allow to recover the initial capacity of the structure, mainly with reference to existing building built around the '60 and '70s, very often characterized by low concrete strength, insufficient concrete cover and designed without any durability requirement.

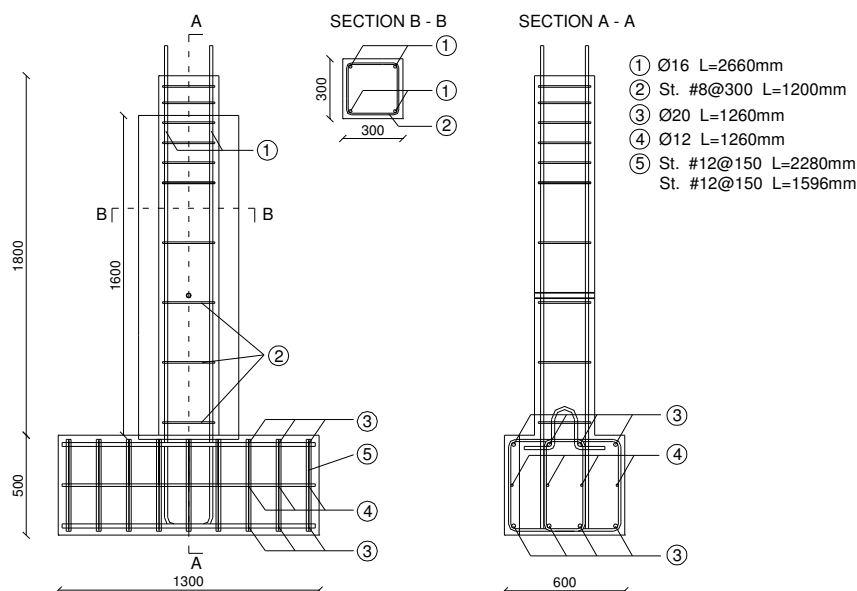
Traditional jacketing presents some inconvenience, as the jacket thickness is governed by the steel cover (both external and internal), and then it is, often, higher than 70-100 mm (Fib Bulletin 24, 2003). As a consequence the increase of the section geometry is not negligible, leading to an increase of both mass and stiffness, which can give some problems with respect to the seismic behaviour. This aspect is particularly important when small columns are considered (e.g. 250-300 mm of side). Several different repair techniques have been proposed for reinforced concrete structures, such as FRP wrapping, which is often affected by bond failure between the laminate and the concrete, particularly when the existing concrete has poor mechanical properties. Furthermore, FRPs are useful to enhance ductility, but are not always suitable when a strength increase of the column, often subjected to compressive and bending forces, is also needed. Recently a new technique based on the use of thin jackets in high performance fiber reinforced concrete (HPFRC) has been developed by Martinola et al. (2010). This class of materials exhibits a hardening behaviour in tension coupled with a high compression strength, larger strain capacity and toughness compared with traditional FRCs, which makes them ideal for use in members subjected to large inelastic deformation demands. As a consequence, the traditional steel reinforcement in the jacket can be avoided allowing the use of a thin HPFRC layer (30-40 mm).

The effects of corrosion, in particular the reduction of strength and ductility, can jeopardize the behaviour of structures for horizontal loads (seismic action). In this research, the attention has been devoted to the effects of high performance jackets on the increase of the carrying capacity of RC columns with problems of reinforcement corrosion. Three full-scale experimental cyclic tests on column specimens have been performed. One column was used as reference specimen, one column was tested after the artificial corrosion of the rebars to estimate the residual structural strength while the last column, after the reinforcement corrosion, was strengthening by applying a high performance fiber reinforced jacket with a thickness of 40 mm. The test was performed up to failure by applying cyclic horizontal loads of increasing amplitude in order to verify the performances of the proposed solutions.

## 2.0 Specimens geometry

The effectiveness of this new technique, based on the HPFRC jacket application, was studied through three full-scale columns having a height of 1.8 m and a square section of 300x300 mm. The elements have been cast on a 500 mm thick foundation as shown in Figure 1. The reinforcement and the concrete strength of the columns are typical of structures built in the 60's

and 70's. The specimens have been reinforced with 4Ø16mm diameter longitudinal rebars and 8mm stirrups spaced at 300mm. The columns were cast with a low strength concrete: the average compressive strength, measured on 150 mm side cubes, is equal to 20 MPa. The steel reinforcement can be classified as B500C, as the rebars exhibited an average yield strength equal to 520 MPa and an average maximum strength equal to 620 MPa.



### 3.0 Specimens corrosion

The artificial corrosion of the reinforcement rebars has been carried out through the use of electrolytic cells (Figure 2). The concrete specimens were partially immersed in 3% chloride solution so that the upper end of the specimens was above the solution. The corrosion of the reinforcements steel was accelerated by impressing a constant current value of 0.5 A.

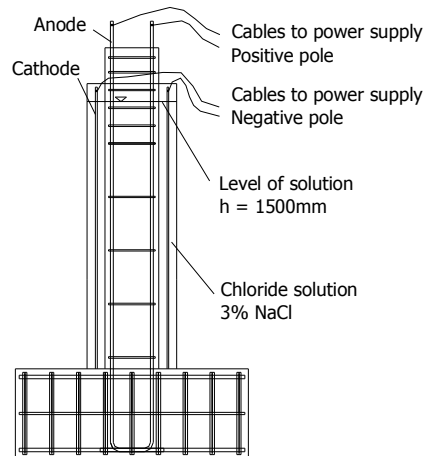


Figure 2. Electrolytic cell used for artificial corrosion process



Figure 3. Crack pattern of the columns after the corrosion process

Each reinforcing bar has been connected to a single power supply in order to achieve a level of corrosion as uniform as possible. The direction of the current was adjusted so that the reinforcing steel of the columns became an anode and four 10 mm diameter bars placed within the chloride solution served as a cathode.

The level of the corrosion is expressed as a percentage loss of mass of the rebars since this parameter is a direct index of the loss strength of the bar. The reinforcement of the columns has been corroded to a theoretical level equal to 20% in terms of mass loss. In order to induce the level of the reinforcement corrosion Faraday's law was used to establish the relationship between the duration of the impressed current and the corresponding degree of reinforcement corrosion. Faraday's law, however, was modified by introducing a corrective coefficient equal to 1.3, (as highlighted by preliminary calibration tests) in order to take into account the volume of concrete around the reinforcing bar. At the end of the corrosion process the production of rust caused the formation of four vertical cracks in correspondence of the corroded bars which extended for the entire height of the columns as shown in Figure 3.

In order to evaluate the mechanical properties of the corroded bars a preliminary test on a column with the same section and reinforcement of the columns to be tested was prepared. At the end of the corrosion process the reinforcing bars have been extracted from the column, cleaned and weighed to verify the effective loss of mass. The bars corroded inside the concrete show a localized corrosive attack and the loss of weight is not homogeneously distributed along the rebars (Figure 5). Each of the four bar extracted has been divided into two segments of length equal to 60 cm, which were subjected to tensile test. The stress-strain curves for non-corroded and corroded rebars are plotted in Figure 4. The nominal stress for the corroded bars indicates the relationship between the measured force and the nominal area of the undamaged, i.e not corroded, specimen. The obtained results clearly highlight that the corrosion attack significantly reduces both the strength and the deformation of the bars.

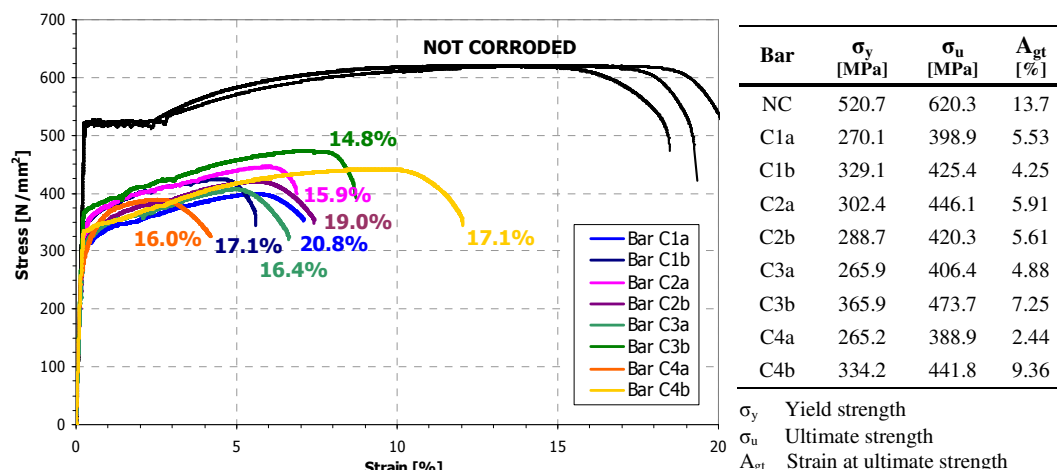


Figure 4. Stress-strain curve and main values from tensile tests of bars

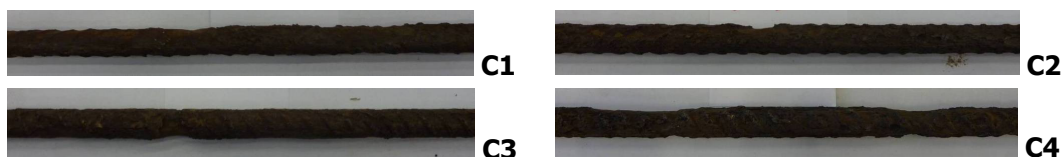


Figure 5. Corroded rebars extracted from the columns



Figure 6. a) Sandblasting of the column and surfaces before and after the treatment; b) Cast of the high performance jacket.

The reduction of the yield strength and of the ultimate strength is directly proportional to the increase of the level of corrosion of the rebars. For the evident phenomena of pitting, the reduction of ductility is less regular and not strictly dependent of the level of corrosion. The bars corroded inside the concrete show a brittle behaviour.

#### 4.0 Strengthening material and jacket application technology

One of the two corroded specimen was strengthened with a high performance fiber reinforced jacket having a thickness of 40 mm. The HPFRC presents an almost self levelling rheology, that should be cast in moulds, a compressive strength of 130 MPa and a tensile strength of 6 MPa. Direct tensile test on dog-bone specimens and four point bending tests on small beams were performed in order to characterize the material in tension and the results show the strain hardening behaviour in tension of the material. The strengthening material is reinforced with straight steel fibers having a length of 15 mm and a diameter of 0.175 mm. The content by volume is 0.2% and the aspect ratio ( $l/\phi$ ) is 85.7.

Before the casting of the jacket, the deteriorated cover in correspondence of the four longitudinal bars has been removed and the reinforcements were manually cleaned to remove the corrosion products. In order to connect the jacket to the column base, a pocket 80 mm deep was realized in the foundation. The pocket allows the anchoring of the fiber reinforced concrete to the reinforcing bars in the foundation by providing a joint at the base of the column. The specimen were then sandblasted in order to obtain a roughness of about 1 mm, so as to ensure perfect bond between the existing concrete and the applied high performance concrete. This technique has been demonstrated effective in previous research (Martinola et al. 2010). Figure 6 shows the sandblasting of the column and, in detail, the difference of the surfaces before and after the treatment. The HPFRC material was prepared in a vertical axis mixers and was cast in moulds without vibration. Since curing was carried out at ambient temperature and humidity, a plastic sheet was placed on the upper surfaces in order to limit water evaporation.

#### 5.0 Test set-up

For each specimen, the foundation of the column was anchored to the laboratory basement with two steel profiles and four pre-tensioned high strength rebars. The axial load was applied with two hydraulic jacks and monitored by a pressure transducer. To ensure that the axial load was centred with respect to the column, a self-balanced system was used for the load application. Such system was made of two steel profiles, one placed on the upper head of the column and one in contact with the lower face of the foundation, connected with two high strength rebars, pinned to the lower crossbeam and fixed at the top. The horizontal cyclic load was applied 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 in which a load cell was placed. The horizontal force was applied at a height of 1.5 m from the column foundation connection. Test set-up is shown in Figure 7.

The tests were done applying to the specimens an axial load equal to 400 kN and then cyclic loads of increasing amplitude.

In order to measure the horizontal displacements, potentiometric transducers were placed on the column at the level of the load application, at a height equal to 1.5 m from the column-foundation interface (instruments 2-3 in Figure 8). The rotations at the column base were measured by means of a series of potentiometric transducers placed on one of the column face: the devices 10-11 of Figure 8 were placed in order to measure relative displacements between the column and the foundation base, whereas the devices 4-5-6-7-8-9 of Figure 8 were placed on the column to measure relative displacements between points of the column itself. To measure possible slip movements of the bench, two LVDT devices were adopted (14-15 in Figure 8). A pressure transducer was connected to the pump for the axial load monitoring.

The tests were performed by applying the horizontal load with cycles characterized by increasing amplitude up to failure. The horizontal displacement applied to the column is indicated with  $\delta$  and the distance between the load application point and the upper face of the foundation is indicated with  $h$ ; the ratio between the horizontal displacement of the load application point and its height is



defined as drift ( $\text{drift} = \delta/h$ ). The experimental setup defines three fully reversed cycles at each drift level with a middle unloading cycle between a triplet and the next one. The initial drift (0.15%) was chosen so that it fell within the linear elastic range of the specimens' behaviour. The subsequent drifts were chosen so that each drift was included between 1.25 and 1.5 times the drift of the previous triplet.

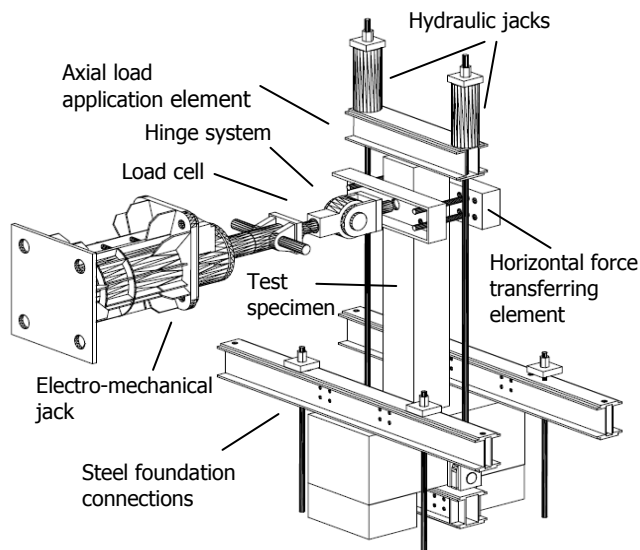


Figure 7. Test set-up

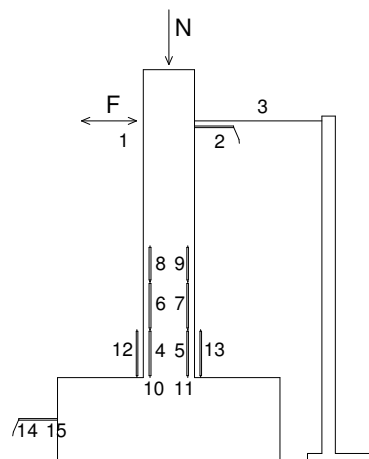
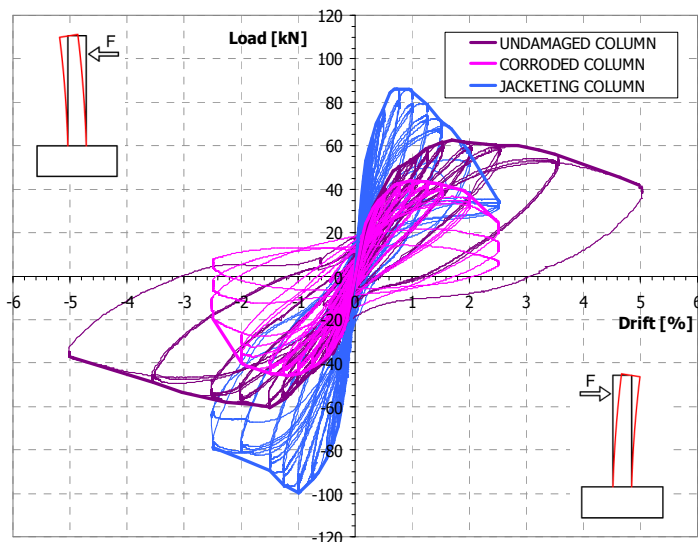


Figure 8. Instrument device

## 6.0 Test results

The results in terms of horizontal load versus displacement at the level of the load application point are shown for all the specimens in Figure 9.



	CNC	CC	CJ
$M_{\max+}$ [kNm]	92.6	65.0	130.0
$M/M_{\text{CNC}}$	1.00	0.70	1.40
$M_{\max-}$ [kNm]	89.1	67.3	147.1
$M/M_{\text{CNC}}$	1.00	0.76	1.65
$\delta_{\max+}$ [%]	2.00	1.00	0.75
$\delta_{\max-}$ [%]	1.50	1.25	1.00
$\delta_{u+}$ [%]	5.00	2.50	2.00
$\delta_{u-}$ [%]	5.00	2.50	2.50

CNC Undamaged column  
CC Corroded column  
CJ Jacketing column

Figure 9. Horizontal load versus horizontal displacement curves for the three specimens tested



The specimen not corroded (CNC) reached its maximum strength, equal to 63 kN for the horizontal load and 92.6 kNm for the moment, at a drift equal to  $\pm 2\%$ . In the following cycles a progressive strength degradation was observed, up to a value of about 50 kN, at a drift of 5%, equal to the 80% of the column strength. The test were stopped after the execution of the first cycle corresponding to a drift of 5%, after which cover spalling and concrete crushing occurred at the column base for a height approximately equal to the section side. It was observed, moreover, the deformation of one of the reinforcing bars due to buckling.

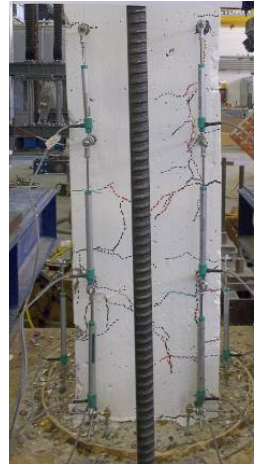
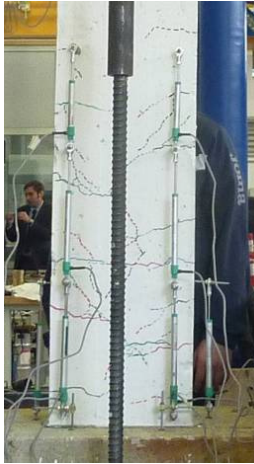


Figure 10. Specimen CNC at a drift of 2% and at the end of the test

Figure 11. Specimen CC at a drift of 2% and at the end of the test

The maximum load measured for the corroded columns (CC) was about 46 kN, corresponding to a moment of 67 kNm, reached at a drift equal to 1.25%. The strength in correspondence of the final cycle, that occurred at a drift of 2.5% is of 36 kN, i.e. approximately 78% of the maximum load reached. From cycles ranging from a drift of 0.25% to 1.00% the specimen shows horizontal cracks which grow in number and extension and are placed in an area of height of about 70 cm from the base of the foundation. From the cycle corresponding to a drift of 1% the vertical cracks due to corrosion, visibly open. From a drift of 2% cover spalling occurred. The test was interrupted in correspondence of a drift of 2.5% after the complete crushing of the concrete. It is clearly noted the buckling phenomenon occurring in all the reinforcement bars.

Figure 10 and Figure 11 show the crack pattern of the specimen not corroded and corroded for a drift of 2% and at the end of the tests.

The maximum load for the jacketing column (CJ) for positive cycles was about 86 kN for the horizontal load and 127 kNm for the moment, reached at the 0.75% drift cycle, while for negative cycles the maximum strength was about 100 kN for the load and 147 kNm for the moment in correspondence at a drift of 1%. The appearance of the first crack due to the bending in the jacket occurred at a drift of 0.30%. The cracks, that affect an area of about 60 cm height of the level of foundation, developed with a spacing of about 300 mm, equal to the stirrup spacing. From a drift of 0.75% the flexural crack in the external jacket was stable (Figure 12) while a local damage of the HPFRC jacket was occurred at the interface column-foundation (Figure 13). In the case of positive drift damage is not localized exclusively to the interface column-foundation, but there was a gradual hoist of the fiber reinforced jacket by the base foundation. This phenomenon, that not corresponds to the real behaviour of the column, has caused a significant loss of strength in the case of positive drift. 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 corresponding to a drift of 2%, due to the rupture of one of the longitudinal rebars for positive drift. In order to deepen the knowledge of the specimen behaviour, as for the negative drift load was still high, it was decided to perform even the cycles of 2.5% drift. The test is terminated at the second cycles equal to a drift of 2.5% at the breaking of the second reinforcing bar. At the time of the collapse load was equal to 82 kN, corresponding to 82% of the maximum stress reached for positive displacement values.

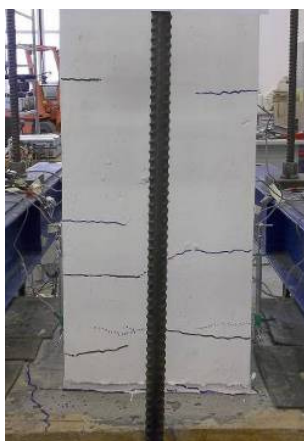


Figure 12. Specimen CJ at drift of 0.75% and 2%

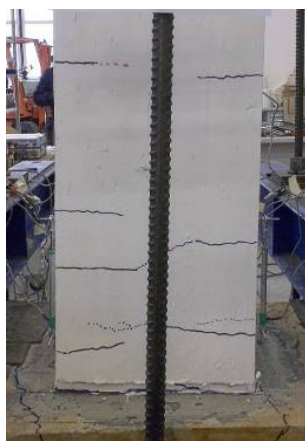


Figure13. Localized damage at the interface column - foundation

## 7.0 Comparison

The comparison between not corroded specimen (CNC) and corroded column (CC) shows the effectiveness of the methodology of the accelerated corrosion of reinforcing bars. The corroded column has both a decrease in the maximum strength (the maximum load is about 73% of the load achieved by the undamaged specimen) and a marked decrease of deformation since the not corroded column reached the collapse for a drift of 5%, while the maximum drift for the corroded element is only 2.5%. The results obtained from the jacketing specimen showed the efficacy of this technique for strengthening columns with corroded longitudinal rebars. The maximum load for both positive and negative stress is higher than the peak load reached by the undamaged specimen. Observing the values obtained for negative drifts, the direction in which the strengthening specimen showed a correct mode of failure, the maximum load of the column shows an increase of 65% compared to that of the undamaged column and an increase of 118% in comparison to the peak load of the column with corroded reinforcement. The shape of the envelope curve is typical of the behavior of a section characterized by a RC core with a HPFRC jacket. After reached 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 and the foundation. In the cycles after the peak load (for negative drifts) the load was however higher than that of the unreinforced specimen for the compression contribution of the HPFRC jacket. The specimen with HPFRC jacket has not shown crushing of the concrete cover or deformation of the longitudinal rebars due to the confinement action carried out by the layer of high performance concrete. A comparison between the experimental results of the three specimens can be performed in terms of dimensionless dissipated energy, as shown in Figure 14. The specimen with fiber reinforced jacket shows a better behavior in terms of energy dissipation. For cycles at high drift (0.75% - 1.00%) the HPFRC jacketing specimen with corroded longitudinal rebars dissipated 30%

more energy than specimen with corroded rebars and no jacketing and 50% more energy compared to the undamaged specimen. The energy dissipated for undamaged and corroded columns in the final cycles (dashed lines) results to be high due to the complete expulsion of the concrete cover and buckling of the longitudinal reinforcements (see Figures 10-11-12). It is observed that the dissipated energy for the strengthening columns during the cycles triplets is stable, proving the validity of the proposed rehabilitation method.

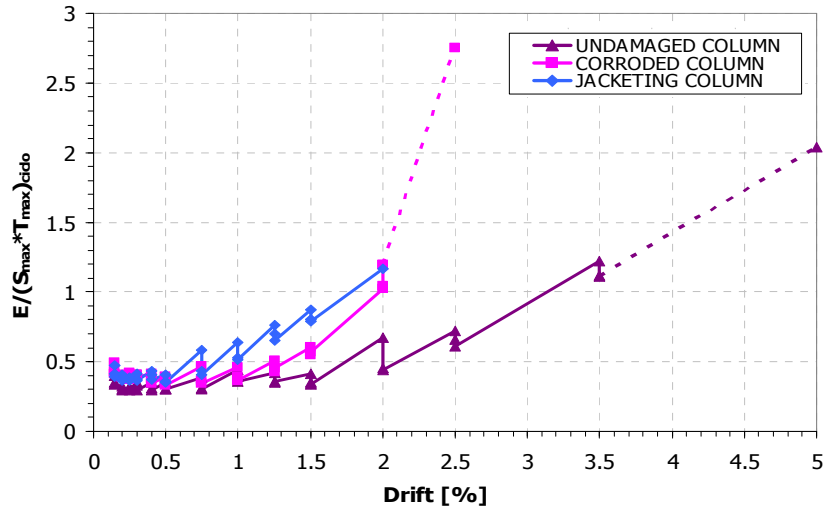


Figure 14. Comparison between dimensionless dissipated energy

## 8.0 Conclusion

The three full-scale tests presented demonstrated the effectiveness of the HPFRC jacketing technique for columns with problems of corrosion of longitudinal rebars. With the application of a high performance jacket it was possible to increase the bearing capacity of the column with corroded rebars reaching a maximum strength greater than that of the corresponding not damaged element. This technique resulted suitable for strengthening existing RC structure characterized by low concrete strength, low reinforcement ratio, concrete damage and corrosion of rebars. The use of the high performance concrete layer can protect the internal column, by increasing its durability, as shown in Figure 15 where it is reported the difference in the penetration of CO<sub>2</sub> for a normal concrete and for the HPFRC used in this research. The proposed technique can be easily used in structural application as it allows strengthening R/C elements by means of a thin jacket: a curing at ambient temperature and humidity is sufficient to allow the development of the strength characteristics and a simple sandblasting ensures a good bond between substrate and HPFRC.



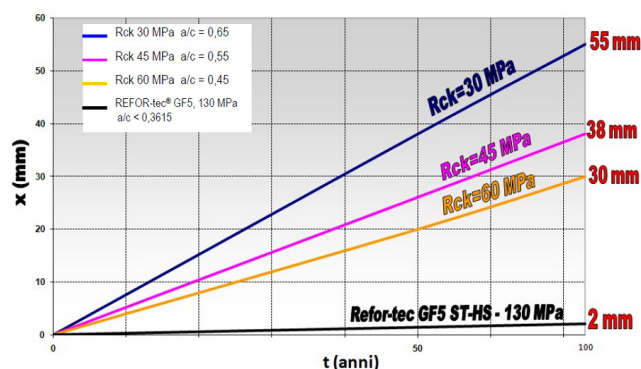


Figure 15. Penetration of CO<sub>2</sub> for normal concretes and for HPFRC used in this research

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