SEISMIC BEHAVIOR OF R.C. COLUMNS WITH ZINC COATED REBARS

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Abstract

The experimental results on five pairs of R.C. columns subjected to cyclic horizontal displacements are presented. One pair of columns is reinforced with traditional reinforcing bars while the other four are reinforced with galvanized rebars, coated with different industrial processes and different passivating films.

The results show that the mechanical behavior of the columns with galvanized bars is similar to that with traditional reinforcement. The plastic hinge behavior is ductile and the resistance degradation is due to concrete spalling in compression and, consequently, to the buckling of the longitudinal bars between two adjacent stirrups. The zinc coating is also preserved under the prescribed exceptional mechanical actions that simulate the effects of a severe earthquake.

1. Introduction

Corrosion of reinforcing bars represents the most important cause of deterioration in reinforced concrete structures. In fact, chlorides and carbon dioxide can penetrate inside the concrete and destroy the passive film protecting the steel. In these conditions, corrosion of rebars can occur provided that oxygen and humidity are present at the steel surface.

The most effective approach to produce durable structures is to manufacture a low porosity, high quality concrete (w/c <0.50), with an adequate cover thickness (40-50 mm), as recommended by several building codes [1]. However, even if the concrete is correctly designed, defects may still occur due to lack of control, poor workmanship or accidental causes. Therefore, in aggressive environments, the durability of the structures can only be guaranteed by providing additional protection to the steel reinforcement.

Among the methods proposed to improve the corrosion resistance of reinforcement in concrete, new consideration has recently been given to the use of galvanized rebars, in view of their relatively low cost when compared to other protection systems, and to the fact that the coating on the bars, based on polymeric resins, has also had very bad results in the presence of concrete contaminated by chlorides [2]. However, although successful practical results with the use of galvanized reinforcements have been reported in the literature [3], laboratory results remain fairly controversial [4]. Therefore, the scientific debate on the galvanized reinforcement remains open on some subjects such as:

1. the bond between galvanized rebars and concrete;
2. the mechanical characteristics of galvanized bars, as compared with the black bars;
3. as in 2 but referring to high and low cycle fatigue resistance;
4. global behavior of galvanized bars in the development of the plastic hinge;
5. the passivation of zinc coating to improve the corrosion resistance.

The loss of adhesion between galvanized steel and concrete [5], is considered due to hydrogen evolution on the bar surface resulting from the aggressive effect that the pore solution has on the zinc coating during cement hydration, and also to the reduction of the relative rib area due to the zinc accumulated between the ribs. Passivation of the zinc coating by chromate ions is a valid preventive method of inhibiting hydrogen evolution; however, it should be pointed out that chromate, which is the most effective passivating agent for zinc, is hazardous to human health and the European Standards limit its use [6]. Therefore, alternative equally effective and harmless agents which could replace chromate in the passivation surface treatment, are needed [7].

In this paper, the experimental results on five pairs of R.C. columns subjected to cyclic horizontal displacements that simulate the effects of a severe earthquake [8] are presented. One pair of columns is reinforced with traditional reinforcing bars while the other four are reinforced with galvanized rebars, coated by different industrial processes and different passivating films. Ultimate load, structural ductility, and plastic hinge behavior at the concrete-foundation interface are carefully analyzed.

2. Materials

Five different types of bar coatings were used on rebars coming from the same steel casting:

- black steel rebars as received from steel manufacture;
- galvanized steel bars, obtained by the normal hot dip galvanizing process after an immersion time in the melted zinc bath of 6-7 minutes, without any passivation or protective surface treatment;
- galvanized steel bars, produced by an innovative galvanizing process which removes the excessive zinc from the bar surface by an air-knife so that the rib geometry is slightly changed, without any passivation or protective surface treatment;
- innovative galvanized steel bars with a hexavalent chromium based passivation treatment. This treatment was obtained by immersion of galvanized bars in an

aqueous solution containing hexavalent chromate ions, according to ASTM A7676/A767 M-90, followed by water rinsing and drying at room temperature;

- innovative galvanized steel bars with the surface protected by a thin acrylic polymeric film obtained by immersion of bars in an aqueous solution containing the organic substance followed by drying at 60°C.

The steel bars had a yield stress (fsy) of 582 MPa, a tensile strength (fst) of 668 MPa (fst/fsy=1.14), while the maximum strain, measured over a length of 80 mm (5 times the bar diameter), was 22%.
Concrete was made with a cement class 42.5R type CEM II/A-M (UNI-ENV 197) with a total and soluble alkali content respectively of 1.04% and 0.76% as Na_2O. Siliceous aggregates, having a rounded shape and a maximum diameter of 15 mm, were adopted.
The concrete mix proportions are the following: 250 kg/m^3 of cement, 1960 kg/m^3 of aggregates, water-cement ratio (w/c) = 0.66. The latter was intentionally chosen low in order to obtain a cement matrix similar to the one often used in practice. The average compressive strength, as determined from cubic samples at the time of the tests, was about 30 MPa.
Five different batches of concrete specimens were cast, one for each type of coating previously described. All specimens were kept out in the air after demolding, as well as the cubic specimens to test compressive strength.

3. Specimen description and experimental setup

Figure 1 shows the specimen geometry and the reinforcement, that is very similar to the one adopted by Macchi et al. [9], Pipa and Carvaho [10], and Franchi et al. [11]. It simulates the behavior of a R.C. column having a height of 3.0 m (distance between the foundation and the first floor) when assuming that the rotation of the first floor is negligible.
The load was applied by imposing a horizontal displacement of the column, at a distance from the column base of 1.35m (Fig. 1), by means of an electro-mechanical jack and a contrast bench present in the laboratory of the Department of Structural Engineering of Politecnico di Milano. In order to avoid rigid rotations, the concrete block simulating the foundation was fixed to the pavement of the laboratory by means of 8 steel bars having a diameter of 22 mm (Fig. 1).
The specimens were suitably instrumented to measure the horizontal load, the load point displacement (LPD), and the rotation at the column base. In order to avoid any reduction of the section area of the rebar, strain gauges were also applied on two additional steel bars, having a diameter of 6 mm and a length of 1000 mm, placed at the column base (Fig. 1). The displacement data were acquired by LVDTs (Linear Variable Differential Transformer), while the load measurements were acquired by a reversible load cell present in the bench. The rotation at the column base was measured by means of two pairs of LVDTs, having a base length of 90 and 180 mm, placed on the longer side of the column base at a distance of 180 mm (Fig. 1). The rotation allows one to determine the

average curvature of the column base, where the plastic hinge forms. All the data were acquired by the data acquisition system and then stored in a PC.

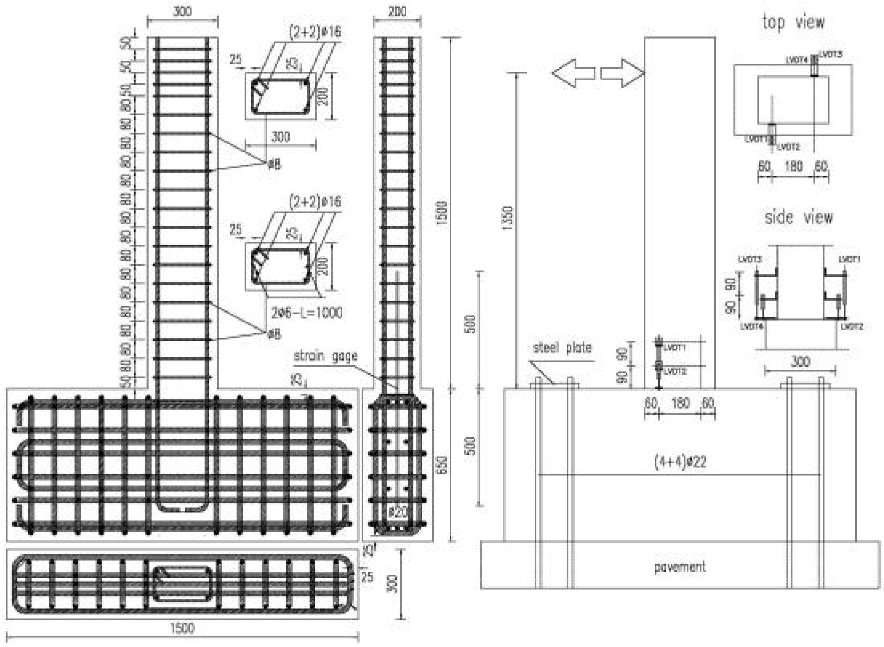

Figure 1: Specimen geometry, reinforcement and instrumentation.

4. Experimental results

Figures 2 and 3 exhibit typical load-displacement curves, as obtained on a specimen with plain (black) bars and on a specimen with the innovative galvanized rebars. The figures also show the planned cycles of loading. In the first cycle, a constant displacement was imposed up to the yield strength of the tension bars, whose corresponding displacement is defined as δy. Then, the reference signal was inverted up to a displacement of - δy. The second, third, and fourth full cycles were applied up to a LPD of ±3 δy. The fifth, sixth, and seventh cycles were applied up to a LPD of ±6 δy. The eighth and ninth cycles were applied up to a LPD of ±7 δy and ±8 δy respectively. The values of the maximum force during the positive LPD (+Fmax) are different from the ones measured during the negative displacements (-Fmax). This fact seems to be explained by the unsymmetric response induced by the inelastic behavior (steel+concrete) that has occurred since the first half cycle, and by the geometrical unsymmetries (slightly different values of the concrete covers). It can be noticed that no significant differences exist between the curves corresponding to different coatings of the rebar. Similar curves were obtained from all specimens, indicating that the structural behavior is not influenced by the surface coating.

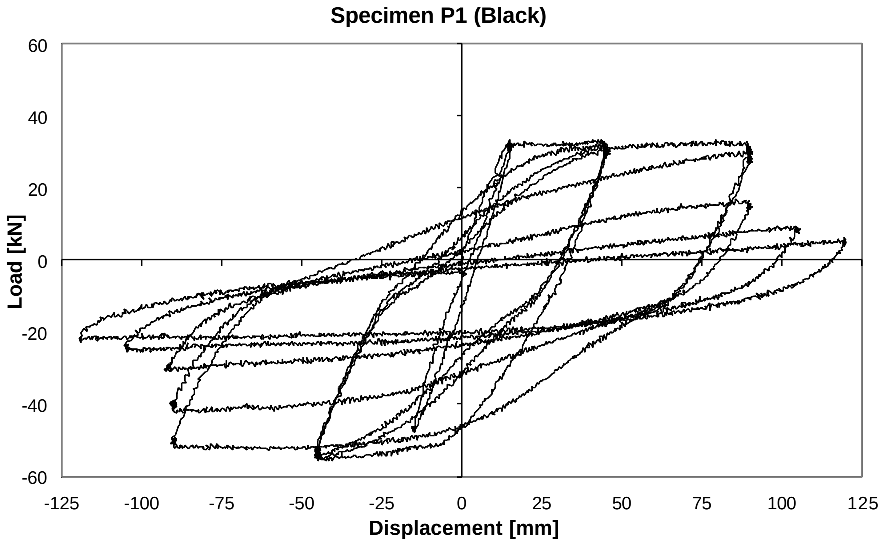

Figure 2: Typical load-displacement relationship as obtained from a specimen (P1) with bars without coating.

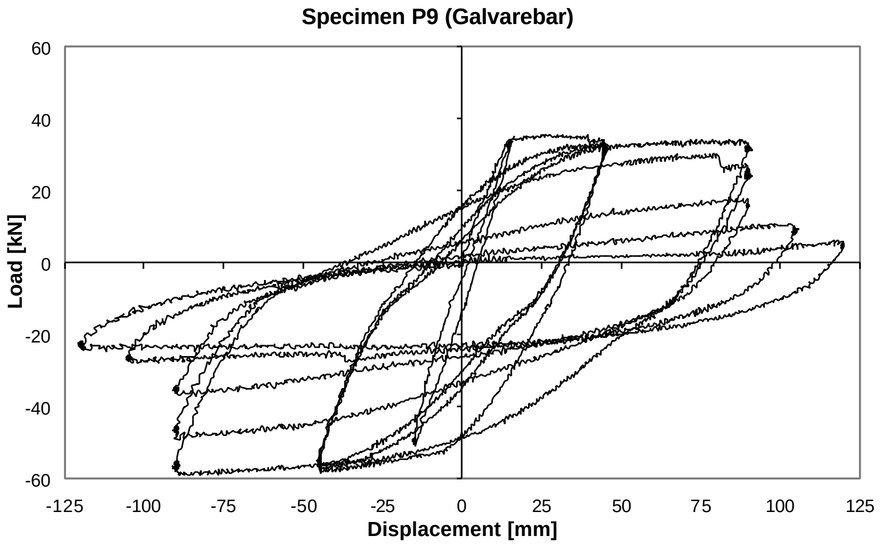

Figure 3: Typical load-displacement relationship as obtained from a specimen (P9) with innovative galvanized steel bars.

This behavior is clearly shown in Figure 4, where the load amplitude of each cycle (|Fmax|+|Fmin|) is plotted versus the number of cycles. One can observe that all the curves are very similar and that the differences are within the normal scatter of experimental results on concrete specimens. The reduction of the load amplitude is mainly related to concrete spalling that usually occurred during the cycles at ±6 δy, and consequently to the buckling of the compressed bars between two stirrups [12]. Similar curves could be obtained when plotting the stiffness degradation.

The sudden strength reduction during the sixth cycle (at ±6 δy) in the curve of Fig. 3 is due to the failure of the bar (ϕ=6mm) utilized to measure the steel strains (Fig. 1).

Figure 5 shows a typical moment-rotation relationship, as obtained by the specimen with the innovative galvanized rebars, up to the concrete spalling (when the LVDTs at the column base were removed to avoid their damage), that usually occurred when a displacement of 6 δy was applied (Fig. 6a). Similar curves were obtained from specimens with the different rebar coatings.

At the end of the tests, the zinc coatings did not show significant damage, even in the plastic hinge where the most significant damage due to plastic bending and rebending of the bars, and concrete pushing against the bars occurred.

Figure 6 exhibits some photographs showing the plastic hinge development, as obtained from a specimen (P3) with bars having a thin acrylic polymeric film; in particular it shows the crack pattern in the tension concrete fibers after the sixth cycle (a); the concrete spalling and the steel bar under compression (b); a detail of the unstable configuration of the bar under compression (c). The length of the plastic hinge, which is given by the extension of damaged concrete (over more than three stirrups), is remarkable. This indicates a very ductile behavior of the columns under consideration. Further details on the experimental results can be found in [13].

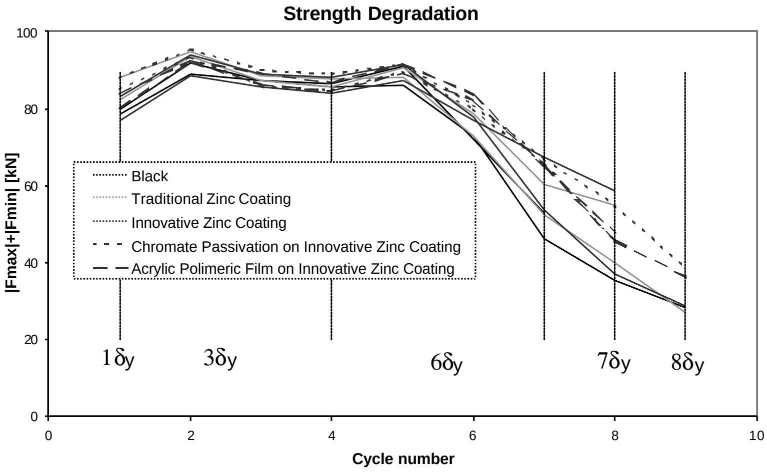

Figure 4: Strength degradation versus the number of cycle as obtained from all the specimens tested.

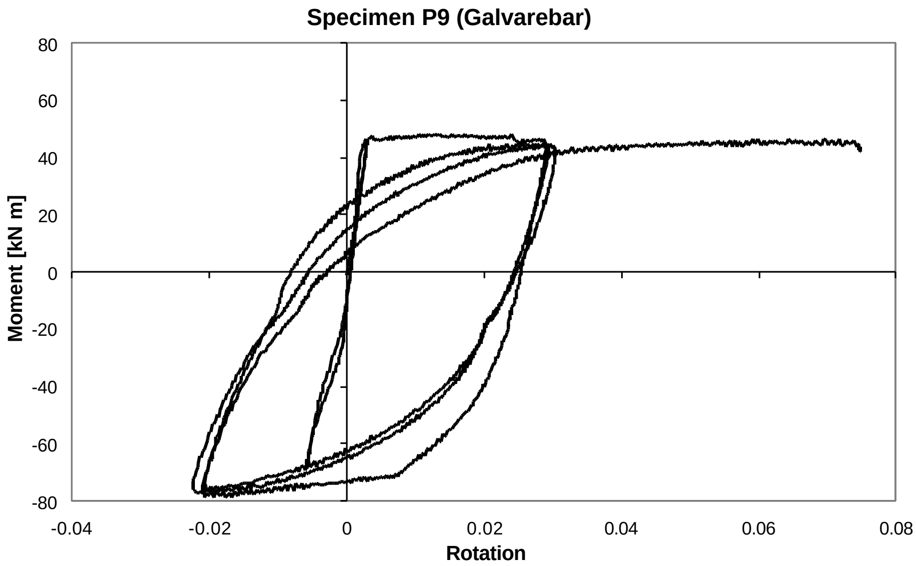

Figure 5: Typical moment-rotation relationship as obtained from a specimen (P9) with innovative galvanized steel bars.

+6 δy (6th cycle) (a) +6 δy (7th cycle) (b) -8 δy (9th cycle) (c)

Figure 6: Photographs of the column base as obtained from a specimen (P3) with bars having a thin acrylic polymeric film during (a,b) and at the end of the test (c).

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