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Efficiency of RC square columns repaired with polymer-modified cementitious mortars

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ABSTRACT

This paper regards the axial behavior of reinforced concrete columns repaired by polymer-modified cementitious mortars. Tests were performed on eight columns with square cross-section: six were repaired with three types of polymer-modified cementitious mortars on all faces, two were in non-damaged and non-repaired condition (control elements). Tests were repeated varying mechanical properties (elastic modulus and compressive strength) of repair materials, maintaining the same repair thickness, including the reinforcement bars. Comparisons between repaired and control elements showed that polymer-modified cementitious mortars cannot restore the original load-bearing capacity of columns. In spite of this, selection of mortar mechanical properties plays a significant role. Among the three types of repair mortar tested in this experimental study, using the material with the most similar elastic modulus and higher compressive strength than that of the concrete substrate is recommended.

1. Introduction

Reinforced concrete often shows its vulnerability to time dependent phenomena, including weathering, well before reaching the intended service life of the structure. The phenomenon is so widespread that systematic replacement of existing structures is not a possible measure. Thus, interest in rehabilitation and strengthening of reinforced concrete structural elements has been rapidly increasing around the world in the past two decades. Various research programs were aimed at developing materials and methods for improving the safety and reliability of existing concrete structures. In this framework, externally bonded fiber reinforced polymers (FRPs) sheets/plates have several attractive properties, such as low weight-to-strength ratios, non-corrosiveness, and ease of application. A number of experimental and analytical studies have already been carried out at the University of Padova on flexural [1], shear [2] and bond behavior [3] of FRP strengthened elements. Adding or applying mortar, or spraying concrete or mortar with the aim of rehabilitating and/or strengthening of existing reinforced concrete structures are also possible ways of intervening with a more traditional and common material.

Emberson and Mays [4] discussed the mechanical and physical properties of mortar repair systems and created two- and three-dimensional linear elastic finite element models to reproduce axial load transfer through simple patch repairs in reinforced concrete members. They also worked on reinforced concrete beams in flexure and studied the effect of repairs in both compression and tension zones [5]. Pellegrino et al. [6] investigated the efficiency of rehabilitation interventions on reinforced concrete columns with polymer-modified cementitious mortar. Axially loaded elements were tested by varying repair thickness, which included or did not include reinforcement bars. The mortar was applied on one face only of square columns. The authors found that the repair could not restore the same load-bearing capacity as non-damaged control columns. However, if repairs include longitudinal reinforcement bars, the repaired element shows stable behavior, sharing of loads and plasticization of the material before failure. The same authors also studied the effect of repairs in both compression and tension zones, and including or not reinforcement bars, on reinforced concrete beams in flexure [7].

Mangat and O'Flaherty [8] studied the influence of elastic modulus on stress redistribution and cracking in repair patches for axially loaded elements. Results showed that repairs applied with relatively stiff materials display efficient structural interaction with the structure. High stiffness repairs are effective in redistributing shrinkage strain to the substrate and attracting external loads in the long term. Low stiffness repair materials are much more likely to undergo tensile cracking due to restrained shrinkage, and are ineffective in redistributing strain. Sharif et al. [9] conducted an experimental investigation to assess the effectiveness of patch repairs in axially loaded columns. The load distribution between patch repair, concrete core and steel reinforcement depended on the modulus of elasticity and areas of these components in the composite repaired section. In order for patch repair to be structurally effective, the loads before

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Table 1
Details of specimens.

Type and no. of elements	Condition	Designation	Section (mm^2)	Longitudinal reinforcement	ρ_l (%)	Transverse reinforcement	ρ_w (%)
2 Columns	Control	P0_1; P0_2	300 × 300	4ø12	0.50	1ø8/140 mm	0.24
2 Columns	Repair *a*	P50_a1; P50_a2					
2 Columns	Repair *b*	P50_b1; P50_b2					
2 Columns	Repair *ab*	P50_ab1; P50_ab2					

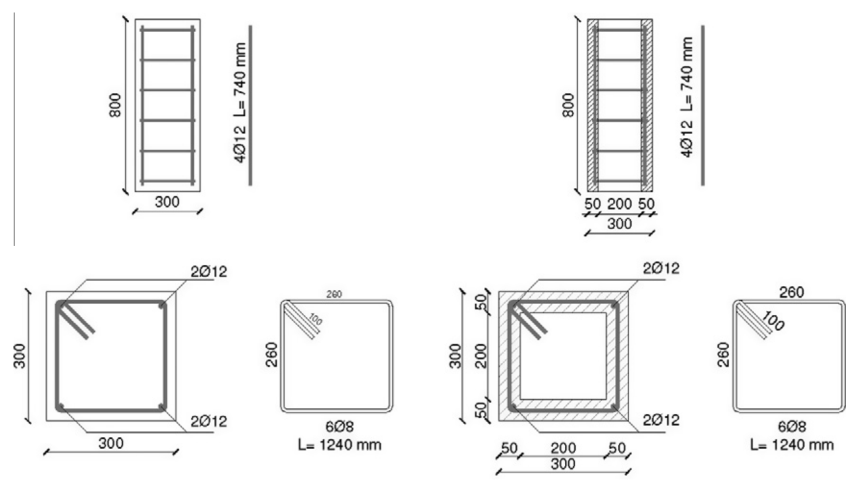

Fig. 1. Dimensions, bars and repairs: control column (left) and repaired column (right).

Table 2
Mechanical, physical and chemical properties of materials.

Property	Concrete C42/50	Mortar type *a*	Mortar type *b*	Mortar type *ab*
Mean tensile strength (N/mm^2) [15]	3.35	3.96	4.78	4.52
Mean flexural strength (N/mm^2) [16,17]	–	6.79	8.20	7.76
Mean cubic compressive strength (N/mm^2) [16,17]	50.83	60.92 (+20%)	44.40 (−12%)	55.15 (+9%)
Mean elastic modulus (N/mm^2) [18]	31,350	29,210 (−7%)	25,540 (−19%)	28,180 (−10%)
Granulometry (mm) [19]	–		0.00–4.00	
Water content (l/kg)	–		0.17	
Degradability to sulfates [20]	–		Absent	
Density (kN/m^3) [21]	–		20.00	
Diffusion resistance of CO_2 [22]	–		$\mu > 190$	
Diffusion resistance of vapor	–		$\mu > 60$	
pH	–		>12	

undertaking the intervention must, when possible, be relieve, either partially or totally,

A number of works have also focused on bonds between concrete and repair materials. Tokushige et al. [10] experimentally and analytically estimated the deformation of concrete members overlaid with unsaturated polyester polymer mortars. They also evaluated peeling and shearing stresses at the interface between concrete and polymer mortar. Courard [11] analyzed the factors affecting the repair system/concrete support interface, and proposed a sequential flow sheet related to these parameters. Kamada and Li [12] presented the influence of surface preparation on the kink-crack trapping mechanism of engineered cementitious composites for concrete repair. In their experiments, the "smooth surface" showed more desirable behavior in terms of crack pattern and crack widths than the "rough surface" system. Garbacz et al. [13] studied the effect of various surface treatments (grinding, sandblasting, shot blasting, hand and mechanical milling) on interventions, on the basis of three main parameters: surface geometry, superficial concrete micro cracking, and adhesion. Yubin et al. [14] tested a method for controlling shrinkage cracking in repaired concrete structures, based on an intermediate layer of carbon fiber reinforced cement mortar.

Although the application of mortar around the entire perimeter of axially loaded elements is a quite common rehabilitation intervention in practice, its efficiency has not yet been studied from the experimental point of view. Hence, the aim of this study is to give some new insights on the effect of repair mortar properties on the structural behavior of square columns repaired on four sides. Starting from the results obtained by Pellegrino et al. [6], who tested columns repaired on one side only and with one mortar type only, an experimental study on eight axially loaded square columns was carried out. In this study, three polymer-modified cementitious mortars for repair, having different elastic moduli and compressive strengths, were applied over the entire perimeter of six columns. The repair was sufficiently thick to include longitudinal and transverse reinforcement bars. Two columns, named control elements, were prepared and tested in non-damaged and non-repaired condition.

2. Specimens and testing procedures

Column dimensions and repair thickness were selected to compare the test results with those obtained in the previous experimental research [6]. Columns were made with a square section area of 300 × 300 mm, having 50 mm of repair mortar applied in more than one layer, and a total height of 800 mm. Longitudinal reinforcement involved four 12-mm diameter reinforcing bars. Stirrups were made of 8-mm diameter reinforcing bars, placed at 140-mm spacing. The columns were cast leaving the reinforcement uncovered, with a curing process of 28 days. After this period, the uncovered surface was prepared to improve the adhesion between concrete substrate and mortar. The preparation of the surface included roughening, cleaning of dust and powders, and wetting. After evaporation of any water in excess, the polymer-modified cementitious mortar was applied. Repair mortar was 50 mm thick and included reinforcement bars in all columns, as the previous experimental study had shown this condition develops better behavior than repairs that substitute the concrete cover only. Table 1 lists the details of tested columns, and Fig. 1 shows the geometry of elements.

2.1. Materials

The main mechanical properties of concrete were experimentally assessed after 28 days of curing. Eight cubic specimens of 150 × 150 × 150 mm, cast during column construction, had an average compressive strength of 50.83 N/mm^2. Mean tensile strength, measured by splitting tests on seven cylindrical samples having 155-mm diameter and 300-mm height, was 3.34 N/mm^2. Elastic modulus was measured on cylindrical samples (height 300 mm, diameter 150 mm) and the average value was 31,530 N/mm^2.

Ribbed bars used for longitudinal reinforcement and transverse reinforcement were both tested in tension. The yield stress of the reinforcing bars was on average 594 N/mm^2, and the ultimate strength was 660 N/mm^2 .

The repair materials used in these tests were of three types. All were thixotropic, polymer-modified mortars with high-strength hydraulic binders and aggregates having a maximum thickness of 4 mm. These products have high bond properties, low CO_2 and vapor permeability, and limited shrinkage. Elastic modulus and compressive strength were the two parameters chosen to distinguish the three types of mortars (*a*, *b*, *ab*) and the corresponding types of repaired columns (*P50_a*, *P50_b*, *P50_ab*).

The mechanical properties of repair mortars were measured on specimens having dimensions of 40 × 40 × 160 mm, cast during the repair interventions on columns. Their mechanical, physical and chemical properties are listed in Table 2, which also compares the mechanical properties of repair materials and concrete substrate. The experimental program was planned to obtain various ratios of the mechanical properties of concrete core and repair

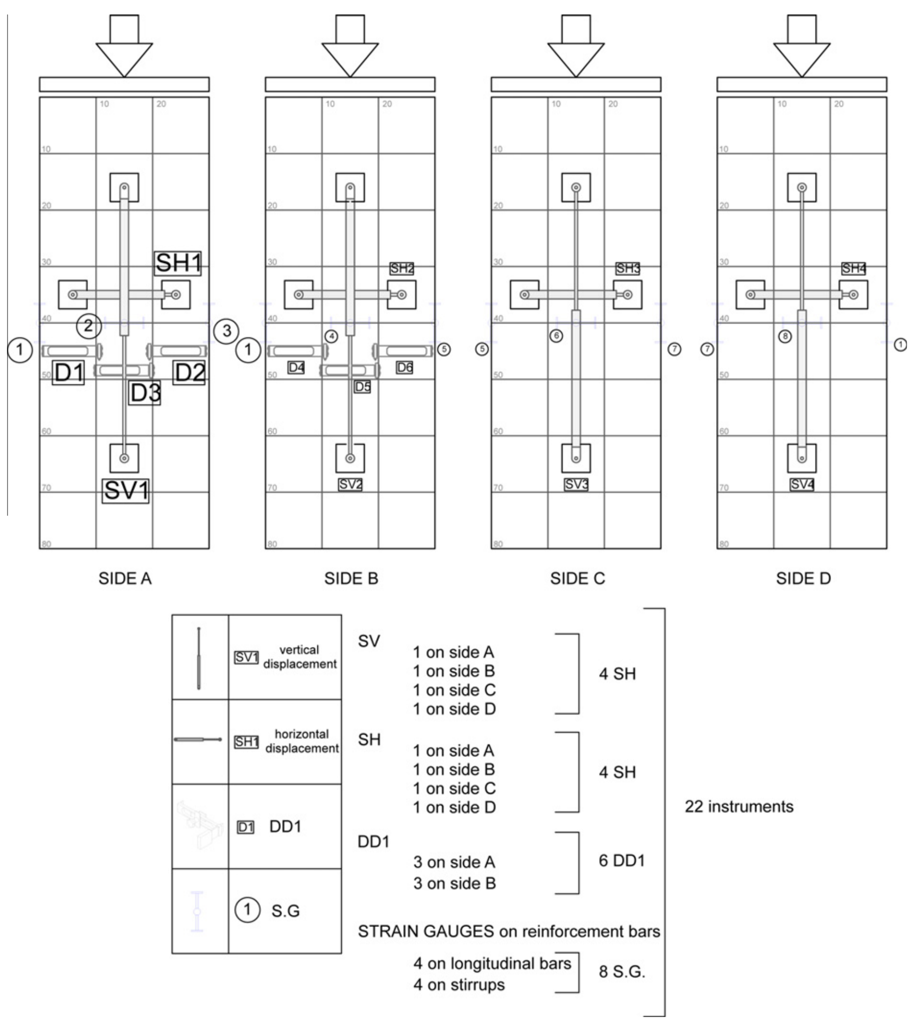

Fig. 2. Test set-up and instrumentation for axial tests.

materials. Type *a* mortar had an elastic modulus slightly lower than that of the concrete substrate (−7%) and higher compressive strength (+20%); type *b* mortar had both mechanical properties lower than those of concrete (elastic modulus −12%, compressive strength −19%), and type *ab* mortar had elastic modulus slightly lower (−10%) and compressive strength slightly higher (+9%) than those of the concrete substrate (Table 2).

2.2. Loading and measurement

The reinforced concrete columns were loaded monotonically under a 10,000 kN loading machine, in control displacement (1/400 mm/s). The same type and same number of instruments were placed in both control and repaired columns.

Eight displacement transducers, with a variable measuring base, were vertically (SV1 to SV4) and horizontally (SH1 to SH4) installed on all column external faces to measure the overall axial and transverse strains of columns. Six strain transducers (DD1; 100 mm measuring base) were also placed horizontally on two adjacent faces (three on each side), to measure transverse strains. Fig. 2 shows the test set-up and instrumentation on the four column sides. In addition, before the concrete was cast, four strain-gauges were installed on the longitudinal bars and four on the stirrups, at mid-height along the columns (Fig. 3), for information on strains on the longitudinal and transversal reinforcement bars.

3. Test results

3.1. Failure modes

The test results indicated that all columns exhibited typical compressive failure, with crushing of concrete and mortar. Vertical cracks generally developed close to the column top and bottom, where damage was concentrated. Differences in failure modes and crack distribution were caused by the various repair materials applied. Figs. 4–7 show crack patterns of the tested columns.

In control columns P0_1 and P0_2, failure occurred by crushing of concrete mostly at the upper ends of columns (Fig. 4). Cracks were vertical and distributed on the four column sides, mainly close to the corners.

Columns P50_a1 and P50_a2 (Fig. 5) were repaired on all four sides with 50 mm thick mortar layer of type *a*. Failure was quite similar to that of columns P0, with crack uniformly distributed on the four sides, and close to the corners. Some portions of repair were detached from the elements only after ultimate load (Fig. 4 and 6).

Columns P50_b1 and P50_b2 were repaired on all four sides with 50-mm thick mortar layer of type *b*. Cracks had vertical and horizontal patterns at failure, and were especially concentrated at the upper ends of elements. A limited number of cracks developed in P50_b2. Conversely, P50_b1 presented the highest number of vertical cracks along all the faces, and horizontal cracks mainly located at mid-height. In the most damaged areas, various layers of mortars, corresponding to different application phases, were progressively detached one from the other (Fig. 6).

Columns P50_ab1 and P50_ab2 were repaired on all four sides with 50-mm thick mortar layer of type *ab*. Compared with columns P50_a and P50_b, the crack pattern had intermediate features, and was distributed on the four column sides. Cracks developed from the beginning of the loading phase and were located both close to column ends and in the middle of the element, with a uniform pattern. Also in this case some phenomena of repair mortar layer detachment, similar to that of columns P50_b, occurred (Fig. 7).

3.2. Stresses and strains

Table 3 lists the compressive test results of the eight concrete columns. Stress values at ultimate load for P0_1 and P0_2 were 25.55 N/mm^2 and 28.49 N/mm^2. The value assumed for the control columns was the average of the two, i.e., 27.00 N/mm^2. The average maximum stress of P50_a columns was 25.36 N/mm^2, which is about 95% of the average maximum stress of control columns; the maximum stress of P50_b and P50_ab columns was between 85% and 86% of that of control columns. These results indicate that mortar *a*, with its higher compressive strength, allowed the columns to bear higher loads and to withstand lower crushing. In terms of load, type *b* mortar showed the worst behavior, due to its lower elastic modulus and compressive strength. Indeed, mortar *ab* gave slightly higher values of ultimate load than mortar *b*, thanks to its intermediate properties.

Figs. 8, 10 and 11 show the stress–strain curves measured during compression tests. Axial strains (compression) are plotted negative and transversal strains (tension) positive. In particular, Fig. 8 compares strains of concrete/mortar and those of reinforcement bars in all columns. On control columns, the stress–strain curves measured on reinforcement bars (by means of strain gauges) and concrete (by means of displacement transducers and strain transducers) completely overlap, demonstrating the perfect bond between the two materials. They (repair mortar and reinforcement bars) had good adhesion and uniform behavior even in columns repaired with type *a* mortar, even after cracking. Conversely, the behavior of columns repaired with type *b* and *ab* mortar was different, and worst in the case of type *b* mortar. The diagrams of

Fig. 3. Strain-gauges on stirrups and longitudinal reinforcement bars.

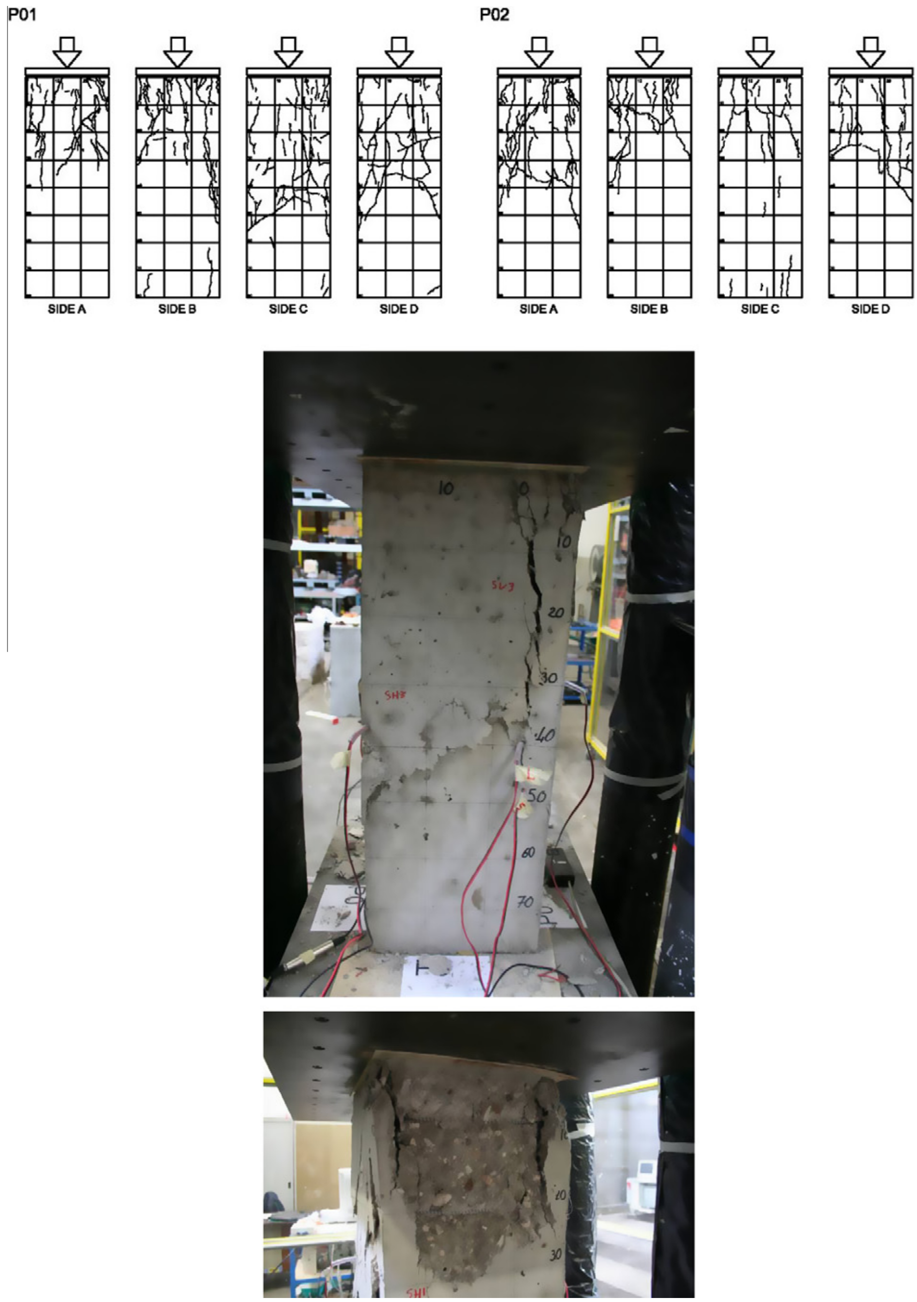

Fig. 4. Crack pattern of control columns.

P50_ab1, P50_ab2, P50_b1 and P50_b2 do show that there was no perfect bond between bars and repair mortar, therefore stress transfer within the element cross section, in particular between concrete core and reinforcement bars and external layer of repair mortar, could not occur properly. This may be due to the values of the mortar elastic modulus, which was higher and more similar to that of the concrete core of the column, in the case of type *a* mortar, allowing homogeneous behavior to develop, whereas it was smaller by 10% and 19%, respectively, type *ab* and *b* mortars. This phenomenon is further confirmed Fig. 9, which shows the ratio of longitudinal bars to external layer strain, on average for each pair of columns, versus the axial stress normalized to the stress at ultimate load. This ratio is generally one for control columns and columns repaired with type *a* mortar. Conversely, strains on longitudinal bars were about 80% of those externally measured on the element, in columns repaired with type *ab* mortar, and only 50% in columns repaired with type *b* mortar. Lastly, Fig. 8 shows that transversal strains on columns and stirrups were similar, and only close to the ultimate load they started to differ.

Fig. 10a shows the stress-axial strain curves, measured on both concrete and the repair mortar, and Fig. 11a the stress-axial strain curves, measured on longitudinal bars, of all columns. Comparing the two figures, it can be seen that the behavior of reinforcement bars in columns was more homogeneous than that of the external layer of the columns, whether they were made of concrete (control columns) or mortar (repaired columns). More in detail, Fig. 10a shows that, besides bearing higher loads, the columns repaired with type *a* mortar were stiffer than the others and showed the most similar behavior to control columns. Columns repaired with type *b* mortars had the lowest strength and stiffness, and columns repaired with type *ab* mortars had intermediate behavior, according to their progressively lower mechanical properties. Conversely,

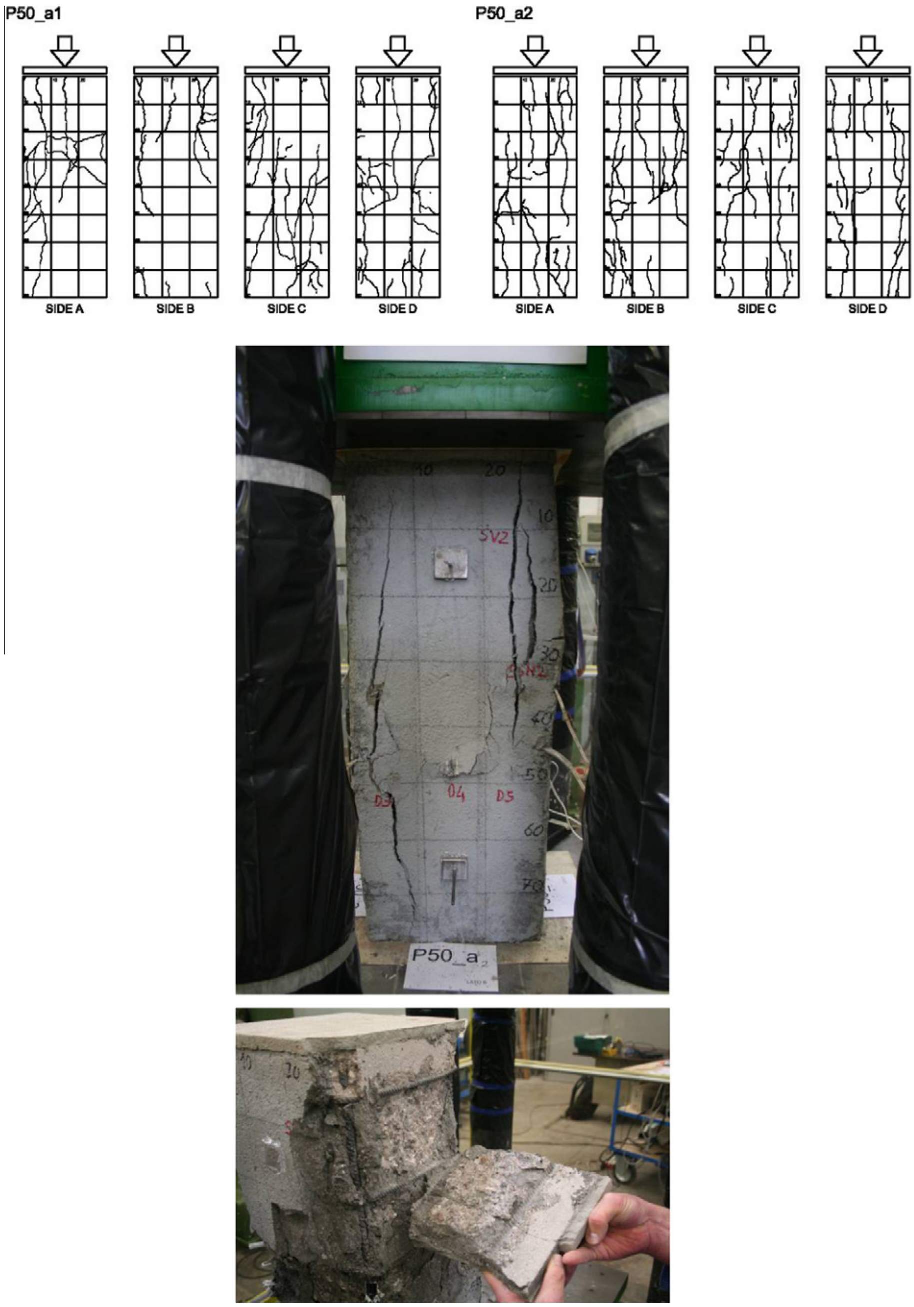

Fig. 5. Crack pattern of columns repaired with type *a* mortar.

analyzing the strain-gauge measurements on longitudinal reinforcement bars of all columns (Fig. 11a), the diagrams show that, except for the lower ultimate load reached, the stress–strain curves of bars in P50_b columns are the most similar to those of control columns. This is consistent with Figs. 8–10a, as the worst behavior of the repair layer in those columns, and the worst adhesion between repair mortar and steel reinforcement, caused stiffer behavior of the bars and earlier collapse, whereas repaired columns, having lower global stiffness but better adhesion, allowed strain compatibility between bars and repair mortar to occur, and resulted in better global behavior.

Fig. 10b shows the stress-transversal strain curves measured on both concrete or the repair mortar, and Fig. 11b the stress-transversal strain curves measured on the stirrups of all columns. These figures show that the behavior of the external layer of columns and stirrups did not vary significantly in the various columns. Comparing the two figures, it can be also confirmed in Fig. 8, i.e., in each column, the strains measured on the external layer of columns, whether they were made of concrete (control columns) or mortar (repaired columns), and on stirrups, were similar. More in detail, Figs. 10 and 11b show that, only after the elastic phase, and more evidently close to the ultimate loads, the measured transversal strains started differentiating. Columns repaired with type *b* mortar developed the highest horizontal strain, due to the smaller confining effect given by that repair mortar. Conversely, columns repaired with type *a* mortar developed the lowest horizontal strain, and showed the most similar behavior to control elements. Columns repaired with type *ab* mortar had intermediate behavior.

The typical Poisson's ratio of concrete, ν, is around to 0.20. This was confirmed by control columns, which showed an average value of transverse to axial strain ratio of one-third of the ultimate

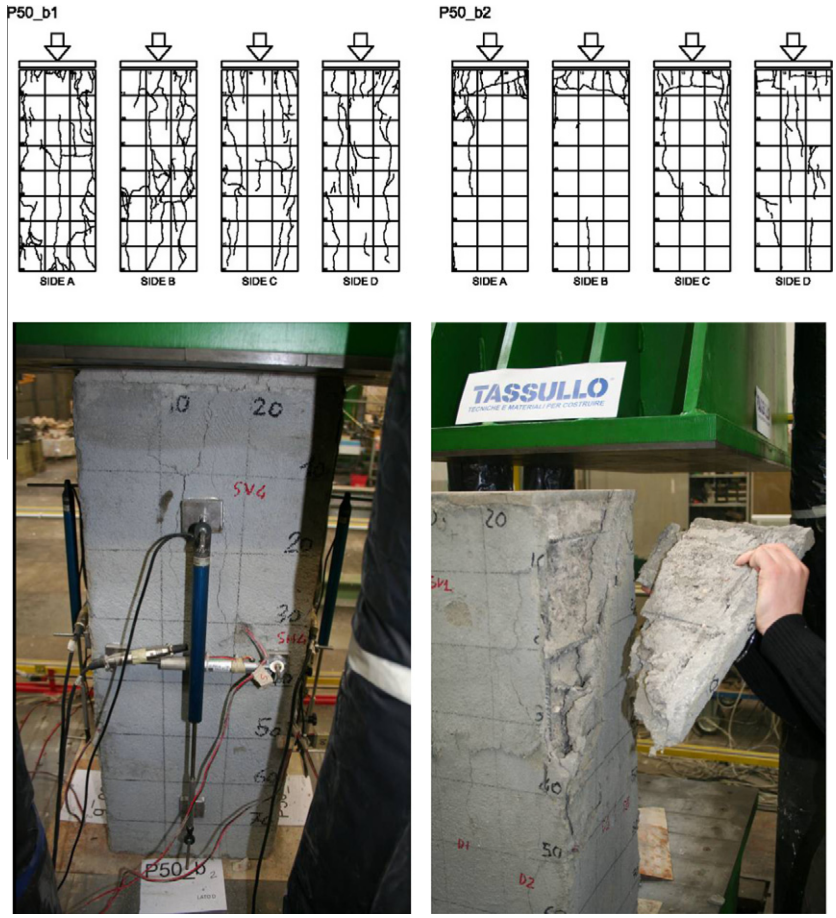

Fig. 6. Crack pattern of columns repaired with type *b* mortar.

load at 0.17. At the same load level, repaired elements showed a lower transversal to axial strain ratio. Although the transversal strains were all similar and very small, axial strains in repaired columns were generally higher than in control columns (Table 4). Columns repaired with type *a* mortar, having the most similar elastic modulus compared with control columns, also had the most similar behavior, with average transversal to axial strain ratios of 0.14. This result shows that these repair mortars could develop some confinement effects but, due to the lower elastic modules, caused a loss of global stiffness in repaired columns.

Axial strains at ultimate load were on average -2.90×10^{-3} on control columns, -2.00×10^{-3} on columns repaired with mortar *a* (-2.40×10^{-3} on P50_a1, -1.61×10^{-3} on P50_a2), -2.83×10^{-3} on columns repaired with mortar *ab*, and -2.90×10^{-3} on columns repaired with mortar *b*, i.e., failure always occurred, in both control and repaired columns, after concrete plasticization (see last column of Table 4), as well as in P50_a2, due to anticipated failure.

The last two rows of Table 4 list stress and strain values on similar columns tested in a previous experimental study (Pellegrino et al., 2009).

3.3. Stiffness

In this experimental research, all columns (excluding control columns) were tested after being repaired with polymer-modified cementitious mortars. To better understand the results, a comparison of global stiffness was also carried out.

Fig. 12 shows that during the elastic phase the columns repaired with type *a* mortar developed axial stiffness which was about 87% of that of control columns. Columns repaired with type *ab* mortar developed lower stiffness (63% of that of control columns), whereas those repaired with type *b* mortar had an axial stiffness which was only 55% of that of control elements. These results show that, for columns repaired with type *a* mortar, the loss of axial stiffness (−13%) is about twice the reduction of the elastic modulus of mortar compared with the concrete substrate (−7%). However, this result is non-proportional in the case of elements repaired with type *ab* and *b* mortars, where the loss of axial stiffness (respectively −37% and −45%) is more than twice the reduction of the elastic modulus of mortar (respectively −10% and −19%). Hence, the global behavior of repaired columns is influenced not only by the values of the mortar elastic modulus and their ratio with the substrate concrete modulus, but also by local behavior at section level and the failure modes which developed.

4. Discussion

Repair mortar cannot restore the load-bearing capacity of non-damaged control columns (from −5% to −15% of control columns). However, the difference in elastic modulus and compressive strength between mortar and concrete may lead to various failure modes, global stiffness and behavior of the repaired column. It was found that all repaired columns developed a more widespread crack pattern at failure than that of control elements. In addition, although delamination affects all repaired elements, detachment of the repair layer takes place locally after reaching the ultimate load in the columns repaired with mortar type *a*. This mortar followed the deforming mode of the embedded longitudinal bars and stirrups (Fig. 8) like the control columns, whereas collaboration and transfer of stresses between steel

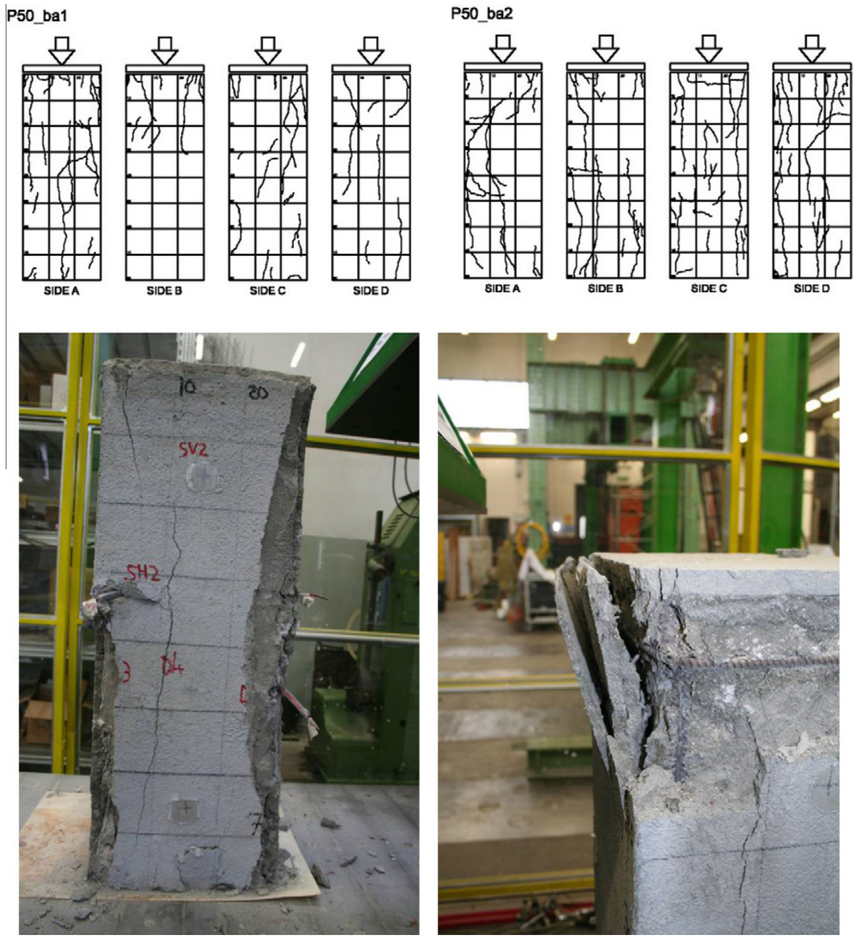

Fig. 7. Crack pattern of columns repaired with type *ab* mortar.

Table 3
Results of axial tests.

Column	Stress at ultimate load (N/mm^2)	Ratio repaired column/control column
P0_1	25.55	–
P0_2	28.49	–
P50_a1	25.55	0.95
P50_a2	25.18	0.93
P50_b1	23.15	0.86
P50_b2	22.97	0.85
P50_ab1	23.36	0.86
P50_ab2	23.38	0.86

and mortar was less effective in the columns repaired with mortar type *b* and *ab*.

Analysis of stress–strain curves in Figs. 10 and 11 emphasizes that the behavior of the columns repaired with mortar type *a* is close to that of control elements, both in terms of mortar and reinforcement bar deformation. The good properties of the mortar type *a* are also confirmed in Fig. 12. Although stiffness in all repaired columns was lower than that of control elements, during the elastic phase the columns repaired with mortar type *a* develop the smallest loss of axial stiffness (−13%). Instead, in the case of repair layers with mortar type *b* and *ab*, the reduction of axial stiffness was respectively −37% and −45%.

Considering the mechanical properties of mortar type *a*, it may be argued that the elastic modulus of repair mortar, combined with appropriate values of compressive strength, is a crucial parameter in the effectiveness of the repair. In this work the best combination of elastic modulus and compressive strength in a repair mortar is found in mortar type *a*, characterized by an elastic modulus similar to that of the concrete substrate (−7%) and slightly higher compressive strength (+20%).

5. Conclusions

Compressive tests were carried out to evaluate the behavior of reinforced concrete columns repaired on all four sides with three types of mortars.

The main conclusion was that repaired columns developed a lower load capacity than non-damaged, non-repaired control elements. For columns repaired with mortar *a*, the repair material did not restore the load-bearing capacity of non-damaged control columns, although it gave acceptable results (95% of ultimate capacity of control columns). Columns repaired with mortar *b* reached an ultimate load which was 85% of the ultimate capacity of control columns, and columns repaired with mortar *ab* reached an ultimate load of 86%. Columns repaired with a mortar having an elastic modulus similar to that of the substrate concrete and a higher compressive strength (mortar *a*) did have some confining effect on the columns, as happens in non-damaged elements.

The results of a previous experimental study [6] showed that, for effective repair of axially loaded elements, it is necessary for the mortar layer to include the reinforcement (both stirrups and longitudinal bars). In that study, the repair was applied to only one side of the columns (Fig. 13). Comparing the results of the cur-

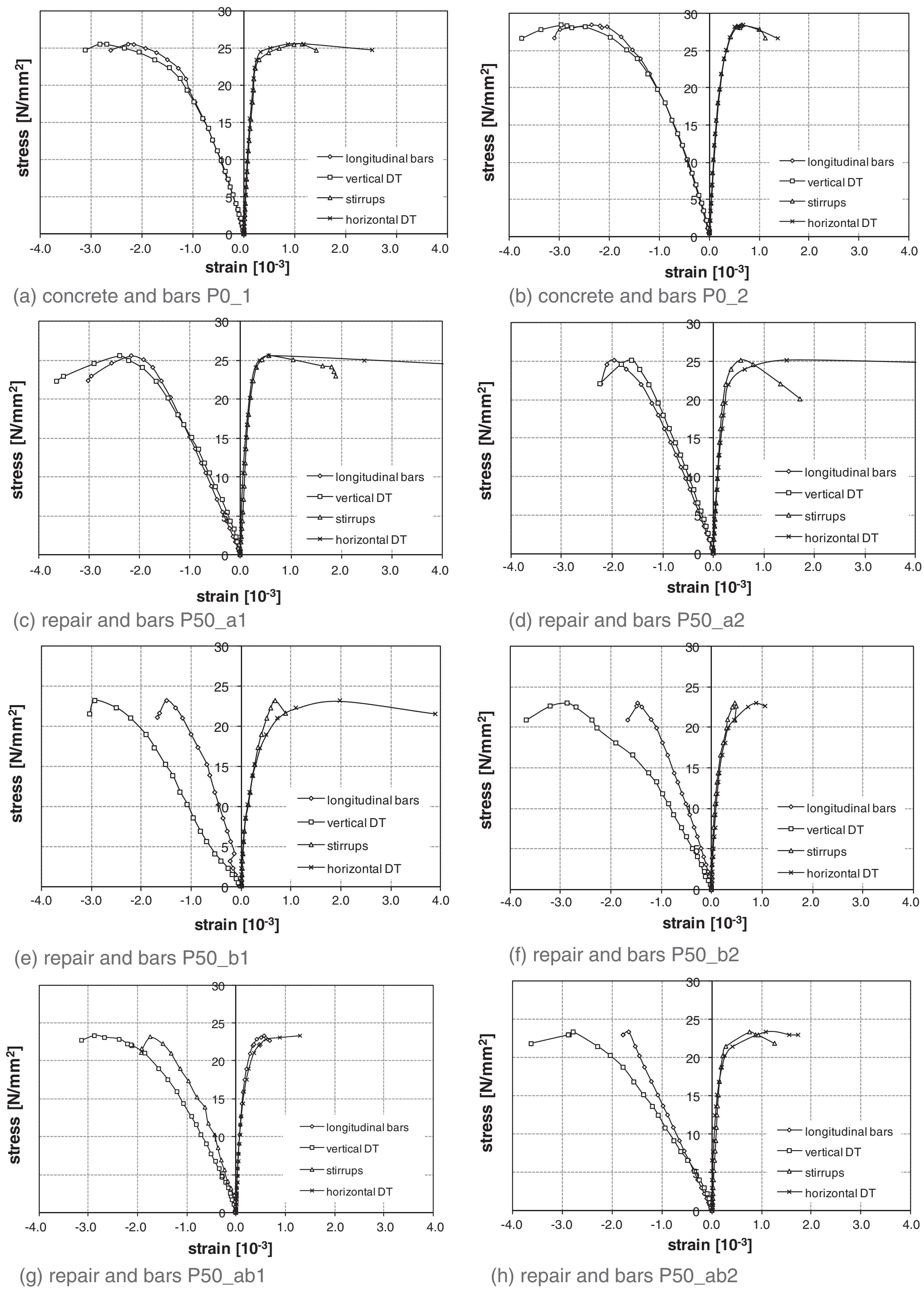

Fig. 8. Average stress–strain diagrams of all specimens.

rent study with those of the previous one, we confirm that it is necessary to use mortars with elastic modulus at least similar or equal to that of the concrete substrate, and preferably higher compressive strength. The listed conclusions are based on a limited number of mortar property variations and tests. It is thus recommended that more research be carried out on this topic, for complete and reliable knowledge of the influencing parameters to be taken into account during the design and execution of interventions.

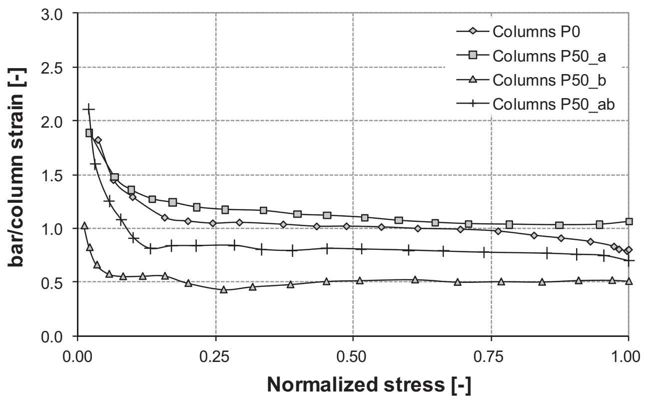

Fig. 9. Ratio of longitudinal bars and column strains, versus normalized axial stress.

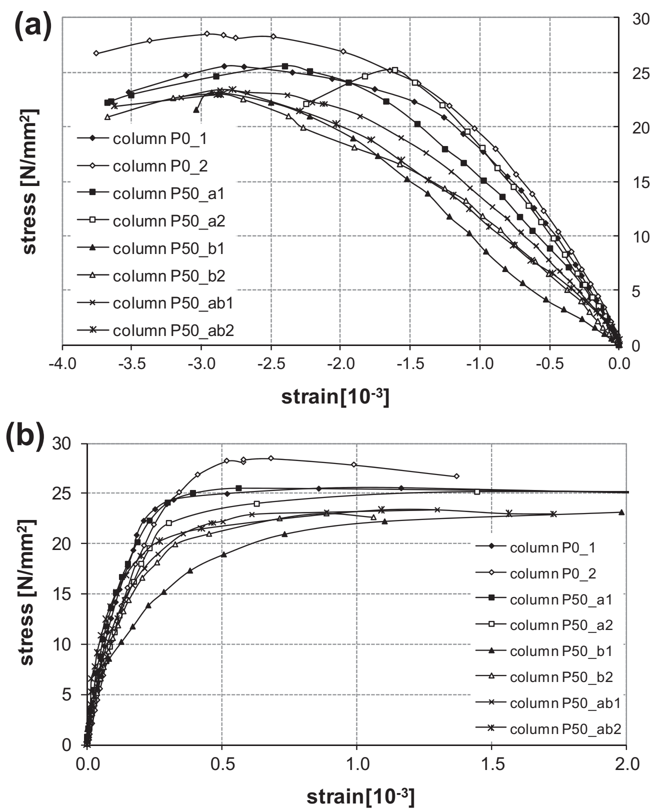

Fig. 10. Average stress-axial strain (a) and stress-transversal strain (b) on all columns.

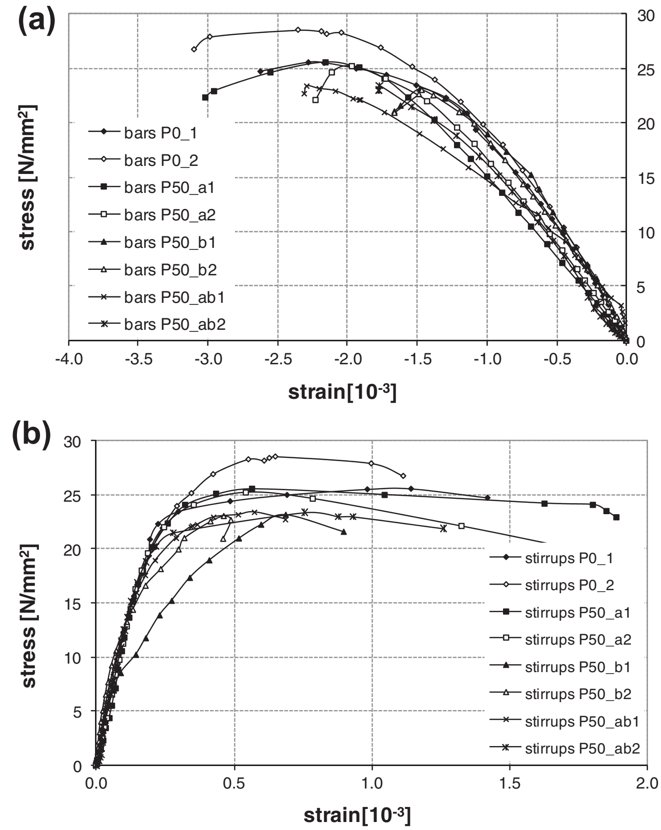

Fig. 11. Average stress-axial strain on longitudinal bars (a) and stress-transversal strain on stirrups (b).

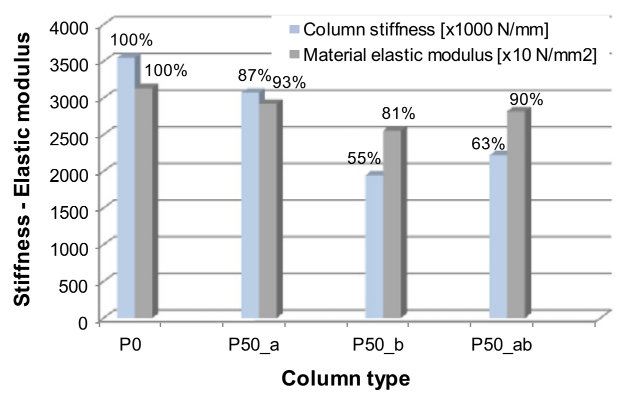

Fig. 12. Average stiffness of columns and elastic modulus of concrete/mortar.

Table 4
Stress and strain values of axial tests.

Column	1/3 Ultimate load				Ultimate load	
	Stress (N/mm^2)	Transv. strain (a) (10^{-3})	Axial strain (b) (10^{-3})	(a)/(b)	Stress (N/mm^2)	Axial strain (10^{-3})
P0_1	8.51	0.05	−0.37	−0.14	25.55	−2.83
P0_2	9.50	0.08	−0.39	−0.21	28.49	−2.96
P50_a1	8.50	0.05	−0.49	−0.10	25.55	−2.40
P50_a2	8.39	0.07	−0.39	−0.18	25.18	−1.61
P50_b1	7.71	0.07	−0.88	−0.08	23.15	−2.93
P50_b2	7.65	0.06	−0.60	−0.10	22.97	−2.88
P50_ab1	7.78	0.05	−0.51	−0.10	23.36	−2.87
P50_ab2	7.78	0.04	−0.63	−0.06	23.38	−2.78
P50_a2009	9.70	0.12	−0.74	−0.16	29.00	−3.30
P50_b2009	9.30	0.24	−1.00	−0.24	27.80	−2.71

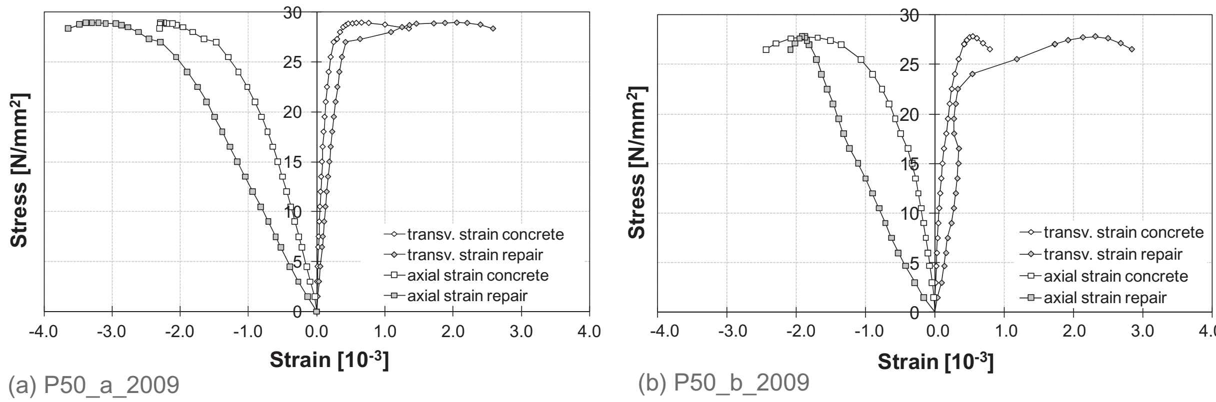

Fig. 13. Average stress–strain diagrams on concrete and repairs (previous experimental study).

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