Cement-based mortar patch repair of RC columns. Comparison with all-four-sides and one-side repair

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Abstract

This paper describes an experimental study on patch-repaired reinforced concrete columns subjected to axial loads until failure. The behaviour of four series of columns repaired with Class R3 and R4 cement-based mortar was analysed both with and without a bonding agent. The results obtained were compared with control series of undamaged and damaged but unrepaired columns to determine the effectiveness of the repairs and the subsequent improvement in the behaviour of the columns. The results of this study were compared with those of previous work by the authors on the analysis of all-four-side repairs and one-side repairs. The conclusion reached was that patch repairs are highly effective as compared to the other techniques studied and that using Class R3 mortar achieves better results on damaged columns made with low-quality concrete. It was also concluded that applying a bonding agent does not improve the results, although this element was found to be necessary to prevent the premature detachment of the repair when there is a substantial difference between the stiffness of the column concrete and that of the mortar used in the repairs.

Keywords: *Patch repair, Bonding agent, RC repair, Repair mortar*

1. Introduction

Patch repairs are widely used for local damage in reinforced concrete (RC) structural elements. The technique consists of restoring the concrete manually, as indicated in Principle 3 of the EN 1504-9:2008 [1]. The repairs are thus restricted strictly to the damaged area and so are less costly than other techniques such as repairs to one side only [2] or to all four sides [3].

The technique is simple and cheap and widely resorted to for RC structures damaged by several types of deterioration, including defects of the pouring or consolidations (voids, pockets and honeycombs) physical (hits, installations holes, etc.) or chemical damage, excessive moisture, incipient corrosion, etc. Unlike one or four-side repairs, they are used when the damage is small, concentrated or punctual, and also when the damage is in an incipient process. In contrast, other types of repairs as all-four-side repairs are used for generalised damages, as fire action, widespread reinforcement corrosion, environmental actions, etc.

The patch repair process consists of eliminating the damaged concrete, cleaning and passivating the reinforcement (according to the degree of corrosion) and applying the patching material or repair mortar (RM) to restore the element to its original geometry. The RM is generally a commercial pre-packed material that may contain different additives, products or materials to modify its properties, reduce shrinkage and improve its performance. In all cases the RM must comply with the requisites of EN 1504-3:2005 [4] as regards structural repair mortars: R3-mortar and R4-mortar. A bonding agent (BA) as specified in EN 1504-4:2004 [5] may be used to ensure that the repair material adheres to the concrete of the column, so that the concrete-BA-RM combination forms a new structure able to support the loads it is subjected to.

In all cases it is necessary to ensure that RM is compatible with the column concrete in order to guarantee its durability and correct functioning. A number of studies have been carried out on the compatibility of materials, such as those by Emberson & Mays [4], Mangat et Limbachiya [8] and Emmons & Vaysburd [9]. Later studies analysed patch repairs and considered other aspects such as shrinkage cracking [10,11], concrete-RM bond strength [12] and their influence on the efficiency and durability of the repairs. Some studies have specifically focused on patch repairs on corrosion-damaged RC structures, usually in aggressive environments, to avoid a repeat of the corrosion in the repair zone [13–19]. Some have analysed the influence of the shape and depth of the patch and emphasized that it must enclose the reinforcement in order to improve the load-bearing capacity of the repaired element [13–19].

However, only a few studies have focused on the behaviour of patch-repaired RC elements later subjected to axial loads. Shambira & Nouno [21,22] analysed patch repairs on short columns and found that although the repairs helped to support short-term loads, long-term shrinkage and creep finally caused the repairs to lose their load-bearing capacity. Li et al. [21] determined that the relations between the elastic moduli and strengths of the RM and the column concrete were the most important factors for their compatibility. Sharif et al. [22] analysed the influence of the RM's elastic modulus on the effectiveness of repairs on loaded and unloaded columns. Aurrekoetchea [23] found that pouring the RM was more effective than manual repairs with a trowel. Hong et al. [24] showed that the failure of repaired columns was due to the RM separating from the column concrete. Achillopoulou et al. [25,26] studied the influence of defective pouring on the behaviour of repaired structural elements. Finally, Monteiro et al. [27] monitored an actual case of chlorine-damaged columns that had been repaired by materials that included a corrosion inhibitor.

This paper describes a study carried out in the laboratories of the Concrete Science and Technology Institute (ICITECH) on 15 patch-repaired RC columns subjected to axial loads until failure. The results obtained were compared with others from three undamaged control columns. Two commercial pre-packed RMs were used in the repairs that complied with the specifications in EN 1504-3:2005 [4] for R3 and R4 mortars, applied with a trowel, both with and without bonding agents, to analyse the behaviour of the repairs and their contribution to the load-bearing capacity of the repaired element. Four types of repairs were thus involved: R3-mortar with BA, R3-mortar without BA, R4-mortar with BA and R4-mortar without BA. These results were then compared with the results of previous studies by the authors on repairs on all four column sides [28] and on one side only [29].

The main novelty of this work lies in its analysis of the effectiveness of patch repairs on RC columns subjected to axial loads. Although this is a commonly used technique, thanks to its economy and apparent simplicity, to date few experimental studies have been performed. Another of its novelties is that it compares the three repair techniques for the first time: patch repairs, all-four-sides and one-side repairs.

The paper is organized as follows: Section 2 reviews the results obtained by the authors in previous studies on one-side and four-side repairs. Section 3 describes the experimental program used. Section 4 analyses the results of the experiments. Section 5 compares the results of patch repair, one-side and four-sides and the main conclusions drawn from the work are given in Section 6.

2. Brief review of previous experimental research at the ICITECH

In previous research the authors studied the behaviour of square cross-section columns repaired on all four sides [28] and on one side only [29]. The results are given below for later comparison with the results of the present work.

Fifteen columns repaired on one side only plus fifteen repaired on all four sides were tested under axial compression until failure (see designations in Table 1). The different specimens were as follows:

a) 3 unrepaired damaged columns.

b) 3 damaged columns repaired with R3-mortar and BA.

c) 3 damaged columns repaired with R3-mortar and no BA.

d) 3 damaged columns repaired with R4-mortar and BA.

e) 3 damaged columns repaired with R4-mortar and no BA.

Three undamaged control columns (C) were also tested, for a total of 33 specimens.

The square cross-section columns tested had sides of 200 mm, the shafts were 520 mm long and were dogbone-shaped to simulate the presence of beams and avoid the heads failing through excessive compression, which would have distorted the results. The heads measured 400×200 mm with a height of 420 mm, so that the total height of the specimens was 1360 mm.

Table 1. Specimen identification

Repair Type	Element Type	Condition	RM	BA	Designation
NOT REPAIR	Control Undamaged Columns	Non-Damaged	-	-	C-1
					C-2
					C-3
ALL-FOUR-SIDES REPAIR	Control Damaged Columns	Non-Repaired	-	-	FD-1
					FD-2*
					FD-3*
	All-four-sides Repaired Columns	Repaired	R3	yes	F3B-1
					F3B -2
					F3B -3
				no	F3W-1
					F3W-2
					F3W-3
			R4	yes	F4B-1
					F4B-2
					F4B-3
				no	F4W-1
					F4W-2
					F4W-3*
ONE-SIDE REPAIR	Control Damaged Columns	Non-Repaired	-	-	OD-1
					OD-2
					OD-3*
	One-side Repaired Columns	Repaired	R3	yes	O3B-1
					O3B-2
					O3B-3
				no	O3W-1
					O3W-2
					O3W-3
			R4	yes	O4B-1
					O4B-2
					O4B-3*
				no	O4W-1
					O4W-2
					O4W-3
PATCH REPAIR	Control Damaged Columns	Non-Repaired	-	-	PD-1
					PD-2
					PD-3
	Patching Repaired Columns	Repaired	R3	yes	P3B-1
					P3B-2
					P3B-3
				no	P3W-1
					P3W-2
					P3W-3
			R4	yes	P4B-1
					P4B-2
					P4B-3
				no	P4W-1
					P4W-2
					P4W-3

* Failed specimen

The columns were meant to simulate old and deteriorated concrete, typical of the structures built in the 1940s and 50s, which are the ones typically repaired by these methods. The compressive strength of the concrete was 9.21 MPa at 28 days of age and the elastic modulus was 18,938 N/mm^2.

The column reinforcement consisted of four 10 mm diameter longitudinal rebars with 6 mm diameter stirrups every 50 mm. The stirrups in the heads were also separated by 50 mm and were 8 and 10 mm in diameter. The yield stress of the reinforcement steel was 500 MPa.

In both repaired and unrepaired specimens, the damage in the columns was simulated by placing 50 mm thick sections of expanded polystyrene (EPS) around the reinforcement in the formwork before pouring. The columns were repaired 59 days after being produced and included wirebrushing the surfaces before being washed down with a pressure hose. Two layers of RM were applied manually without BA, when this was not included, and over the previously applied BA, when it was.

In the all-four-sides repairs, the RM was applied to two opposite sides by means of formwork fixed to the other two sides, after which the roles were reversed for application to the second pair of sides. This involved the creation of dry joints between the repaired surfaces in both cases. In the one-side-only repairs, only the damaged surface was repaired, so that the dry joints were between the repaired surface and the sides in contact with it.

In all cases, commercial, single-component, fibre-reinforced, low-shrinkage, pre-packed cement-based RM was used, in compliance with EN 1504-3:2005 [4] for structural repairs with R3 and R4 mortars. The BA was a single-component, cement-based product with added synthetic resin and silica fume, in accordance with EN 1504-4:2004 [5]. The characteristics of these materials as specified in the product data sheets can be seen in Table 2.

The specimens were subjected to vertical axial compression, as shown in Fig. 1, by means of a 2,500 kN hydraulic jack at a constant application rate of 0.5 mm/second.

Table 2. Mechanical requirements and properties of R3-mortar, R4-mortar and BA

		Performance characteristic of materials			
		Compressive strength	**Adhesion to concrete**	**Modulus of elasticity**	**Flexural strength**
Class R3 mortar	**Requirements EN 1504-3**	≥ 25 MPa	≥ 1.5 MPa	≥ 15 GPa	-
	Performances 28 days	40.3 MPa	1.9 MPa	25.2 GPa	8.3 MPa
Class R3 mortar	**Requirements EN 1504-3**	≥ 45 MPa	≥ 2 MPa	≥ 20 GPa	-
	Performances 28 days	54 MPa	2.5 MPa	36.7 GPa	9.0 MPa
Bonding Agent	**Requirements EN 1504-3**	≥ 30 N/mm^2	-	-	-
	Performances 28 days	39 MPa	8 MPa	-	3 MPa

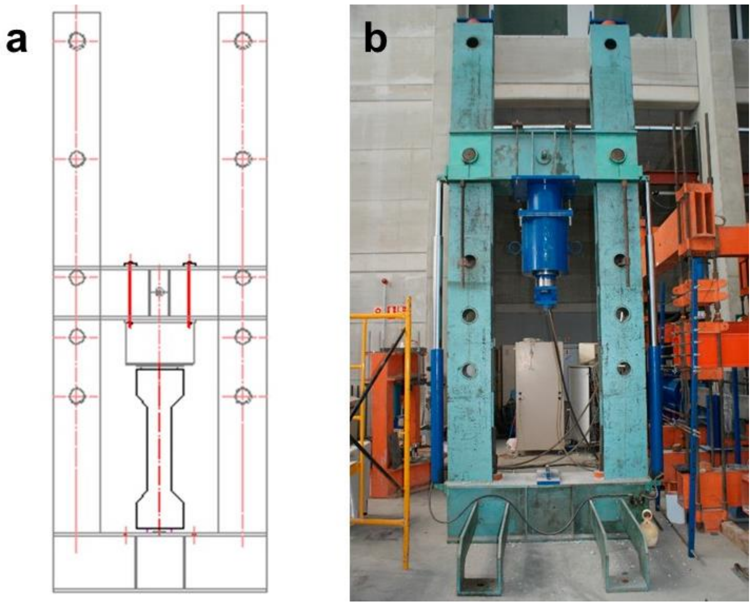

Fig. 1. Testing frame

To compare the results of the different tests, the repair efficiency of the individual specimens and series was determined as the ratio (%) between the specimen's ultimate load (or the mean ultimate load of the series) and the mean ultimate load of the undamaged control specimens. The improved damaged column (or series) ratio (%) was defined as the ratio of the ultimate column load (or mean of the series) and the mean ultimate load of the unrepaired damaged columns.

Table 3. Experimental results and ratios of all-four-sides repair and one-side repair columns

Type of repair	Serie	Specimen	N (kN)	N_{mean} (kN)	Efficiency ($N_{Repaired}/N_{Control}\times 100$)		Improvement respect damaged columns ($N_{Repaired}/N_{Damaged}\times 100$)	
CONTROL UNDAMAGED	C	C-1	637.34	617.51	-	-	-	-
		C-2	590.14		-		-	
		C-3	625.06		-		-	
ALL-FOUR-SIDES REPAIR	FD	FC-1	282.84	282.84	-	-	-	-
		FC-2	-		-		-	
		FC-3	-		-		-	
	F3B	F3B-1	557.01	509.97	90.20%	82.58%	196.93%	180.31%
		F3B-2	544.71		88.21%		192.59%	
		F3B-3	428.20		69.34%		151.39%	
	F3W	F3W-1	575.25	520.37	93.16%	84.27%	203.38%	183.98%
		F3W-2	506.82		82.07%		179.19%	
		F3W-3	479.04		77.58%		169.37%	
	F4B	F4B-1	398.24	438.00	64.49%	70.93%	140.80%	154.86%
		F4B-2	475.64		77.03%		168.17%	
		F4B-3	440.14		71.28%		155.61%	
	F4W	F4W-1	400.42	391.94	64.84%	63.47%	141.57%	138.58%
		F4W-2	445.69		72.18%		157.58%	
		F4W-3	329.72		53.40%		116.57%	
ONE-SIDE REPAIR	OD	OC-1	461.51	397.17	-	-	-	%
		OC-2	332.83		-		-	
		OC-3	-		-		-	
	O3B	O3B-1	462.46	598.78	74.89%	96.97%	116.44%	150.76%
		O3B-2	658.78		106.68%		165.87%	
		O3B-3	675.11		109.33%		169.98%	
	O3W	O3W-1	551.72	580.72	89.35%	94.04%	138.91%	146.21%
		O3W-2	578.94		93.75%		145.77%	
		O3W-3	611.49		99.02%		153.96%	
	O4B	O4B-1	411.29	406.71	66.60%	65.86%	103.56%	102.40%
		O4B-2	402.13		65.12%		101.25	
		O4B-3	-		-			
	O4W	O4W-1	453.75	403.76	73.48%	65.38%	114.25%	101.66%
		O4W-2	339.69		55.01%		85.53%	
		O4W-3	417.84		67.66%		105.20%	

Terminology

N	Maximum load for each column
N_{mean}	Mean maximum load for each series of columns
$N_{Repaired}$	Average maximum load for each series of repaired columns (F3B, F3W, F4B, F4W)
$N_{Control}$	Average maximum load for control undamaged columns (C)
$N_{Damaged}$	Average maximum load for control damaged columns (FD, OD)

Table 3 gives the results obtained from the tests and the calculated improved efficiency ratios of all the one and four-side series. It can be seen that the R3 mortar functioned better than the R4, with a bigger difference in the one-side than the four-side repairs. In all cases, applying a BA improved the behaviour slightly, but not significantly.

Repair efficiency (with respect to the control columns) in both cases was high: in the one-side repairs this was almost 97% and approximately 83% in the four-side repairs. The columns repaired on four-sides reached an initial load value of 180%, while the one-side repairs only reached 150%, due to the fact that the unrepaired four-side damaged columns only maintained a nucleus of concrete and reinforcement, which meant a considerably reduced cross section and load-bearing capacity.

In both repair methods failure was due to the detachment of the RM from the dry joints, as can be seen in the different series of specimens shown in Fig. 2. This detachment produced asymmetric loads on the cross section which generated eccentric compression on the column and caused it to fail.

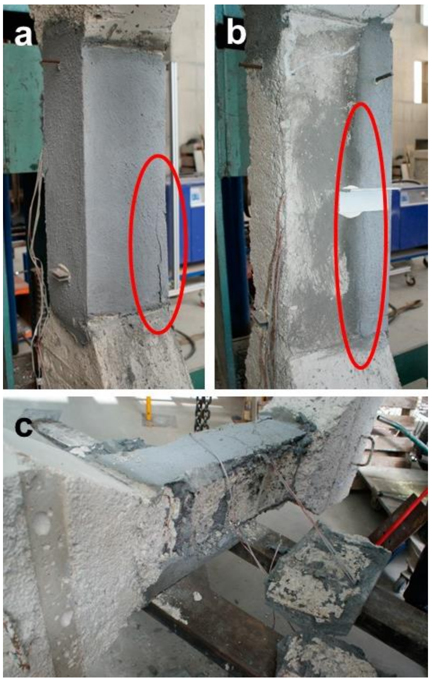

Fig. 2. Column failure through the dry joints: a) Specimen F4W (all-four-sides repaired with R4-mortar and no BA); b) Specimen O3B (one-side repaired with R3-mortar and BA); c) Specimen F3B (all-four-sides repaired with R4-mortar and BA), detachment of the repair

3. Description of the new experimental program

The present experimental study was carried out in the same conditions as for those described in the previous section for one-sided and four-sided repairs. All the specimens were prepared at the same time to avoid variations in the concrete characteristics, temperature and ambient moisture, as described below.

It has to be taken into account that patching repair is used in columns with small or punctual damages, that is, in those cases where the damage has not yet spread to the entire side or the complete column. For that reason, only the central third of the side was repaired. On the contrary, in the previous cases (one-side and all-four-side repairs), the sides were completely repaired, simulating a major or complete damage in the columns. For this reason, in the patching repair the damage was located only in the central third of the column, while in the one and a four-side repair, the damage was simulated in the whole length of the column.

The first phases of the repair include to remove the old concrete and to replace it for a new one, after cleaning the reinforcement. To simulate this process, 50 mm thick sections of EPS wrapping the reinforcement was used. The EPS was placed in the formwork before pouring the concrete. This approach was used to obtain identical damaged-unrepaired specimens that guaranteed the homogeneity between them to compare their performance after the repair. Besides that, the economy and simplicity of execution of this method made it suitable to produce 48 comparable specimens in a reasonable period of time.

The columns were poured horizontally with the simulated damage in the upper section. The EPS representing the simulated damage was placed in position before the pouring, as shown in Figs. 3a and 3b. The formwork was filled manually, and the concrete was compacted by an electric vibrator (see Fig. 3c).

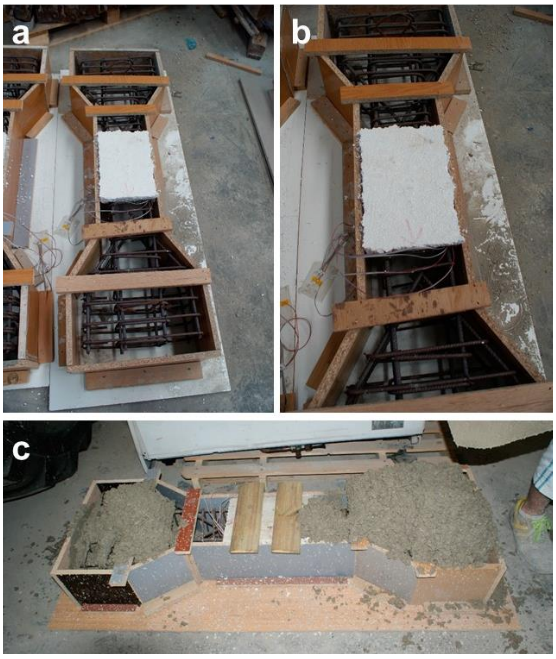

Fig. 3. a, b) Specimens' formwork with EPS to simulate the damage; c) Pouring concrete

As in the preceding one and four-side tests, the surfaces were wirebrushed and washed with a pressure hose to eliminate all traces of EPS before applying the same RM as before (Table 2), two layers of which were applied with a trowel (Fig. 4).

As in the previous tests, for repairs without BA the procedure was as follows: the first layer of approximately 20 mm of RM was applied to the wet surface, filling the spaces between the column concrete and the reinforcement. This was followed by a further layer to give a total thickness of 50 mm. In those with BA, the surfaces were first impregnated with the product just before applying two layers of mortar, as before. When this was dry, the surface was smoothed to obtain a better finish.

Fig. 4. a) Detail of the column hollow to perform the patching repair; b) Filling the first layer of column patching

The monitoring equipment attached to the specimens was formed by strain gauges on the four longitudinal rebars and three LVDTs, as shown in Fig. 5, on both the repaired side (Side 1) and on the opposite intact side (Side 3) to record the different deformation on both sides caused by the different stiffness of the RM on the repaired side and the column concrete on the unrepaired side. The third LVDT was placed on the interface concrete-RM (Side 2) to record the relative displacement of both materials.

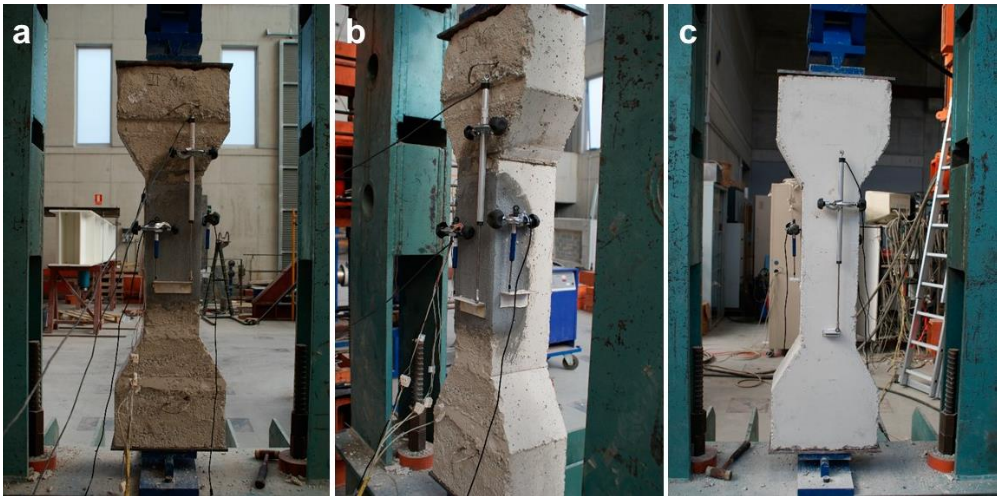

Fig. 5. a) Instrumentation of patch repaired columns: a) Side 1; b) Side 2; c) Side 3

4. Results and analysis

This section gives the results obtained in the tests and an analysis of the behaviour of the columns repaired with R3-mortar and R4- mortar with and without BA.

4.1. Results

The failure of the undamaged control column was by axial compression and was accompanied by the typical vertical cracks in the central areas. However, in the unrepaired and damaged column (Fig. 6) failure was caused by buckling of the reinforcement on Side 1 due to the absence of concrete on the prepared repair zone. The crack on Side 3, which spread to Sides 2 and 4, also showed the effects of eccentric compression.

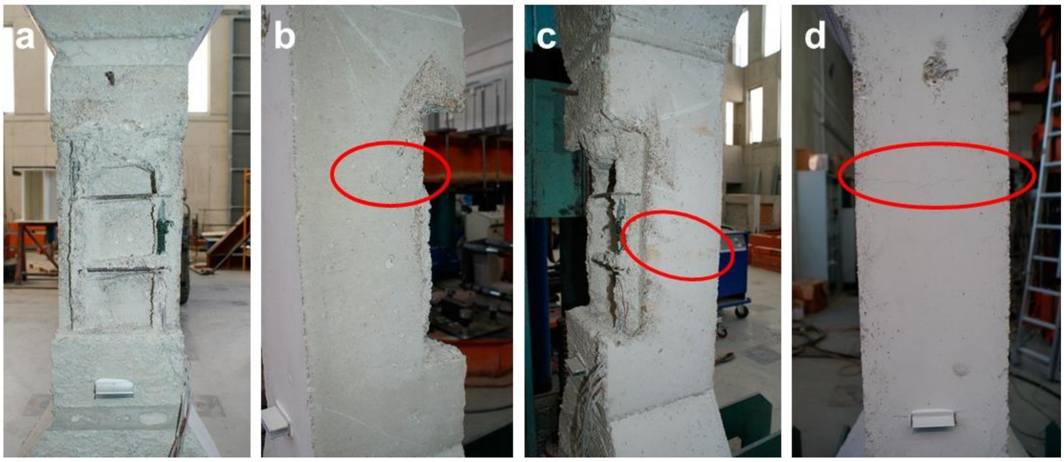

Fig. 6. Column failure: Specimen PD (damaged control column): a) Side 1; b) Side 2; c) Side 4; d) Side 3

The four series of repaired columns presented the following failure modes:

a) Specimens repaired with R3-mortar and BA (P3B, Fig. 7): the repaired side (1) had a vertical crack on one of the sides of the patched zone, while the opposite side (3) had an almost imperceptible horizontal crack in the centre as a result of the bending due to the asymmetric cross-sectional stiffness in this direction. The lateral sides only showed the typical dry joint crack between the column and the RM in the initial stage of detachment.

b) Specimens repaired with R3-mortar and no BA (P3W, Fig. 8): the repaired side (1) had very fine vertical cracks, while its opposite side (3) had a very slight horizontal crack in the centre, indicating similar behaviour to the preceding case. The lateral sides showed vertical cracks in the repair, in the initial stage of RM detachment.

In both cases of repair with R3 mortar, the different stiffness of the RM and the column concrete was seen to cause asymmetric load distribution, so that failure was due to eccentric compression generating tensile stresses on the unrepaired side (3).

c) Specimens repaired with R4-mortar and BA (P4B, Fig. 9): in this case, the repaired side (1) had vertical cracks on both sides, while its opposite side (3) had no cracks at all. Dry joint cracks were seen on the lateral sides between the base mortar and the RM. These cracks, already seen in the specimens repaired with R3-mortar and BA, in this case were much wider and caused failure due to detachment of the RM.

d) Specimens repaired with R4-mortar and no BA (P4W, Fig. 10): in this case the detachment of the RM can be clearly seen. This generated eccentric compression, as shown by the horizontal crack on the opposite side (3). This phenomenon had already appeared in the series repaired with R3-mortar but was much more severe in this case and spread to both lateral sides, which also show RM detachment (Fig.11).

In the specimens repaired with R4-mortar, the load eccentricity was more marked and generated larger tensile stresses on the unrepaired side (3) and complete RM detachment.

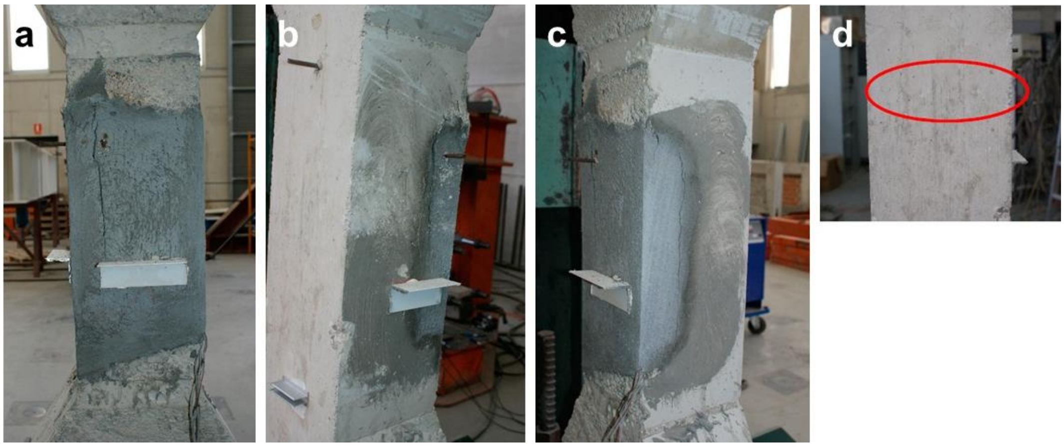

Fig. 7. Column failure: Specimen P3B (repaired column with R3-mortar and BA): A) Side 1; b) Side 2; c) Side 4; d) Side 3.

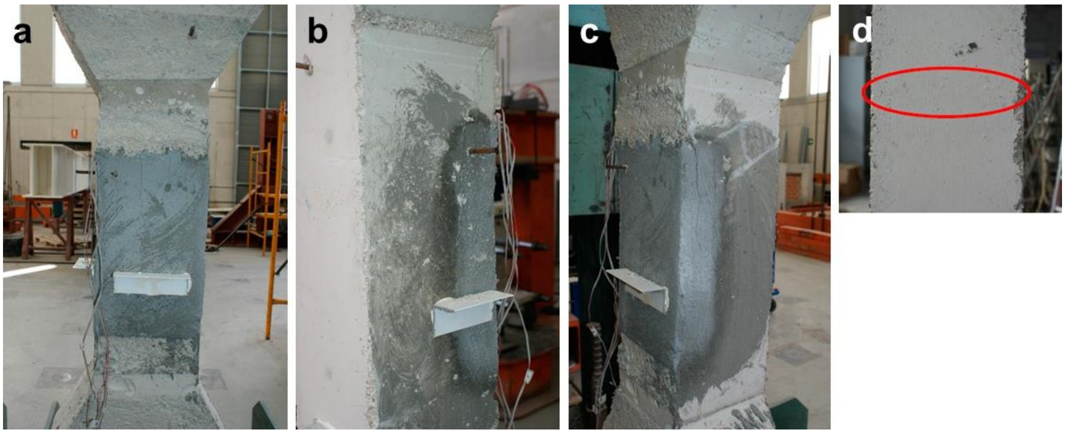

Fig. 8. Column failure: Specimen P3W (repaired column with R3-mortar and no BA) : a) Side 1; b) Side 2; c) Side 4; d) Side 3

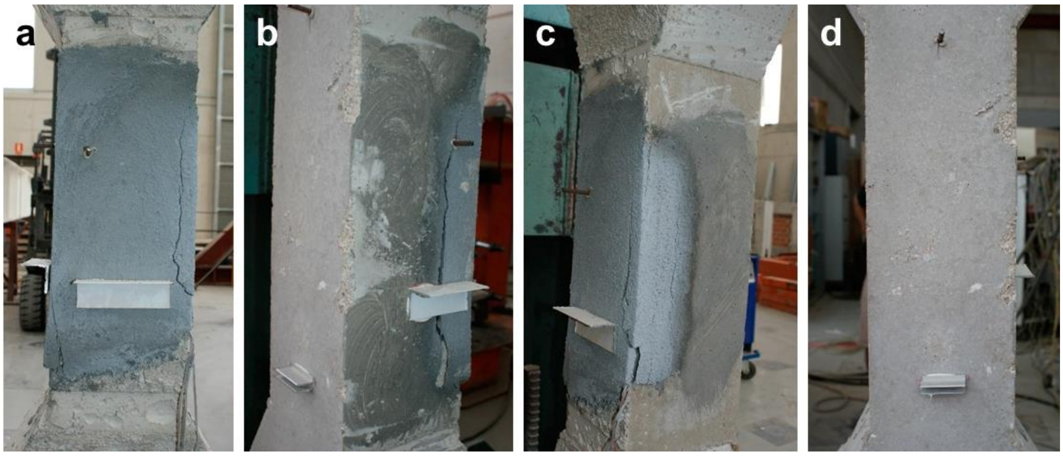

Fig. 9. Column failure: Specimen P4B (repaired column with R4-mortar and BA) : a) Side1; b) Side 2; c) Side 4; d) Side 3

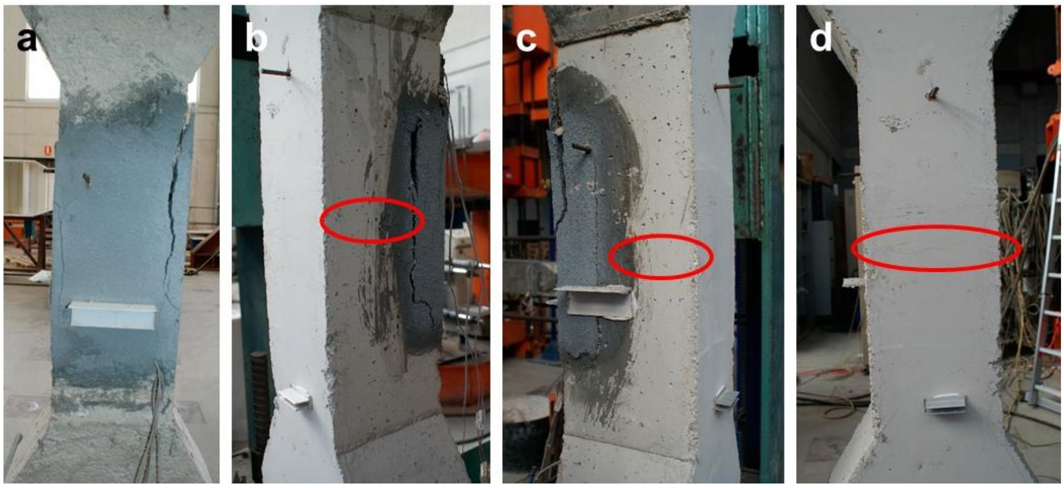

Fig. 10. Column failure: Specimen P4W (repaired column with R4-mortar and no BA): a) Side 1; b) Side 3; c) Side 2; d) Side 4

Fig. 11. Column failure: Specimen P4W (repaired column with R4-mortar and no BA). Detail of the detachment of the patch

The load deformation curves of all the repaired series can be seen in Fig. 12; each series is compared with the average curve of the undamaged control specimens (C) and the average curve of the unrepaired damaged columns (PD). Both the unrepaired damaged (PD) and repaired columns (P3B, P3W, P4B and P4W) show deformation on both the repaired (1) and opposite (3) sides. The different behaviour of both sides can thus be appreciated; this was due to asymmetric cross-sectional stiffness generating eccentric compression, and thus tensile stresses on Side 3.

The results obtained experimentally, and the efficiency ratio values can be seen in Table 4. The latter were calculated for each specimen and for the average of each series as the ratio between the specimen's ultimate load and that of the undamaged control specimen, as a percentage. The improvement ratio was also calculated with respect to the unrepaired damaged columns, which gave the percentage improvement of the load-bearing capacity of each column and series of columns. These ratios allow the behaviour of the different series to be compared. Firstly, they show the percentage load they can bear with respect to their original undamaged state, which provides a value for the safety of the repair. And secondly, they indicate the percentage improvement with respect to their previous damaged state, which allows the benefits of the repair to be evaluated.

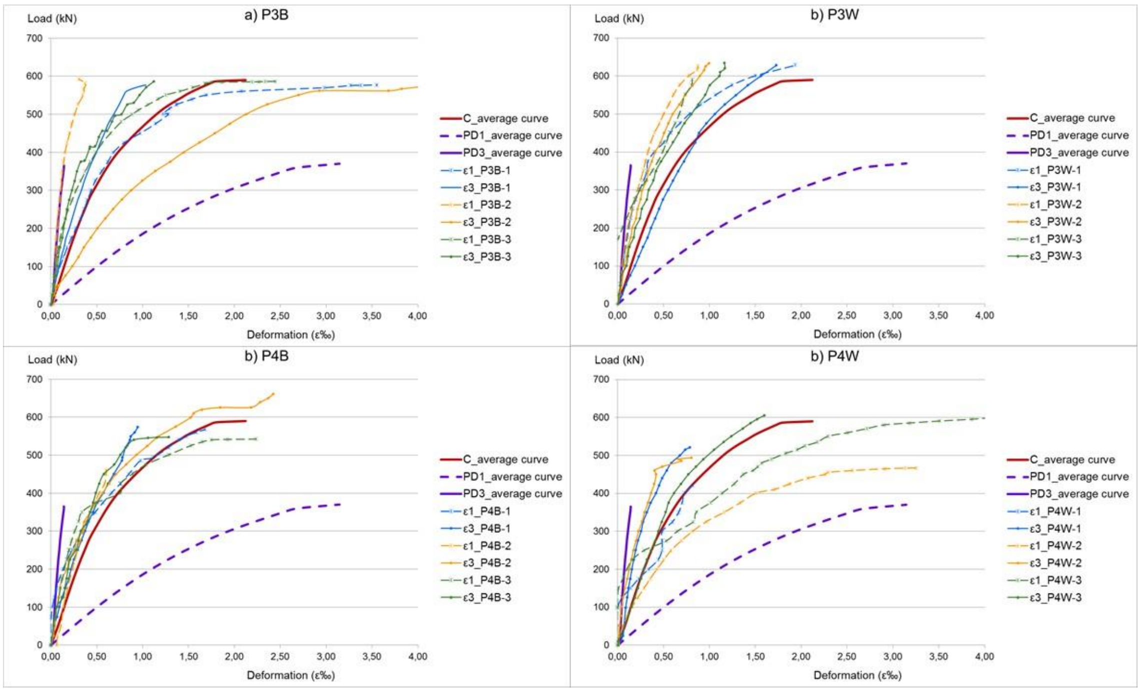

Fig. 12. Load-deformation curves of average-control-columns (C), sides 1 and 3 of average-damaged-columns (PD) and sides 1 and 3 of repaired-columns: a) Specimens P3B; b) Specimens P3W; c) Specimens P4W; d) Specimens P4W

4.2. Analysis and discussion

This section contains an analysis of the results of the series of repaired columns, which are compared with each other and with the undamaged and damaged and repaired control columns. It can be seen from the load deformation curves (Fig.12) that the damaged side (1) and its opposite side (3) sustained different deformation due to the eccentric compression of the horizontal section caused by the repairs. The difference between the sides is much more pronounced in the unrepaired damaged columns, due to the absence of concrete in the prepared repair zone. From the curves it can be seen that the undamaged side remained much stiffer with almost no deformation, while the damaged side is considerably deformed and its reinforcement is buckled. In these cases, the loss of resistance is of the order of 30% with reference to the undamaged control columns, as shown in Table 4. The details for each type of specimen are:

Table 4. Experimental results and ratios of patching repair columns

Type of repair	**Serie**	**Specimen**	**N (kN)**	**N_{mean} (kN)**	**Efficiency ($N_{Repaired}/N_{Control}\times 100$)**		**Improvement respect damaged columns ($N_{Repaired}/N_{Damaged}\times 100$)**	
CONTROL UNDAMAGED	C	C-1	637.34	617.51	-	-	-	-
		C-2	590.14		-		-	
		C-3	625.06		-		-	
PATCH REPAIR	PD	PD-1	479.93	432.19	-	-	-	-
		PD-2	446.44		-		-	
		PD-3	370.21		-		-	
	P3B	P3B-1	577.26	581.88	93.48%	94.23%	133.57%	134.63%
		P3B-2	-		-		-	
		P3B-3	586.50		94.98%		135.70%	
	P3W	P3W-1	628.33	632.14	101.75%	102.37%	145.38%	146.26%
		P3W-2	633.44		102.58%		146.57%	
		P3W-3	634.64		102.77%		146.84%	
	P4B	P4B-1	573.83	594.09	92.93%	96.21%	132.77%	137.46%
		P4B-2	661.10		107.06%		152.97%	
		P4B-3	547.33		88.64%		126.64%	
	P4W	P4W-1	521.03	540.22	84.38%	87.48%	120.56%	124.99%
		P4W-2	493.96		79.99%		114.29%	
		P4W-3	605.67		98.08%		140.14%	

Terminology

N	Maximum load for each column
N_{mean}	Mean maximum load for the series of columns
$N_{Repaired}$	Average maximum load for repaired columns (P3B, P3W, P4B, P4W)
$N_{Control}$	Average maximum load for control undamaged columns (C)
$N_{Damaged}$	Average maximum load for control damaged columns (PD)

a) Specimens repaired with R3-mortar and BA (P3B, Fig. 12a): repair efficiency in this case is of the order of 94%, i.e. the repairs restored almost the whole load bearing capacity of the element, showing that the concrete-BA-RM combination functioned well. As can be seen in Fig. 12a, the difference in the behaviour of the repaired and intact sides is quite small, showing that the degree of eccentricity is not significant. The restored load bearing capacity of the damaged column with reference to the unrepaired damaged column is 135%, which can be considered as a significant improvement in view of the size of the repair zone.

b) Specimens repaired with R3-mortar and no BA (P3W, Fig. 12b): in this series the repair failed due to detachment of the RM, causing asymmetry in the cross section and leading to bending forces in the column. As in the previous case, this produced cracks on Side 3. Fig. 12b shows that the repair restored practically the entire symmetry of the section and that the deformation was quite similar on both Sides 1 and 3. Repair efficiency was 102%, confirming the above. The element's load bearing capacity after the repairs is approximately 146% that of the unrepaired damaged column, somewhat more than in the previous case. It should be noted that the ultimate strength of the series with R3-mortar without BA is 9% higher than those repaired with the same class of mortar with BA. It would thus appear that the repairs were more successful than in the previous case with BA. This was due to the stiffness of the concrete and the RM not being much different and thus not requiring a bonding agent since there was sufficient adhesion between the materials to ensure a good repair.

c) Specimens repaired with R4-mortar and BA (P4B, Fig. 12c): in this series the repairs failed due to detachment of the RM, which occurred close to the maximum load, as can be seen from the curves. The repairs practically restored the cross-section geometry until detachment. The difference between the behaviour of both sides was due to the different mechanical properties of the concrete and RM, although there was not a marked difference due to the adhesive effect of the BA. Efficiency was 96% and the load bearing capacity was 138% higher than that of the damaged column. These values are quite similar to those obtained for the columns repaired with R3-mortar and BA, or even a little better. The results show that the presence of the BA was important in this case since it reduced the difference between the stiffness of the RM and the concrete and maintained the bond almost up to the ultimate load.

d) Specimens repaired with R4-mortar and no BA (P4W, Fig. 12d): as in the previous series, repair failure was due to detachment of the RM (Fig. 11). The loss of the bond between the RM and concrete can be seen; this was found to be due to RM detachment and the tensile cracks on Side 3 on reaching 95% of maximum load. Repair effectiveness was 87% of that of the undamaged control column, while the improvement over the unrepaired damaged column was 125%, the lowest values of all the series, indicating that the repairs contributed least to the improvement and that this combination is the least appropriate of the four cases studied. In this case the ultimate strength of the columns repaired without BA is 9% lower than those repaired with BA, unlike the series repaired with R3-mortar. This is due to the fact that the excessive stiffness of the R4, which causes the RM to detach, can be offset by using a BA to improve the bond between both materials. All the indicators studied show that that this type of repair is the least appropriate for patch repairs on columns with poor quality concrete, due to the difference in stiffness between the R4 and the concrete. The results in this case therefore depend largely on the characteristics of the concrete in the columns, i.e. on the relationship between the stiffness of the RM and the concrete. The closer their elastic moduli are to each other, the less the eccentricity produced and the higher the quality of the repairs.

It can therefore be concluded that R3 gives better results than R4 mortar for patch repairs on columns made with poor quality concrete, basically due to the former having lower stiffness and an elastic modulus more in line with the original concrete, which means less asymmetric stiffness in the cross section and lower bending forces. This explains why the repaired Side 1 and its opposite Side 3 show similar behaviour in these cases, unlike R4, with its higher stiffness and strength.

In the patch-repaired columns, when a BA was applied with R4, the behaviour improved due to the better bonding of the materials, while a BA with R3 mortar did not improve the behaviour of the element, due to the different stiffness of the materials. With R3, the adherence between the materials is good enough to guarantee that they will not detach, as the R3´s elastic modulus is only one third higher than that of the concrete. However, R4´s stiffness is about twice that of concrete and implies much larger eccentric loads, different behaviour from concrete and the need for a bonding agent to guarantee the adhesion of the materials.

Finally, it should be noted that patch repairs can restore up to 100% of the load bearing capacity of a damaged element if the right RM is used. For example, in the case under study, R3 mortar without a BA is the most appropriate technique for patch repairs on columns made with low quality concrete similar to those found in buildings constructed forty or fifty years ago. It is therefore advisable in this type of repair to use an RM with an elastic modulus as similar as possible to that of the concrete in the column. It can also be said that if the difference in stiffness is small, previous application of a BA is not necessary, highlighting the economy and simplicity of this technique when the damage is limited and does not spread along the element.

5. Comparison of all-four-sides and one-side repairs

Fig. 13 gives the average curves of the four series of specimens (R3-mortar and R4-mortar with or without BA) of each repair method (all-four-sides, one-side only and patching repairs) obtained by the authors in previous research (see Section 2). All the curves are compared with the undamaged control column average curve. For the one-side and patching repairs series, the results shown are those of the repaired side (1) and its opposite side (3), while only the curve of one side is given for the all-four-sides repairs, as they all showed similar behaviour.

Comparing the results of Tables 3 and 4 it can be seen that the four-side repairs are the least effective while the patch repair is the most effective, since the ultimate load of the four-side repairs is less in all cases, reaching 84% in the series with R3 mortar, as against 94% in one-side repairs (O3W) and 102% in patch repairs (P3W). This is fundamentally due to the ratio between the repaired zone and the column concrete in four-side repairs being much larger than the others. For this reason, even though the efficiency ratio with regard to the undamaged column is lower, the improvement as regards the damaged column is much higher in all cases, being 183%

in the same series (F3W) as against 146% in the one-side repairs (O3W) or patching (P3W). On the other hand, in this type of repair the dry joints created on the different faces during the process reduce its efficiency. The cracks that cause the RM to detach first appear in these joints and thus induce the premature failure of the repairs, so that for this method it may be advisable either to pour the RM into a formwork or spray it on, as alternatives to the manual application indicated in EN1504-9:2008 [1], although these practices are somewhat complicated to carry out and less common in practice.

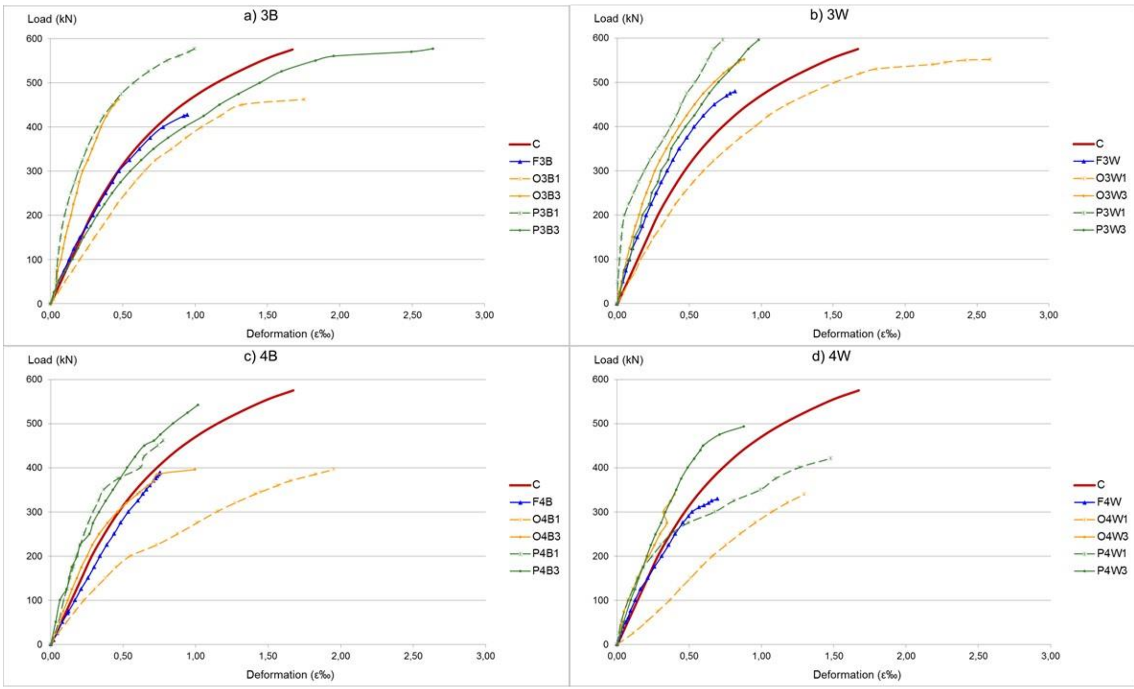

Fig. 13. Load-deformation average curves: Control-columns (C), all-four-sides repaired-columns (F), sides 1 and 3 of one-side repaired-columns (O) and sides 1 and 3 of patch repair-columns (P) with different RM: a) R3-mortar and BA (3B); b) R3-mortar and no BA (3W); c) R4-mortar and BA (4W); d) R4-mortar and no BA (4W)

R3 mortar was seen to work quite a lot better than R4 in all three repair techniques analysed. As indicated in the previous section, this is due to the difference in stiffness between the RM and the concrete being greater in R4 than R3; R4's elastic modulus is approximately twice that of the concrete in the column, while R3's is only one-third higher. This behaviour is more marked in the one-side repair series, in which failure occurs basically because of the complete detachment of the repaired face. In these cases, there is hardly any improvement in the behaviour of the columns repaired with R4 with reference to the unrepaired damaged columns.

It may be advisable to apply a BA to ensure the bonding of concrete and RM, depending on the class of mortar used and the repairs carried out. Repairs with R3 mortar work better without a BA, especially in patching and four-side repairs, while one-side repairs work better after a BA has been applied. This is due to the dry joints formed between the repaired side and the column concrete causing the RM to detach, which can be attenuated by applying a BA. However, in all-four-side and patching repairs, when R3 is used the contact between both materials is enough to ensure bonding, so that there is no need to apply a BA, even though in no case is the behaviour substantially different.

On the other hand, when using R4 mortar the previous application of a BA before applying the RM in all cases improves the behaviour, due to this mortar's stiffness being much higher than that of the concrete and thus causing the RM to detach. It is therefore necessary to apply a BA to ensure bonding with the column to avoid or delay detachment. This is especially important in one-side and four-side repairs, but not so much in patch repairs, since the area of the repaired zone is smaller and thus does not cause such high eccentric loads on the cross section.

Therefore, in this analysis, it is necessary to consider the magnitude of the damage in the element. In the specimens with patch repair, the damaged concrete occupies only the central third of one side of the column; whereas in one-side and four-side repairs, it takes up the whole length of the column. Furthermore, all-four-side repair simulates damage in all sides of the column, thus all the covering concrete has to be replaced. To this extent, if the repair does not improve the confinement of the column and, consequently, the bonding between the new and the old concrete, even with the use of a BA the detachment of the RM will occur. Accordingly, the magnitude of the repair also influences its effectiveness. In this sense, the smaller the repaired area, the greater the bonding between the materials and the more effective the repair will be.

6. Summary and Conclusions

This paper describes an experimental study carried out at the ICITECH laboratories in which 12 square cross-section RC columns were patch repaired and subjected to axial compression until failure. The results were compared with the results of 3 undamaged (C) and 3 unrepaired damaged control columns (PD). The results were also compared with those obtained from previous studies carried out by the authors on all-four-sides and one-side repairs.

R3 and R4 mortars were used in the repairs both with and without previous application of a BA in the following series:

- P3B: repaired with R3-mortar and BA
- P3W: repaired with R3-mortar and no BA
- P4B: repaired with R4-mortar and BA
- P4W: repaired with R4-mortar and no BA

From the results obtained it can be concluded that R3 mortar works better than R4 in patch repairs on columns, since it practically restores their original load bearing capacity. Applying a BA does not have any beneficial effects; in fact these may be adverse when used in conjunction with R3 mortar. However, with R4 the results are worse without a BA.

As regards the comparison with the results of previous studies on four-side and one-side repairs, it can be stated that patch repairs are more effective and, in some cases, managed to recover the total original strength of the elements. On the contrary, four-side repairs produced the worst results, since in no case did they restore the elements' original load bearing capacity. One-side repairs are able to restore practically 95% of this capacity.

R3 mortar worked better than R4 in all the cases studied, with the biggest differences being found in the one-side repair technique. While with R3 using a BA does not make any significant difference, the behaviour is better in four-side and patch repairs when it is omitted and, on the contrary, one-side repairs can be improved by using a BA. However, with R4 mortar it is advisable to always use a BA to ensure the bond between the RM and the column concrete, otherwise the RM will detach, and the repair will fail.

These experimental results will be validated with advanced numerical models in further research. In these models, it will be able to include some variables as the damage produced in the structure by the repair method that could not be taken into account in the experimental models.

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