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Axially loaded RC columns repaired on one side with cement-based mortars

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Abstract

This paper describes and analyses the results of an experimental programme carried out at the Universitat Politècnica de València on 18 reinforced concrete (RC) columns, 12 of which had been repaired on one side with cement-based mortar before being subjected to axial loading until failure. The objective of the research was to determine the performance of the columns that had been repaired using different mortars, evaluate the influence of Class R3 and R4 mortar used and of the application of a binder or bonding agent. The results obtained were compared with those of the undamaged control columns and those of the unrepaired damaged columns to obtain values for the efficiency of the repairs and for the improvement in the load-bearing capacity of the columns. The results obtained indicate that the columns repaired with Class R3 mortar, with a lower elasticity modulus, function in better way than the Class R4 repaired ones. The presence or absence of a binder was not found to be a determining factor in improving the behaviour of the repaired elements. The chief novelty of the study lies in the fact that it is the first experimental study on RC columns totally repaired on one side only, using different types of mortar with and without the application of a binder.

Keywords: *Retrofitting, RC column, cement-based mortar, deterioration, experimental tests*

1. Introduction

At the present time, retrofitting reinforced concrete (RC) structures due to ageing is becoming increasingly important. In the USA it is estimated that in the period 2016-2025 an investment of $4,590 billion (at 2015 prices) will be required to retrofit and maintain infrastructures [1]. In Europe, 50% of the annual construction budget is spent on repairs and retrofitting [2], while 40% of the RC building structures in the Valencia coastal region of Spain are said to be damaged by the effects of the marine environment and will need to be repaired within a few years [1].

A study by Tilly and Jacobs [3] indicates that 50% of the repaired structures fail or show signs of failure within 10 years. According to Matthews and Molridge [2], 38% of these structures fail because of a badly designed intervention and 15% because of the incorrect choice of repair materials. In other words, more than half of these repairs fail due to the lack of knowledge of the proper technique and materials to apply to each case.

Although columns are now among the critical elements in a building structure most often found to be in need of repairs, these are often carried out using the wrong technique, the wrong materials, or without knowing to what extent the element will recover its load-bearing capacity and how long the repairs will last.

Most of the studies on damaged columns focus on their strengthening by the commonly-used techniques of jacketing with: concrete [4–6], steel [7–12], ferrocement [13], or fibre-reinforced polymers (FRP) [14]. There are also studies focused on repairing all four sides of the columns with cement-based mortars in order to recover the column’s original load-bearing capacity [15]. The latest studies in this field have researched new combinations of materials to improve the effectiveness of the repairs, focusing on structures that have been seriously damaged, mostly during seismic events [16,17]. The new materials used in these studies include fabric-reinforced cementitious matrix (FRCM) [18], textile reinforced concrete (TRC) [19,20], strain-hardening cement-based composites (SHCC) [21], or high-performance fibre-reinforced cement based-composites (HPFRCCs) [22].

However, when all four sides of the column do not require strengthening or repairs but local repairs only, more traditional techniques are normally used, as in the case of columns damaged on one side only, to which mortar is applied manually by trowel. As this type of repair does not confine the column, it is difficult to recover the element's original load-bearing capacity, as was shown in Pellegrino et al. [23], who studied the behaviour of columns repaired on one side with polymer-modified cementitious mortars, with mechanical characteristics similar to the original concrete. The results showed that if the reinforcement was covered by the repairs, 91% of the original load-bearing capacity could be recovered, but if this was not the case, then the figure was only 67%.

This paper shows the research carried out at the laboratories of the ICITECH (Universitat Politècnica de València) in which 18 RC columns were tested to failure. Twelve of the columns were repaired on one side only by trowel-applied cementitious mortar and subjected to axial loads, with the aim of determining the efficiency of this type of repair and comparing the use of two types of mortar for the repairs, Class R3 and Class R4, in accordance with EN 1504 [24]. The effects of including or omitting a binder or bonding agent between the repair mortar and the base concrete of the column were also studied. In all cases the column reinforcement was completely covered by the mortar used in the repairs. In no case were the column's original dimensions increased, nor was the reinforcement modified.

The main novelty of this work is its study of the effectiveness of one-sided repairs of axially-loaded RC columns, considering the mortar class used (R3 or R4) as well as the use of a binder to bond the column and the mortar. This was done by comparing the behaviour of the undamaged control columns with that of damaged unrepaired columns and that of four different series of repaired columns: 1) R3 mortar and binder, 2) R3 mortar without binder, 3) R4 mortar and binder, and 4) R4 mortar without binder.

The paper is organised as follows: Section 2 describes the main characteristics of the specimens studied, types of repairs carried out, materials used, test set-up and instrumentation. Section 3 gives the results obtained from the different specimens, and these are analysed and compared in Section 4. Section 5 gives the main conclusions and outlines further research proposals in this field.

2. Material and methods

The experimental program involved testing 18 specimens, including 3 undamaged columns (U), and another 3 damaged unrepaired columns (D). The remaining 12 columns were repaired as follows: 3 columns repaired with R3 mortar with binder (B3), 3 columns repaired with R3 mortar without binder (W3), 3 columns repaired with R4 mortar with binder (B4), and 3 columns repaired with Class R4 mortar without binder (W4). Table 1 gives the designations of the tested specimens.

Table 1. Tested specimens

Type of column	Mortar	Binder	Nomenclature
Undamaged columns	-	-	U-1; U-2; U-3
Damaged columns - Unrepaired	-	-	D-1; D-2; D-3
Repaired columns	R3	yes	B3-1; B3-2; B3-3
		no	W3-1; W3-2; W3-3
	R4	yes	B4-1; B4-2; B4-3
		no	W4-1; W4-2; W4-3

The square cross-section dog-bone shaped specimens were tested under axial loading to failure. This type of specimen has been shown to be adequate in previous studies by other authors, such as Emberson and Mays [25], Fukuyama et al. [26], and Pereiro-Barceló and Bonet [27].

The central part of the specimens was 520 mm long and a 200×200 mm^2 cross-section. The upper and lower heads had cross-sections of 400×200 mm^2 and were 420 mm long. These were thus “scaled columns” with a total height of 1370 mm. This way of working is usual in many studies and allows extrapolating the results to real columns, as in Ramírez [28], Colomb et al. [16], Pellegrino et al.[23], Rousakis and Tourtouras [29], and Jain et al. [17].

The column reinforcement was made up of four 10 mm diameter longitudinal bars with 6 mm diameter stirrups in the central zone. Reinforcement in both heads consisted of 8 and 10 mm diameter stirrups (Fig.1a). The reinforcement yield stress was 500 MPa.

The compressive strength of the concrete used in the columns was 9.21 MPa to simulate the type used in typical 40 to 50 year old buildings [7,8,10,29]. The columns were poured in a horizontal position to facilitate execution and simulate damage. Damage was simulated by making cavities in the column formwork with 5 cm thick expanded polystyrene (EPS) plates of the "damaged" side of the columns (Fig.1b). These surfaces were roughened and then washed by high-pressure hose to remove any remnants of EPS and prepare the surface for the application of the repair materials. Fig. 2 shows a damaged column before being repaired.

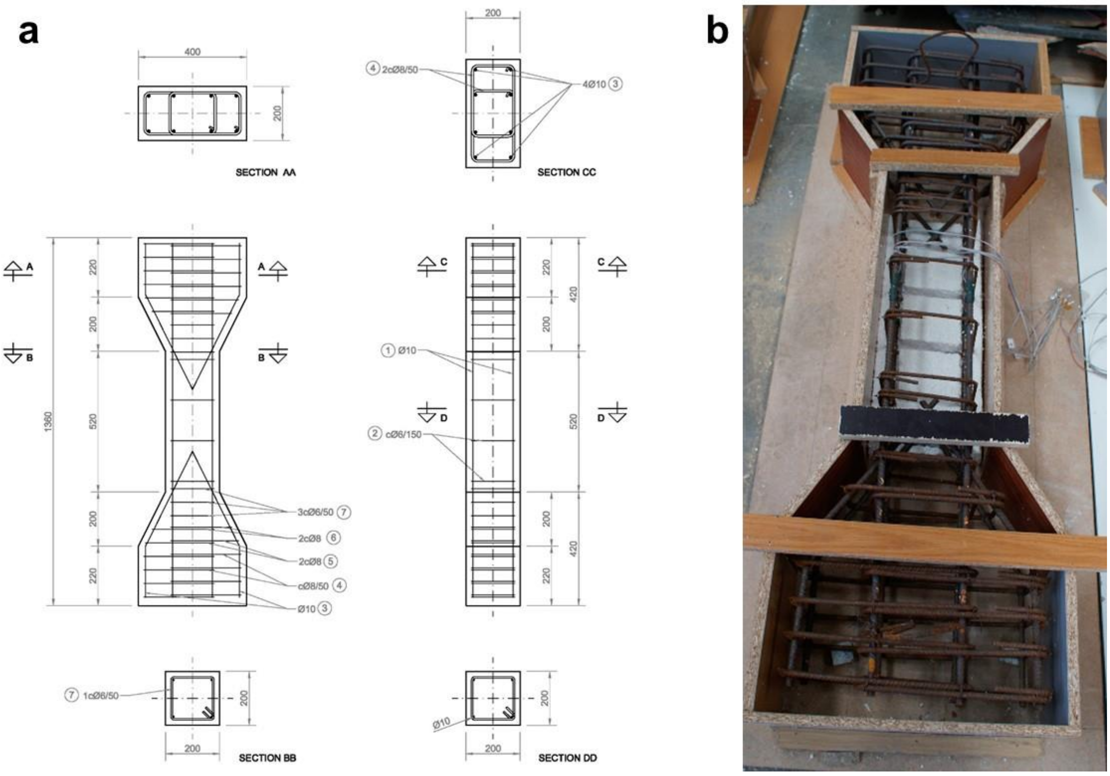

Fig. 1.a) Specimen geometry and reinforcement (in mm); b) Specimen contained by formwork.

The repairs on the columns were carried out when the concrete was 59 days old at an ambient temperature of between 28 and 34º C using pre-dosed commercial products applied by trowel as specified in the EN 1504-3 [24]. The mortar characteristics (at 28 days) can be seen in Tables 2 and 3.

Fig. 2. Damaged Column before being repaired

Table 2. Characteristics of Class R3 mortar

Parameter	**Value at 28 days**
Compressive strength	40.3 MPa
Adhesion	1.9 MPa
Modulus of elasticity	25.2 GPa
Flexural strength	8.3 MPa

Tabla 3. Characteristics of Class R4 mortar

Parameter	**Value at 28 days**
Compressive strength	54.2 MPa
Adhesion	2.5 MPa
Modulus of elasticity	36.7 GPa
Flexural strength	9.0 MPa

The products were applied as follows:

- In the columns with no binder, the surface was dampened before applying the first coat of mortar to a thickness of approximately 20 mm to fill any small irregularities. This was allowed to harden slightly, after which the remaining mortar was applied.
- In those repaired with a binder, this was first brushed on immediately before applying the first layer of repair mortar (Fig.3) to approximately 20 mm (Fig.4a), after which the procedure followed was exactly the same as before. The characteristics of the binder can be seen in Table 4.

In both cases the surfaces were smoothed after applying the mortar to achieve a better finish (Fig.4b).

Fig. 3.a) Damping the surfaces; b) Applying the binder.

Table 4. Characteristics of the binder

Parameter	**Value at 28 days**
Compressive strength	39 MPa
Flexural strength	8 MPa
Adhesion	3 MPa

Fig. 4.a) Placing the first layer of the repair mortar; b) Smoothing the surface.

Strain gauges were fitted to the four longitudinal reinforcement bars of the specimens. Displacement sensors were placed on the repaired surface and its opposite surface, in contact with the repair mortar and the concrete, respectively, also on one of the other sides of the column to measure the relative displacement of the concrete and mortar (Fig.5). The columns were tested under vertical compressive load by means of a 2,500 kN hydraulic jack.

Fig. 5. Instrumentation

3. Results

3.1. Failure patterns

This section gives the results obtained in the laboratory and compares the results of the undamaged columns (U) and damaged unrepaired columns (D) with the four types of repaired columns (B3, W3, B4, W4). The intact side (opposite to the repaired side) was labelled Side 1, while the damaged and subsequently repaired side was Side 3. The others were labelled Sides 2 and 4.

The undamaged columns (U) showed typical compression failure with vertical cracks on the sides. The damaged unrepaired columns (D) failed by eccentric compressive loads due to the asymmetry of the cross section caused by the damage to one side, which buckled the longitudinal reinforcement on the damaged side (Fig.6), while the opposite side presented horizontal cracking which spread to the lateral surfaces.

Fig. 6. Failure pattern in specimen D (damaged unrepaired columns). Buckling in rebars in side 3.

The failure patterns of the specimens tested were:

a) The columns repaired with Class 3 mortar and binder (B3) had a slight horizontal crack halfway up the intact side (Side 1) which spread to both lateral sides. The damaged and repaired side (Side 3) showed vertical cracking at a third of its height, while the horizontal crack on Side 1 was seen to slightly affect the sides. A vertical "cold joint" was seen to appear between the repair mortar and the specimen's original concrete. The detached repair mortar after the test can be seen in Fig. 7.

Fig. 7. Failure pattern in Specimen B3. Detachment of a mortar layer

b) The columns repaired with R3 mortar with no binder presented a horizontal crack halfway up the (intact) Side 1 (Fig.8a) which spread to the sides (Figs. 8b and 8d) and a short vertical crack at approximately 1 cm from the corner with Side 2 (Fig.8a). The (repaired) Side 3 had no cracks (Fig.8c). A vertical crack can be seen on Sides 2 and 4, which detached the repair mortar from the concrete (Fig. 8b and Fig.8d). This crack later caused the mortar on the repaired side to come detached, as seen in Fig. 9.

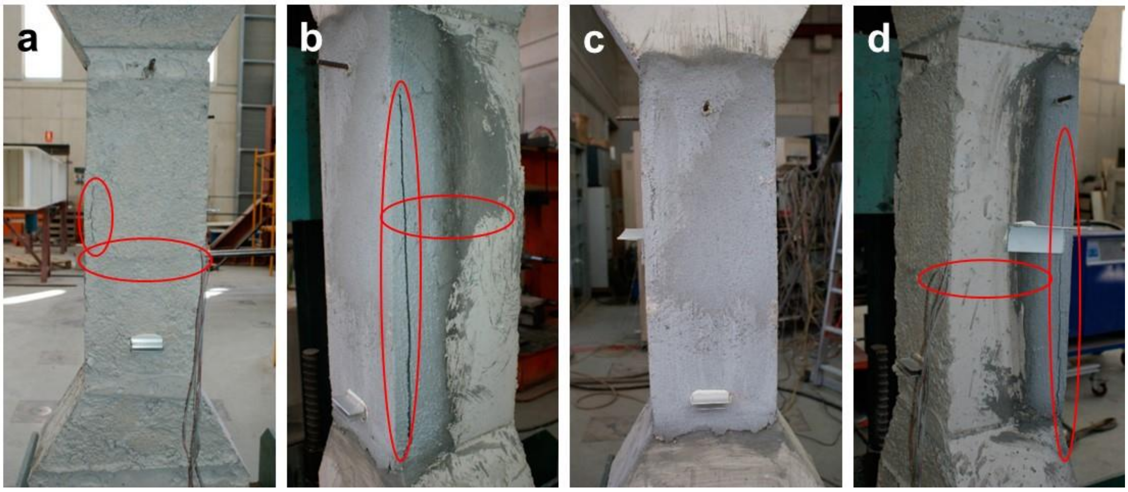

Fig. 8. Failure patterns in specimen W3. Sides: a) 1; b) 2; c) 3 and d) 4.

Fig. 9. Failure pattern in specimen W3. Detachment of a mortar layer

c) The columns repaired with R4 mortar and binder (B4) had a fine horizontal crack halfway up Side 1 which spread to the other sides (Fig.10a). The (repaired) Side 3 had no cracks (Fig.10c). On the other sides, especially Side 4 (Fig.10b and Fig.10d), a crack can be seen that caused the repair layer to come detached to a thickness of approximately 1.5 cm (Fig. 11).

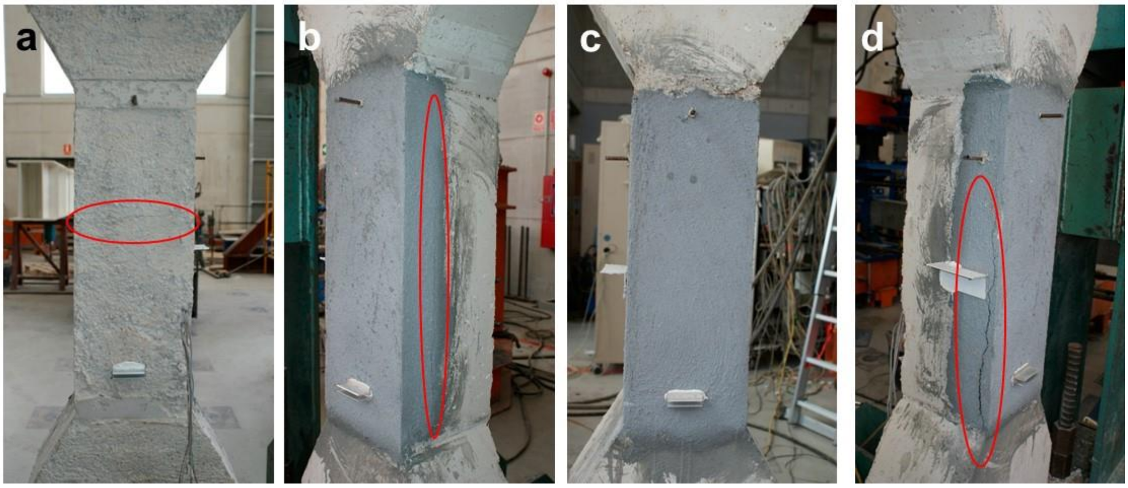

Fig. 10. Failure patterns in specimen B4. Sides: a) 1; b) 2; c) 3 and d) 4.

Fig. 11. Failure patterns in specimen B4. Detachment of a mortar layer

d) The columns repaired with R4 mortar and no binder (W4) had a horizontal crack halfway up Side 1 that spread to both sides (Fig.12a). Unlike the previous cases, the (repaired) Side 3 had vertical cracks (Fig.12c). As previously, a crack is seen on the other sides (2 and 4) that caused the repair mortar to come detached (Fig.12b and Fig.12d).

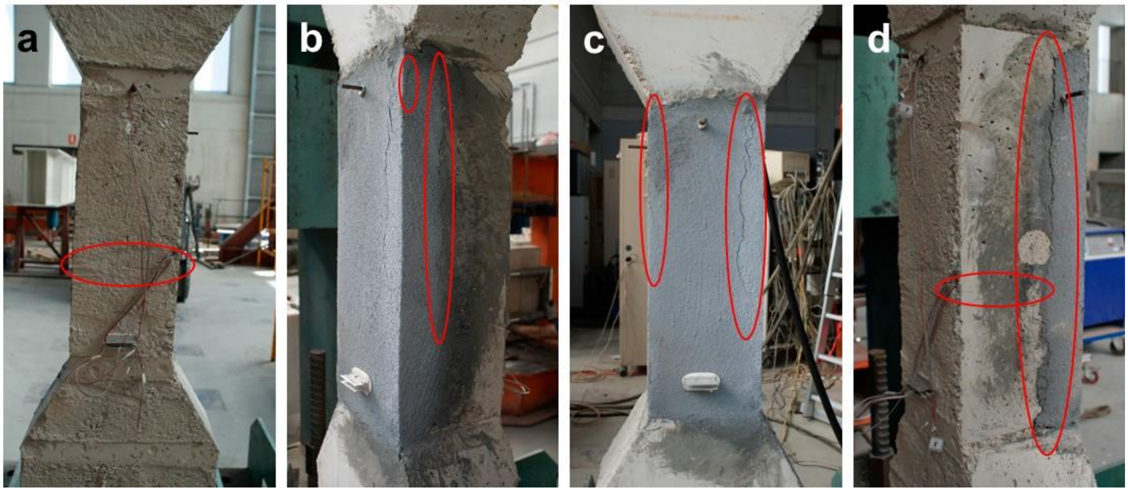

Fig. 12. Failure patterns in specimen W4. Sides: a) 1; b) 2; c) 3 and d) 4.

As has been seen, the failure patterns were quite similar in all four types of specimen: the repair mortar detaches from the column, after which the column behaves similarly to the DC and fails under eccentric compressive loads. The only variation is in the R4 columns, in which the mortar also fails due to compressive load.

3.2. Load-deformation curves

Fig. 13 shows the load-deformation curves of the repaired specimens (B3, W3, B4 and W4), which are compared to the average undamaged column (U) curve and that of the damaged unrepaired columns (D). As both the damaged unrepaired (D) and the repaired columns have a marked asymmetry, which is geometric in the former and due to the change in stiffness produced by the mortar in the latter, two load-deformation curves are shown that give the results obtained from the displacement sensors on the (intact) Side 1 and (damaged and repaired) Side 3, respectively.

In order to compare the results, the “repair efficiency” is defined to indicate the percentage of load-bearing capacity recovered for each column with reference to the undamaged column. This is determined by the ratio between the maximum load borne by each column that has been repaired (N_R) and the maximum load borne by the undamaged column (N_U). The increased resistance of the repaired column is also indicated in relation to the damaged unrepaired column, as the ratio between the ultimate load of each column that has been repaired (N_R) and that of the damaged column that has not been repaired (N_D) in the form of a percentage. Table 5 shows the experimental results obtained and the indicated parameters.

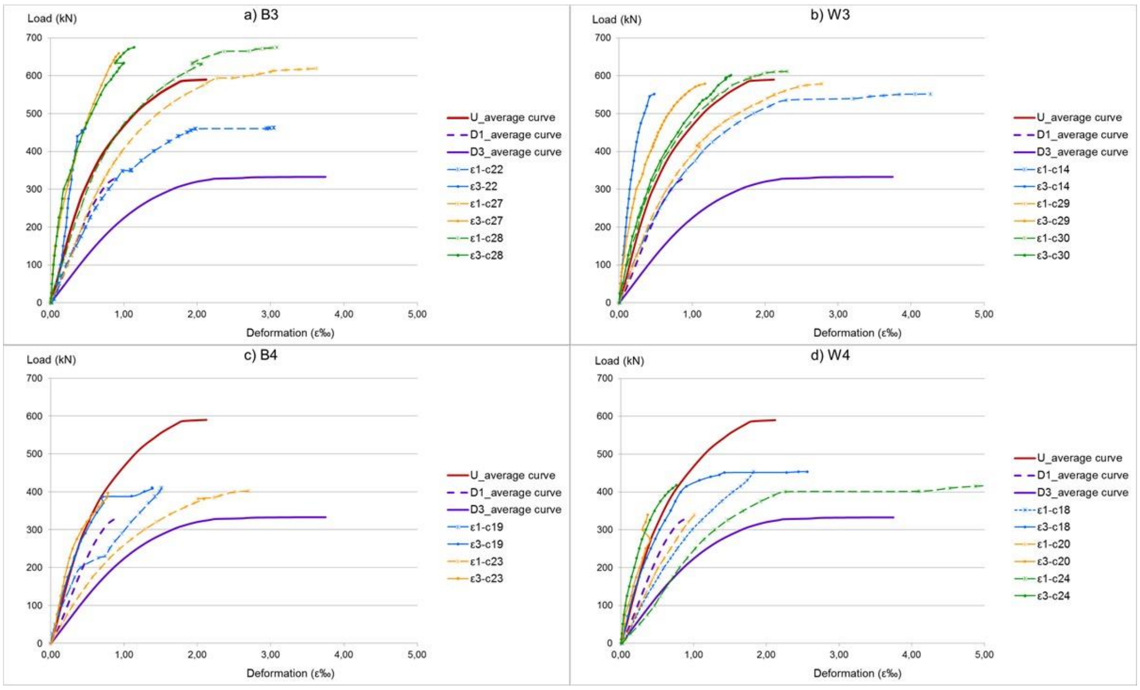

Fig. 13. Load-deformation curves. Undamaged columns (U) average curve and damaged unrepaired columns (D) average side 1 and side 3 combined with: a) Specimens B3; b) Specimens W3; c) Specimens B4; d) Specimens W4

4. Analysis and Discussion

This section analyses and makes the comparison among the results of the different types of repair with each other, with the undamaged columns (U) and with the damaged unrepaired columns (D). The behaviour and efficiency of each repair mortar are studied to determine the most suitable.

The results obtained from the measuring devices on two sides of the columns are given for each family: (intact) Side 1 and (damaged or damaged-repaired) Side 3, to obtain the asymmetry of the behaviour due to the use of mortar stiffer than the original concrete. This asymmetry is higher in the unrepaired damaged columns, which suffer a change in the centre of gravity of the cross-section that gives rise to eccentric compression in the column. In this case, the maximum axial load is reduced by an average of 36%.

Table 5. Summary of the results

Serie	Specimen	N (kN)	N_{mean} (kN)	Efficiency (N/N_U × 100)	Efficiency (N_R/N_U × 100)	Improvement with respect to specimen D (N/N_D × 100)	Improvement with respect to specimen D (N_R/N_D × 100)
U	U-1	637.34	617.51	-	-	-	-
	U-2	590.14		-		-	
	U-3	625.06		-		-	
D	D-1	461.51	397.17	-	-	-	-
	D-2	332.83		-		-	
	D-3	-		-		-	
B3	B3-1	462.46	598.78	74.89	96.97	116.44	150.76
	B3-2	658.78		106.68		165.87	
	B3-3	675.11		109.33		169.98	
W3	W3-1	551.72	580.72	89.35	94.04	138.91	146.21
	W3-2	578.94		93.75		145.77	
	W3-3	611.49		99.02		153.96	
B4	B4-1	411.29	406.71	66.60	65.86	103.56	102.40
	B4-2	402.13		65.12		101.25	
	B4-3	-		-		-	
W4	W4-1	453.75	403.76	73.48	65.38	114.25	101.66
	W4-2	339.69		55.01		85.53	
	W4-3	417.84		67.66		105.20	

N: Maximum load for each column

N_{mean}: Mean maximum load for the specimen families (U, D, B3, W3, B4, W4)

N_R: Average maximum load for each family of repaired specimens (B3, W3, B4, W4)

N_U: Average maximum load for the family of control specimens (U)

N_D: Average maximum load for the family of damaged specimens (D)

4.1. Columns repaired with Class R3 mortar and binder (B3)

The curves that show the load-deformation in Fig. 13a indicate that the stiffness of the sides repaired with mortar (Side 3) is much higher than the intact sides (Side 1). Their behaviour is practically linear up to failure, which occurs with very little deformation. As mentioned in Section 3.1, failure occurs when the repair mortar detaches from the column. On the other hand, the intact sides show much higher ductility, with linear behaviour up to 50% of the ultimate load and considerable deformation at 90%.

The maximum load of two of the repaired columns is somewhat greater than the mean of the control columns, although one of these failed at 75% of the control column load. This means that the mean maximum load of the repaired columns is slightly lower than the control columns and their efficiency is 97%. It can therefore be said that the columns repaired with R3 mortar plus binder recover almost all their initial load-bearing capacity and perform 150% better than the damaged columns.

4.2. Columns repaired with R3 mortar and no binder (W3)

The curves that show the load-deformation (Fig.13b) indicate that the ultimate load of the repaired columns is very similar to that of the control columns. As in the previous case, the repaired sides (Side 3) present higher stiffness, while the intact sides (Side 1) have greater ductility.

The behaviour of the repaired sides is practically linear, while that of the intact sides is linear only up to 50% of the ultimate load. The plastic phase of this type of column is shorter than in the previous case, except in one specimen. The two sides of the other two columns behaved more similarly in relation to each other and to the control columns than in the previous case.

Repair efficiency is 93%, slightly less than in the previous case, which did have a binder. Resistance improvement, at 146%, is also slightly lower than in specimens B3.

The specimens repaired with Class R3 mortar with and without a binder show similar behaviour, although the ultimate loads are higher in those with a binder (B3) than without (W3).

4.3. Columns repaired with R4 mortar and binder (B4)

In this case, curves that show the load-deformation (Fig.13c) of the specimens indicate quite different behaviour, although their ultimate load is similar, in the order of 2/3 of that of the control columns, nearer to that of the unrepaired damaged columns than the control columns. For this reason, the repair efficiency is 65%, considerably lower than in the previous cases, which used R3 mortar. The same effect can be seen in the improvement of their maximum load in relation to the damaged columns, which only reaches 102%.

As in the previous cases, the repaired side (Side 3) is stiffer than the intact Side 1, although the difference between them in this respect is smaller than in the previous cases, which used R3 mortar.

4.4. Columns repaired with Class R4 mortar and no binder (W4)

The behaviour shown in the load-deformation curves (Fig.13d) is similar to that in the previous case, which did use a binder. The repair efficiency is 65%, while the improved capacity with respect to the damaged columns is only 102%, showing that using a binder hardly affects the column's resistance. This type of repair with Class R4 mortar therefore does not significantly improve the load-bearing capacity of the columns that have been repaired over that of the damaged columns, either with or without a binder.

4.5. Discussion

Fig. 13 shows the load-deformation curves of the four families of specimens tested. From the analysis of these curves and of the results in Table 5 it can be seen that using a binder has very little effect on the results of both types of mortar, although it appears that two columns repaired with R3 mortar (B3) reached in the order of a 10-15% higher ultimate load. However, the fact that the third column in this series reached a lower ultimate load is a warning of the possible dispersion of the results of this type of repair.

In the columns repaired with Class 3 mortar, it can be seen that the ultimate load reached is close to that of the control columns and that the original load-bearing capacity of the specimen is almost completely recovered, both with and without a binder.

However, even though the ultimate column capacity can be recovered by using Class 3 mortar, the behaviour is notably modified due to the difference in stiffness introduced by the layer of mortar, which means there is less deformation and that the failure is brittle, due to the mortar detaching from the column.

In the case of columns repaired with R4 mortar, very little improvement in load-bearing capacity can be seen over that of the unrepaired damaged columns.

5. Summary and Conclusions

This paper presents the experimental results obtained at the ICITECH laboratory (Universitat Politècnica de València) after testing 18 axially loaded RC columns. Of the 18 columns tested, 3 were undamaged control columns (U) and 3 others were damaged but unrepaired (D). The remaining 12 specimens were repaired with pre-dosed commercial mortars, with and without the application of a binder, divided into groups as follows:

- B3: Repaired columns with binder and R3 mortar.
- W3: Repaired columns with R3 mortar and no binder.
- B4: Repaired columns with binder and R4 mortar.
- W4: Repaired columns with R4 mortar and no binder.

From the results obtained in the tests, a repair efficiency value and the increase of the load-bearing capacity were calculated by comparing the behaviour of each group of specimens with the control columns.

The results obtained indicate that Class R3 repair mortar gives better results, since the columns repaired with this type recovered practically all the load-bearing capacity of the undamaged columns. On the other hand, the columns repaired with Class R4 mortar recovered very little of this capacity and show similar behaviour to the unrepaired damaged columns. The authors consider that this different behaviour is due to the compressive strength and Young’s modulus of the Class R3 mortar being lower than those of the R4, which make it more compatible with the column’s original low-quality and low-strength concrete.

As regards including or excluding a binder, although when it is included the ultimate strength is higher, the difference is not large enough to justify its use. Although when it was not used there was less difference in the behaviour of the repaired and intact sides, it can be considered that without a binder the behaviour of the repaired column is more homogeneous.

From the results obtained, the authors consider that further studies should be carried out on columns using other types of repair, such as patching with Class R3 and R4 mortars. Numerical studies should also be carried out to validate the experimental results.

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