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

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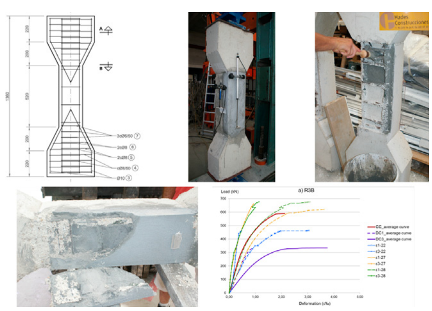
HIGHLIGHTS

- Retrofitting RC structures is now becoming increasingly important.
- This work studies the effectiveness of one-sided repairs on RC columns.
- Columns are repaired with R3 and R4 cement-based mortars.
- 18 RC columns were experimentally tested to failure.

GRAPHICAL ABSTRACT



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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.

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 $4590 billion (at 2015 prices) will be required to retrofit and maintain infrastructure [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 [3].

A study by Tilly and Jacobs [4] 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

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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 [5–7], steel [8–13], ferrocement [14], 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. That is the case of columns damaged on one side only, to which mortar is applied manually by trowel. In this type of repair, the characteristics of the material used are relevant to its success. In this sense, the repair materials with its strength and elastic modulus more similar to the original concrete produce a more efficient performance [23,24].

As this type of repair does not produce the confinement of the column, it is difficult to recover the element's original load-bearing capacity, as was shown in Pellegrino et al. [25]. These researchers 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 91% of the ultimate load could be recovered if the repair material was placed surrounded the reinforcement. On the contrary, columns with thinner repairs, that substituted only the reinforcement cover, only could recover 67% of the original load-bearing capacity.

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 [26]. 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.

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.

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 [27], Fukuyama et al. [28], and Pereiro-Barceló and Bonet [29].

The central part of the specimens was 520 mm long and a 200 $\times$ 200 mm^2 cross-section. The upper and lower heads had cross-sections of 400 $\times$ 200 mm^2 and were 420 mm long. These were thus "scaled columns" with a total height of 1360 mm. This way of working is usual in many studies and allows extrapolating the results to real columns, as in Ramírez [30], Colomb et al. [16], Pellegrino et al. [25], Rousakis and Tourtouras [31], 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 [8,9,11,31]. 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. 2). 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.

The repairs on the columns were carried out when the concrete was 59 days old at an ambient temperature of between 28 and 34 °C using pre-dosed commercial products applied by trowel as specified in the EN 1504-3 [26]. These products were one-component cementitious repair mortar with fibre reinforced. The mortar characteristics (at 28 days) can be seen in Tables 2 and 3.

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).

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

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