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Additional Information

Experimental testing on axially loaded RC columns repaired on all four sides with cementitious mortars

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Abstract

Structural ageing, action by aggressive agents, accidents, etc., all make it increasingly necessary to apply conservation and maintenance programs to building structures. Columns are some of a building's most critical elements, since the failure of a single column can lead to the collapse of the entire structure or a large part of it. Although great strides have been made in recent years in the field of reinforced concrete (RC) column repair and strengthening, there is room for further improvement in certain areas. This paper describes a study carried out in the ICITECH laboratories (Universitat Politècnica de València) on RC columns repaired on all four sides with cementitious-based mortars. A total of 18 specimens were tested, representing a group of square 20x20 mm^2 columns subjected to compressive axial loads. Different repair scenarios were considered in order to study the influence of the type of mortar used and the presence or absence of bonding agents between the mortar and the column concrete. The results obtained showed that bonding agents have no appreciable effect on the behaviour of the repaired columns. Of the two types of mortar used in the study (Classes R3 and R4), the columns repaired with the lower grade mortar (R3) were seen to behave better. The main novelty of this work lies in the fact that this is the first time that two types of mortar are compared in the repair of four column sides, in addition to the possible use of bonding agents between the mortar and the column.

Keywords: *Column, Repair, Reinforced Concrete, Building, Experimental, Mortar*

1. Introduction

The need for repairs to structural reinforced concrete (RC) elements increases as buildings and infrastructures get older. In the USA, the American Society of Civil Engineers (ASCE) [1] has estimated that an investment of $3.6 trillion will be required before 2020 to bring the country's infrastructures up to date. According to a report by the Spanish Confederation of Business Associations (CEOE) [2] in 2011 almost 2% of Spain's buildings were in extreme need of conservation, 7.6% required urgent repairs, and a total of almost 1 million buildings were below standard.

Columns are critical elements in a structure since if one fails the others may follow suit and lead to the collapse of the entire building or most of it. If the structure is of RC, the columns may suffer mechanical or chemical damage due to ageing materials, aggressive environments, earth settlement, natural disasters (earthquakes), accidents (fires, explosions, collisions), among others. As repair and strengthening of RC columns are therefore often necessary, the scientific community has given a lot of attention to this area in the form of research on the different techniques available.

Frangou et al. [3] carried out one of the first studies on the repair and strengthening of columns using different techniques based on concrete confinement and compared the results with those proposed by Eurocode 8 [4]. Another interesting study was that by Ramírez [5], who analysed the characteristics and effectiveness of different methods of strengthening columns by concrete or steel elements.

Later innovations included concrete jacketing [6,7], self-compacting concrete jacketing [8], high performance fibre-reinforced concrete jacketing [9], ferrocement jacketing [10], steel jacketing [11–16], and FRP jacketing [17], which were used to increase the column's level of concrete confinement to improve their resistance [18]. Most of the studies [6-17] focused on strengthening columns to increase their resististant capacity [19].

One of the first studies to distinguish between repairing and strengthening damaged columns was that by Fukuyama et al. [20], who proposed that they should either be repaired or strengthened according to the extent of the damage they had suffered. They proposed filling cracks and replacing damaged concrete in the case of slight or moderate damage, i.e. a system of patching. When the damage was more serious, they suggested steel or concrete jacketing.

This paper focuses on repairing rather than strengthening RC columns, in order to restore the columns to their original state of safety [19] without increasing their size. The European Standard EN 1504-9:2008 [21] recognises three types of repair:

- Local applications of mortar by hand or trowel.
- Filling with liquid mortar using formwork.
- Spraying with concrete or mortar.

The three methods are described in EN 1504-3:2005 [22], which defines the requirements to be satisfied by products used to repair concrete elements. Repair mortars are divided into four classes: Classes R1 and R2 for non-structural repairs and Classes R3 and R4 for structural repairs. In all cases, bonding between the column concrete and the repair mortar must be guaranteed. This bonding must be due solely to the characteristics of the materials and the conditions of the joint, although the use of a bonding agent is allowed under certain conditions to create an adhesive joint between the column and the new mortar. The specifications of the bonding agents are given in EN 1504-4:2004 [23].

Repairs can also be classified by the zones in which they are carried out in three ways:

- Patching repairs on one or more local column zones.
- Complete repair on one side in which the entire surface is covered with mortar.
- Complete repair of all four sides, replacing all the concrete to a depth that includes the longitudinal reinforcement.

An interesting study was carried out by Aurrekoetxea [24], simulating the repairs on square columns with corroded rebars and comparing the behaviour of the repair according to the method and type of mortar used, validating the experimental results by FE modelling. The repairs were on simulated damage to two and four corners. The results obtained showed that the columns that had lost all their cover and 43% of their resistance could recover 40% of their resistant capacity, and that liquid mortar placed in formwork worked better than when applied manually.

Da Porto et al. [25] carried out an experimental study on repairing four sides of square RC columns subjected to axial loads by three types of polymer-modified cementitious mortar but were unable to recover 100% of their original load-bearing capacity. They also found that repair mortar worked best with a compression strength and elasticity modulus similar to those of the column concrete.

When RC elements are repaired, it is fundamental that the basic substrate and repair mortar be compatible. Certain authors, such as Emberson and Mays [26,27], Morgan [28] and Hassan et al. [29], state that the most important requirement to guarantee this compatibility is to ensure that the elasticity modulus of the column concrete is similar to that of the repair material and that the compressive strength of the latter be equal to or higher than that of the concrete in the column.

The scientific community is aware of the importance of the joint between concretes of different ages, or between concrete and repair mortar. In this regard, one could point to the work by Júlio et al. [30,31,32,], Qian et al. [33], Elbakry and Tarabia [34], and Mousa [35]. When columns are repaired by cementitious mortar, the way in which the materials are joined (dry joint or with bonding agents) must be carefully considered.

This paper describes a study carried out in the ICITECH laboratories of the Universitat Politècnica de València on repairs on four sides of RC columns subjected to axial loads by means of one of the most frequently used techniques at the present time: cementitious mortar applied by trowel. In no case was the column cross-section or reinforcement increased. Eighteen columns were repaired with R3 and R4 Class mortars, as defined in EN 1504-9:2008 [21], both including and excluding the use of bonding agents between column and mortar to compare the effectiveness of four repair methods: a) R3 mortar with bonding agent, b) R3 mortar without bonding agent, c) R4 mortar with bonding agent, and d) R4 mortar without bonding agent.

The main novelty of this study is that it is the first to analyse the relative importance of the different repair components in the complete repair of the four sides of RC columns by mortar applied with a trowel. The study includes the effectiveness of bonding agents between column and mortar and also of the influence of the different types of mortar proposed in EN 1504-9:2008 [21] on the behaviour of the repaired columns.

The remainder of the paper is laid out as follows: Section 2 gives the main characteristics of the tests, including specimens, repairs, and column loading and monitoring. Section 3 describes the failure modes of the specimens studied and defines terms such as *effectiveness* and *improvement of load-bearing capacity* used to evaluate the success of the repairs. Section 4 analyses the results obtained and the different series of specimens are compared. Section 5 gives the main conclusions drawn from the tests together with future lines of research.

2. Experimental study

2.1. Specimen geometry

The study consisted of tests on eighteen 1370 mm long specimens to simulate axially loaded RC columns. Although these dimensions are not those of normal columns, the results can be extrapolated to real columns, as has been previously shown: Emberson and Mays [26,27], Ramírez [5], Mourad and Shannag [10], Pellegrino et al. [36], Achillopoulou and Karabinis [37], Fukuyama et al. [20] and Dubey and Kumar [8].

The specimens were dogbone-shaped to avoid failure in the load application zones. The central section of the specimens was 520 mm long and a 200×200 mm^2 cross-section. The heads were 420 mm long with a cross section of 400×200 mm^2. The specimen dimensions are shown in Fig. 1.

Damage requiring repair was simulated in 15 columns, while three were left untouched (Control Columns). The damage was simulated by using expanded polystyrene (EPS) placed in the formwork before pouring to create hollows (see Fig. 2). The “damaged” columns were devoid of concrete down to the level of the reinforcement rebars to simulate the concrete loss necessary for the rebars to be immersed in the repair mortar, as is usually the case.

In the 15 simulated damaged columns, three were tested without repair (Damaged Columns), and the remaining 12 (Repaired Columns) were repaired by different variants of R3 and R4 mortar, with and without bonding agents between the column concrete and repair mortar. The central section of the specimens was repaired on all four sides by mortar applied with a trowel.

2.2. Specimen material

A low quality concrete with a 10 MPa compressive strength was used to make the specimens, similar to those used in previous studies to simulate the concrete in use 40 to 50 years ago [11-13]. The central section of the specimens was reinforced by four 10 mm diameter rebars with 6 mm diameter stirrups every 150 mm. The heads were strengthened so as to be able to transmit the load applied by the jack to the centre section, on which the study was focused. All the reinforcements had a tensile strength of 500 MPa. The specimen geometry and reinforcement placing can be seen in Fig. 1.

The currently available repair materials present very different mechanical, physical and chemical properties to those used to make the elements now in need of repair. According to Emberson and Mays [26,27], it is more difficult to obtain compatibility between the original concrete and the repair materials than between these and modern concrete.

R3 and R4 Class mortars were used for the repairs as specified in EN 1504-3:2005 [22] in the form of predosed commercial products (see Tables 1 and 2) applied by trowel. A bonding agent (see Table 3) was applied between mortar and concrete to the centre section of the specimens repaired with R3 and R4 mortar to determine its influence on this type of repair.

2.3. Characteristics of the repairs

As can be seen in Fig. 3, full repairs on all four sides involved recovering the column's original geometry and included the inner side of the reinforcement, simulating slightly more than the complete loss of the reinforcement concrete cover to ensure the reinforcement became embedded in the layer of mortar (50 mm), as is the usual practice in such cases. In the damaged control columns, the damage only reached as far as the outer side of the reinforcement (about 30 mm).

The specimens were repaired 59 days after being made. The surfaces were brushed manually and then washed with water under high pressure to eliminate all traces of EPS. The repairs were carried out in the following steps:

- Mortar was applied with a trowel.
- The surface of the columns without a bonding agent was wetted before applying the first layer of approximately 2 cm of mortar to fill any hollows. When this mortar started to harden, mortar was applied to two parallel column sides, which were then protected by wooden formwork (Fig. 3). After waiting 2 or 3 hours more, the other two sides were given the same treatment.
- When a bonding agent was used, this was brushed onto all surfaces immediately before applying the first layer of approximately 2 cm of mortar, then continuing with the treatment described above.

2.4. Test planning, monitoring and procedure

Three of the 18 specimens tested were undamaged and designated CC (Control Columns). Three others were damaged and tested without repairs and designated DC (Damaged Columns). The remaining 12, damaged on all fours sides, were repaired before testing: 3 with Class R3 and 3 with R4 mortar applied directly to the substrate concrete (designated R3 and R4). Six were given a bonding agent between repair mortar (3 R3 and 3 R4) and concrete (designated R3B and R4B). Table 4 gives the designation codes of the 18 specimens.

The tests were carried out in the ICITECH laboratories at the Universitat Politècnica de València (UPV). The specimens were instrumented with strain gauges at the centre of the four rebars and with LVDTs in the concrete and repair mortar (Fig. 4a) and placed vertically on test beds, with an axial compression load applied by a 2500 kN hydraulic jack at a constant speed of 50 kN/min.

3. Test results

3.1. General behaviour and failure mode

This section describes and compares the failure modes of the four types of repaired specimens (R3, R3B, R4, and R4B), control columns (CC) and damaged columns (DC). The typical vertical cracking pattern of a compression failure of one of the CC can be seen in Fig. 4.b. The failure mode of the DC shows the same behaviour pattern, with vertical cracks on all sides (see Fig. 5.a). In this case the column was reduced to a concrete core without reinforcement. Results were only obtained from one DC specimen, as the others could not be correctly tested; one was discarded for not having the correct head geometry and the other broke before testing.

The failure modes of the four series of repaired columns were as follows:

a) Repaired columns with Class R3 mortar and bonding agent (R3B, Fig. 5.b). The vertical cracks can be seen typical of the dry joint due to the repair being made in two phases. Smaller cracks can also be seen coinciding with the reinforcement on the sides with no dry joint and the bonding between the repair mortar and concrete can be seen to be adequate.

b) Repaired columns with Class R3 mortar without bonding agent (R3, Fig. 6.a). The failure mode is similar to the R3B (Class 3 mortar with bonding agent) with vertical cracks identifying the dry joints. However, here the mortar became completely separated from the sides to which mortar was applied in the second phase (Fig. 6.b), which did not happen in the previous case.

c) Repaired columns with Class R4 mortar and bonding agent (R4B, Fig. 7). Vertical cracks were also seen here on all sides, the most serious coinciding with the dry joints between both layers of mortar, as in the R3 and R3B series. However, unlike the previous cases, breakage was due to the failure of the mortar under compression, but in this case the mortar did not become unstuck, as occurred in the R3 specimens.

d) Repaired columns with Class R4 mortar without bonding agent (R4, Fig. 8.a). Failure was very similar to the R3 specimens (Class 3 mortar without bonding agent), with vertical cracks marking the dry joints and separation of the mortar from the two sides repaired in the second phase (Fig. 8.b), as occurred in R3 specimens. This separation did not happen in the series with a bonding agent (R3B and R4B).

3.2. Load-bearing capacity

Fig. 9 give the load/deformation curves of R3B, R3, R4B and R4 specimens, respectively, in comparison with the average curve of the control specimens (CC) and the damaged column (DC).

The "Efficiency" parameter is defined to determine the percentage of resistance recovered by a repaired column, defined as the maximum axial force supported by each repaired column (N_R) divided by the maximum axial force supported by the control column (N_{CC}). Also, to evaluate the improvement in load bearing capacity achieved by a repair with respect to the damaged column, the ratio between the load-bearing capacity of the repaired column (N_R) and that of the damaged column (N_{DC}) can be determined. Table 5 gives the results obtained for both parameters.

4. Analysis of results and discussion

This section analyses the behaviour of the repaired columns and compares it with that of the control and damaged columns. It also compares the results of the different repairs with each other in order to determine the effectiveness of each method.

4.1. Repaired columns with Class R3 mortar and bonding agent (R3B)

The load/deformation curves (Fig. 9.a) show that the repaired columns recovered almost all the stiffness of the original column, as represented by the control column (CC) and even obtained increased stiffness at high load levels, although the repaired columns show less ductile behaviour than the control columns. Of the three specimens tested, two have practically identical behaviour, while the third suffered the first partial failure at around 300 kN, when it began to lose its stiffness. The ultimate load of this specimen was around 20% lower than the other two.

The load/deformation curves show practically linear behaviour up to about 50% of the maximum load, when the curve changes slightly until 90% of maximum load, when it abruptly falls until failure.

Mean repair efficiency with respect to the control columns (CC) was 83%, and mean improved load-bearing capacity was 180% better than the ultimate load of the damaged column.

4.2. Repaired columns with Class R3 mortar without bonding agent (R3)

It can be seen in the load/deformation curves (Fig. 9.b) that the repaired column is stiffer than the control column and has thus recovered or is even slightly stiffer than the control, especially above 50% of the ultimate load. The curves are practically linear up to 50% of maximum load and then climb less steeply until 90%, at which point they enter a plastic state.

As regards efficiency as compared with the control column, the mean resistance of repaired columns was 84% of the original, while the mean load-bearing improvement of the repaired elements was 184% higher than the ultimate load of the damaged column.

Specimens R3B and R3 showed very similar behaviour (see Figs. 9.a and 9.b), with the R3s slightly better than the R3Bs. The R3s had more deformation at failure than the R3Bs, whose behaviour was more brittle. Using R3 Class mortar therefore does not offer any perceptible improvement when a bonding agent is applied between mortar and substrate concrete.

4.3. Repaired columns with Class R4 mortar with bonding agent (R4B)

As seen in the load/deformation curves (Fig. 9.c), the three specimens tested had very different stiffness values, even though the ultimate loads were similar. Two specimens had markedly lower stiffness, while the third had clearly higher stiffness than the control columns. Behaviour during the tests was practically linear up to about 2/3 of the ultimate load, where the curve became less steep.

The mean resistance of repaired columns was 71% of that of the control (CC), with a 155% better load-bearing capacity than the damaged column (DC).

The behaviour of the R3B and R4B series are shown in Fig. 9.a and 9.c, in which bonding agents and R3 and R4 mortars were used. The columns repaired with R3 mortar are seen, in general, to have better behaviour, with higher ultimate loads and higher deformation at failure than the R4B. Only one R3B specimen had a similar ultimate load to the R4B and much lower than the other R3Bs, apparently due to a behavioural anomaly.

4.4. Repaired columns with Class R4 mortar without bonding agent (R4)

As can be seen in Fig. 9.d, the load/deformation curves of these specimens are widely dispersed, although they do have similar ultimate loads. Their deformability at low loadings is in the same range as the control columns (CC) and rises notably at high loads.

The mean resistance of repaired columns was 64% that of the controls and their load bearing improvement was 139% better than the ultimate resistance of damaged columns.

The load/deformation curves of specimens repaired with R4 Class mortar and those with R3, with and without bonding agent (R4B and R4) are shown in Fig. 9. It can be seen that there are no notable differences between the behaviour of both series, although there are wide variations in deformability at low loads, especially in specimens with a bonding agent (R4B).

There is a difference of the order of 10% in the repair effectiveness between both types of repair (63.47% for R4 and 70.93% for R4B (see Table 5)), in favour of the use of a bonding agent.

4.5. Discussion

Fig. 9 contains the load/deformation curves of all the tests carried out on repaired columns. It can be seen that those repaired with Class R3 mortar behave better than those repaired with R4. The former reached higher deformations at failure and effectiveness than the latter.

When a bonding agent was used, the ultimate axial load of those repaired with R3 was about 25% higher than those repaired with R4. When no bonding agent was used, the load-bearing capacity of those repaired with R3 was 45% better than those repaired with R4.

No significant differences were noted between the presence or absence of a bonding agent in specimens repaired with R3. However, in those repaired with R4, the use of a bonding agent improved effectiveness by about 10% and caused wide variations in behaviour.

5. Conclusions

This paper presents the results obtained from an experimental study carried out at the ICITECH laboratories of the Universitat Politènica de València. Eighteen specimens were produced to simulate a section of an RC column; 12 specimens were repaired with cementitious mortar and then tested to failure under compression. The repaired specimens were divided into four series as follows:

- R3: Using Class 3 mortar without a bonding agent between the column concrete and repair mortar.
- R3B: As above, but including a bonding agent.
- R4: Using Class 4 mortar, without a bonding agent.
- R4B: As above, including a bonding agent.

The four series were designed to test the effectiveness of the type of mortar used in the repairs and the bonding agents used. As the bonding agents did not have an appreciable effect on the behaviour of the repaired columns, their use therefore cannot be recommended.

It was also found that of the two classes of mortar used (R3 and R4) the lower grade Class R3 mortar gave the best results. Although further studies are needed along these lines with a numerical simulation and parametric study, the authors consider that the reason for the present findings lies in the incompatibility of concrete with a low and mortar with a high elasticity modulus.

The study also revealed the need to go on advancing in the field of repairing RC columns with cementitious mortars. For example, it would be desirable to apply the present findings to local patching repairs, or repairing only one side, using R3 and R4 Class mortars with and without a bonding agent. The continuation of the study could either be in the form of a new experimental program or a wide parametric study with advanced numerical models.

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Table 1. Class R3 mortar. Mechanical properties

Mechanical parameter	Requirement (EN 1504-3 table 3)	Real parameters at 28 days
Compressive strength	≥ 25 MPa	40.3 MPa
Adhesive bond	≥ 1.5 MPa	1.9 MPa
Elastic modulus	≥ 15 GPa	25.2 GPa
Flexural strength	-	8.3 MPa

Tabla 2. Class R4 mortar. Mechanical properties

Mechanical parameter	Requirement (EN 1504-3 table 3)	Real parameters at 28 days
Compressive strength	≥ 45 MPa	54,2 MPa
Adhesive bond	≥ 2 MPa	2,5 MPa
Elastic modulus	≥ 20 GPa	36,7 GPa
Flexural strength	-	9 MPa

Table 3. Bonding agent. Mechanical properties

Mechanical parameter	Requirement (EN 1504-4 table 3.2)	Real parameters at 28 days
Compressive strength	≥ 30 N/mm^2	39 MPa
Flexural strength	-	8 MPa
Adhesion	-	3 MPa

Table 4. Tested specimens

Type of element	Condition	Mortar type	Bonding agent	Designation
Control Columns	Non-Damaged	-	-	CC-1; CC-2; CC-3
Damage Columns	Non-Repaired	-	-	DC-1; DC-2; DC-3
Repaired Columns	Repaired	R3	no	R3-1; R3-2; R3-3
			yes	R3B-1; R3B-2; R3B-3
		R4	no	R4-1; R4-2; R4-3
			yes	R4B-1; R4B-2; R4B-3

Table 5. Experimental results and ratios

Serie	**Specimen**	**N (kN)**	**N_{mean} (kN)**	**Efficiency ($N_R/N_{CC} \times 100$)**	**Improvement with respect to DC ($N_R/N_{DC} \times 100$)**
CC	CC-1	637,34	617,51	-	-
	CC-2	590,14			
	CC-3	625,06			
DC	DC-1	282,84	282,84	-	-
	DC-2	-			
	DC-3	-			
R3B	R3B-1	557,01	509,97	82,58	180,31
	R3B-2	544,71			
	R3B-3	428,20			
R3	R3-1	575,25	520,37	84,27	183,98
	R3-2	506,82			
	R3-3	479,04			
R4B	R4B-1	398,24	438,00	70,93	154,86
	R4B-2	475,64			
	R4B-3	440,14			
R4	R4-1	400,42	391,94	63,47	138,58
	R4-2	445,69			
	R4-2	329,72			

Nomenclature used in this Table:

N: Maximum load for each specimen

N_{mean}: Mean maximum load for different series of specimens (CC, DC, R3B, R3, R4B, R4)

N_R: Maximum load for each group of repaired columns (R3B, R3, R4B, R4)

N_{CC}: Maximum load for control columns (CC)

N_{DC}: Maximum load for damaged columns (DC)

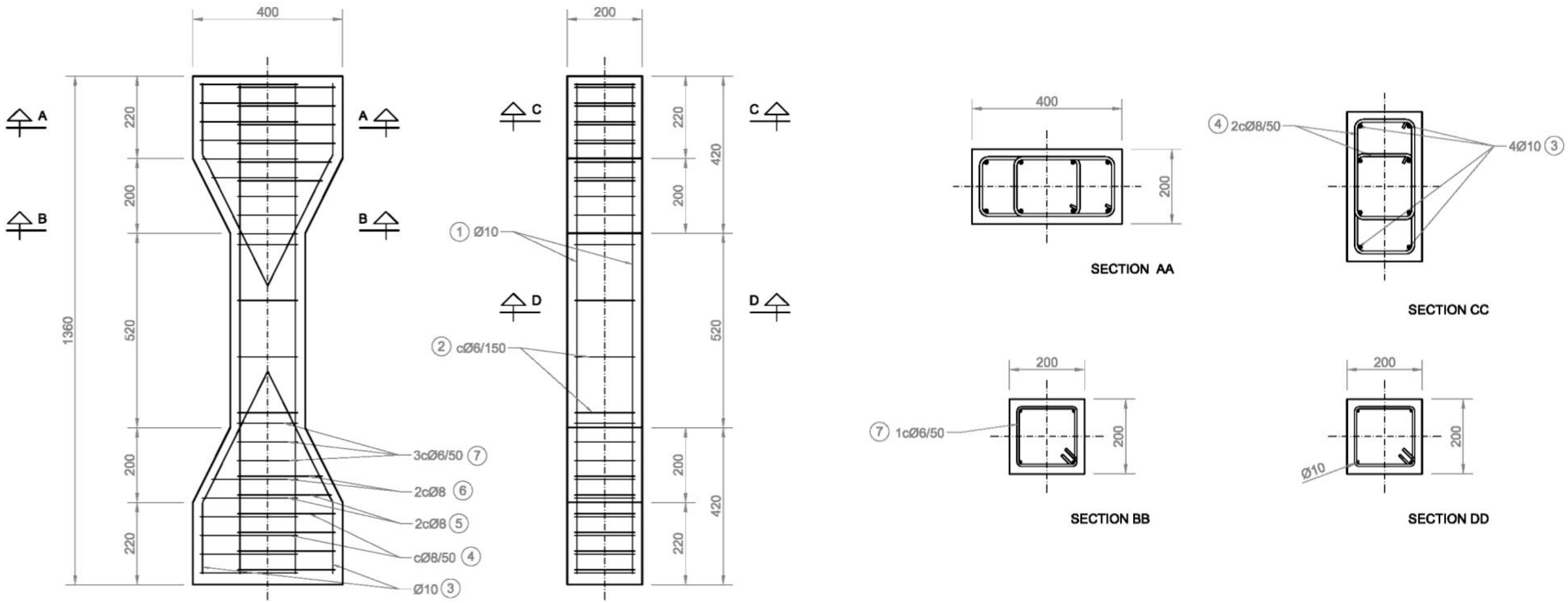

Fig. 1. Specimen geometry and reinforcement.

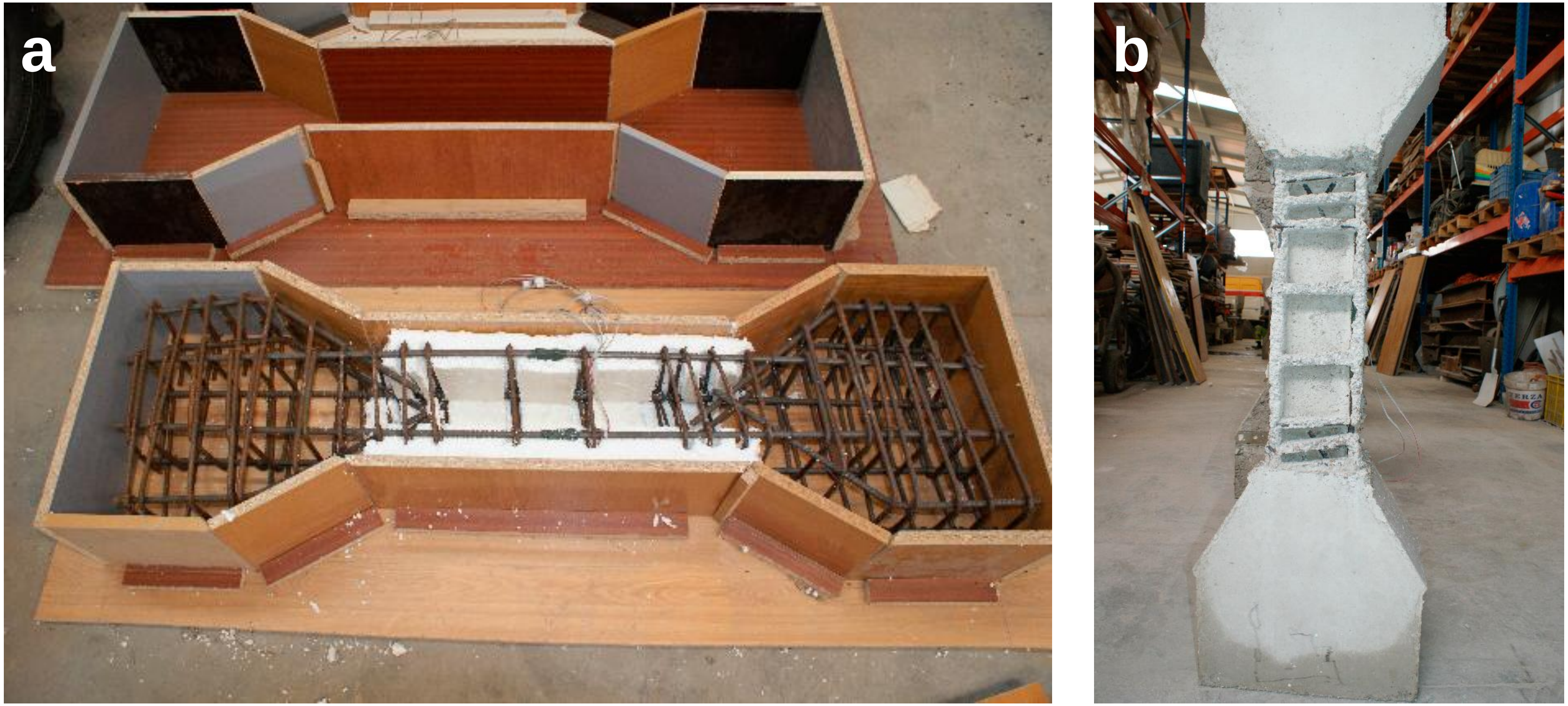

Fig. 2. a) Specimen contained by formwork; b) Damaged Column (DC) before repair.

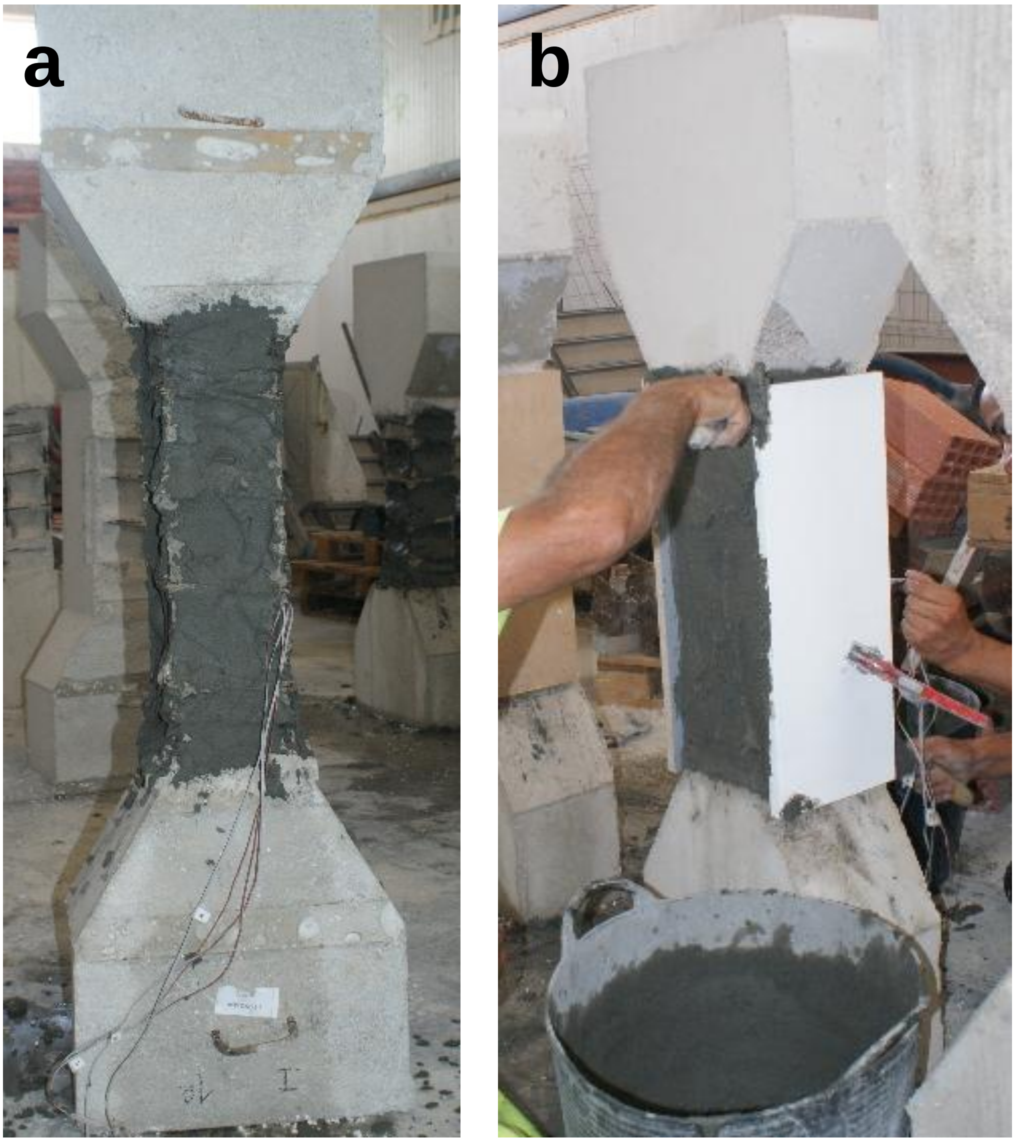

Fig. 3. a) Filling the first face of the column; b) Two-sided formwork and filling the rest of the front and back faces of the specimen.

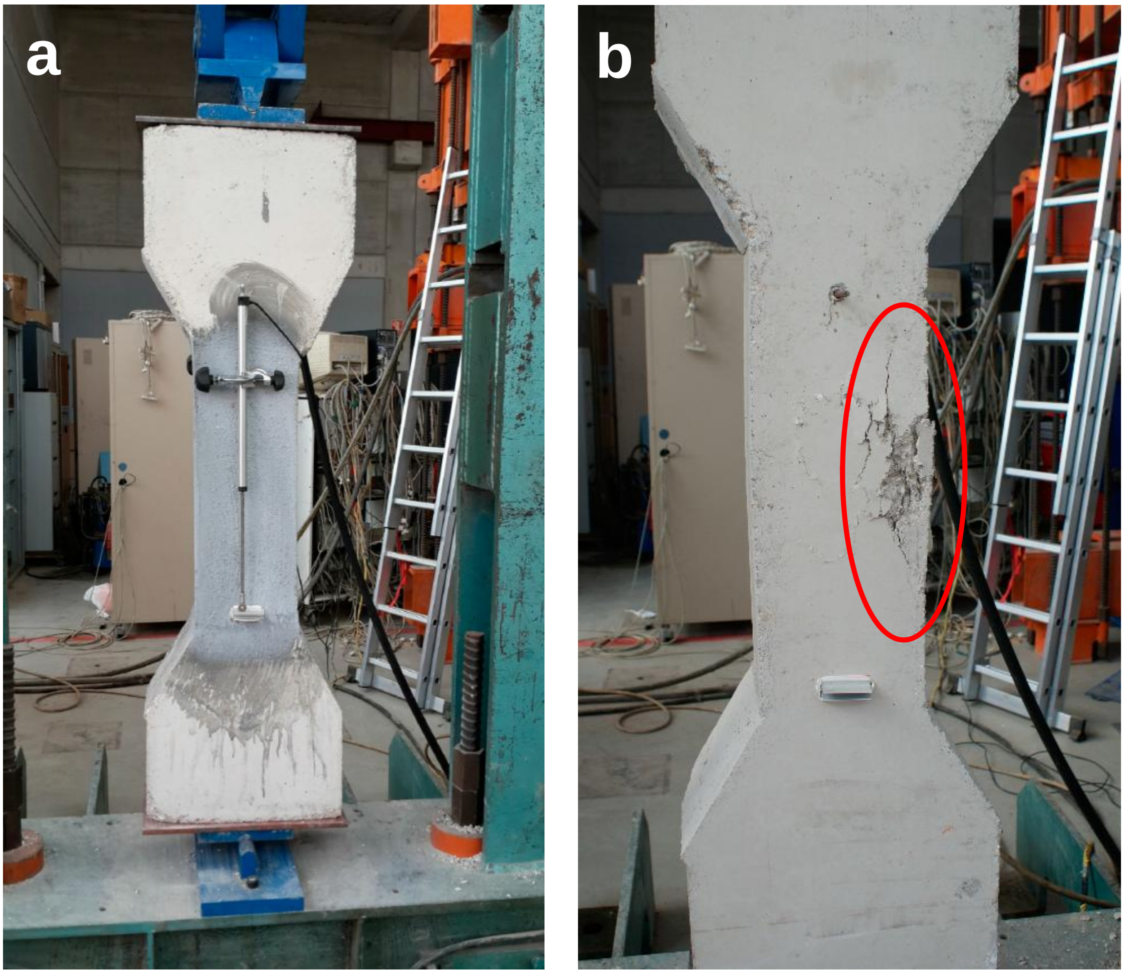

Fig. 4. a) Instrumentation of specimen; b) Failure mode: Specimen CC (control column)

Fig. 5. a) Damaged column (DC); b) Failure mode: Specimen R3B (repaired column with Class R3 mortar with bonding agent).

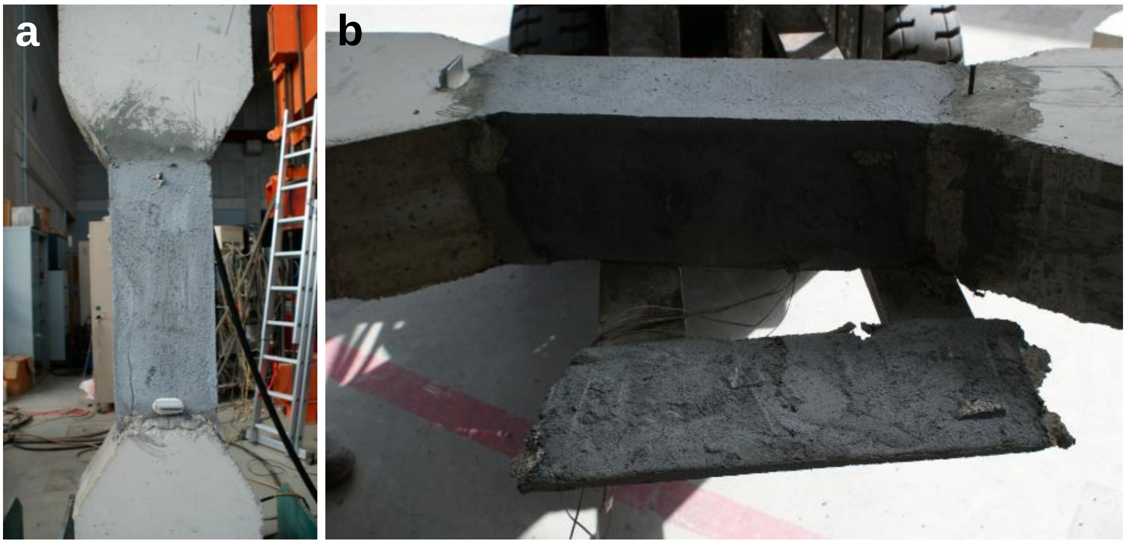

Fig. 6. a) Failure mode: Specimen R3 (repaired column with Class R3 mortar without bonding agent); b) Detachment of one of the repair mortar layers after the test.

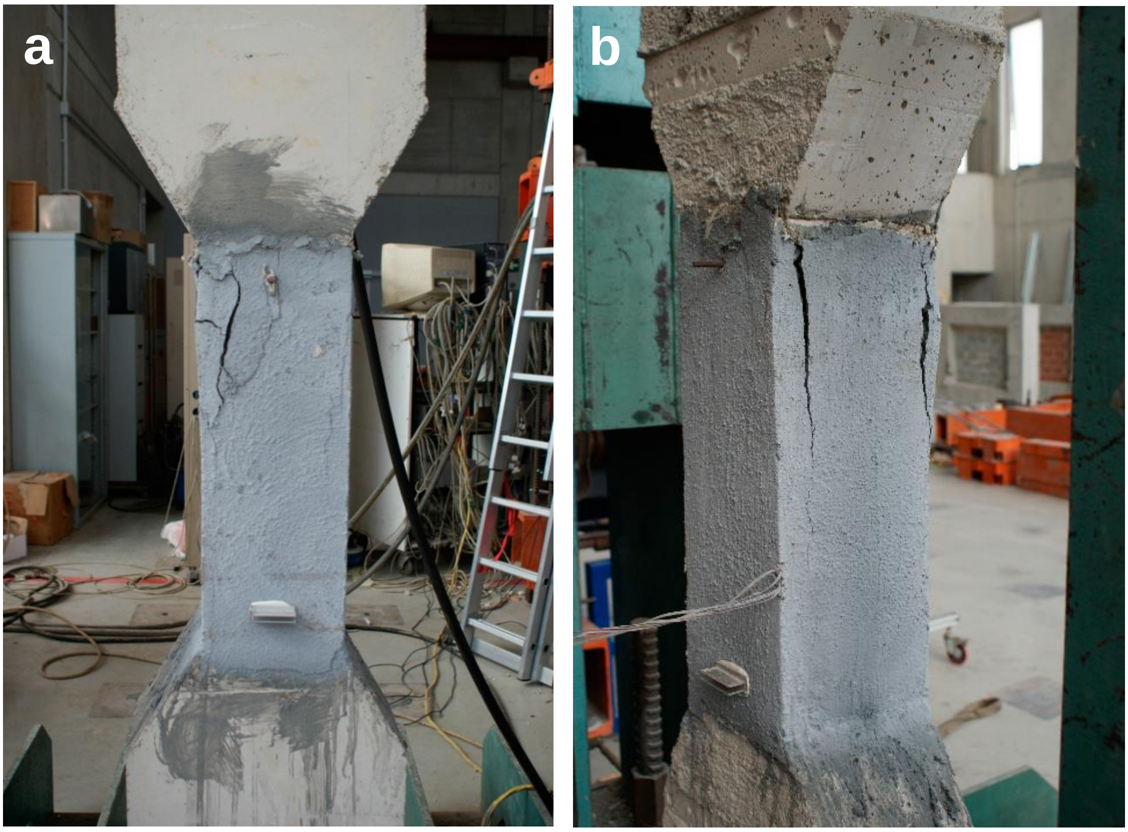

Fig. 7. Failure mode: Specimen R4B (repaired column with Class R4 mortar with bonding agent).

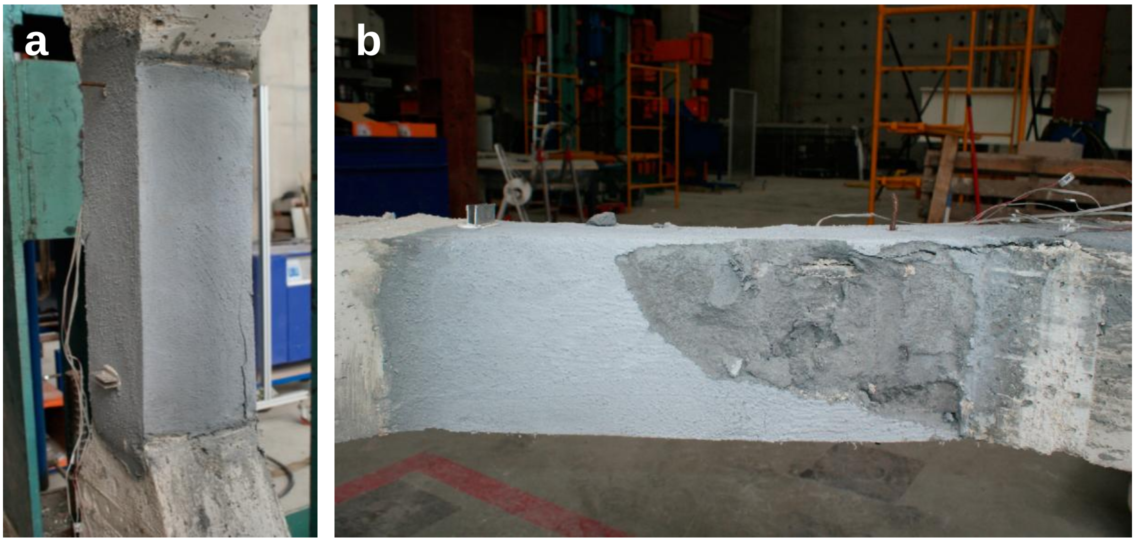

Fig. 8. Failure modes: Specimen R4 (repaired column with Class R4 mortar without bonding agent)

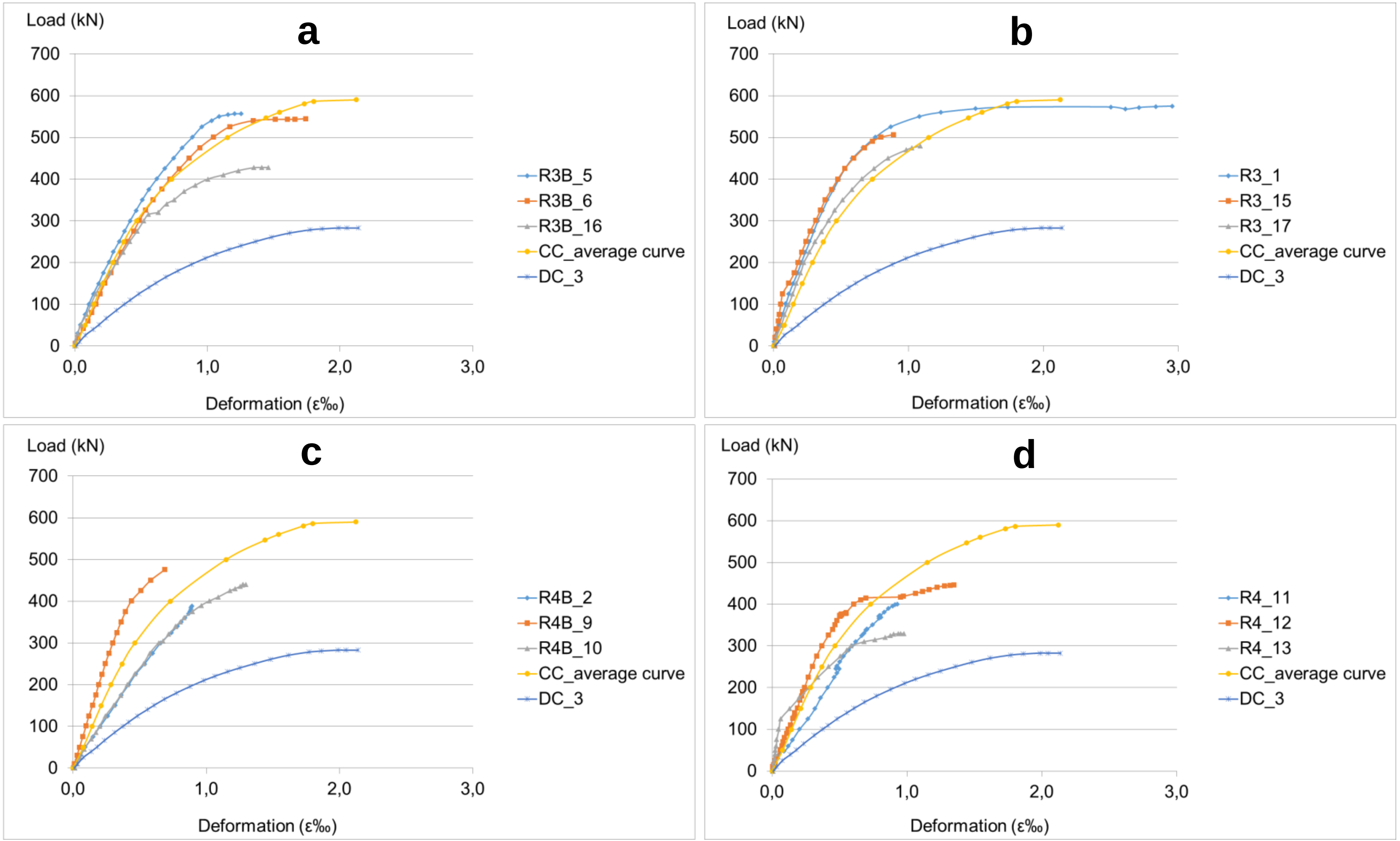

Fig. 9. Load-deformation curves: CC average curve and DC combined with: a) R3B; b) R3; c) R4B; and d) R4.