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STUDY OF THE BEHAVIOR OF RC COLUMNS STRENGTHENED WITH RC JACKETS CONTAINING DOWELS AND DIFFERENT CONFINEMENT RATIOS

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Abstract. *The current paper studies the force transfer mechanisms in retrofitted columns containing dowels crossing the interface of old and new concrete. It includes 10 specimens of square section (150x150x500mm) of 24,37 MPa nominal concrete strength with 4 longitudinal steel bars of 8mm diameter (500 MPa nominal strength) and different transverse reinforcement ratios (ω_c= 0,075, ω_c=0,15). All columns were subjected to initial axial compression up to maximum load. After repair with thixotropic high strength concrete, all columns were retrofitted with RC jacket of 80mm width of 31,8 MPa concrete strength, including 4 longitudinal bars of 8mm diameter (500 MPa nominal strength) and different confinement ratios(ω_{cj}= 0,035/0,071/0,142). The retrofitted columns contain dowel bars of either 10 or 14mm diameter that cross the interface. Two loading patterns were selected to test the strengthened columns, the behavior of which is investigated through P-δ, energy absorbed diagrams and the levels of ductility achieved. The results indicate that the initial damages affect the total behavior of the column and the capacity of the interface to shear mechanisms and to slip: a) the maximum bearing load of old column is decreased affecting at the same time the loading capacity of the jacketed element, b) suitable repair of initially damaged specimens increases the capacity of the jacketed column to transfer load through the interface.*

1 INTRODUCTION

Elements of high importance in reinforced concrete structures are columns due to their capacity in load-bearing. Columns can stand damages either due to overloading (gravity loads: changes in usage of the building, storey super induction, earthquakes, etc), due to construction damages (poor consolidation of concrete) or even due to exposure to environmental effects (corrosion, carbonation, etc). The need of repair of even strengthening of damaged columns is obvious in order to rehabilitate their capacity in loads and deformation [1], [2], [3], [4]. Nevertheless, structures designed with older seismic codes with luck of ductility need also retrofitting in order to upgrade their strength and capacity in deformation [6].

In recent decades extensive research has been conducted in repair and strengthening methods and the materials used for those purposes. Materials are usually of high strength in order to eliminate the loss in bearing capacity. After repair, when strengthening is decided several methods are applied such as: FRP wrapping (fibre reinforced polymer laminates, jacketing, etc.) or even reinforced concrete (RC) jacketing. All these methods have been proven efficient in enhancing the load capacity and the ductility of elements [7]. In all cases, the shear transfer mechanisms of the interface affect the transferring of loads and the effectiveness of the retrofit method, constituting its design crucial and of high interest [8], [9]. More specifically, in cases of strengthening with RC jacketing the main mechanisms that act are concrete-to-concrete cohesion and friction (aggregate interlock) and dowel action of the reinforcement the interface between old and new concrete (dowels, tack-welds, butt-welds, bend down bars etc.).

Researchers have studied the shear mechanisms apart or in combination, analytically or/and experimentally. The modern codes world-widely adopt results and semi-empirical relations considering the design of the jacket and the calculation of the shear mechanisms' components. Though, the initial damages of the column is ignored [10], the way of loading is not defined (directly- indirect loading of the jacket area) and finally parameters beyond the limits of design deformations are still vague. These parameters are investigated separately or in combination in this paper. In real structures columns are also subjected to horizontal forces (earthquake). In this paper only the parameters of shear transfer mechanisms examined. For those reasons the specimens were subjected to axial compression only. The experimental program held at the Reinforced Concrete Lab at Democritus University of Thrace (D.U.Th.). They contain different percentages of transverse reinforcement at core and jacket, providing different mean normal stress at the interface. The different treatment of the interface between old and new concrete such as the different kind of cohesion developed is tested (ex. due to coating with synthetic polymer sheets). In the current paper the factor of possible initial damage due to construction imperfections that is not referred and analysed extensively in the various codes that affects the efficiency of the repair is not examined.

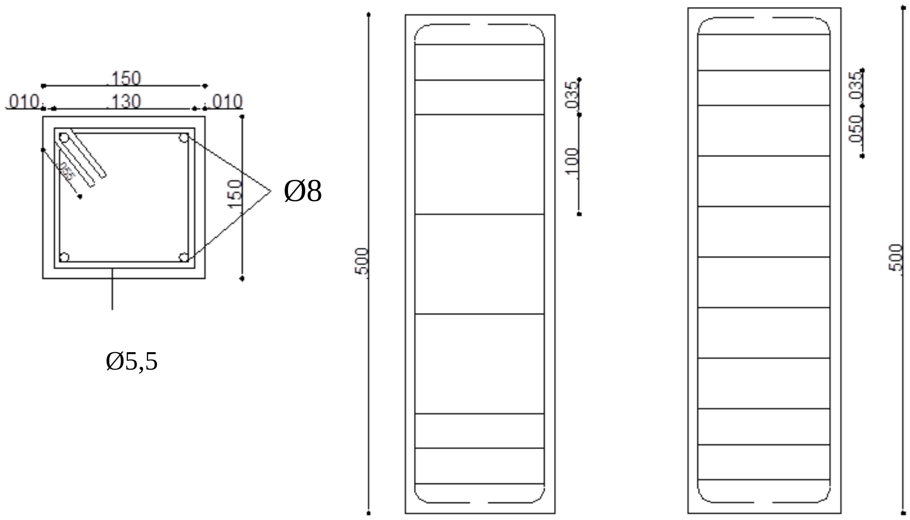
2 SHEAR TRANSFER MECHANISMS

As already referred, the shear transfer mechanisms are concrete-to-concrete cohesion and friction (aggregate interlock) [11] and dowel action. The concrete-to-concrete cohesion depends strongly on the kind of the interface [12], [13], [14]. The treatment of the interface varies (smooth, rough, very rough, high pressure jetting, shotcrete etc.) providing different values of cohesion stress. The cohesion mechanism depends strongly on the tensile strength of the weakest of the two concretes in contact. As far as friction is concerned, it depends strongly on the friction coefficient between the two different concretes and the normal stress applied at the interface. Again, the kind of the interface provides different values of friction coefficient. The normal stress applied at the interface is the result of the clumping action of stirrups during loading due to the expansion of concrete. Dowel action refers to the reinforcement crossing the interface keeping the two concretes in contact [15], [16], [17], [18]. It depends on the yield stress of the bar itself and of the angle forming with the interface (normal to etc.).

3 EXPERIMENTAL INVESTIGATION

3.1 Columns cores

The experimental investigation includes results of 10 columns of square section with 150 mm width and 500 mm height in scale 1:2 (typical column used in real structures) (Figure 1a). In the considered old columns (cores) concrete of 24,37MPa strength was used (24,4GPa modulus of Elasticity), commonly used in building structures in the last decades and 32mm maximum size of aggregate. Two columns were made of plain concrete (UR). The rest include four longitudinal steel bars of 8mm diameter (500MPa nominal strength), that is the minimum volumetric ratio defined by old and new codes (ρ=1%). One column contain closed stirrups spaced at 100mm (mechanical ratio of transverse reinforcement: ω_{wc}=0,075, 220MPa nominal strength, measured yield stress through tension tests f_y=250,76 MPa) and six with 50mm stirrup spacing (ω_{wc}=0,15), all adequately anchored (Figure 1b,c). The selection of the reinforcement was made according to the minimum percentage of longitudinal reinforcement (approximately 1%) and to low and medium transverse reinforcement ratios as practiced in structures with no high ductility requirements. Also, the diameters were selected in order to avoid any possible scale phenomena (Table 1).



a. Square section (mm) b. ω_{wc}=0,075 c. ω_{wc}=0,15

Figure 1. Section and transverse reinforcement of columns

a. Specimen B-$R_cR_jD_b$-7
Figure 2 View of specimens

Table 1. Details of Specimens

Specimen	Dowels	Longitudinal Reinforcement (Core/Jacket)	Transverse Reinforcement		Coating of Interface	Pre- Loading of Core
			Core ω_{wc}	Jacket ω_{wj}		
A-UR-2	-	-	-	-	-	YES (UR-2)
A-$R_cR_jD_b$-3	6Ø10	4Ø8/4Ø8	0,075 (Ø5,5/10)	0,4 (Ø5,5/10)	-	-
A-$R_cR_jD_b$-4	6Ø10	4Ø8/4Ø8	0,15 (Ø5,5/5)	0,92 (Ø5,5/5)	POLYMER	-
A-$R_cR_jD_b$-5	6Ø14	4Ø8/4Ø8	0,15 (Ø5,5/5)	0,92 (Ø5,5/5)	POLYMER	-
B-UR-3	-	-	-	-	-	-
B-URD_b-4	6Ø10	-	-	-	-	-
B-$R_cR_jD_b$-1	6Ø14	4Ø8/4Ø8	0,15 (Ø5,5/5)	0,035 (Ø5,5/10)	POLYMER	-
B-$R_cR_jD_b$-2	6Ø10	4Ø8/4Ø8	0,075 (Ø5,5/10)	0,035 (Ø5,5/10)	POLYMER	-
B-$R_cR_jD_b$-6	6Ø10	4Ø8/4Ø8	0,15 (Ø5,5/5)	0,71 (Ø5,5/5)	-	YES (Rc-6)
B-$R_cR_jD_b$-7	6Ø10	4Ø8/4Ø8	0,15 (Ø5,5/5)	0,035 (Ø5,5/10)	-	YES (Rc-7)
B-$R_cR_jD_b$-8	6Ø10	4Ø8/4Ø8	0,15 (Ø5,5/5)	0,142 (Ø5,5/10)	-	YES (Rc-8)
Note:			**Note:**			
A: Load Pattern A, B: Load Pattern B D_b: dowels			**UR: unreinforced core UR_j: unreinforced jacket R_c: reinforced core R_j: reinforced jacket**			

3.2 Pre-Loading

Four columns (Figure 2) were pre-loaded monotonically up to maximum bearing load (A-UR2, B-RcrjDb-6, B-RcRjDb-7, B-RcRjDb-8). The pre-loading procedure held in order to simulate any possible minor damages of design gravity loads happening at structures before strengthening is decided. The specimens were tested in a compression machine with a capacity of 3000 KN under axial monotonic loading (Figure 3). The stress strain curves are shown in Figure 4.

Figure 3 Experimental Setup

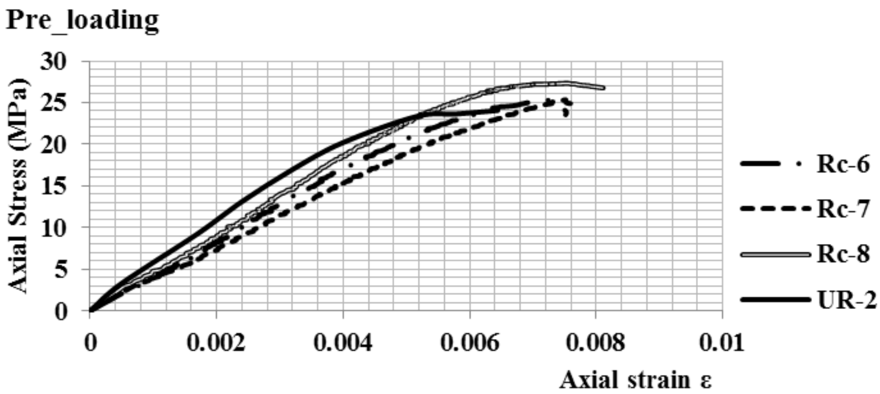
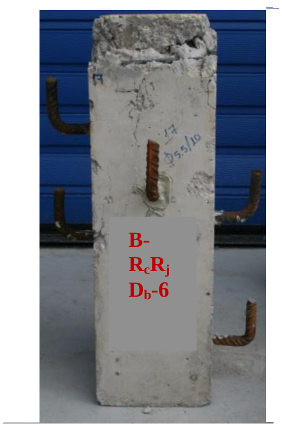


Figure 4 Axial stress vs axial strain diagram of pre-loading

3.3 Retrofit

All ten columns were strengthened with RC jacket of 80 mm thickness (total dimension of width: 310 mm) of high strength concrete (nominal compression strength: f_c=31,52 MPa, modulus of Elasticity: E_c=31,6 GPa, maximum aggregate: d_{AGR}=8 mm).

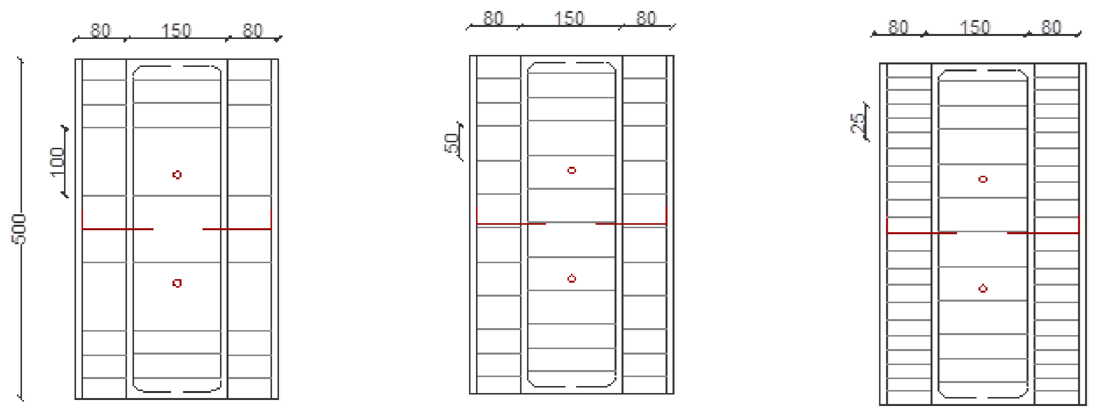
In six columns six dowels of 10 mm diameter (500 MPa nominal strength) were placed (A-$R_cR_jD_b$-4, B-URD_b-4, B-$R_cR_jD_b$-2, B-$R_cR_jD_b$-6, B-$R_cR_jD_b$-7, B-$R_cR_jD_b$-8) (Figure 5 a) with injected cementitious grout of very small particle size and thixotropic consistency (steady expansion grout), (Sika Ancorfix3) to connect core and jacket. In two columns the dowel diameter was 14mm (A-$R_cR_jD_b$-5, B-$R_cR_jD_b$-1). Dowels were designed according to the minimum percentage of reinforcement normal to the interface per area given by codes. EN 1998 part 3-GRC defines as minimum ratio ρ=1,2‰ but were placed ρ=1,6‰. Five columns were coated with resin of two-component without solvents (Sikadur-32N, LP), so as to achieve adequate adhesion between old and new concrete. Four columns were coated with synthetic polymer sheets so as to minimize the friction forces at the interface (Figure 5 b). Finally, two columns contain no bars, both core and jacket is made of plain concrete.



a. Specimen (core) with dowels (B-$R_cR_jD_b$-6)

b. Specimen coated with synthetic polymer sheet (B-$R_cR_jD_b$-2)

Figure 5 Preparation of specimens before jacketing



a. w_c=0,075 - w_j=0,035 b. w_c=0,15 - w_j=0,071 c. w_c=0,15 - w_j=0,142

Figure 6 Transverse reinforcement of core and jacket

The jackets included 4 longitudinal bars of 8 mm diameter and closed stirrups spaced at 25 mm (ω_{wj}=1,86: mechanical percentage of stirrups, normalised at the confined area of the jacket only), 50 mm (ω_{wj}=0,92) and 100 mm (ω_{wj}=0,40), again of 220 MPa nominal yield stress (measured yield stress through tension tests f_y=250,76 MPa). The top and bottom of each specimen contain more stirrups in order to secure that in these regions no damage will take place during test (Figure 6). Table 1 resumes all specimens' characteristics. The jacketed specimens were subjected to axial compression only according to two different Load Patterns (Figure 7):

Table 1. Details of Specimens

Specimen	Dowels	Longitudinal Reinforcement (Core/Jacket)	Transverse Reinforcement		Coating of Interface	Pre- Loading of Core
			Core ω_{wc}	Jacket ω_{wj}		
A-UR-2	-	-	-	-	-	YES (UR-2)
A-$R_cR_jD_b$-3	6Ø10	4Ø8/4Ø8	0,075 (Ø5,5/10)	0,4 (Ø5,5/10)	-	-
A-$R_cR_jD_b$-4	6Ø10	4Ø8/4Ø8	0,15 (Ø5,5/5)	0,92 (Ø5,5/5)	POLYMER	-
A-$R_cR_jD_b$-5	6Ø14	4Ø8/4Ø8	0,15 (Ø5,5/5)	0,92 (Ø5,5/5)	POLYMER	-
B-UR-3	-	-	-	-	-	-
B-URD$_b$-4	6Ø10	-	-	-	-	-
B-$R_cR_jD_b$-1	6Ø14	4Ø8/4Ø8	0,15 (Ø5,5/5)	0,035 (Ø5,5/10)	POLYMER	-
B-$R_cR_jD_b$-2	6Ø10	4Ø8/4Ø8	0,075 (Ø5,5/10)	0,035 (Ø5,5/10)	POLYMER	-
B-$R_cR_jD_b$-6	6Ø10	4Ø8/4Ø8	0,15 (Ø5,5/5)	0,71 (Ø5,5/5)	-	YES (Rc-6)
B-$R_cR_jD_b$-7	6Ø10	4Ø8/4Ø8	0,15 (Ø5,5/5)	0,035 (Ø5,5/10)	-	YES (Rc-7)
B-$R_cR_jD_b$-8	6Ø10	4Ø8/4Ø8	0,15 (Ø5,5/5)	0,142 (Ø5,5/10)	-	YES (Rc-8)
Note:			**Note:**			
A: Load Pattern A, **B: Load Pattern B** **D_b: dowels**			**UR: unreinforced core** **UR_j: unreinforced jacket** **R_c: reinforced core** **R_j: reinforced jacket**			

• Load Pattern A (LPA): Direct loading of old column (core) and support of jacket section only. The purpose is the investigation of load transfer from core (old concrete) to jacket (new concrete) depending on the resistance mechanisms of the interface (cohesion, aggregate interlock, dowels, anchors).

- Load Pattern B (LPB): Direct loading of core with the entire retrofitted element supported. That case simulates the function of a retrofitted column of a real structure where the growth of the axial load takes place through the old column (core).Even if the jacket crosses the beam- column joint, due to the different time of casting; the concrete of the jacket presents shrinkage phenomena. As a result there is a region of the old column not fully jacketed.

Briefly, the current experimental program considers the following parameters: a. kind of connection of core and jacket: cohesion, epoxy glue, dowels and anchors, b. percentage of transverse reinforcement (stirrups) of core and jacket, c. type of loading- Load Patterns, d. damages of the core (construction or overloading). In the current paper the construction damages are not examined.

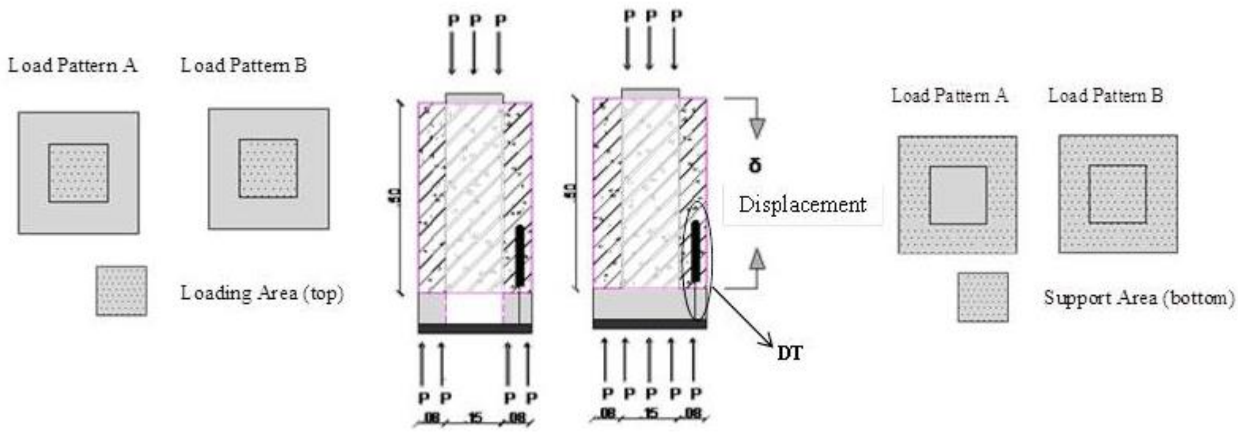


Figure 7 Shape of Load Patterns

4 EXPERIMENTAL RESULTS

4.2 Load Pattern Results

Table 2 shows the results of the specimens tested in the specific Load Pattern. Also the envelopes of the results of the cyclic test are shown in Figure 8 to 13. It is noted that columns were tested in high levels of axial displacements that are not feasible to the real structures in order to investigate the load transfer mechanisms. Table 2, though, includes the measured quantities: δ_{peak} is the displacement that corresponds to the maximum load (P_{max} also included), δ_u is the displacement corresponding to the ultimate load (δ_u>25mm, P_u=20%Pmax), E_n is the total absorbed energy normalized to the volume of the core and μ are the deformation ductility achieved. All deformations are the relative displacements of the two loading plates at the top and bottom of the specimens as shown in Figure 7. It is assumed that all deformations equal with the slip of the interface between core and jacket.

In Load Pattern B which simulates a retrofitted column in real structures, (Figure 7) specimen with no reinforcement at all (B-UR-3) presents higher load than an unreinforced column with dowels crossing the interface (B-URD$_b$-4). Specimen only with dowels crossing the interface (B-URD$_b$-4) proves that their presence affects the maximum load in small levels but increases the resistance of the interface to slip. The strong difference between those specimens is the actual mechanism of failure. The unreinforced column works only with tensile strength of the weakest concrete. The presence of dowels, on the other hand, creates damaged regions around the dowel bar that augment throughout the loading and the make the failure easier to expand. The influence of dowels is shown in Figure 9.

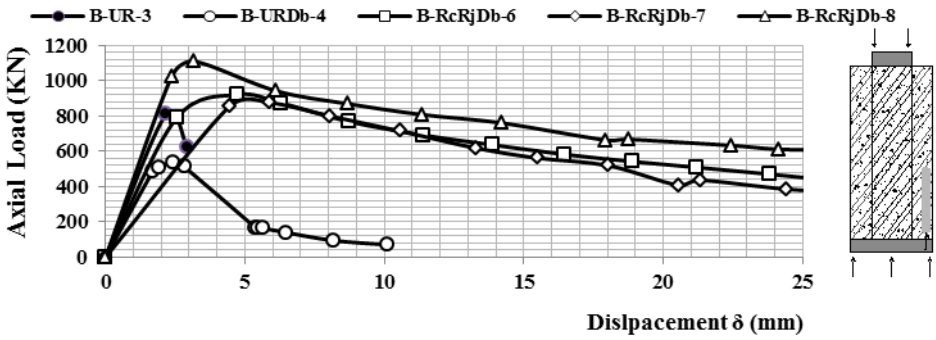


Figure 8 Displacements versus Axial Load for Load Pattern B (Envelopes)

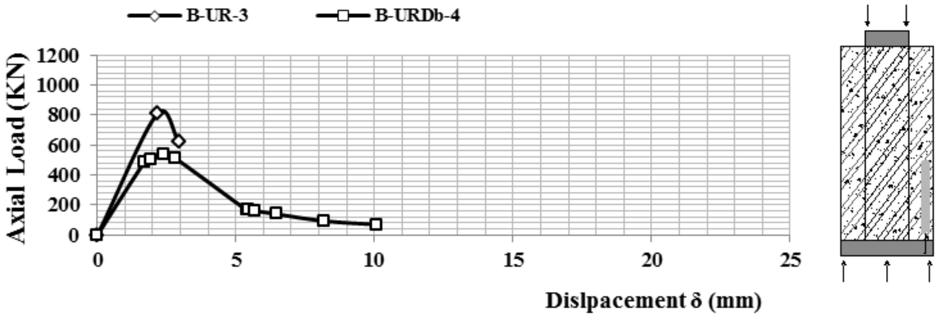


Figure 9 Cohesion and dowel contribution to the shear transfer mechanisms

The influence of the diameter of dowels is again examined by the columns covered with polymer sheets. Dowels of larger diameter (B-$R_cR_jD_b$-1, 6Ø14) presented 28% higher maximum load at 96% lower values of slip than smaller diameters (B-$R_cR_jD_b$-2, 6Ø10) (Figure 10).

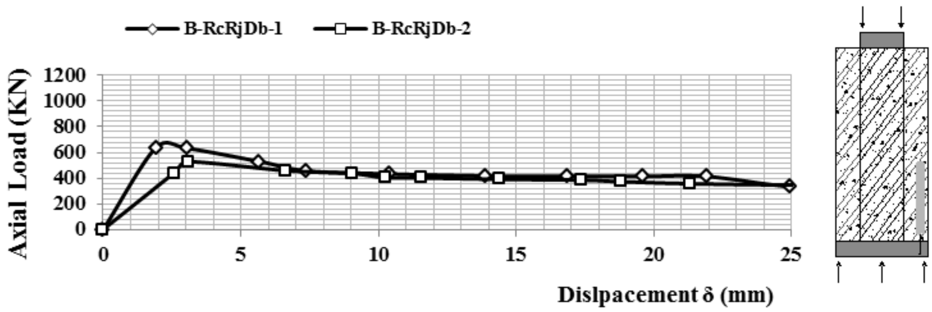


Figure 10 Dowel action

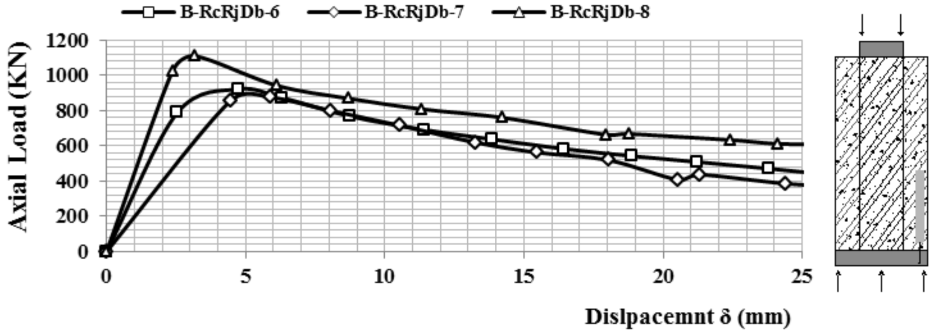


Figure 11 Confinement effect of the jacketed area

The mechanical percentages of stirrups in the jacket area affect the maximum bearing load, as shown in Figure 11. Specimen with dense stirrups (B-$R_cR_jD_b$-8) presented the highest axial load capacity up to 19,7%, proving the activation of the confinement mechanisms of jacket.

All above are also confirmed by the energy absorbed diagram (Figure 12). The activation of confinement is also obvious specimen with the high percentage of stirrups absorbed the most energy (B-$R_cR_jD_b$-8: ω_{wj}=0,142). Finally, again, the energy of the dowel action or cohesion alone or even in combination (B-UR-3, B- URD_b-4, B-$R_cR_jD_b$-1, B-$R_cR_jD_b$-2,) range in lower values.

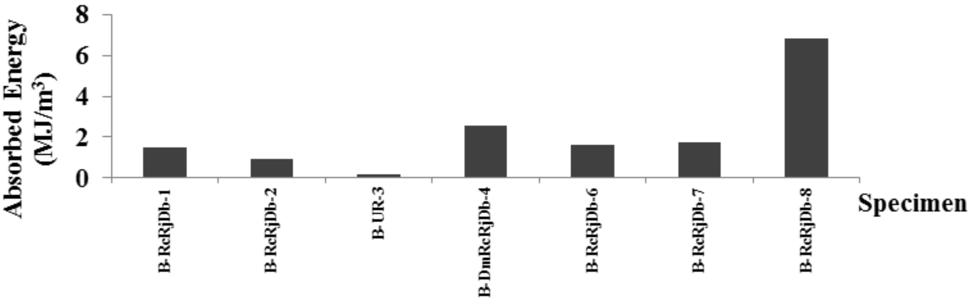


Figure 12 Energy Absorbed Diagram for Load Pattern B

In both Load Patterns the pre-loading effect is proven to be of minor importance to the final behavior of the retrofitted element. Pre-loaded specimens were not affected in terms of maximum bearing load.

It is important to note that the values of the bearing load of Load Pattern A are similar to those of Load Pattern B. This means, that in Load Pattern B the forces are totally transferred to the jacket area.

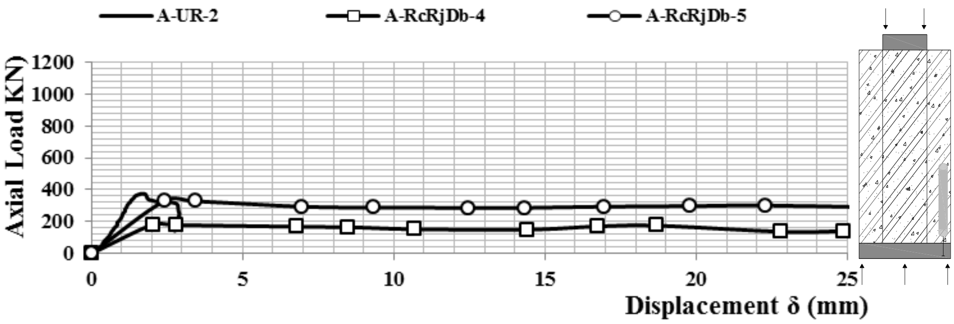


Figure 12 Displacements versus Axial Load for Load Pattern A (Envelopes)

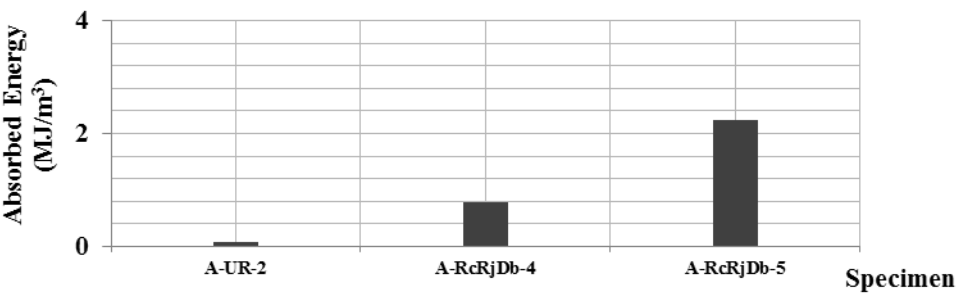


Figure 13 Energy Absorbed Diagram for Load Pattern A

Table 2. Experimental Results

Specimens	Cores					Jackets					
	δ_u (mm)	δ_{peak} (mm)	P_u (KN)	P_{peak} (KN)	E_n (MJ/m^3)	δ_u (mm)	δ_{peak} (mm)	P_u (KN)	P_{peak} (KN)	μ_δ	E_n (MJ/m^3)
A-UR-2	-	-	-	-	-	2.86	1.63	303.11	375.10	2	0.08
A-RcRjDb-4	-	-	-	-	-	66.86	2.03	54.74	181.60	33	0.77
A-RcRjDb-5	-	-	-	-	-	90.95	2.42	246.36	329.74	38	2.24
B-UR-3	-	-	-	-	-	5.02	2.17	169.11	810.31	2	1.51
B-RcRjDb-1	-	-	-	-	-	45.01	1.92	318.30	638.83	23	0.93
B-RcRjDb-2	-	-	-	-	-	27.73	3.09	352.40	526.72	9	0.19
B-DmRcRjDb-4	-	-	-	-	-	53.17	6.52	268.24	1062.00	8	2.56
B-RcRjDb-6	-	-	-	-	-	43.38	4.73	160.53	922.34	9	1.62
B-RcRjDb-7	-	-	-	-	-	46.54	5.87	176.04	876.39	8	1.75
B-RcRjDb-8	4.85	3.60	532.13	612.00	0.12	145.94	3.17	443.85	1110.78	46	6.83

5 CONCLUSIONS

The present study focuses on the shear mechanisms that contribute to the behaviour of a retrofitted element strengthened with RC jacket. The different Load Patterns demonstrate the variable activation of the transverse reinforcement of the jacket and the dowel action. These factors contribute to maximum bearing load as well as to the resistance of the interface to slip. What is more, in both Load Patterns the load is transferred to the jacket in the same way. Initial damages up to design loads do not affect the ability of the element to act as monolithic even when repair is not applied.

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