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INVESTIGATION OF FORCE TRANSFER MECHANISMS IN RETROFITTED RC COLUMNS WITH RC JACKETS CONTAINING WELDED BARS SUBJECTED TO AXIAL COMPRESSION

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Abstract. *In the current research program the force transfer mechanisms are investigated in retrofitted columns containing bend down welded steel bars. It includes 6 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 jacket's longitudinal bars are welded to the ones of the core using steel bars of either 8 or 10mm diameter. To test the strengthened columns a loading pattern is selected in order to simulate the real structures, even though the experimental set up includes only axial loads (moments and horizontal loads are not examined). The behavior of specimens is investigated through P-δ, σ-ε, 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) welded bars of higher diameter present early phenomena of buckling and as a result the retrofitted columns can bear lower maximum load, b) the presence of dowel action increases the capacity of the jacketed column to transfer load through the interface.*

1 INTRODUCTION

The ability of columns to transfer loads and bear horizontal loads makes them crucial elements for design. In reinforced concrete structures, 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). In order to rehabilitate their capacity in loads and deformation repair or even strengthening is inevitable. What is more, in structures designed without ductility (older generation codes) need also retrofitting in order to upgrade their strength and capacity in deformation.

In recent decades extensive research has been conducted in repair and strengthening methods [1], [2], [3]. High strength materials are commonly used in order to upgrade the bearing capacity [4]. After repair, in cases of strengthening several methods are used 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 [5], [6], [7]. The key to the strengthening design is proven to be the interface capacity in transferring loads and in terms of deformation [8], [9], [10]. More specifically, in cases of strengthening with RC jacketing the main mechanisms that act in shear transfer 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.).

All these mechanisms have been studied apart or in combination, analytically or/and experimentally. Modern codes of all scientific communities adopt results and semi-empirical relations considering the design of the jacket and the calculation of the shear mechanisms' components. The initial damages of the column are ignored, the type of loading is not defined (directly- indirect loading of the jacket area) and finally the state beyond the limits of design deformations is still vague. These parameters are investigated separately or in combination in this paper. In real structures columns are also subjected to bending and 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. In the current paper the factor of possible initial damage due to construction imperfections [11] that is not referred and analyzed extensively in the various codes that affects the efficiency of the repair is not examined.

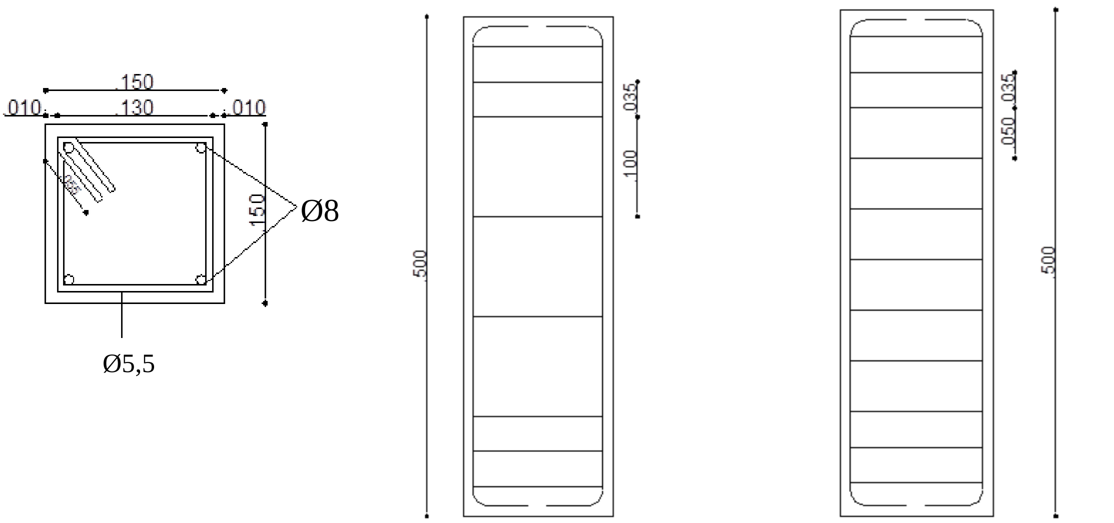
2 TRANSFER MECHANISMS

As already discussed, the shear transfer mechanisms are concrete-to-concrete cohesion and friction (aggregate interlock) [12] and dowel action. The concrete-to-concrete cohesion depends strongly on the kind of the interface. The treatment of the interface varies (smooth, rough, very rough, high pressure jetting, shotcrete etc.) resulting in different values of cohesion stress. The cohesion mechanism depends strongly on the tensile strength of the weakest concrete of the interface. Friction coefficient between the two different concretes and the normal stress applied at the interface affect the friction values [13]. Again, the kind and the treatment of the interface provide different values of friction coefficient. The normal stress applied 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. It depends on the yield stress of the bar itself and of the angle forming with the interface (vertical, etc.). Instead of dowels, welding the longitudinal bars of both old and new column with bend down bars crossing the interface has been common use during the last years [14].

3 EXPERIMENTAL INVESTIGATION

3.1 Old Columns

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) (Fig.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. Columns include four longitudinal steel bars of 8mm diameter (500MPa nominal strength), which is the minimum volumetric ratio defined by old and new codes (ρ=1%). Half columns contain closed stirrups spaced at 100mm (mechanical ratio of transverse reinforcement: ω_c=0,075, 220MPa nominal strength, measured yield stress through tension tests f_y=250,76 MPa) and the rest three with 50mm stirrup spacing (ω_c=0,15), all adequately anchored (Fig.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.



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

Figure 1. Section and transverse reinforcement of columns

3.2 Pre-Loading Effect

The pre-loading procedure held in order to simulate any possible minor damages of design 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 or repeated loading (pseudo-seismic loading) of cycles of 5‰ axial strain (Figure 2). Two columns were pre-loaded up to maximum bearing load (Rc-9, Rc-10). The stress strain curves are shown in Figure 3.

Figure 2 Experimental Setup

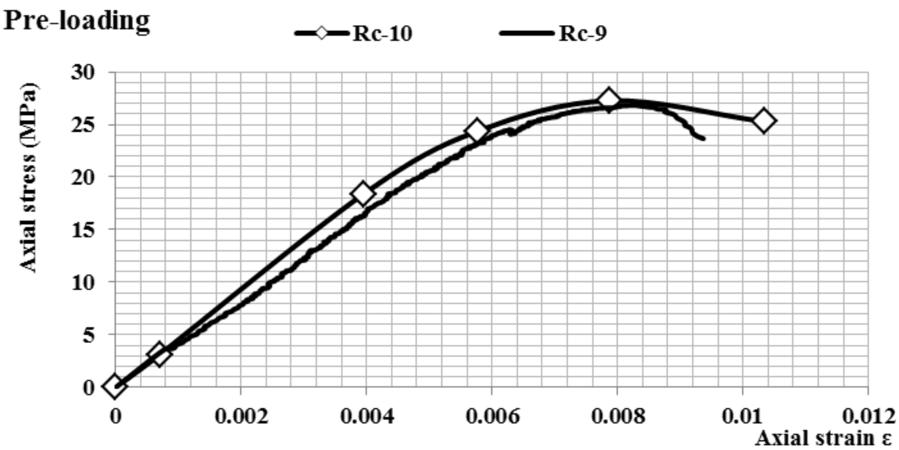


Figure 3: Axial stress vs axial strain diagram of pre-loading.

3.3 Repair and Retrofit Procedure

All six 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 two columns four (4) welded bend-down bars of diameter 8 mm (500 MPa nominal strength) were placed (Fig. 4) to connect core and jacket. The rest four columns contained welded bend-down bars of 10mm diameter.

The jackets included 4 longitudinal bars of 8 mm diameter and closed stirrups spaced at 50 mm (ω_{wj}=0,071: mechanical percentage of stirrups, normalized at the confined area of the jacket only) and 100 mm (ω_{wj}=0,035), 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 (Fig. 4 a, b). Table 1 resumes all specimens' characteristics.

a. ω_{wj}=0,071 b. ω_{wj}=0,035

Figure 4 Preparation of specimens before jacketing:
Transverse reinforcement of jackets and bend down bars.

Table 1. Details of Specimens

Specimen	Dowels	Bend down bars	Longitudinal Reinforcement (Core/Jacket)	Transverse Reinforcement		Pre- Loading of Core
				Core ω_{wc}	Jacket ω_{wj}	
B-$R_cR_jD_w$ -9	-	4Ø8	4Ø8/4Ø8	0,15 (Ø5,5/50)	0,035 (Ø5,5/100)	Repeated (Rc-9)
B-$R_cR_jD_w$-10	-	4Ø10	4Ø8/4Ø8	0,075 (Ø5,5/100)	0,035 (Ø5,5/100)	-
B-$R_cR_jD_w$-11	-	4Ø10	4Ø8/4Ø8	0,15 (Ø5,5/50)	0,071 (Ø5,5/50)	-
B-$R_cR_jD_w$-12	-	4Ø10	4Ø8/4Ø8	0,075 (Ø5,5/100)	0,035 (Ø5,5/100)	YES (Rc-6)
B-$R_cR_jD_w$-13	-	4Ø8	4Ø8/4Ø8	0,15 (Ø5,5/50)	0,035 (Ø5,5/100)	YES (Rc-7)
B-$R_cR_jD_bD_w$-14	6Ø10	4Ø10	4Ø8/4Ø8	0,15 (Ø5,5/50)	0,071 (Ø5,5/50)	YES (Rc-8)
Note:						
A: Load Pattern A, **B: Load Pattern B** **D_b: dowels** **D_w: bend down bars (welded)**				**UR: unreinforced core** **UR_j: unreinforced jacket** **R_c: reinforced core** **R_j: reinforced jacket**		

The jacketed specimens were subjected to axial compression only according to Load Pattern B (Fig.5):

Load Pattern B (LPB): describes the 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 construction damages are excluded.

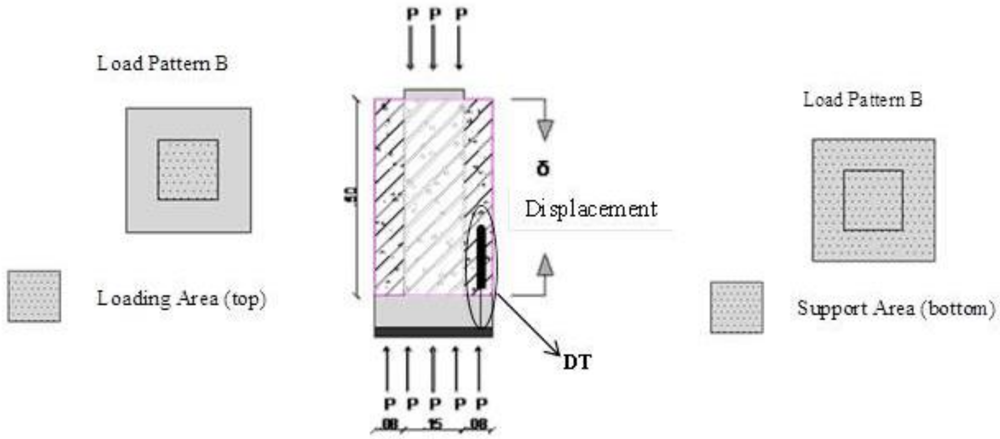


Figure 5 Shape of Load Patterns

4 RETROFITTED COLUMNS' EXPERIMENTAL RESULTS

Table 2 shows the results of each Load Pattern and the specimens tested respectively. Also the envelopes of the results of the cyclic test are shown in Figure 6 to 13. It is noted that the 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 and the remaining strength. 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_δ are the deformation ductility achieved at the jackets' loading. All deformations are the relative displacements of the two loading plates at the top and bottom of the specimens as shown in Figure 5.

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)
B-RcRjDw-9	4.65	4.25	537.08	599.18	0.10	87.98	1.58	207.95	1127.72	56	2.96
B-RcRjDw-10	-	-	-	-	-	121.76	2.09	236.00	793.21	58	3.66
B-RcRjDw-11	-	-	-	-	-	54.14	2.48	235.50	1055.75	22	2.26
B-RcRjDw-12	-	-	-	-	-	48.20	2.15	271.54	1016.86	22	1.70
B-RcRjDw-13	-	-	-	-	-	108.84	2.63	537.65	1158.68	41	3.44
B-RcRjDbDw-14	4.82	3.59	568	613.4	0.18	131.56	2.41	126.54	1053.48	55	5.34

The envelopes of all tested specimens are shown in figure 6. The preloading procedure doesn't seem to affect the total behaviour of the retrofitted element in terms of maximum bearing load and of deformation (Figure 7). Slightly, after the maximum bearing load, the preloaded specimen (B-$R_cR_jD_w$-9) presents lower load (15%) at the same values of displacement.

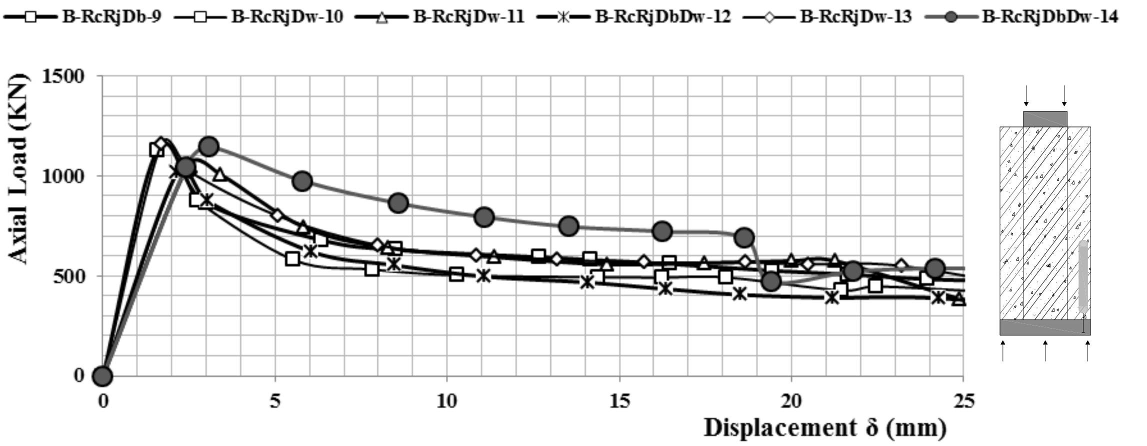


Figure 6 Displacements versus Axial Load for Load Pattern B (Envelopes)

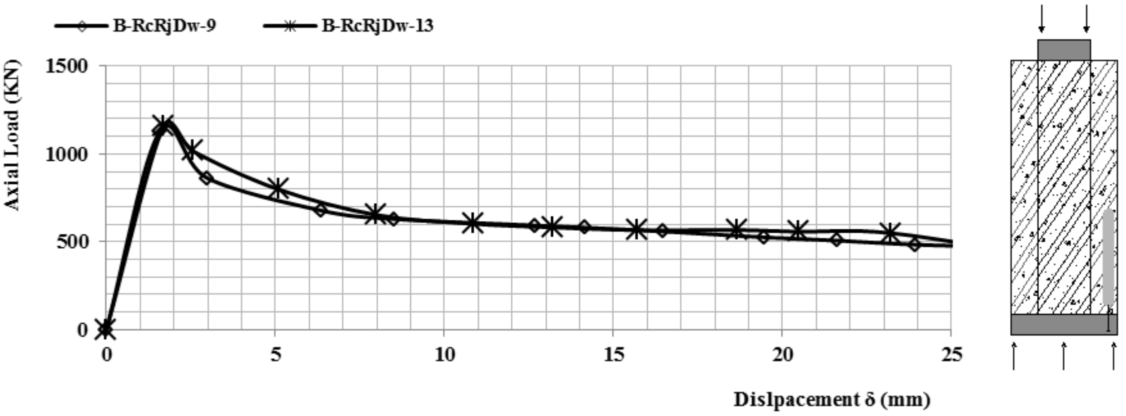


Figure 7 Pre-loading effect on total behaviour of column (Envelopes)

What is more, the contribution of confinement is examined (Figure 8). Specimen with dense stirrups is capable of bearing higher load than the one with lower percentage of transverse reinforcement. In fact, with twice the percentage of stirrups (B-$R_cR_jD_w$-11) 25% higher load is achieved at the same values of displacement. It is concluded that the load is transferred at the jacketed area energising the confinement mechanisms.

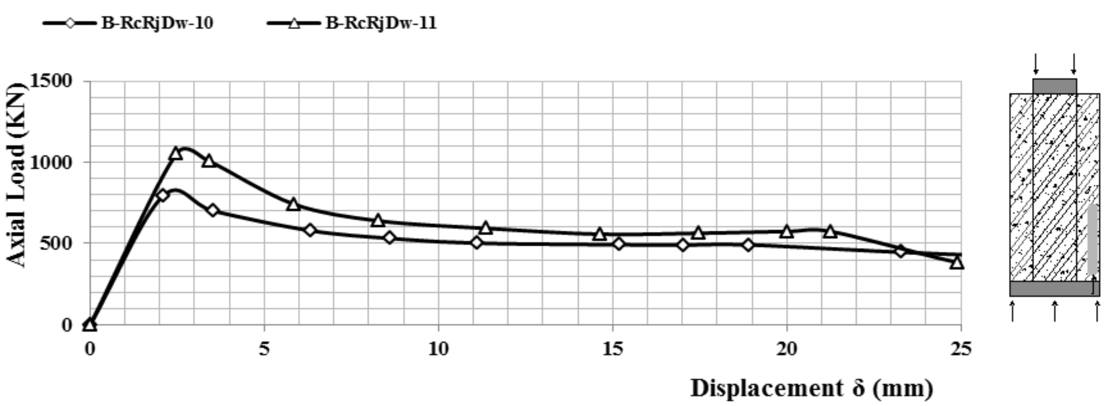


Figure 8 Confinement effect at the behaviour of the retrofitted element (Envelopes)

An important remark is that columns containing welded bars of diameter higher than that of the longitudinal bar (B-$R_cR_jD_w$-10) can bear lower maximum load in higher values of slip (Figure 9). The welded bars absorb and transfer the load at the jacketed area and provoke lateral stress at the longitudinal bar. As shown in figure 10 the failure of specimen with 4Ø10 welds crossing the interface is provoked by the buckling of the longitudinal bars of the jacketed area. On the other hand (Figure 11) the buckling of longitudinal reinforcement of a column with the same diameter in welds and longitudinal bars is in lower levels.

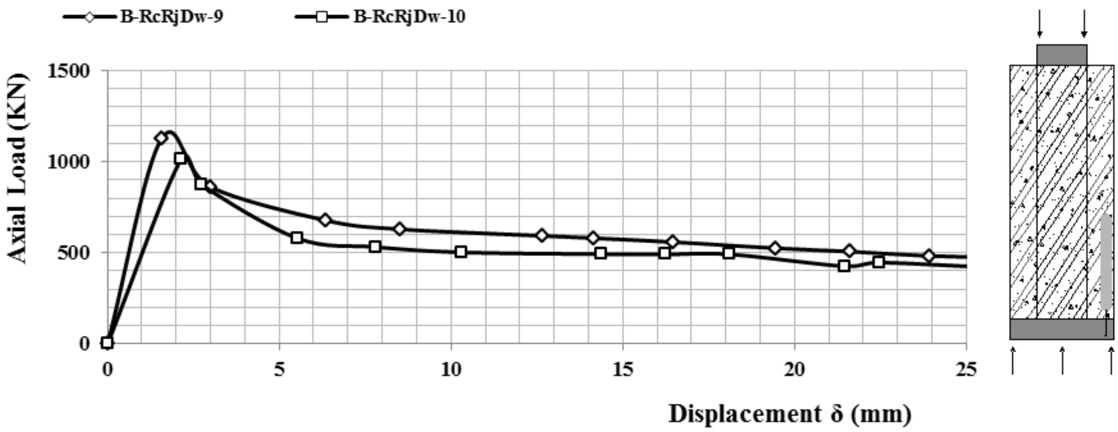


Figure 9 Welds' diameter effect on the jacketed columns performance (Envelopes)

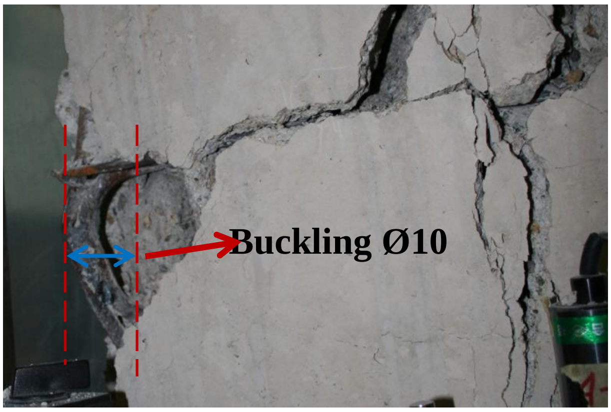


Figure 10 Buckling of the longitudinal bar_ welds 4Ø10

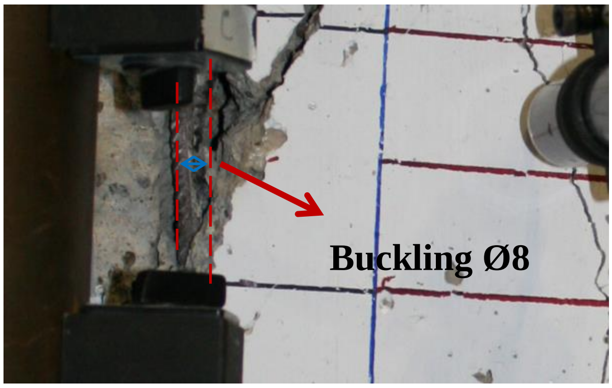


Figure 11 Buckling of the longitudinal bar_ welds 4Ø8

Additionally, the column containing both welds and dowels (B-$R_cR_jD_bD_w$-14) presents higher load than the one without dowels (B-$R_cR_jD_w$-11). Both initial branches coincide fully but the descending ones differ: it remains 24% higher at all the deformation spectra (Figure 12). Even though the regions near the dowel bars pass to a plastic behaviour due to the local damage been done through loading, the column continues to bear more load. In higher values of slip (over 3mm- almost 6‰) the dowel action stops and the bar continues to act in tension.

All above are also depicted at the energy absorbed diagram (Figure 13). The column with welds and dowels (B-$R_cR_jD_bD_w$-14) absorbs up to 68% higher energy of all. Again, specimens containing smaller welds (B-$R_cR_jD_w$-9, B-$R_cR_jD_w$-13) present higher energy than the ones with larger welds.

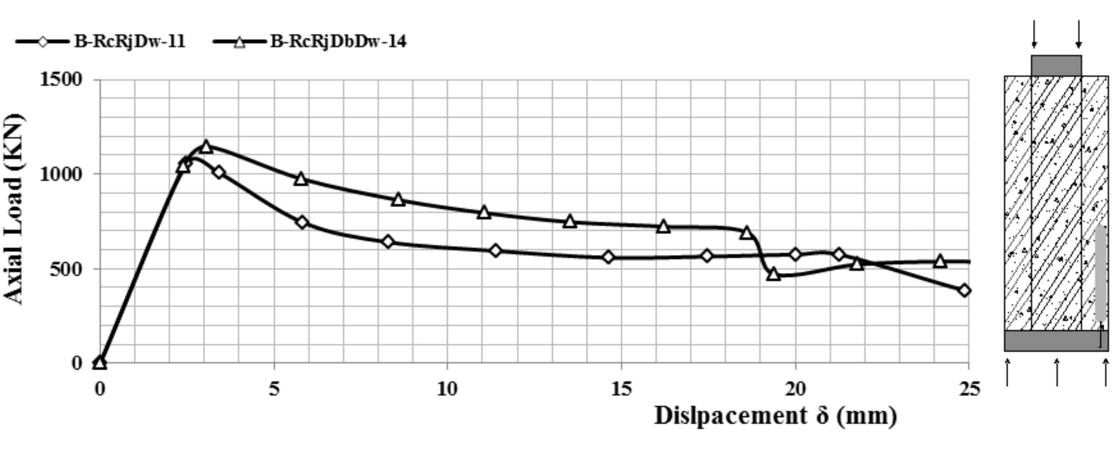


Figure 12 Dowel contribution on the behaviour of the retrofitted column containing welded bars (Envelopes)

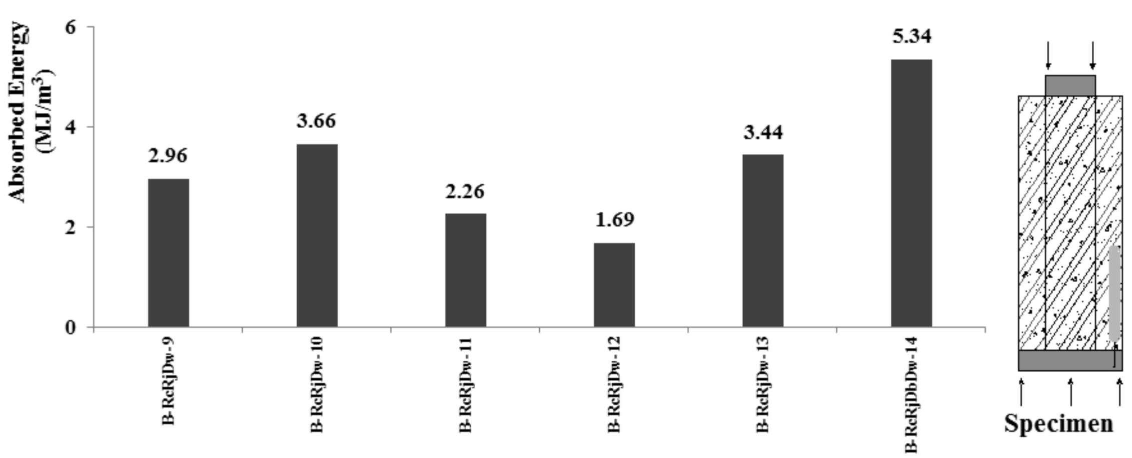


Figure 13 Total absorbed energy (MJ/m^3)

In terms of ductility (Table 2), even though the columns were subjected to high values of deformation that does not happen in real structures, specimen with small diameter of welded bars (B-$R_cR_jD_w$-10) presented up to 62% higher ductility of deformation. It is remarkable that specimen with both dowels and welds (B-$R_cR_jD_bD_w$-14) presents 6% lower ductility than the one without dowels (B-$R_cR_jD_w$-10). The plastic regions created around the dowel bar affect the ability of the interface to slip.

5 CONCLUSIONS

The present study focuses on the capacity of welded bend down bars-placed at the interface of old and new concrete in retrofitted RC columns with RC jackets- to the final bearing load. Due to initial overloading damages the loading capacity is decreased but the deformation ability is affected (pre-loading effect). The welded bars are proven to transfer the loads from old to new concrete since the confinement mechanisms are activated rising the maximum bearing load. Though, large diameters of welds connected to smaller diameters of longitudinal reinforcement bars lead to early phenomena of buckling. Buckling results in lower maximum loads and decreased stiffness. Finally, the dowel presence results in plastic regions around the dowel bars that do not reduce the capacity of the interface to transfer loads, but on the other hand result in higher percentages of bearing loads.

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