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INTERFACE BEHAVIOUR OF RETROFITTED COLUMNS SUBJECTED TO REPEATED LOADING

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ABSTRACT

The current study examines experimentally the interface behaviour of retrofitted columns subjected to pseudoseismic axial loading. It includes 13 specimens of square section (150x150x500 mm) of 24.37 MPa nominal concrete strength with 4 longitudinal steel bars of 8 mm (500 MPa nominal strength) diameter with transverse reinforcement ratio ω_c=0.15. All columns were retrofitted with reinforced concrete jackets (RC) of 80 mm width of approximate 30 MPa concrete strength including 4 longitudinal bars (500 MPa nominal strength) and different confinement ratios along with two kinds of interface reinforcement: dowels crossing vertically the interface plane and welded bend-down bars. Interface treatment differs from smooth to roughen with chipping method for comprehension of the shear mechanisms along the contact of the two different-time casted concretes. Results indicate that: A) Interface treatment ended up to higher initial chord stiffness; B) the presence of the welded bend-down bars increase the initial cord stiffness of the upgraded element but due to buckling phenomena the secant stiffness is reduced, C) increase of the normal stress of the interface due to confinement decreases the load reduction rate, D) all elements' capacity is upgraded

Keywords: RC jacketing, interface, reinforced concrete, dowel bars, welded connectors

INTRODUCTION

The primary concern of modern structural engineering is to effectively restore existing structures. Appropriate materials, techniques and procedure selection for the rehabilitation of a given structure has been a major challenge. Innovative techniques (use of fiber reinforced polymer-Teng & Lam 2004, smart memory alloys- Park et al. 2011, NSM- Singh et al. 2014, etc.) in structural repair have many advantages over the conventional techniques (jacketing through reinforced concrete). Reinforced concrete jacketing can be employed as a repair or strengthening scheme. The main purpose of jacketing of columns is to increase the shear capacity and stiffness of columns in order to accomplish a strong column-weak beam design.

All methods have been proven efficient in enhancing the load capacity and the ductility of elements (Júlio & Branco 2008, Júlio et al. 2005(a), Achillopoulou & Karabinis 2013). The key to the strengthening design is proven to be the interface capacity terms of load and slip (Santos & Júlio 2014, Achillopoulou et al. 2013a,b Achillopoulou et al. 2012).

In cases of strengthening with RC jacketing the main mechanisms that act in shear transfer are concrete-to-concrete cohesion and friction- aggregate interlock (Tasios & Vitzileou 1987) and dowel

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action (Vitzileou & Tasios 1987) 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 (EN1998/3, ACI 318-08, G.Re.Co.) of all scientific communities adopt results and semi-empirical relations considering the design of the jacket and the estimation 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. In real structures, columns are also subjected to bending and horizontal forces due to earthquake. In the current study only the parameters of shear transfer mechanisms examined. For these reasons suitable experimental format selected in order to examine the interface shear transfer mechanisms simulating real structures' loading state. The experimental program held at the Reinforced Concrete Lab at Democritus University of Thrace (D.U.Th.). They contain different percentages of confinement ratio at core and jacket, providing different mean normal stress at the interface.

The load transfer mechanism of shear forces between concrete parts cast at different times results from the combination of three components: cohesion, friction, and dowel action. The quantification of these components is present in all shear-friction design provisions.

The bond strength is controlled by parameters such as surface preparation, weakest concrete strength, shear reinforcement, differential shrinkage, and differential stiffness. The authors experimentally investigated the influence of these parameters on the behavior of composite reinforced concrete (RC) members.

EXPERIMENTAL INVESTIGATION

Old Columns

The experimental investigation includes results of 13 columns of square section with 150 mm width and 500 mm height in scale 1:2 (typical column used in real structures) (Figure 1).In the considered old columns (cores) concrete of 24,37MPa strength was used, commonly used in building structures in the last decades. 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%). All thirteen columns contain closed stirrups spaced at 50mm (mechanical ratio of transverse reinforcement: $\omega_{cc} = 0.15$, 220MPa nominal strength, measured yield stress through tension tests $f_y = 250.76$ MPa), all adequately anchored. The selection of the reinforcement was made according to the minimum percentage of longitudinal reinforcement (approximately 1%) and with 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.

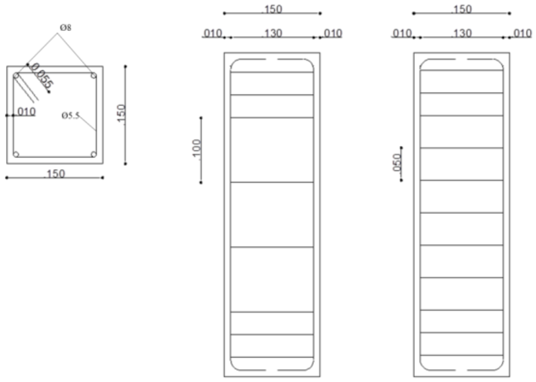


Figure 1.Cores' reinforcement details

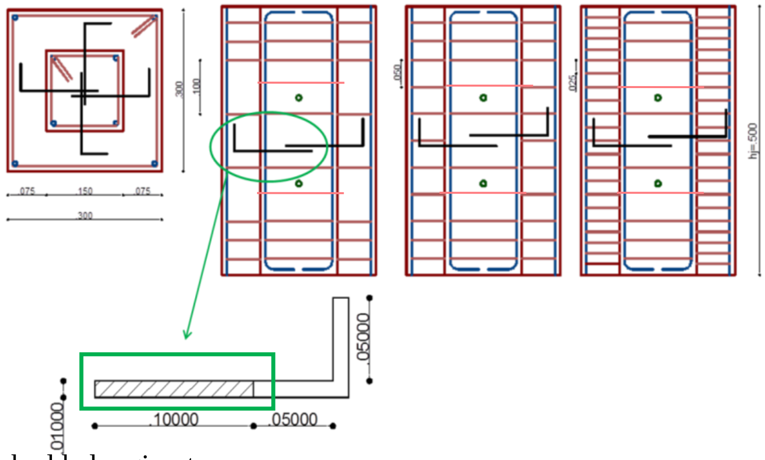
Repair and Retrofit Procedure

All thirteen columns were strengthened with RC jacket of 80 mm thickness (total dimension of width: 310 mm) of high strength concrete (nominal compression strength: fc = 31.52 MPa).

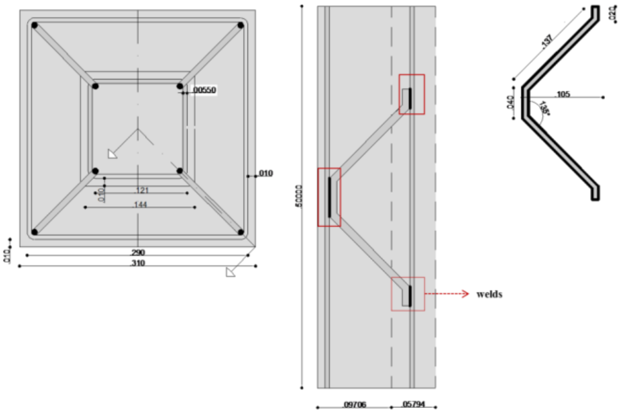
In four columns four (4) welded bend-down bars of diameter 8 mm (500 MPa nominal strength) were placed (Figure 2.) to connect core and jacket and other three columns contained welded bend-down bars of 10mm diameter. The rest three columns contained dowels of diameter 10 mm (500 MPa nominal strength).

Before jacketing, the interface of six specimens was roughened. The use of chipping method as defined at the EN 1504 standard was used. The evaluation of this method in plane concrete is investigated in the past resulting in remarkable outcomes, enhancing the capcity of the element in load terms (Júlio et al. 2005(b), Júlio et al. 2004).

The jacketed section included 4 longitudinal bars of 8 mm diameter and closed stirrups spaced at 25 mm (ω_{cj} = 0,142: mechanical percentage of stirrups, normalized at the confined area of the jacket only), 50 mm (ω_{cj} = 0,071) and 100 mm (ω_{cj} = 0,035), 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 2). Table 1 resumes all specimens' characteristics.



a) Jacketed specimens containing dowels (m)



b) Jacketed specimens containing welded-bend down bars (m)

Figure 2. Reinforcement details of jacketed specimens

Table 1. Specimens' characteristics.

No	Specimens	D_{bwc} (mm)	s_{wc} (mm)	ω_{wc}	D_{bwj} (mm)	s_{wj} (mm)	ω_{wj}	D_b (mm)	D_w (mm)	ρ_{db}	Interface Definition
1	B-S-RcRjDb-6	5,5	50	0,15	5,5	50	0,071	10	-	0,0016	S
2	B-S-RcRjDb-7	5,5	50	0,15	5,5	100	0,035	10	-	0,0016	S
3	B-S-RcRjDb-8	5,5	50	0,15	5,5	25	0,142	10	-	0,0016	S
4	B-S-RcRjDw-9	5,5	50	0,15	5,5	100	0,035	-	8	0,0013	S
5	B-S-RcRjDw-11	5,5	50	0,15	5,5	50	0,071	-	10	0,0021	S
6	B-S-RcRjDbDw-14	5,5	50	0,15	5,5	50	0,071	10	10	0,0037	S
7	B-S-RcRjDw-15	5,5	50	0,15	5,5	25	0,142	-	10	0,0021	S
8	B-R-RcRjDb-1	5,5	50	0,15	5,5	100	0,035	10	-	0,0016	R
9	B-R-RcRjDb-2	5,5	50	0,15	5,5	50	0,071	10	-	0,0016	R
10	B-R-RcRjDb-3	5,5	50	0,15	5,5	25	0,142	10	-	0,0016	R
11	B-R-RcRjDw-5	5,5	50	0,15	5,5	100	0,035	-	8	0,0013	R
12	B-R-RcRjDw-6	5,5	50	0,15	5,5	50	0,071	-	8	0,0013	R
13	B-R-RcRjDw-7	5,5	50	0,15	5,5	25	0,142	-	8	0,0013	R

Notes:

A: Load pattern

S: Smooth interface

R: Rough interface

UR: Unreinforced concrete

R_c: Reinforced core

R_j: Reinforced jacket

$D_{bw\,c}$: Bar diameter of core stirrup

D_{bwj}: Bar diameter of jacket stirrup

S_{wc}: Core's stirrups spacing

S_{wj}: Jacket's stirrups spacing

ω_{wc}: Core's mechanical percentage

ω_{wj}: Jacket's mechanical percentage

Db: Dowels bar diameter

Dw: Welded bars diameter

ρ_{db}: Volumetric percentage of interface reinforcement

The jacketed specimens were subjected to axial compression according to Load Pattern B (Figure 3):

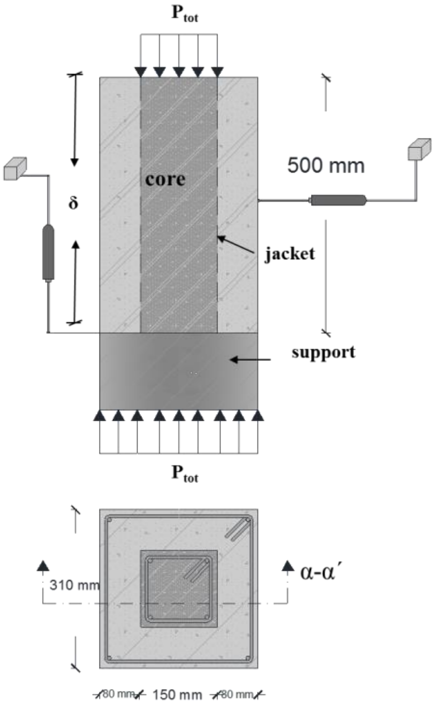


Figure 3. Shape of load pattern.

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 jacket and c) the interface treatment (smooth, rough).

RETROFITTED COLUMNS' EXPERIMENTAL RESULTS

Figure 4 shows the influence of jacket's confinement in smooth interfaces of specimens with dowels containing average percentage of core confinement (ω_{cc} = 0.15). The specimen with the lowest jacket's confinement level (B-S-RcRjDb-7, ω_{cj} = 0.035) presented ultimate normalized load value n = 1.6 at 7 ‰ axial strain. The specimen with doubled level of jacket's confinement (B-S-RcRjDb-6, ω_{cj} = 0.075) presented ultimate normalized load v_{max}=1.68 at 9.45 ‰ axial strain (increased 35% compared with specimen B-S-RcRjDb-7). For even greater jacket's confinement (B-S-RcRjDb-8, ω_{cj} = 0.142) the maximum load is n = 1.83 in 4.0 ‰ normalized axial strain. For axial strain values ranging between 0 and 5 ‰ the bearing load is independent of the jacket's confinement ratio. As shown in Figure 4, as the jacket's confining increases the element's bearing load is not proportionally increased.

Figure 4 shows that due to low and average ratio of jacket's confinement (ω_{cj} = 0.035-0.075) the descending branch presents the same slope (angle b ~ angle c). In case of higher confinement the descending branch is steeper. For middle and high confinement levels, branches overlap in the values of axial strains greater than 15 ‰ (point A). In greater values of axial strain (15 ‰ r 30 ‰ <<), overpassing the boundaries of design and speaking of inelastic axial strains, high confinement levels act favorably on bearing load capacity of concrete elements. Finally, in all specimens, due to the percentage of bearing load, in all range of loading, an upgrade at the overall load capacity of the element is observed. In fact, the total dissipated energy is increased together with the increase of the jacket's confinement ratio up to 36% (B-S-RcRjDb-8-B-S-RcRjDb-6).

Normalized load-axial strain diagram of Figure 5 shows the experimental results in specimens with welded bars. All specimens have the same amount of stirrups in core (ω_{cc}=0.15). Specimen B-S-RcRjDw-9 with low jacket confinement ratio (ω_{cj} = 0.035) bears ultimate axial load v=1.94 in 1.9 ‰ normalized axial strain. Specimen B-S-RcRjDw-11 containing double confinement percentage bears almost the same axial load (n = 1.93) in 30% higher axial strain than specimen B-S-RcRjDw-9. The element with the greater confinement level (B-S-RcRjDw-15, ω_{cj}= 0.142) shows no significant difference in maximum load and axial strain comparing to other elements.

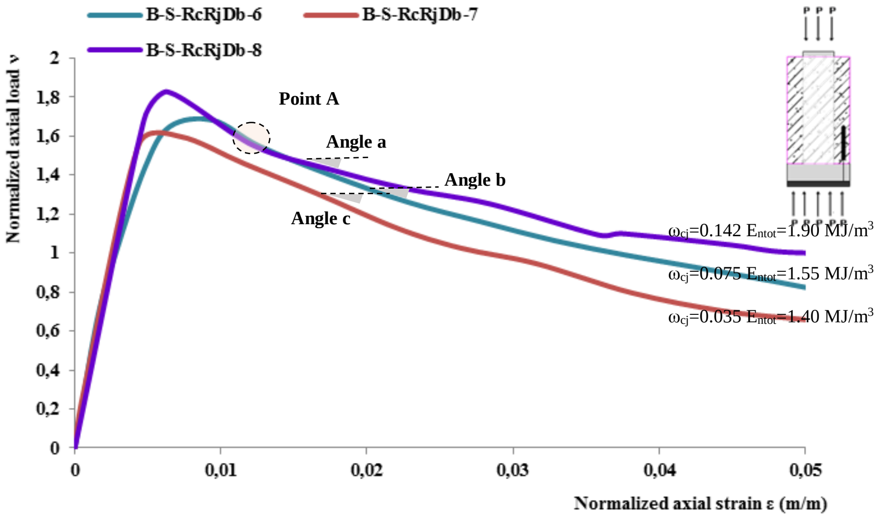


Figure 4. Jacket's confinement influence in smooth concrete interfaces with dowel bars crossing.

The substantial difference of specimens lies in the smaller rate of load reduction as the percentage of stirrups remains in high levels, surpassing the ultimate load. Jacket's confinement seems to affect favorably since in higher ratios the reduction rhythm is lower. In fact, specimens B-S-RcRjDw-9 and B-S-RcRjDw-11 (ω_{cj} = 0.035-0.075) presented intense load reduction after the ultimate point up to 15 ‰ axial strain. After this value of axial strain the load remains practically constant (very slight reduction). This reduction is due to steel buckling of the longitudinal bar of the jacket (Figure 6a). Concentrated stress around the welded bar causes, locally, lateral displacement of the longitudinal bar. Buckling lead to higher reduction levels of axial load. The dense spacing of stirrups (B-S-RcRjDw-11, B-S-RcRjDw-15) offers lateral bracing to the bars and reduces the buckling length (Figure 6b), resulting in lower levels of load reduction.

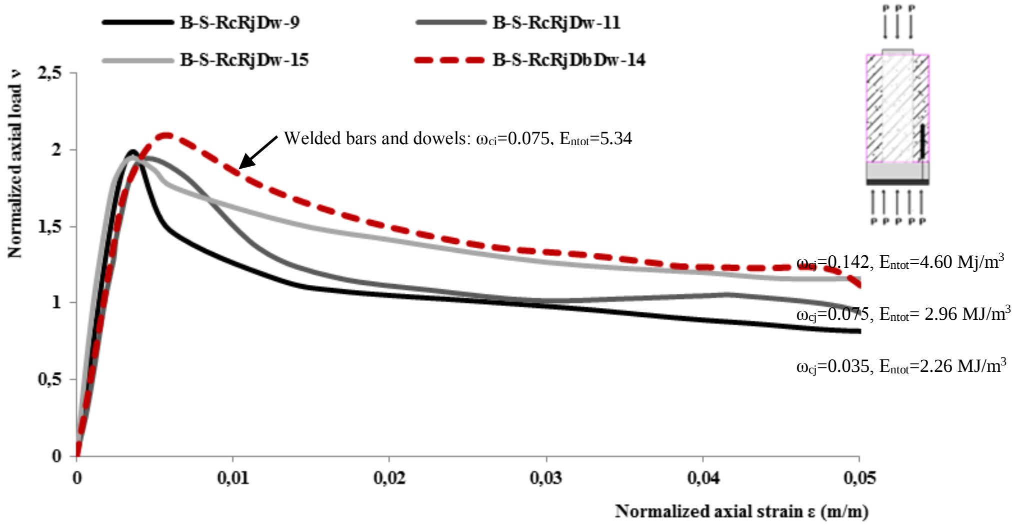


Figure 5. Jacket's confinement influence in smooth concrete interfaces with welded bend down bars.

(α) buckling of longitudinal steel bars of jacketed area (B-S-RcRjDw-7)

(β) buckling of longitudinal steel bars of jacketed area (B-S-RcRjDw-15)

Figure 6. Failure mode- buckling of the longitudinal steel bar of jacket

At the same figure (Figure 5) the mechanical behavior of the specimen containing dowels and welded bars (B-S-RcRjDbDw-14) with average confinement ratio of core and jacket (ω_{cc} = 0.15-ω_{cj} = 0.075) is also presented. The failure mode imposes the incorporation of both dowels and welded bars. According to the international regulations, steel connectors are usually placed as supplementary interface reinforcement bars when dense dowel bars are necessary. The existence of two different types of connectors (B-S-RcRjDbDw-14) works favorably in terms of load. The bearing load is increased by 15% at 60% greater axial strain in comparison with the specimen with no dowels B-S-RcRjDw11. In higher levels of axial strain (ε >20%) there is a negligible difference of the bearing load. In each case there is a clear upgrading of mechanical properties of the strengthened structural element.

In the comparative diagram of Figure 7 the results of specimens with different types of connectors between old and new concrete (core-jacket) are presented. It is observed that the Group of specimens with welded bars presents greater initial stiffness until the maximum load is achieved. After the maximum load value, the rate of load reduction for these elements is higher. Instead, specimens containing dowels show less initial stiffness but lower load reduction rate after the maximum value. The failure mode is different. In the case of welded bars, the jacket's longitudinal bars presents buckling failure in normalized axial strain equal to ε = 0.035. In case of dowels the failure is noted due to the plastic regions of concrete that are created around the dowel bar.

Figure 8 shows experimental results of specimens with rough interface between old and new concrete (core-jacket). Specimen with the lower rate of jacket confinement (B-R-RcRjDb-1, ω_{cj} = 0.035) bearded 1.82 normalized axial load at 4‰ normalized axial strain. The behavior of specimen is brittle, although, there is a clear upgrade of bearing capacity according to the load levels. By doubling the jacket's confinement ratio (B-R-RcRjDb-2, ω_{cj} = 0.075) the ultimate load does not have proportional increase. Specifically, the load remains at the same level but the corresponding axial strain increases 43%. For further increase of jacket's confinement, the normalized axial strain in which the maximum bearing load is observed- augments up to 62.5% (v = 1.84)(B-R-RcRjDb-3, ω_{cj} = 0.142).Though for load values there is no substantial change.

Confinement increase works favorably in terms of load capacity after the peak point. The load reduction rate is lower, while for high levels of confinement, the bearing load is higher in large axial strains (ε >). It is noted that all specimens bear almost constant load for values of axial strain greater than 3%. The residual strength values state the capacity upgrade of the initial element (v> 1).

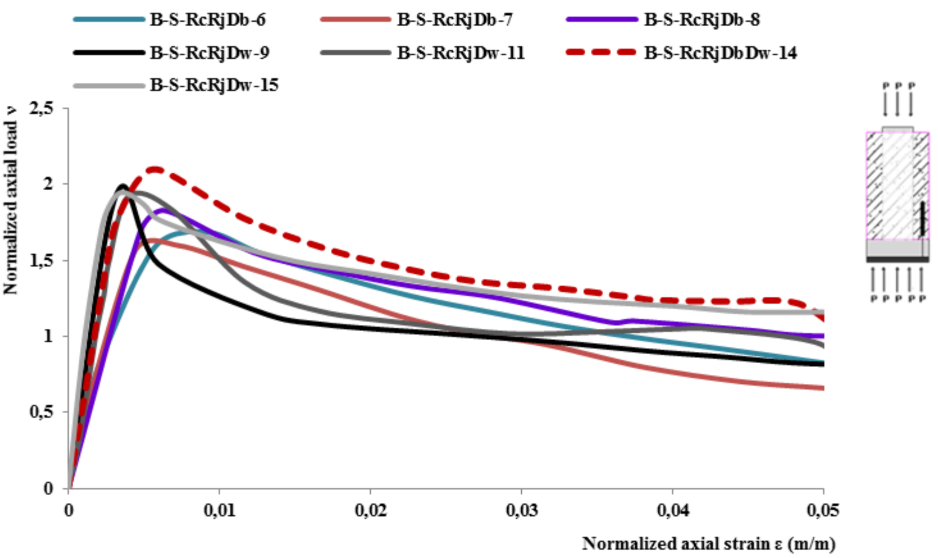


Figure 7. Connector's effect on smooth concrete interfaces.

Figure 9 shows the influence of the jacket's confinement in specimens with rough interfaces that contain welded bars and average core confinement ratio. Specimens with the lower confinement ratio (B-R-RcRjDw-5, $\omega_{cj} = 0.035$) presented ultimate load (ν) = 1.85 at 3.5 ‰ corresponding axial strain. Respectively, specimen B-R-RcRjDw-6 with twice the ratio of jacket's confinement than B-R-RcRjDw-5 ($\omega_{cj} = 0.075$) beard 8% greater load in 60% greater axial strain. In even greater confinement ratios, specimen's maximum normalized axial load was 2.02 (B-R-RcRjDw-7, $\omega_{cj} = 0.142$) in 4.6 ‰ axial strain (10% larger load at 32% greater axial strain comparing to B-R-RcRjDw-5: $\omega_{cj} = 0.035$).

Same as in the case of dowel bars, the increase of confinement, contributes to the rate of load reduction which is lower. What is more, specimens' remaining capacity in large axial strains permits a constant value of carrying load. Load values indicate the upgrade of bearing capacity in all levels of axial strain. In this subgroup, failures happened due to buckling of the jacket's longitudinal bar.

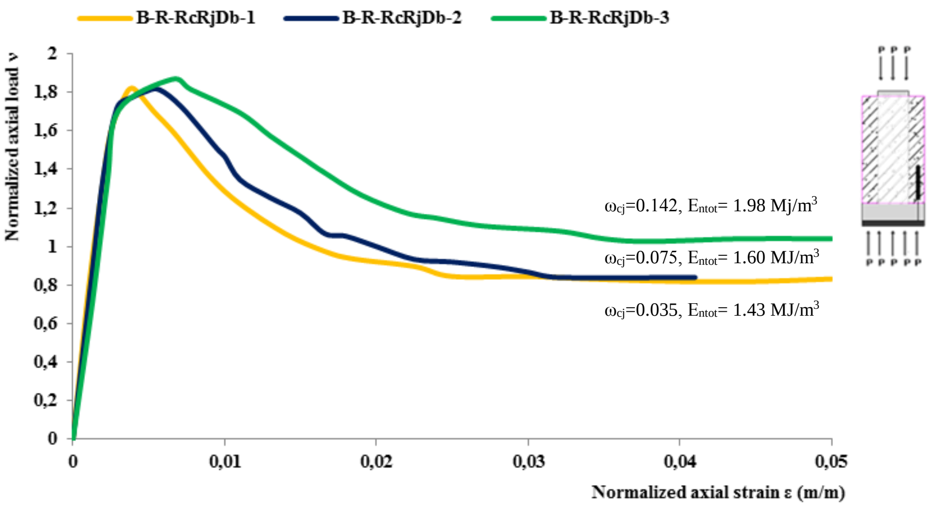


Figure 8. Confinement effect on rough concrete interfaces with dowel bars.

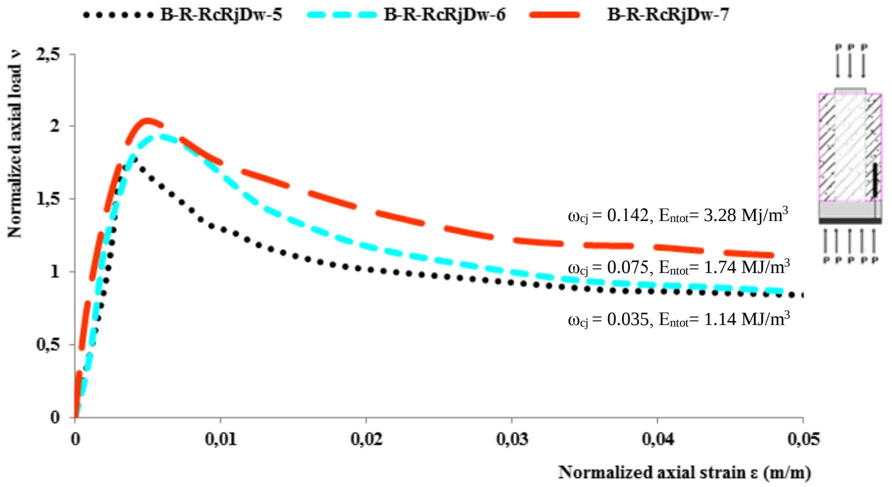


Figure 9. Confinement effect on rough concrete interfaces with welded bars.

The influence of roughing of the interface between old and new concrete shown in diagram of Figure 10. Due to the roughness of the interface the initial stiffness of the element is increased, the brittle failure tends to change, while the axial strain in which the interlock of the aggregate is lost and the rough interface acts as smooth, varies due the confinement ratio.

Figure 11 shows comparatively the influence of different kind of connectors on mechanical behavior of the reinforced structural elements. The type of connector seems not to have a significant influence on the behavior of the specimens. It is concluded, therefore, that the roughness of the interface has a dominant role in the transfer of loads to the reinforced area (jacket) and the remaining capacity of the whole upgraded element.

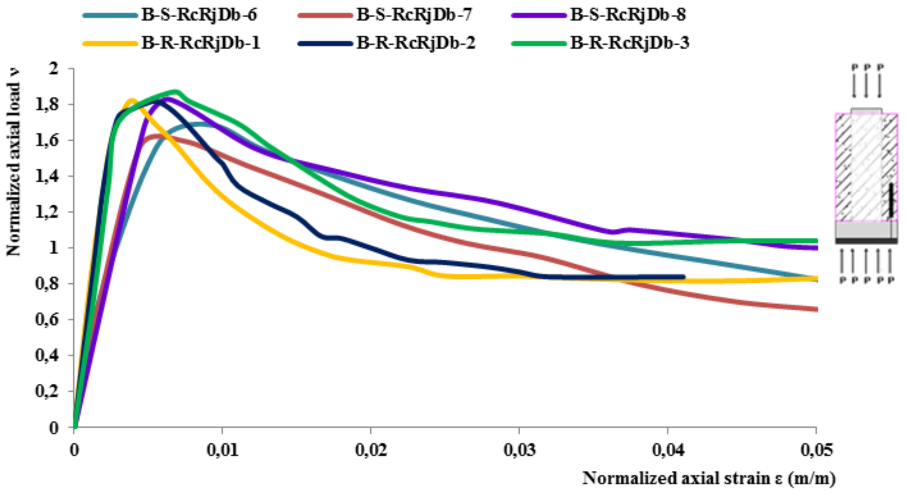


Figure 10. Roughness effect on the interface capacity of strengthened RC elements through RC jackets.

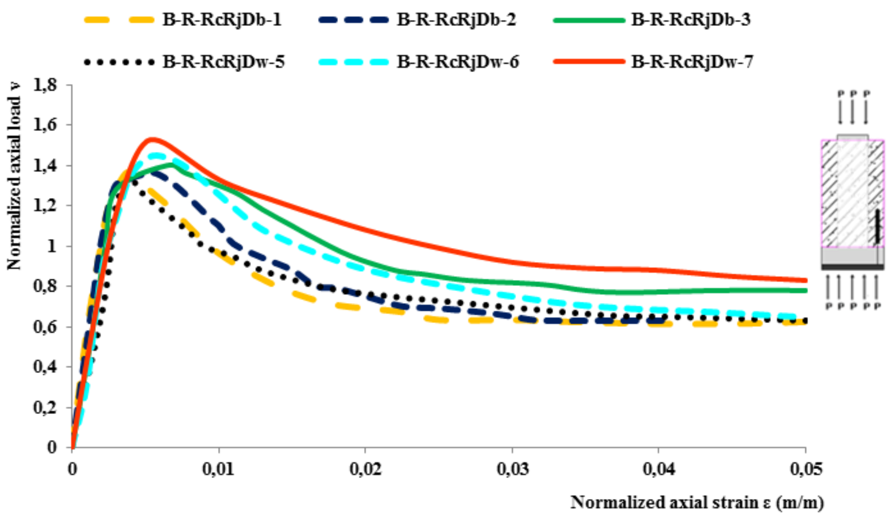


Figure 11. Connector's effect on rough interfaces of strengthened RC elements.

Finally, table 2 summarises the experimental results of the specimens.

Table 2. Experimental results.

No	Specimens	ε_{peak} (‰)	ε_u (‰)	v_{peak} (KN)	v_u (KN)	E_{ntot} (MJ/m^3)
1	B-S-RcRjDb-6	9	50	1,68	0,81	1,90
2	B-S-RcRjDb-7	7	50	1,6	0,66	1,40
3	B-S-RcRjDb-8	6	50	1,82	1	1,55
4	B-S-RcRjDw-9	3,1	50	2,05	0,85	2,26
5	B-S-RcRjDw-11	5,4	50	1,88	0,95	2,96
6	B-S-RcRjDbDw-14	6,1	50	2,09	1,2	3,34
7	B-S-RcRjDw-15	3,5	50	1,95	1,16	4,60
8	B-R-RcRjDb-1	4	50	1,81	0,84	1,43
9	B-R-RcRjDb-2	6,5	50	1,86	0,84	1,60
10	B-R-RcRjDb-3	7,8	50	1,81	1.03.	1,98
11	B-R-RcRjDw-5	4	50	1,77	0,83	1,14
12	B-R-RcRjDw-6	6,4	50	1,44	0,65	1,74
13	B-R-RcRjDw-7	5,8	50	2,01	1,1	3,28

CONCLUSIONS

To conclude, the experimental investigation has resulted in the following remarks:

- The existence of different kind of connectors (dowel or welded bars) leads to different kind of failure modes. Specimens with dowel bars present plastic regions around the connectors' bars, while specimens with welded connectors end to the buckling of longitudinal steel bars.
- The augmentation of jackets' confinement and the produced normal stress at the interface of old and new concrete decreases the load reduction rate after the peak load.
- Roughening of the interface through chipping ends up to increased initial stiffness.
- The element's capacity is upgraded in all cases and values of axial strains.

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