Force transfer between existing concrete columns with reinforced concrete jackets subjected to axial loading.

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SUMMARY:
The study presents the results of an experimental program concerning the force transfer between reinforced concrete (RC) jackets and existing columns. It includes 16 columns (core) of low concrete strength (f_c= 24,37 MPa) with square section (150 mm side, 500 mm height, and scale 1:2). Fourteen columns have full jacketing at all four faces with 80 mm thickness and contain longitudinal bars and closed stirrups spaced at 25 mm, 50 mm or 100 mm. Twelve specimens contain dowels between the interface of old and new concrete. Ten columns have initial (construction) damages. All columns are subjected to repeated (pseudo-seismic) axial compression with increasing deformation cycles up to failure. The effects of the initial damages, of the reinforcement of the interface (dowels) and of the confinement generated by the stirrups are investigated through their axial force-deformation (slip) diagrams.

Keywords: Force transfer, concrete jacket, dowels, interface, initial damage

1. INTRODUCTION

Strengthening of columns through reinforced concrete (RC) jacketing is widely applied (Rodriguez et al., Julio et al.) during last decades. RC jacketing has been proven an efficient method to enhance the axial load capacity and strain at failure of concrete. The efficiency of jacketing depends strongly on the behaviour of the interface of old and new concrete and of its capacity in transferring loads. The shear transfer mechanisms are concrete-to-concrete cohesion and friction (aggregate interlock) (Tasios et al., 1987, Walraven 1988), and dowel action (Vintzileou et al., 1987). The load transfer has been studied (analytically or experimentally) thoroughly and suggestions are made about how every mechanism works (Vintzileou 1986, Tasios 1986). All these suggestions have been incorporated in various codes world-widely such as *fib* (Model Code 2010), and ACI-318R-08 Building Code, Greek Retrofit Code (Table 1.1). These mechanisms are investigated separately or in combination through an experimental program held at the Reinforced Concrete Lab at Democritus University of Thrace (D.U.Th.) which includes 57 specimens with different percentages of transverse reinforcement at core and jacket as well as different treatment of the interface between old and new concrete. Also, the factor of initial damage due to construction imperfections that is not referred and analysed thoroughly/ extensively in the various codes. In the current paper, a part of this program is presented that includes 16 jacketed columns: nine columns with and seven without initial damages.

2. SPECIMENS' CHARACTERISTICS

This part of the experimental program included results of 16 columns of low strength concrete (average compressive strength f_c=24,37 MPa, modulus of Elasticity E_c=24,4 GPa and maximum d_{AGR}=32 mm) of square section (150x500 mm) in scale 1:2. They were subjected to repeated axial compression up to failure. The research included also 2 plain concrete columns (UR33, UR34). All columns contained 4 steel bars of 8 mm diameter with 500 MPa nominal yield stress. Seven of them had stirrups of 5,5 mm diameter spaced at 50 mm and the rest six had stirrups spaced at 100 mm, adequately anchored. Ten out of sixteen columns had initial construction damages (figure 2.1, 2.3). All seven columns were subjected to initial axial loading (pre-loading). Four of them were pre-loaded repeatedly and two monotonically. All damaged columns were repaired with high strength thixotropic type concrete (EMACO S-55). The specimen details are included in Table 2.1.

Table 2.1. Details of Specimens

Specimen	Load Case	Dowels	Longitudinal Reinforcement (Core/Jacket)	Transverse Reinforcement		Repair of Core with Initial (structural) damage (EMACO)	Coating with resin	Pre-Loading of Core
				Core	Jacket			
UR32	4	6Ø10	0	0	0	NO	NO	N0
UR33	-	NO	0	0	0	NO	NO	N0
UR34	-	NO	0	0	0	NO	NO	N0
14	1	6Ø10	4Ø8/4Ø8	Ø5,5/5	Ø5,5/2,5	YES	YES	NO
19	1	6Ø10	4Ø8/4Ø8	Ø5,5/10	Ø5,5/10	YES	YES	YES
26	1	6Ø10	4Ø8/4Ø8	Ø5,5/10	Ø5,5/10	NO	NO	YES
16	2	6Ø10	4Ø8/4Ø8	Ø5,5/10	Ø5,5/10	YES	YES	YES
18	2	NO	4Ø8/4Ø8	Ø5,5/10	Ø5,5/5	NO	YES	YES
22	2	6Ø10	4Ø8/4Ø8	Ø5,5/10	Ø5,5/5	YES	YES	YES
24	2	6Ø10	4Ø8/4Ø8	Ø5,5/10	Ø5,5/10	YES	YES	YES
6	3	6Ø10	4Ø8/4Ø8	Ø5,5/5	Ø5,5/10	YES	YES	YES
2	4	NO	4Ø8/4Ø8	Ø5,5/5	Ø5,5/10	YES	YES	YES (Repeated)
5	4	6Ø10	4Ø8/4Ø8	Ø5,5/5	Ø5,5/2,5	YES	YES	YES (Repeated)
7	4	6Ø10	4Ø8/4Ø8	Ø5,5/5	Ø5,5/5	YES	YES	YES (Repeated)
8	4	6Ø10	4Ø8/4Ø8	Ø5,5/5	Ø5,5/5	NO	NO	YES
10	4	6Ø10	4Ø8/4Ø8	Ø5,5/5	Ø5,5/10	NO	NO	YES

All columns (cores) were strengthened with RC jacket (of 80mm thickness) of high strength concrete (f_c=31,52 MPa, E_c=31,6 GPa, d_{AGR}=8 mm) which included 4 longitudinal bars of 8 mm diameter and closed stirrups spaced at 25 mm, 50 mm and 100 mm, again of 220 MPa nominal yield stress.

Figure 2.1.
Specimen with construction (initial) damages

Figure 2.2.
Core with dowels: 6Ø10

Figure 2.3.
Specimen without damages

Figure 2.4: Experimental Setup

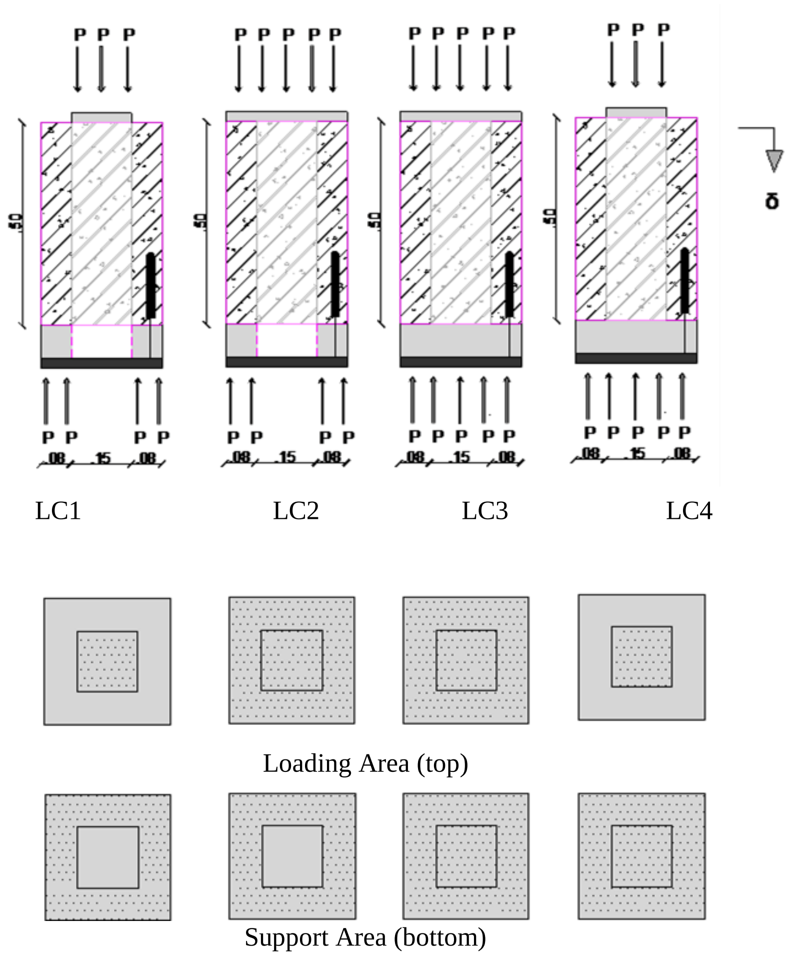


Figure 2.5: Load Cases

In twelve out of sixteen columns 6 dowels of 10mm diameter were placed (Figure 2.2) with injected cementitious grout of very small particle size and thixotropic consistency (steady expansion grout), (Sika Ancorfix3). Finally, ten columns were coated with resin of two-component without solvents (Sikadur-32N, LP), so as to achieve adequate adhesion between old and new concrete.

The axial loading is applied in a compression machine with a capacity of maximum load 3000 KN, and the ability to fit specimens with maximum height 950 mm and maximum side 310 mm (figure 2.4). Four different load cases are investigated as shown in figure 2.5.

- **Load Case 1 (LC1):** 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 Case 2 (LC2)**: Direct loading of the jacket section only, while the retrofitted column is supported both in core and jacket. The mechanical behaviour of the jacket is investigated as part of the retrofitted element (core and jacket).
- **Load Case 3 (LC3)**: Direct loading of both core and jacket in order to investigate the mechanical behaviour of the jacketed column considering monolithic behaviour.
- **Load Case 4 (LC4)**: 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).

The deformations of the column come out from the measurement of the relative displacements between the two loading platens with the use of one Linear Variable Displacement Transducer, shown in figure 2.5

Thus, the current experimental program considers the following parameters: a. kind of connection of core and jacket: cohesion, epoxy glue, dowels and anchor, b. percentage of transverse reinforcement of core and jacket, c. type of loading- Load Cases, d. the initial damages.

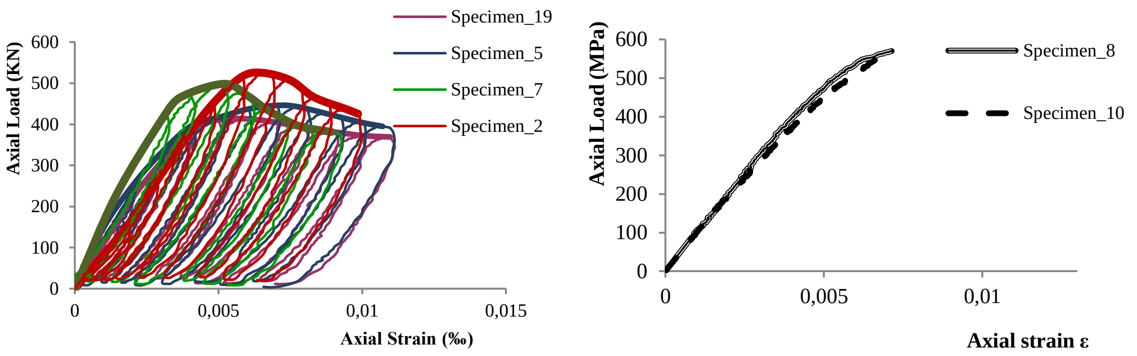
3. Influence of Initial Damage

The initial damages refer to: Construction damages (I) and damages due to loading (pre-loading) of core, repeatedly or monotonically (II).

3.1. Construction Damages/ Pre-Loading

The construction damages simulate the effect of poor consolidation of concrete with large size of aggregate observed in some cases in construction joints. For these purposes, concrete of nominal strength f_c=24,37MPa with d_{AGR}=32mm was used. The consolidation took place without all the necessary provisions. After removing the formworks the active height and active section of each specimen was calculated. Finally, the specimens were repaired with high strength thixotropic type concrete (EMACO-S55) before jacketing.

Seven columns were subjected to initial loading (pre-loading), two of them without construction damages, so as to create loading damages. Specimens no 8 and no 10 were subjected to axial loading monotonically to maximum axial load (ε_{pr-l}^{max}=6‰) before jacketing (figure 6b), while specimens 2, 5, 7 and 19 were subjected to pre-loading repeatedly at maximum strain ε_{pr-l}= 10‰ (cycles of 0,5‰ axial strain) (figure 3.1.1a and 3.1.1b).



(a) (b)

Figure 3.1.1. (a) Axial load- axial strain diagram of specimens subjected to repeated pre-loading. (b) Axial load- axial strain diagram of specimens subjected to monotonic pre-loading.

3.2. Definition of Damage Index

In order to define the percentage of initial damaged caused to the columns, an equal damage indicator d_{equ} (expr.3.2.1) is adopted consisted by two individual ones, d_s referring to the penetration of damage in the section and d_h referring to the expansion of damage axially.

$$d_{equ} = 1 - [(1 - d_s) \cdot (1 - d_h)] \qquad \text{(expr.3.2.1)}$$

The indicator d_s referring to the section is a quotient/percentage of the damaged area (f_1) to the original section area (f_{tot}) (expr. 3.2.1a), as shown in figure 3.2.2(a).

$$d_s = \frac{f_1}{f_{tot}} \qquad \text{(expr.3.2.1a)}$$

The indicator d_h referring to the height is a quotient/percentage of the damaged height (h_1) to the original height (h_{tot}) (expr. 3.2.1b), as shown in figure 3.2.2(b).

$$d_h = \frac{h_1}{h_{tot}} \qquad \text{(expr.3.2.1.b)}$$

Indicatively, figure 3.2.2 (c), (d) show the columns with structural damages and table 3.2.1 resumes all the calculated damage indicators. The effect of initial damages is shown in figure 3.2.1.

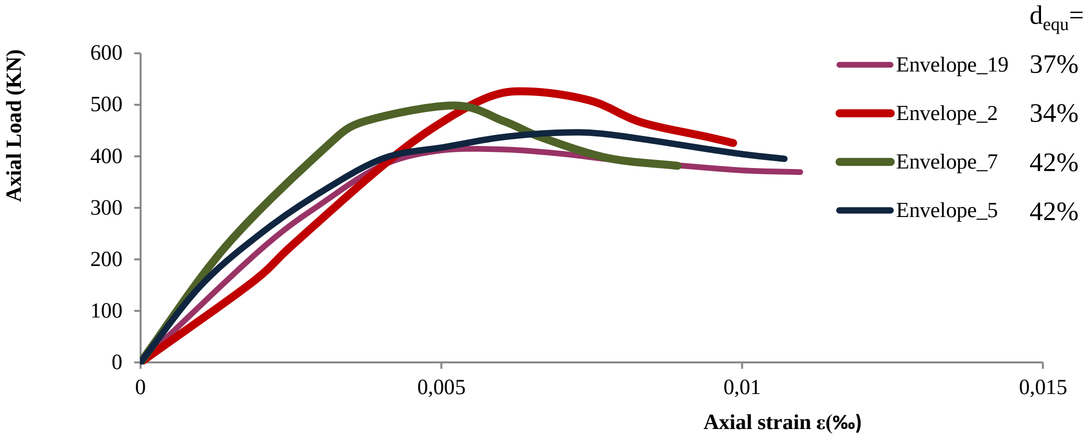


Figure 3.2.1. Envelopes of axial load- axial strain diagram of specimens subjected to repeated pre-loading with different percentage of initial (construction) damages.

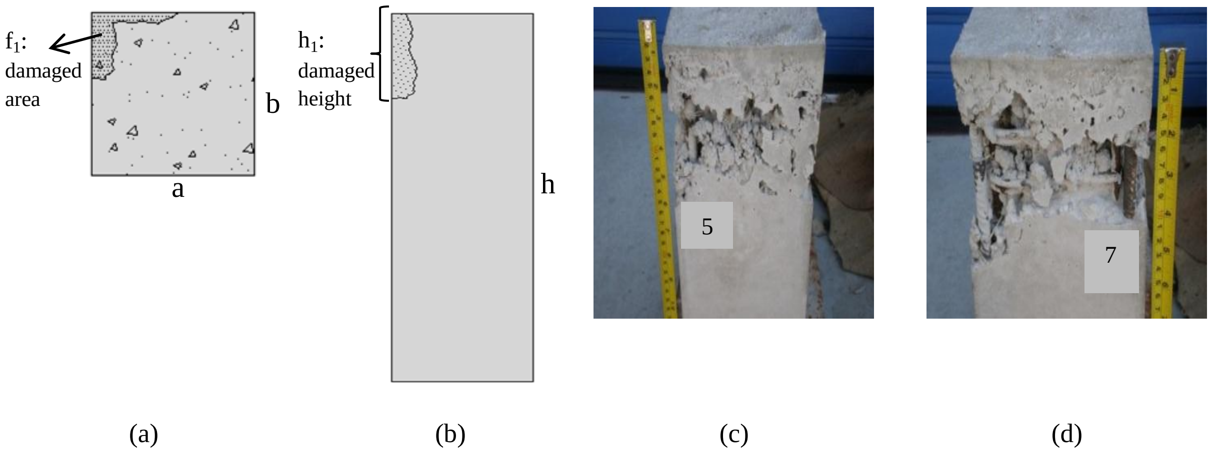


Figure 3.2.2. (a) Section index, (b) Height index, (c) Structural initial damages of specimen 5 (d) Structural initial damages of specimen 7

Table 3.2.1 Damaged Index

Specimen	d_s (%)	d_h (%)	d_{equ} (%)
2	13	24	34
5	25	28	41
6	37	26	50
7	31	22	41
14	25	20	36
16	25	10	31
19	31	14	37
22	25	14	33
24	13	14	24

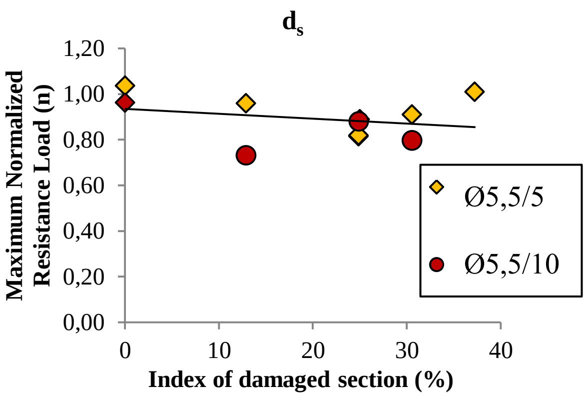


Figure 3.2.3. Maximum normalized resistance load versus section damage index (n-d_s)

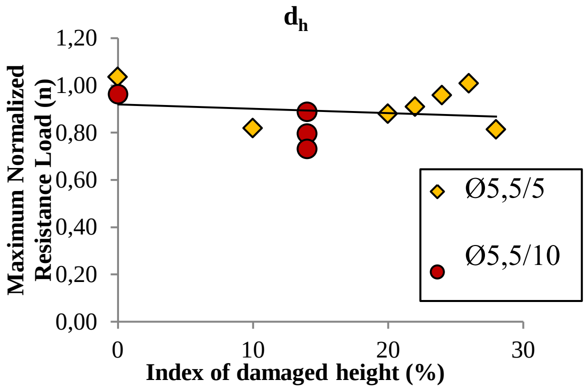


Figure 3.2.4. Maximum normalized resistance load versus height damage index (n-d_h)

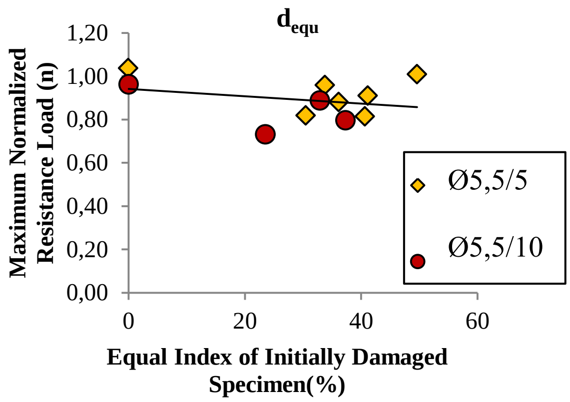


Figure 3.2.5. Maximum normalized resistance load versus equal damage index (n-d_{equ})

Figure 3.2.3, 3.2.4 and 3.2.5 show the maximum normalized resistance load of core versus the percentage of the damage of the section d_s, the percentage of the damage of the height d_h and the equal damage d_{equ} respectively. The maximum resistance load in all occasions is normalized to the total section (A_c=150x150mm) and to the nominal concrete strength f_c according to expression 3.2.1 c.

$$n = \frac{P}{A_c \cdot f_c} \qquad \text{(expr. 3.2.1 c)}$$

Figures 3.2.3 and 3.2.4 show high dispersion and testify the need of the combination of the two indexes to the equal index in order to predict the resistance load accurately, which is also confirmed from figure 3.2.5. Figure 3.2.5 shows that the damaged cores present lower resistance load than the ones without damages which means that the damage was not fully repaired. Also, minor damages do are not necessarily effectively repaired.

4. RESULTS

Table 4 shows that specimens 14, 19, 26 are subjected to Load Case 1 (figure 4.1), specimens 16, 18, 22, 24 to Load Case 2 (figure 4.4), specimen 6 to Load Case 3 (figure 4.5) and finally specimens 2, 5, 7, 8, 10, 32 to Load Case 4 (figure 4.6). The envelopes of the results of the cyclic test are shown in figures 12, 15, 16, 17 and in Table 4. It is noted that in Load Case 1 and 4 the columns were tested in high levels of axial displacements that are not feasible to the real structures. The diagrams presented above are terminated to the levels of displacements of Load Case 2 and 3 for comparison reasons. Table 4, though, includes all 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%P_{max}) and E_n is the total absorbed energy normalized to the volume of the core. All deformations are the relative displacements of the two loading plates at the top and bottom of the specimens as shown in figure 5.

In Load Case 1(figure 4.1) specimen 26 with mechanical percentages of stirrups in core and jacket (normalized at the confined area of the jacket only and calculated with the measured yield stress of the steel bar f_y=250,76 MPa) ω_{wc}=0,075 and ω_{wj}=0,46 respectively, presented maximum bearing load 452,63 KN at 1,32 mm slip (for LC1 deformation equals slip). As a result, damage due to pre-loading affected the jacketed column's load capacity in compression since the load is lower 14% than that of the core alone (528,59 KN). Specimen 19 with the same percentages of transverse reinforcement both in core and jacket which had 37% initial damage (d_{equ}) and was repaired and coated with resin before jacketing presents higher maximum load 782,21 KN at 1,50 mm slip, that is 30% higher load than specimen 26 in 12% higher values of slip. Fact that leads to consider the repair and the use of coating of the specimen effective. Specimen 14 contained the highest percentage of stirrups of all specimens (ω_{wc}=0,15 and ω_{wj}=1,86) and appeared maximum load 897,27 KN at 1,86 mm slip. This shows that the confinement mechanisms were activated and contributed to the load capacity and the resistance of the interface in slip. It is noted that the maximum values of bearing load happened in values of slip from 1,32 mm to 1,86 mm, values of slip in which cohesion is considered to be lost (marked in figure 4.1 for specimens 14 and 19). After that, specimens 14 and 26 remain to a rather stable friction resistance. On the other hand specimen 19 presents a descending branch after maximum load. Figure 4.2 shows a cut of the specimen 14 after loading and in figure 4.3 is shown the opening of the stirrups at the end of loading.

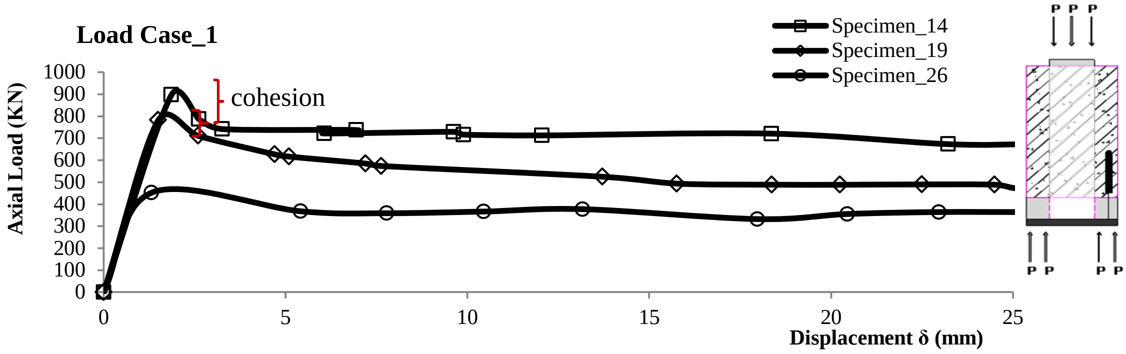


Figure 4.1. Results of Load Case 1

Figure 4.2 : Cut of jacketed specimen 14 after loading- dowel deformation

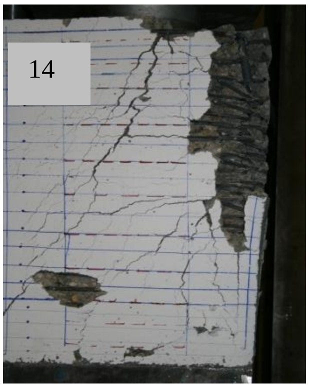


Figure 4.3: Jacketed specimen 14 after loading- opened stirrups

In Load Case 2 (figure 4.4) specimen 16 with the lowest percentages of stirrups (ω_{wc}=0,075 and ω_{wj}=0,46) and equal damage index d_{equ}=31% shows maximum capacity load 1787,91 KN at 8,60 mm slip. Specimen 22 with double percentage of stirrups and same level of initial damages (d_{equ}=33%) had maximum bearing load 2107,64 KN at 7,40 mm slip. That is 15% higher load than specimen 16 at 14% lower slip. This means that the confinement was not fully activated but contributed to the resistance of the interface. Specimen 24 had the highest maximum load of this load case at 2211,15 KN in 13 mm slip. Specimen 24 had lower equal damage index (d_{equ}=24%) than 22 (d_{equ}=33%) and 16 (d_{equ}=33%) and in comparison 5% and 20% higher load in 43% and 33% increased slip respectively. This practically means that the damage was restored fully and repair was effective since it took higher load with lower stirrup percentages. Specimen 18 presented maximum bearing load 2187,66 KN at 10 mm slip. That is 4% higher load than specimen 22 at 26% increased slip. This means that the initial construction damages of specimen 22 (d_{equ}=33%) affected the load capacity. Also, the lack of dowels in specimen 18 leads to higher slip. This does not happen to specimen 22 with dowels. Finally, comparing to a monolithic jacketed column the maximum load in pure compression is not achieved (calculated theoretical maxP_{cr}=3041,05 KN- 27% decreased). Yet, the values of maximum load are higher than the corresponding of Load Case 1 (60% increased) due to the activation of confinement even if it doesn't act fully.

Load Case 3 (figure 4.5): The maximum load of specimen 6, that is 2111,24 KN in 3,75 mm slip, appears decreased than the one expected as a monolithic element in pure compression (calculated theoretical maxP_{cr}=3041,05 KN, 30% decreased). This points out the influence of the initial construction damage to the carrying load of the retrofitted column and that the repair was not fully successful. It's worth noticing that the loading level approaches that of Load Case 2.

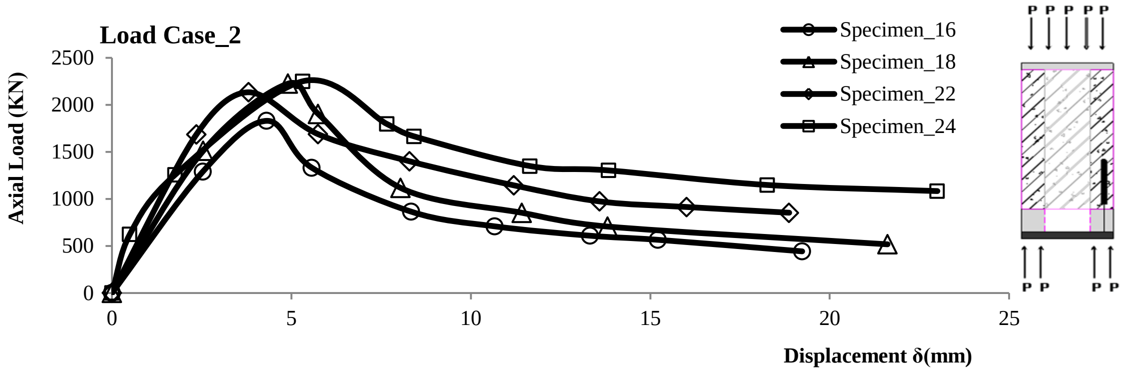


Figure 4.4. Results of Load Case 2

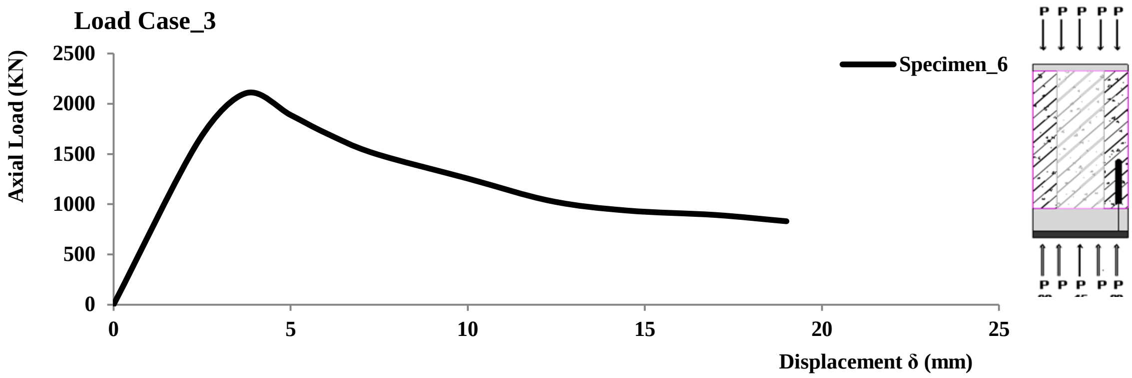


Figure 4.5. Results of Load Case 3

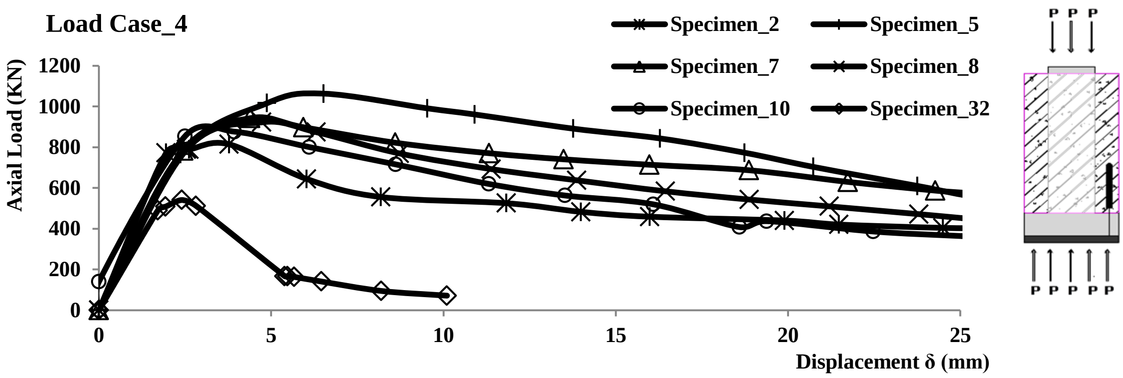


Figure 4.6. Results of Load Case 4

In Load Case 4, specimen 2 with no dowels shows maximum bearing load 814,22 KN at 3,78 mm slip. Specimen 10 containing dowels appeared maximum bearing load 876,38 KN at 2,50 mm slip, 7% higher load than specimen 2 at 34% lower slip (figure 4.6). Specimen 32 containing only dowels, shows 540,67 KN maximum load at 2,41 mm slip. The presence of dowels affects the maximum load in small levels but increases the resistance of interface to slip. Specimen 5 with damage index (d_{equ}=41%) containing the highest percentages of transverse reinforcement of the jacket (ω_{wc}=0,15 and ω_{wj}=1,86) presents the highest bearing load in this Load Case, 1062,98 KN at 6,52 mm slip. Specimen 7 (d_{equ}=41%) had maximum load 942,43 KN at 4,73 mm slip. Specimen 8, without initial construction damages, took 922,33 KN at 4,73 mm (42% increased comparing to the maximum pre-load). That is, the restore and repair of the initial damages as well as the coat of resin of specimen 7 was effective (2% for the load and 7% considering slip).

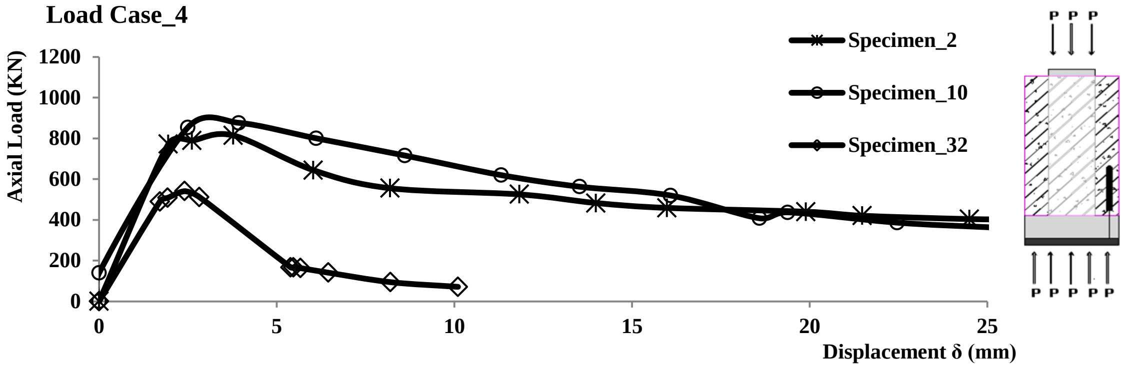


Figure 4.7. Influence of Dowel action

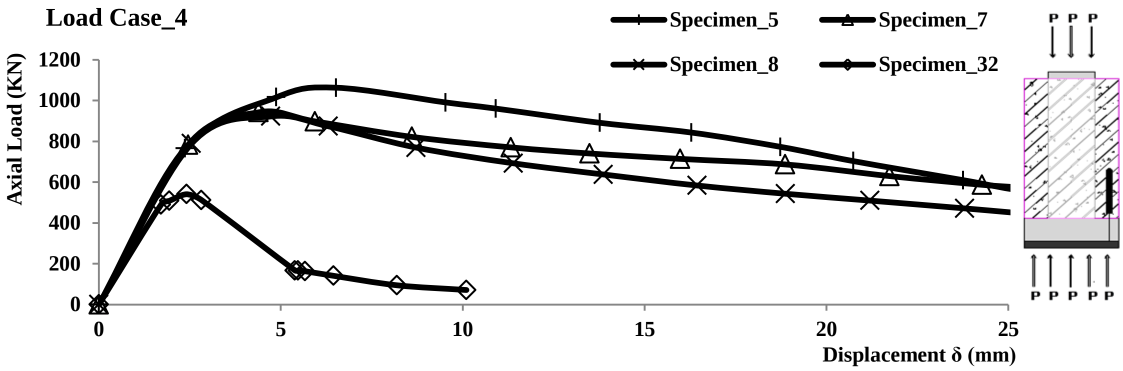


Figure 4.8. Influence of jacket confinement

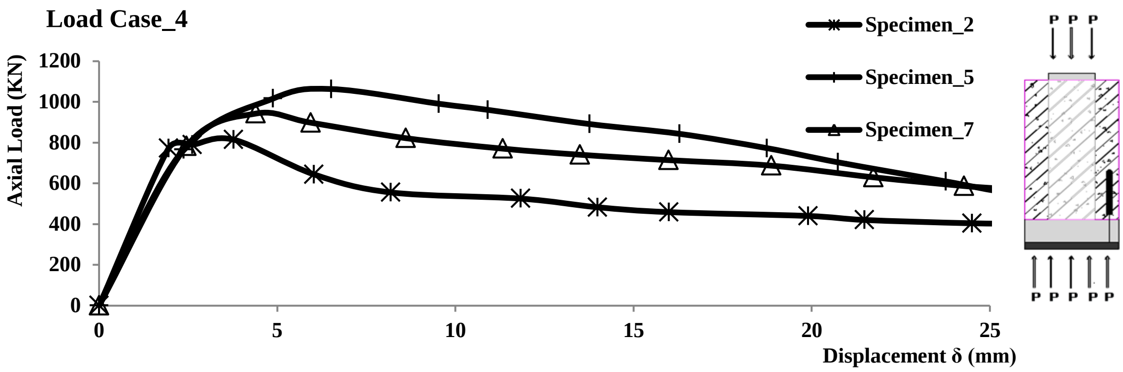


Figure 4.9. Influence of initial damage to the effectiveness of the retrofitted column

Also, the influence of confinement is obvious in figure 4.8. Specimen 5 had 11%, 32% and 49% higher load comparing to specimen 7, 8 and 32 at 33%, 27% and 63% increased slip respectively. The mechanisms of confinement were activated, yet not fully, compared to a monolithic element (figure 4.6). The values of the bearing load appear similar to those of Load Case 1. Figure 4.9 shows that specimen 5 (d_{equ}=41%) and specimen 7 with the same equal damage index presented 23% higher bearing load and 14% at 42% and 14% increased slips compared to specimen 2 (d_{equ}=34%), respectively. Again, the repair was effective.

Table 4. Test Results

Specimen	R.C. CORE (pre-loading)				R.C. JACKETED				
	δ_{peak} (P_{max}) (mm)	δ_u (P_u=20%P_{max}) (mm)	P_{max} (KN)	E_n (MJ/m^3)	Load Case	δ_{peak} (P_{max}) (mm)	δ_u (P_u=20%P_{max}) (mm)	P_{max} (KN)	E_n (MJ/m^3)
33	6,30	7,60	563,15	0,10	-	-	-	-	-
34	5,00	5,30	465,62	0,07	-	-	-	-	-
14	5,80	11,00	482,73	0,18	1	1,86	70,38	897,27	3,45
19	3,00	5,45	436,97	0,15	1	1,50	62,00	782,21	2,20
26	6,40	6,60	528,59	0,09	1	1,32	72,41	452,63	2,07
16	7,00	12,00	448,69	0,17	2	8,60	40,00	1787,91	0,35
18	7,60	10,00	523,66	0,15	2	10,00	45,00	2187,66	0,67
22	6,90	10,00	487,08	0,15	2	7,40	39,00	2107,64	0,66
24	7,10	12,00	401,20	0,16	2	13,00	74,00	2211,15	0,74
6	7,00	10,00	553,29	0,15	3	3,75	36,00	2111,24	0,70
2	3,25	4,92	525,49	0,13	4	3,78	52,23	814,22	1,79
5	3,90	5,45	441,9	0,18	4	6,52	50,95	1062,98	2,90
7	2,60	4,45	498,45	0,16	4	4,39	49,23	942,43	2,14
8	3,50	3,50	532,7	0,10	4	4,73	43,38	922,33	2,14
10	3,50	3,50	533,00	0,13	4	2,50	44,60	876,38	1,90
32	-	-	-	-	4	2,41	10,10	540,67	0,16

5. CONCLUSIONS

The present study focuses on the effect of the initial damages of core to the final bearing load of the jacketed column. Due to initial (construction) damages the loading capacity is decreased and the deformation ability is affected. Suitable repair of damaged core can lead to increased maximum transferred load through the interfaces. The load capacity of the jacketed column is affected more from the initial damages and less from the pre-loading ones. The different Load Cases 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. Initial construction damages reduce the ability of the element to act as monolithic even when suitably repaired. Though, the more extensive is the damage and the repair of it, the better is the final behaviour of the column. As a result, an accurate model is required to quantify and predict the behaviour of the jacketed column in terms of damages, load capacity and deformation

6. ACKNOWLEDGEMENTS

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