DUCTILITY UPGRADE RETROFITTING SOLUTIONS FOR REINFORCED CONCRETE COLUMNS. EXPERIMENTAL STUDY

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SUMMARY

The results presented in this paper are obtained from a test program for columns implemented in the Structural Testing Laboratory of the National Center for Seismic Risk Reduction at Technical University of Civil Engineering of Bucharest, Romania. One objective of this experimental work is to study about the influence of the transversal and longitudinal reinforcement ratio on the ultimate displacement and shear capacity of jacketed reinforced concrete columns. The analyzed specimens represent the old buildings columns constructed before the implementation of the first Romanian seismic design code. These columns are characterized by a low ductility mainly due to the high intensity of axial load and the poor transversal reinforcement ratio (usually less than 0,001). A widely used procedure in Romania for retrofitting this type of columns is the reinforced concrete jacketing. Usually this procedure is used both for shear and flexural capacity improvement (having continuous longitudinal reinforcement trough joints). If only shear capacity and ductility upgrade is intended no continuous longitudinal reinforcement is necessary for reinforced concrete jackets. Also other types of materials can be used for the jackets (e.g. steel, FRP), which can diminish the building occupancy disruption during the construction work. The results of an experimental study for various retrofitting techniques are presented in this paper.

INTRODUCTION

This paper presents some results of an extended experimental and theoretical study on reinforced concrete (RC) columns designed and detailed according to Romanian practice before 1977 Vrancea earthquake. This study aims to identify the appropriate methods for evaluation and retrofitting. The Romanian old type columns are characterized by very low transversal reinforcement ratios and high axial force ratios. Due to this, in many cases the existing RC columns have a low displacement and energy dissipation capacity. As a direct consequence fragile shear failures can appear. In this study three ductility upgrade retrofitting methods have been analyzed: RC jacketing, carbon fiber wrapping and steel jacketing.

TESTED SPECIMENS

In this paper the results obtained on eight testing specimens are described and analyzed. The name of the specimens and their main characteristics are presented in table 1. Specimen C5 represents the original unretrofitted old type column. It is characterized by a low concrete quality, with a mean compressive strength of 18MPa, and an axial force ratio of 0.4 (computed using the mean strength). The transversal reinforcement ratio is 0,075% and the longitudinal reinforcement ratio is 0,96%.

Specimen, C9, was obtained by retrofitting specimen C5. RC jacketing has been considered for retrofitting. Since only the increase in the shear capacity has been intended, gaps were provided at both ends of the jacket (2 cm wide). The shear reinforcement ratio has been increased from 0.075% to 0.56% while the flexural capacity has not been significantly modified. The amount of additional transversal reinforcement corresponds to the

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current code requirements. Specimen, C8, has been derived from specimen C9 by increasing the longitudinal reinforcement ratio in order to obtain shear failure and consequently the shear capacity. The RC jacketed columns (C8 and C9) were constructed in two steps. At first the original column was cast and, in the second step, the additional transversal reinforcement (ϕ8/60) was arranged. A 70 mm thickness concrete jacket was pored. ϕ8/60 stands for the 8mm diameter steel bar stirrups spaced at s_h=60mm. The additional stirrups were positioned at the middle of the concrete jacket. The position of the 20 mm gap at column' ends can be observed in figure 1. The RC jacket was applied on the unloaded columns. The difference between these tested columns and real retrofitting cases has been assumed due to technological limitations.

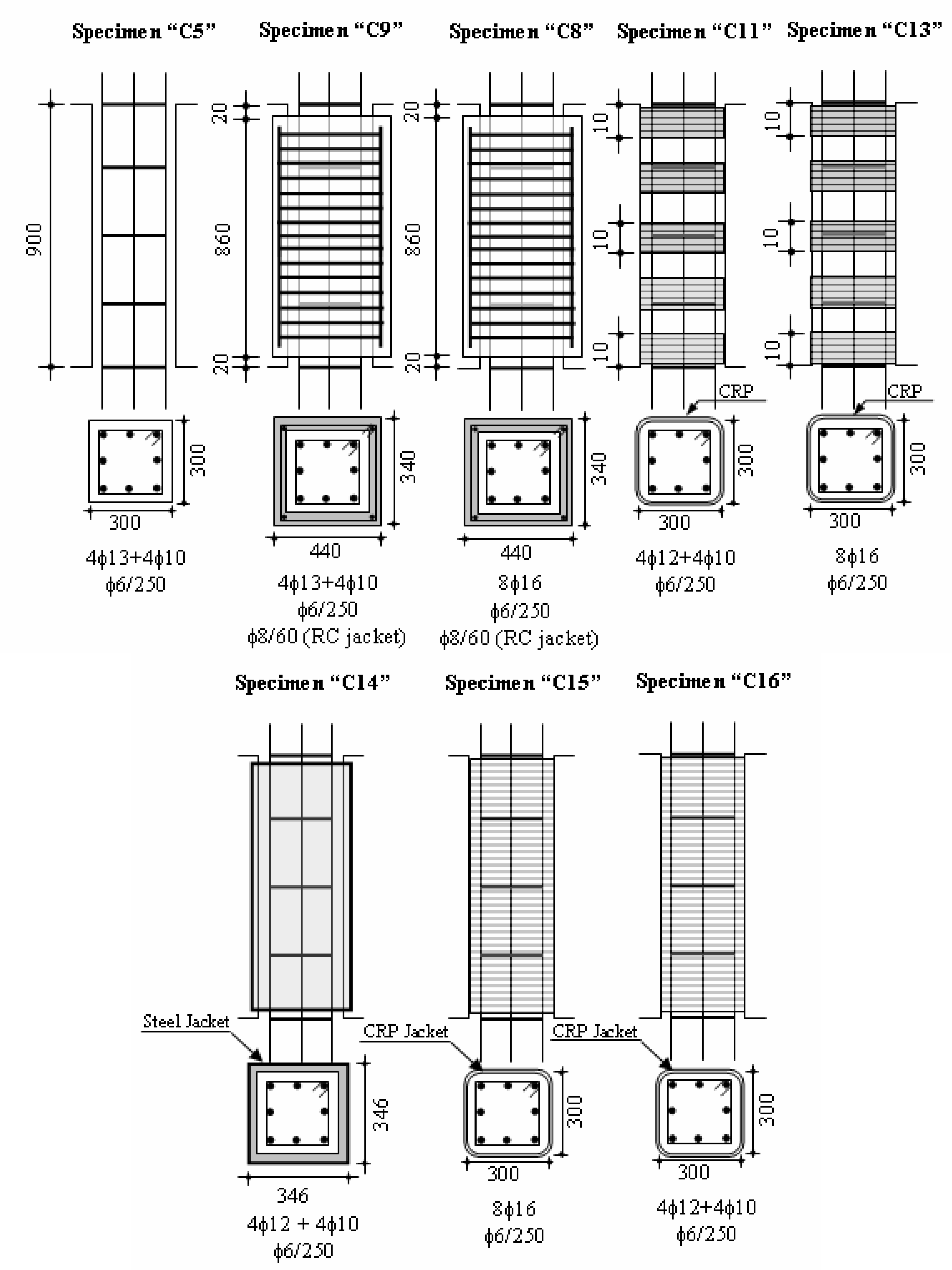

Figure 1: Specimens' details

Carbon fiber jacketing represents an alternative solution for shear capacity and ductility upgrade. Four specimens retrofitted using this method were tested. A minimum amount of fiber was used for the first two specimens. Specimens C11 and C13 were obtained from specimen C5 by carbon fiber jacketing using five single layers discrete fiber straps (see figure 1). Specimen C13 has the same shear capacity as specimen C11. The flexural capacity of specimen C13 was increased in order to obtain shear failure and consequently the shear capacity. As in case of specimens C8 and C9 the fiber was applied on the axial unloaded columns.

Specimens C15 and C16 were obtained from the damaged C11 and C13 columns by repairing and retrofitting. This implied epoxy resin injection of the cracks and carbon fiber wrapping (two layers continuous CRP wrapping).

Specimen C14 was obtained from an undamaged C5 type column by retrofitting using a 3mm thick steel jacket. A 20mm space between the jacket and column was considered. This gap was filled with a non-shrinkage mortar. Also a 20 mm gap was provided at both ends of the column.

Table 1: Tested columns data

Spec.	**Section width**	**Section height**	**Column height**	**Column type**	**Jacket type/ thickness**	f_y	**Axial force ratio**	**Long. reinf. ratio**	**Trans. reinf. ratio**
	[mm]	**[mm]**	**[mm]**		**[mm]**	**[N/mm²]**		**[%]**	**[%]**
C5	300	300	900	Old	-	405	0.4	0.96	0.075
C9	440	440	900	Retrofitted	RC/70	405	0.4	0.96	0.56
C8	440	440	900	Retrofitted	RC/70	405	0.4	2.00	0.56
C11	300	300	900	Retrofitted	CRP	405	0.4	0.96	0.075
C13	300	300	900	Retrofitted	CRP	405	0.4	2.00	0.075
C14	300	300	900	Retrofitted	Steel/3	405	0.4	0.96	0.075
C15	300	300	900	Retrofitted	CRP - full wrapping	405	0.4	2.00	0.075
C16	300	300	900	Retrofitted	CRP- full wrapping	405	0.4	0.96	0.075

LOADING PROCEDURE

The specimens have been subjected to a cyclic, statically applied, lateral force under a constant axial load. The lateral force has been applied using two horizontal 100t hydraulic jacks. Displacement based control of the test was considered. The lateral loading protocol included one cycle at ±0,25% lateral drift and two cycles for ±0.5%, ±1%, ±1.5%, ±2%, ±3%. After 3%, the lateral displacement has been increased in one direction up to failure ("pushover type loading"). The lateral load protocol is presented in figure 2.

The axial load was applied using one 200t vertical jack. This force was applied at the beginning of the test and maintained constant up to failure. The tests were stopped when the loss in the axial force carrying capacity occurred. The columns were tested in "double curvature". The rotation of the both columns' ends was blocked.

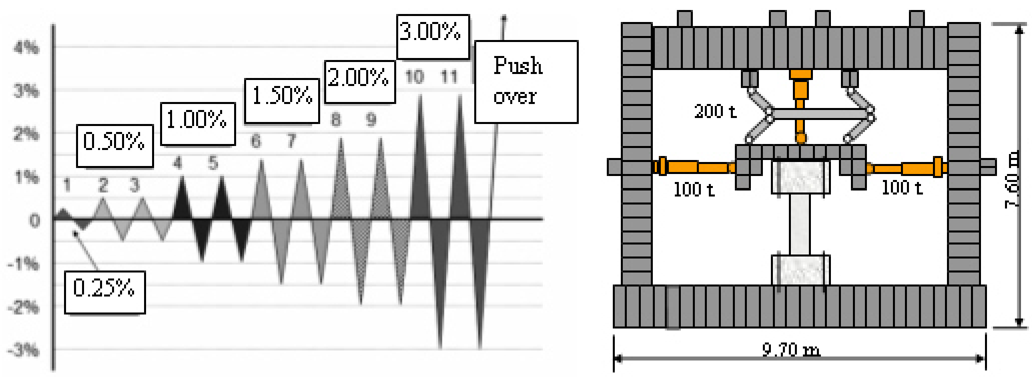

Figure 2: Loading protocol and loading frame

MEASUREMENT SYSTEM

The horizontal and vertical displacements were measured using four digital displacement transducers T1….T4. The plastic hinge rotation can be calculated using the displacements measured with other four displacement transducers (T5…T8). The longitudinal and transversal reinforcement' strains were measured using strain gauges.

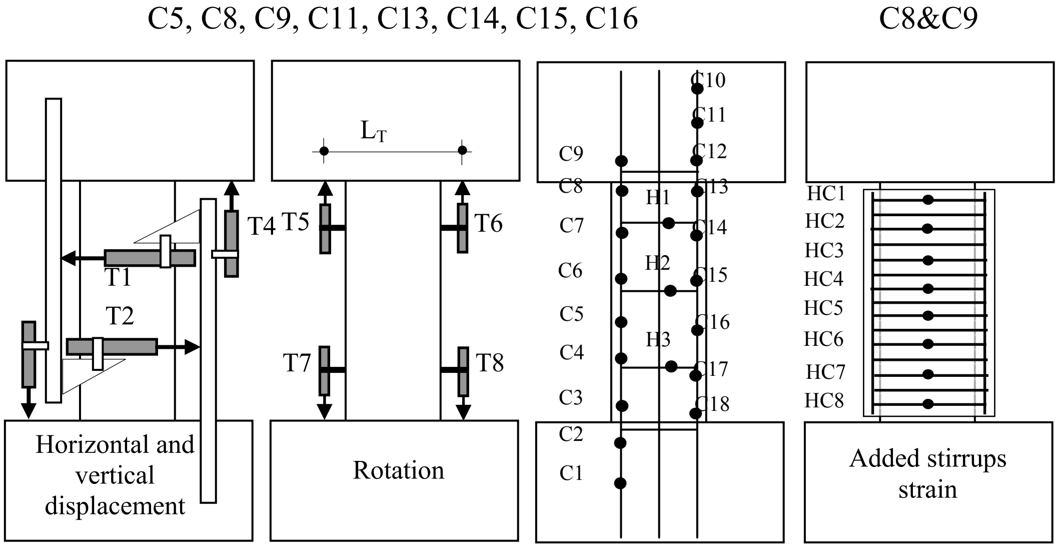

Figure 3: Measurement system

$$\Delta_H = \frac{\Delta_{T1} + \Delta_{T2}}{2} \tag{1}$$

$$\Delta_V = \frac{\Delta_{T3} + \Delta_{T4}}{2} \tag{2}$$

$$\theta_p = \frac{\left|\Delta_{T5} - \Delta_{T6}\right|}{L_T} \tag{3}$$

where: Δ_H horizontal displacement
Δ_V vertical displacement
θ_P plastic hinge rotation
$\Delta_{T1..T6}$ displacement measured using transducer T1…T6

TEST RESULTS

Specimen C5 proved to be a shear controlled column. It failed in shear at 1.5% lateral drift when the diagonal concrete strut attained its capacity to carry the compression stress. The main load carrying mechanism was the arch mechanism. The truss mechanism could not be mobilized due to the lack of transversal reinforcement. This has been proven by the observed cracking pattern. Instead of a distributed cracking pattern which is usually associated with the truss mechanism a singular diagonal crack has been observed. At small values of the lateral drift only inclined cracks at member ends occurred. These cracks are due to the combined action of the bending moment and shear force. At 1% a significant drop of the lateral force was noticed in the second loading cycle. Since the decay was grater than 20% of the maximum lateral strength this was considered to represent the drift capacity. However the test continued until a severe loss in the lateral capacity has been measured.

The retrofitting procedure applied in case of specimens C8 and C9 proved to be efficient. In case of specimen C9 the shear transfer mechanism changed from arch to truss mechanism. This was shown by the cracking pattern of the reinforced concrete jacket. As it can be seen in figure 5 a distributed cracking pattern occurred. After two percent lateral drift, the lateral capacity began to decrease. At the second cycle at 3% the lateral capacity was almost half of the maximum one. This happened despite the fact that no severe damage has been observed on the exterior face of the RC jacket. It is obviously, looking at the damage state presented in figure 5, that the shear failure did not occurred so the main purpose of the retrofitting work have been achieved. It can be seen in the chart presented in figure 12 that the stirrups din not yield prior to 2.5%. The lateral strength decay can be associated with the damage of the interior original column. Severe settlements have been observed after 2.5% lateral drift (see figure 10). As a matter of fact the test has been stopped at 6% lateral drift when the 2cm gaps where completely closed at both ends (figure 8). This settlement might have two causes: the crushing of the concrete at the column ends together with the buckling of the longitudinal reinforcement. The recorded hysteretic loops for specimen C9 showed a good energy dissipation capacity, at least comparing to specimen C5. However severe stiffness and strength degradation have been noticed after 2% lateral drift.

In general, specimen C8 had a similar behavior with specimen C9. The shear force was transferred trough a truss mechanism confirmed by the RC jacket distributed cracking pattern. No severe settlement has been recorded. This is mainly due to the higher amount of longitudinal reinforcement. Despite the increase in the

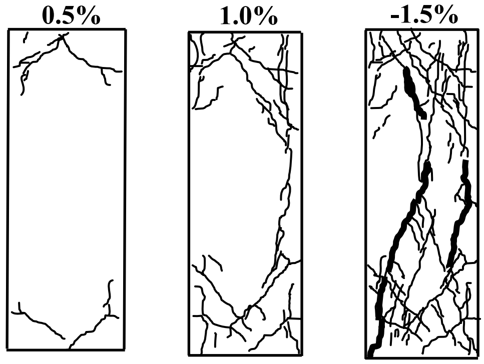

Figure 4: Specimen "A" crack pattern

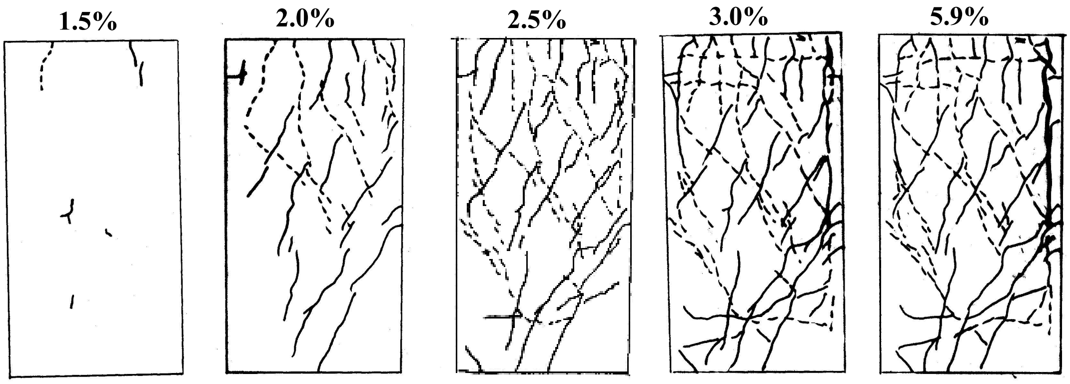

Figure 5: Specimen "C9" crack pattern

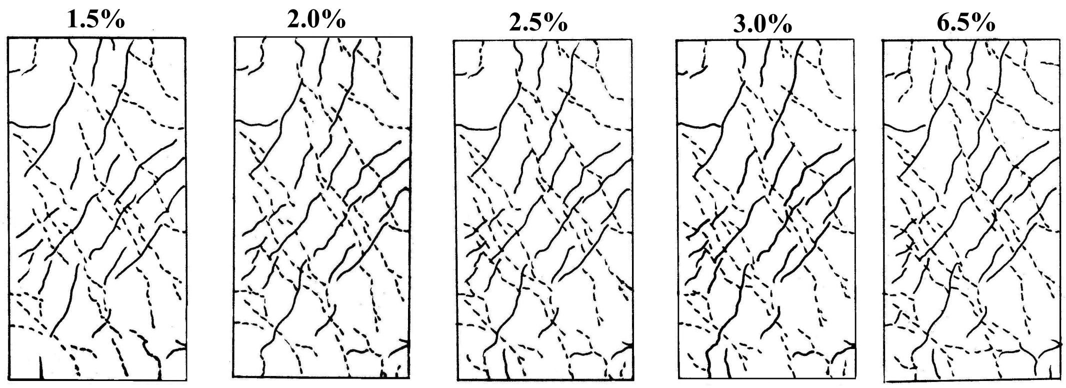

Figure 6: Specimen "C8" crack pattern

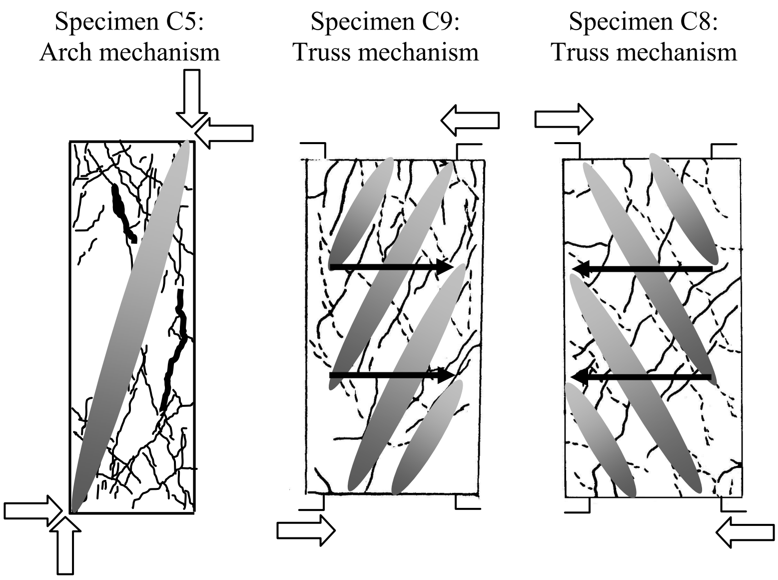

Figure 7: Load carrying mechanisms

flexural capacity no shear failure has been observed. The test have been stopped at 10% lateral drift when it was considered that further loading is irrelevant for current design and evaluation problems. The energy dissipation capacity of specimen C8 is rather poor but little damages have been recorded (figure 9).

The results obtained directly from the test measurements and a comparison between the three specimens are presented in the following charts. Figure 9 displays the lateral load – lateral drift history for the three specimens. The lateral drift is calculated as the ratio between the lateral displacement and column height and is expressed in percents. As can be seen in the charts presented in figure 9 specimens C9 and C8 had an increased ultimate displacement and energy dissipation capacity comparing to specimen C5.

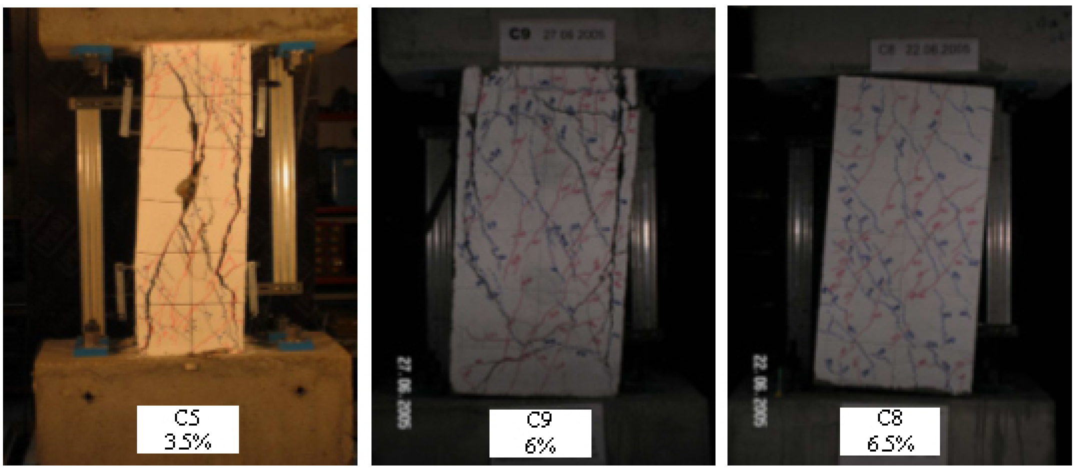

Figure 8: Test pictures

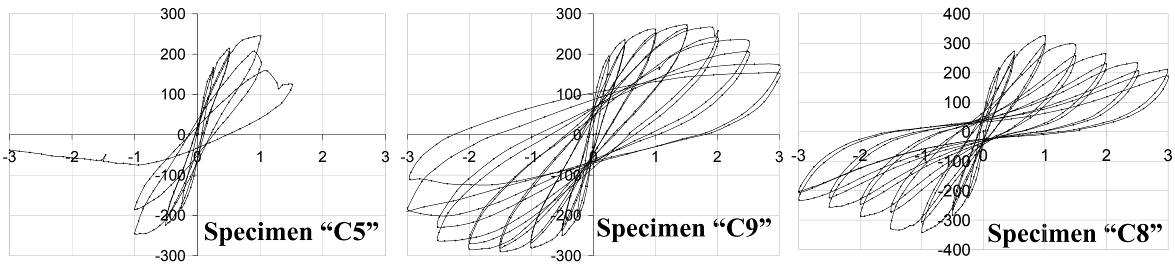

Figure 9: Lateral Drift - Lateral Load

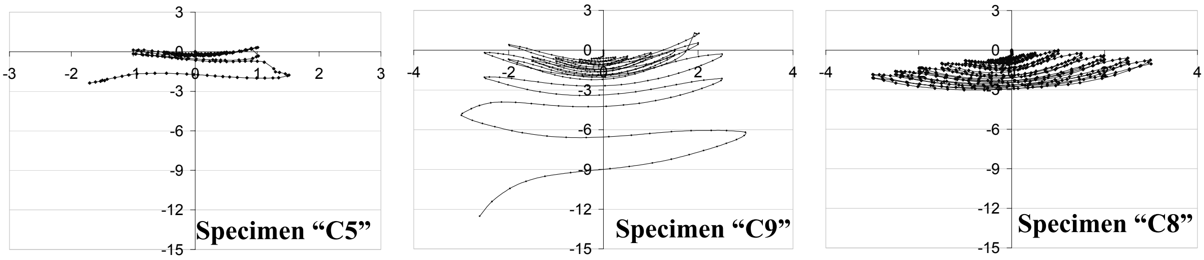

Figure 10: Lateral Drift – Vertical Displacement

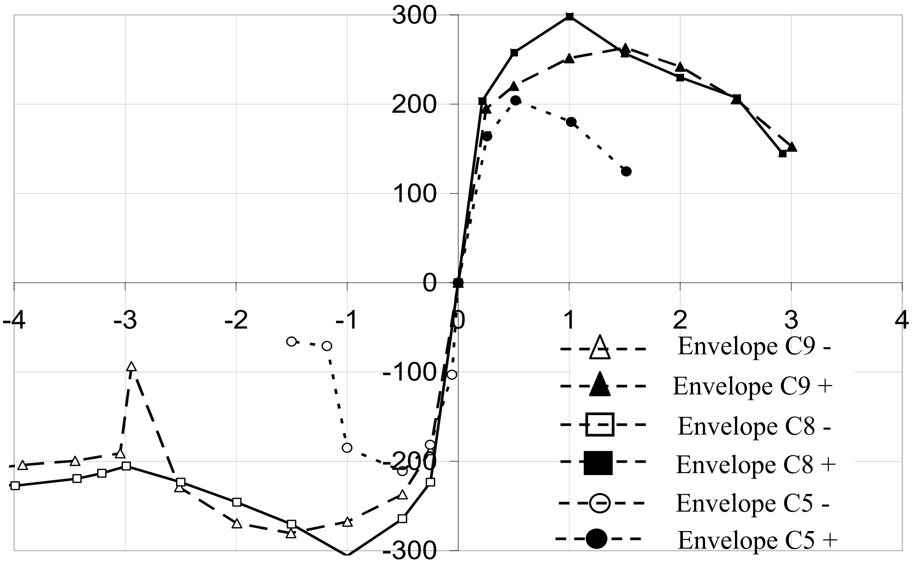

Figure 11: Comparison between lateral drift – lateral force envelopes

Figure 12 presents the strains in the added stirrups over the column height. The strains values are directly obtained from test.

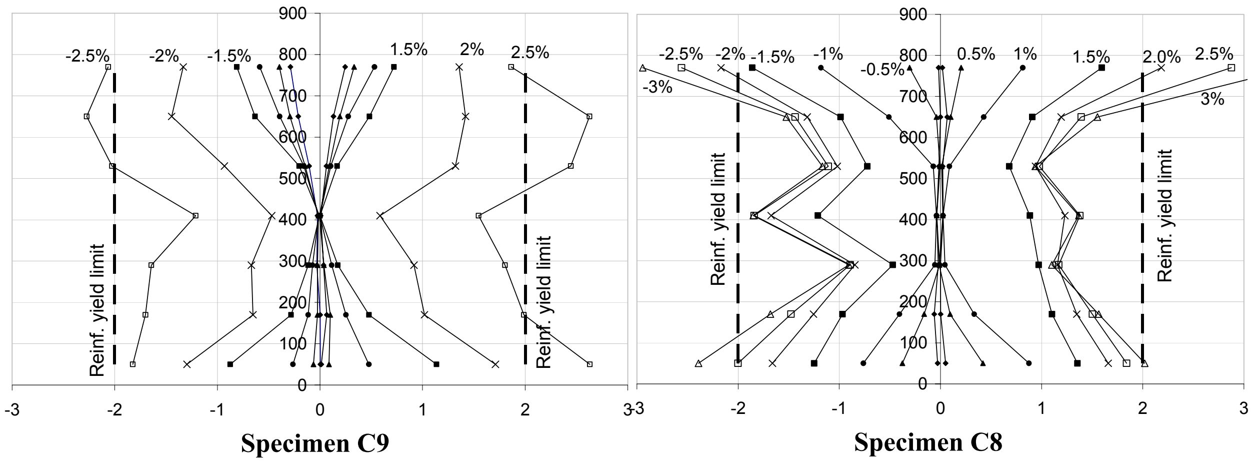

Figure 12: Stirrups strain (‰) over the column height (mm)

The second retrofitting solution used for this test series is carbon fiber jacketing. In case of specimens C11 and C13 a minimum quantity of fiber was used. The idea was to obtain the same shear capacity as a steel reinforced column having a transversal reinforcement ratio of 0.6% (3.41ϕ6/60).

$$\rho_{wf} = \rho_{ws} \frac{f_{yd}}{\sigma_f} \tag{4}$$

where: ρ_{wf} shear reinforcement ratio of carbon fiber sheet

ρ_{ws} shear reinforcement ratio given by the steel stirrups

f_{yd} steel yielding strength

σ_f tensile strength of carbon fiber sheet

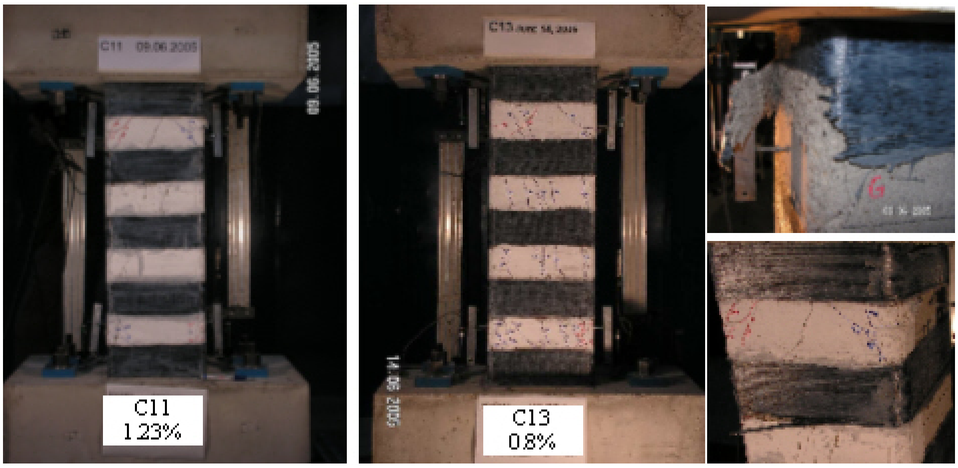

Figure 13: Test pictures

The effectiveness of this retrofitting method is questionable even though a small improvement have been observed. The shear failure occurred at 1.23% lateral drift in case of C11 and 0.8% lateral drift in case of C13. Even though the equivalent reinforcement ratio is quite high meeting the requirements of the current codes the lateral displacement capacity of the columns was rather poor. This can be explained by the lack of ductility of the CRP sheets.

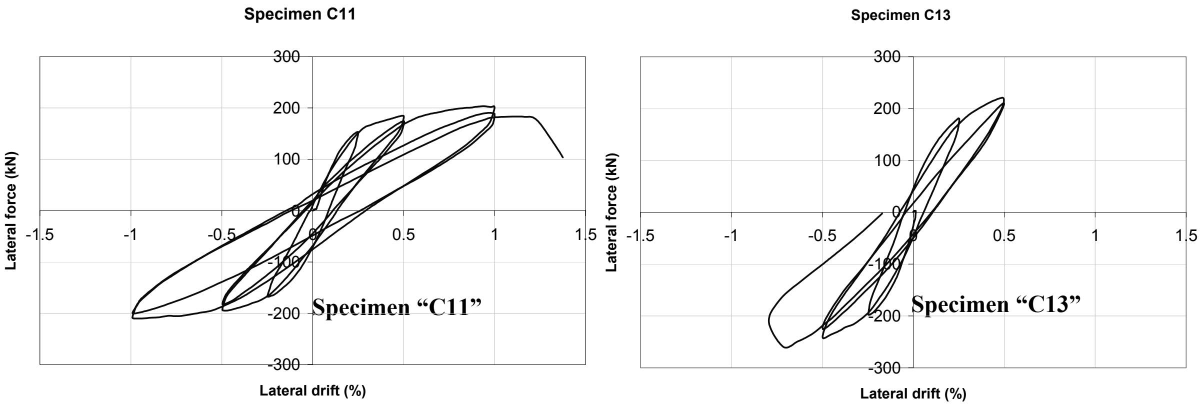

Figure 14: Lateral Drift - Lateral Load

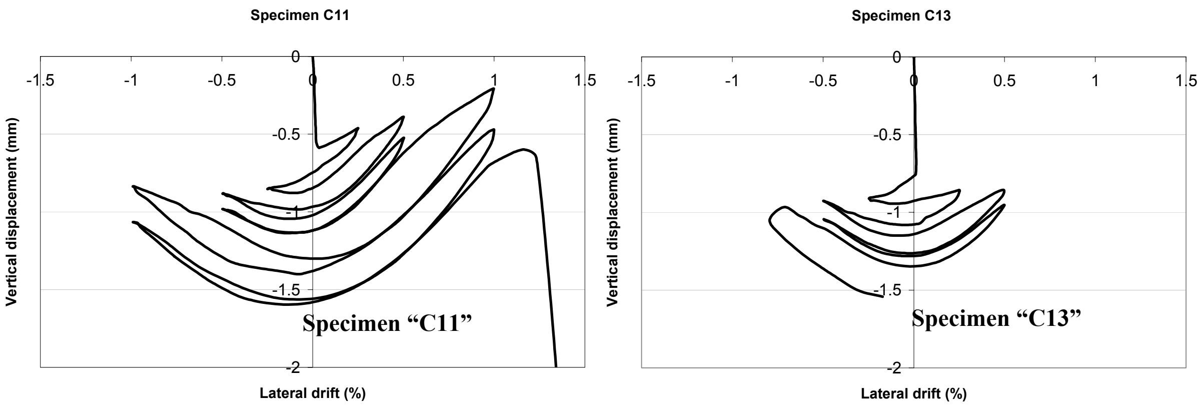

Figure 15: Lateral Drift – Vertical Displacement

Given the poor results obtained for specimens C13 and C11 they have been further repaired and retrofitted to obtain specimens C15 and C16. Specimen C15 has a 2% longitudinal reinforcement ratio and C16 has a 1% ratio. The repairing was made using epoxy resin injection of the shear cracks. Wrapping with two continuous layers of CRP sheets have been considered as the suitable retrofitting technique.

The results obtained from tests showed a clearly improved behavior of these specimens. The ultimate displacements increased from around 1% (in case of spec. C11 and C13) to 7-8%. A cyclic lateral loading was used up to 3% lateral drift followed by a pushover loading up to failure. In Figure 17 only the force-displacement history up to 3% lateral drift is presented.

It can be noticed that specimen C15 showed a higher flexural strength than specimen C16 and a slight decrease of the lateral strength after 2% drift. Also for this specimen rather high strength decay can be observed at each second cycle. Specimen C16 showed a clearly stable hysteretic behavior. Almost no strength decay has been observed during the cyclic loading up to 3%.

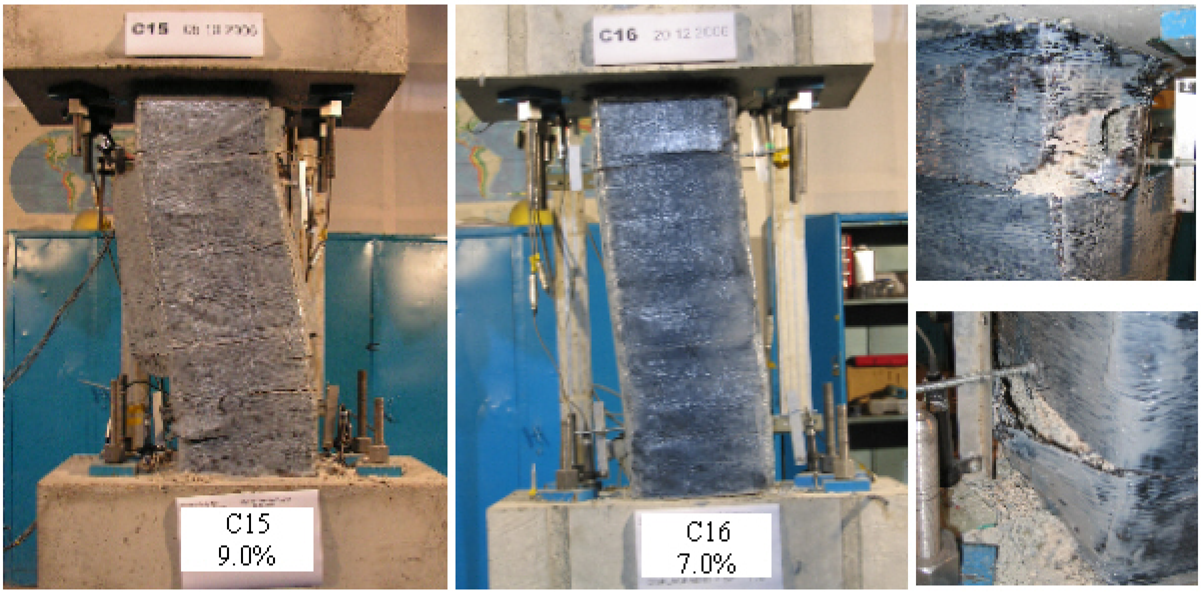

Figure 16: Test pictures

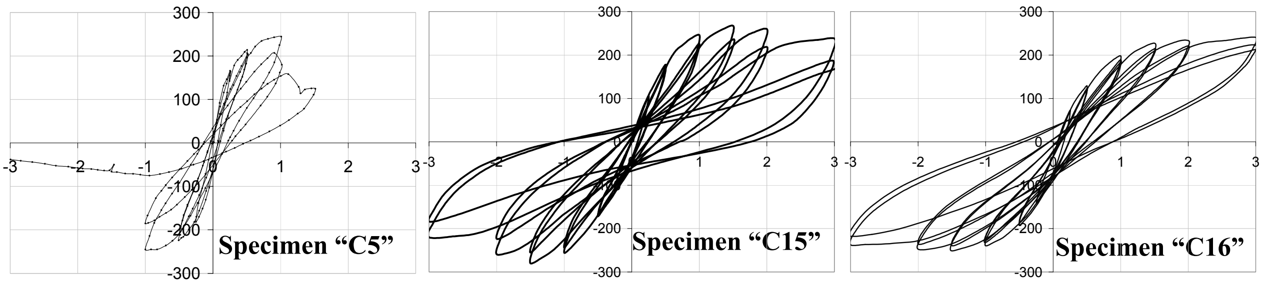

Figure 17: Lateral Drift - Lateral Load

In case of specimen C15 a smaller vertical settlement can be observed in comparison with specimen C16. This can be explained by the higher longitudinal reinforcement ratio. The longitudinal reinforcement contribution to the axial load carrying capacity of the columns is very important after the cyclic deterioration of the concrete core.

It can be stated that this retrofitting solution is suitable for increasing the ductility of reinforced concrete columns detailed according to Romanian practice.

The last specimen in this test series presented in this paper is C14. Specimen C14 has been derived from specimen C5 by steel jacketing. The main purpose of the retrofitting procedure was the ductility improvement. No flexural capacity improvement has been intended. In this respect a 2cm gap has been provided at each end of the steel jacket. No additional longitudinal reinforcement has been installed. A 3mm thick continuous steel jacket has been installed. The thickness of the jacket has the minimum value for on site welding. The narrow gap between the jacket and the existing column has been filled with a low viscosity non shrinkage mortar.

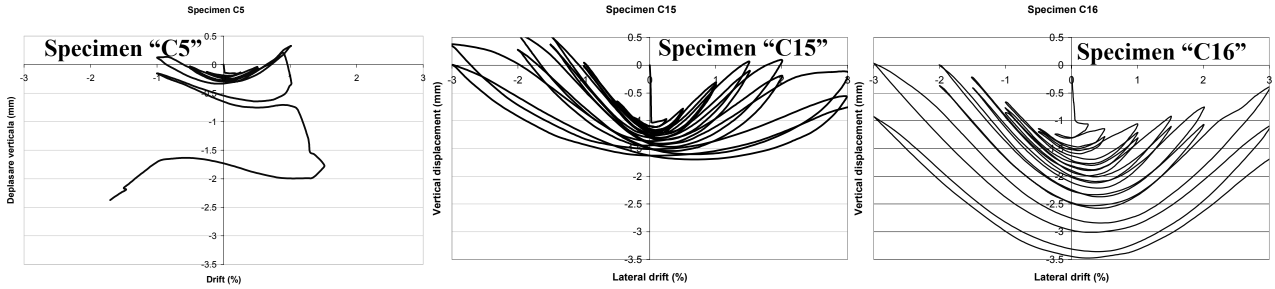

Figure 18: Lateral Drift – Vertical Displacement

This specimen showed a good hysteretic behavior without strength decays due to cyclic loading. The pushover loading was applied after 3% lateral drift up to 9%. The test has been stopped at this drift limit for safety reasons considering that this limit is far beyond the interesting limit for design or research. The vertical settlement is quite large at this large lateral drifts. The lateral drift – vertical displacement relation (figure 21) resembles the results obtained for specimen C16.

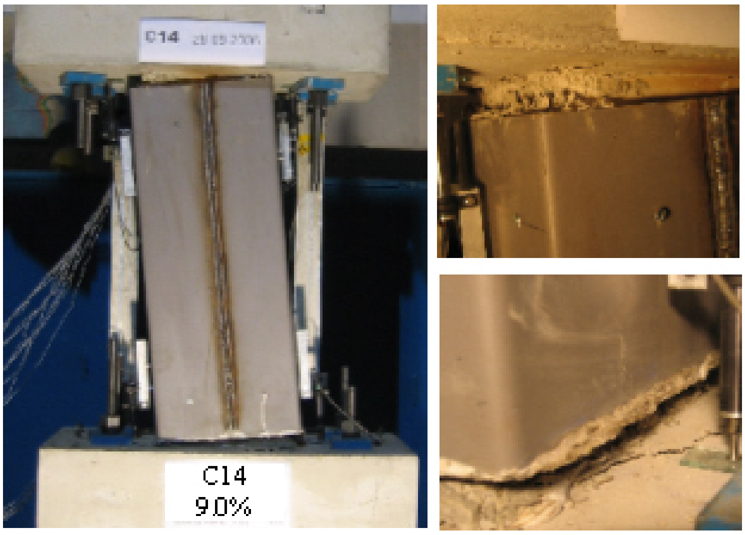

Figure 19: Test pictures

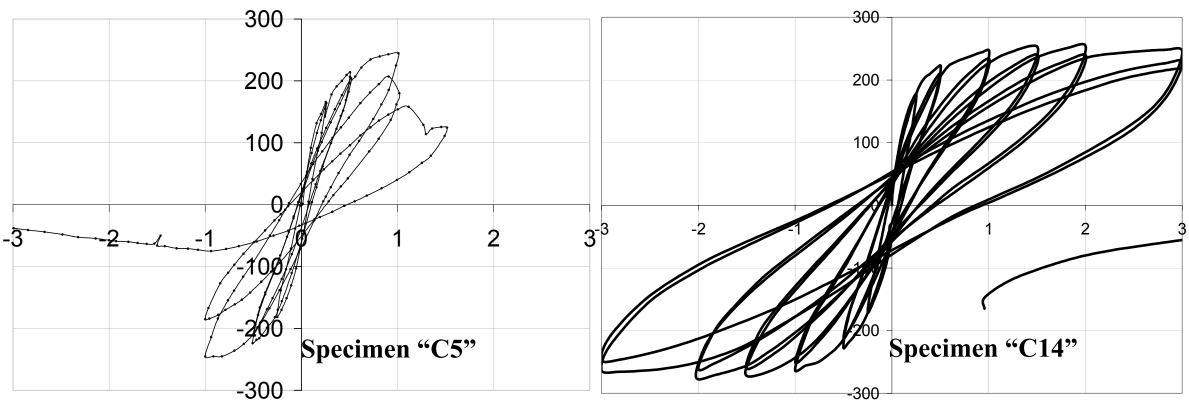

Figure 20: Lateral Drift - Lateral Load

The steel jacketing proved to be a good solution for the retrofitting of RC columns. It should be mentioned that the cost of retrofitting materials is cheaper in case of steel jacketing in comparison with CRP jacketing.

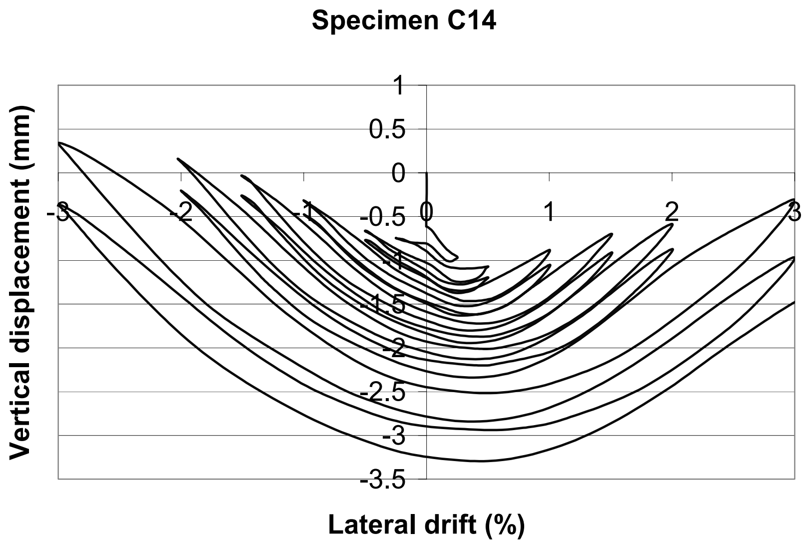

Figure 21: Lateral Drift – Vertical Displacement

CONCLUSIONS

All three ductility improvement retrofitting methods proved to be effective for old columns designed and detailed according with Romanian practice.

The suitable retrofitting solution should be selected tacking into account many criteria, like construction cost, activity disruption, space consumption, fire resistance.

The reinforced concrete jacketing involves the lowest material cost. The disadvantages come from time consuming construction procedures and changes in the building's architecture (the column's sizes increase more than 20 cm). From the fire resistance point of view this is the most suitable solution.

The carbon fiber jacketing is appropriate for ductility upgrade if a proper shear reinforcement ratio of fiber sheet is selected. The main disadvantages are the materials' cost and low fire resistance. The following advantages can be mentioned: minimum changes in the building architecture and a reduced construction period in comparison with the other two solutions.

The steel jacketed column presented a good ductility. The material cost is moderate. The jacket width can be reduced if a non shrinkage high fluidity mortar is used.

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