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Experimental Evaluation of Repairing Techniques for Holes Made in Reinforced Concrete Columns for Core Tests

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A R T I C L E I N F O

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A B S T R A C T

This paper presents the experimental and theoretical studies of reinforced concrete short columns drilled laterally with a hollow of a 50 mm in diameter. As known, the purpose of the core test is to evaluate the strength of the existing concrete. Seven square reinforced concrete columns of 150 mm x 150 mm cross-sectional area with 520 mm height were cast and tested. The specimens were reinforced with 8-Ø10 mm having yield strength of 570MPa and concrete compressive strength of 31.0MPa. Five different strengthening techniques were adopted to drilled columns. The results indicated that the combination method of strengthening like filling the drilled hole with cement base grout and wrapping it with CFRP sheets lead to an increase in load carrying capacity up to 19.5% and 50.5% relative to solid and drilled columns, respectively. While strengthening with steel pipe and wrapping by CFRP sheets enhanced the load capacity by 13.6% and 43.0%, respectively when compared to solid and drilled column specimens. Briefly, the strengthening process of the drilled column can lead to load carrying capacity even more than that of the solid column. The modified ACI Code equations gave conservative results ($P_{Exp.}/P_{Theor} \geq 1.0$) for tested strengthened specimens of this study, and they showed good agreement when applied to the available drilled columns from literature.

1. INTRODUCTION

Column is a vertical compression supporting element in the skeleton of buildings that carries roof/floor loads to the columns of lower stories or to the footings. The column may also be used in transferring the heavy loads of bridge trucks or trains with the superstructure weight in proper way to the footings.

The column load carrying capacity depends mainly on the compressive strength of its concrete. The potential strength of column concrete can be evaluated by control specimens (cylinders or cubes) cast separately at the same time of casting the relevant column. When the test results of control specimens (after 28 days of casting) are found to be lower than the specified design strength, the engineers shall go through methods of getting the in-situ concrete compressive strength.

Core test is one of the precise and reliable way to assess the quality of concrete in an existing structural elements. Core test techniques in engineering application are appearing in China since 1981 (Lie et al., 2010). Cylinders of different height to diameter ratios are drilled (cored) from the in-situ concrete to assess the concrete quality. The diameter of the specimen depends on corecutting machine while the height of the core depends on the thickness of the element (slab, beam, wall, footing, column, …., etc.)(Neville and Brooks, 2008). Core test is needed in assessment of concrete strength quality due to one of the following reasons:

i. If the test results of the control specimens are below the specified design strength value.
ii. The demand of sustainability development leads the scientists to go toward utilization and re-habitation of the existing structures. Core is one of the techniques to assess the concrete quality.
iii. The concrete deterioration of structural members due to overloading stresses (e.g., fatigue, frost action at early age, explosion, and seismic).

The location of the drilled cores is preferred to be in an area of approximately zero internal stresses, which can be determined easily in the case of beam, slab, and footing. Columns, unlike other members, the entire cross section and length are under axial loads, therefore, drilling a hole in the column may affect significantly its carrying capacity. Accordingly, re-habitation and retrofit of the damaged reinforced concrete columns are required.

In the past, engineers used different methods of strengthening the existing members by providing external confinement materials like; steel plates, reinforced concrete, or fiber reinforced polymer (FRP) jacketing. Carbon fiber reinforced polymer (CFRP) laminates have proved to be the pioneering material in strengthening over the last years due to its attractive mechanical properties. The FRP materials gain a world-wide recognition as strengthening material to increase the ductility and load carry capacity of the existing structural members (Al-Saloum, 2007, Chastie and Silva, 2010, Pham et al., 2013 and Son et al., 2006).

A large number of studies addressed the strengthening and repair of reinforced concrete columns enhanced using external FRP sheets. However, the behavior of drilled hole on compressive member is still has a lack of studies (Son, 2006 and Masi et al., 2012]. Therefore researches were needed on strengthening and repair of drilled reinforced concrete columns.

2. Research Significance:

In practice, engineers avoid the core test in the column and depend on nondestructive tests. These tests give just an indication on the strength of concrete, and they may be useful in checking the uniformity of the concrete, while the core test is the most reliable method to evaluate the strength of the existing concrete at the site.

In order to reduce the effect of core drilling, this research used different techniques of strengthening like filling with cement base grout, inserting steel pipe into the hole, wrapping with CFRP sheets, and the combinations of the above types. The research concentrated on columns subjected to pure axial load that represent interior columns (with approximate equal beam span at both sides of the column).

The drilling and strengthening processes were done during unloading stage of the element which can be guaranteed at the site when the floors are supported (i.e., shored).

3. Experimental Programs:

In this investigation, seven reinforced concrete columns with dimensions 150mmx150mm and length of 520mm were cast with control specimen. The intended cylinder compressive strength was 31.0MPa, with maximum aggregate size of 19mm. The longitudinal reinforced consisted of eight steel bars of Ø10 mm with yield strength of 570MPa and confined with ties of Ø6mm of tensile strength of 571MPa.

The specimens consisted of two reference columns; one of them is solid, and the other one is drilled with diameter of 50mm at the mid height. The others five were drilled column strengthened with cement base grout, steel pipe, CFRP sheets, Combination of cement base grout with CFRP and combination of steel pipe with CFRP sheets as shown in Table -1 and Fig.1.

The filled material for the hollow is cement based one component, polymer modified, and self- compacting non-shrink grout (EMACO® S55). Compliances with ASTM C1107 Type B ve Type C. The properties of this material were tested and found 39.4MPa in compressive strength and 6.17MPa in splitting tensile strength. 50mm in external diameter steel pipe of thickness 1.75mm with 329MPa yield strength were used to fill the opening (drilled hole). In the practice, the gap surrounding the pie should be filled with cement base grout. SikaWrap®-300 C/60 a unidirectional woven carbon fiber polymer (CFRP) sheet fabric for structural strengthening was used with three layers wrapped see Table-2. The sheet was cut with width of 150mm; this mean that the sheet is wrapped the hole of the column and 50mm at top and bottom of the hole. A Sikadur®-330 epoxy based impregnating resin – adhesive is used to fix the CFRP. The axial strain of the concrete at mid height of the column was measured using two dial gauges, for all columns.

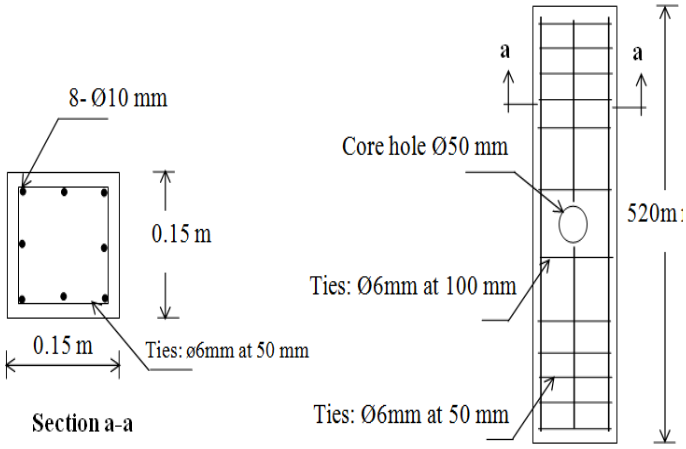


Fig. 1 Details of column reinforcements

Table-1 Details of tested columns.

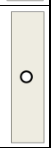
Spec. No.	Specimens	Hole condition	Column Elevation
C1	Solid column	without	
C2	Drilled column	exist	
C3	Column hole is filled with cement based Grout	filled	
C4	Column hole is confined by CFRP sheets	exist	
C5	Column hole is filled with cement based grout and confined by CFRP	filled	
C6	Column hole is strengthened by steel tube	exist	
C7	Column hole is strengthened by steel tube and CFRP	exist	

Table 2- Properties of CFRP sheet.

Fabric Design Thickness	**0.166 mm (based on fiber content).**
real Weight	300 g/m^2 + 15 g/m^2
Fiber Density	1.79 g/cm^3
Tensile strength:	3900 N/mm^2 (nominal).
Tensile E-modulus:	230 000 N/mm^2
Elongation at break:	1.5% (nominal).

4. Experimental Results:

4.1 Ultimate Carrying Capacity:

In this section, the main results of core drilled axially loaded short columns carrying capacity with different kinds of strengthening are presented. Table-3 shows the experimental results of the tested column specimens. The photos of the columns before and after testing are shown in Appendix A.

4.1.1 Solid and Drilled:

Drilled columns with core size of 50 mm showed up to 20.6% reduction in load carrying capacity when compared to the solid specimens. In spite of that the size of column cross section was reduced due to drilling by one-third and two bars were cut through drilling (25% of the bars), the ratio of the reduction in the column load capacity is not significant.

4.1.2 Strengthened Columns:

Strengthening by filling the drilled hole with cement based grout, the ultimate carrying capacity of the filled column (C3) increased by 20.6% relative to the drilled column (C2), but it did not reach the solid column carrying capacity (only 4.2% less). The filled core was split out at final stages of column failure. Column C4, which was strengthened by CFRP sheets, showed an increase in the carrying capacity of about 35.7% when compared with the drilled column specimen and 7.8% when compared with the solid specimen. Therefore, CFRP sheet is effective in confining the concentric loaded column.

Column filled and strengthened with CFRP sheets (C5): this technique represents a combination of C3 and C4 specimens. The increase in load carrying capacity were 50.5% and 19.5%, respectively when compared with the drilled and solid columns. This methods is very effective when compared to other kinds of strengthening used in this research. It's noticeable that the separate effect of filling (C3) and strengthening with CFRP sheets (C4) reached to an increase of 20.6% and 35.7% with respect to the drilled column, respectively, while the combined method gave an increase of 50.5% which means that the effects are not cumulative (56.3% > 50.5%).

Column strengthened with steel pipe (C6): an increase of about 13.5% was noticed in comparison with the drilled one, while the strength of the solid column was not obtained by applying this method of strengthening. This may be attributed to the fact that the steel pipe is circular (cylinder) and the compressive stress path rearranged its distribution and prevents stress concentration around the steel pipe, and the plate of the pipe supported part of stresses from the surrounding concrete. At the final stage of failure, the pipe was buckled after the concrete reached its strength.

Finally, in specimen C7 and due to the existence of steel pipe and CFRP sheets, an increase of 43.0% was obtained compared to the drilled column capacity and an increase of 13.6% compared to the solid column specimen.

When comparing this result with that of specimen strengthened with steel pipe alone (13.5% increase) and with the CFRP confined specimen C4 (35.7% increase), again the effects are not cumulative and that the CFRP confined specimen behaved better than inserting pipe.

Table-3 Experimental ultimate carry capacity of the columns with different strengthening techniques

Specimen No.	Specimen condition	Ultimate Load P (kN)	Ratio of P/P_{solid}	Ratio of $P/P_{Drilled}$
C1	Solid column	793	-	-
C2	Drilled column	630	0.794	-
C3	Drilled and filled cement base –type	760	0.958	1.206
C4	Drilled and strengthened with CFRP	855	1.078	1.357
C5	Drilled, filled and strengthened with CFRP	948	1.195	1.505
C6	Drilled and strengthened with steel pipe	715	0.902	1.135
C7	Drilled, strengthened with steel pipe and CFRP	901	1.136	1.430

4.2 Load-Axial Deformation Relationship:

The axial deformation of the column specimens are shown in Figs.2 to 4. The relation between the applied axial load and the measured axial deformation showed that there is slight difference among the relationships during the elastic range (up to about 400 kN).

At the same applied load the strain in specimen C3, filled with cement based grout, has a strain less than in the solid column, Fig. 2, since the used cement based grout material, has strength properties better than the concrete itself. In inelastic range, there is an obvious difference in the drilled column C2, relative to the others. The effect of the confinement by CFRP sheet , C5, shown in Fig.3 appears more clearly during the inelastic stage; this improvement technique has significant benefit in increasing ductility and ultimate strain. In Fig.4, the combination of steel pipe and CFRP has an effect on load –strain relationship at elastic range and significant increase in inelastic strain, i.e., the ductility of the column C7 has improved.

Usually, the building is working under service loads (in spite of the design done by ultimate strength method) this means that, in practice, the core is taken under this loading or less (elastic range). From the load-strain curves, the relationship of solid column is close

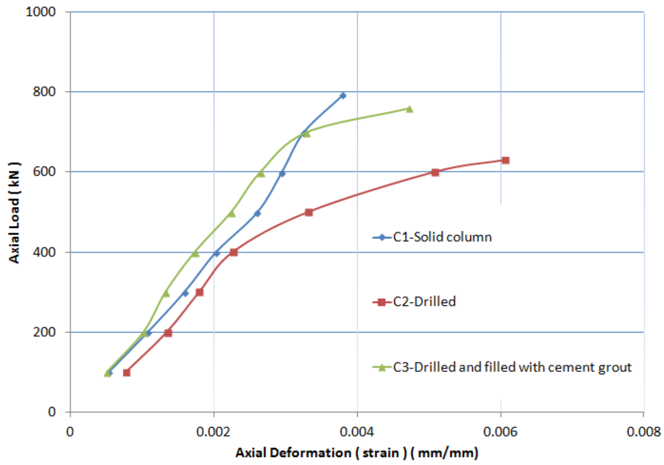


Fig2. Axial load versus axial deformation for the loaded columns

to the drilled column in the elastic range. Based on that, the cores can be taken from columns carefully and strengthened with a suitable method.

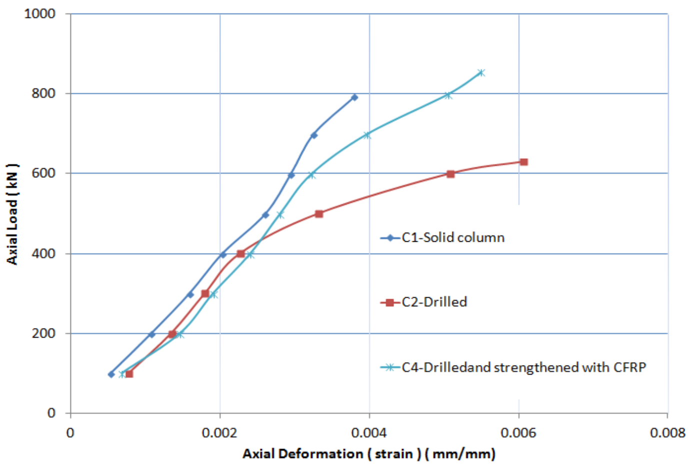


Fig.3 Axial load versus axial deformation for the loaded columns

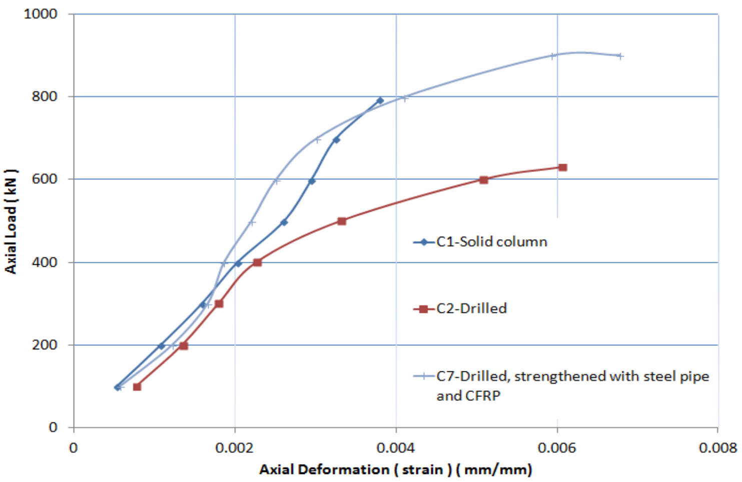


Fig.4 Axial load versus axial deformation for the loaded columns

5. Theoretical Analysis:

The solid and drilled column were analyzed theoretically according to ACI-318 Code; the results are shown in Table-4. A modification of ACI Code equation was done to predict the load carrying capacity of columns strengthened by filling the core hole with cement base grout (C3), an additional part of strength was included, as follows:

$$P = 0.80\,[0.85\, f`_c\,(A_g - A_{st}) + f_y\, A_{st} + P_{Split}\,] \quad \text{....(1)}$$

Where P_{Split} is taken from the following equation:

$$f_{ct} = \frac{2P_{Split}}{\pi\, L\, D} \quad \text{......(2)}$$

Where

f_{ct} is the splitting tensile strength of cylinder taken from test results.

L is the length of the cylinder specimen(150mm)

D is the diameter of the cylinder specimen 50mm).

$f`_c$ is the cylinder compressive strength of concrete(MPa).

f_y is the yield strength of steel bar reinforcements (MPa)

A_g is the gross area of column section(mm^2).

A_{st} is the area of steel bar reinforcements (mm^2).

CFRP sheets were used to strengthened specimen C4, ACI-318 and ACI-440R equations for column were developed to take effect of opening and strengthening, the following are the main equations:

$$P = 0.80\,[\,0.85\, f`_{cc}\,(A_g - A_{st}\,) + f_y\, A_{st} + P_{Split}\,] \quad \text{....(3)}$$

$$f`_{cc} = f`_c + \psi_f\ 3.3\ k_a\ f_l \quad \text{..... (4)}$$

$$f_l = \frac{2\, E_f\, n\, t_f\, \epsilon_{fe}}{D_e} \quad \text{......(5)}$$

Where :

$f`_{cc}$ is the compressive strength of confined concrete due to CFRP sheets (MPa)

f_l is maximum confined pressure due to CFRP jacketing (MPa)

ψ_f is the CFRP strength reduction factor.

ka is the efficiency factor of CFRP in determination of $f`_{cc}$(based on geometry of the cross section).

E_f is tensile modulus of elasticity of CFRP .

n is the number of plies of CFRP sheets.

t_f is the nominal thickness of one ply of CFRP sheet (mm).

ϵ_{fe} is the effective strain level in CFRP attained at failure (mm/mm).

D_e is the diameter of compression member cross section or equivalent (mm).

The research included another type of strengthening with steel pipe as adopted in specimen C6. The theoretical contribution of the steel pipe for the column was found from cylindrical model subjected to vertical loads, as shown in Fig. 5, which depends on the yield strength and thickness properties of 329MPa and 1.75mm, respectively from tested of steel pipe. Finally, for the columns C5 and C7 combinations of previous methods were done.

6. Experimental and Theoretical Comparison:

The modified equations proposed in this paper have been applied to evaluate the load carrying capacity of column specimens of this research and those from literature. The results of the comparison are shown in term of $P_{Exp.}/P_{Teor}$ in Table-4 and plotted in Fig. 6 for the column specimens of this study. As shown in Fig. 6, most of the data are located above and near to the diagonal line with a mean value of 1.183. This means that the proposed equations are conservative. Thirty-seven reinforced concrete drilled columns were collected from previous works (Lei et al., 2010 and Campione et al. 2015), and they were analyzed to evaluate their load carrying capacity using the modified equations. The results of comparison are shown in Fig. 7, and the mean value of $P_{Exp.}/P_{Teor}$ was 0.923 with standard deviation of 0.144. The comparison showed good agreement and the proposed equations can be applied in determining the load carrying capacity of drilled (cored) columns.

Table 4- Ultimate and theoretical carrying capacity of the column with different strengthening techniques

Specimen No.	Specimen condition	Ultimate Load $P_{Exp.}$ (kN)	Theoretical Load $P_{Theor.}$ (kN)	Ratio of $P_{Exp.}/P_{Theor.}$
C1	Solid column	793	752.6*	1.054
C2	Drilled column	630	525.0*	1.200
C3	Drilled and filled cement base -grout	760	580.0	1.310
C4	Drilled and strengthened with CFRP	855	681.0	1.256
C5	Drilled, filled and strengthened with CFRP	948	739.0	1.283
C6	Drilled and strengthened with steel pipe	715	663.4	1.078
C7	Drilled, strengthened with steel pipe and CFRP	901	819.4	1.100

*Sample calculations for C1 and C2 are shown in Appendix B.

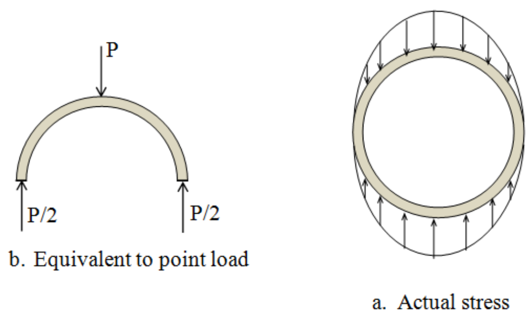


Fig.5- Stress distribution on steel pipe inserted inside concrete

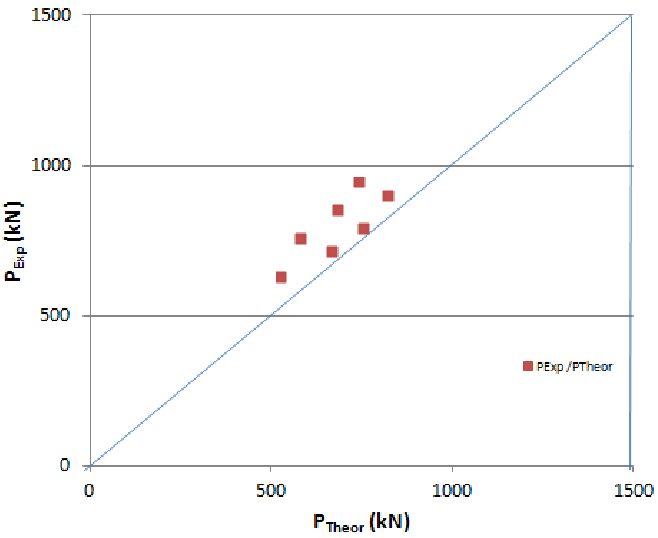


Fig.6 Experimental to theoritical carrying capacity of drilled and strengthened columns (from this research)

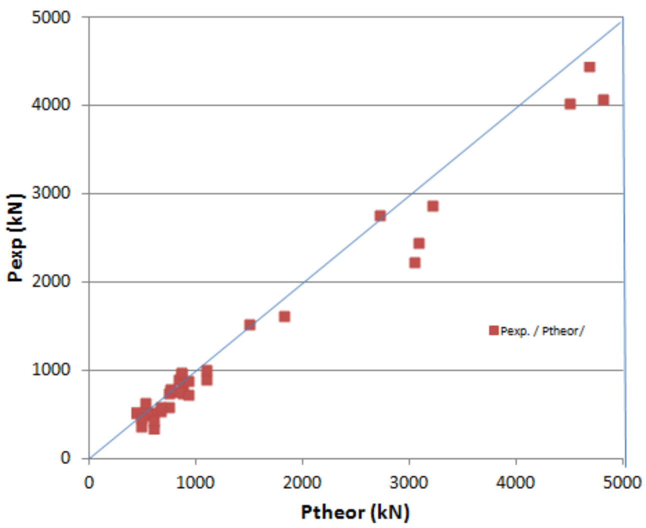


Fig. 7-Experimental to theoritical carrying capacity of drilled columns (37 colums)

7. Conclusions:

The following are some of the main conclusions:

a. Drilled columns with core size of 50 mm showed a 20.6% reduction in the load carrying capacity compared to solid column. This reduction in strength is small compared to the amount of reduction in column section and its reinforcement.

b. The enhancement in column load carrying capacity reached 20.6% when the drilled hole was filled with cement based grout material.

c. A significant increase in the load carrying capacity was obtained (35.7%) compared to the drilled column when the drilled hole was wrapped by three layers of CFRP sheets. Therefore, CFRP sheet is active in confining the concentric loaded column.

d. The combination of filling the drilled hole and confining it by CFRP sheets is superior to other kinds of strengthening used in this research.

e. The relation between the applied load and the measured axial deformation showed that the relations are almost the same during elastic range (up to about 400 kN), while the strengthened columns showed better behavior from the drilled column at the inelastic range.

f. The effect of the confinement by CFRP sheets on the ductility and the ultimate deformation was pronounced during inelastic stage.

g. The predicted column load carrying capacity showed that the proposed modified ACI Code equations are conservative when applied to the column specimens of this study. Good correlation was obtained when these equations are applied to the drilled column from literature. The mean value of $P_{Exp.}/P_{Theo.}$ was 0.923 with standard deviation of 0.144.

Recommendations:

1. Since the safety in the building is very important, more researches are required on the columns drilled and strengthened in order to verify the conclusions done in this paper, considering different $f`_c$, column dimensions, loading, …
2. In order to take into account making a core in the columns, during construction, for expecting failure in control specimens or for future extensions, the designer can design the columns with overdesign strength not less than 20%.

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Appendix A:

Photo A1–Solid column C1

Photo A2 – Drilled Column

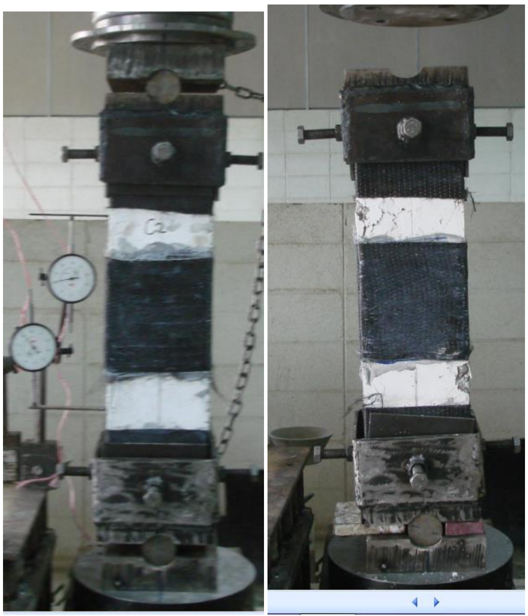

Photo A3 –Strengthened with CFRP,C4

Photo A4- Filled with Cement grout base, C3

Photo A5–Filled and strengthened column C5 (After Loading)

Photo A6 – Strengthened with pie, C6

Photo A7–strengthened with pipe and CFRP C7

Appendix B:

Samples calculations:

$P= 0.80\ [0.85\ f`_c\ (A_g\text{-}A_{st})\ +\ f_y\ A_{st}\ +\ P_{Split}\ ]$ ….(1)

For C1:

P=0.80[0.85x 31.0 x(150^2 -8x80)+570x8x80] /10^3 = 752.6kN

For C2:

P=0.80[0.85x31.0x(150^2-150x50-6x80)+570x6x80] /10^3 = 525.0kN