# Ductility of Reinforced Concrete Columns Confined with Stapled strips

M. F. Tahir[1], Q. U. Z. Khan[2], F. Shabbir[3], M. B. Sharif [4], N. Ijaz[5]

[1,2,3,5]Civil Engineering Department, University of Engineering and Technology Taxila
[4]Civil Engineering Department, University of Engineering and Technology Lahore
[1]fiaz.tahir@uettaxila.edu.pk

***Abstract-***Response of three 150×150×450mm short reinforced concrete (RC) columns confined with different types of confining steel was investigated. Standard stirrups, strips and stapled strips, each having same cross-sectional area, were employed as confining steel around four corner column bars. Experimental work was aimed at probing into the affect of stapled strip confinement on post elastic behavior and ductility level under cyclic axial load. Ductility ratios, strength enhancement factor and core concrete strengths were compared to study the affect of confinement. Results indicate that strength enhancement in RC columns due to strip and stapled strip confinement was not remarkable as compared to stirrup confined column. It was found that as compared to stirrup confined column, stapled strip confinement enhanced the ductility of RC column by 183% and observed axial capacity of stapled strip confined columns was 41% higher than the strip confined columns.

***Keywords-***Columns, Confinement, Strength, Stirrups, Stapled Strips

## I. INTRODUCTION

Confinement of concrete increases both axial strength and ductility of RC columns[1] At peak loads after spalling of concrete cover the strength and ductility of the member will depend upon the confinement of concrete core [i]. Knowledge of behavior of confined concrete helps in calculating the most suitable quantity of confining steel. Confinement also enhances the moment capacity of columns. Affect of confinement on concrete was first time studied by Richart et al[2] and he found that improvement in strength of concrete when confined with lateral fluid pressure is same as when concrete was confined with spirals. It was found that [ii]:-

1. Confinement compensates the strength loss which results due to spalling of concrete cover.
2. Confinement increases the capacity of concrete to carry on large deformations without considerable strength loss.

On the bases of tests researchers suggested that confinement can be improved by [ii-vi]:-

1. Reducing transverse reinforcement spacing
2. Addition of overlapping hoops and ties
3. Uniformly distributing the column bars around perimeter
4. Increasing the ratio between total volumes of transverse reinforcement and the volume of concrete core
5. Increasing yield strength of transverse reinforcement
6. Replacing rectangular ties and cross hoops with spirals or circular ties or strips

The emphasis of this paper is on RC column response in terms of compressive strength and post elastic behavior in terms of stress strain relations. Ductility ratios of concrete columns confined with stirrups, strips and stapled strip have also been calculated and compared. Interestingly it was concluded that by using stapled strip confinement ductility of RC columns can be improved significantly.

## II. EXPERIMENTAL PROGRAM

Three RC and one plain concrete column each 150×150×450mm were tested under cyclic axial load. Structural detailing of RC columns is shown in Figures 1 and 2. Center to center spacing of stirrups as per ACI code recommendation comes out to be 37mm, resulting in clear spacing of 31mm. Strips and stapled strips were also placed at 31mm clears spacing. In all RC columns clear cover to longitudinal bars was 13mm. Type of confining steel used in RC columns and end anchorage conditions of stirrups and strips are summarized in Table I. Nomenclature is explained in the bottom of the table. In second column of this table, 25-S means that 25×1.28mm stapled strips were used as confining steel and 25-H means, 25×1.28mm strips were provided with 135° hooked at the end.

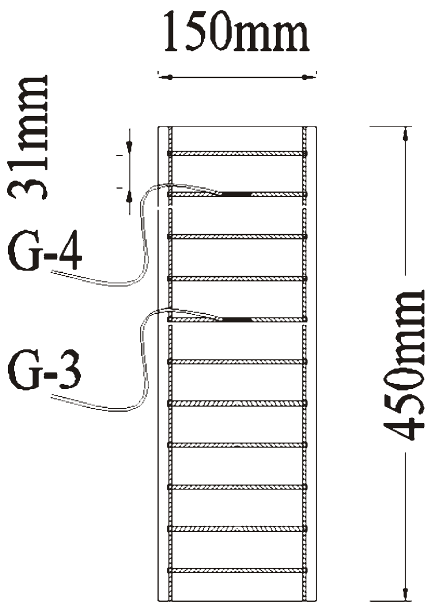


Fig. 1. Structural detailing of stirrup confined columns

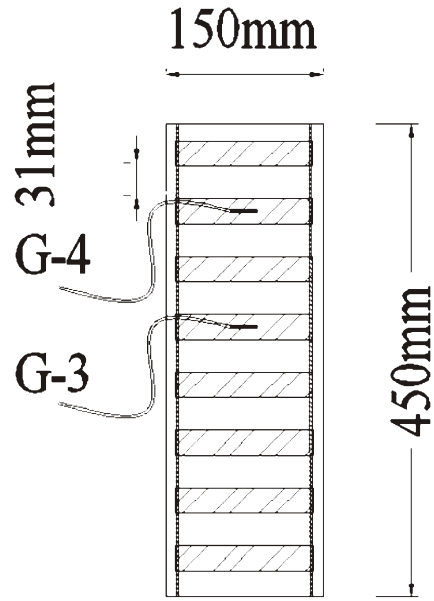


Fig. 2. Structural detailing of stapled strip confined columns

TABLE I
TYPE OF CONFINING STEEL AND END ANCHORAGE CONDITION

| Column No | Type of confinement | Detail of confining steel | End anchorage condition of legs |
|---|---|---|---|
| 1 | *25-#S | 25×1.28 mm strips | Stapled |
| 2 | 25-H | 25×1.28 mm strips | 135° seismic hooks |
| 3 | @BAR-H | 6.35mm diameter deformed bars | 135° seismic hooks |
| 4 | Plain | Confinement was not provided | |

*-25×1.28mm Strip,#-Stapled,@ Round stirrups

Column no 1 and 2 were confined with stapled strips and strips respectively. Figure 3 shows a typical stapled strip used as confining steel. Figure 4 shows the end anchorage condition of strips. Column no 3 was confined with 6.35mm diameter round stirrups. Both stirrup and strips were anchored at ends with 135° seismic hooks.

Fig. 3. End anchorage condition of hooked strip

Fig. 4. End anchorage condition of stapled strip

*Material Properties*

Strength of concrete cylinders at the time of testing of RC columns was 27.6 MPa. Grade 40 (276 MPa), 6.35mm diameter bars were used for stirrups as well as for longitudinal steel. Strips and 35×40mm wide staples (to be used in stapled strips) were cut from the same 1.28mm thick mild steel plate.

Tension test was performed on the coupons cut from plates as per Standard Test Methods for Tension Testing of Metallic Materials "E8M-04". Yield strength and ultimate strength of tested coupons were 286 MPa and 309 MPa respectively

## III. INSTRUMENTATION AND TEST METHODOLOGY

Axial deformation in columns was measured with two gauges installed on opposite faces. Axial deformation in stirrups as well as on strips was measured using electrical resistant strain gauges (ERSG) pasted onto mid of stirrup/strip/stapled strip with M100 glue conforming to ASTM D1002 and 638. In each column, gauges were fixed on two stirrups. G-1 and G-2 gauges were used to measure axial deformation of columns. ERS gauge, G-3 was applied on strip placed in middle height of column and G-4 was pasted on upper half portion. Top and bottom surface of all the columns were capped with plaster of Paris if required. A mild steel 35mm wide and 2mm thick collar was also fixed externally on top and bottom of the column to avoid crushing of concrete in this region. Samples were tested in universal testing machine and loading rate was controlled manually.

Load was applied in cycles at ASTM C-39 recommended loading rate of 0.15-0.35 MPa/sec and was automatically recorded using 1814KN capacity load cell connected to data acquisition system. Initially load cycles applied were load controlled. After reaching the maximum capacity when first few cracks began to appear, load was applied using displacement controlled criteria. Instrument setup is shown in Fig. 5 and 6. Response of all gauges and load cell was automatically recorded using data acquisition system.

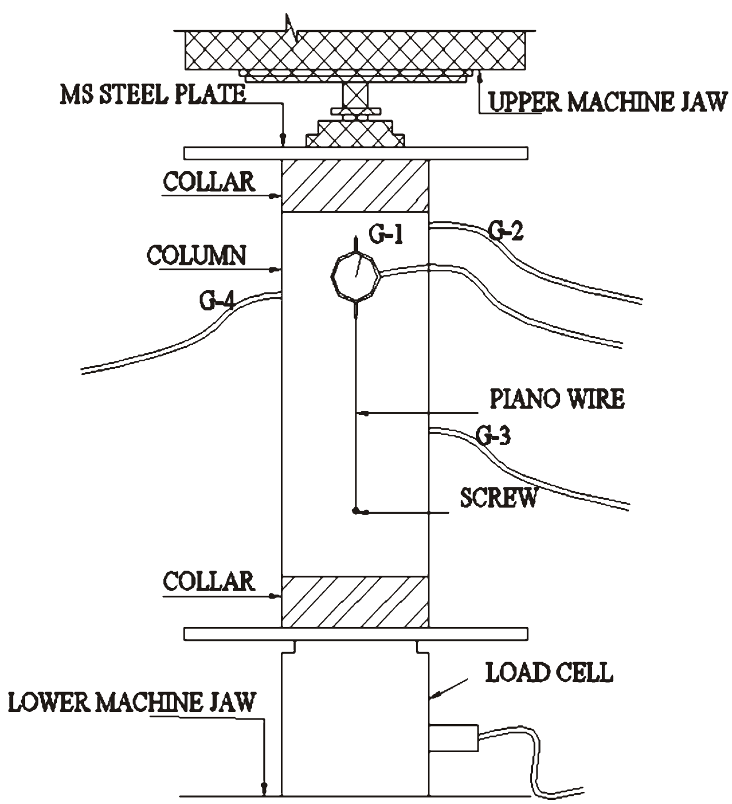


Fig. 5. Instrument setup for axial test

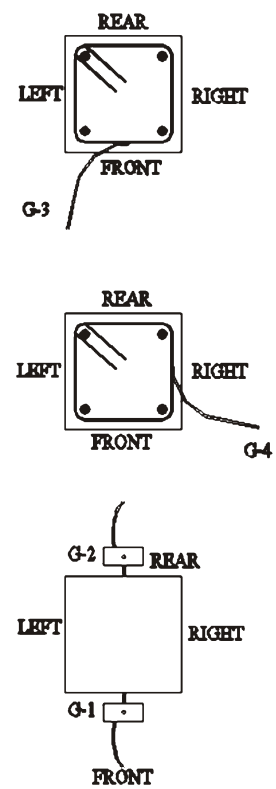


Fig. 6. Location of gauge 1,2,3 and 4

## IV. TEST RESULTS AND OBSERVATIONS

Tested columns are shown in Fig. 7 (a, b and c). As shown in Fig. 7(a) stirrups legs did not open at peak load even after cover spalling. At peak load after initiation of concrete crushing due to loss of bond, seismic hooks tend to open up resulting in loss of anchorage of stirrups. A damaged strip confined column, showing failure of strip confinement at anchorage is presented in Fig. 7 (b). Loss of both strength and ductility as compared to stirrups confinement is obvious Fig. 8. Fig. 7 (c) depicts excellent response of stapled strip confined columns. Staples did not open and provided excellent support to core concrete that improved ductility of columns.

In order to further probe into the response of column theoretical axial capacity of columns, concrete contribution and core concrete contribution towards column strength were calculated for all columns, using equations 1, 2 and 3 respectively. The results were compared experimental results.

*A*. BAR-H confinement *B*. 18-H confinement *C*. 18-S confinement

Fig. 7. Response of columns towards different confining steel.

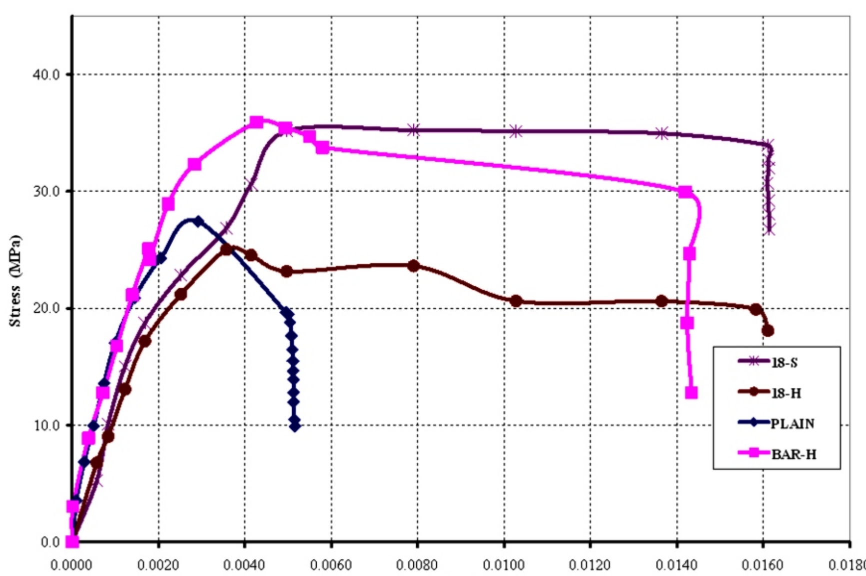


Fig. 8. Stress strain relationship of RC columns.

Axial capacity of the column "$P_o$" was computed using relation [ix]:-

$$P_o = \alpha f_c^{'}\left(A_g - A_s\right) + A_s f_y \quad (1)$$

Value of $\alpha$ varies between 0.85 and 0.9 for large size samples 3 and in this tested program, value of $\alpha$ was "1".

$A_g$ = Gross area of column

$A_s$ = Area of longitudinal steel

$f_y$ = Yield strength of steel

$f'_c$ = concrete strength in this case it is the strength of cylinder at the time of testing

Computed concrete contribution to the column strength under pure concentric loading $P_{oconc}$ is given as [ix]:-

$$P_{oconc} = \alpha f_c^{'}\left(A_g - A_s\right) \quad (2)$$

Computed core concrete contribution under concentric loading was obtained using this relation[8]:-.

$$P_{ocore} = \alpha f_c^{'}\left(A_{core} - A_s\right) \quad (3)$$

$A_{core}$ = Area of core

$P_{test}$ = Maximum column load applied in the test.

$$P_{c\,max} = P_{test} - A_s f_y \quad (4)$$

Comparison of test results and computed values are presented in Table II.

TABLE II
SUMMARY OF TEST RESULTS

| Column No (1) | Type of confinement (2) | Po (kN) (3) | $P_{o\ cocn}$ (kN) (4) | $P_{ocore}$ (kN) (5) | $P_{test}$ (kN) (6) | $P_{cmax}$ (kN) (7) | $P_{test}/P_o$ (8) | $P_{cmax}/P_{ocore}$ (9) |
|---|---|---|---|---|---|---|---|---|
| 1 | 18-S | 652.1 | 617.2 | 427.5 | 792.8 | 666.19 | 1.22 | 1.56 |
| 2 | 18-H | 652.1 | 617.2 | 427.5 | 563.0 | 436.42 | 0.86 | 1.02 |
| 3 | BAR-H | 652.1 | 617.2 | 427.5 | 807.6 | 680.94 | 1.24 | 1.59 |

*A. Axial Capacity of Columns*

The ratio $P_{test}/P_o$ compares the tested capacity of columns with the computed one. For strip confined column the ratio 0.86 shows that capacity of column was 14 % less than expected, due to poor response of strip confinement. This can be further confirmed by comparing the stress strain relation plots of all columns in figure 8. There is not any major difference in strength enhancement as for as columns no 1 and 3 are concerned. By stapling the strips the axial capacity of columns was improved by 41 %.

*B. Core Concrete Strength*

After cover is spalled off, behavior of column largely depends on the performance of core concrete. Core concrete response affects the ductility of column and is largely affected by the degree of confinement. Effect of type of confinement and end anchorage condition on behavior of core concrete was studied with the help of ratio $P_{cmax}/P_{ocore}$. Due to poor response of strips against lateral concrete pressure $P_{cmax}$ was 36% less than stirrup confined columns. However by using stapled strips as confining steel the enhancement in $P_{cmax}$ as compared to strip confined columns was 53%.

*C. Strength Enhancement Factor*

Strength enhancement factor is another term that can be used to evaluate the contribution of confining steel towards over all column capacity. Strength enhancement factor "Ks" is defined as the ratio of maximum confined concrete strength to cylindrical strength of concrete and mathematically it was calculated as [vii].

$$K_s = f_{cc} / 0.85 f'_c \quad (5)$$

The strength enhancement factor for the columns is given in Table III and a graphical representation is given in Fig. 9. Ks for stirrup confined columns and stapled strip confined columns is same with out any major difference. However as was observed in axial capacity, stapled strip confined columns show 41 % improvement in strength enhancement factor.

TABLE III
STRENGTH ENHANCEMENT FACTOR AND DUCTILITY RATIO AT 0.004 STRAINS

| Column No | Type of confinement | $f_{cc}$ (Mpa) | $\varepsilon_{0.85}$ | $K_s$ | $\mu_e$ |
|---|---|---|---|---|---|
| 1 | 18-S | 35.24 | 0.0103 | 1.50 | 4.03 |
| 2 | 18-H | 25.02 | 0.0027 | 1.07 | 2.57 |
| 3 | BAR-H | 35.89 | 0.0040 | 1.53 | 1.42 |

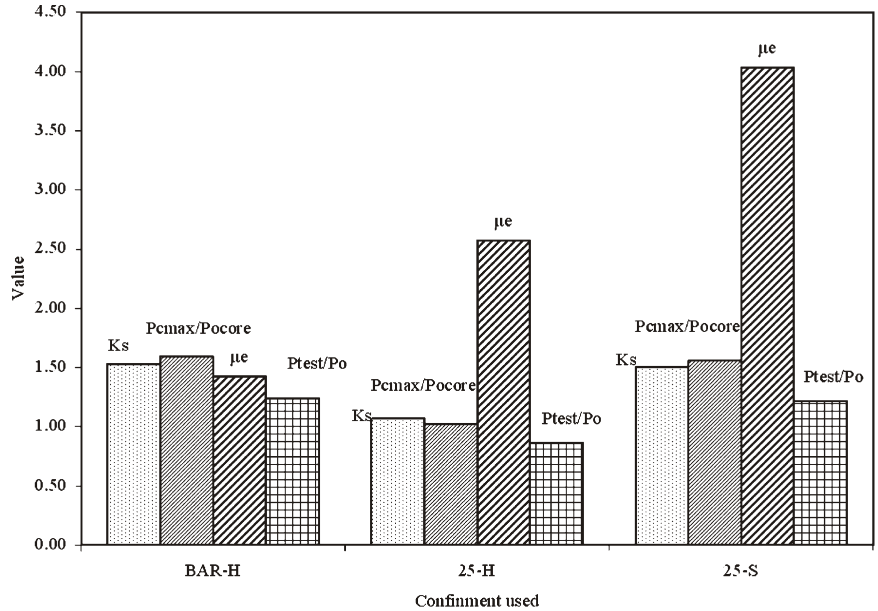


Fig. 9. Response of columns in terms of $K_s$, $P_{cmax}/P_{ocor}$ $\mu_e$ and $P_{test}/P_o$

*D. Ductility Ratio*

Effect of confinement on ductility was evaluated by calculating the ductility ratio $\mu_e$ defined as ratio of core concrete strain to an assumed strain of (0.004) [viii]:-

$\mu_e = \varepsilon_{0.85}\ /0.004$

$\varepsilon_{0.85}$ = Core concrete strain corresponding to the stress at $0.85f'_c$

Although there was not any remarkable increase in strength of strip or stapled strip confined columns as compared to stirrup confined columns but the increase in ductility was significant. Ductility ratio of stapled strip confined column was 183% more than stirrup confine columns and 57% more than strip confined columns. Strip confined columns did not show any strength enhancement but amazingly depicted 80% improvement in ductility ratio.

## V. CONCLUSIONS

Stapled strip confinement as employed in this experimental program depicted an amazing increase in ductility of RC columns. Following conclusions were drawn from this effort:-

1. Core concrete contribution towards over all columns axial capacity, in stapled strip confined columns was 53% higher than strip confined columns.
2. Increase in axial capacity of stapled strip confined columns as compared to strip confined columns was 41%.
3. Strip confined column did no show any improvement in axial capacity. However stapled strip confinement augmented the axial strength of RC column to the level of stirrup confined columns.
4. Ductility ratio of stapled strip confined column was 183% more than stirrup confine columns and 57% more than strip confined columns.
5. Strip confined column did not show any strength enhancement but amazingly as compared to stirrup confined column it depicted 80% improvement in ductility ratio.

## VI. ACKNOWLEDGMENT

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