Effect of Steel Confinement on Axially Loaded Short Concrete Columns

H Farooq¹, M Usman¹, K Mehmood², M S Malik¹, A Hanif²

¹School of Civil and Environmental Engineering, National University of Science and Technology, Sector H-12, Islamabad, Pakistan
²Department of Civil Engineering, Mirpur University of Science and Technology, Allama Iqbal Road, Mirpur AJ&K, Pakistan

E-mail: asadhanif@must.edu.pk

Abstract. This paper presents experimental investigations of Reinforced Concrete columns strengthened with steel strips and steel jacket under axial compression loading. Total of six specimens were prepared in the laboratory, out of which; 1) two columns were unconfined columns, 2) two columns were strengthened with steel strips and 3) remaining two columns were strengthened with a steel jacket. All specimens were subjected to axial compression loading in increment until the failure of specimens using UTM at NUST. It was concluded after the experimental work that the steel strips enhanced axial load carrying capacity by a factor up to 1.54 times and steel jacketing enhanced the capacity by a factor of 2.38. It has also been observed that the steel confinement increased the cracking load by a factor up to 1.5 to 2.66 for strips and jacketing respectively. The failure occurred due to the crushing of concrete and buckling of steel strips and jacket between the fasteners. The steel strips and jackets are economical and feasible options for confining the concrete to increase its axial load carrying capacity.

Keywords: Aging, steel, concrete, reinforced columns

1. Introduction

Aging and adverse conditions are increasing the vulnerability of many old deteriorated concrete buildings [1]. The need to improve the behavior and safety of un-confined concrete buildings is becoming increasingly important [2]. Some of the methods to strengthen load bearing structures are to apply fiber-reinforced polymers (FRP), Steel Jacketing [3]. Taghdi [4] strengthened the masonry walls for improving their shear behavior by diagonally applying the steel strips and stated them to be quite effective. Despite the effectiveness of diagonal steel strips, the problems associated with the modification in aesthetics and augmented mass were not addressed, K C Voon [5] employed vertical and horizontal arrangement of steel rebars to enhance the shear strength of walls, and eventually stated them to be effective in their results. The same research also concluded that the employed arrangement of rebars also improved the post-tensioned behavior of walls. The research conducted by Farooq et. al. [6, 7] also stated improvements in the compressive and shear behavior of masonry by means of lightweight steel strips, mounted on their surface. The research also concluded that no significant improvement in compressive strength was observed by reducing the spacing of horizontal strips. Strengthening is essentially a requirement for reinforced concrete (RC) columns, manufactured with low quality of materials, with inadequate reinforcements, and insufficient splice lengths. In addition to improvement in the load-bearing capacity, strengthening is often executed in a manner that it results in altering the failure pattern from brittle to ductile, and for strengthening, numerous techniques are available and utilized, as indicated by the literature [8].

Each strengthening methodology has its own suitability along with particular limitations. One such prominent technique is the use of steel jackets in which versatile configurations i.e. steel caging; wrapping, etc. are adapted to confine the columns. The most common form among these is the steel caging in which four steel angles, followed by the welding of horizontal steel straps at particular
intervals along a column’s height, are positioned at the corners of an RC column. Such a technique is usually employed during the strengthening process of square and rectangular X-Section columns. Tarabi and Albakry [9] has stated that such a method is typically considered swift and economically feasible. Moreover, the worthy contribution towards the enhancement of dynamic performance, improvement in the axial load bearing behavior, and increased ductility are other advantages attributed to this strengthening technique [9-13]. The technique is broadly employed and practiced in the United States, Japan, and Taiwan [11, 14], and has been regarded as highly effective for post-earthquake retrofitting of axial structural elements [15]. From the literature, it can be stated that columns, after being strengthened by means of steel jackets, may exhibit two different failure configurations. The first pattern of failure indicates the yielding of angles [9, 16, 17], while the second configuration of failure may be observed when yielding occurs in horizontal strips. This particular failure pattern is witnessed when the length of a cross-sectional dimension of a column is bigger than the length of angles. Thus, after the application of an axial load, the lateral dilation of concrete exposes the horizontal strips to additional pressures [9, 10]. The structural capacity of a column is greatly influenced by the spacing of strips. In this regard, [16] made an extensive study to assess the variation in the load carrying capacity of strengthened columns by varying the spacing of the horizontal steel strips throughout the columns’ height. The research concluded that increased spacing eventually resulted in decreasing the structural capacity of columns. Similarly, the behavior of steel-jacketed RC columns was also studied by Belal [18]. In his research, C-sections, steel angles, batten plates, and steel plates with specific intervals were used for strengthening purposes. The experimental test revealed that strengthening increased the failure load and load carrying capacity by 18% - 45%.

Considering the cost and difficult implementation of available concrete strengthening procedures, the need for some cost-effective technique was highly desirable which should involve local materials and nominal skill [19-21]. To cater to this issue, the technique used by Farooq et. al. [7] for strengthening masonry was used for the confinement of the un-strengthened concrete columns. The concrete columns were strengthened using lightweight Steel Strips and compared with the already available Steel Jacketing technique to study the efficacy of lightweight steel strips strengthening on existing concrete short columns. The application of steel strips has effectively addressed the issues of alterations in aesthetics and the augmented mass and is found to be quite cost-effective. This research is, however, limited to investigate the axial strengthening of columns only. The behavior of the strengthened columns will be carefully studied with due importance to the stress-strain behavior, composite action and the confinement effect. Experimental results revealed that steel strengthening resulted in significant increase in axial capacity, modulus of elasticity and improved compressive behavior.

2. Specimen preparation and material properties

This study is focused on the experimental testing of strengthened short columns with the geometry of 152.4 x 152.4 x 355.6 mm with 4#3 longitudinal bars and 3#2 ties @ 100 mm c/c with 25 mm cover in the laboratory. The Specimen columns were prepared in the laboratory for carrying out compression test using the universal testing machine. Total six short columns were prepared. Out of six specimens; two specimens were reference specimen, two were strengthened with steel strips and two were strengthened with steel jacket as shown in table 1.

The specimens were prepared using 1:2:4 cement-sand-aggregates with w/c ratio of 0.55 and the mechanical properties of the material is shown in table 2. To achieve uniform compaction up to the best possible level vibratory compactor was used. After a moist curing period of 28 days, samples were taken out of the curing tank and placed in the laboratory at normal conditions of temperature and moisture until their surface became dry. The materials were tested in the concrete laboratory of Military College of Engineering Risalpur, Pakistan. Galvanized steel sheet was used for jacketing of columns. For both categories, steel strips as well as steel jackets the same 17-gauge steel with a thickness of 1.41 mm was used. The cross-sectional dimension of steel strips was 50.8 x 1.41 mm. The steel strips were anchored all around the columns using Hilti-Impact Anchors. Each anchor had a
capacity to resist a force of 0.25 KN. These anchors were 45mm long with 6mm diameter. Six columns were prepared all having a height of 355.6 mm with same aspect ratio as shown in figure 1.

Table 1. Designation of concrete specimens.

| Specimen Type                          | ID  | No of Specimen | Cross section (mm) | Height (mm) | Steel confinement       |
|----------------------------------------|-----|----------------|--------------------|-------------|-------------------------|
| Reference specimen                     | RCC | 2              | 152.4x152.4        | 355.6       | nil                     |
| Strip strengthened column              | SSC | 2              | 152.4x152.4        | 355.6       | Horizontal strips; spacing 101.6 mm, thickness 1.41 mm, cross section 50x1.41 mm Vertical strips; spacing 101.6 mm, thickness 1.41 mm, cross section 50x1.41 mm |
| Steel jacket strengthened column       | JSC | 2              | 152.4x152.4        | 355.6       | Steel jacket Thickness 1.41 mm, Cross section 152.4x1.41 mm |

Figure 1. Test specimens; (a) Reference Concrete Columns- RCC, (b) Stripped strengthened Columns- SSC, and (c) Jacket strengthened columns– JSC.

Table 2. Results of the material characterization test.

| Item                  | Properties              | Values    | Standard          |
|-----------------------|-------------------------|-----------|-------------------|
| Fine Aggregate        | Fineness Modulus        | 2.42      | ASTM-127/128      |
|                       | Bulk Specific Gravity   | 2.328     |                   |
|                       | Avg Absorption          | 1.56%     |                   |
|                       | Unit weight             | 1489.53 Kg/m³ |               |
| Coarse Aggregate      | Specific Gravity        | 2.665     | ASTM-127/128      |
|                       | Avg Absorption          | 1.066%    |                   |
|                       | Unit weight             | 1225.63 Kg/m³ |               |
|                       | Crushing value          | 24.46%    | BS882:1965        |
|                       | Impact value            | 15.42     | BS812:1967        |
| Confining Steel       | Yield strength          | 235 MPa   | -                 |
|                       | Ultimate strength       | 303 MPa   | -                 |
2.1. Test specimens
Six columns were prepared all having a height of 355.6 mm with same aspect ratio. These specimens were divided into two groups. Each column accompanied 3 concrete cylinders for its 28 days compressive strength (f’c).

2.2. Instrumentation of specimens
Universal Testing Machine was used to subject the columns to tests. Strain and deformations were measured by employing strain gauges, mechanical gauges and LVDTS. The two faces of column contained strips in which the horizontal and vertical strains were recorded by using four strain gauges. Similarly, the horizontal and vertical strains in concrete were recorded by using four mechanical gauges, while for measuring the out of plane deflections in the columns, three LVDT were eventually employed, as depicted by the figure 2.

![Figure 2](image)

**Figure 2.** (a) Instrumentation of test specimens, (b) Cross section with reinforcement details

3. Results and discussion
3.1. Stress-strain relationship
Stress-axial strain relationship is shown in Figure 3a. The un-strengthened column failed at a stress value of 16.63 MPa and strain recorded was 0.0087 whereas, steel strip confined column failed at a value 54 % greater and jacket strengthened columns at a value 138 % greater than the un-strengthened column. This shows that the increase in the amount of confinement affects significantly the load carrying capacity that is evident from the proportion of the increase in strength with the amount of confinement. The cracking stress (stress at which the first crack appeared in the masonry during loading) and strain for strengthened columns have increased considerably. The increase in cracking stress for strengthened columns as compared to specimen RCC is by a factor of 1.5 for SSC, 2.66 for JSC column specimens as summarized in table 3.

| Specimens | 28days f’c (MPa) | Compressive Stress (MPa) | Normalized Stress | Ultimate Strain | Cracking Stress (MPa) | Normalized Stress |
|-----------|------------------|--------------------------|-------------------|----------------|----------------------|------------------|
| RCC       | 19.72            | 16.63                    | -                 | 0.0087         | 11.52                | -                |
| SSC       | 18.7             | 25.58                    | 1.54              | 0.00943        | 17.91                | 1.50             |
| JSC       | 21.45            | 39.65                    | 2.38              | 0.0089        | 30.69                | 2.66             |

Table 3. Summary of Test results.
The obtained stress versus strain relationships in axial and lateral directions of the specimens are presented in figure 3b. In almost all the cases, the curves come out to be bilinear, possessing no descending branch. The ultimate stress has been increased by the virtue of confinement provided by the steel strips; nevertheless, the unconfined columns exhibited bigger ultimate lateral strains in comparison with those of confined columns. For confined columns, with a substantial increase in stress, the escalation of lateral strain is less. Thus, it is observed that the ultimate stress of SSC and JSC specimens are 1.54 and 2.38 times higher than those of RCC specimen respectively. Similarly, the cracking stress and strain have also increased considerably. The increase in the lateral strain value in comparison to the axial strain value in a column for confined ones was very less than the unconfined specimens causing the increase in strength. These less lateral strains were definitely arrested by the steel strips. The unconfined columns showed contraction initially and then dilated because of the crushing of unconfined concrete. The very fewer strain values will also be there in steel strips which give the direct contribution of steel in strengthened is less and the main enhancement comes from the confinement effect and the composite behavior of the columns. Stress-axial Strain behavior of steel strips indicated that steel strips maintained their elastic limit and did not step into plasticity. All confined columns manifested extremely small axial strains. The smaller values of strain essentially indicate that the strength gain is attributed to the confinement provided by the strips and steel jacket. It is evident from the results that the axial strength of columns confined with steel strips has increased considerably due to confinement and the composite behavior but with variations.

3.2. Failure pattern

For specimen RCC, minor cracks appeared at a compressive stress of 11.52 MPa. More cracks appeared and widening of existing cracks occurred with increasing load. Splitting of the concrete cover was observed followed by complete failure of the RCC specimen. The column failed at a compressive stress of 16.63 MPa and a strain value recorded was 0.0087. The un-strengthened RCC specimen experienced brittle failure and crushing / spalling of concrete was observed as shown in figure 4a. A brittle failure was observed for RCC with cracking initiated at the top and penetrated to the bottom, eventually resulting in the crushing of concrete.

Figure 4. Pictorial view of test specimens after failure; ((a) Reference Concrete Columns RCC, (b) Stripped strengthened Columns SSC, and (c) Jacket strengthened columns JSC.)
Minor cracks appeared at a compressive stress of 17.91 MPa was observed in case of strip-strengthened concrete columns specimen SSC and failure of the column occurred at a compressive stress of 25.58 MPa with strain value of 0.00943 at the failure. Both confined columns exhibited an analogous pattern of failure. After the development of cracks in concrete, they became wider, eventually causing the crushing of the material inside the columns. The confinement of concrete columns with steel resulted in a considerable increase in cracking stress. The cracks were well distributed and both the confined specimens experienced ductile failure. The bending and pulling out steel strips due to crushing of concrete was observed at failure in case of specimen SSC (figure 4b). In case of specimen JSC, at failure bulging and crushing of concrete was observed causing opening of steel jacket at corner (figure 4c). At a stress value of 30.69 MPa minor cracks appeared in case of specimen JSC. The column failed at a compressive stress of 39.65 MPa with a strain value of 0.0089 was recorded at the failure as summarized in table 3.

3.3. Poisson’s ratio
Poisson’s Ratio plays an important role in describing the behavior of unconfined and confined reinforced concrete columns. Figure 5 and Figure 6 show the relation between Poisson’s ratios versus the axial strain for the unconfined and confined reinforced concrete columns. The failure of the concrete tied column is characterized by the development of hairline cracks which make the compression member, incapable of resisting tensile stresses. This abrupt failure of columns with outward buckling of longitudinal bars between ties is changed to gradual and ductile failure by confining patterns of steel strips and jacketing. As shown in Figures, Poisson’s Ratio of confined columns is higher in all of the two groups as compared to unconfined columns. In case of group 1, the values of confined columns are greater than unconfined columns by a factor of 2 to 3 in case of SSC and JSC which indicates the effectiveness of steel strips and steel jacket in strength enhancement and improving the behavior of specimens. In addition, for the strengthened specimens the value of lateral/axial strain stabilized at approximately the same value regardless whether the strengthening was by steel strips of steel jacket.

![Figure 5. Poisson’s Ratio vs vertical strain plot.](image)

![Figure 6. Volumetric Strain vs Vertical Strain.](image)

3.4. Volumetric strains
Volumetric strain for all the specimens was calculated using the equation 1 and figure 6 shows the axial strain / volumetric strain $\varepsilon_v$ relationship. The negative value designates contraction, whereas a positive value specifies expansion or the dilation. Figure 6 shows that the phenomenon of contraction has been observed by all the columns with no dilation during the test and volumetric strain value is increasing with increase in axial strain. This particular behavior is mainly attributed to the elastic response rendered by the steel strips and steel jacketing systems respectively which caused the rupture of the specimen because of the consistent increase in confining pressure. For all confined columns, the contraction has been observed which is followed by no recovery, while for unconfined specimen RCC, initially the contraction was observed which was followed by the recovery branch. Due to the
compressive load, the contraction was observed in specimen RCC. Eventually, the lateral strain escalated after the initiation of cracking in comparison with the axial strain. This increased in lateral strain ultimately caused the expansion and final failure of columns. While in confined columns, steel jacketing and steel strips effectively countered the proliferation of lateral strain which ultimately resulted in increasing the strength and eventually postponed the cracking itself. Equation 1 was used to calculate volumetric strains and maximum values recorded were 0.018, 0.028 and 0.049 respectively for RCC, SSC, and JSC.

\[ \varepsilon_A + 2\varepsilon_l \]  
\[ \text{where } \varepsilon_A = \text{axial strain}; \varepsilon_l = \text{lateral strain}. \]  

3.5. Axial – lateral strain relationship
Axial verses lateral strain nexus for concrete is shown in figure 7, which is based on the absolute values of compressive axial strains. For the case of unconfined columns, the almost linear relationship is observed between axial and lateral strains from 0.1% to 0.2% of axial strain values. Afterward, the concrete begins to laterally dilate at a higher rate because of the accretion of damage, which ultimately renders the softening in the relationship of axial/ lateral strain. For the case of confined columns, the axial/lateral strain relationship remained immune to the effects of steel jacket and the steel strips. This essentially implies that response of unconfined columns and confined columns were almost similar initially because of the insignificant concrete lateral dilation. After that, the imposed axial strain initiates to increase at a higher rate than that of the lateral strain during a transition regime where the concrete dilation is counteracted because of the presence of steel jacketing and steel strips. Finally, the strengthened specimens dilated laterally because of the accumulated damage due to an increase in axial strain.

The Modulus of Elasticity values of confined specimen columns were 42% and 133% higher than the specimen RCC for specimens SSC and JSC respectively as shown in figure 8. Higher values of modulus of elasticity is due to additional strengthening being provided by steel confinement. The steel jacket was the most effective in increasing the strength.

![Figure 7. Axial strain vs lateral Strain.](image)

![Figure 8. Comparison of E values for columns.](image)

3.6. Confinement effects
Steel strips were responsible to provide passive confinement to concrete columns; however, the horizontal strips remained essentially unstressed for the small axial load. The lateral strain in concrete got elevated and the additional strain was taken by the steel strips, thus forming a confinement pressure at axial loads ranging from 11.52 to 14.06 MPa. Vertical stripes, due to their confinement effects, significantly improved the axial strength of the specimens, as projected by the figures above. Equation 2 is used to calculate the axial strength of the specimens.
\[ P = P_m + P_c + P_{st} \]  
\[ P = \text{Axial strength of the specimen} \]
\[ P_m = \text{Strength due to concrete} \]
\[ P_c = \text{Strength due to confinement} \]
\[ P_{st} = \text{Steel strips contribution to the axial strength} \]

The following equation number 3 was used to calculate the rendered impact of the steel strips to the axial load:

\[ P_{st} = n \varepsilon_{st} E A \]  
\[ n = \text{total number of steel strips} \]
\[ \varepsilon_{st} = \text{strain in steel strips} \]
\[ E = \text{Young’s Modulus of the steel strips} = 16875 \text{ MPa} \]
\[ A = \text{Cross-sectional area of a steel strip} = 76.2 \text{ mm}^2 \]

Substituting these values in Eq. 3, the contribution of the steel strips to the axial load can be calculated. According to one of the module by Triantafillou is derived on the basis of Mander’s Model. The model was originally proposed to evaluate the effective confinement pressure for tangular concrete cross sections, confined with steel. In Mander’s model, the effect of confinement can be calculated and the same model was used by Triantafillon for calculating the effect of steel confinement on compressive strength of unconfined concrete. The relation between the compressive strength of unconfined concrete \( f'_{co} \) and confined concrete \( f'_{cc} \) is evaluated using the following equation.

\[ \frac{f'_{cc}}{f'_{co}} = 2.254 \sqrt{1 + 7.94 \frac{f'_{1}}{f'_{co}} - 2 \frac{f'_{1}}{f'_{co}} - 1.254} \]  
\[ \text{Where } [f']_1 \text{ is the effective confining lateral pressure. The percentages of confining pressure, i.e., } [f']_1/[f']_co \text{ for SSC and JSC are 0.094, 0.33 respectively.} \]

4. Conclusions
The conclusions are drawn and observations made from the study of confinement of short concrete columns are as follows:

- Axial strength of concrete columns is greatly enhanced by using steel strips. The steel strips also proved to be effective in increasing the axial strength of confined columns.
- The significant increase in axial strain with respect to lateral strain shows increased ductility and when coupled with high compressive strength, it justifies the used of additional confinement in retrofitting and new construction.
- The strength enhancement was mainly attributed to the confining effect provided by the steel for a composite behavior, while the direct contribution made by the steel for increasing the strength was less.
- Considering the easy availability of raw materials for the proposed strengthening technique, it offers a great advantage over more sophisticated strengthening techniques.
- Additionally, with the minimum additional cost, this study will help the strengthening and retrofit of rural structures.
- The use of steel strips can further study for other types of loadings also in order to develop it into a more comprehensive retrofitting technique.

References
[1] Bhasker P T 2015 Aging Effects on Structural Concrete and Long-term Storage of Spent Nuclear Fuel in DCSS at ISFSIs Transactions, SMiRT-23 Manchester, United Kingdom - August 10-14, 2015
[2] Wewin I 2018 Strengthening method of concrete structure IOP Conf. Series: Earth and Environmental Science 126 012051
[3] Kim S W 2017 Strengthening methods for reinforced concrete infrastructure using FRP composites Proc. of the Inst. of Civil Engrs. – Str.and Bldg. 1-10
[4] Mustafa T et al 2000 Seismic retrofitting of low rise masonry and concrete walls using steel strips J. of Str. Engg. 126 1017-1025
[5] Voon K C and Ingham J. M. 2007 Design Expression for the In-Plane Shear Strength of Reinforced Concrete Masonry J. of Str. Engg. 133 706-713.
[6] Farooq S H. et al 2006 Technique of Strengthening Masonry Wall Panels using Steel Strips Asian J. of Civil Engg. 7 625-642.
[7] Farooq S H. et al 2008 Effect of Horizontal Reinforcement in Strengthening of Masonry Members Mehran Uni. Res. J.of Engg. & Tech. 27 49-62.
[8] Shri B. and Pravin W 2011 Materials and Jacketing Technique for Retrofitting of Structures Int. J.of Adv.Engg Res. and Stud. 1 5-19.
[9] Tarabi A M and Albakry H F 2014 Strengthening of RC columns by steel angles and strips Alexandria Engg J 53 615–626.
[10] Badalamenti V et al 2010 Simplified model for compressive behavior of concrete columns strengthened by steel angles and strips ASCE J. Eng. Mech. 136 (2) 230–238.
[11] Choi E et al 2013 Effect of steel wrapping jackets on the bond strength of concrete and the lateral performance of circular RC columns Engg. Str. 48 43–54.
[12] AreemIt N et al 2015 Strengthening of Deficient RC Columns by Steel Angles and Battens under Axial Load Department of Civil Engineering, Khon Kaen University, Thailand.
[13] Adam J M et al 2009 Axially loaded RC columns strengthened by steel caging. Finite element modeling Const. and Blög Mat. 23 2265–2276.
[14] Lin M L et al 2010 Seismic steel jacketing of rectangular RC bridge columns for the mitigation of lap-splice failures Earthquake Eng.Struc. Dyn. 39 1687–1710.
[15] Wasti S T and Ozcebe G 2006 Advances in earthquake engineering for urban risk reduction Nato Science Series: IV: Earth and Environmental Sciences 66 1-552.
[16] Cittek L. 2001 RC columns strengthened with bandage experimental programme and design recommendations Const. and Bldg Mat. 15 341-349.
[17] Calderón P A et al 2009 Design strength of axially loaded RC columns strengthened by steel caging Mat.and Des.30 4069–4080.
[18] Belal M F et al 2015 Behavior of Reinforced Concrete Columns Strengthened by Steel Jacket HBRC J. 11 201-212.
[19] Hsu C T et al 2003 Flexural strengthening of reinforced concrete beams using carbon fibre reinforced polymer strips Mag. Conc.Res. 55 (3) 279-288.
[20] Das A K et al 2018 Design of propping schemes of 60-storey reinforced concrete building: a case study Proc. of the Inst. of Civil Engrs. – Str.and Bldg. 171 (5) 409-424.
[21] Lu C et al 2018 An investigation on the behavior of a new connection for precast structures under reverse cyclic loading Engg. Str. 169 131–140.