Strengthening of Reinforced Concrete Columns by Steel Jacketing: A State of Review

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Abstract—**This paper aims to review the strengthening techniques of Reinforced Concrete (RC) column using steel jacket. Steel jacket usually consists of steel plates or angles and batten plates/strips with different configurations. Both experimental and analytical investigations conducted by researchers have been reviewed. Most of the investigations were focused to know the effect of strengthening configurations on load carrying capacity, ductility, lateral strength and flexural strength by changing parameters like strip thickness, size and spacing, concrete strength, angle size and thickness. Comparisons between the results of the experimental investigation and analytical equations proposed by different researchers and design codes have been illustrated. It has been found from the literature that load carrying capacity depends on aforementioned parameters. The experimental investigations conducted by several researchers reveal that the overall increase in axial strength ranges from 18.65% to 109% and that of lateral strength from 63% to 68%.**

***Key words*—angles, strips, strengthening, steel jacketing, steel plates.**

I. Introduction

The Reinforced Concrete (RC) columns having inadequate longitudinal and transverse reinforcement, and inadequate length of lap splice of longitudinal reinforcement, use of inferior quality material, misalignment or misplacement of reinforcements are often required to be strengthening. Strengthening is done in a manner so that it can change the failure mechanism from brittle to ductile mode in addition to enhancement of load carrying capacity. It is also expected that strengthening technique would be non-interruptive, less time consuming, less expensive, and the least floor area user.

Different techniques of RC column strengthening are available in the literature [1]. Each of these strengthening system possess of both certain conveniences and specific shortcomings. The following sections illustrate the advantages and disadvantages of various strengthening system according to their behavior and engineering point of view.

A. Steel Jacketing

One of the promising strengthening techniques is steel jacket in which steel angles / Plates are used for confining the column concrete with different configurations like steel wrapping Fig.1 (for circular column), Steel Plates and steel caging Fig. 2(a). Steel caging is one of easiest and common version among them, which consists of four steel angles, placed at the corners of RC column and steel straps/battens are used horizontally, welded to the angles with a specific interval along the height of the column Fig. 2(a). The tiny gap between the concrete and the caging is filled up with non-shrink cement mortar or epoxy grout. It is commonly used strengthening technique of RC columns with rectangular and/or square cross-section. The method is generally regarded as realistic, swift and cost-effective [2]. Additionally, it improves overall seismic performance of the structure by developing lateral strength, axial load carrying capacity, the ductility and shear capacity of structural members [2, 3, 5, 6, 18]. The technique is widely used in construction field, particularly in Japan, Taiwan and the United States [4, 5] and has been found applicable in retrofitting of damaged RC columns after earthquakes [17].

B. RC Jacketing

The application of a thin layer of reinforced concrete around an existing RC column is referred as RC jacketing Fig.1 (a), Fig 2(b). For ensuring the proper bond between the surface of old and new concrete, adequate numbers of anchored bars/shear keys and adhesive materials are used. It is expected that confinement can be improved easily, as the transverse reinforcement can be placed in the exterior of the longitudinal bars at any spacing required. However, the confinement through RC jacketing on rectangular or square cross section are not as effective as for circular cross sections. Literally, it is easy to install, and improves the ductility, shear capacity and load carrying capacity. In contrast, one of the most remarkable disadvantages of RC jacketing is the section enlargement, which is often not accessible. In addition, RC jacketing needs dowelling the reinforcing bars to the footing, eventually in many cases the failure mode is shifted there and becomes vulnerable, thus retrofitting of that specified footing is required.

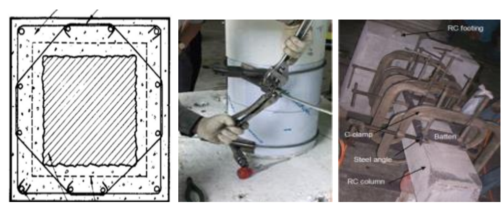


Fig. 1.Cross section of RC jacket; Steel wrapping; Installation of steel cage.

Fig. 2. (a) Steel Jacketing(b) RC jacketing (c) FRP jacketing.

C. Composite Jacketing

Composite jacketing is named due to use of different composite fibers, commonly carbon or aramid fibers with organic resin or epoxy resin. It is also referred as fiber reinforced polymer (FRP) which is recently considered as "new" and highly reliable materials in the construction industry. The fibers are a type of unidirectional flexible sheets or fabrics (can be woven or unwoven) that contains fibers in at least two different directions. The fibers are then wrapped to the concrete using the resin Fig. 2(c). In composite jacketing, the fibers are only considered for carrying the stresses in the respective directions. Composite jackets are light weighted about one-fourth of the steel. It includes easy to application in limited space, cut the necessity of intensive surface preparation that result reducing the labor costs and provide the substantial ductility. However, the worst things observed over the composite jacketing are: vulnerable to fire, composite materials behave linearly elastic, which causes member failure without yielding or plastic deformation results low ductility. Furthermore, the fibers and resign are very expensive as compared to steel or concrete. Composite jacketing is effective only for the columns with circular or elliptical in shape. Unlike steel and RC jacketing, it has incompatible thermal expansion coefficients.

II. Capacity Of Steel Jacketed RC Columns

In the past decades, several analytical models have been proposed for the determination of load carrying capacity of RC strengthened columns using steel caging, by design codes as well as researchers. The following are some of the proposed models.

A. Eurocode No. 4 (1994)

According to Eurocode No. 4 [7] the ultimate load carrying capacity of a RC column, strengthened with steel angles and strips can be calculated as follows

$$P_{EC4} = 0.85(b.d)\,f_c + A_s.f_{ys} + 8.(L_1.t_1).f_{yL} \quad (1)$$

where,b, d= side dimension of RC column; f_c= compressive strength of concrete; A_s= area of longitudinal steel; f_{ys}= yield stress of longitudinal steel; L_1= leg length of angle; t_1= thickness of angle, and f_{yL}= yield stress of steel angles respectively.

B. Regalado (1999)

Regalado's design equation [8] evaluates the allowable load carrying capacity due to the deformation variation between concrete column and the strengthening system. It reflects a lower ultimate load capacity of strengthened RC column than from Eurocode No. 4 [7], according to Eq. (2)

$$P_{Reg} = 0.6*(0.85b.d.f_c + A_s.f_{ys} + 8.L_1.t_1.f_{yL}) \quad (2)$$

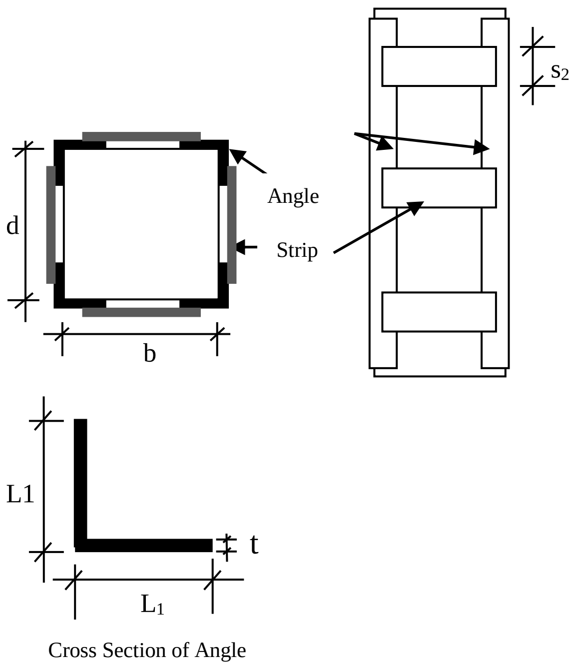


Fig. 3: Components of Steel Jacketing.

C. Calderon et al. (2009)

Calderon et al. [9] proposed a design equation for determining the ultimate load that is carried by a RC column strengthened with steel angles and battens. The formula is founded on the analysis of failure mechanisms observed in experimental and numerical approaches performed on full-scale specimens. Finally, the proposal was verified by comparing the results obtained from application of proposed formula, laboratory specimens test and FE models test. However, the proposed design formula is expressed by Eq. (3).

$$P_{cal} = 0.85b.d.f_c + A_s.f_{ys} + 2.5.f_l.b.d + N_L \quad (3)$$

where, f_l= confinement pressure; N_L= axial force carried by angles.

The parameters f_l and N_L are calculated by considering two possible types of failure modes: failure by yielding of angles or failure due to yielding of stripsof the strengthened column. The following section deals with the earlier two cases.

1) Failure caused by yielding of angles

Failure by yielding of angles is one of the criteria in which angles are buckled in the middle portion of two strips. When it happens it is obvious that the angles are no longer able to

confine the concrete. The mechanism is that three plastic hinges are formed at three locations of an angle similar as Fig.4 (a) that indicate the weakest point of the angles.
To calculate the axial force N_L in the angle, let us consider the initial load N_0 is subjected to the column, N_L is derived from Eq. (4), thus reaching at the axial load carried by the angles between the two strips. For finding maximum confinement pressure (f_l), the formations of the three plastic hinges are assumed to occur at three different locations indicated in Fig. 4(a). Analyze the angle between two strips as a fixed ended beam subjected to a uniformly distributed load of q_h which is determined from Fig. 4(a). by considering the equilibrium condition of the angle as illustrated in Fig. 4(c) and Fig. 4(b). Thus plastic moment M_p is obtained, f_l can be calculated by applying Eq. (8), obtained from Eq. (6) and Eq. (7).

$$N_L = N_o.(1-e^{-m.s_2}) \quad \text{.......(4)}$$

$$m = \frac{\mu.4.\upsilon_c}{b.\left(1-\upsilon_c+\frac{b.E_c}{2.t_2.E_L}\right)} \quad \text{.......(5)}$$

where, *μ= the friction co-efficient; b = the side of column; υ_c = Poission ratio of concrete; s_2= width of strip; t_2 = thickness of strip; E_L, and E_c = elastic modulus of caging steel and concrete respectively.*

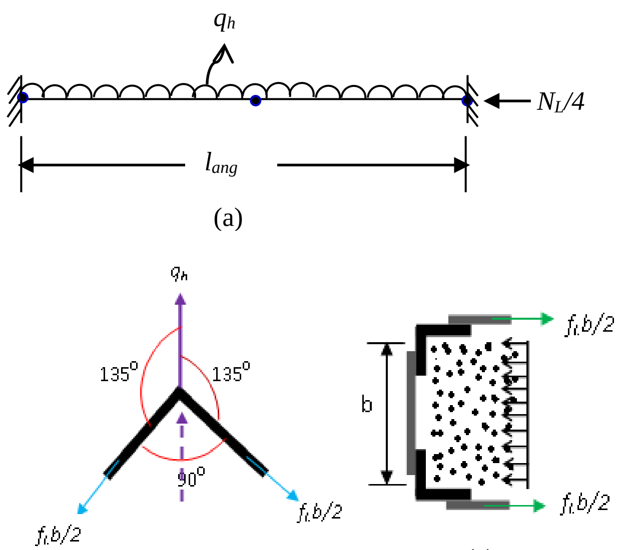


Fig. 4. (a) Formation of plastic hinge; (b) force acting on an angle, and (c) confinement pressure on angle

$$q_h = \frac{16}{l_{ang}^2}.M_p \quad \text{.......(6)}$$

$$f_l = \frac{q_h.\sqrt{2}}{b} \quad \text{.......(7)}$$

$$f_l = \frac{16.M_p\sqrt{2}}{l_{ang}^2.b} \quad \text{.......(8)}$$

The ultimate load for the case of failure by yielding of the angles will be obtained from Eq. (3) after adding the N_L and f_l parameters, which were obtained by the procedure described above.

2) Failure caused by yielding of strips

A second type of failure is observed due to the yielding of strips when it is subjected to an axial load of $t_2.s_2.f_{yL}$ perpendicular to the longitudinal axis of the column. Confinement pressure that is induced on the column by steel caging when a strip yields can be expressed by Eq. (9):

$$f_l = \frac{2.t_2.s_2.f_{yL}}{b.s} \quad \text{.......(9)}$$

The confinement pressure f_l and axial load are calculated and added to Eq. (3) to obtain the ultimate load carrying capacity of a strengthened column.

D. Giuseppe Campione (2012)

Campione [10] proposed a design equation for determining the ultimate load that is carried by a RC column strengthened with steel angles and battens. The formula is expressed as Eq. (10).

$$P_{Ucampione} = n_a.8.t_1.L_1.f_{yL} + b.d.f_{cc.} + A_s.f_{ys} \quad \text{.......(10)}$$

where, f_{cc}= compressive strength of confined concrete; n_a= Maximum axial force in angles; n_a and f_{cc} are calculated by the following way,

$$f_{cc} = f_{co}(1+4.74\frac{f_L}{f_{co}})^{0.87} \quad \text{.......(11)}$$

$$n_a = \frac{\sqrt{t_1.f_{yL}\left(t_1.f_{yL}.L_1^2-\frac{q_{\max}.S^2}{3}\right)}}{2L_1.t_1.f_{yL}} \leq 1.0 \quad \text{.......(12)}$$

$$M_P = \left\{\frac{L_1^2.t_1}{4}f_{yL}-\frac{(N_P)^2}{16.f_{yL}.t_1}\right\} \quad \text{.......(16)}$$

Where f_{co}= compressive strength of unconfined concrete Mander et al. [11]. f_L= average confining pressure on the concrete core which can be calculated by considering two possible failure types as yielding of strips and yielding of angles. This parameter (f_L) can be determined by Eq. (14) and

Eq. (15) for the case of yielding of strips and angles respectively.

$$f_L = \left[f_{ystrip} \cdot \frac{t_2}{S} \cdot \frac{S_2}{b} \cdot e^{\left(1-1.5\frac{S}{b}\right)} \right] \quad \text{.........(14)}$$

$$f_L = \left[\frac{16 M_P \sqrt{2}}{f_c} \frac{1}{b(S - S_2)} \right] \quad \text{.........(15)}$$

Where, M_p is the plastic moment of the angles depends on the plastic axial loads and can be determined by Eq. (16).

$$M_P = \left\{ \frac{L_1^2 . t_1}{4} f_{yL} - \frac{(N_P)^2}{16. f_{yL} . t_1} \right\} \quad \text{.........(16)}$$

$$N_P = 2 L_1 . t_1 . f_{yL} \quad \text{.........(17)}$$

$$q_{\max} = \frac{16}{(S - s_2)^2} M_P \quad \text{.........(18)}$$

E. Tarabia A. M. and Albakry H. F. (2014)

Tarabia and Albakry [2] proposed an equation for predicting the load carrying of a column strengthened by steel caging, similar to that presented by Calderon et al. [9] only with different approaches for determining confining pressure and axial load carried by steel angles. The average confining pressure and axial load are obtained by using Eq. (19), Eq. (20) and Eq. (21).

$$f_l = \frac{N_c}{b^2} \frac{\upsilon_c}{\left(1 - \upsilon_c + \frac{b S E_c}{2 s_2 t_2 E_s}\right)} \quad \text{.........(19)}$$

The axial load is carried by the angles when axial shortening of the column occurs or due to friction, referred as directly loaded. However, if the angles are not connected to the head of the column it is called indirectly loaded angles and the axial force of one angle evaluated as:

$$N_L = 2. L_1 . t_1 . f_{yL} \quad \text{.........(20)}$$

$$N_L = \sqrt{2} . f_l . b . S . \mu \quad \text{.........(21)}$$

where, μ= 0.5, friction co-efficient; N_c= axial load carried by concrete.

III. Failure Modes Of Steel Jacketing

Two possible types of failures of a column strengthened by steel jacketing are observed from the literature. Failure occurs in caging steel like- yielding in angles and yielding in horizontal strips Cirtek,[12] Calderon et al.,[9] Tarabia and Albakry [2].

The confining effect induced by steel angles and strips on reinforced concrete members in compression. According to this model, a compressed member when subjected to axial loads the concrete laterally expands, results confining stress on angles and strips.

1) Yielding of angles

Failure by yielding of angles is one of the criteria in which angles are buckled in the middle portion of two strips. When it happens, it is obvious that the angles are no longer able to confine the concrete. The mechanism is that three plastic hinges are formed at three locations of an angle similar as Fig.4 (a) that indicate the weakest point of the angles Calderon et al. [9]. When column is subjected to bending and axial force, the concrete starts to expand laterally that results angles yielding Badalamenti et al. [3].

2) Yielding of strips

A second type of failure is yielding of horizontal strips. This type of failure is observed when angles are remained indirectly loaded (lengths of angles are less than the length of column). When axial load is imposed to column the expansion of concrete exerts pressure on strips [2], [3].

IV. Effect Of Parameters On Load Carrying Capacity

Several factors are available in the literature that influences the load carrying capacity of a column strengthened by steel caging. The most important parameters are: size and thickness steel angles and strips, spacing of strips, confining pressure and concrete strength.

Effect of strip spacing

Spacing of the strip has a great role on load carrying capacity of RC strengthened column. Closely spaced strips can confine the concrete greatly therefore resist the concrete to expand laterally when subjected to compressive loading. Cirtek L. [12] investigated the effect of strip distance over the entire height of column in carrying capacity of RC strengthened column. According to the experimental results conducted by him, it was found that the load carrying capacity is decreased with increasing the spacing of strips.

Effect of Strip Area

Cirtek L. [12] conducted an experimental investigation by testing specimens of RC column strengthened by using both continuous and non-continuous angles with different strip and angles sizes, aiming to find the changes in load carrying capacity with changing different parameters. The figure shows changes in the axial capacity of three columns strengthened with continuous angles and varying strip sizes of 50 mm ×6 mm, 55 mm ×6 mm and 60 mm ×6 mm. It was found from the investigation that load-carrying capacity is increased with increasing the area of strip Fig. [5]. Larger width of the strip provides larger area of confined concrete.

Effect of Angle Area

Steel angles carry a part of the load carrying capacity of strengthened columns. It is transparent from the literature that load carrying capacity is increased with increasing angles size Fig. 6.

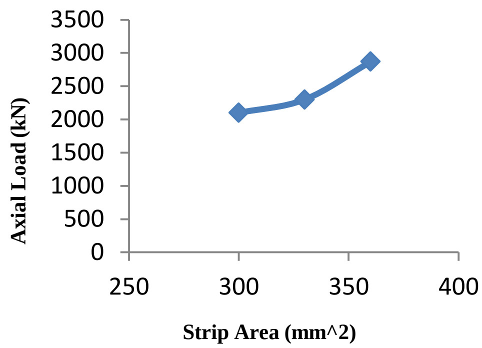


Fig. 5.Effect of strip area on load carrying capacity investigated by Ciirtek.

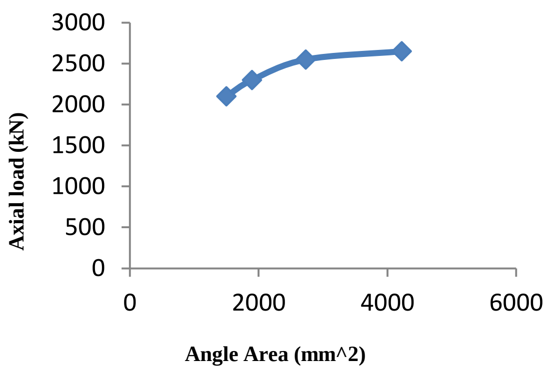


Fig. 6.Effect of strip area on load carrying capacity.

Effect of confining pressure

Confining pressure has a great effect on load carrying capacity of strengthened column with steel jacket. Steel jacket is considered as the passive or external confinement. The degree of confinement or effectiveness is mostly depends on arrangement of strips and angles. However, for prediction of capacity different Codes and researchers have been proposed different approaches for determining confinement pressure Eq. (8), Eq. (9), Eq. (14), Eq. (15) and Eq. (19).

V. Existing Experimental Investigations

In the past decade, several analytical models have been proposed for the determination of load carrying capacity of RC strengthened columns using steel caging, by design codes as well as researchers. The following are some of the proposed models.

A. *Belal et al. (2014)*

Belal et al. (2014) [13] conducted an investigation on the behavior and failure load of strengthened column with steel jacket in Fig. 6. The strengthening system was done by using steel angles or plates, or C-sections and batten plates with a particular interval. All the columns were 200 mm × 200 mm × 1200 mm in dimensions. The control specimens were without strengthening and remaining was strengthened with different configurations. The details of the strengthening components are illustrated in TABLE I.

The experimental test revealed that specimen (Col.04.C.6P) strengthened with vertical C-sections and six horizontal battens at the two sides had the largest failure load of 1841 kN. The load carrying capacity was increased by 45.10% of ref. specimen. While, the specimen (Col.01.L.3P) strengthened with vertical angles at the four corners and three horizontal battens at all the four sides, endured slightly lower failure load of 1821 kN. The load carrying capacity was increased by 45.10% of control ones. The minimum increment of load carrying capacity was observed 18.65% for specimen Col.05.P1, Strengthened with steel plate.

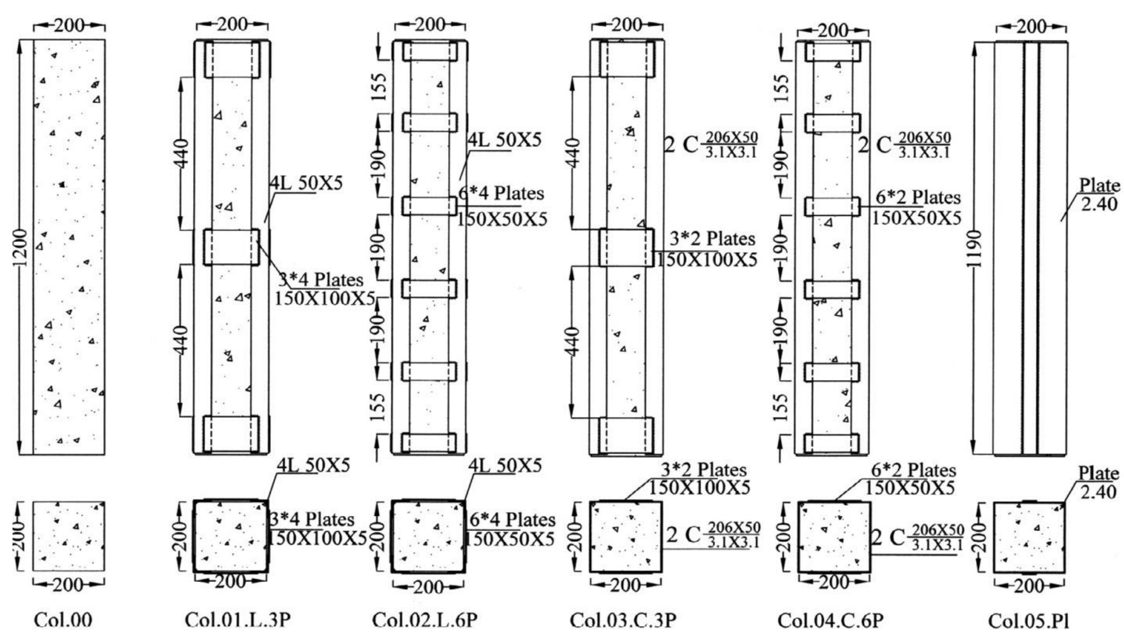


Fig. 6: Column strengthening configuration.

TABLE I

STEEL JACKET CONFIGURATIONS AND TEST RESULTS

Specimen ID	Thickness (mm) Nos. angles/Plates-Size	Confinement (Batten Nos.* Nos. of Sides *Batten Size)	Failure load (kN)	P_u/P_u(ref.)	% increases
Col.00 (ref)	-	-	1255	1.00	-
Col.01.L.3P	4L-50*50*5	3*4 plates 150*100*5	1821	1.45	45.10%
Col.02.L.6P	4L-50*50*5	6*4 plates 150*50*5	1649	1.31	31.39%
Col.03.C.3P	2C-(206*50)/(3.1*3.1)	3*2 plates 150*100*5	1545	1.23	23.11%
Col.04.C.6P	2C-(206*50)/(3.1*3.1)	6*2 plates 150*50*5	1841	1.47	46.69%
Col.05.P1	4 Plates @ 4 sides	4*4 plates 200*2.4	1489	1.19	18.65%

B. Hay and Fawzy (2014)

Hay and Fawzy [14] investigated the column capacity and global behavior of partially strengthened RC columns defected in decreasing compressive strength and in bad stirrup arrangements. The specimens were 200 mm × 200 mm in cross section and 1500 mm in height, defected with partial stirrups at top and bottom thirds of the column only, while the middle thirds was without any stirrups. The specimens were strengthened by using steel plates connected to the columns with anchor bolts, stirrups at the middle thirds regions with specific intervals and using four steel angles with batten plates welded to the angles in Fig. 7.

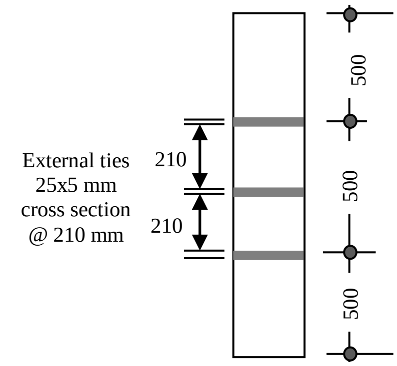
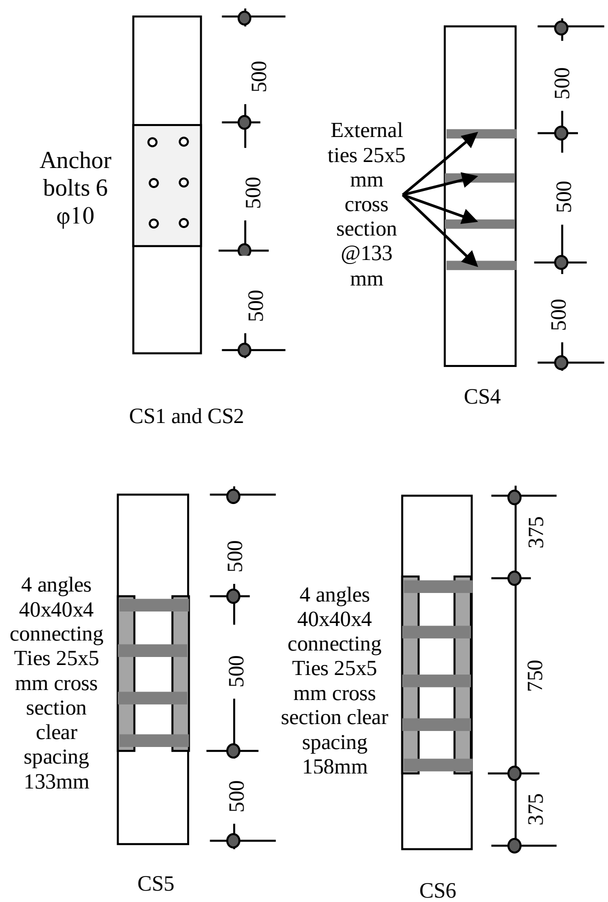


Fig. 7: Details of Steel Jacket Configuration.



The result exposed that the load carrying capacity were dramatically increased by 31% and 21% of control specimens for CS4 and CS6, strengthened with three ties and four angles connected with battens. On the contrary, the failure loads were found decreasing by 5%, 3%, 9%, and 17% of control ones for the specimen CS1, CS2, CS3, and CS5 respectively in Table II. Additionally, it was found that the thickness of external plate improves the ductility with strain behavior of strengthened columns while, the jacketing height of RC column with steel angles enhanced the overall behavior.

TABLE II

STEEL CAGING DETAILS AND TEST RESULTS

Specimen ID	Thickness (mm) Angle No./ Plates-Size	Jacket Height (mm)	% increases / Decrease
C1	Control	-	-
CS1	4 Plates @ 1.5 mm thickness	500 mm	5% decrease
CS2	4 Plates @ 3.0 mm thickness	500 mm	3% decrease
CS3	3 Ties (25 * 5 mm-X section) @ 210 mm c/c	500 mm	9% decrease
CS4	4 Ties (25 * 5 mm-X section) @ 133 mm c/c	500 mm	31% increase
CS5	4 Angles 40 * 40 * 4 and battens 25 * 5 mm	500 mm	17% decrease
CS6	4 Angles 40 * 40 * 4 and battens 25 * 5 mm	750 mm	21% increase

C. *Lin et al. (2010)*

Lin et al [4] investigated the effectiveness of steel jackets for seismic retrofitting of rectangular RC columns with insufficient lap splices and inadequate transverse reinforcement. In this study, they also examined the shape effect (i.e Octagonal and Elliptical shape) of steel jackets in improving the ductility and strength of the column specimens. Three cantilever type specimens 600 mm × 750 mm in cross section were made, fixed with large footing individually. The details of the specimen are presented in Table III. The specimens (SRL1 and SRL2) were retrofitted by using 6 mm thick octagonal and 3 mm thick elliptical steel jackets respectively, as shown in Fig. 8.

TABLE III
COLUMN AND STEEL CAGING DETAILS

Design parameters	BMRL100, SRL1, SRL2
Column dimension (mm)	600×750
Column height (mm)	3250
Design concrete strength (MPa)	17.5
Longitudinal steel	32 - #6 (19 mm)
Longitudinal steel ratio (%)	2
Longitudinal steel design strength (MPa)	420
Transverse steel spacing	#3 (10 mm) @130mm (plastic hinge region) #3 (10 mm) @240mm (non-plastic hinge region)
Transverse steel configuration	Double U shape
Transverse steel design strength (MPa)	280
Cross tie bar (each direction)	2 - #3
Cover thickness (mm)	25
Base height (mm)	750
Base dimensions (mm)	2450×1800

The investigation revealed that, confinement was effectively increased when Octagonal steel jacket was used. Ductility performance and energy dissipation ability of the specimens were also found improved. However, the lateral strength was increased by 68.6% and 63.1% for the specimens SRL1 and SRL2 respectively. The failure of the specimens was observed prevented as the results of inadequate lap splices length and transverse reinforcement.

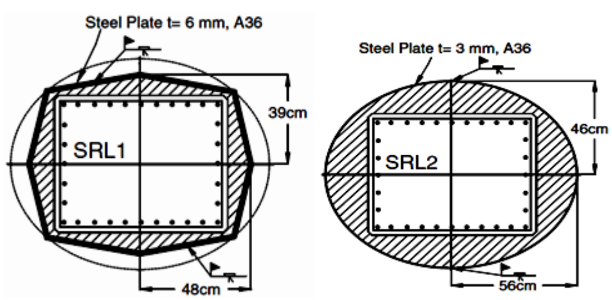


Fig .8. Steel jacketing details of lap-splice deficient columns: (a) specimen SRL1 and (b) specimen SRL2.

D. *Areemit et al.*

Areemit et al [6] studied the effect of batten plate configurations as well as the amount of batten plates with different spacing for strengthening of deficient RC columns strengthened with steel caging. The column specimens were 200 mm × 200 mm in cross section and 700 mm in height Fig. 9. The specimens were strengthened by using four steel angles (L40 mm × 4 mm) at the corners. For Specimen B, 200 mm × 50 mm × 5 mm batten plates were used at an interval of 150 mm while, the same amount of steel battens (200 × 25 mm × 4 mm) were used in specimen D with an interval of 75 mm.

The specimen C contained the same size of batten plates as specimen B with an extra batten plates at both end of the specimen Fig.9. The yield strength of the steel angles were 335 MPa whereas for steel battens of 50 mm and 25 mm wide were 412 MPa and 304 MPa respectively. The investigation stated that strengthening of RC columns with steel angles and battens are quite effective in improving the load carrying capacity and ductility when compressive strength is very low. It was also found that the same amount of steel batten with different spacing had a little effect on load carrying capacity but much on ductility.

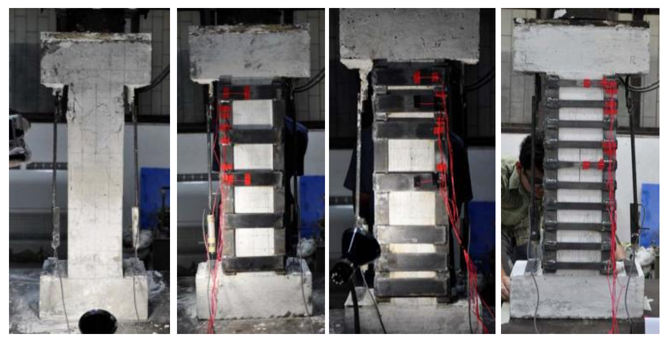


Fig. 9. Steel caging details.

TABLE IV
COLUMN AND STEEL CAGING DETAILS

Specimen	Angle/ Strip/ spacing (mm)	Ultimate Load(kN)	% increase
Ref.		607	N/A
A	40*4/200*50*5/150	1035	70%
B	40*4/200*50*5/150-2 additional strips	1066	75%
C	40*4/200*25*4/75	1031	69%

E. *Roca et al. (2011)*

Roca et al [15] investigated the effectiveness of steel caging on strengthening of RC columns, considering beam column joint, subjected to combined bending moments and axial loads. The column specimens were 260 mm × 260 mm in cross section and 1275 mm in height. All the specimens were categorized into two type of specimens A and B, in which the capitals connected to the joints by using chemical anchor and steel bars respectively.

The strengthening system was adopted by using steel angles (L60.6) at each corner of the columns and strips (230×140×8) with variable intervals, welded to the angles. The specimen (ref.a) was tested under only axial load and all the other specimens including ref.b were tested under both axial plus bending moments. It was concluded that type B specimens exhibited higher resistance and ductility than type A. Besides, strengthening was found more effective when capitals were connected to the joints by steel bars. Steel caging increased the overall ultimate load carrying capacity effectively.

F. *Tarabia and Albakry(2014)*

Tarabia and Albakry [2] studied the effect of parameters on load carrying capacity of strengthened RC columns contained steel angles and battens. The parameters were - size of steel angles, spacing of strips, types of grout materials and fixity of steel cage with column head. Each column was 150 mm × 150 mm in cross-section and 1000 mm in height. All the columns had 4 -10mm diameter longitudinal bars and 6 mm diameter stirrups at 100 mm spaced. 10 mm Steel head were used at both ends of the columns. The specimens were strengthened into two groups with two different angle sizes (50*50*4.5 mm and 30*30*3 mm) at each corners of the specimen. Each group comprised four strengthened and one un-strengthened specimens.

TABLE V
PERCENTAGE INCREASE IN LOAD CARRYING CAPACITY

Col. ID	Angle Size	Strip Spacing (mm)	f'c (MPa)	f_{yL}(MPa)	Failure Load (kN)	(%) increase
N1	N.A	N.A	57.8	-	1475	
SC1	50*50*4.5	170		415	2570	74
SCN1	50*50*4.5	170			1990	35
SCW 1	50*50*4.5	260			2310	57
SE1	50*50*4.5	170			2600	76
N2	N.A	N.A	47.5	-	1050	
SC2	30*30*3	170		485	2190	109
SCN2	30*30*3	170			2000	90
SCW 2	30*30*3	260			2050	95
SE2	30*30*3	170			2090	99

The investigation exhibited that the axial load capacity was increased about 109% for specimen SC2, strengthened with 4L-30*30*3 angles and strips at a spaced 170 mm. The ductility was increased about 50 % for all the strengthened specimens. The specimen SCN2 gained the lower axial load capacity that was strengthened by 4L-50*50*4.5 vertical angles with similar horizontal strips and spacing. The study also showed that concrete with lower strength (f_{cu}= 47.50 Mpa) achieves higher ductility and axial load capacity compared to the concrete of greater strength (f_{cu}= 57.80).

VI. COMPARISON BETWEEN RESULTS THAT OBTAINED FROM PROPOSED MODELS AND EXPERIMENTAL INVESTIGATIONS

A comparison between results that obtained from analytical equations proposed by different researchers and codes and those found from experimental investigations available in the literatures has been conducted. In this purposes experimental investigation done by Cirtek [12] and Tarabia and Albakry [2] has been used.

The analytical equations proposed by Campione [10], Calderon et al. [9], Regalado [8], Eurocode4 [7] and Tarabia and Albakry have been considered. Table VI represents the result obtained from analytical models/codes and experimental investigation performed by Tarabia and Albakry [2] while table VII illustrates the result of analytical formulae/codes with experimental test done by Cirtek [12].

TABLE VI
EXPERIMENTAL RESULTS VERSES ANALYTICAL RESULTS

S	C1 (kN)	C2 (kN)	C3 (kN)	C4 (kN)	C5 (kN)	Expt. (kN)
SC1	1789	2207	1170.5	1950.8	2194.6	2570
SCN1	1789	2207	1170.5	1950.8	1590.6	1990
SCW1	1789	2207	1170.5	1950.8	2115.5	2310
SE1	1789	2207	1170.5	1950.8	2194.6	2600
SC2	1366	1759	823.3	1372.1	1562.3	2190
SCN2	1366	1759	823.3	1372.1	1330.6	2000
SCW2	1366	1759	823.3	1372.1	1497.3	2050
SE2	1366	1759	823.3	1372.1	1562.3	2090

Note: S= specimen ID; CX= Load carrying capacity determined by using the formulae (C1= Campoine, C2= Calderon et al., C3= Regalado, C4= Eurocode4, C5= Tarabia and Albakry)

TABLE VII
EXPERIMENTAL RESULTS VERSES ANALYTICAL RESULTS

S	C1 (kN)	C2 (kN)	C3 (kN)	C4 (kN)	C5 (kN)	Expt. (kN)
F1	1782.5	1759.57	1208.7	2014.5	1906.9	2100
F2	1604.5	1744.54	995.1	1658.5	1814.8	2300
F3	1662.1	1747.67	1064.2	1773.7	1843.6	2550
F4	1996.7	1765.81	1465.8	2443.0	2022.1	2650
F5	1782.5	1764.94	1208.7	2014.5	1906.9	2870
F6	1782.5	1764.94	1208.7	2014.5	1906.9	2575
F7	1782.5	1764.94	1208.7	2014.5	1906.9	2917

Note: S= specimen ID; CX= Load carrying capacity determined by using the formulae (C1= Campoine, C2= Calderon et al., C3= Regalado, C4= Eurocode4, C5= Tarabia and Albakry)

VII. DESIGN EXAMPLE

This section considers an arbitrary RC concrete column of 300 mm × 300 mm cross section and 3000 mm of height. The area of longitudinal reinforcement is 1609 mm^2 (As=8-16 mm), with a yield strength of 260 MPa. The compressive strength of concrete is 13 MPa. The column has to be strengthened by using steel caging/jacketing.

First trial: Consider the minimum angles and strips sizes as recommended by Cirtel [12].
Angle size = 60 mm × 60 mm ×6 mm; yield strength of angle and strip = 210 MPa; Thickness of angle $t_{ang} \geq 0.1L_1$ = 0.1*60 =6 mm (ok); leg length $L_1 \geq 0.2\beta$ where, $\beta = 0.5(a+b)$ = 0.5(300+300) =300 mm;
L_1= 0.2*300 = 60 mm (ok)
Strip Thickness $t_{str} \leq t_{ang}$;t_{strip} = 6 mm (ok).
Area of strip should satisfy the condition
$A_{str} \geq 0.004\beta^2$ = 0.004* $(300)^2$= 360 mm, so width of strip =360/6= 60 mm

Using proposed models of different researchers for predicting the carrying load capacity:

Carrying Capacity before using steel caging = 1394 kN.
After strengthening:

According to,
i) Tarabia and Albakry [2] = 2414 kN (73% increase)
ii) Eurocode4 [7] = 1987 kN (42% increase);
iii) Regalado [8] = 1192 kN (Not increasing);
iv) Calderon et al. [9] = 2327 kN (66% increase);
v) Campione [10] = 1875 kN (34% increase).

VIII. Conclusion

The experimental results of the previous investigations have been reviewed. Factors affecting design formulae for the square reinforced concrete columns strengthened by steel jackets are presented. In addition, comparison between available experimental results and that obtained by using recommended analytical equations have been conducted. Finally, design example of an arbitrary column has been done considering the recommendation proposed by Cirtek [12]. The expected load carrying capacity was determined according to formulae proposed by the researchers. On the basis of the review, experimental investigations may be carried out to evaluate the effect of concrete strength of light weight concrete and concrete made with brick aggregate which are largely used in Bangladesh and parts of India. It has been noticed that various models are available in the literature for finding the confinement pressure around the column. Further studies may also be conducted by varying the confining arrangement of strips.

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