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COMPRESSIVE RESPONSE OF THE PARTIAL STEEL JACKETED SUBSTANDARD PRELOADED RC COLUMNS: END CONFINEMENT BEHAVIOR

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ABSTRACT

Strengthening of the substandard reinforced concrete (RC) columns is frequently required to improve their load carrying capacity and behavior to sustain under the service loads. This research presents an experimental investigation on the substandard RC columns using the partial steel jacket method under compressive axial loads until failure. In the study, Structural Steel angles and Strips were used as the partial steel jacketing strength enhancement solution. A low compressive strength of 15.2 MPa was used to represent the substandard RC columns. To obtain a more realistic prediction of load-carrying capacity enhancement, the test column was preloaded by applying 70% of the ultimate compressive strength before the installation of the jackets on them. The principle objective of this study is to explore the efficiency of the end confinement applied by fixing short height jackets at the ends of the column and effects of the preload on the end strengthened test columns. However, the experimental results of the strengthened columns were analyzed with respect to the unstrengthened column. Remarkable enhancement in the ultimate load carrying capacity of the strengthened column was obtained with this study. Finally, the experimental results were compared with respect to some analytical models available in the existing literature and a good agreement was found between the experiment results and capacity prediction models.

KEYWORDS: Steel Jacket, Angles, Strips, Preload, Strengthened, Ductility Index, End

confinement.

1. INTRODUCTION

Steel Jacketing is one of the promising strengthening techniques endorsed to enhance the strength capacity and deformation compatibility of the existing substandard RC column. Various processes are available for installing steel jacket wrapping around the column in the construction industry. One of the common, easy and low cost processes is the partial steel jacketing technique that typically installed by means of assembling an additional cage with steel angles and strips around the deficient existing RC column.[1,2,3] Cement mortar or epoxy or other high strength glue is grouted between the interface of the concrete and the steel cage in order to enhance the bonding interlock in them.

The partial steel jacketing technique has proven itself as an efficient strengthening technique for upgrading the behavior of the existing substandard RC column in many researches.[4,5,6,7,8,9,10,11,12,13,14,] Badalamenti et al.[1] developed a simplified analytical model to predict the compressive behavior of RC columns strengthened by steel angles and strips, which has become a benchmark in the field. Akter and Begum[2] explored the behavior of preloaded RC columns strengthened with partial steel jacketing, demonstrating the technique’s capability to significantly enhance the axial load-bearing capacity even under preloading conditions. Giménez et al.[3] investigated the influence of strip configuration on the axial performance of steel-jacketed columns, emphasizing the importance of optimizing strip placement for effective lateral confinement.

Further experimental studies, such as those by Abdel-Hay and Fawzy[4] examined the behavior of partially defective RC columns strengthened using steel jackets, validating the technique's potential in practical applications. Chin et al.[14] conducted a review of external steel-confinement methods, including partial steel jacketing, highlighting its versatility and cost-effectiveness in strengthening RC structures. Liu and Yang[8] investigated the seismic performance of RC frames retrofitted with prestressed steel strips, demonstrating the broader applicability of steel jacketing techniques beyond axial load enhancement.

Analytical and numerical studies have also contributed significantly to the understanding of partial steel jacketing. Ferrotto et al.[6] employed finite element modeling to simulate the behavior of partially steel-jacketed columns, addressing variables such as frictional effects and preload conditions. Tarabia and Albakry[7] proposed an analytical model for predicting the ultimate capacity of steel-jacketed RC columns, which was validated against experimental results. Mander et al.[9] developed a theoretical stress-strain model for confined concrete, which remains a foundational reference for evaluating the effects of confinement provided by steel jackets.

Many studies have also focused on the interfacial bonding between the steel cage and the concrete column. This is typically achieved by grouting the interface with cement mortar, epoxy, or other high-strength adhesives, as explored by Abdel-Hay and Fawzy[4] and Campione et al.[5] These studies demonstrate the importance of proper bonding in achieving effective lateral confinement and enhancing structural behavior under axial loads.

This research builds upon the insights provided by previous literature, adopting analytical models proposed by Badalamenti et al.[1], Tarabia and Albakry[7], and Ferrotto et al.[6] to predict the behavior of confined concrete strengthened with steel jacketing. These models were selected due to their robust theoretical foundations and widespread validation in existing studies. The experimental findings obtained in this study were compared with these models to assess their predictive accuracy and applicability to partial steel jacketing. summary of the expressions for the determination of the confinement parameters are provided in Table 1.
A general form of expression for the strength of external steel confined concrete is given by.

$N_u = f_{ys} A_s + f_{cc} A_{cc}$ Eq 1

Also, all the models defined the strain corresponding to the maximum confined concrete stress according to[9] model and given by: $\varepsilon_{cc} = \varepsilon_{c0}\left[1 + 5\left(\frac{f_{cc}}{f_{co}} - 1\right)\right]$ Eq 2

Table 1 Expressions of the confinement parameters for different models.

Analytical Model	Strength of confined concrete, f_{cc}	Lateral confinement pressure, f_l
Badalamenti V. et al.[1]	$\left[f_{c0}\left(1 + 3.7\left(\frac{f_l(\varepsilon)}{f_{co}}\right)^{0.87}\right)\right]$	$f_l = \frac{2F}{bs}$ $F \cong \frac{\nu \varepsilon b e^{[-1.5(\frac{s}{b})]}}{(1+\mu)\left\{\frac{1}{E_s}\left(\frac{L_1}{st_1} + \frac{L_2}{S_s t_2}\right) + \left(\frac{b(1-\nu)}{E_c L_1}\right)\right\}}$
Tarabia A. M. et al.[7]	$\left[f_{c0}\left(1 + 3.7\left(\frac{f_l(\varepsilon)}{f_{co}}\right)^{0.87}\right)\right]$	$f_l = \frac{N_c}{b^2} \frac{\nu}{\left(1 - \nu + \frac{bSE_c}{2l_2 t_2 E_s}\right)}$
Ferrotto M. F. et al.[6]	$\left[f_{c0}\left(1 + 3.7\eta\left(\frac{f_l(\varepsilon)}{f_{co}}\right)^{0.87}\right)\right]$ $\eta = 1 - \frac{f_{co}\, n_p(0.165 + 0.34 n_p)}{f_{cc(np=0)}}$ $0 \le np \le 1$	$f_l = \frac{2 E_s \varepsilon_l e^{[-1.5(\frac{S_b}{b})]}}{(1+\mu)\left\{\left(\frac{L_1}{t_1} + \frac{S_b(b - L_1)}{S_2 t_2}\right)\right\}}$

However, despite numerous investigations on the cross section of the jacket, concrete strength, interface materials, and type of connections to the head of the column - variables, true behavior and suitable configuration of this particular technique still remained obscure to the scientific association. Deficiencies are identified in the realm of the height and position configurations of the jacket attached to the part of the column with the initial preload or no preload variables in the existing literature.

For these reasons and in order to contribute enlighten the knowledge on the behaviour of the partial steel jacket RC columns, an experimental investigation was carried out on half scale substandard strengthened RC columns. The RC column was preloaded approximately 70% of the ultimate axial load. The preloaded column was then strengthened partially with vertical steel angles and horizontal strips. The height of the jacketing was schemed as one fourth of the column height and placed at the top and bottom ends of the column only.[4]

2.0 METHODOLOGY

The selection of the most suitable strengthening method for this research was one of the most challenging aspects of the study. This critical decision required a thorough understanding of the deficiencies present in commonly employed strengthening techniques. To address these gaps, an extensive literature review was conducted, which helped identify key parameters for investigation. The focus was placed on areas where traditional methods were inadequate, ensuring that the study could provide meaningful insights and potential improvements to existing practices.

Once the research parameters were determined, a detailed experimental program was developed. This program included several preparatory steps such as scheduling, estimating required materials and costs, and casting the specimens. Precision during the casting process was critical, as the integrity of the specimens directly influenced the reliability of the experimental outcomes. Each step was carefully planned and executed to ensure a methodical approach that aligned with the study's objectives.

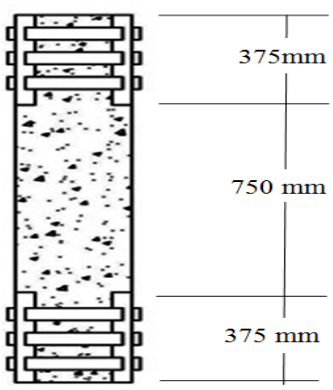
An innovative aspect of the research was the development of two separate instrumentation setups for compressive axial load application. These setups were designed to cater to the specific needs of the preloading and testing stages. Their purpose was to ensure uniform distribution of loads across the specimens, minimizing inconsistencies that could compromise the accuracy of the results. By customizing the instrumentation for these stages, the study achieved a high level of precision and reliability in the experimental data.

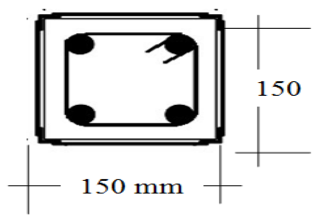
The experimental program was conducted in three main stages of loading. The first stage focused on establishing a reference point by testing a column to determine its ultimate axial load capacity. This reference column provided a baseline for comparison throughout the study. In the second stage, a column was preloaded to 70% of the ultimate axial load of the reference column. This specimen, referred to as the preloaded column, allowed the study to evaluate the influence of preloading conditions on the effectiveness of the strengthening method. After the preloading stage, all columns, including both preloaded and non-preloaded specimens, were strengthened at their top and bottom ends. These critical zones were chosen for strengthening because they are highly influential in determining the structural performance under axial loads. By applying the strengthening method to these areas, the study aimed to assess its effectiveness in enhancing the load-bearing capacity and overall structural behavior of the specimens.

In the final stage, all strengthened specimens were subjected to compressive axial loads until failure. The responses of the specimens under these loads were carefully recorded, focusing on parameters such as ultimate load capacity, deformation characteristics, and failure modes. This data was then analyzed to evaluate the performance of the strengthening method and its effectiveness in improving the structural behavior of the specimens. Additionally, the results were compared with predictions from existing analytical models for confinement. This comparison was essential to validate the applicability of these models to the proposed strengthening method and to identify areas where the models might require refinement.

3. EXPERIMENTAL PROGRAM

3.1 Tested Specimens





Column Height	1500 mm
Main bar	4- Ø10 mm
Tie bar	Ø8 mm @ 150 mm c/c
Steel Angle	L 25 ×25×5
Steel Strip	PL 50×5
Mortar Thickness	5 mm
Weld Type	Fillet

Figure 1 Geometry of the strengthened column test specimens.

All the columns were constructed with the same cross section dimension of 150 × 150 mm and height of 1500 mm. the specimens were reinforced with 4- Ø10 mm of main bar and Ø8 mm @ 150 mm c/c of tie bar. The detailed geometry of the test specimens are presented in Figure 1.

One column was kept unstrengthened for reference column and the other columns were strengthened using the steel angles and strips. The steel angles were placed vertically on the corner of the column. The Angle was selected following the Euro Code 4 (CEN 1994). Before placing the angles on the column, the concrete surface was roughened by chipping off the plaster from the four corners. Cement mortar was grouted on the roughened concrete surface. The strips were welded on to the angles placing horizontally.

3.2 MATERIALS

The test results of the tension coupon steel samples and compressive strength of the concrete cylinder and mortar cube samples are summarized in Table 2 and Table 3, respectively.

Table 2 Mechanical properties of the concrete cylinder and mortar cube.

Cylinder Designation	Cylinder Strength (MPa)		Cube Designation	Cube Strength (MPa)	
	7 Day	28 Day		7 Day	28 Day
NSC - 1	10.32	-	NSCC - 1	19.2	-
NSC - 2	11.12	-	NSCC – 2	21.6	-
NSC - 3	9.16	-	NSCC – 3	24.2	-
NSC - 4	-	15.2	NSCC – 4	-	28.7
NSC - 5	-	16.3	NSCC – 5	-	32.2
NSC - 6	-	14.1	NSCC - 6	-	36.1
Average	10.2	15.2	Average	21.7	32.3
Standard Dev.	0.99	1.10	Standard Dev.	2.50	3.70

Table 3 Mechanical properties of the steel material.

Steel Properties		f_y (MPa)	ε_y (mm)	f_u (MPa)	ε_u (mm)
Reinforcement	Ø10 mm	320	0.0015	434	0.262
	Ø8 mm	350	0.0017	493	0.019
Angle	L 25 ×25×5	360	0.0019	451	0.322
Strip	PL 50×5	270	0.0014	338	0.0161

3.3 Test Set-up and Instrumentation: All the column specimens were tested under axial compression using universal testing machine with 2000 kN capacity. The monotonic incremental loading was applied initially at a stroke rate of 3 mm/min. This rate was maintained throughout the experiment. During the preloading stage steel cap (Figure 2-3) was used while the testing stage the steel plate was used.

4. RESULTS AND DISCUSSION

4.1 Failure Modes: For reference unstrengthened column NC1, a sudden failure occurred when parts of the concrete cover spalled-off and buckling of the longitudinal reinforcement bars was observed as shown in Figure 4-5. The location of the concrete crushing was mainly to the end of the column. In the case of the strengthened columns (NS1 and NS2), the failure was started with the inclined cracking in the concrete followed by the buckling of the reinforcement steel bars and eventually a crushing of concrete section near the middle of the column as demonstrated in Figure 6-9. Before the failure load reached, no local failure of the column was observed. Due to the attachment of the steel cage at the ends of the column, the failure mode was shifted from the end of the column to the middle section. That's how it prevents the early failure of the jacketed column.

4.2 Load Shortening Behaviour: For reference columns, NC1, the axial shortening increased in a linear manner till failure. In the case of the strengthened columns of NS1 and NS2, the relation between load and axial shortening was almost linear till about 85% of the failure load followed by some nonlinear increase in the axial shortening curve. Afterwards the curve began to decrease indicating the softening behaviour of the test columns. The relationships between applied axial load and column axial shortening of the tested specimens obtained from the experiment are presented in Figure 10. The initial stiffness of the strengthened specimens was higher than that of the reference column. Comparatively higher maximum axial shortenings were achieved with the end strengthened column than those of the reference columns without steel cages (Table 5).

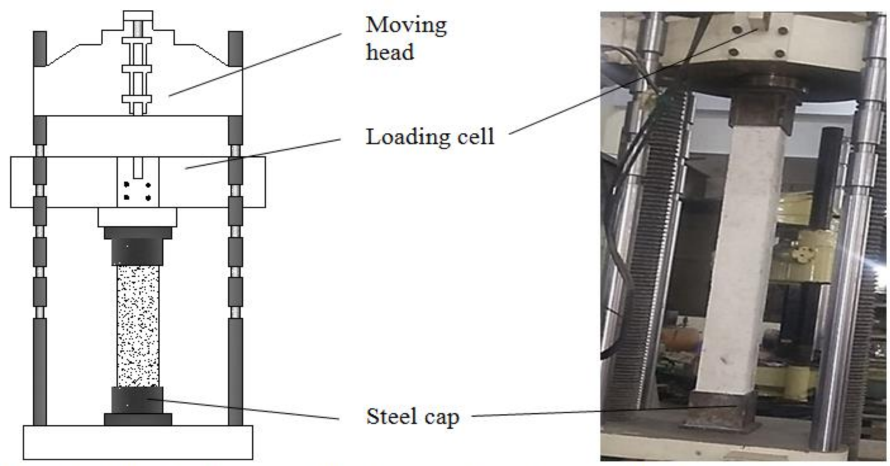


Figure 2: Schematic diagram of the test set up for preloading stage using steel heads.

Figure 3: Preloading test set up using steel heads at Top and Bottom of the Specimen.

4.3 Effects of Partial End Strengthening Method: To investigate the effects of partial end strengthening method, the ultimate axial loads and the corresponding displacement of the strengthened column specimens with preloaded and no preloaded both were compared with respect to the unstrengthened reference unstrengthened column. The enhancement in the ultimate strength and ductility index due to the effects of partial end strengthening method are tabulated in Table 4-5 and presented in Figure 10-12. The responses were found to be higher for all the partially end strengthened columns with respect to the reference column. The preloaded column resulted in a reduced behavioral strength and ductility with respect to the partially strengthened column with no preload. The column ductility was measured in terms of Displacement Ductility Index.[2]

Table 4 Effects of partial end strengthening method on the ultimate axial loads.

Col.	Preload Force, (kN)	Displacement at preload force, ∇(mm)	Preload Level	Ultimate Load, P_u (kN)	Increase in Ultimate Strength, (%)
NC1 (ref)	-	-	-	457	-
NS1	-	-	×	555	21%
NS2	320	4	70%	535	17%

Table 5 Effects of partial end strengthening method on the displacement ductility index.

Col.	Displacement at ultimate load, ∇_u(mm)	Displacement at 85% of peak, $\nabla_{0.85}$(mm)	Displacement at 80% of peak, $\nabla_{0.80}$(mm)	Displacement Ductility Index
NC1 (ref)	9.2	9.6	7.7	1.24
NS1	9.5	10.6	6.8	1.56
NS2	7.6	8.8	6	1.47

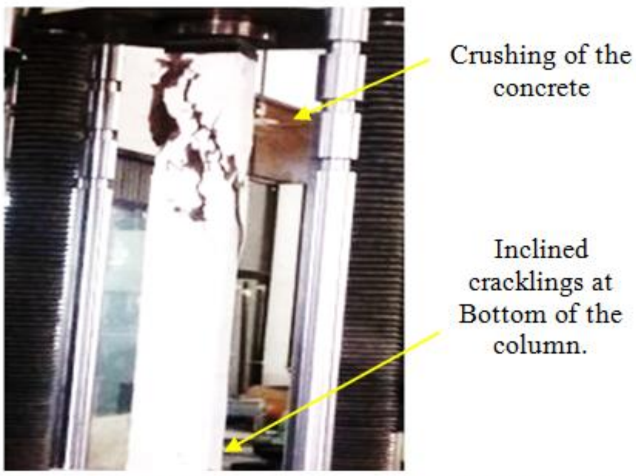


Figure 4 Failure mechanism of the unstrengthened Reference RC column NC1.

Figure 5 Crushing of the concrete at the Column NC1.

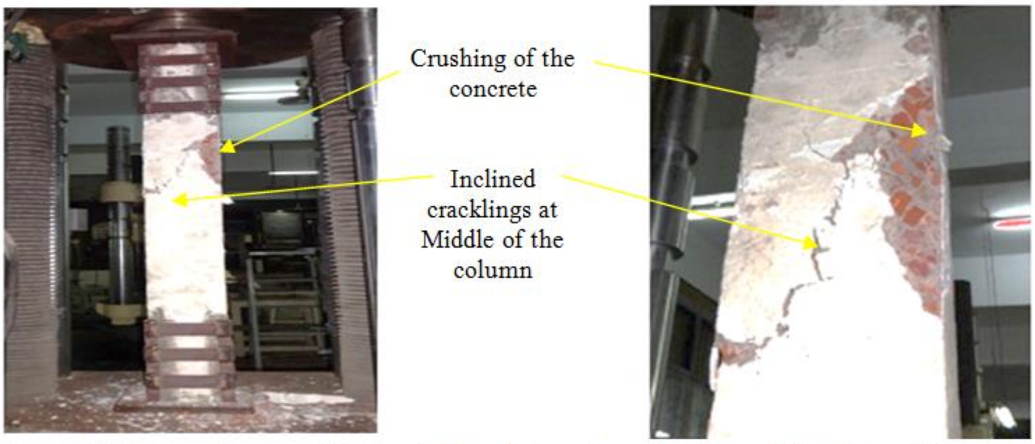


Figure 6 Failure mechanism of the partially end strengthened RC column NS1.

Figure 7 Crushing of the concrete at the Column NS1.

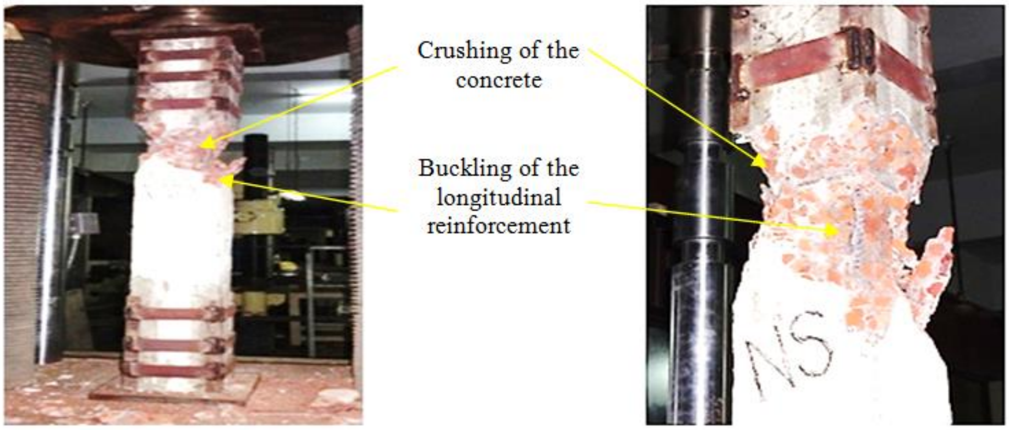


Figure 8 Failure mechanism of the Partially end strengthened preloaded RC column NS2.

Figure 9 Crushing of the concrete and buckling of the longitudinal reinforcement at the Column NS2.

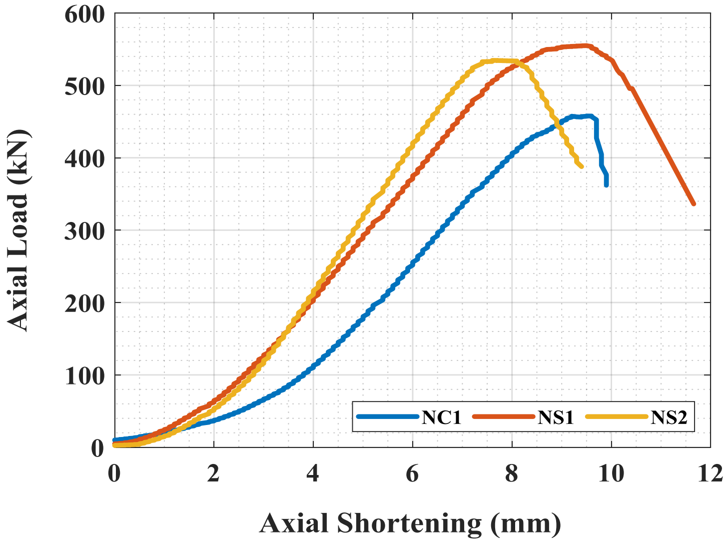


Figure 10 Axial load verses axial shortening responses of the test specimens.

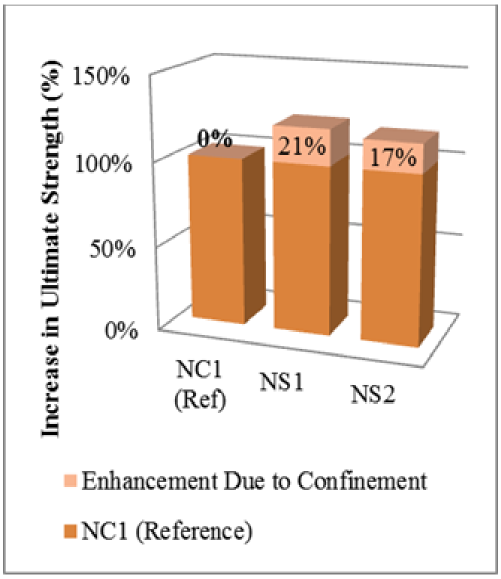


Figure 11 Ultimate Strengthened Enhancement due to partial end strengthening method.

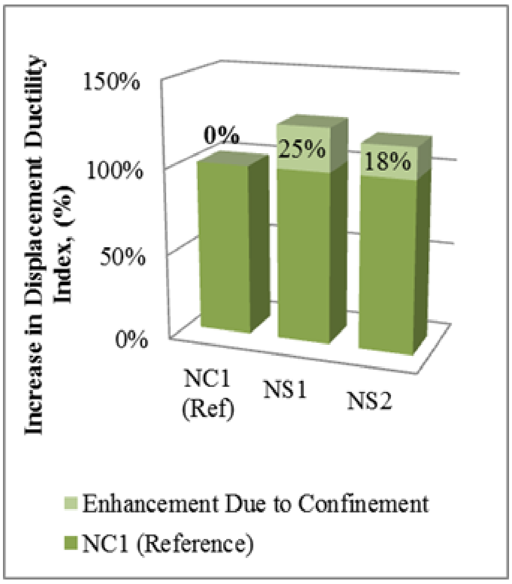


Figure 12 Ductility Enhancement due to partial end strengthening method.

The ultimate strength enhancement for the strengthened column without preload was 21% higher than the unstrengthened column. It was also higher than the preloaded column by 17%. The strength enhancement of the strengthened column with preload was 14% higher than the unstrengthed column. This is due to the additional steel cage and concrete confinement effect at the end regions provided by the steel cage. Moreover, the ductility index was also found to be improved for both of the jacketed columns. This indicates that the strengthening of the L/4 part of the column is efficient in improving the load-carrying capacity and ductility of the columns.

4.4 Comparisons between experimental results and analytical models:

The theoretical confinement pressures were determined according to the adopted analytical models referred in Table 5. The theoretical ultimate compressive capacity and strain corresponding to the peak axial loads were obtained using Eq 1 and Eq 2 and summarized in Table-6. The comparisons of the predicted ultimate capacity with the obtained experimental results are presented in Figure 13-14. It shows that the adopted three models are reliable in predicting the ultimate strength capacity for the partial end strengthening method studied here. However, the models proposed by Badalamenti V. et al.[1] and Tarabia A. M. et al.[7] slightly overestimated the ultimate strength compared to the model by Ferrotto M. F. et al.[6], as the latter model considered the preloaded effect in the concrete confinement pressure f_{cc}.

Table 6 Theoretical confinement parameters from different capacity prediction models.

Specimens	Badalamenti V. et al.[1]		Tarabia A. M. et al.[7]		Ferrotto M. F. et al.[6]	
	f_l (MPa)	f_{cc} (MPa)	f_l (MPa)	f_{cc} (MPa)	f_l (MPa)	f_{cc} (MPa)
NS1 (Unpreloaded)	0.040543	15.5241	0.935118	20.17159	1.307066	21.85304
NS2 (preloaded)	0.032434	15.46694	0.935118	20.17159	1.307066	15.52413

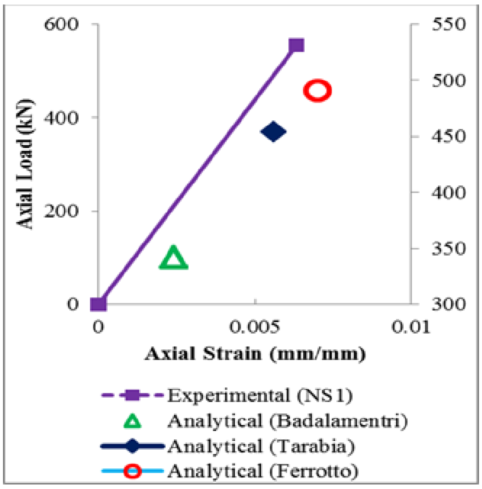


Figure 13 Comparisons between experimental results and Analytical Models for Unloaded strengthened RC column.

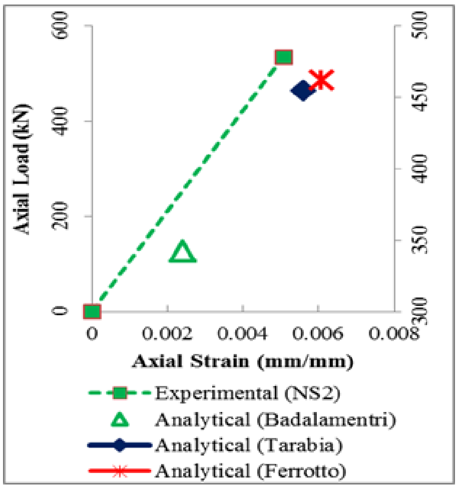


Figure 14 Comparisons between experimental results and Analytical Models for Preloaded strengthened RC column.

5. CONCLUSIONS

The partial steel jacketing method using angles and strips functioned well with the substandard RC columns under compressive axial loads when the caging fastened to both ends of the column simply. A considerable enhancement in ultimate strength ranging from 17% to 21% and ductility ranging from 18% to 25% with respect to the unstrengthened column was achieved in this study. The preloaded strengthened column was found to lessen strength and ductility comparing to the strengthened column with no preload parameter as expected. The failure of the strengthened columns observed at the middle part for both cases of preloaded and no preloaded columns. That was mainly due to lateral confinement exerted from the steel cage adhering at the ends of the column. The analytical models established by Ferrotto M. F. et al[6] demonstrated better agreement with the experimental results obtained in this study than the models developed by Badalamenti V. et al.[1] and Tarabia A. M. et al.[7]

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CONFLICT OF INTEREST

The corresponding author states that there is no conflict of interest.

REFERENCES

1 Badalamenti, V.; Campione, G.; Mangiavillano, M.L. Simplified Model for Compressive Behavior of Concrete Columns Strengthened by Steel Angles and Strips. J. Eng. Mech., 2010; 136: 230–238.

2 Akter, F.; Begum, M. Behaviour of the Partial Steel-Jacketed Preloaded RC Columns under Concentric Axial Load. Asian J. Civ. Eng., 2021; 22: 713–726, doi:10.1007/s42107-020-00342-z.

3 Giménez, E.; Adam, J.M.; Ivorra, S.; Calderón, P.A. Influence of Strips Configuration on the Behaviour of Axially Loaded RC Columns Strengthened by Steel Angles and Strips. Mater. Des., 2009; 30: 4103–4111.

4 Abdel-Hay, A.S.; Fawzy, Y.A.G. Behavior of Partially Defected R.C Columns Strengthened Using Steel Jackets. HBRC J., 2015; 11: 194–200, doi:10.1016/j.hbrcj.2014.06.003.

5 Campione, G.; Cavaleri, L.; Di Trapani, F.; Ferrotto, M.F. Frictional Effects in Structural Behavior of No-End-Connected Steel-Jacketed RC Columns: Experimental Results and New Approaches to Model Numerical and Analytical Response. J. Struct. Eng., 2017; 143: 04017070, doi: 10.1061/ (ASCE) ST.1943-541X.0001796.

6 Ferrotto, M.F.; Cavaleri, L.; Di Trapani, F. FE Modeling of Partially Steel-Jacketed (PSJ) RC Columns Using CDP Model. Comput. Concr., 2018; 22: 143–152.

7 Tarabia, A.M.; Albakry, H.F. Strengthening of RC Columns by Steel Angles and Strips. Alex. Eng. J., 2014; 53: 615–626.

8 Liu, R.; Yang, Y. Experimental Study on Seismic Performance of Seismic-Damaged RC Frame Retrofitted by Prestressed Steel Strips. Bull. Earthq. Eng., 2020; 18: 6475–6486, doi: 10.1007/s10518-020-00931-y.

9 Mander, J.B.; Priestley, M.J.N.; Park, R. Theoretical Stress-Strain Model for Confined Concrete. J. Struct. Eng., 1988; 114: 1804−1826, doi: 10.1061/ (ASCE) 0733-9445(1988)114:8(1804).

10 Pan, Y.; Rui, G.; Li, H.; Tang, H.; Xu, L. Study on Stress-Strain Relation of Concrete Confined by CFRP under Preload. Eng. Struct., 2017; 143: 52–63.
11 Shafei, E.; Rahmdel, J.M. Plasticity Constitutive Modeling of Partially Confined Concrete with Steel Jacketing. KSCE J. Civ. Eng., 2017; 21: 2738–2750. doi: 10.1007/s12205-017-1772-6.
12 Farjana, A. Behaviour and Strength of Steel Jacketed RC Columns under Concentric Axial Load, 2018.
13 Akter, F.; Habib, H. Steel Angles and Strips Jacketing of Existing RC Columns: A State of Art. IARJSET., 2019; 6: 17–22.
14 Chin, C.-L.; Ma, C.-K.; Tan, J.-Y.; Ong, C.-B.; Awang, A.Z.; Omar, W. Review on Development of External Steel-Confined Concrete. Constr. Build. Mater, 2019; 211: 919–931.