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Research Article

Modeling of the Axial Load Capacity of RC Columns Strengthened with Steel Jacketing under Preloading Based on FE Simulation

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Reinforced concrete (RC) columns often require consolidation or rehabilitation to enhance their capacity to endure the loads applied. This paper aims at studying the conduct and capacity of RC square columns, those reinforced with steel jacketing under static preloads. For this purpose, a three-dimensional model of finite element (FE) is devised mainly to investigate and analyze the effect of this case. The model was tested and adjusted to ensure its accuracy using the previous experimental results obtained by the author. Results of testing, experimentally, the new developed FE model revealed the ability to use the model for calculating RC columns' axial load capacity and for predicting accurate failure modes. The new model that tends to predict the axial load capacity was suggested considering the parametric analysis results.

1. Introduction

Reinforced concrete (RC) columns often require strengthening to enhance their axial load capacity to endure loads. This reinforcement may be needed because of the alteration in the use which ended in addition to loads that are live; errors of design, problems in the construction while making erection, elevating for confirming to existing code necessities or aging of RC columns itself were studied.

There are three commonly used methods for reinforcing RC columns including concrete and/or steel jacketing and fiber-strengthened polymer (FRP) jacketing. All these methods have led to an effective rise in the load capacity of RC columns. This study refers to RC columns loaded by axial compressive load strengthened under load by steel jacketing. Strengthened existing steel columns under preloading through welding steel plates is frequently rendered [1, 2], but there is hardly any study of RC columns under preloading exists. Some researchers [3–10] reproduced the findings of an experimental test chain on some RC columns fortified with the angles of steel jacketing under axial load without preloading. There was a witness confirming that the jacketing of steel enhances the failure load of the fortified RC columns.

Because the existing experimental research [3–10] ignores the effect of the preloading that found when the strengthening is done on the axial load capacity, reliance on the research that already exists is problematic for an accurate prediction of the axial load capacity relating to RC columns reinforced with steel jacketing under preloading. Moreover, the existing codes ACI Committee 318 [11] and Eurocode 4 [12] only predict the axial load capacity, based on the composite concrete-steel structure without preloading effect.

Other studies [13–16], using FE modeling, revealed that the conduct of RC members can be simulated precisely, especially the RC members that was strengthened by steel jacketing. At the same time, conducting experimental researches taking into account all the parameters which affect the ultimate capacity of the load is not sensible, especially if the strengthening is under preloading. Accordingly, there is a need to develop a special FE model that could be used for simulating RC columns reinforced by steel jacketing and investigate the behaviors of each parameter under preloading.

While predicting RC columns' axial load capacity, fortified with steel jacketing, it is necessary to take into consideration the factors mentioned above and under preloading. In this research, the FE simulation model was built in 3D aiming at predicting the axial load capacity of steel jacketing-reinforced RC columns with and without preloading. On the basis of the findings derived from the parametric study, it is proposed to resort to prediction model to consider the effect of the preloading on the load capacity pertaining to steel jacketing-fortified RC columns. Moreover, experimental outcomes of tests conducted on RC columns as reflected in the literature review [3, 4] were gathered to use the same for verification of the precision of the analytical results obtained through the FE program (ANSYS-15) [17].

2. Existing Models

Many authors introduced design models for a similar problem. However, Campione [5], ACI Committee 318 [11], and Eurocode 4 [12] reported that the designed axial load capacity P_u of the steel jacketing-reinforced RC column is basically calculated from

$$P_u = P_c + P_s + P_{sj}, \tag{1}$$

where P_c, P_s, and P_{sj} represent the contribution of concrete, steel reinforcement, and steel jacketing, respectively.

The models offered by ACI Committee 318 [11] and the majority of the models that already exist implement the equation given below for calculating the design axial load capacity of the RC column without strengthening:

$$\phi P_{n,\max} = 0.80\phi\left[0.85 f'_c\left(A_g - A_{st}\right) + \left(f_y A_{st}\right)\right]. \tag{2}$$

For designing, the ACI code allows using the factors, such as ϕ, $0.85 f'_c$ and 0.80 to equivalent rectangular compressive stress distribution to replace the more exact concrete stress distribution and to make safety design. So if there is a need to predict failure axial load capacity, then the equation is formulated to

$$P_{u.f} = f'_c\left(A_c - A_{st}\right) + \left(f_y A_{st}\right). \tag{3}$$

As stated by Eurocode 4 [12], the ultimate load capacity of RC columns fortified with steel jacketing as a combined cross section is expressed by the following equation:

$$N_{pl,Rd} = 0.85 A_c f'_{cd} + A_{st} f_{yd} + A_a f_{sd}, \tag{4}$$

where $N_{pl,Rd}$ is the plastic resistance to compression; A_a, A_c, and A_{st} are the cross-sectional domains of steel jacketing, concrete, and steel reinforcement, correspondingly; and f_{sd} and f_{cd} together with f_{yd} are their design values characteristic strengths. For concrete-filled sections, the coefficient 0.85 may be replaced by 1.0, so equation (4) will be reduced to

$$P_{u.f} = N_{u.f} = A_c f'_{cd} + A_{st} f_{yd} + A_a f_{sd}. \tag{5}$$

However, several authors proposed models to acquire a precise equation for the axial load capacity of RC column reinforced by steel angles jacketing and horizontal steel plat strips.

Campione [5] stated an analytical expression for predicting the axial load capacity of reinforced RC columns with steel angles and strips jacketing. The final axial load capacity is given by

$$P_{u.Campoine} = A_c f'_{cc} + A_s f_{sk} + n_a \cdot A_a \cdot f_y, \tag{6}$$

where f'_{cc} shows the compressive strength of confined concrete and n_a represents a dimensionless ratio of the axial force existing in the vertical steel angles jacketing.

3. ANSYS Finite Element Model Study

3.1. Concrete Modeling and Properties. While making an analysis, the commercial program of FE (ANSYS) was employed. For modeling the concrete, 65 solid elements were used ANSYS-15 [17]. Such an element consists of 8 nodes together with freedom of 3 degrees between every translations and node in the nodal x, y, and z directions. Also, such an element can result in deforming of the plastic, breaking in 3 orthogonal directions with a simultaneous crushing. For modeling the concrete, to have a simulation of real concrete behavior, ANSYS needs linear and multilinear isotropic substance characteristics for centering, together with a few supplementary properties of the concrete substance.

The shear transfers coefficient β, relating to the state of the cracked face [17]. The range of the coefficient value is from 0.0 to 1.0, with 0.0, and 0.0 represents a smooth crack, and 1.0 suggests a rough crack [13, 14]. An open crack coefficient, $\beta_t = 0.2$, and the closed crack coefficient, $\beta_c = 0.8$, were taken in the study in hand [15]. The calculation about the modulus of elasticity of the concrete is possible to be carried out using the following equation:

$$E_c = 4700\sqrt{f'_c}. \tag{7}$$

The calculation of uniaxial tensile stress can be made from the following equation:

$$f_r = 0.623\sqrt{f'_c}. \tag{8}$$

Poisson's ratio of concrete of 0.2 was applied. The calculation of the compressive uniaxial stress-strain values for the concrete can be made using equation (9) [16]:

$$\begin{aligned} E_c &= \frac{f_{el}}{\varepsilon_{el}}, \\ \varepsilon_0 &= \frac{2 f'_c}{E_c}, \\ f &= \frac{E_c \varepsilon}{1 + \left(\varepsilon/\varepsilon_0\right)^2}, \end{aligned} \tag{9}$$

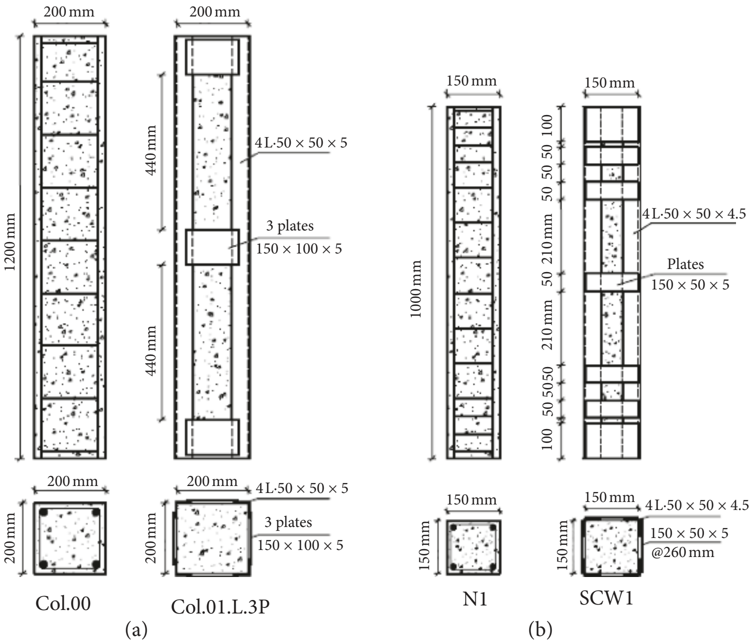

Figure 1: RC column geometrical details according to previously published work. (a) Belal et al. [3]. (b) Tarabia and Albakry [4].

where the modulus of elasticity is E_c, compressive strength is f'_c, and tensile stress is f_r, which are in MPa; f_{el} is the stress at the elastic strain (ε_{el}) in the elastic range $f_{el} = 0.30f'_c$; ε_0 is the strain at the ultimate cylinder compressive strength, f'_c; and f is the stress at any strain ε.

3.2. Strengthening of Steel, Steel Angles, and Steel Plates Modeling and Characteristics. SOLID186 elements ANSYS-15 [17] were employed for modeling the steel strengthening, steel angles, and steel plates. SOLID186 is a 3D 20-node solid element of higher order, which displays how quadratic displacement behaves. The definition of this element is made as 20 nodes having 3 degrees of independence at each node. This element also assists plasticity, creep, hyperelasticity, large deflection, stiffening of stress, and larger capabilities of strain. Also, it carries a blend of the capability of the formulation to simulate the deformations of elastic-plastic materials almost incompressible and the hyperelastic materials that are completely compressible. SOLID186 is an identical structural solid that is very suitable for modeling asymmetrical meshes. The steel reinforcement, steel angles, and the plates of steel integrated into the FE models were expected to be materials of linear elasticity together with a modulus of elasticity concerning 210 GPa and Poisson's ratio of 0.3. The yielded stress is another thing that depends upon the use of the element.

The maximum size of the meshing elements was taken as 20 mm in length, 10 mm in height, and 10 mm in width. The contact between steel and concrete was modeled using a set of TARGE170 and CONTA174 contact elements [17], which function on the basis of Coulomb's friction model.

3.3. Model Studies Pertaining to the Structure. Seventeen RC columns (with variable cross sections and heights) exposed to axial loading were considered in the present study. The columns were divided into two groups:

> First group: consists of four columns according to previously published work [3, 4], as shown in Figure 1, which were examined to testify the accurateness of the FE model.
>
> Second group: consists of thirteen columns under preloading with different percentages of preloading on the strengthened column, which were analyzed to propose a new model for predicting RC column's axial load capacity, reinforced with steel jacketing. Tables 1 and 2 demonstrate the key material and geometric characteristics of the test data.

4. Comparison of FE Modeling with the Experimental Results

To scrutinize the FE model for its validity and reliability, a comprehensive verification was done utilizing a chain of experimental data that exist in the background literature. The database taken into account comprises the outcomes of four experimental tests, together with the outcomes of tests on 2 columns without reinforced and 2 columns strengthened with steel angles jacketing. The key material, as well as geometrical characteristics about the experimental data, has been summarized in Tables 1 and 2.

Table 3 illustrates loads of failure including the findings of both experiments and analysis also showing the ratios between them. Figure 2 graphically compares the values derived through experiment and analysis. The table and the figure show the mean values of $P_{\mathrm{Exp}}/P_{\mathrm{FE}}$ as 1.003, the conforming coefficient of variation as 3.16%, and the coefficient of correlation as 0.987. The given values illustrate that the FE model turns out to be an excellent match from a

Table 1: A brief account of RC columns assessed in the current study using FE modeling.

Group	Studies FE model based on	Column specimen	Concrete, f_{cu} (MPa)	Column dimensions (mm)	Steel reinforcement		Stirrups	
					Long bars	f_y (MPa)	Size	f_y (MPa)
First	Belal et al. [3]	Col.00	34.0	200 × 200 × 1200	4Φ12 mm	360	φ8@ 150 mm	240
		Col.01.L.3P	34.0	200 × 200 × 1200	4Φ12 mm	360	φ8@ 150 mm	240
	Tarabia and Albakry [4]	N1	57.8	150 × 150 × 1000	4Φ10 mm	420	φ6@ 100 mm	240
		SCW1	57.8	150 × 150 × 1000	4Φ10 mm	420	φ6@ 100 mm	240
Second	New FE model	Control-300	34.0	300 × 300 × 4000	8Φ16 mm	360	φ8@ 150 mm	240
		Control-400	43.75	400 × 400 × 4000	12Φ16 mm	420	φ8@ 150 mm	240

Table 2: Summary of RC columns reinforced with steel jacketing in the present study.

Group	Studies FE model based on	Column specimen	Column dimensions (mm)	Strengthening configuration			Confinement stirrups		% preloading
				Type	Size (mm)	f_y (MPa)	Plates (mm)	Spacing (mm)	
First	Belal et al. [3]	Col.00	200 × 200 × 1200	Control	—	—	—	—	Without
		Col.01.L.3P	200 × 200 × 1200	Angles	4L50 × 50 × 5	360	150 × 100 × 5	540	Without
	Tarabia and Albakry [4]	N1	150 × 150 × 1000	Control	—	—	—	—	Without
		SCW1	150 × 150 × 1000	Angles	4L50 × 50 × 4.5	415	150 × 50 × 5	260	Without
Second	New FE model	Control-300	300 × 300 × 4000	Control	—	—	—	—	Without
		Str.300.L50.P00	300 × 300 × 4000	Angles	4L50 × 50 × 10	360	280 × 100 × 5	500	Without
		Str.300.L50.P22	300 × 300 × 4000	Angles	4L50 × 50 × 10	360	280 × 100 × 5	500	22
		Str.300.L50.P43	300 × 300 × 4000	Angles	4L50 × 50 × 10	360	280 × 100 × 5	500	43
		Str.300.L50.P85	300 × 300 × 4000	Angles	4L50 × 50 × 10	360	280 × 100 × 5	500	85
		Str.300.L50.P94	300 × 300 × 4000	Angles	4L50 × 50 × 10	360	280 × 100 × 5	500	94
		Str.300.L100.P00	300 × 300 × 4000	Angles	4L100 × 100 × 10	360	240 × 100 × 10	500	Without
		Str.300.L100.P22	300 × 300 × 4000	Angles	4L100 × 100 × 10	360	240 × 100 × 10	500	22
		Str.300.L100.P43	300 × 300 × 4000	Angles	4L100 × 100 × 10	360	240 × 100 × 10	500	43
		Str.300.L100.P85	300 × 300 × 4000	Angles	4L100 × 100 × 10	360	240 × 100 × 10	500	85
		Str.300.L100.P94	300 × 300 × 4000	Angles	4L100 × 100 × 10	360	240 × 100 × 10	500	94
		Control-400	400 × 400 × 4000	Control	—	—	—	—	Without
		Str.400.L100.P37	400 × 400 × 4000	Angles	4L·100 × 100 × 10	420	340 × 100 × 10	500	37

statistical perspective, and it can be observed for all RC columns with or without strengthening the configurations dealt with while making an analysis.

Figures 3 and 4 bear the curves showing how the load is displaced for specimens used on the experiments and the resultant FE modeling. One comparing the curves of load displacement attained from findings of experiments with the ones attained from the FE models for RC columns with or without strengthening can note an excellent match between them.

The way how FE models deal with all the specimens together with deformed shapes, failure loads, and failure modes was recorded. Figures 5 and 6 illustrate the deformations, failure modes, and locations for experimental specimens and the corresponding FE modeling. When comparing the deformations, failure modes, and locations acquired from the experimental outcomes with the ones acquired from the FE models for RC columns with or without strengthening, it can also be observed as an excellent match.

5. Predicting the Axial Load Capacity under Preloading of RC Columns Founded on Simulation of FE

For assessment of the influence of the parameters on a load of axial capacity, a parametric study was carried out. These parameters incorporated the column dimensions, the concrete strength, the cross section of the zone and yield stress of the steel fortification, the cross section of the zone and the stress yielded by the steel jacketing, and the percentage of preloading. Meanwhile, the typical model from Eurocode 4 [12] was utilized for comparison.

TABLE 3: Comparison of failure load and ratios of $P_{\text{Exp}}/P_{\text{FE}}$ for experimental and FE results.

Studies FE model based on	Column specimen	Experimental failure load (kN)	FE failure load (kN)	$P_{\text{Exp}}/P_{\text{FE}}$
Belal et al. [3]	Col.00	1255	1230	1.020
	Col.01.L.3P	1821	1900	0.958
Tarabia and Albakry [4]	N1	1475	1487.5	0.992
	SCW1	2310	2213	1.043

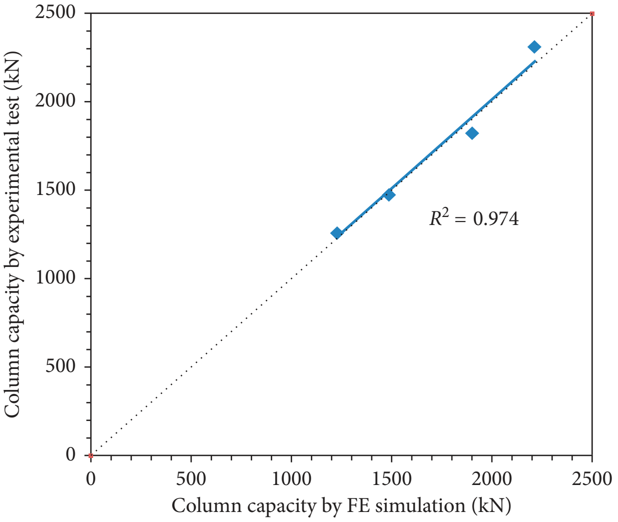

FIGURE 2: A comparison of the experimental and FE analysis values for axial load capacity.

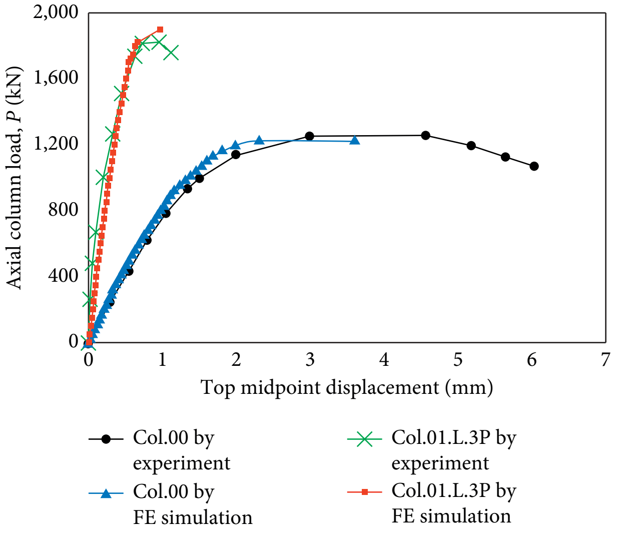

FIGURE 3: Curves showing displacement of load gained from both experimental outcomes Belal et al. [3] and FE results.

5.1. Behavior of Axial Load Displacement. Figures 7 and 8 illustrate how the axial load and column axial displacement are related to each other. Generally, the final load increases when steel jacketing strengthening was used. When the RC column is strengthened under preloading, the ultimate load decreases when the preloading increases.

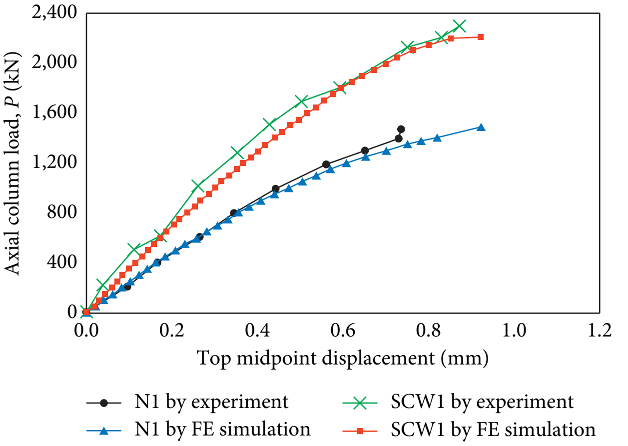

FIGURE 4: Curves showing displacement of load gained from both experimental Tarabia and Albakry [4] and FE outcomes.

5.2. Predicting the RC Columns' Axial Load Capacity Based on FE Simulation. By means of the parameters considered in the present research, it is possible to calculate the axial load capacity of RC columns through the addition of the normal force from concrete and the normal force from steel reinforcement, independently for RC column without strengthening. Furthermore, by making an addition of steel jacketing contributions right to the normal force of the RC column, the procedures ACI Committee 318 [11] and Eurocode 4 [12] come to an excellent match. As a result, the axial load capacity of a reinforced RC column is articulated as the total of the 3 normal constituents in consonance with the internationally accepted procedures as incorporated in equation (2). Table 4 demonstrates the RC column parameters appraised in the current study and the eventual axial loads, derived from simulating and analyzing the FE. The prediction regarding the axial load capacity by the Eurocode 4 [12] design model proposed can be seen in Table 4.

For the evaluation of the FE results' reliability, the findings attained from the design model suggested by Eurocode 4 [12] is compared with the results obtained from the FE simulation, as illustrated in Figure 9. An identical prediction between the Eurocode models and the FE simulations for RC columns can be seen without preloading. In this figure, the mean value of $P_{\text{u.Eurocode}}/P_{\text{u.FE}}$ is 0.998, the corresponding coefficient of variation is 2.01%, and the coefficient of correlation is 0.99. The aforementioned values reveal that the FE model is an excellent match, and it can be observed for all RC columns without preloading with the prediction values from the Eurocode 4 [12] model. Otherwise, for RC columns with preloading, the mean value of $P_{\text{u.Eurocode}}/P_{\text{u.FE}}$ is 1.199, the

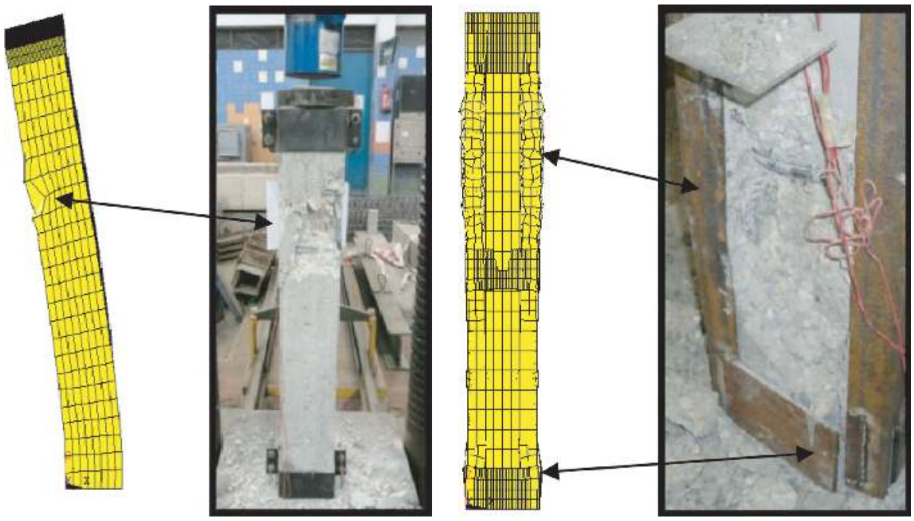

Figure 5: Deformations, failure modes, and locations obtained from both experimental Belal et al. [3] and FE results.

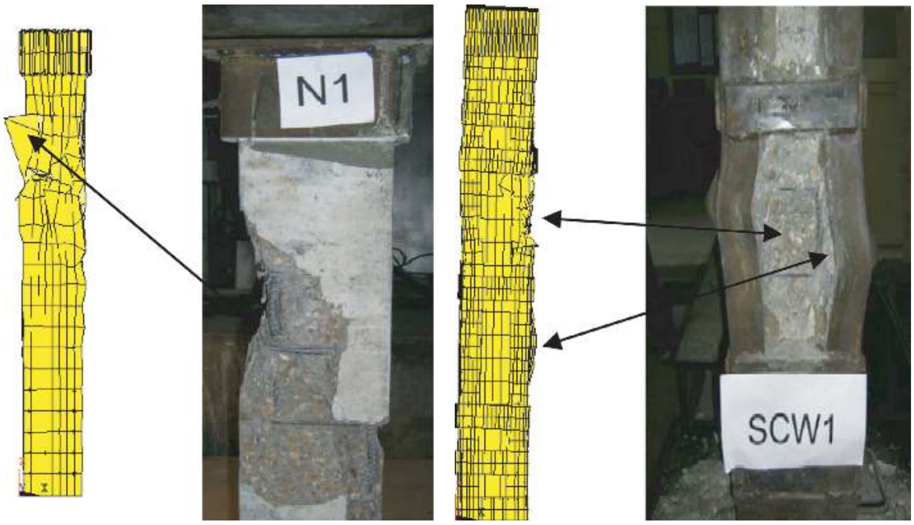

Figure 6: Deformations, failure modes, and locations obtained from both experimental Tarabia and Albakry [4] and FE results.

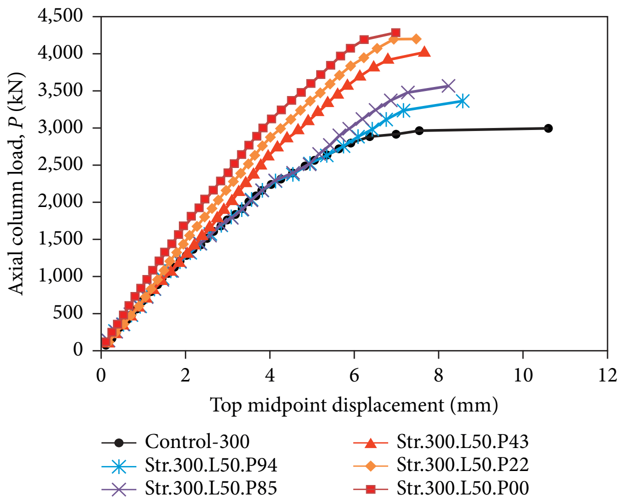

Figure 7: The curves relating to load displacement obtained from FE simulation for columns strengthened by 4L·50 × 50 × 10 with different percentages of preloading.

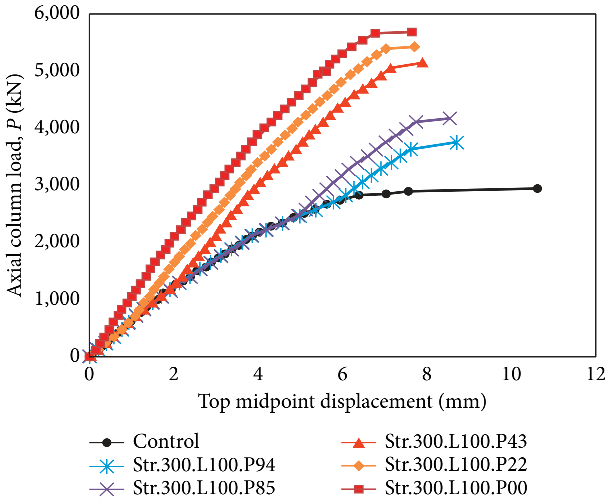

Figure 8: The curves relating to load displacement obtained from FE simulation for columns strengthened by 4L·100 × 100 × 10 with different percentages of preloading.

TABLE 4: Summary of RC columns strengthened with steel jacketing in the present study.

Column specimen	% preloading $P_{\text{pre}}/P_{\text{u.control}}$	$P_{\text{u.f}}$ Eurocode (kN)	FE failure load (kN)	Increase in failure load (kN)	Area of steel jacketing, A_{sj} (mm^2)	Steel jacketing stress, $f_s = (P_{\text{increase}}/A_{\text{sj}})$(MPa)	f_y (MPa)	f_s/f_y
Col.00	0.0	1250.7	1230	0.0	0.0	0.0	0.0	0.0
Col.01.L.3P	0.0	1934.7	1900	670	1900	353	360	0.981
N1	0.0	1432.4	1487.5	0.0	0.0	0.0	0.0	0.0
SCW1	0.0	2145.8	2213	725.5	1719	422	415	1.016
Control-300	0.0	3026.9	3000	0.0	0.0	0.0	360	0.0
Str.300.L50.P00	0.0	4322.9	4290	1290	3600	359	360	0.997
Str.300.L50.P22	22	4322.9	4200	1200	3600	334	360	0.928
Str.300.L50.P43	43	4322.9	4050	1050	3600	292	360	0.811
Str.300.L50.P85	85	4322.9	3570	570	3600	159	360	0.442
Str.300.L50.P94	94	4322.9	3360	360	3600	100	360	0.278
Str.300.L100.P00	0.0	5762.9	5820	2820	7600	371	360	1.030
Str.300.L100.P22	22	5762.9	5550	2550	7600	336	360	0.933
Str.300.L100.P43	43	5762.9	5250	2250	7600	296	360	0.822
Str.300.L100.P85	85	5762.9	4260	1260	7600	166	360	0.461
Str.300.L100.P94	94	5762.9	3810	810	7600	107	360	0.297
Control-400	0.0	6613.0	6545	0	0.0	0.0	0.0	0.0
Str.400.L100.P37	37	9805.0	9185	2640	7600	347	420	0.826

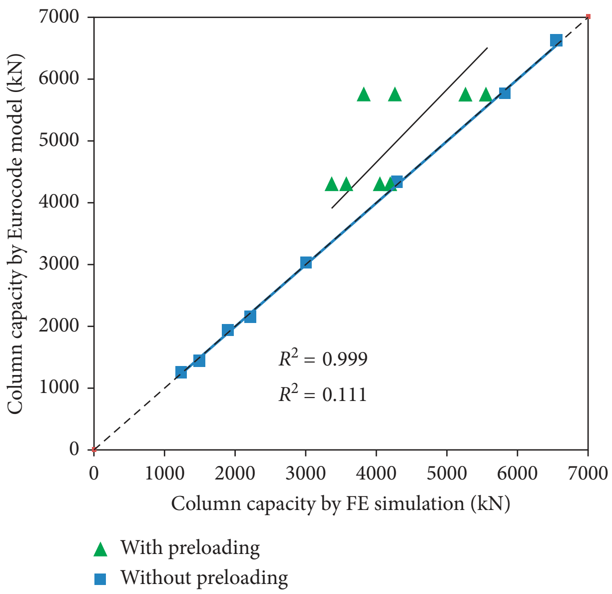

FIGURE 9: Comparison between the Eurocode model [12] and FE simulation for axial load capacity.

conforming coefficient representing variation is 13.58%, and the coefficient of correlation is 0.33; these values show that the prediction values from the Eurocode 4 [12] model are too far from the values obtained from FE simulation. So the Eurocode model needs to be modified to take the preloading when strengthening into consideration.

On the basis of FE simulating 17 RC columns, a clarification was made earlier regarding the rise in the axial load capacity that registered variation with the fluctuation of percentage in preloading; hence, the relationship between the rise in the axial load capacity and percentage of preloading is framed in equation (10), where the equation is a polynomial of the relationship between the ratios of the percentage of preloading with ultimate failure load of the control RC column ($P_{\text{P.L}}/P_{\text{u.f}}$) and percentage of steel jacketing stress obtained from the FE simulation with yield stress ($f_{\text{sj}}/f_{\text{yj}}$), as shown in Figure 10:

$$\frac{P_{\text{P.L}}}{P_{\text{u.f}}} = -1.167\left(\frac{f_{\text{sj}}}{f_{\text{yj}}}\right)^2 + 0.184\left(\frac{f_{\text{sj}}}{f_{\text{yj}}}\right) + 0.992. \tag{10}$$

Equation (5), which is employed in the majority of the prevailing models for predicting the axial load capacity for RC column without strengthening, and the proposed new model in equation (10) predict the steel jacketing stress under preloading. The new model that has been recently proposed for predicting the axial load capacity and can be applied to RC columns extrinsically reinforced with steel jacketing strengthening is formulated in the following equation:

$$P_{\text{u.f}} = f_c' A_c + f_{\text{sy}} A_{\text{st}} + f_{\text{sj}} A_{\text{sj}}. \tag{11}$$

6. Conclusions

The introduction of the FE simulation model has been made for predicting the contribution of steel jacketing to the RC columns' axial load capacity. There are parametric studies conducted for assessing the influences of several parameters on the capacity of axial load and failure modes relating to RC columns. The investigative findings derived from the FE model were subjected to a comparison with outcomes attained from previously published work cited in the literature, involving a different structure, concerning test geometries. There is a proposal for a new model which takes into account the investigated parameters. On the basis of this research, the conclusions drawn are given below:

(1) In comparison with the findings of the experiments, the FE model is considered to be more accurate in making a prediction about the mode of failure and determining the axial load capacity. The mean value

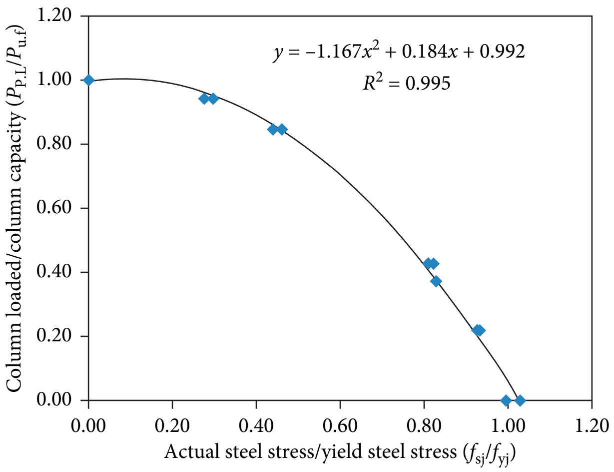

FIGURE 10: The relation between percentage of preloading columns and the corresponding percentage of steel jacketing stress obtained from the FE simulation.

of $P_{\text{Exp}}/P_{\text{FE}}$ is 1.003 for columns that strengthened by steel jacketing or without strengthening. The corresponding coefficient of variation is 3.16%, and the coefficient of correlation is 0.987.

(2) Evaluation with the results obtained from the design model in Eurocode 4 [12] is compared with the results obtained from the FE simulation; there is an excellent match prediction between the Eurocode models and the FE simulations for RC columns without preloading.

(3) The new model equation (10) can predict steel jacketing stress and the RC columns' axial load capacity strengthened by means of steel jacketing under preloading.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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