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Finite Element Analysis of Reinforced Concrete Column Strengthened with Concrete Filling and Steel Tubes Jacket

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Abstract

Column strengthening is used to restore the ultimate load capacity of RCC. The RCC strengthened contains a reinforcement cage, RCC, filled concrete, and steel tubes. The study was focused on the capacity of RCC strengthened by steel jackets. All parameters in the models were used to carry out in FE software Abaqus 6.14. Nonlinear behavior of steel tubes, reinforcement and concrete (RCC and fill concrete) are included in FE models. In this paper, 12 specimens were taken to evaluate the capacity of RCC, the axial load-shortening curve, and failure modes of column strengthened by steel tube jacket. From output, since the concrete strength increased from C-30 to C-50, the axial force increased by 22.45% and 37.71% of RCC without and with strengthened by steel tubes respectively. Similarly, when thickness of steel tubes increased in FE models the axial forces of the column strengthened was increased. As same dynamic load was applied in the model, the RCC without strengthening was more damaged than the strengthened column due to the weight of fill concrete. Since the concrete grade was increased the CCR directly increased but, the CF decreased. Similarly, the comparative analysis done between FEA with EC-4 and AISC predictions. The mean values of the Nu, AISC/Nu, FEA ratio was 0.90084 and the standard deviation value was 3.90%. The EC4 result yield more acceptance prediction rather than other with the mean values of 0.93075 from Nu, EC4/Nu, FEA ratio, and with 3.77% standard deviations. In both codes, the results predicted were conservative when compared with FE results.

Keywords: *Finite element modeling; strengthened of column; steel tubes; compressive load-shortening curve; confinement factor (CF); concrete contribution ratio (CCR).*

1. Introduction

The working conditions of reinforced concrete structures (RC) are subject to their own fluctuations and deteriorate or are prone to failure due to various causes. All reinforced concrete elements are most often subject to overloading, poor maintenance, environmental influences, material quality, etc. Analytically, new seismic and other standards often render an older reinforced concrete structure unable to withstand earthquakes and other impact loads. In all of these situations, column bracing is a process used to increase or restore the final load-bearing capacity of reinforced concrete columns, which means running steel cover the full height of the column. It is used to accommodate additional live load or dead weight not included in the original design, to relieve stress due to design or construction flaws, or to restore damaged structural members to their original carrying capacity. One of the techniques used to reinforce reinforced concrete columns is steel pipe sheathing. This technique is chosen when the loads applied to the column increase, and at the same time, increasing the column cross-section is not allowed. Installation of a steel casing of the required size and thickness according to the project and drilling holes for pouring epoxy material, which will ensure the necessary connection of the concrete column to the steel casing. Fill the space between the concrete column and the steel shell with a suitable epoxy material. Any reinforced element is able to withstand the application of a load and a sudden impact on it [1]– [14]. When different structural elements are combined with different materials, the efficiency was also high [12]. Due to the coupling effect with the concrete, the steel casing enables the formation of circular stresses, which significantly increase the performance of the bond and the load-bearing capacity of the column [13]. Concrete-filled tubular steel columns (CFST) are widely used in many engineering structures because they combine the best properties of steel and concrete materials, including high strength, high ductility, and high stiffness [2.3]. Investigation of the behavior of concentrically loaded concrete columns encased in Steel Reinforced Polymer (SRP) sheathing [15].

2. Nonlinear FE Modelling

2.1. General

To achieve the aim of the study, 12 samples were modeled in a finite element simulation. In addition, a control sample was run in the Abaqus validation software to assess the load-bearing capacity, or axial loading, of the reinforced column. The prefabricated samples (SPC-1 to SPC-3) were modeled as reinforced concrete columns and the other remaining samples (SPC-4 to SPC-12) were modeled as reinforced concrete columns reinforced with steel pipes and a concrete infill. Reinforcement was carried out on a prefabricated reinforced concrete column, which was inserted into a steel tube and the remaining empty space was filled with fresh concrete. The reinforced rectangular pier interacted with a concrete infill containing different grades of concrete, and the entire height was completely covered by a steel tube that acted as a sheath over the entire surface a load in frequency table form was applied at the top of the column, the load was applied with the tabular form of frequency. The applied load was increased as dynamic explicit in the Abaqus software package. For the study, the non-linear finite model in the Abaqus software package [16] was considered which has a wide capability of capturing material non-linearity response. All components in the reinforced column strengthened by steel tube were accurately modeled to obtain good results from finite element models. This finite element model includes different components such as a square RC column, reinforcement bar for main and for stirrups, steel tubes for jacketing, and infill concrete layers between the RC column and steel tubes. All geometrical and nonlinearity material was taken into consideration in the finite element model. An experimental test was used to verify the simulation output obtained from FE analysis and the scale of the FE models was chosen in consideration of the limitations of the laboratory testing equipment, in which the largest model could be around 90 cm high. Then, an aspect ratio of 1 by 3.3 was obtained by considering that a typical RC building has a 300 cm high story [13]. All components in the test were well modeled separately and modeled in finite elements to form as scale in the models of laboratory test specimens.

2.2. Parametric study

To evaluate the carrying capacity of the reinforced column without strengthening and with strengthening, the thickness of steel tubes, cross-section of the column, and filled concrete with different grades and confinement factors were the parametric data for this study. The parametric study in this paper was well described in figure 1(a, b, and c) with all the geometrical dimensions like; diameter, type of section, thickness, and pieces of the bar in the arrangement of reinforcements. The reinforced concrete column without strength size was squared in sections (12x12cm) with a length of 90cm. but, the strengthened column has circular (diameter of 19.4cm) and have similar in length to RC concrete column. The concrete strength, dimension, and thickness of the steel tubes are also considered a parametric study which were more arranged in Table 1 in detail with respective their specimens. The depth to the thickness of the steel ration was presented in [17].

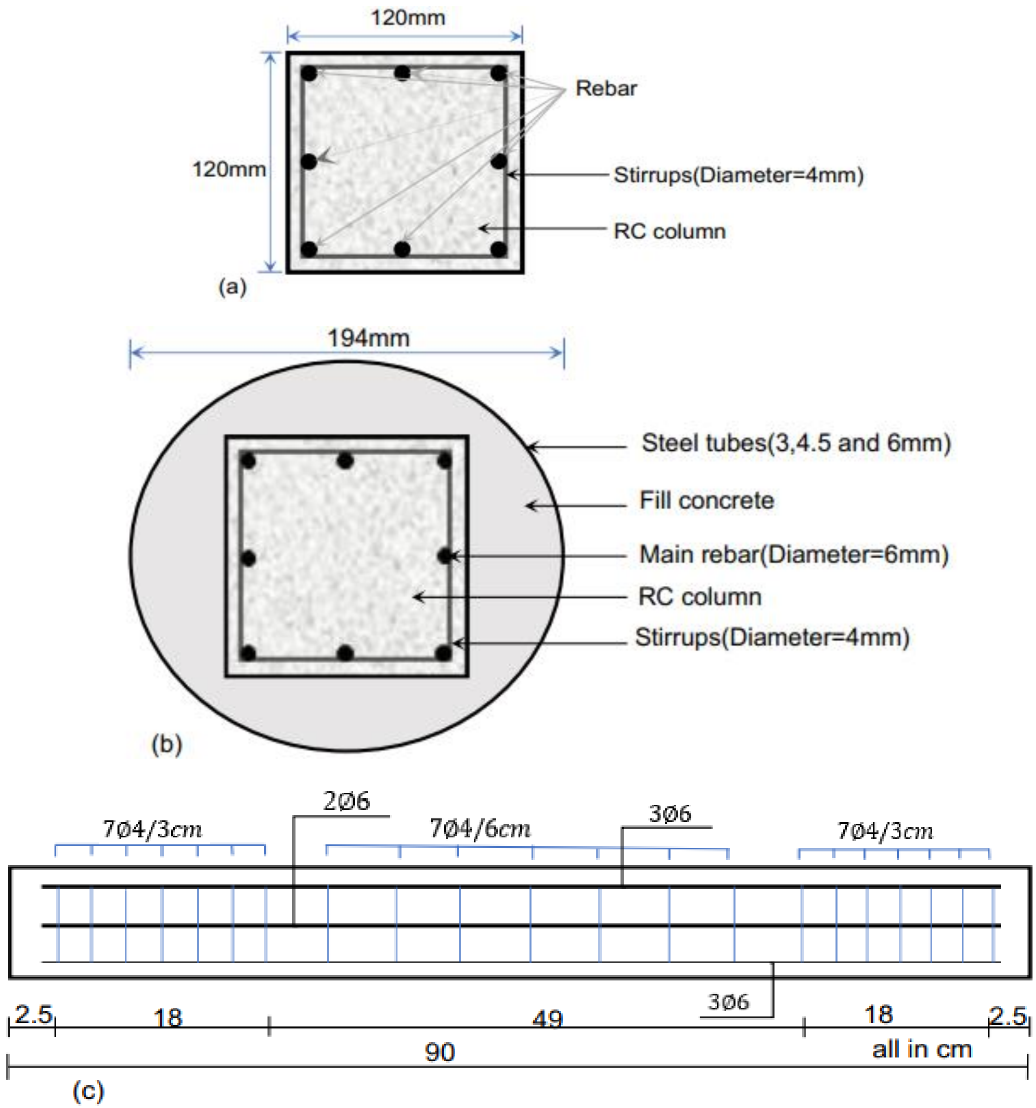


Figure 1. Schematic view of the RC column (a), Strengthened column by Steel tubes(b) and the reinforcement arrangement (c)

Table. 1.All dimensions and parametric study

Group	Specimen	B or D(cm)	L(cm)	t(mm)	t/D	Concrete grade (MPa)
C-1	SPC-01	12	90	-	-	30
	SPC-02	12	90	-	-	40
	SPC-03	12	90	-	-	50
C-2	SPC-11	19.4	90	3	65	30
	SPC-12	19.4	90	4.5	43	30
	SPC-13	19.4	90	6	32	30
C-3	SPC-21	19.4	90	3	65	40
	SPC-22	19.4	90	4.5	43	40
	SPC-23	19.4	90	6	32	40
C-4	SPC-31	19.4	90	3	65	50
	SPC-32	19.4	90	4.5	43	50
	SPC-33	19.4	90	6	32	50

2.3. Parts created in modeling

Several parts are involved in this study to create a model. These parts include a reinforced column including main frame and brackets, a layer of concrete filler and steel tubes as shown in Figure 2(a-b). The reinforced concrete column was modeled in 3D modeling space as deformable types with base bodies and extrusions. Otherwise, the reinforcement cage elements (main bars and stirrups) figure 2 (c-d) are modeled in the 2D modeling space as flat base wire deformable types, and the steel tubes covering the concrete outer faces completely filled with parts are modeled in the 3D modeling space in the form of the deformable type with coating and embossed bottom.

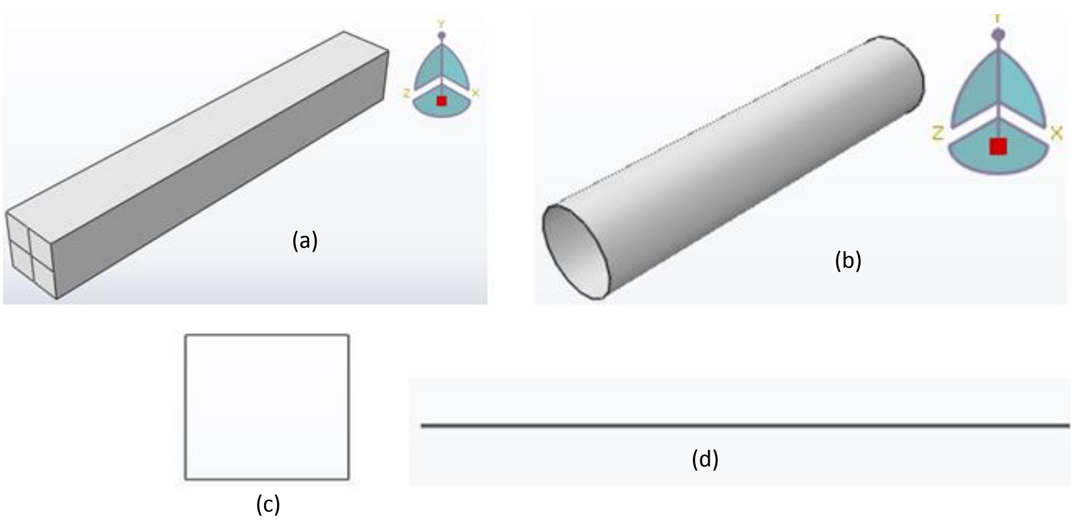


Figure 2. Parts modeled in FE software package

2.4. Material Modelling

Column crushing or buckling was more dependent on the material (concrete and steel) in the model. This error was evident in the model output for each sample. For a good result, the exact material and its properties must match for the ES models. There were different materials which were created in the model, such as strains, stresses and other damaged materials as shown in [1], [18],[19]. The mechanical properties of a cementitious material under simple tension or compression are analyzed using the finite element method [20]. The FE model predicts the behavior of fill concrete, steel bar, and other steel tubes under applied loads involving the dynamic loading. In this section the property of stress, stains, and all inelastic materials were analyzed with the form of the damage to the elements in the models [21]. In this study, the damage plasticity model was adopted and the maximum tensile strength of concrete was taken as one-tenth of its compressive strength [20]. Both compressive and tensile behavior equations for damage parameters to capture damage behavior and the modeling approaches are developed in [18]. According to this circumstance, the value of 0.0022 and 0.0035 was taken at peak and the nominal ultimate strain, respectively. Concrete compressive cylinder strength having a magnitude of 30, 40, and 50MPa has been used for the modeling. Furthermore, the material properties for steel tubes, main and stirrups reinforcement bar have been proposed in the model based on [22] provision as illustrated in Table 2.

Table 2.material property for reinforcement cage and steel tubes.

Part	Yield Strength (Gpa)	Poison ratio	Ultimate Strength (Gpa)	Ultimate Strain (%)	Elastic Modulus (Gpa)
Main Reinforcement	550	0.3	650	2.5	200
Steel tubes	230	0.3	340	2.5	210
Stirrups	550	0.3	650	2.5	200

2.5. Part assembly in Model

The assembled model was done in the instance of FE simulation which was after different material property, profile, sections assignments, and all parts were created. In this study, the assembled component was organized its relative position, and also all elements of the dependent instance were employed as the FE package simulation. Figures 3. (a) and (b) show the assembled model based on the arranged position of the reinforced column and strengthened column by the steel jacket respectively.

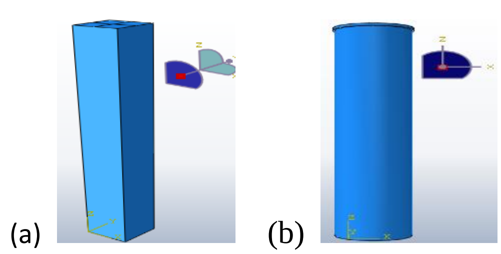


Figure 3.Reinforced concrete column (a) and strengthened of column by steel jacket(b)

2.6. Boundary conditions, loading, analysis steps and interactions

In finite element analysis models, the dynamics explicit was used in addition to steps to get the output in this study. To minimize the analysis time in FEA the model was scaled according to the laboratory tests arrangements. After all components in the model were assembled there was an interaction between the parts which were used as merge the element to form a model which can resist the applied load and formulate the performance of structures as model. This interaction was done from surface to surface of the parts. in the reinforced column, the stirrups were merged into the main reinforcement and all parts of the bar (merged stirrups and main reinforcement) were embedded in the total part of the reinforced concrete column. But in a strengthened column by steel tubes, the RC column was embedded in the infill concrete and the surface between steel tubes and concrete interact by penalty, which was used the friction of coefficient of 0.45 between the surface surfaces to develop the adhesive forces between material property. Other additional parts which mean steel plates were created and assembled at the top of the strengthened column used to distribute the concentric load apply on the top of the model in z-directions. The steel plate was in contact directly with the top of the model and interacted as a rigid body. The model is castrated which is used to control the movement of all parts from its position. At the bottom of the model of the column, all parts were fully castrated to resist movement through X, Y, and Z coordinates. Figure 4 (a & b) indicate the boundary condition and other application of load for the model for both RC column and strength column respectively.

(a) (b)

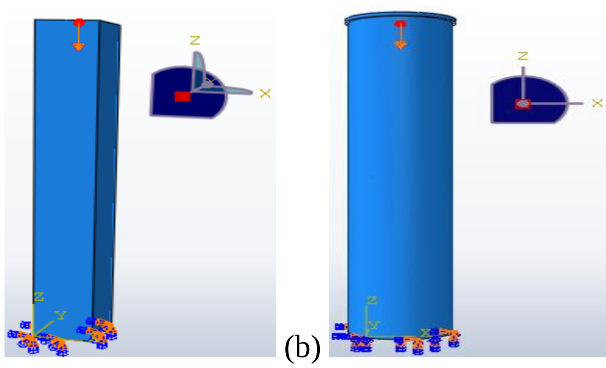


Figure 4.boundary condition and loading for RC column(a) and strengthened column(b)

The concentric load was directly applied on the top of the model in dynamic with time incremental which means a frequency increase of 0.1sec by numerical values in the FE software package. All specimens were performed on a 2000 KN load applied on each model which was taken from the tests were performed on [13] to get the capacity of the column before and after strengthened results.

2.7. Element types and Meshing

Meshing is the process of the large element in the model convert to a fine element to study the internal property of the model which is the full integration of elements. The mesh size was determined by iteration until the FEA result was constant. In this study the main and stirrups reinforcement by 8-meshed size within T3D2, A2-node linear in 3-D truss of element types. RC column meshed 15 sizes with C3D8R-An 8 nodes linear bricks, reduced integrations, and hourglass control element types. Similarly, steel tubes meshed by 16 in sizes and have S4R-A4 nodes double curved or thick shell reduced integration, hourglass control with finite membrane strains element type in all specimens in models' analysis by FE simulation. The mesh of all parts in the whole specimen were illustrated in Figure 5(a-c).

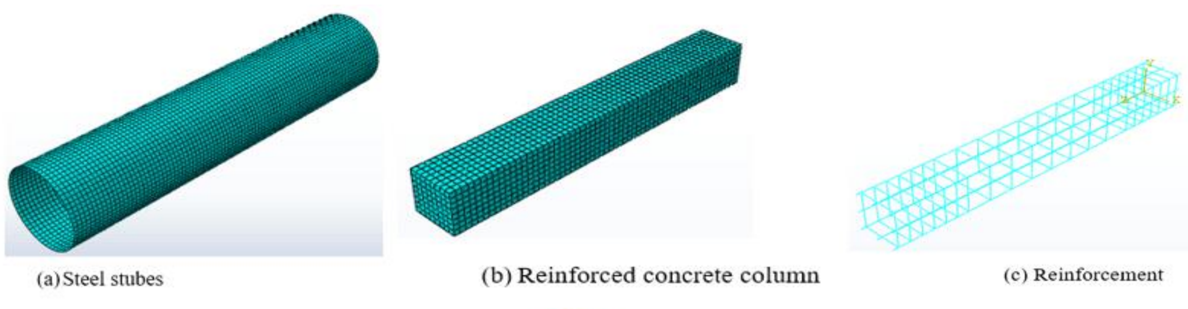


Figure 5. Mesh and Element type of parts

3. Results and Discussion

3.1. Validation of the FE analysis model

The experimental part of the presented research was carried out on a model of a reinforced concrete column in the paper[13] which was represented by the nominal name of SO4 in specimens. So, before starting any model in this study, the validation was done with the numerical value present in the test and the model result obtained from FE simulations. The failure modes, the axial load, and deformation obtained from the FEA model were directly compared with experimental results. According to the experimental result observed the failure of the reinforced concrete column occurred at top of the column, similarly when it was analyzed by FE simulation the damage was formed at top of the model, which means the failure of the column was formed at the direction of load applied on the models. Figure 6 illustrated the comparison of finite element analysis and experimental result regarding modes of failure of each component of the model.

Table 3. Comparative study of FEA models with experimental results.

Specimen	Parameter	FE model result	Experimental result	% of difference
Control	Axial load(KN)	639	624	2.35
Model	Shortening(mm)	1.98	1.91	3.53

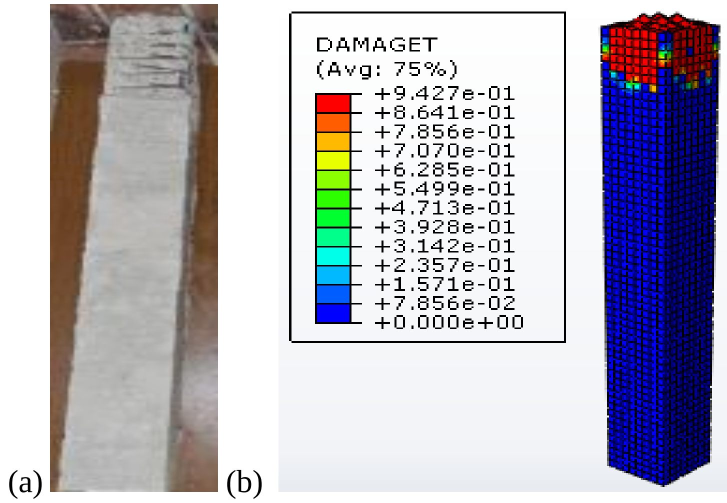


Figure 6. comparison of experimental result (a) and FE model output (b)

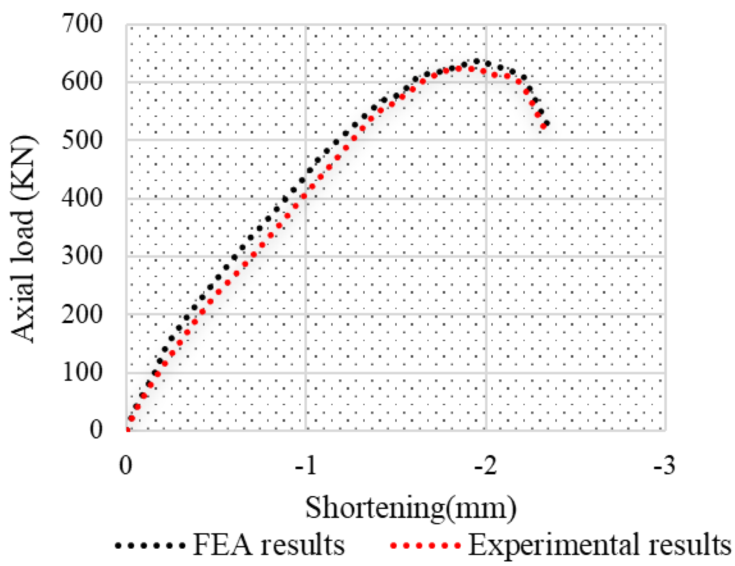


Figure 7.Comparative study of FE models with experimental results

Table 3. indicates the axial load and shortening obtained from both finite element analysis and the experimental model for the reinforced concrete column. As the Figure 6 (a, b) illustrates the concrete column from the experimental and FE model fracture at the top part in the direction of the dynamic load exerted. Similarly, the figure 7 indicated that there was a comparative output result values between both obtained from FEA and experiment with the versus of axial load to shortening as parametric study.

3.2. Effects of concrete strength on reinforced concrete column without strengthened and with strengthened by steel tubes.

The figure 8, shows the effects of concrete strength as a parameter of study on both reinforced concrete columns without the jacket and with a jacket by steel tubes. As described in figures

8(a) and (b) the concrete strength has more effects on the reinforced column without the jacket and strengthened by steel jacket respectively. In this study, the reinforced concrete column without and with a strengthened steel jacket analysis in FE models with a concrete grade of C-30, C-40, and C-50 MPa by taking steel tubes of 3mm thick for the strengthened column. The capacity of the column is significantly increased, as the concrete grade increases. When the concrete grade was increased from C-30 to C-50 the axial load was also increased by 22.45% and 37.71% in a reinforced concrete column without strengthened and columns strengthened by steel jacket respectively.

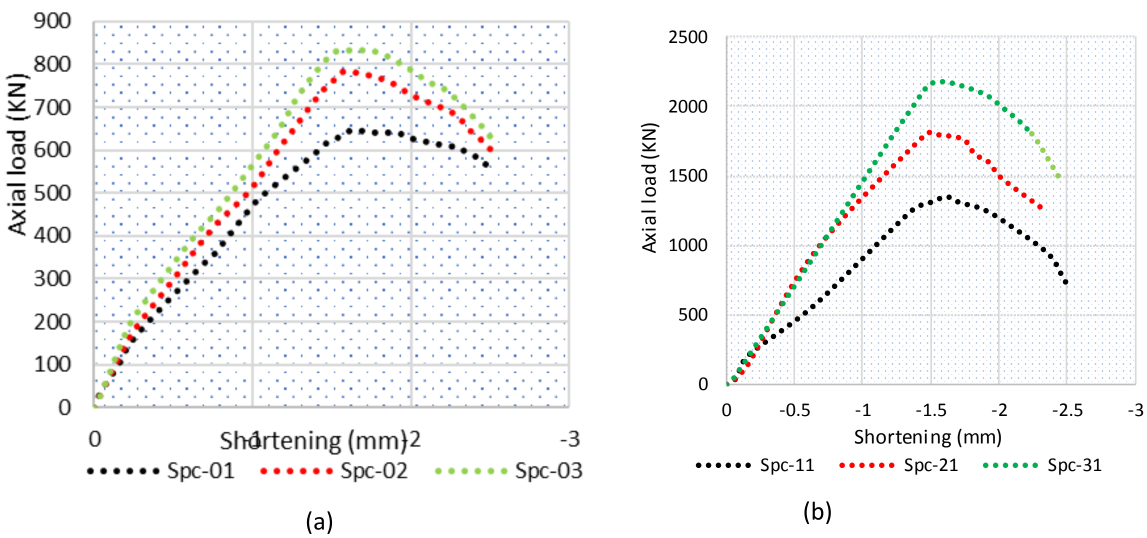
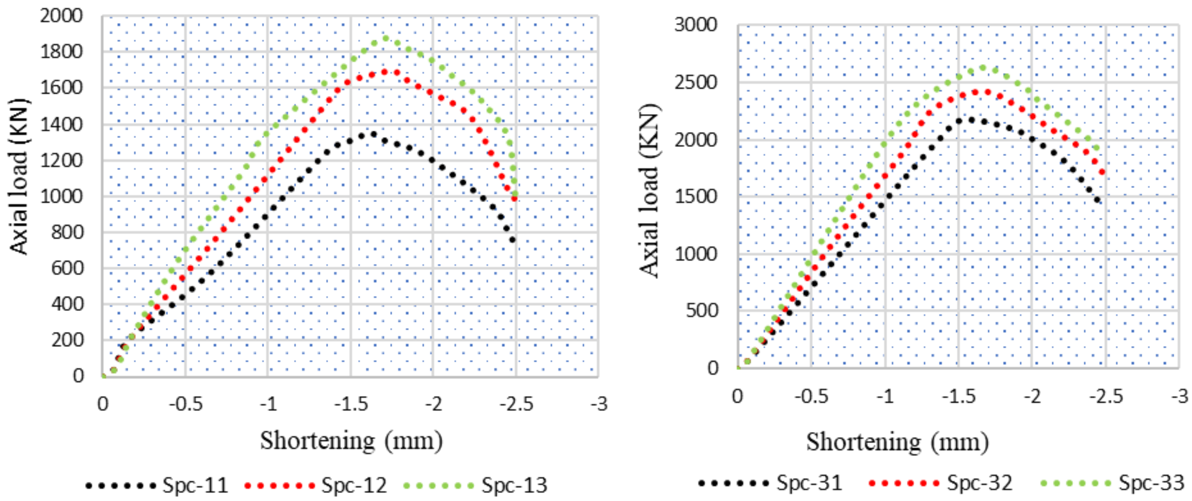


Figure 8. effect of concrete strength on Reinforced column without strengthened (a) and with strengthened by steel jacket (b) with in C-30, C-40 and C-50MPa.

3.3. Effects of change the thickness of steel tubes on strengthened column

As the dimension and parametric study in Table 1, there were three thickness of steel tubes modeled in FE simulations concerning specimens. When the thickness of steel tubes increases, the steel thickness to a depth of column cross-section ratio was decreased within the same depth and length of the column. There were three different steel thicknesses (3mm,4.5mm, and 6mm) was used to strengthen the column with a steel tubes jacket. All thicknesses were analyzed with each concrete strength as illustrated in the parametric study. Figure 9(a, b) illustrated the effect of changing the steel tube thickness on the column steel tubes jacket model with concrete strength of C-30 and C-50MPa respectively. Since the steel tube increased from 3mm to 6mm in the specimen of Spc-11 to Spc-13 the axial load increased by 27.61% with the same values of concrete strength as shown in figure 9 (a). Similarly, with the same increment of steel tubes thickness in specimen Spc-31 to Spc-33 the axial load of the strengthened column increased by 10.56% within the same data of concrete strength as shown in figure 9(b).

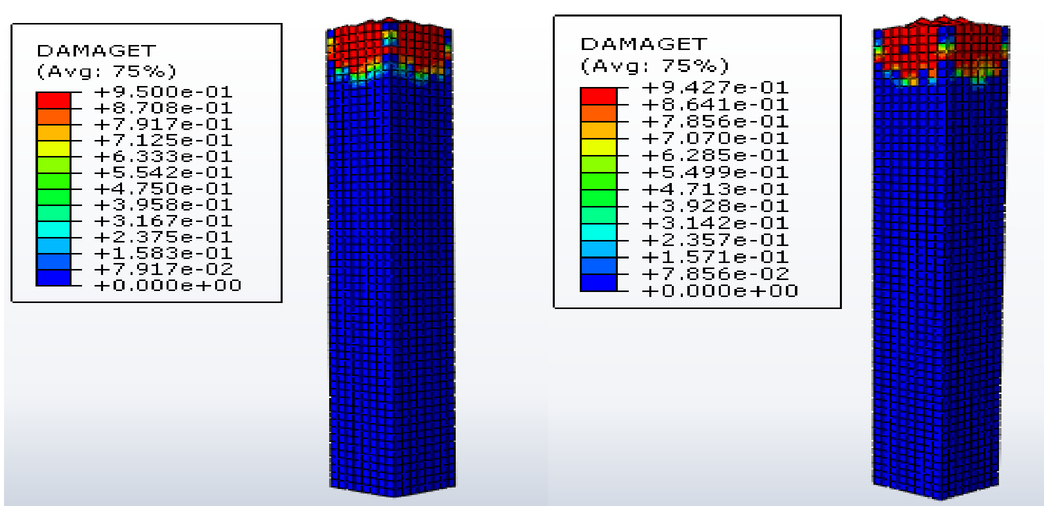


(a) (b)

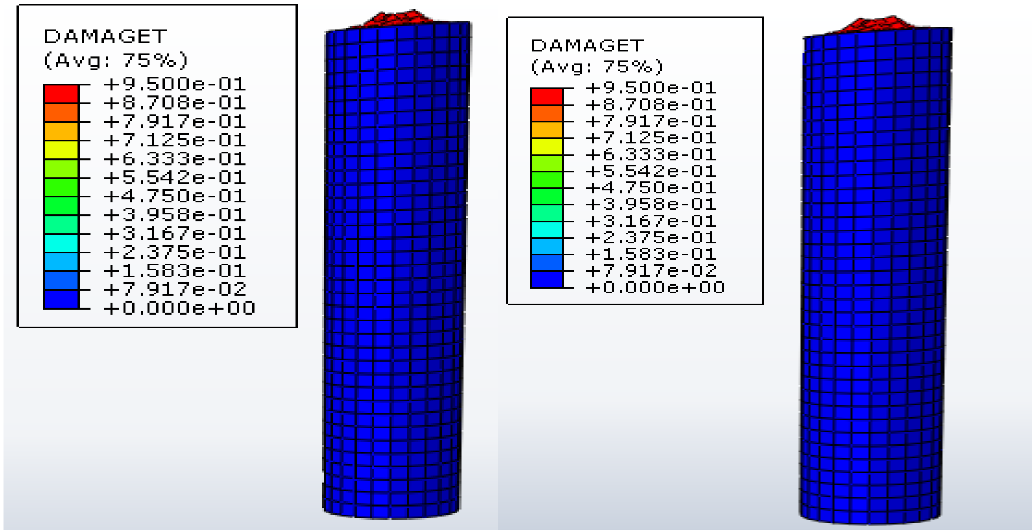
Figure 9.effects of change thickness of steel tubes on strengthened column with C-30 (a) and within C-50 model

3.4. Damage of components in the Models

Figure 10 indicates the failures of column components in the phase of the models. Column parts were damaged through the part of applied loads on it. The RC column without strengthening was crushing on the top of the models and the RC column which was strengthened by steel tubes which was no more crushed and damaged, which indicates that the jacket column can resist any application load on it. Both failures of RC without and with a strengthened steel jacket were modeled and analyzed by FE simulations. As observed in figure 10(a-b) failures of the reinforced column and figure 10(c-d) damage of reinforced column strengthened by a steel jacket. In the case of jacketing column, there was no more failure in the model, because has a high weight of fill concrete, and it is used to resist any application of load on the phase of columns.



(a) (b)



(c) (d)

Figure 10.damage of RC column without strengthened (a-b) and strengthened of column by steel tubes(c-d)

3.5. Comparison of Axial load obtained from finite element analysis and Code specification

3.5.1 Eurocode - 4

The plastic resistance of steel-concrete composite members subjected to axial compression can be estimated with increased core concrete strength caused by the confinement stresses achieved by the steel tube [23]. The axial strength according to EC4 (Nu, EC4) of a CFST is determined as:

$$N_{U,}EC4 = \eta_a A_a f_{yd} + A_c f_{cd}\left(1 + \eta_c \frac{t}{d}\frac{f_y}{f_{ck}}\right) + A_s f_{sd} \qquad (1)$$

$N_{U,}EC4 = \eta_a A_a f_{yd} + A_c f_{cd}\left(1 + \eta_c \frac{t}{d}\frac{f_y}{f_{ck}}\right) + A_s f_{sd}$ ……………………………Where, t is the thickness of steel tubes, d is outer diameter and A_{sr} and f_{sd} are the area and the design strength of the steel reinforcing bars, respectively. For members with e = 0 the values ηa = η_{ao} and ηc = ηco are given by the following expressions: Coefficient η_{ao} and η_{co} were expressed by η_{ao}=0.25(3+2$\bar{\lambda}$) ≤ 1.0 and η_{co} = 4.9-18.5$\bar{\lambda}$+17$\bar{\lambda}^2$ ≥ 0. The relative slender of column can be calculated as $\bar{\lambda} = \sqrt{N_{pl,Rk}/N_{cr}}$, where: $N_{pl}R_K$ is the characteristic value of the plastic resistance to compression of the design strengths and N_{cr} is the elastic critical normal force for the relevant buckling mode, calculated with the effective flexural stiffness (EI)eff which determined from equation of $E_a I_a + E_s I_s + K_e E_{cm} I_c$ where, K_e is a correction factor that should be taken as 0,6 and I_i are the second moment of area of steel structural sections with the E_{cm} is the modulus of elasticity of concrete.

3.5.2. AISC – 360

American standard AISC - 360 gives the compressive strength of compact axially loaded doubly symmetric filled composite members with a round cross-section, so the axial load-bearing capacity (Nu, AISC) of the CFST member is calculated as a sum of the strength of its parts [24]:

$$N_{U,}\text{AISC} = f_y A_s + 0.95 f_{c,f} A_{c,f} + 0.95 f_{c,c}\left(A_{c,c} + A_{sr}\frac{E_s}{E_{c,c}}\right) \quad (2)$$

Table 4 indicates the comparison of result obtained from FEA and code specification (for both EC4 and AISC with the value of confinement factors.

Table 4 Comparison of Axial load obtained from finite element analysis and Code specification.

Group	Specimen	FEA	Nu, EC4	Nu, AISC	EC4/FE	AISC/FEA	ξ
C1	SP-01	646	710	597	1.09907	0.92415	-
	SP-02	780	786	741	1.00769	0.95	-
	SP-03	833	789	766	0.94718	0.91957	-
C2	SP-11	1353	1236	1208	0.91353	0.89283	0.240
	SP-12	1708	1542	1488	0.90281	0.87119	0.360
	SP-13	1869	1748	1698	0.93526	0.90851	0.482
C3	SP-21	1808	1633	1698	0.90321	0.93916	0.180
	SP-22	2143	1899	1901	0.88614	0.88707	0.270
	SP-23	2347	1986	2014	0.84619	0.85812	0.361
C4	SP-31	2172	1930	1995	0.88858	0.91851	0.143
	SP-32	2426	2196	2091	0.90519	0.86191	0.216
	SP-33	2614	2442	2298	0.9342	0.87911	0.289
Mean					0.93075	0.90084	

According presented in table 4, the adopting design code predicts the axial load capacity of RC column strengthened with steel jacketing and fill in concrete. The comparison between predicted result by code (Nu, codes) and FEA as axial load and Nu, codes/FEA as ratios of the RC-column strengthened by a steel jacket. The result obtained from the code of AISC-360 gives conservatives predictions. The mean values of the Nu, AISC/Nu, FEA ratio is 0.90084 and the standard deviation value was 3.90%. Additionally, the EC4 result yield more acceptance prediction rather than other with the mean values of 0.93075 from Nu, EC4/Nu, FEA ratio, and also with 3.77% standard deviations. But from both codes results, there were no overestimated results noticed gained from all specimens with each parametric study. According to the specimen studied as reinforced concrete column without strengthened (Group C-1) with different concrete strength, code EC4 and AISC-360 both gave conservatives predictions that were outsides the $\pm 1.70\%$ and $\pm 6.90\%$ of limits respectively. Similarly, other groups (C-2 to C-4) which column strengthened by steel jacket predicted in both EC4 and AISC-360 codes that were the outsides of ±9.83 and ± 9.82 limits respectively, which means those results were under conservatives.

3.6. Concrete contributions ratio (CCR) and confinement factors (ξ).

The concrete contribution ratio (CCR) was used as a way to estimate the effect of enhanced strength of the core concrete in concrete-filled steel tubes. It was gained from the ratio of ultimate axial force of the column to the test ultimate axial force of hollow steel tubes. Since the hollow steel column was not tested experimentally, its ultimate force was calculated from the expression: $N_U=f_yA_s$.The relationship between the confinement factor and the concrete contribution ratio is shown in Figure 12.

The confinement factor for CFST was defined by:

$$\xi = \frac{A_s f_y}{A_c f_{ck}} \tag{3}$$

Where A_s, A_c are the area of steel jacket, basic column concrete and f_y, f_{ck} are the steel yield strength and the characteristic compressive strength of basic column concrete respectively. From the presented values in figure 11, it was observed that the values of CCR in strengthened columns filled with high-strength concrete were greater than values for specimens filled with lower strength concrete. Oppositely, with the rise of the confinement factor, the contribution of the core concrete strength on values of the CCR decreased.

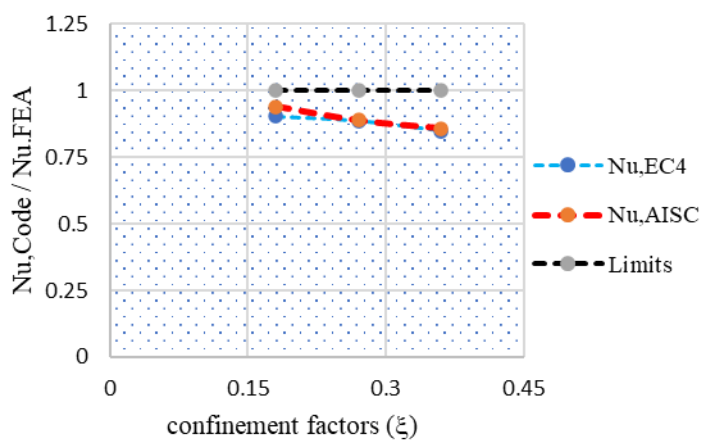
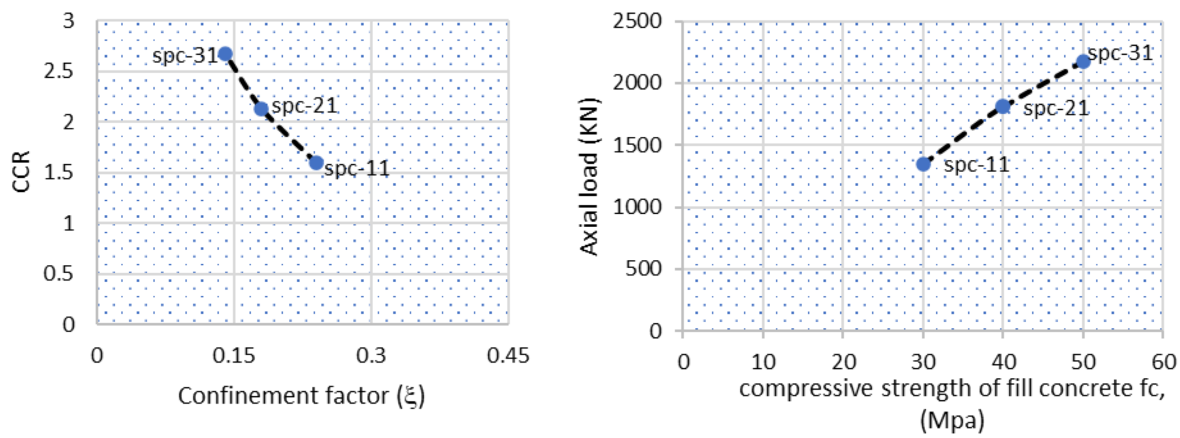


Figure 11.Comparison of axial compressive strengths ratios of the code predicted and the FEA results within the simulation range 0.140 – 0.482 of ξ.



(a) (b)

Figure 12.(a) Confinement factor versus concrete contribution ratio relationship. (b) Effects of FEA parameters for strengthened columns.

According to figures 12 (a and b) the confinement factors versus concrete contribution ratio and the axial load versus compressive strength of fill concrete have the opposite value in the strengthening of the concrete column in a steel jacket. Since the axial column and the concrete strength were increased directly the CCR was increased. Similarly, as the values of the concrete strength were increased in the specimen but the value of confinement was decreased, and it's an indication that the resistance of concrete materials in this composite part was developed rather than the other constituent material.

4. Conclusion

The results of FE simulations and theoretical predictions on the performance of reinforced concrete columns strengthened with steel tube jackets and filled concrete with different concrete strengths were presented in this paper. Thus, result from finite element simulations is more depend on the parametric studied and creations of the parts in the models and assembled, which describe that the gained results to refers the full summarizes of the paper.in nonlinear material there were different part created in the models like as reinforcement cage, reinforced concrete column, fill concrete layer and steel tubes jacket as parametric study in finite element analysis. From this Abaqus software simulation as the models, different result was obtained like shortening, axial compressive force and damage of the models was observed. Depend on the result obtained in above with in the well-arranged of the simulation models, the following conclusion are drawn:

i. The concrete strength is one of the most parametric studies which can affect the capacity of the composite column. In this study, both reinforced columns without strengthened and with strengthened steel tube jackets were affected by concrete grades. The capacity of the column is significantly increased when the concrete grade increases. As the concrete grade increased from C-30 to C-50 in MPa the axial compressive load was also increased by 22.45% and 37.71% in reinforced concrete columns without strengthened and with strengthened by steel tube jacketing respectively.

ii. In Finite element simulation, there were different values of results obtained when the models were created from different thicknesses of steel tubes during the reinforced column strengthened by a steel tube jacket. In addition to that, the thickness of steel tubes was affected the results obtained from the simulation. Since the steel tube thickness in reinforced column strengthened was increased in the FE models, directly the axial compressive load of column strengthened was increased.

iii. Both columns without strengthened and strengthened by steel tubes were affected by the formation of damage in the models. Column without strengthened was more damaged at the top phase of the model through application of load. At the top phases of models' damage and crushing of column obtained, it indicated that, the column without strengthened affected by failures. But in the column strengthened by steel jacket, the only top phase has the formation of damage and no more failures in the models. This indicated that, there was a high weight of fill concrete which was jacketed by steel tubes used to resist any application of load.

iv. The considered codes give a good prediction of the axial compressive load of the strengthened column. The mean value of axial compressive load ratio of $Nu, AISC/Nu, FEA$ and $Nu, EC4/Nu, FEA$ were 0.90084 and 0.93075 with standard deviations of 3.90% and 3.77% respectively. This indicates the results predicted by codes are more conservatives when compared with finite element results.

v. The concrete contribution ratio and confinement factor could be examining the capacity of the column. Since the concrete strength in the model was increased the concrete contribution ratio was also increased but the values of the confinement factor were decreased.

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