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Numerical Analysis of Reinforced Concrete Columns Strengthened with Steel Jacket

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Abstract

Reinforced concrete (RC) columns are the backbone of RC buildings, essential for supporting the structure's weight. If an RC column is not designed to carry the expected live loads, it may be necessary to strengthen it. One of the most effective methods for strengthening RC columns is steel jackets. This research conducted a numerical investigation of the effect of strengthening RC columns with a steel jacket on the axial load capacity. The steel jacket consisting of two C-channels connected with various numbers of welded batten plates was adopted. The finite element (FE) analysis of 7 columns was conducted using Abaqus/CAE software. All the columns have a cross-section of 300 x 300 mm with a 2500 mm height and are reinforced with four longitudinal bars of 16 mm diameter with five stirrups per meter of 8 mm diameter. The strengthened columns were divided into two groups. The first group consisted of four strengthened columns; the two C-channels connected with 2, 3, 5, and 7 batten plates from both sides. The second group consisted of two strengthened columns; the two C-channels connected with one large plate. The results showed that using two C-channels as a steel jacket is very effective as a relatively rigid jacket can increase the failure load of the columns by a minimum value of 21.46 %. Also, the more batten plates connecting the two C-channels steel jackets, the more confinement of the column and, hence, the more the column failure load increases. Moreover, connecting the two C-channels steel jacket by a single large plate to form a complete box around the column gives the best confinement and could increase the failure of the column by 75.92 %.

Keywords

RC columns; Steel jacket; Strengthening of RC columns; Numerical analysis; Finite element analysis.

1. Introduction

Reinforced concrete (RC) columns are the backbone of RC buildings, essential for supporting the structure's weight, transferring loads to the foundation, and resisting lateral forces, such as wind and earthquake loads, enhancing the structural integrity and safety of the building. RC columns are typically made of concrete and steel reinforcement. The concrete provides compressive strength, while the steel reinforcement provides tensile strength and ductility. This combination of materials makes RC columns incredibly strong and resilient, able to withstand various loads and environmental conditions (Zeng, 2017). If an RC column is not designed to carry the expected live loads, it may be necessary to strengthen it. One of the most effective methods for strengthening RC columns is steel jackets. Steel jackets are typically made of high-strength steel plates that are welded together to form a closed tube. The jacket is then fitted around the existing RC column and anchored using steel bars or bolts. The steel jacket will provide the column with the additional strength and stiffness it needs to carry the higher live loads (Montuori & Piluso, 2009). Once the jacket is in place, it provides additional confinement to the concrete core of the column. This confinement helps to increase the column's strength, stiffness, and ductility. In some cases, steel jackets can be used to double or even triple the load-carrying capacity of a column (Adam, et al., 2007). In recent years, there has been significant research in the development of steel jackets for strengthening normal-strength RC columns. Tarabia and Albakry (Tarabia & Albakry, 2014) carried out research on the influence of particular parameters related to the strengthening steel cage on seismically weak RC columns. The criteria that have been researched include the size of the steel angles, the size and spacing of the batten plates, the kind of bonding grout used between the RC concrete column and the steel angles, and the connection between the head of the column and the steel angles. The results of the tests revealed that the strengthening system increased the load-bearing capacity of the tested specimens and that the use of battens increased the ductility of the strengthened specimens owing to confinement effects. (Belal, et al., 2014) experimentally investigated the behavior of strengthened RC columns using angles and C-channels. The results showed that the strengthening method has a major impact on the column capacity. Also, The behavior and efficiency of a reinforced concrete square column strengthened by steel angles were investigated by Saraswathi and Saranya (M.SARASWATHI & S.SARANYA, 2016). Salman and Al-Sherrawi (Salman & Al-Sherrawi, 2017) proposed two analytical methods for constructing the axial load-bending moment interaction diagram of an RC column fortified with a steel jacket. Expressions were derived by assuming similar stress block parameters for constrained concrete. The provided models accord well with the existing experimental data and design ideas. In 2018, (Salman & Al-Sherrawi, 2018) provided a finite element model for simulating and investigating the behavior of adding a steel jacket to a preloaded, undamaged reinforced concrete column. Two different instances have been explored, depending on the loading status of the non-strengthened reinforced concrete column and the goal of adding the steel jacket. This research numerically investigated the effect of strengthening RC columns with a steel jacket on the axial load capacity. The steel jacket consisting of two C-channels connected with various numbers of welded batten plates was investigated. The finite element (FE) analysis of 7 columns was conducted using Abaqus/CAE software. All the columns have a cross-section of 300 x 300 mm with a 2500 mm height and are reinforced with four longitudinal bars of 16 mm diameter with five stirrups per meter of 8 mm diameter. The first column is the reference column without strengthening, while the other columns were strengthened with 2 C-channels with different numbers of connecting batten plates.

2. FE Modelling

The FE modeling was conducted using Abaqus/CAE software. The second-order geometric effects, the non-linear behavior of the concrete and steel (in both steel jacket and reinforcing bars) were considered in the FE models. This is to accurately simulate the behavior of the RC column strengthened with a steel jacket.

2.1. Columns' geometry

The concrete column, C-channels, and batten plates were modeled using three-dimensional eight-node reduced integration (C3D8R) while the reinforcement longitudinal bars and stirrups were modeled using beam (B31) Lagrangian elements (Corporation, 2017). The reference column has a cross-section of 300 x 300 mm with a 2500 mm height and is reinforced with four longitudinal bars of 16 mm diameter with five stirrups per meter of 8 mm diameter. Figure 1. (a) shows the geometry of the reference column, Figure 1. (b) shows the reinforcement details of the reference columns, and Figure 1. (c) shows the cross-section of the reference column.

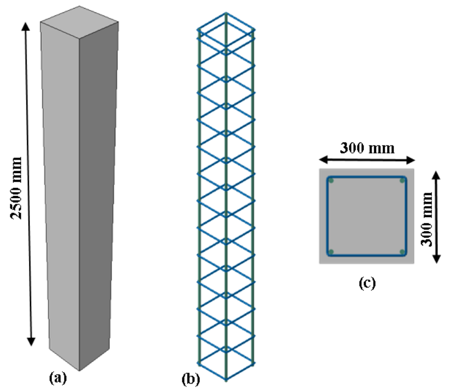

Figure 1. (a) Geometry of the reference column; (b) Reinforcement details; (c) Cross-section.

All columns were strengthened with a steel cage consisting of two C-channels of thickness 5 mm, the details of the two C-channels cross-section are shown in Figure 2 (a). The connecting batten plate used for connecting four strengthened columns of dimensions 260 x 150 x 5 mm is shown in Figure 2 (b). The strengthened columns were divided into two groups. In the first group consisting of four strengthened columns; the two C-channels were connecting with 2, 3, 5, and 7 batten plates from both sides with the clear distance between plates shown in Figure 3. In the second group consisting of two strengthened columns; the two C-channels were connecting with one large plate. In the first column of this group, a large plate of dimensions 2450 x 260 x 5 mm was used to connect the two C-channels from outside as shown in Figure 4. While in the second column of this group, a large plate of dimensions 2500 x 150 x 5 mm was used to connect the two C-channels from outside forming a complete box steel jacket as shown in Figure 4. The modeled columns will be referred to as shown in Figure 3 and Figure 4.

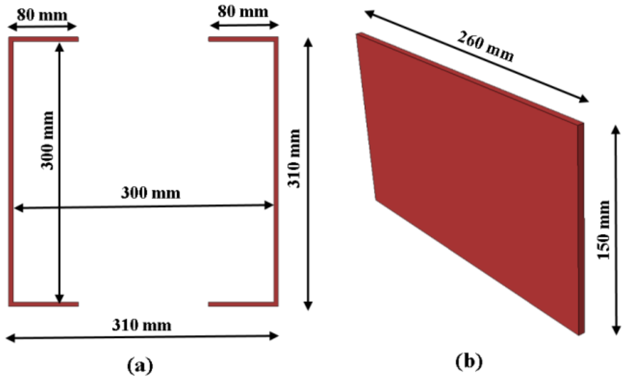

Figure 2. (a) Details of the two C-channels steel cage; (b) The connecting Batten plate.

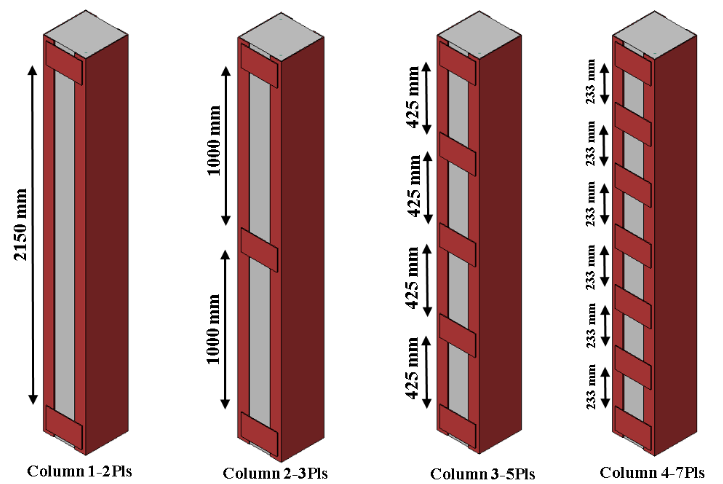

Figure 3. The first group of strengthened columns.

2.2. Constitutive model of concrete

The concrete damage plasticity (CDP) model was used to simulate the behavior of 25 MPa compressive strength concrete using the built in CDP model in Abaqus. The stress-strain relation of the CDP is given by:

$$\sigma_t = (1 - d_t)\, E_0\, (\varepsilon_t - \tilde{\varepsilon}_t^{pl}) \quad (1)$$

$$\sigma_c = (1 - d_c)\, E_0\, (\varepsilon_c - \tilde{\varepsilon}_c^{pl}) \quad (2)$$

Where σ_t is the concrete tensile stress, σ_c is the concrete compressive stress, d_t is the concrete tensile damage factor, σ_c is the concrete compressive damage factor, E_0 is the initial elastic modulus of concrete, ε_t is the concrete tensile strain, and ε_c is the concrete compressive strain.

2.3. Constitutive model of steel

The stress-strain behavior of the reinforcement steel and the steel jacket was modeled using the Johnson-Cook (JC) plasticity model for 520 MPa ultimate strength steel. According to the JC model (GR & WH., 1983) and (Børvik T, 2001), the equivalent stress (σ) is given by:

$$\sigma = (A + B\varepsilon^n) * (1 + C\, ln\varepsilon^*) * (1 - T^{*m}) \qquad (3)$$

Where A, B, C, m, and n are the model parameters, T* is the homologous temperature, and ε*is the plastic strain which equals:

$$\varepsilon^* = \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0} \qquad (4)$$

Where $\dot{\varepsilon}$ the equivalent plastic strain rate, and $\dot{\varepsilon}_0$ is the reference strain rate.

3. FE analysis

The FE analysis was conducted on the reference column and the six strengthened columns using Abaqus\CAE standard solver. A mesh sensitivity analysis was done to determine the mesh size of each element. The mesh size of both the column and steel jacket was 25 mm and was perfectly aligned together to accurately simulate the interaction between the column and the steel jacket. The mesh size for the reinforcement vertical bars and stirrups was 50 mm and 25 mm, respectively. The reinforcement steel and stirrups were defined as embedded regions into the concrete column to simulate the bond between the concrete and the steel. The interaction between the column and the steel jacket was modeled using the tie property in Abaqus. For the reference column and the strengthened columns, the stresses and the displacement in all directions were calculated. Also, the load-displacement curve for all columns was plotted.

4. Validation of the FE model with experimental data

In order to validate the FE model used in this study the experimental results of two RC columns tested by (Belal, et al., 2014) shown in Figure 5 were compared to the FE models with the same parameters. The first RC column of 200 x 200 mm cross-section with a height of 1200 mm reinforced with four longitudinal bars of 12 mm diameter and six stirrups per meter of 8 mm diameter was tested to investigate the failure load of the column. The same column with the same parameters was modeled using Abaqus/CAE. The load-displacement curves were plotted for the experimental and the FE column and compared to each other as shown in Figure 6 (a). The results showed a good agreement between the experimented and the modeled column as shown in Table 1. The second strengthened column tested by (Belal, et al., 2014) was modeled using Abaqus/CAE the results were compared to the tested column. The column was strengthened with a steel jacket consisting of four angles of dimensions 50 x 50 x 5 mm and connected with 3 batten plates of dimensions 150 x 100 x 5 mm from the four sides. The load-displacement curves for the tested column and the FE column were plotted and compared as shown in Figure 6 (b). The results showed a good agreement between the experimented and the modeled column as shown in Table 1.

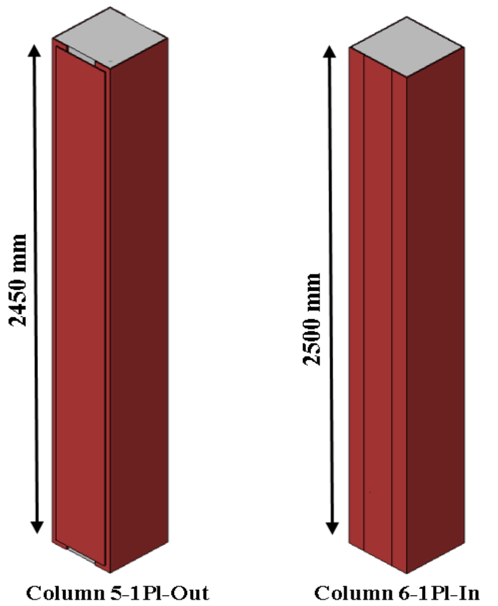

Figure 4. The second group of strengthened columns.

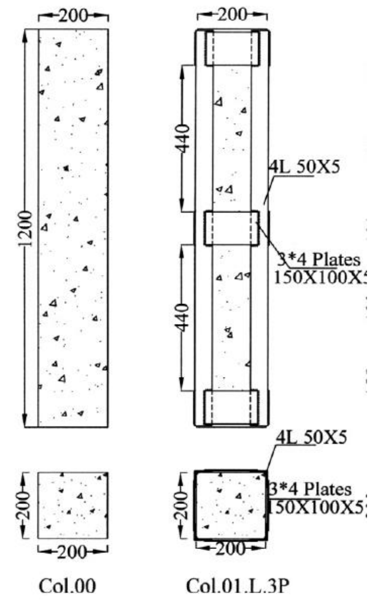

Figure 5. The geometry of the tested columns. (Belal, et al., 2014)

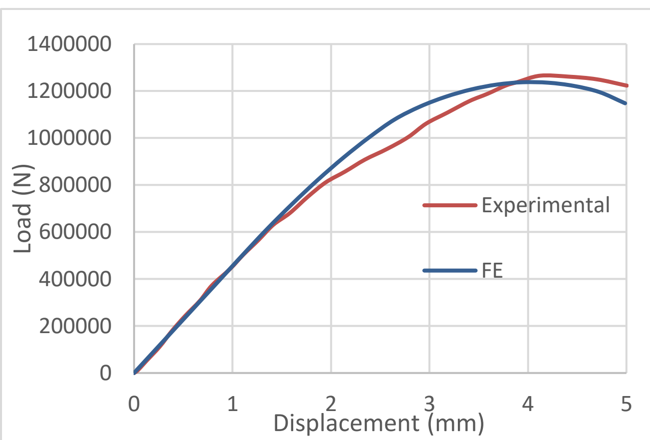

Figure 6. The load-displacement curve of the experimental and FE model of the first column.

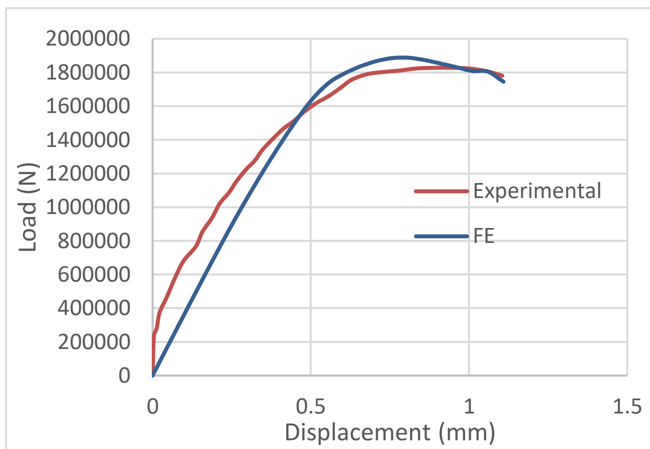

Figure 7. The load-displacement curve of the experimental and FE model of the second column.

Table 1. The failure load and corresponding displacement for the tested and FE columns.

Column	Failure Load- (Tested) (N)	Failure load-(FE) (N)	Corresponding displacement-(Tested) (mm)	Corresponding displacement-(FE) (mm)
Col.00	1255000	1237610	4.24	3.04
Col.01.L.3P	1821000	1887330	0.89	0.81

5. Results and discussion

For the reference column, as the load increased cracks started to appear in the upper third of the column until the total collapse occurred as shown in Figure 8 (a). Figure 8 (b) shows the displacement of the column in the Y-direction (U2) while the displacement in the reinforcement steel is shown in Figure 8 (c) and Figure 8. (d), respectively. The column collapsed at a load of 2565210 N with a corresponding displacement of 5.84 mm.

For the first group of columns, column 1-2Pls, as the load increased cracks started to appear in the upper third of the column and started to increase until the total collapse as shown in Figure 9 (a). Also, dents in the two C-channels flange start to appear as the load closed from the failure load as shown in Figure 9 (a). Figure 9 (b) shows the U2 displacement of the column while the displacement in the steel cage in X-direction (U1) and Z-direction (U3) are shown in Figure 9 (c) and Figure 9 (d), respectively. The confinement provided by the steel cage increased the column failure load to 2705980 N with a corresponding displacement of 5.94 mm. There isn't a significant increase in the failure load in this case because the two channels were connected only by two plates from both sides at the top and bottom of the column.

For column 2-3Pls, as the load increased cracks started to appear in the upper and the lower thirds of the column, simultaneously and started to increase until the total collapse as shown in Figure 10 (a). Also, dents in the two C-channels started to appear in the upper and lower thirds as the load closed from the failure load as shown in Figure 10 (a). Figure 10 (b) shows the U2 displacement of the column while the U1 and U3 displacements of the steel cage are shown in Figure 10 (c) and Figure 10, respectively. (d). The confinement provided by the steel cage increased the column failure load to 3115737 N with a corresponding displacement of 4.97 mm. With the third connecting batten plate in the middle of the column, the steel cage is more effective and the failure load increased significantly.

For column 3-5Pls, as the load increased cracks started to appear in the upper and the lower thirds of the column, simultaneously and started to increase until the total collapse as shown in Figure 11 (a). Also, dents in the two C-channels started to appear in the upper and lower thirds as the load closed from the failure load as shown in Figure 11 (a). Figure 11 (b) shows the U2 displacement of the column while the U1 and U3 displacements of the steel cage are shown in Figure 11 (c) and Figure 11. (d), respectively. The confinement provided by the steel cage increased the column failure load to 3738700 N with a corresponding displacement of 5.23 mm.

For column 4-7Pls, as the load increased cracks started to appear in the lower part of the column and started to increase until the total collapse as shown in Figure 12 (a). Also, dents in the two C-channels started to appear in the lower part as the load closed from the failure load as shown in Figure 12 (a). Figure 12 (b) shows the U2 displacement of the column while the U1 and U3 displacements of the steel cage are shown in Figure 12 (c) and Figure 12. (d), respectively. The confinement provided by the steel cage increased the column failure load to 3910770 N with a corresponding displacement of 5.64 mm. The failure load didn't significantly increase than column 4-7pls meaning that the five plates and the seven plates provided almost the same rigidity to the steel cage.

For the second group of columns, for column 5-1Pl-Out, as the load increased cracks started to appear in the upper and lower parts of the column, simultaneously and started to increase until the total collapse as shown in Figure 13 (a). Also, dents in the two C-channels started to appear in the upper and lower parts as the load closed from the failure load as shown in Figure 13 (a). Figure 13 (b) shows the U2 displacement of the column while the U1 and U3 displacements of the steel cage are shown in Figure 13 (c) and Figure 13. (d), respectively. In this case, the steel cage provided full confinement to the column. Also, the overlapping of the connecting plate on the two C-channels' flanges provided more strength to the flanges increasing the failure load to 4512770 N with a corresponding displacement of 5.50 mm.

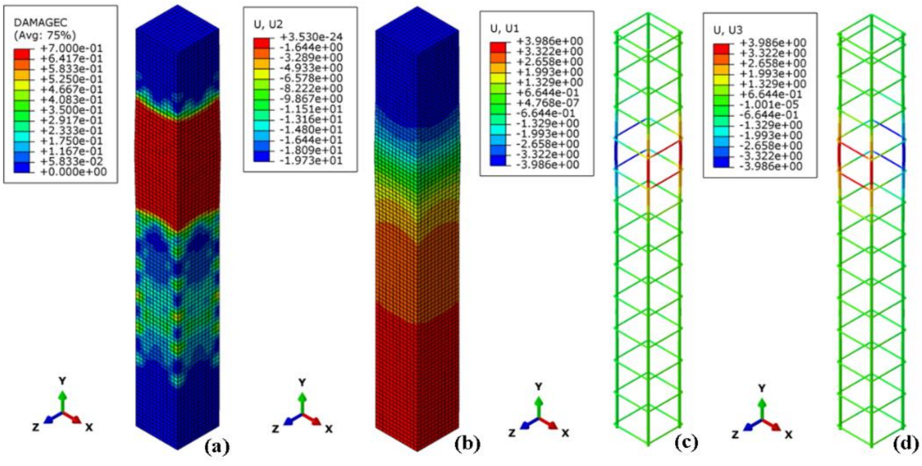

Figure 8. The damage of the reference column and the displacements in the column and the reinforcement steel.

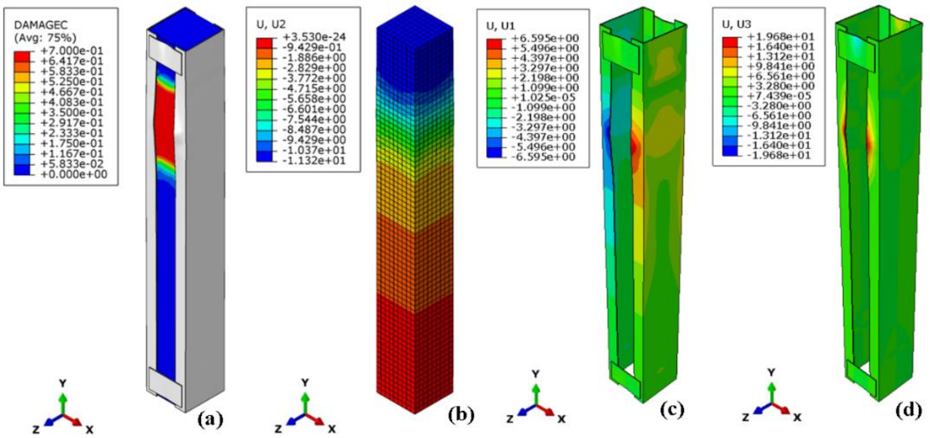

Figure 9. The damage of column 1-2Pls and the displacements in the column and the steel cage.

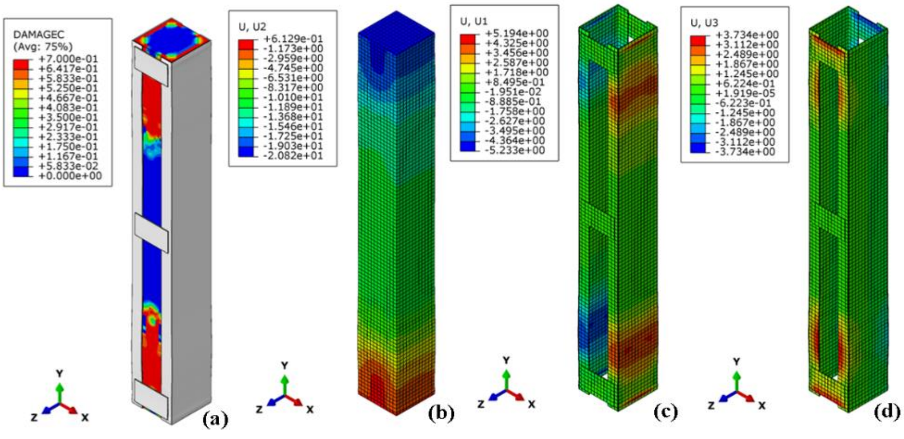

Figure 10. The damage of column 2-3Pls and the displacements in the column and the steel cage.

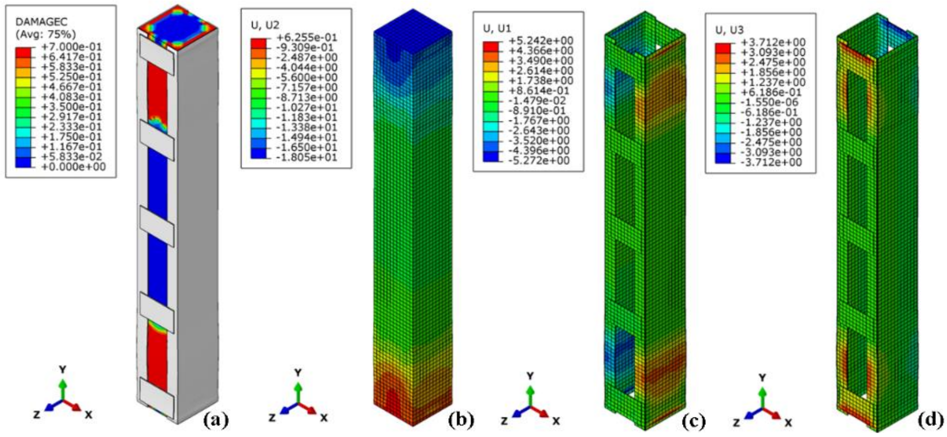

Figure 11. The damage of column 3-5Pls and the displacements in the column and the steel cage.

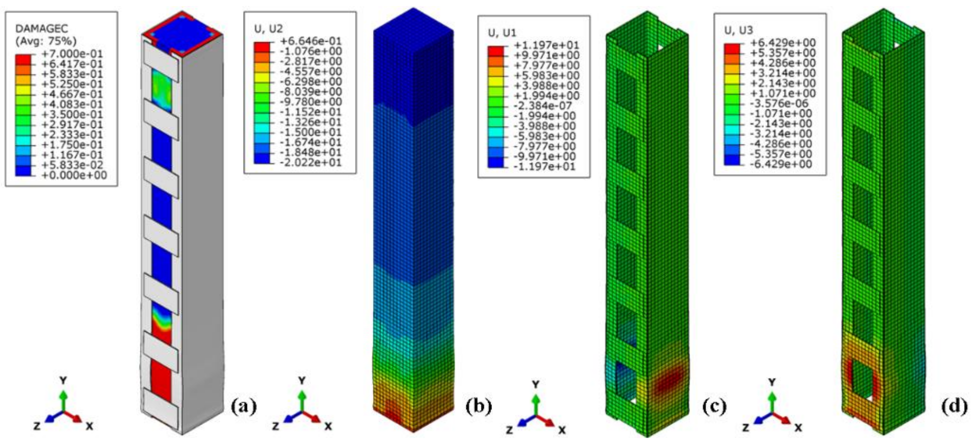

Figure 12. The damage of column 4-7Pls and the displacements in the column and the steel cage.

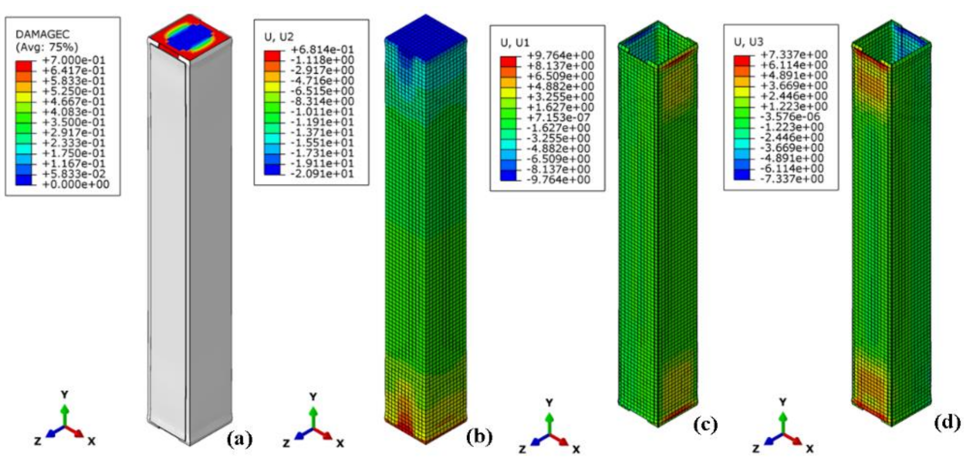

Figure 13. The damage of column 5-1Pl-Out and the displacements in the column and the steel cage.

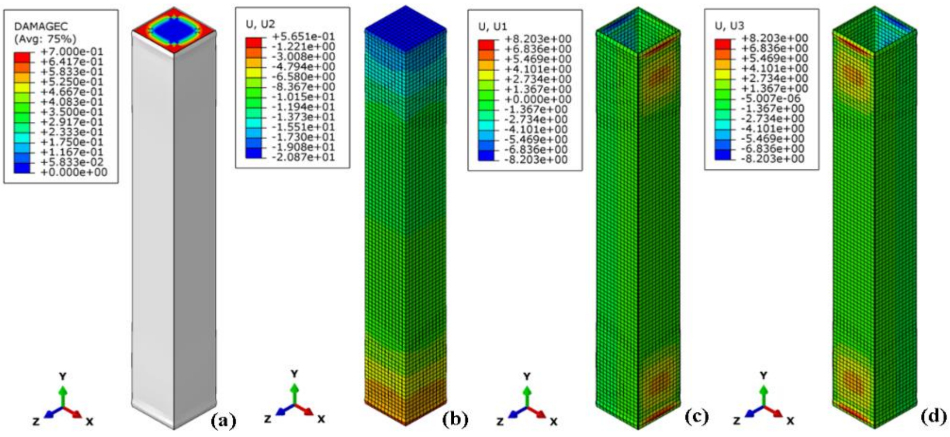

Figure 14. The damage of column 6-1Pl-In and the displacements in the column and the steel cage.

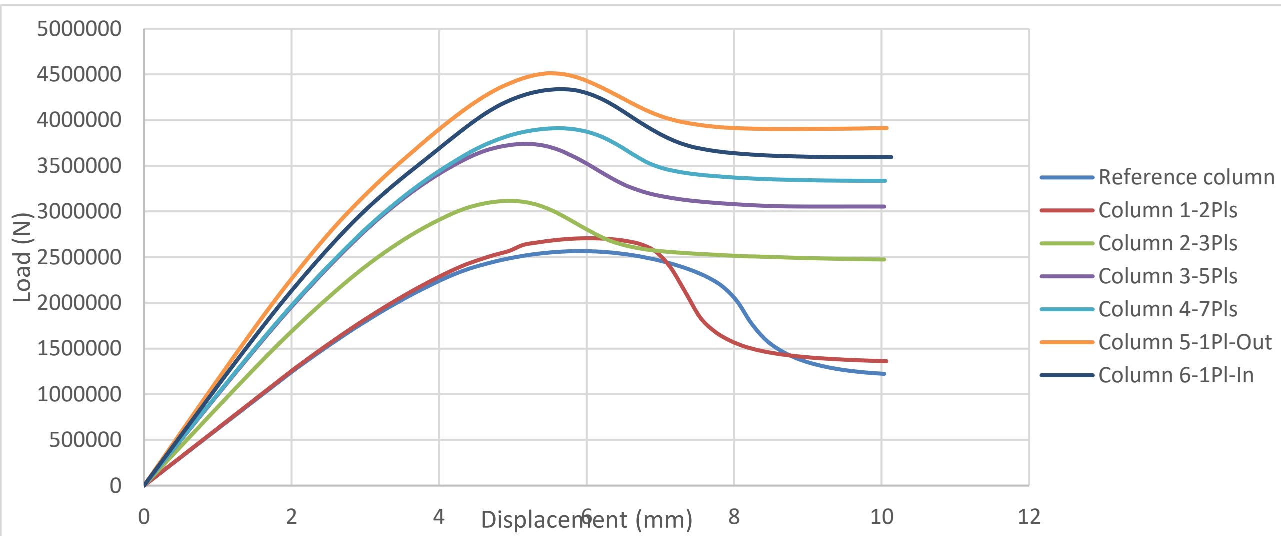

Figure 15. The load-displacement curve for all columns.

Table 2. The failure load and corresponding displacement for the FE columns.

Column	Failure Load (N)	Corresponding displacement (mm)	% of failure load increase
Reference Column	2565210	5.84	
Column 1-2Pls	2705980	5.94	5.49 %
Column 2-3Pls	3115737	4.97	21.46 %
Column 3-5Pls	3738700	5.23	45.75 %
Column 4-7Pls	3910770	5.64	52.45 %
Column 5-1Pl-Out	4512770	5.50	75.92 %
Column 6-1Pl-In	4337970	5.64	69.12 %

For column 6-1Pl-In, as the load increased cracks started to appear in the upper and lower parts of the column, simultaneously and started to increase until the total collapse as shown in Figure 14 (a). Also, dents in the two C-channels started to appear in the upper and lower parts as the load closed from the failure load as shown in Figure 14 (a). Figure 14 (b) shows the U2 displacement of the column while the U1 and U3 displacements of the steel cage are shown in Figure 14 (c) and Figure 14. (d), respectively. In this case, the steel cage provided full confinement to the column forming a full steel cage around the column, increasing the failure load to 4337970 N with a corresponding displacement of 5.64 mm.

The load-displacement curves for all columns are shown in Figure 15. Table 2 summarizes the failure load, the corresponding displacement, and the percentage of increase of the failure load for the strengthened column. For column 1-2Pls the steel cage wasn't quite effective due to the weak connection for the two C-channels using only two plates, therefore the failure load increased only by 5.49 %. Starting from column 2-3Pls the steel cage is more effective providing a failure load increase of 21.46 %. Adding more batten plates to connect the two C-channels provides more confinement to the column hence increasing the failure load significantly. For column 3-5Ps and column 4-7Pls, the percentages of increase of the failure load were 45.75 % and 52.45 %, respectively. For column 5-1Pl-Out the steel cage provided full confinement to the columns and hence increased the failure load by 75.92 %, and for column 6-1Pl-IN the failure load increased by 69.12 %.

6. Conclusions

Based on the numerical simulation and the result analysis the concluded remarks are as follows:

• Using two C-channels steel jacket is very effective as a relatively rigid jacket can increase the failure load of the columns by a minimum value of 21.46 %.

• Using two C-channel steel jacket enhances the ductility of the RC columns.

• The more batten plates connecting the two C-channels steel jackets the more confinement of the column and hence the more increase in the column failure load.

• Connecting the two C-channels steel jacket by a single large plate to form a full box around the column gives the best confinement and could increase the failure of the column by 75.92 %.

• The simulation of the RC strengthened columns using Abaqus/CAE software is acceptable as the failure loads and displacements are very close to the tested columns found in the literature.

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