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Finite Element Analysis of Steel-Jacketed Reinforced Concrete Columns Under Axial Loads

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Abstract- This research presents a finite element analysis of reinforced concrete (RC) columns strengthened using steel jackets to improve axial load capacity. The study models various configurations of steel-jacketed columns, focusing on the effect of lacing plates with or without batten plate connections between two steel C-channels surrounding the RC columns. Utilizing Finite Element Analysis (FEA) in Abaqus/CAE, six column models were examined, each with a cross-section of 300x300 mm and a height of 2500. The models included both partially and fully enclosed steel jackets, with varying numbers of lacing and batten plates. Results indicated that steel jacketing of RC columns significantly enhanced load-bearing capacity. Using a relatively rigid steel jacket of c-channels connected with lacing plates could increase the failure load by 37.96%. Also, Notably, a fully enclosed steel jacket with a single large plate around the column yielded the highest performance, improving failure load capacity by up to 75.92% over unstrengthened columns. These findings underscore the structural benefits of specific steel-jacketing configurations in enhancing the durability and load resistance of RC columns.

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

I. INTRODUCTION

Reinforced concrete (RC) columns are vital structural elements in RC buildings, playing a key role in supporting the overall weight of the structure, distributing loads to the foundation, and resisting lateral forces, such as those from wind and earthquakes, thereby ensuring the building's stability and safety. These columns are typically composed of concrete and steel reinforcement, where the concrete provides compressive strength and the steel reinforcement offers tensile strength and ductility. This combination enhances the strength and resilience of RC columns, enabling them to withstand a wide range of loads and environmental conditions [1].

If an RC column is not adequately designed to handle the expected live loads, reinforcement may be required. One effective method for strengthening these columns is the use of steel jackets. These jackets, usually made of high-strength steel plates welded together to form a closed tube, are fitted around the existing RC column and anchored using steel bars or bolts. The addition of the steel jacket significantly boosts the column's strength and stiffness, allowing it to support higher live loads [2]. Once installed, the jacket provides additional confinement to the concrete core, improving the column's strength, stiffness, and ductility. In some instances, steel jackets can enhance a column's load-carrying capacity by two to three times [3].

Recent research has focused on advancing the use of steel jackets for reinforcing normal-strength RC columns. For instance, Tarabia and Albakry [4] explored the impact of several parameters on the performance of seismically weak RC columns strengthened with steel jackets. These parameters included the size of the steel angles, spacing of batten plates, type of bonding grout used between the column and steel angles, and the connection at the column's head. Their findings demonstrated that the strengthening system increased the load-bearing capacity and that the use of battens enhanced the ductility of the columns by providing additional confinement. Additionally, experimental studies by Belal et al. [5] on strengthened RC columns showed that using steel angles and C-channels had a significant positive effect on the columns' load-bearing capacity. The behavior of RC square columns reinforced with steel angles was also examined by Saraswathi and Saranya [6], revealing the efficiency of the steel angles in enhancing the column's performance.

Salman and Al-Sherrawi [7] proposed two analytical models to construct axial load-bending moment interaction diagrams for RC columns strengthened with steel jackets. Their models, based on similar stress block parameters for confined concrete, showed good agreement with experimental data and design approaches. In a 2018 study, Salman and Al-Sherrawi [8] developed a finite element model to investigate the behavior of RC columns with added steel jackets. This research, which involved numerical simulations of

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found that the steel jacket, consisting of two C-channels connected by various numbers of welded batten plates, significantly improved the axial load capacity of the columns.

In conclusion, there is a need for further investigation into the specific impact of steel jacketing on the axial load-bearing capacity of RC columns, considering different configurations of steel jackets, and isolating the effects of axial loads from other load types like lateral or seismic forces. This would fill the gap in understanding the full potential of steel jackets for strengthening RC columns subjected to axial loads.

II. RESEARCH SIGNIFICANCE

This research is significant as it investigates the strengthening of RC columns under axial loads using steel channels, battens, and lacing plates, a method that can enhance the column's load-carrying capacity and overall structural performance. By focusing on axial loads, which are critical for determining the stability and safety of RC columns, the study explores how this reinforcement technique can improve both the strength and stiffness of columns, enabling them to withstand higher loads without failure. The research employs finite element analysis (FEA) to model and simulate the behavior of these reinforced columns, providing valuable insights into how steel channels and confinement plates affect axial load resistance. This approach offers a practical and cost-effective solution for retrofitting existing columns, particularly in buildings that need to support increased loads. By improving the axial load capacity, this method contributes to safer, more resilient structures, ensuring the long-term stability of buildings under critical loads.

III. FINITE ELEMENT MODEL DEVELOPMENT

This study numerically examined the impact of strengthening RC columns with a steel jacket on their axial load capacity. The steel jacket, composed of two C-channels connected by various configurations of welded batten plates and/or lacing bars, was the primary focus. A finite element (FE) analysis of six columns was performed using Abaqus/CAE software. All columns had a 300 x 300 mm cross-section and a height of 2500 mm, reinforced with four longitudinal bars of 16 mm diameter and five stirrups per meter of 8 mm diameter. The first column served as the reference without strengthening, while the other columns were strengthened using two C-channels with different arrangements of the connecting batten and lacing plates.

The concrete column, C-channels, batten plates, and lacing plates were modeled using three-dimensional eight-node reduced integration elements (C3D8R), while the longitudinal reinforcement bars and stirrups were represented using beam (B31) Lagrangian elements [9]. The reference column has a 300 x 300 mm cross-section and a height of 2500 mm, with four longitudinal bars of 16 mm diameter and five stirrups per meter of 8 mm diameter. Figure 1(a) illustrates the geometry of the reference column, Figure 1(b) displays the reinforcement details, and Figure 1(c) shows the cross-section of the reference column.

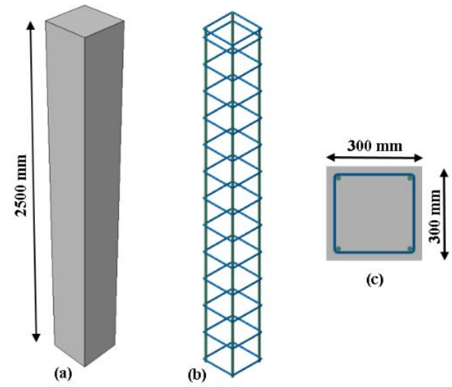

Figure (1): (a) Geometry of the reference column; (b) Reinforcement details; (c) Cross-section.

All columns were strengthened with a steel jacket consisting of two C-channels, each 5 mm thick, with the cross-sectional details of the C-channels shown in Figure 2(a). The connecting batten plate measures 260 x 150 x 5 mm as depicted in Figure 2(b). The lacing bars with a width of 55 mm and a thickness of 5 mm with varying lengths according to each configuration as shown in Figure 2(c). Five strengthened columns were analyzed in this study as shown in Figure 3. In the first column, the C-channels were connected by four lattice bars in both directions. In the second column, the C-channels were connected by five batten plates, along with four lattice bars in both directions. The third column featured six lattice bars connecting the C-channels in both directions. The fourth column was strengthened with seven batten plates and six lattice bars connecting the C-channels in both directions. Finally, in the fifth column, a large plate measuring 2450 x 260 x 5 mm was used to connect the two C-channels externally, forming a complete box.

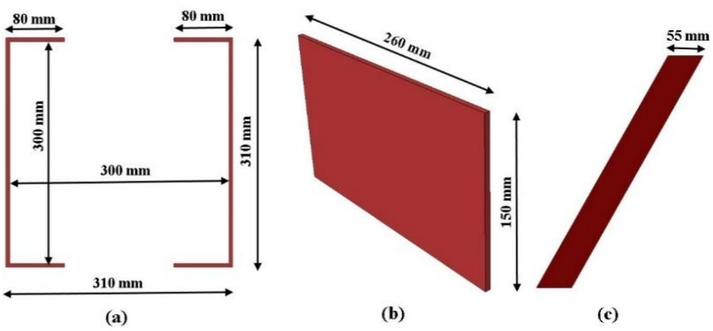

Figure (2): (a) Details of the two C-channels steel jacket; (b) The connecting batten plate; (c) The connecting lattice plate.

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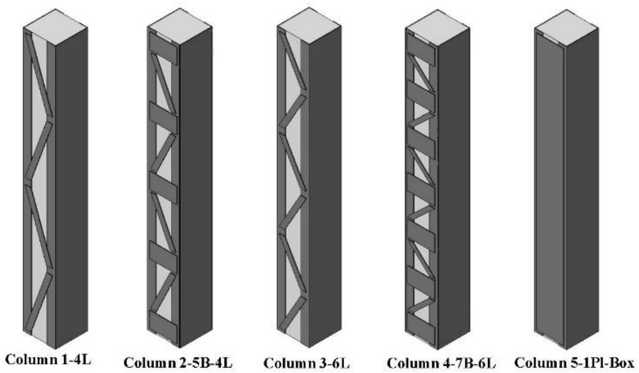

Figure (3): The five strengthened columns with their reference code.

The Concrete Damage Plasticity (CDP) model was employed to simulate the behavior of concrete with a compressive strength of 25 MPa, utilizing the built-in CDP model in Abaqus. The stress-strain relationship for the CDP model is expressed as follows:

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

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

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

The stress-strain behavior of the reinforcement steel and the steel jacket was simulated using the Johnson-Cook (JC) plasticity model, applied to steel with an ultimate strength of 520 MPa [10], [11]. According to the JC model;

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

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

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

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

IV. FINITE ELEMENT ANALYSIS

The finite element analysis was performed on the reference column and the five strengthened columns using the Abaqus\CAE standard solver. A mesh sensitivity study was conducted to determine the optimal element sizes. The mesh size for both the column and the steel jacket was set to 25 mm, ensuring precise alignment to accurately simulate the interaction between the two. For the reinforcement bars, vertical bars were assigned a mesh size of 50 mm, while stirrups had a mesh size of 25 mm. The reinforcement bars and stirrups were defined as embedded regions within the concrete column to simulate the bond between the concrete and the steel effectively. The interaction between the column and the steel jacket was modeled using the tie constraint in Abaqus. For both the reference and strengthened columns, damage, stresses, and displacements in all directions were analyzed, and the load-displacement curves were generated for all columns.

V. EXPERIMENTAL VALIDATION OF THE FE MODEL

To validate the FE model used in this study, experimental results from two RC columns tested by Belal et al. [10] depicted in Figure 4, were compared to their corresponding FE models with identical parameters. The first RC column, with a cross-section of 200 x 200 mm, a height of 1200 mm, and reinforcement comprising four 12 mm diameter longitudinal bars and six 8 mm diameter stirrups per meter, was tested to determine its failure load. This column was also modeled in Abaqus/CAE using the same parameters. The load-displacement curves for the experimental and FE models were plotted and compared, as shown in Figure 5. The results indicated strong agreement between the experimental data and the FE model, as detailed in Table 1.

Similarly, the second column; strengthened with a steel jacket, was modeled in Abaqus/CAE and compared with the experimental results. The steel jacket consisted of four angles measuring 50 x 50 x 5 mm, connected by three batten plates measuring 150 x 100 x 5 mm on all sides. The load-displacement curves for the experimental and FE models of this strengthened column were plotted and compared, as illustrated in Figure 6. Again, the results demonstrated a close match between the experimental and FE models, as summarized in Table 1.

Table (1): The failure load and corresponding displacement for the experimental and FE columns

Column	Col. 00	Col.01.L.3P
Experimental Failure Load (N)	1255000	1821000
FE Failure Load (N)	1237610	1887330
Experimental Displacement (mm)	4.24	0.89
FE Displacement (mm)	3.04	0.81

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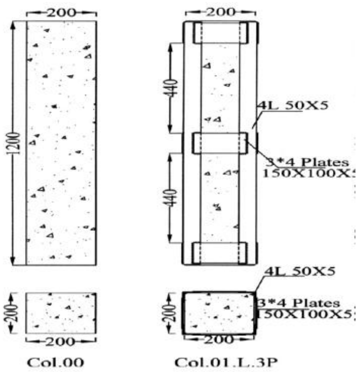

Figure (4): Belal et. al. [10] tested columns.

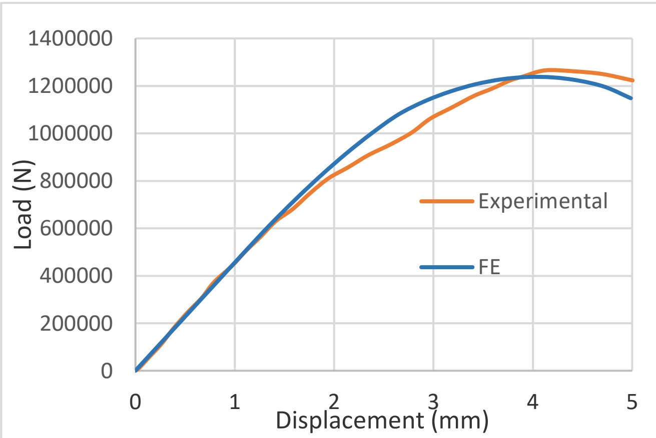

Figure (5): Comparison between the experimental and FE model results of the first column.

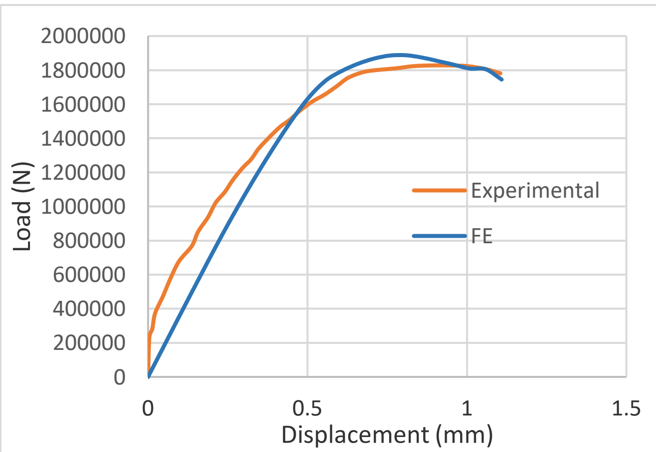

Figure (6): Comparison between the experimental and FE model results of the second column.

VI. RESULTS AND DISCUSSION

Reference Column:

As the load on the reference column increased, cracks began to develop in the upper third of the column. This was followed by concrete spalling, which progressed until the column fully collapsed. The final state, with completely damaged elements removed, is illustrated in Figure 7(a). Figure 7(b) depicts the axial stress distribution in the Y-direction, while Figures 7(c) and 7(d) show the displacement in the reinforcement steel in X-direction (U1) and Z-direction (U3), respectively. The column failed under a load of 2,565,210 N, corresponding to a vertical displacement of 5.84 mm.

Column 1-4L:

For the first strengthened column (Column 1-4L), cracks and spalling were observed simultaneously in both the upper and lower sections as the load increased. These deteriorations intensified, leading to total failure, as shown in Figure 8(a). The Von Mises stress distribution in the steel jacket, along with dents forming in the flanges of the two C-channels and the connecting lacing plates as the load approached the failure point, are presented in Figure 8(b). The displacement in the steel jacket along the X-direction (U1) is illustrated in Figure 8(c), while displacement in the Z-direction (U3) is shown in Figure 8(d). The addition of the steel jacket significantly enhanced the column's confinement and ductility, raising the failure load to 3,546,560 N with a corresponding vertical displacement of 4.75 mm. This represents a substantial 38.26% increase in the failure load compared to the reference column.

Column 2-5B-4L:

As the load on column 2-5B-4L increased, cracks and concrete spalling simultaneously appeared in the upper and lower thirds of the column. These deteriorations intensified until the column reached total collapse, as illustrated in Figure 9(a). Dents began forming in the two C-channels, batten plates, and lacing plates as the load approached the failure point, as shown in Figure 9(b), which also presents the Von Mises stress distribution in the steel jacket. The U1 and U3 displacements of the steel jacket are depicted in Figures 9(c) and 9(d), respectively. The enhanced confinement and ductility provided by the steel jacket increased the failure load to 3,831,590 N, with a corresponding vertical displacement of 5.27 mm. Incorporating the batten plates with the lacing bars significantly improved the column's confinement and ductility, resulting in a 49.37% increase in failure load compared to the reference column. This also represents an 8.04% improvement over column 1-4L, which utilized four lacing plates only. However, the addition of batten plates to the same number of lacing plates did not result in a significant improvement in the failure load.

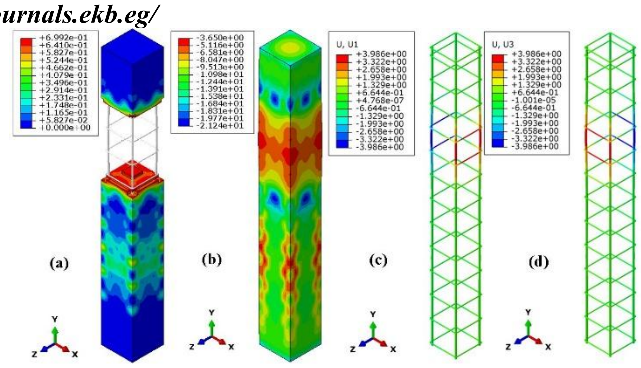

Figure (7): The damage pattern, axial stress distribution, and reinforcement steel displacements for the reference column.

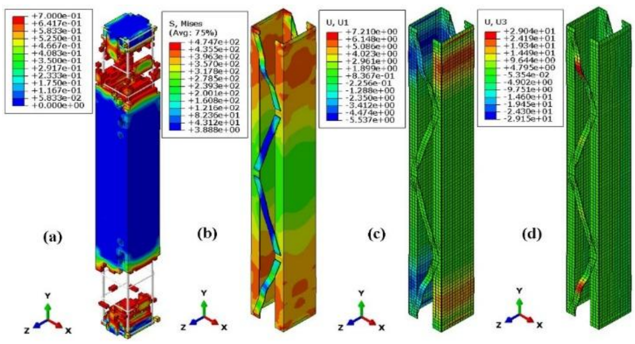

Figure (8): The damage pattern, Von Mises stress distribution, and displacements in the steel jacket for column 1-4L.

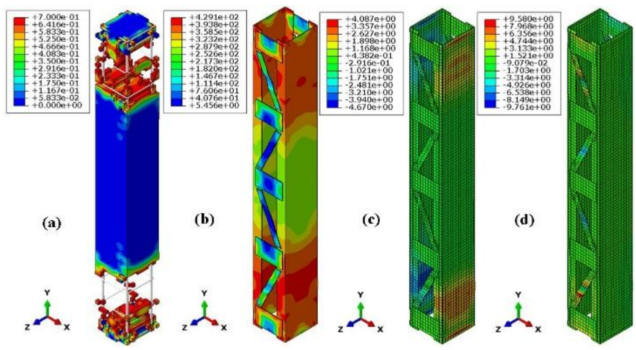

Figure (9): The damage pattern, Von Mises stress distribution, and displacements in the steel jacket for column 2-5B-4L.

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Column 3-6L:

As the load on column 3-6L increased, cracks and concrete spalling simultaneously appeared in the upper and lower parts of the column. These deteriorations intensified until the column reached total collapse, as illustrated in Figure 10(a). Dents began forming in the two C-channels, and the connecting lacing plates as the load approached the failure point, as shown in Figure 10(b), which also presents the Von Mises stress distribution in the steel jacket. The U1 and U3 displacements of the steel jacket are depicted in Figures 10(c) and 10(d), respectively. The enhanced confinement and ductility provided by the steel jacket increased the failure load to 3,539,070 N, with a corresponding vertical displacement of 5.11 mm. Increasing the lacing bars significantly improved the column's confinement and ductility, resulting in a 37.96% increase in failure load compared to the reference column. This improvement is almost the same as that observed for column 1-4L, which utilized four lacing plates only. This indicates that increasing the number of lacing plates from four to six did not result in any significant improvement in the failure load.

Column 4-7B-6L:

As the load on column 4-7B-6L increased, cracks and concrete spalling simultaneously appeared in the upper and lower parts of the column. These deteriorations intensified until the column reached total collapse, as illustrated in Figure 11(a). Dents began forming in the two C-channels, batten plates, and lacing plates as the load approached the failure point, as shown in Figure 11(b), which also presents the Von Mises stress distribution in the steel jacket. The U1 and U3 displacements of the steel jacket are depicted in Figures 11(c) and 11(d), respectively. The enhanced confinement and ductility provided by the steel jacket increased the failure load to 3,969,150 N, with a corresponding vertical displacement of 5.84 mm. Incorporating the batten plates with the six lacing bars significantly improved the column's confinement and ductility, resulting in a 54.73% increase in failure load compared to the reference column. This also represents a 12.15% improvement over column 3-6L, which utilized six lacing plates only. Also, in this case, the addition of batten plates to the same number of lacing plates did not result in a significant improvement in the failure load.

Column 5-1Pl-Box:

For column 5-1Pl-Box, 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 12 (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 12 (b), which also presents the Von Mises stress distribution in the steel jacket. The U1 and U3 displacements of the steel jacket are depicted in Figures 12(c) and 12(d), respectively. In this case, the steel jacket 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 4,512,770 N with a corresponding vertical displacement of 5.50 mm.

Figure 13 illustrates the load-displacement curves for all columns. Table 2 provides a summary of the failure load, the corresponding displacement, and the percentage increase in the failure load for the strengthened column.

Modes of failure:

The failure modes observed varied depending on the level of strengthening applied to the columns. The reference column failed through progressive cracking and concrete spalling in its upper third, ultimately leading to complete collapse. For the strengthened columns, the failure modes demonstrated enhanced performance but followed distinct patterns. In Column 1-4L, cracks and spalling occurred in both the upper and lower sections, with dents forming in the steel jacket's flanges and lacing plates under high loads. Similarly, Column 2-5B-4L exhibited cracks and spalling in the upper and lower thirds, accompanied by noticeable dents in the batten plates, lacing bars, and steel jacket. Column 3-6L displayed a failure mode akin to Column 1-4L, with no significant improvement observed despite the addition of extra lacing bars. Column 4-7B-6L showed enhanced confinement with cracks, spalling, and dents in the steel jacket and connecting plates, although the addition of batten plates provided only limited incremental benefits. Finally, Column 5-1Pl-Box, with its fully enclosed steel jacket, offered superior confinement, delaying significant cracking until higher loads were reached. Dents appeared near failure, resulting in the highest failure load and structural resilience among all configurations. Overall, failure modes were governed by cracking, spalling, and localized deformation, influenced by the degree of confinement and the arrangement of the strengthening elements.

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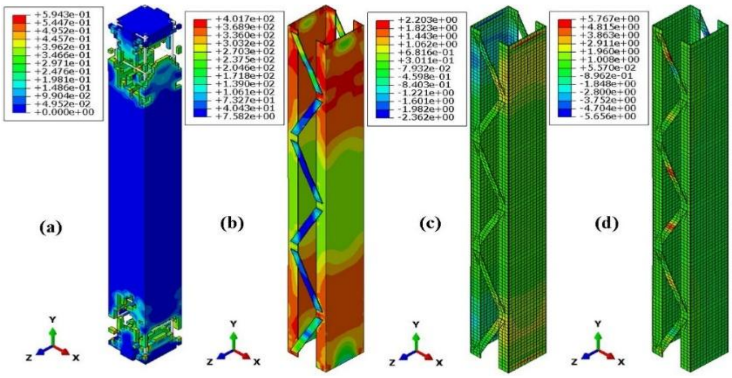

Figure (10): The damage pattern, Von Mises stress distribution, and displacements in the steel jacket for column 3-6L.

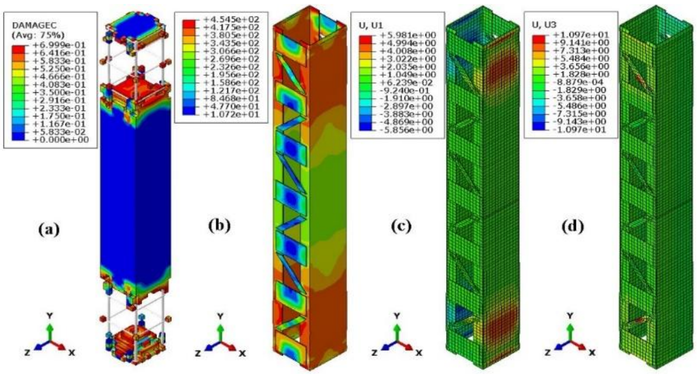

Figure (11): The damage pattern, Von Mises stress distribution, and displacements in the steel jacket for column 4-7B-6L.

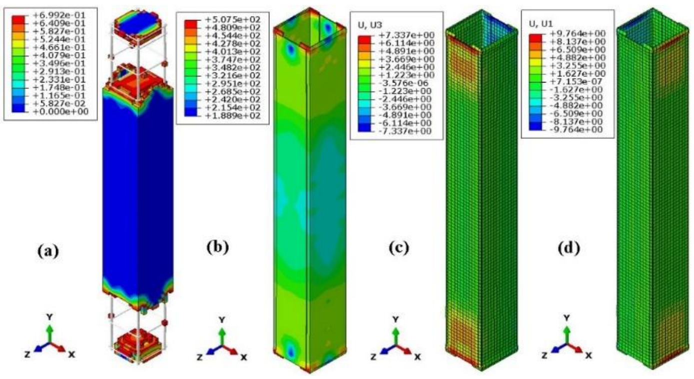

Figure (12): The damage pattern, Von Mises stress distribution, and displacements in the steel jacket for column 5-1Pl-Box.

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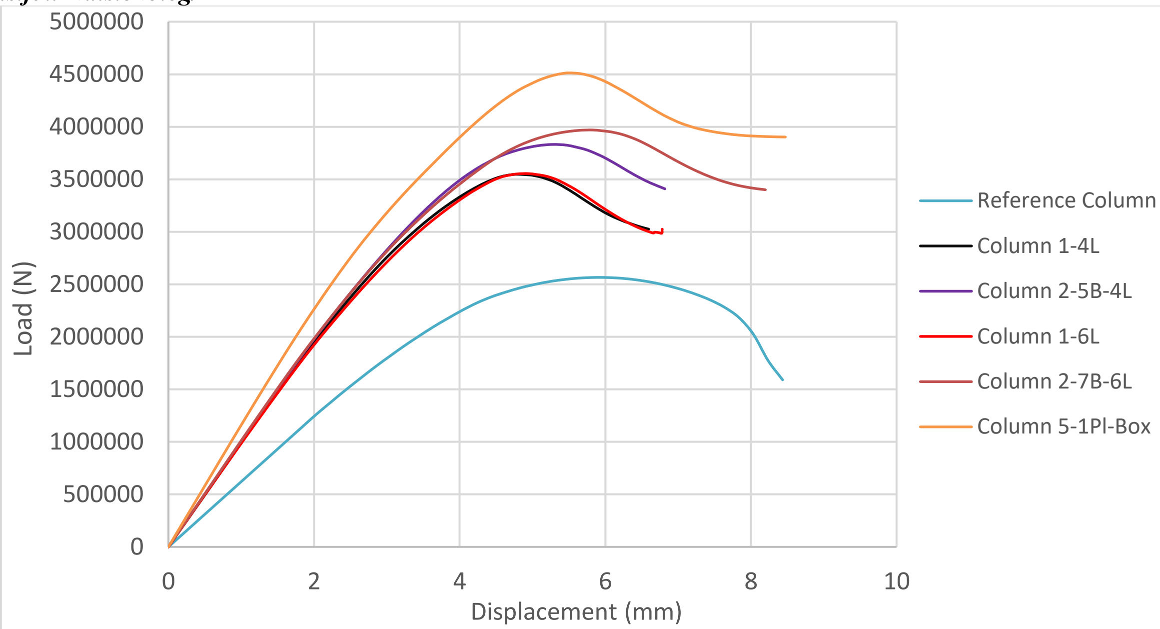

Figure (13): The load-displacement curve for all columns.

Column	Failure Load (N)	Corresponding displacement (mm)	% of failure load increase
Reference Column	2565210	5.84	
Column 1-4L	3546560	4.75	38.25 %
Column 2-5B-4L	3831590	5.27	49.37 %
Column 3-6L	3539070	5.12	37.96 %
Column 4-7B-6L	3969150	5.84	54.73 %
Column 5-1Pl-Box	4512770	5.50	75.92 %

Table (2): The failure load, corresponding displacement, and the percentage of load increase for all columns.

VII. CONCLUSIONS

This study investigated the effectiveness of using steel jackets to enhance the axial load capacity of reinforced concrete (RC) columns through numerical simulations conducted in Abaqus/CAE. Various steel jacketing configurations, including combinations of batten plates and lacing bars, were analyzed for their impact on load-bearing capacity and ductility of RC columns. Based on the numerical simulations and the results analysis the concluded remarks are as follows:

- Employing a two C-channel steel jacket proves to be highly effective, providing a relatively rigid strengthening system that increases the failure load of RC columns by at least 37.96%.
- Increasing the lacing plates from four to six almost has no effect on the failure load of the column.
- Adding batten plates to the lacing plates didn't have significant impact on the failure load. Therefore, its recommended to either use lacing plates or batten plates to connect the two C-channel steel jacket
- Utilizing a single large plate to connect the two C-channels and form a full box around the column offers the best confinement, achieving an exceptional 75.92% increase in failure load.
- The finite element simulations of RC columns strengthened with steel jackets using Abaqus/CAE software show strong agreement with experimental results in the literature, validating the accuracy of the numerical model in predicting failure loads and displacements.

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