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Seismic Behavior of Steel-Concrete Composite Columns Under Cyclic Lateral Loading

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ABSTRACT

Lightweight concrete has been used in the construction industry for many years and by the introduction of modern technologies in the construction industry, this type of concrete has been accounted as one of the powerful and reliable materials in the construction industry. The density of lightweight concrete is about 0.56 that of the ordinary concrete. This type of concrete is commonly used as a flooring material in buildings. Thus there is possibility of its corrosion in different climatic conditions. In the present research, we would investigate the compressive strength and durability of the lightweight concrete in the acid environment, so that by specifying the corrosion rate, one could have a better understanding of the behavior of these concretes. For making the lightweight concrete in the present research use has been made of pumice aggregate in the mix design, and the acid used is 1M sulfuric acid. Also, the effect of adding two types of Nanomaterials i.e., Nano silica and Nano clay on the concrete behavior is assessed. The results have shown that in case of keeping the specimens of lightweight concrete in the acid environment for 90 days, their weight reaches 0.56 that of the ordinary specimens. The results of the current research have shown that the use of Nano silica and Nano lime per 10 wt% of cement could result in the increased compressive strength of the lightweight concrete. So that the concrete compressive strength per 10 wt% of Nano lime increases by 1.43%. On the other hand, the concrete durability in the acid solutions reaches the maximum value per addition of 5% Nano silica and 5% Nano lime, and has lost a lower percentage of its weight.

Key words: **Composite column, thickness of steel layer, cyclic lateral loading**

1. INTRODUCTION

Concrete-filled steel tube (CFST) columns are the box or tube composite steel columns filled with concrete. The steel portion of the section is usually composed of rolled structural boxes or steel tubes, which are produced in Iran on a large scale. The concrete core of the section may utilize ordinary concrete or self-compacting concrete (SCC). Putting the steel around the concrete core creates a composite section. Different types of roof systems and steel beams are used in combination with these columns [1-3]. Various researchers have investigated the use of composite columns. For example, Hajjar et al. (2000) investigated the behavior of circular and rectangular concrete-filled steel tube beam-columns and braces, particularly under the earthquake loading. Also, the column behavior under the cyclic, bending and axial loading was studied and compared with conventional columns [4]. Weng et al. (2005) analyzed the steel beam to steel-concrete column connections under earthquake loading and the results of this study indicated that the composite connection can be effectively used to improve the behavior of the whole column [5]. Liu et al. (2008) studied the behavior of CFT columns under the bending loading. This paper explored the effect of axial load ratio, thickness ratio, concrete compressive strength, slenderness ratio and load angle on the bending behavior of the column [6]. Hu et al. (2010) investigated the behavior of composite columns and beam-column connections. The effect of over-strength, inelastic deformation, and P-Delta on the behavior of composite columns was studied in these columns [7]. Xiao (2011) explored the behavior of composite columns and steel-concrete tubes under earthquake loading. In this paper, after modeling the column, the failure load and axial load were obtained for each column, and the results showed that the finite element methods can effectively estimate the column strength [8]. Yadav et al. (2017) studied the behavior of a new generation of CFT columns, namely CCFT, in the high-rise structures and compared the columns with CFT column. The loading of the axial type was applied to the columns [9]. Badarloo et al. (2019) investigated the behavior of CFT columns under the cyclic loading and analyzed the performance of composite columns under the lateral load using the nonlinear analysis and pushover methods and compared the results with the numerical formulas of regulations [10]. Farajpourbonab et al. attempted to develop compound composite columns and proposed a new steel model for the composite columns. In this study, the steel layer embedded in concrete was used to build CFT columns and the results were verified using the numerical finite element and experimental methods [11]. Liu et al. (2019) investigated the behavior of CFT columns made of high-strength concrete under cyclic loading. This study aimed to enhance the bearing capacity of composite columns and assess their performance under the cyclic loading when using the high-strength concrete in the hollow columns [12]. Jothimani et al. examined the behavior of composite columns under the cyclic axial and lateral loading. In this study, the effects of stiffener and thickness of the layer under load on the column were simultaneously investigated and the effect of the number of stiffeners on the column behavior was studied, and the column response was examined as the load-displacement diagram [13]. The main economic advantage of CFT columns is the reduction of steel consumption and, as a result, project cost while improving the quality and performance of structure. Also, the optimized use of steel and concrete strength, adjusted local buckling of steel portion of column, increased lifespan and concrete strength due to confinement, high allowable ratio of dimension to thickness, and possessed properties of HSS sections cause the significant reduction of steel consumed in the members of CFT section compared to the members, only with steel section to achieve the required strength [14-16]. The numerical and experimental analysis of CFT columns under different loads has been performed in the recent literature, but no research has been conducted up to now in the area of cyclic lateral loading and thickness of steel jacket. Therefore, the present study explores the behavior of composite beams with variable thickness of the steel layer under the cyclic lateral loading and determines how increasing the thickness of the steel layer can affect the behavior of composite columns. The rectangular columns are selected in this study and it is tried to model the column along with the column base in the software to fully examine the behavior of composite columns.

2. METHODOLOGY

In this study, the CFT columns are used for the strengthening of concrete columns because of their unique characteristics, including the low weight and thickness of steel layer, high strength and stiffness, and high resistance to corrosion. Also, the effectiveness of the composite steel layer in improving the ductility and increasing the strength of concrete connections is evaluated using the ABAQUS software [12]. Two columns with the same performance levels and constant heights are subjected to the earthquake accelerogram. Initially, the columns are not strengthened and modeled in the software with the given dimensions. Then, the compound structure is built using steel jackets and the results are compared.

2.1. VERIFICATION

In the present study, a column with an undamaged ordinary concrete is used in the ABAQUS software. The introduced columns are subjected to the axial loading. Figure 1 shows the cross-section of the model in which the modeled steel and rebar are embedded. Figure 2 shows the conditions of samples and the model generated in ABAQUS. The axial load applied to the column is 100 KN and the load-displacement diagrams are plotted for the column and compared with the results of the paper. The modulus of elasticity of the concrete used in the present study is considered equal to 5500 MPa and the modulus of elasticity of steel is 200 MPa. Figure 3 shows the load-displacement diagram after applying the axial load to the columns, which is validated with the paper diagrams [17]. In the present study, the composite column is modeled in the ABAQUS software. Therefore, the attachment of the steel layer to concrete is done similar to the studies of Badarloo [18] and the steel rebar is embedded in the whole concrete [19]. To evaluate the overall behavior of concrete, the modeling of Vulnerable concrete is used according to the research of Jafari et al., and the stress-strain curve of concrete in both tensile and steel modes is introduced into the software [19]. Figure 1 below shows the plan of the column model made in the laboratory, which was then modeled in ABAQUS software, as shown in Figure 2 [20].

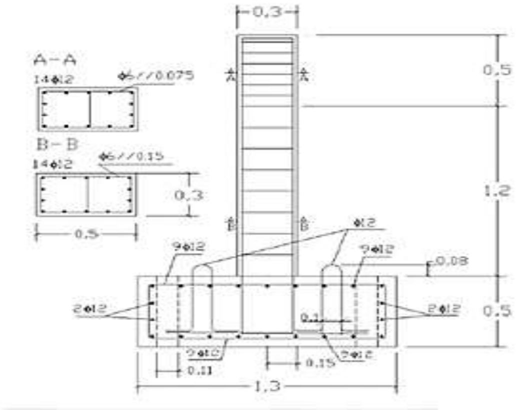

Figure 1. Column with biaxial loading

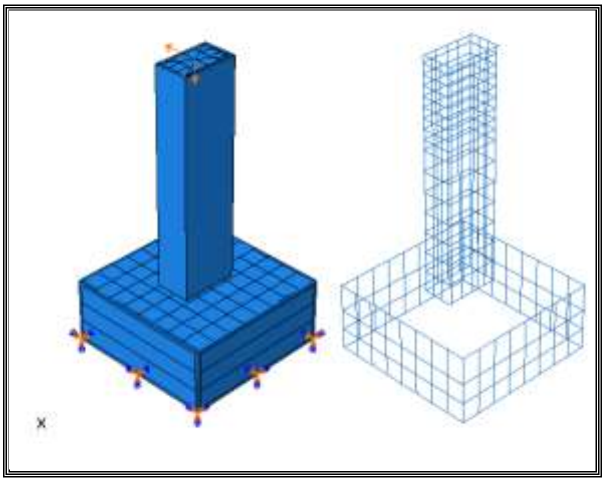

Figure 2. Column with biaxial loading

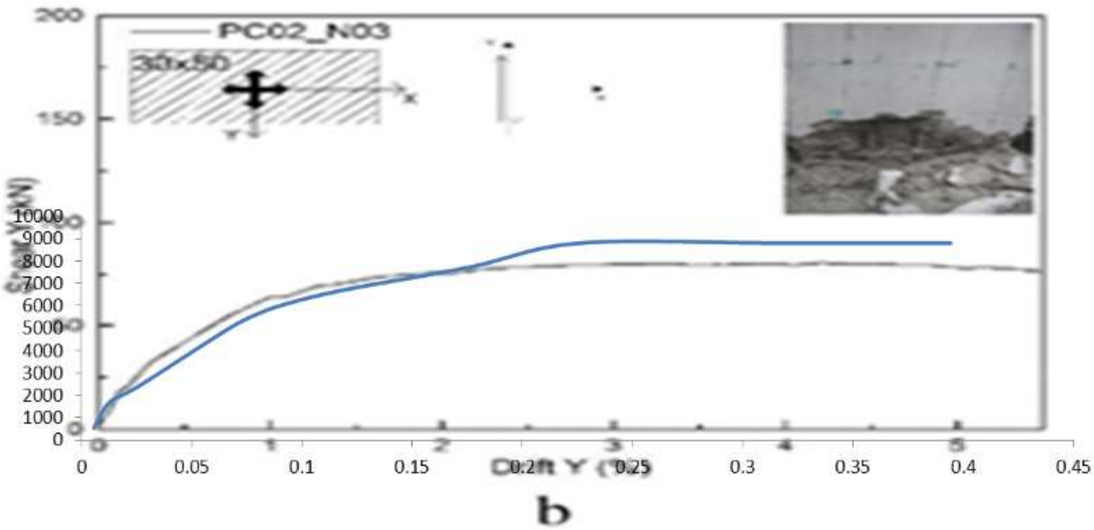

Figure 3. Verification of composite columns in ABAQUS software

[Figure 3]shows the results obtained from the validation of the composite steel-concrete column in the ABAQUS software. According to the results from Figure 3, it can be stated that the ABAQUS software is capable of properly modeling the behavior of concrete columns under the pushover loading with a slight difference with the experimental results. The load-displacement diagram obtained in the laboratory modeling differs slightly from numerical modeling.

2.2. APPLICATION OF CYCLIC LATERAL LOADING

In this research, to study the behavior of CFT columns under the seismic loading according to the criteria, the cyclic load pattern shown in Figure 4 was used where the load was introduced into the ABAQUS software as displacement-time [20-21].

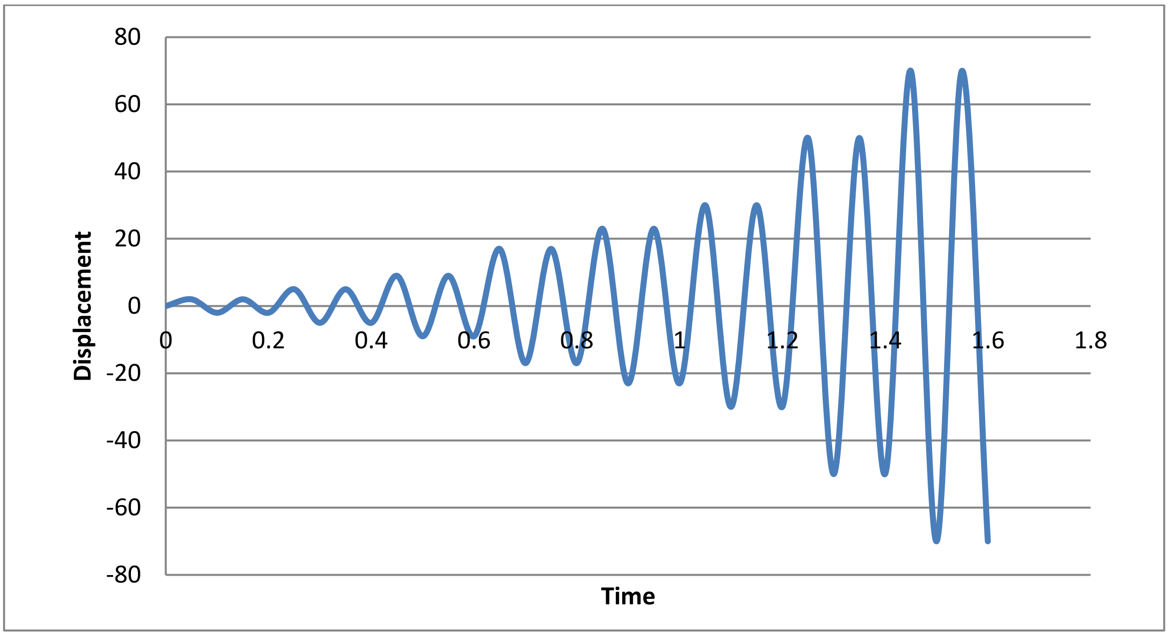

Figure 4. Load-displacement diagram for concrete strengthened with steel rebar and steel jacket [20]

2.3. INTRODUCTION OF STUDY MODELS

In this study, eight steel samples with identical concrete-filled circular section and concrete grade of 30 Mpa, both with and without reinforcement were subjected to the cyclic seismic loads and the results were compared with each other. The specifications of the materials in all the modeled samples are given in Tables 1 and 2.

Table 1. Parameters calculated in sections [17]

v_s	v_c	E_s (N/m^2)	E_c (N/m^2)	$f_c^{/}$(N/m^2)
0.3	0.2	2*10^{10}	2.4*10^{10}	2*10^7

Table 2. General specifications of samples with reinforcement

Type of applied load	Sample with reinforcement	$f_c^{/}$(N/m^2)	h(mm)	b (mm)	T_t (mm)
Dynamic	1	2*10^7	1700	300*500	**5**
	2	2*10^7	1700	300*500	**10**
	3	2*10^7	1700	300*500	**15**
	4	2*10^7	1700	300*500	**20**

3. RESULTS AND DISCUSSION

Figure 5 shows the stress and strain of the columns strengthened with the steel jacket. The ultimate force applied to the column was 298 KN, which is almost identical in the three generated models, but the displacement of the column with the higher thickness decreased to some extent. The stress induced in the concrete column was 320 MPa at its maximum level for the column with the steel layer thickness of 5 mm. Also, the maximum displacement of 100 mm was obtained in the column. The results indicate that the maximum stress was applied at the points of column connection to the base of the columns and the points were selected as sensitive points for the strengthening. The maximum displacement was seen at the column head (load application) points in Figure 6 and the maximum stress was observed at the column end (column connection to base) points. Figure 7 below shows the amount of stress and strain in the steel layer, where the maximum value of 370 Mpa is equal to the yield stress of the steel layer.

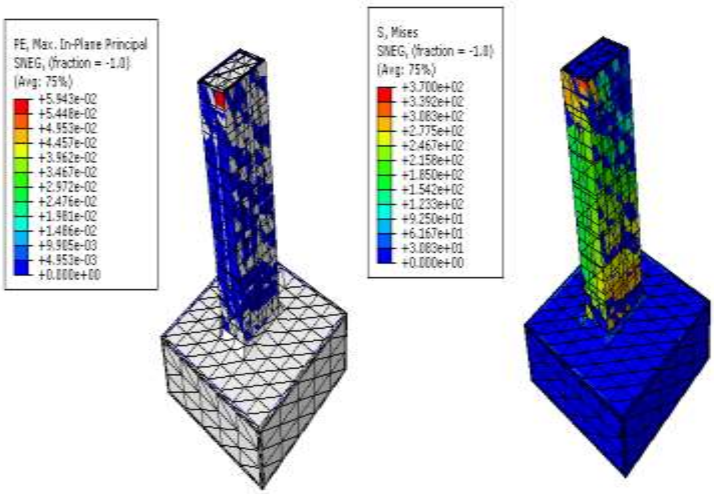

Figure 5. Stress and strain induced in composite column (sample 1)

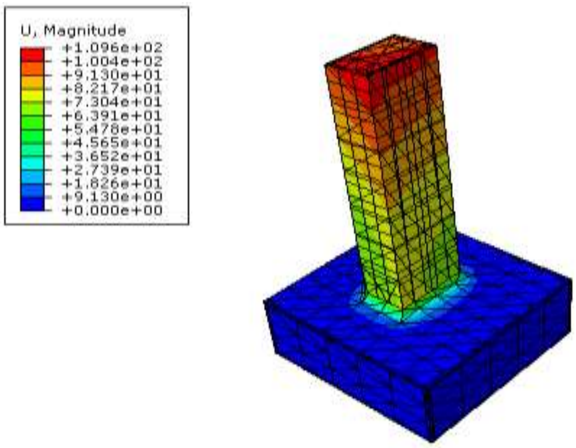

Figure 6. Displacement induced in composite column (sample 1)

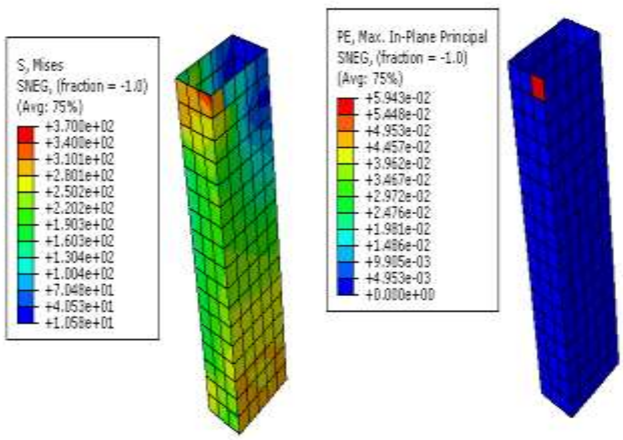

Figure 7. Stress and strain induced in steel plate (sample 1)

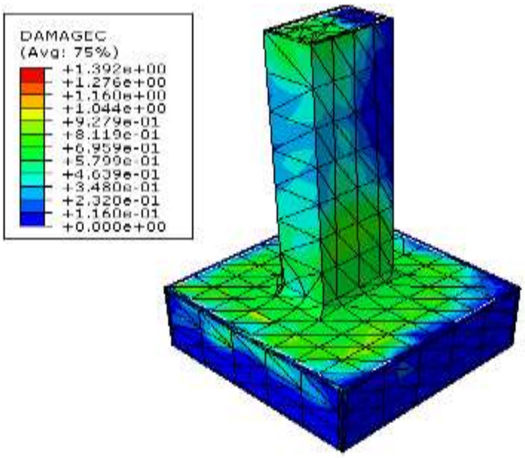

Figure 8. Amount of damage to composite column (sample 3)

In the following, the results of three steel columns with the steel jacket of 15mm thick are shown for the comparison. Increasing the thickness of the steel layer causes the reduction of stress in composite columns and thus, the column fails later. As can be seen from the figures, the maximum displacement and stress and the stress and displacement contours are similar to the previous case, as shown in Figures 9-11, but the magnitude of the stress induced in the composite columns is different. There is also a decrease in the strain induced in the column. Figure 9 shows the stress induced in the concrete columns. As seen in the figure, increasing the thickness of the steel layer improves the behavior of the composite column and enhances the ductility of the column under the applied load. The amount of stress induced in the whole composite column decreased, which indicates that the column with a higher thickness resists less stress. The strain induced in the composite column with more steel layer sharply decreased, reaching 0.45 time the initial value.

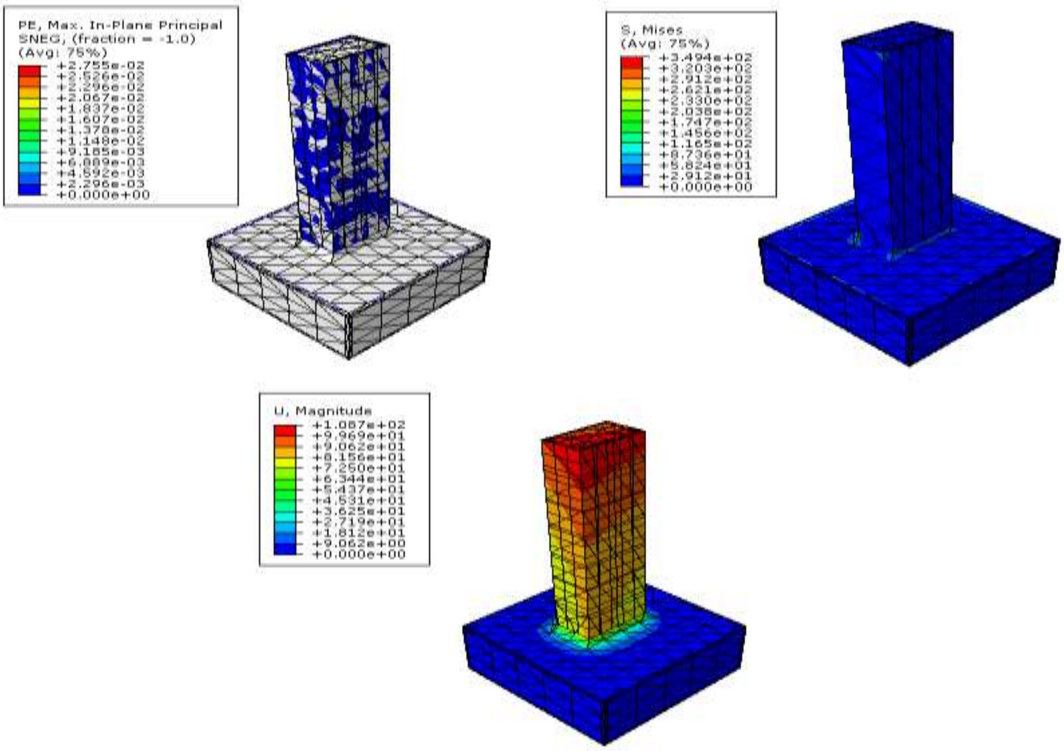

Figure 9. Stress and strain induced in composite column (sample 1)

Figure 10 shows the stress applied to the steel layer. As seen in the figure, the maximum stress of the steel layer is 0.76 time its initial value. Figure 11 below shows the parameters of damage to the composite column where the damage value reached 1.31 and it can be stated that the concrete column damage reached 0.94 time the initial value. Generally, it is found that increasing the thickness of the steel layer leads to reduced damage to the column, reduced stress induced in the column cross-section and increased durability of the column in the cyclic loading.

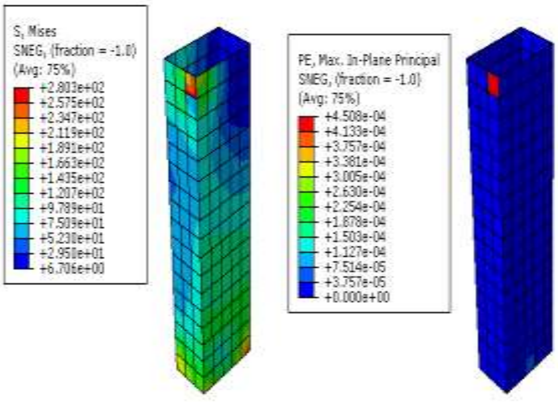

Figure 10. Stress and strain induced in steel plate (sample 3)

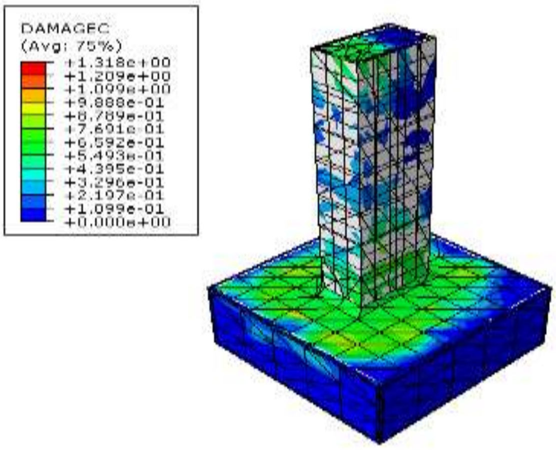

Figure 11. Amount of damage to composite column (sample 3)

Figure 12 below shows the displacement-time diagram for the composite column. The results of the diagram reflect the fact that increasing the column thickness up to 20 mm caused the lower displacement of the column in all loading cycles. In case the thickness of the steel jacket is 20 mm, the column displacement reaches 0.69 time when the thickness of the steel jacket is 5 mm. Figure 12 shows the displacement results for the 4 samples modeled in the study.

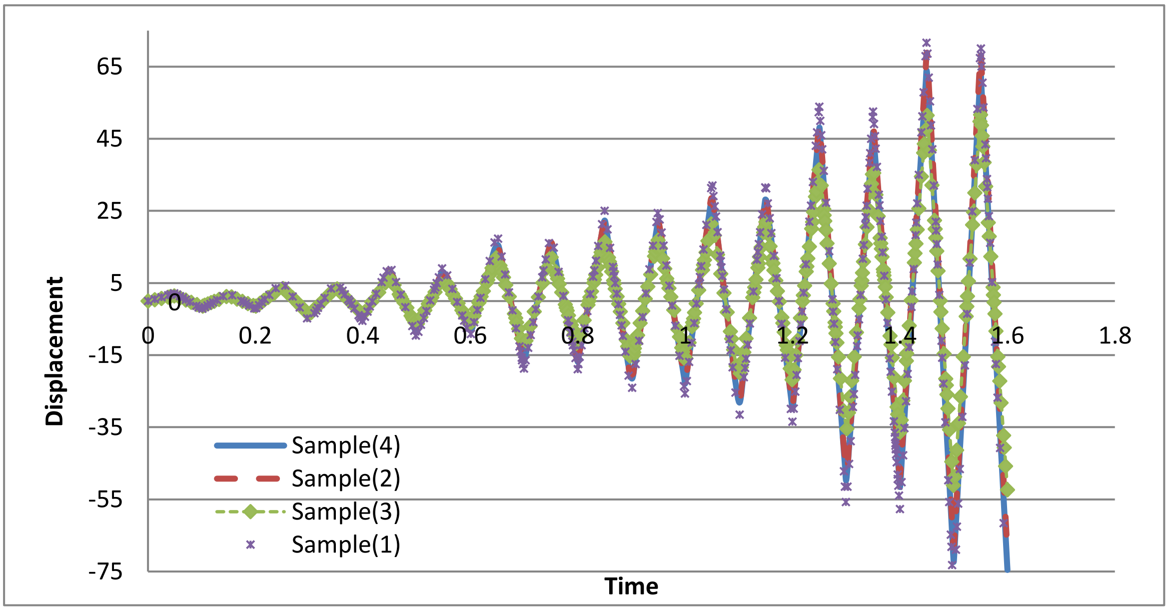

Figure 12. Stress and strain induced in steel plate (sample 3)

Table 3 below summarizes the results of displacement, stress, damage parameter, and plastic strain of the composite column for all samples modeled in the present study. The results generally show that the increased thickness plays a significant role in reducing the displacement and damage in the composite column. Moreover, the plastic strain is significantly reduced in the whole section with increased thickness. Therefore, it can be stated that using composite columns with the appropriate thickness of the steel layer can effectively increase the strength of the concrete column under the cyclic lateral load. The column with a thicker steel-concrete layer experienced a lower displacement, less failure, lower plastic strain and lower stress than the case when the thickness of the steel layer is lower.

Table 3. Summary of results in composite column with variable thickness of steel layer

Damage Parameter	Strain of composite section	Stress of composite section	Stress of steel jacket (Mpa)	Displacement	Sample
3.45	0.0594	370	370	68	1
2.89	0.0435	360	320	59	2
1.318	0.02752	349	283	55	3
1.02	0.0185	328	223	47	4

The application of CFT and its behavior under cyclic and axial loading and have been experimentally investigated in previous research. Jothimani et al. examined the CFT column under the lateral and axial compressive load. The experimental studies were conducted on five samples with the exposed column base and the embedded column base connections. The considered parameters were the number of stiffener and embedment depth of CFT column. The force-displacement responses of the samples were compared with each other. Also, increasing the number of stiffeners led to the increased strength of the connections [22]. Among the issues that need to be examined in the present study is how to perform the study numerically. In this study, the column along with the column base was subjected to the cyclic loading, and the results showed that the stability of the column increased with increasing the thickness of the steel layer. The previous research analyzing the column under the cyclic lateral loading has shown that the CFT column strengthening leads to the increased loading capacity, increased drift ratio, ductility, prevention of steel shell from local buckling, and increased energy absorption capacity. The cyclic displacement diagrams showed that the use of the steel portion of the section stiffener increases the energy dissipation [23]. In the present study, increasing the thickness of the steel layer leads to improved column performance. In general, previous research has shown that it is common to examine the CFT columns under the cyclic lateral loads due to the fact that the concrete structures are subjected to earthquakes during their lifespan. Wang et al. [24] investigated the cyclic seismic behavior of CFT columns and the results showed that the increased tube thickness can effectively improve the column performance. Other researchers, such as [25] evaluated the behavior of CFT columns under the cyclic and lateral loading to find the effect of stiffeners on the behavior of CFT columns in variable temperatures. As such, by exploring the effect of CFT layer thickness, the present study can be considered a comprehensive research in line with previous research.

4. CONCLUSION

It is important to use steel plates in concrete columns, because the stress resisted by the columns due to the use of steel jacket (high modulus of elasticity) leads to the improved behavior and reduced displacement of the column. Therefore, in case of using the equal area for the jackets, increasing the thickness leads to the improved behavior of composite columns. In this way, the structure would resist higher stress while having less deflection. As is evident from the stress contours in this study, the maximum column stress is applied to the column base and thus, the application of the steel jacket leads to the reduced stress in the whole cross-section of the column. Increasing the thickness of steel layer to 20 mm caused the effectiveness of steel in controlling the behavior of the composite column to be increased and contributed to the absorption of applied force and hence, the column displacement was reduced to some extent. However, the column can exhibit more resistant to lateral loading by absorbing the applied stress. According to the above, the least displacement was observed in the column with a jacket of 20 mm thick. The results of the study showed that:

- ✓ The use of CFT columns will allow those involved in the strengthening to be aware of the improvement made in the column behavior under the biaxial loading and will eventually lead to the utilization of the columns as best as possible.
- ✓ The use of jackets with higher thickness leads to the reduced damage in the whole composite column, as the amount of damage to the column in case of using the jacket with the thickness of 20 mm reaches 0.85 time the case when the column with the jacket of 5 mm thick is used.
- ✓ The use of thicker jackets leads to reduced stress and displacement of the column, and due to the flexibility of the composite column, the column deflection is reduced.
- ✓ The plastic strain induced in the composite column was greatly reduced when using the thicker steel jacket. Also, in case of using the steel jacket with the thickness of 20 mm, the plastic strain reached 0.25 time the case when the steel jacket of 5 mm thick was used.
- ✓ All the columns modeled in this study were able to exhibit the maximum strength under the cyclic loading, as all the columns were able to resist the applied load.

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AUTHORS CONTRIBUTION
This work was carried out in collaboration among all authors.

CONFLICT OF INTEREST
The author (s) declared no potential conflicts of interests with respect to the authorship and/or publication of this paper.

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