Periodica Polytechnica Civil Engineering, 69(4), pp. 1354–1366, 2025

Effects of Core Drilling Location on the Response of Eccentric Axially Loaded Columns under Cyclic Lateral Loads

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Received: 01 August 2025, Accepted: 05 November 2025, Published online: 14 November 2025

Abstract

In evaluating the performance of existing reinforced concrete buildings, compressive strength is determined by core samples taken from the structural elements. Regarding ease of application, the core area is selected as close to the column's bottom as possible. Although studies in the literature and relevant regulations state that coring should be done from the middle area of the columns, there is no evaluation of the behavior of the columns under different loading conditions. Besides, the location of the cored area can be ignored for symmetrically loaded columns; it will vary for eccentric axially loaded columns, which are frequently encountered in practice. Only axial load has been considered for the evaluations in studies investigating the effect of the cored area on the load-bearing element. However, this should also be evaluated under horizontal cyclic loadings that change the tensile and compressive zones of the load-bearing element. Therefore, this study aims to determine the most suitable coring area on the column by considering the literature, regulations and application situations in reinforced concrete columns subjected to eccentric axial loading and horizontal cyclic loading with the finite element method. In addition, the study aims to provide an academic basis for the importance of loading type (symmetric/eccentric) in selecting the core drilling area, which is often determined randomly in practice.

Keywords

Abaqus, core drilling, cyclic load, finite element analysis, RC column

1 Introduction

According to material behavior models, the damage levels of structural elements are determined based on critical cross-sectional damage under seismic effects. Consequently, a performance level is assigned to each floor based on the damage levels of its elements, and to the entire building based on the damage observed on each floor. Therefore, material behavior models represent a key parameter in performance evaluation studies. While the design material properties of a structure can be obtained from project documentation, they may change over time due to various factors throughout the structure's service life. As a result, assessing the current material condition of an existing structure requires additional effort. In some cases, original project data may not be available. In such situations, material properties are determined through field investigations and laboratory testing of samples taken from the building.

Two primary methods for assessing the compressive strength of existing reinforced concrete elements are destructive and non-destructive testing. In destructive testing, such as the core-drilling technique, concrete samples are extracted from structural elements and tested to failure under compression. This approach offers several advantages: inspections can be conducted relatively easily, are widely applicable across different types of concrete structures, and yield highly accurate results. Destructive methods are particularly effective in determining the actual material strength and are extensively used for evaluating building structures, guiding rehabilitation efforts, and investigating engineering failures [1, 2]. However, coring every structural element is not feasible. Moreover, core holes can negatively impact an element's load-carrying capacity. Studies examining the effect of core holes on the axial load capacity of symmetrically loaded columns,

Cite this article as: Özmen, R., Tozlu, İ., Gürsoy, Ş., Doğan, S. O. "Effects of Core Drilling Location on the Response of Eccentric Axially Loaded Columns under Cyclic Lateral Loads", Periodica Polytechnica Civil Engineering, 69(4), pp. 1354–1366, 2025. https://doi.org/10.3311/PPci.41809

considering variations in concrete class, column size, and transverse and longitudinal reinforcement, have shown that the presence of core holes can directly alter the failure mode of the specimens. It has also been observed that maximum strength values decrease significantly in core-drilled elements, particularly in low-strength concrete classes. In contrast, high-quality concrete tends to show results similar to those of uncored samples, with only slightly reduced load-carrying capacity [2–5]. A limited number of studies have also investigated the effect of core drilling on the axial load-carrying capacity of eccentrically loaded columns under similar parameters. These studies reported results consistent with those of symmetrically loaded columns. However, the reduction in axial load capacity tends to be greater when the core hole is closer to the loaded region [6]. Although core holes are typically repaired using suitable mortars, some reduction in the structural performance of the repaired elements may still occur [6–9]. Due to these concerns, design codes specify minimum requirements for the number of samples taken per square meter or structural element when determining concrete compressive strength. Non-destructive testing (NDT) methods are commonly used on non-cored elements to verify the consistency and reliability of the results obtained from core samples.

One of the primary investigated issues is determining the most appropriate regions of structural elements for core sampling. Core drilling is typically performed in the tensile zone of structural elements, where concrete contributes minimally to the overall structural performance. Therefore, as long as the core hole does not extend into the compression zone, the overall behavior of the element where tensile stresses are primarily resisted by reinforcement should theoretically remain unaffected [10]. In practice, however, it is often impractical for operators to drill at beam height due to limitations in positioning the core drilling machine. Consequently, vertical structural elements, generally more critical than horizontal ones, become more feasible targets for core sampling. Experimental studies on full-scale, symmetrically loaded specimens have shown that core drilling at one-third of the column height can reduce axial load capacity by approximately 25%, while drilling at mid-height can lead to a 16% reduction [4, 5]. Although design codes provide general recommendations regarding appropriate core drilling locations in vertical structural elements, in practice, the drilling location is often selected based on practical constraints such as existing reinforcement layout, infill wall placement, and the operator's ability to mount the drilling equipment at a workable height (Fig. 1 (a)). Moreover,

(a) (b) (c)

Fig. 1 Core drilling: (a) application; (b) inside; (c) outside the eccentric loading zone codes and standard practices do not consider the axial loading conditions of vertical elements when evaluating the impact of core drilling. In Reinforced Concrete (RC) structures, slabs transfer loads to supporting beams, and these vertical loads are subsequently transmitted as axial forces to the connected vertical elements. In many buildings, eccentric column-beam connections are common, resulting in eccentric axial loading of the columns. As a result, randomly selected core locations may lie within (Fig. 1 (b)) or outside (Fig. 1 (c)) the zone influenced by eccentric axial loads.

Theoretically, core drilling from the tension zone of flexural elements is expected not to influence their structural response significantly. However, the locations of tension and compression zones in column cross-sections can shift under horizontal loads such as wind and earthquakes. While the center of a symmetrical axially loaded column is typically considered the most appropriate location for core drilling under such loading, this assumption may not hold for eccentrically loaded columns. Since eccentrically loaded columns are common in practice, this issue warrants further investigation. To the best of the authors' knowledge, literature lacks sufficient studies to address this topic. Therefore, this study aims to numerically identify the most suitable core drilling regions in eccentric axially loaded columns subjected to horizontal cyclic loading, particularly when the effects of such loading are not accounted for during the drilling process.

2 Material and method

This study investigated the effects of core drilling from different regions of eccentric axially loaded columns' behavior under cyclic lateral loading. Six different column models are prepared to represent the core-drilling cases. Accordingly, three horizontal and two vertical (middle and bottom) regions are considered to model core-drilled column models. In all models, the core diameter and depth are assumed to be 100 mm and 200 mm, respectively. Since stirrup conditions affect the behavior under horizontal loading, two different stirrup conditions are considered to represent well and poor confinement. The concrete compressive strength and reinforcement classes for all models are C16 and S420, respectively. In turn, the width and height of the beam connected to the column are assumed to be 350 mm and 700 mm. Based on the 3100 mm story height assumption, the column's free height is assumed to be 2400 mm (Fig. 2). Column section details are given in Fig. 3. Because the column behavior varies depending on

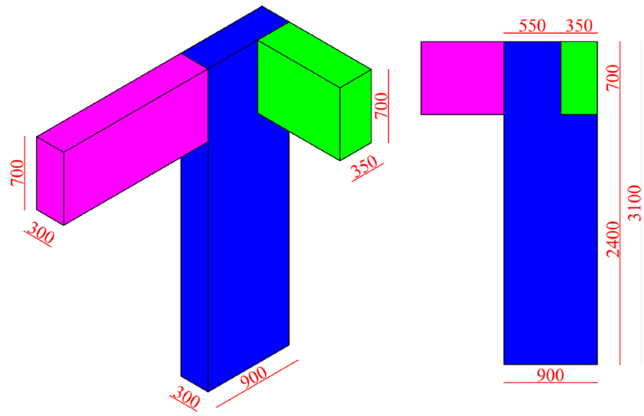


Fig. 2 The column and considered beam dimensions and connection locations (dimensions in mm)

its subjected axial load level, the column models are subjected to 1 MPa compressive load to represent the 270 kN axial load from the upper-story columns via the beam connected at the short end in the vertical direction. An additional 1 MPa compressive load, with green color, is also considered in the eccentrically connected beam-column connection area to represent the 105 kN axial load transferred from the beam (Fig. 4).

2.1 Material parameters

The Concrete Damage Plasticity (CDP) model, provided in Abaqus FEA software [11], is used to model RC columns. Accordingly, the initial elasticity modulus E_c for concrete is calculated using Eqs. (1)–(7), based on the cylinder compressive strength f_c. The three-region model (Fig. 5 (a)), widely used in literature and calculated using Eq. (1), is used for the stress-strain behavior of concrete under compression [12–14]. The first region corresponds to the linear elastic phase and is determined using Eq. (2), depending on the E_c, f_c, and ε_c (strain) parameters. The maximum stress and strain for this linear region is considered to be 40% of the f_c value and the strain associated with that stress level, respectively. The linear region's upper limit stress and strain values are assumed to be 40% of the f_c and the corresponding strain values, respectively. The second region, lying between the upper limit of the linear region and the 0.0035 strain value, is calculated using Eq. (3) based on k_1, ε_0, f_c, and ε_c parameters. The k_1 and ε_0 parameters, in turn, imply the material constant ensuring continuity between the first and second regions, and the strain corresponding to the maximum stress. The strain value corresponding to the remaining f_c value in this region is calculated using Eq. (4). Finally, for the third region, k_2, f_c, ε_c, and ε_0 are calculated using Eq. (5). The k_2 parameter implies the material

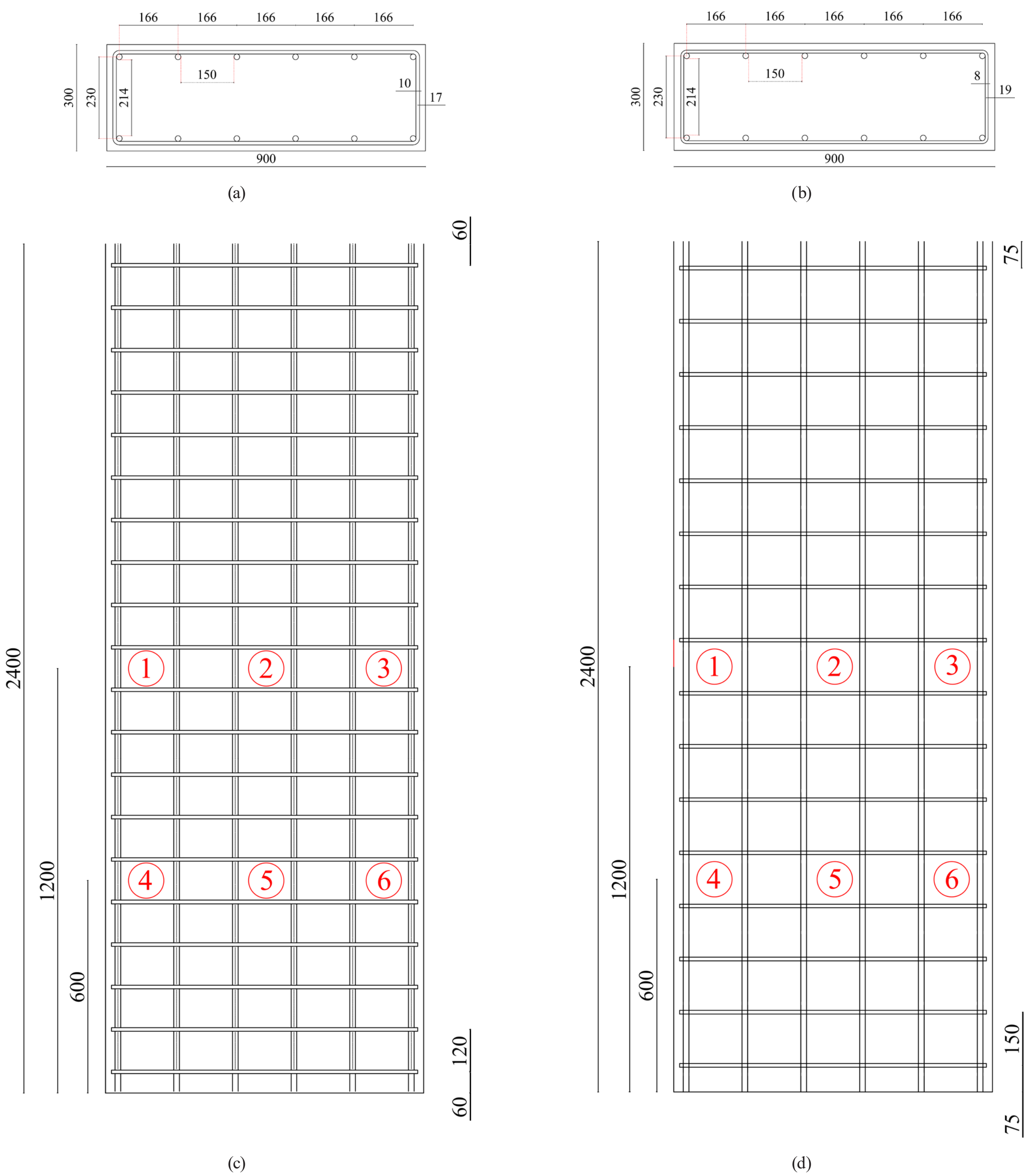


Fig. 3 Column models: (a) well-confined (∅10/12); (b) poorly confined (∅8/15) cross-section detail; (c) well-confined; (d) poorly confined column longitudinal section (1–6 shows different regions where cores were taken.)

constant, ensuring continuity between the second and third regions. The ε_u, taken as 0.08, is given as the maximum concrete strain value for the upper limit of region three. The stress-strain behavior, assumed for tensile stresses in concrete, is given in Fig. 5 (b). The f_t parameter represents the concrete's maximum tensile strength. Besides, the G_f parameter is the area under the stress-crack opening relationship and is calculated using Eq. (6) for normal-weight concrete. In Eq. (6), G_{f0} and f_{cmo} are, in turn, accepted as 0.03 N/mm and 10 MPa per the maximum aggregate size value (12 mm) [14, 15].

$$E_c = 4700 \times \sqrt{f_c} \quad (1)$$

$$\varepsilon_c \le \frac{0.4 f_c}{E_c} \rightarrow \sigma_{c,1} = E_c \times \varepsilon_c \quad (2)$$

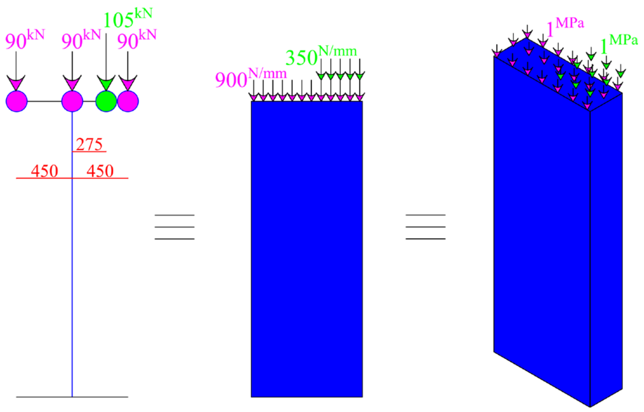
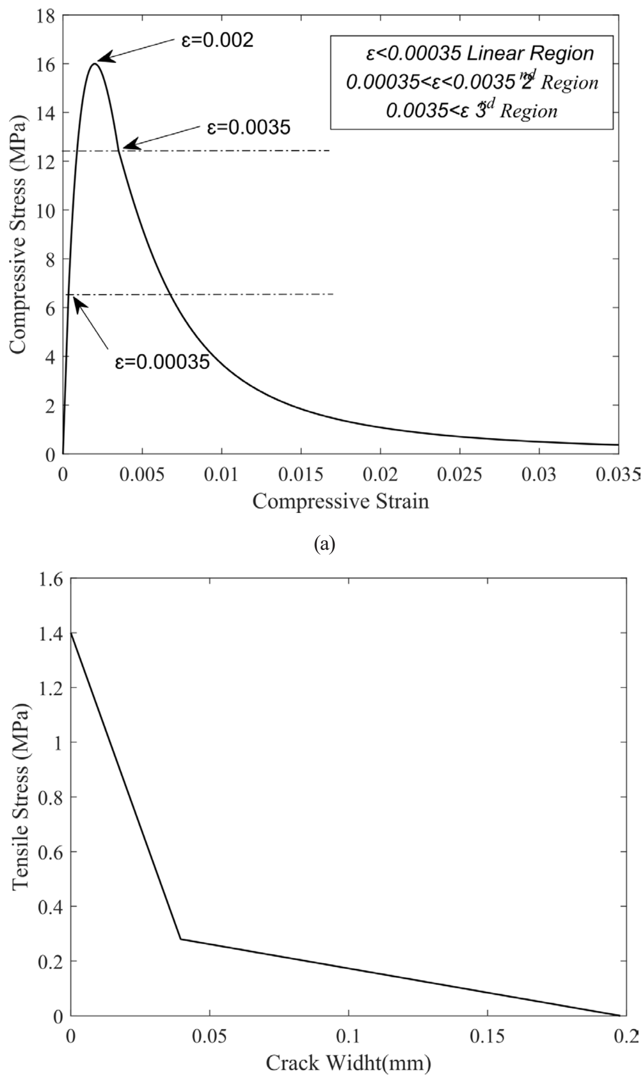


Fig. 4 Axial load cases of column models



(a)

(b)

Fig. 5 Concrete's behavior: (a) pressure; (b) tensile

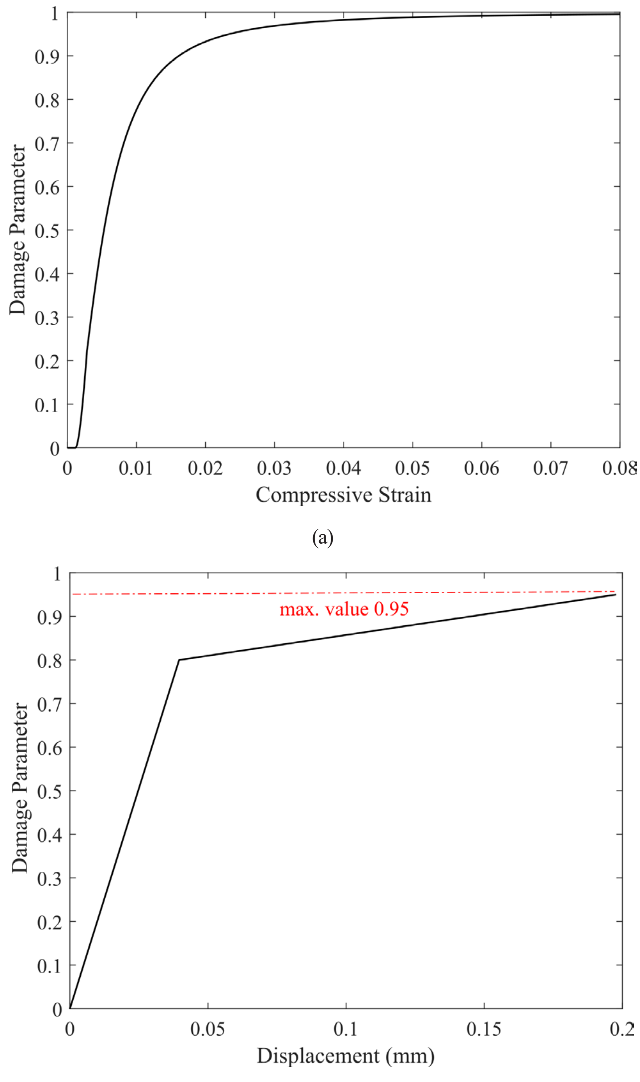
$$\frac{0.4 f_c}{E_c} \leq \varepsilon_c \leq 0.0035 \rightarrow \sigma_{c,2} = \frac{k_1 \frac{\varepsilon_c}{\varepsilon_0} - \left(\frac{\varepsilon_c}{\varepsilon_0}\right)^2}{1 + \left(k_1 - 2\right)\frac{\varepsilon_c}{\varepsilon_0}} \times f_c \tag{3}$$

$$\varepsilon_0 = 2 f_c / E_c \tag{4}$$

$$0.0035 \leq \varepsilon_c \rightarrow \sigma_{c,3} = \left(\frac{2 + k_2 f_c \varepsilon_0}{2 f_c} - k_2 \varepsilon_0 + \frac{k_2 \varepsilon_c^2}{2 \varepsilon_0}\right)^{-1} \tag{5}$$

$$G_f = G_{f0}\left(\left(f_c + 8\right)/f_{cmo}\right)^{0.7} \tag{6}$$

The CDP model's damage parameters (are presented in Fig. 6 (a), (b)) under compression and tension are calculated using Eqs. (7), (8), respectively. For concrete, the damage is assumed to occur only in the softening zone, as the literature recommends [16]. The damage parameter for compression is defined for values above ε_0. It is assumed that the damage parameter reached a value of 0.8 when the strength decreased to 80%. The maximum value for the damage parameters is chosen as 0.95, corresponding to a 95%



(a)

(b)

Fig. 6 Damage parameters: (a) pressure; (b) tensile decrease in strength [14]. Plastic strains are calculated using Eq. (9). The supplementary material parameters used for the CDP model (Table 1) are selected based on similar studies in literature [6, 17–33]. The mechanical properties of the rebar used in the analyses are also given in Table 2.

$$dc = 1 - \frac{\sigma}{f_c} \quad (7)$$

$$dt = 1 - \frac{\sigma}{f_{ct}} \quad (8)$$

$$\varepsilon_c^{in} = \varepsilon_c - \sigma_c / E_c \quad (9)$$

2.2 Loading protocol

A displacement-controlled loading profile is considered in the analyses according to ATC-24 report [34]. Displacement steps are determined according to drift ratios, which are defined as the ratio of the peak horizontal displacement to the column's effective length. A maximum drift ratio of 4% is considered for a well-confined column. While three cycles are considered for each drift ratio value, the number of cycles is reduced by one because the collapse limit is approached for the last two drift ratio values (3~4%). As is known, confinement conditions have a significant effect on the drift ratio capacities of columns [35–39]. In particular, poorly confinement conditions significantly reduce drift ratios. Besides, the energy absorption capacity of such columns also decreases significantly. Therefore, considering the low compressive strength of the concrete, the maximum drift ratio is limited to 1.5% for the cyclic loading protocol of the poorly confined columns. Furthermore, the number of cycles for each drift ratio value is limited to two. The loading protocols used in the analyses are shown in Fig. 7, and the applied loading to the models is shown in Fig. 8.

Table 1 Complementary material parameters

Complementary material parameters	Values	References
Viscosity (μ)	0.001	[6, 17–21]
Shape factor (K_c)	0.667	[11, 12, 19, 22–25]
Dilation angle (Φ°)	40	[6, 14, 16, 26, 27]
f_{b0}/f_{c0}	1.16	[6, 23–25, 28–32]
Eccentricity (*Ecc*)	0.1	[6, 24, 25, 28–30, 33]

Table 2 Mechanical properties of reinforcement

Properties	S420
Yield stress (MPa)	420
Yield strain	0.008
Ultimate stress (MPa)	500
Ultimate strain	0.08

2.3 Modelling process

In this study, finite element (FE) models of the RC column elements are created using Abaqus FEA software [11]. The CDP concrete material model, generally utilized in Abaqus FEA, is used for the column's concrete section, and the required parameters are listed in Table 1. Other FE model development steps are also presented in Section 2.3. To provide a more realistic modelling opportunity, the concrete and reinforcement sections of the column model are modelled using the 3D modelling approach of Abaqus FEA. Accordingly, the concrete sections of the columns are modelled as 3D geometric volumes, and the reinforcement elements within the concrete volumes are also modelled as

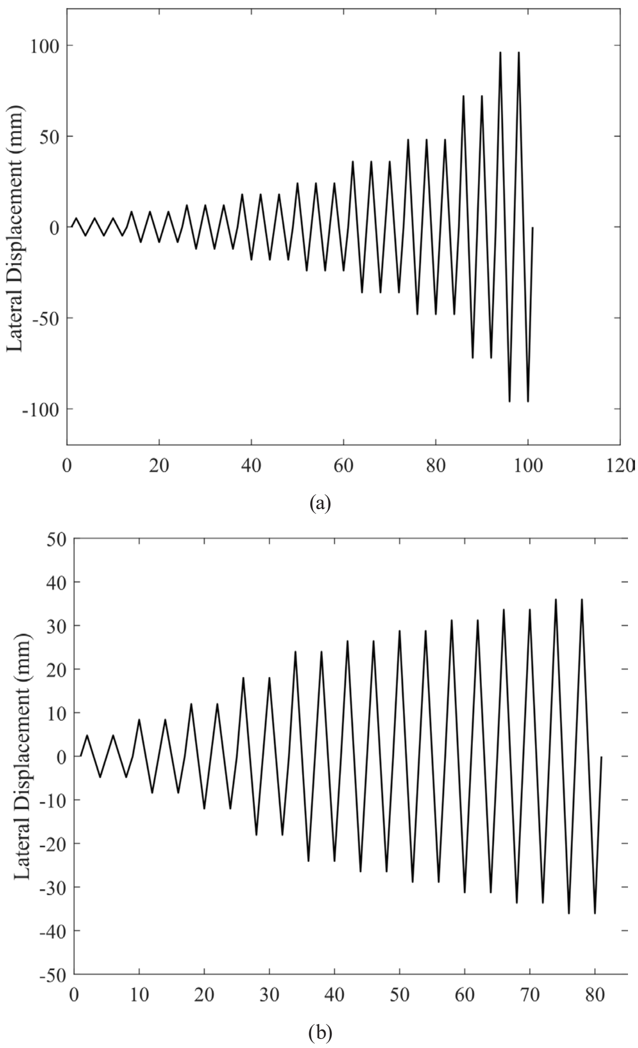


Fig. 7 Cyclic load protocols: (a) to well confined; (b) to poorly confined models

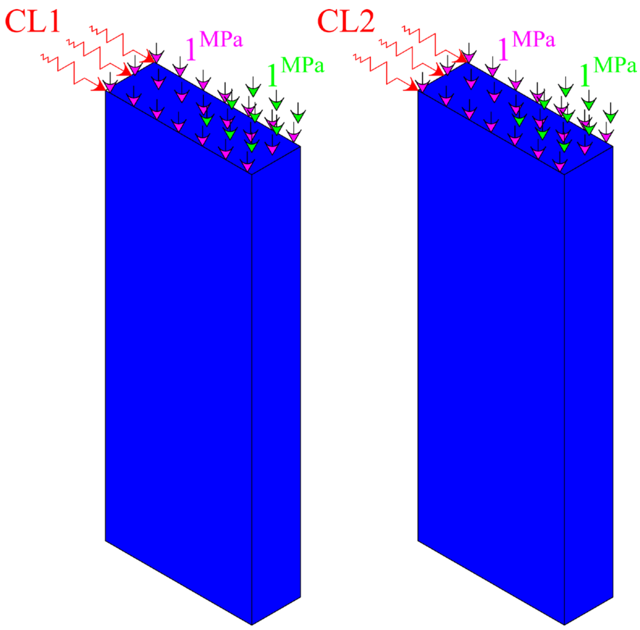


Fig. 8 Considered load effects

bar elements in 3D space. A homogeneous solid section is defined for the concrete, based on the specified CDP material parameters. Besides, the reinforcement elements are also defined as 3D bar elements. The general static analysis option is selected. The interaction between the concrete and reinforcement elements in the FE model is modelled using the embedded element method (*Embedded Element Constraint*). Hence, the concrete volume of the column is defined as the host region, and the reinforcement elements are defined as embedded elements. Since the base of the column is considered a fixed support, all degrees of freedom of the column's lower surface are constrained. Furthermore, horizontal cyclic loading is implemented by applying displacements to a reference point connected to the center of the column's upper section. The finite element model of the column and reinforcement elements is shown in Fig. 9. The mesh size of the concrete and rebars is selected based on the recommendations of Kisa et al.'s [20] study. Accordingly, eight-node 3D reduced integration elements, C3D8R elements, are used for the mesh structure of the concrete section. The reinforcement is modelled using two-node 3D linear bar elements (T3D2).

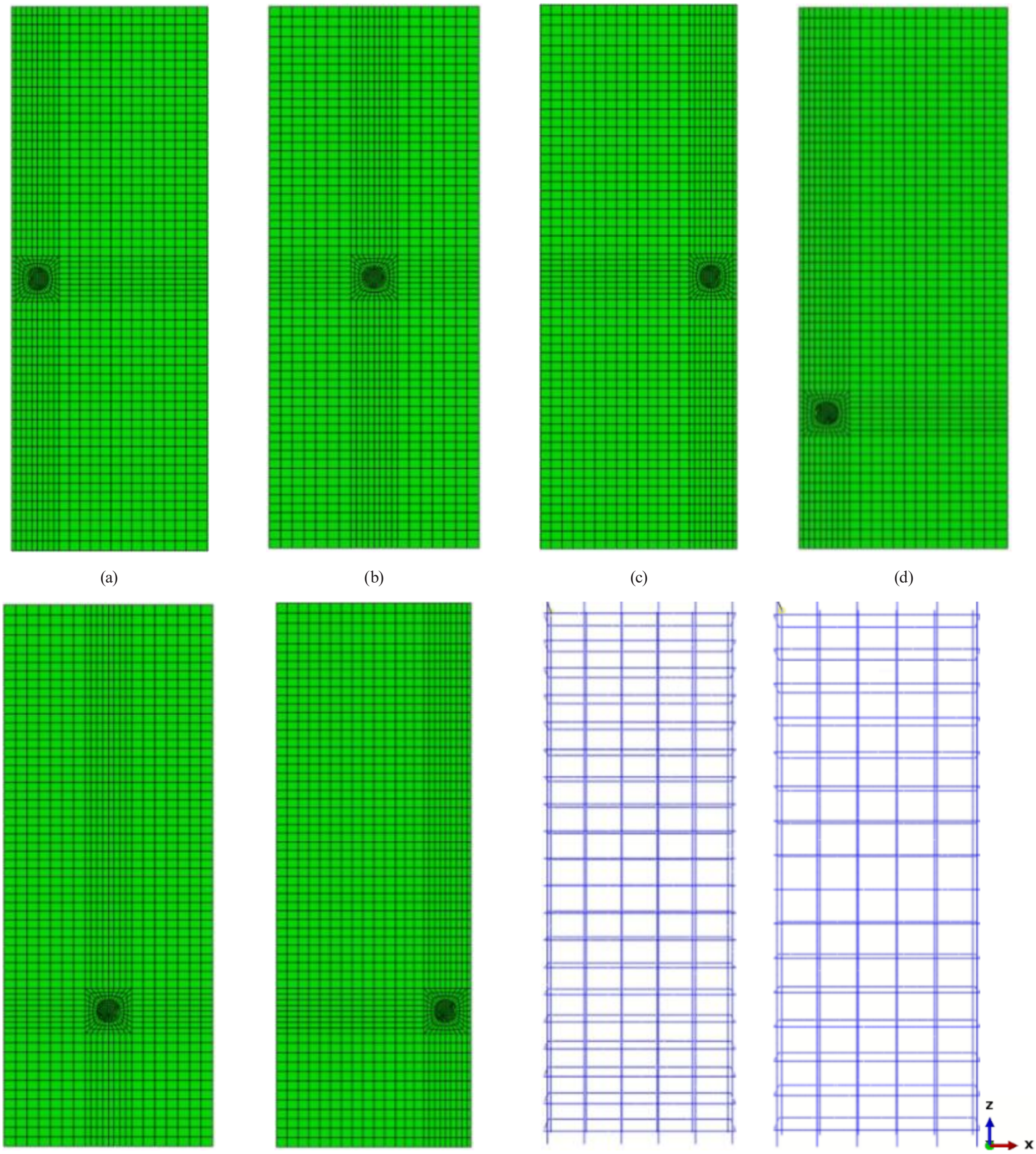
3 Results and discussion

The study investigated the behavior of well and poorly confined column models with the same cross-sectional dimensions based on the core drilling from different regions, under horizontal cyclic loading. Finite element analysis results for well-confined columns (WCC) are presented in Fig. 10, and its cyclic response is shown in Fig. 11. Besides, the poorly confined column's (PCC) FEA results and cyclic response are presented in Figs. 12, 13, respectively. When eccentrically loaded RC columns are evaluated under horizontal cyclic loading in terms of taking cores from different regions, no significant change is observed in the skeleton curve of cyclic behavior (i.e. impact on stiffness degradation and energy dissipation behaviors) of the well- and poorly-confined models.

The absolute maximum horizontal load values obtained for the positive and negative directions of horizontal cyclic loading are shown in Fig. 14. The presence of eccentric axial load differentiated the results in positive and negative directions. Under positive drift ratios (displacements through eccentric load), eccentric axial loading increases the stresses in the compression zone. This condition reduces the maximum horizontal load capacity relative to negative displacements, with the magnitude of reduction varying between 10% and 20%, contingent upon whether the core hole is situated within the compression or tension zone. In this case, eccentric axial load had an adverse effect on the column's horizontal load capacity in positive drift ratios, while it positively contributed to negative drift ratios. Furthermore, eccentric axial load is more effective on the columns' horizontal load-carrying capacity when the core hole is located at the column's bottom (*Core Hole Positions 4-5-6*) than the middle-located ones (*Core Hole Positions 1-2-3*).

The confinement effect is a significant factor affecting the collapse damage pattern and failure mode. Under horizontal cyclic loading, the critical section in cantilever elements is the fixed support region. In weakly confined column models, the stresses induced in the fixed support region cause the column to collapse before the core-drilled areas can be stressed. Therefore, core drilling did not significantly alter the results since the load-carrying capacities are exceeded at the critical sections of weakly confined column models. This effect is evident from the horizontal pattern of the results in Fig. 14 (a).

Due to the high load-carrying capacity at their critical cross-sections of well-confined columns, strains occur in the weakened core hole locations. This situation allows the core hole effect to be seen (Fig. 14 (b)). The core hole in the center of the cross-section (*core hole positions 2 and 5*) yielded the same results as the non-cored columns, regardless of their vertical position. In positive drift ratios, the lowest horizontal load capacities are obtained by locating the core hole at the eccentric load *zone* (*core hole positions 3 and 6*) for well-confined columns. In contrast, the lowest horizontal capacities are obtained for core hole positions 1 and 4 in



(a) (b) (c) (d) (e) (f) (g) (h)

Fig. 9 Column and rebar finite element models and core hole location: (a) 1; (b) 2; (c) 3; (d) 4; (e) 5; (f) 6; (g) WCC; (h) PCC

negative drift ratios. However, these changes are quite limited (5–7%). The location of the core hole near the bottom end or middle of the column did not cause a considerable change in the horizontal load-carrying capacity.

Although no differences in the cyclic behavior of the models are observed depending on the core location, the core hole's presence impacts the column's damage mechanisms and levels. When cores are taken close to the column edges, maximum damage occurs in the concrete elements surrounding the core. Besides, taking cores from the column center, buckling occurs in the longitudinal reinforcements due to the stress increment at the support area.

Considering the column models as vertical cantilever elements, maximum stresses are expected to occur at the

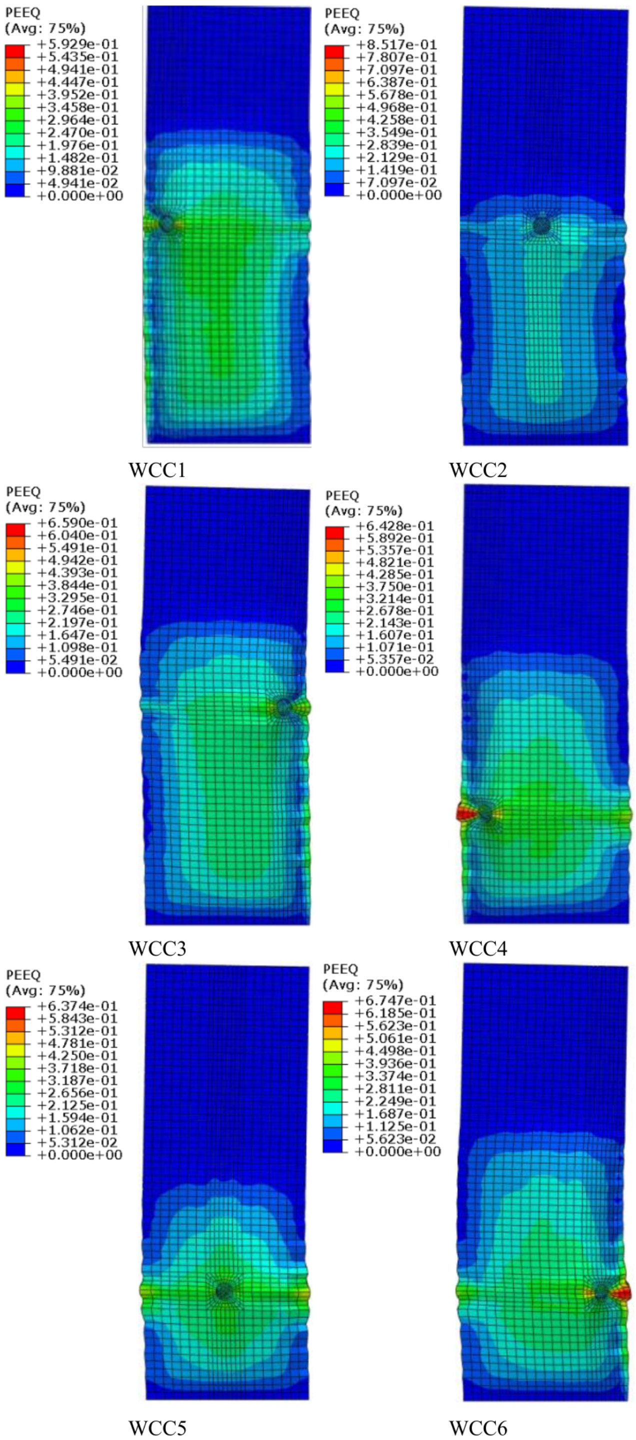


Fig. 10 WCC model's damage patterns

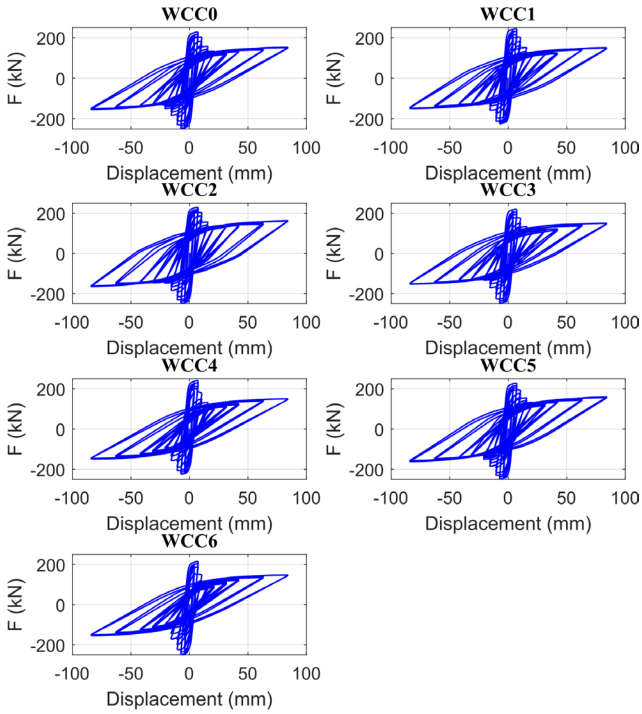


Fig. 11 Hysteretic loading curves for well-confined columns

support area. Fig. 15 shows the maximum stress obtained at the support area for well and poorly confined models without core drilling. In this case, core drilling from the column center is similar to the undrilled situation, and therefore, has no significant impact on the horizontal load capacities. Whether the core drilling location is within the beam's axial load zone or not, due to the displacement of the tension and compression zones under horizontal cyclic loading, core drilling close to the column edges results in the most adverse situation due to the cross-sectional area reduction of the effective concrete in the core area. Therefore, considering the cyclic lateral loadings, the column's middle region is the most suitable area to take the core.

The support region of the column experiences the highest stresses under cyclic loading. When the core hole is located sufficiently far from this critical region, its influence on the overall behavior becomes negligible. It should be noted, however, that the required distance may vary depending on the column's confinement conditions. In practice, coring from this critical region is not feasible due to longitudinal reinforcement lap splices and the high stirrup density. Therefore, considering its potential effect on the column's axial load capacity, the core hole location should be determined. Based on studies conducted under axial loading conditions, coring from the mid-height of a column's effective length generally yields better results than coring near the base [4, 5]. The most suitable coring location for symmetrically loaded columns is at the center of gravity. In the case of eccentrically loaded columns, research has shown that the axial load-carrying capacity decreases as the coring location approaches the point of load application [6]. Therefore, coring is recommended at the mid-height of the effective length for eccentric loaded columns and as far as possible from the eccentric load application point-specifically within the middle third of the cross-section.

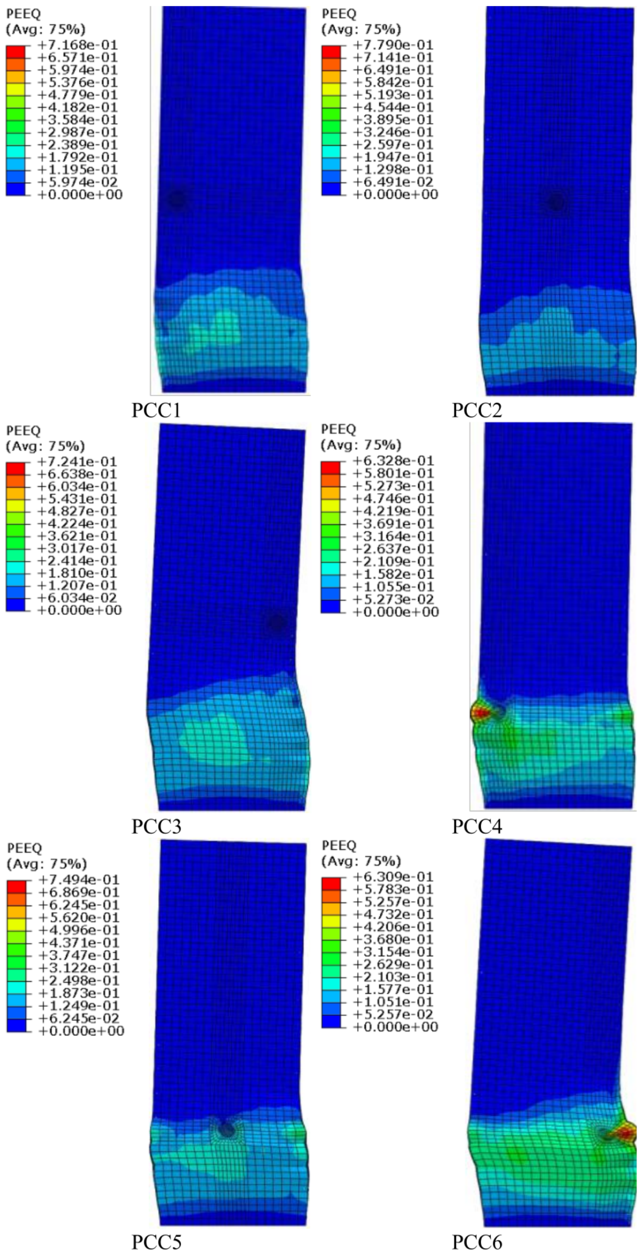


Fig. 12 PCC model's damage patterns

4 Conclusions

This study numerically investigates the optimal core drilling location for RC columns using the finite element method. Two stirrup configurations, representing poorly confined and well-confined conditions, are considered. The columns are subjected to horizontal cyclic loading and eccentric axial loadings. Based on the analyses, the following recommendations are provided for the most suitable core drilling locations:

- For poorly confined columns, the stresses at critical sections exceed the section capacity under horizontal cyclic loading, causing the models to fail without any strain in the core-drilled areas. In well-confined models, capacity increment is seen due to the confinement effect, and strains occur in the core-drilled areas. Under cyclic loading, core drilling from the center of the column yielded a similar response as without core drilling. Core drilling close to the column's lateral edges reduced the column's horizontal load-carrying capacity. However, these changes are quite limited (5–7%).
- Positive drift ratios, displacements toward eccentric load, reduce the column's horizontal load-carrying capacity, while negative drift ratios increase it. Thus, the horizontal loads, obtained from negative drift ratios, are 10~20% higher than those in positive drift ratios.
- Eccentric axial loads have a relatively greater impact on the horizontal load capacity for the core holes close to the column's support (*Core hole positions 4-5-6*) than the core hole in the center of the column (*Core hole positions 1-2-3*).
- The column's tension and compression zones shift under horizontal cyclic loading. Regardless of whether the core area is within the beam's axial load zone, core drilling close to the column edges resulted in the most unfavorable situation due to the reduction in the concrete's effective cross-sectional area. Therefore, the column center is the most suitable area for core drilling under cyclic loading.

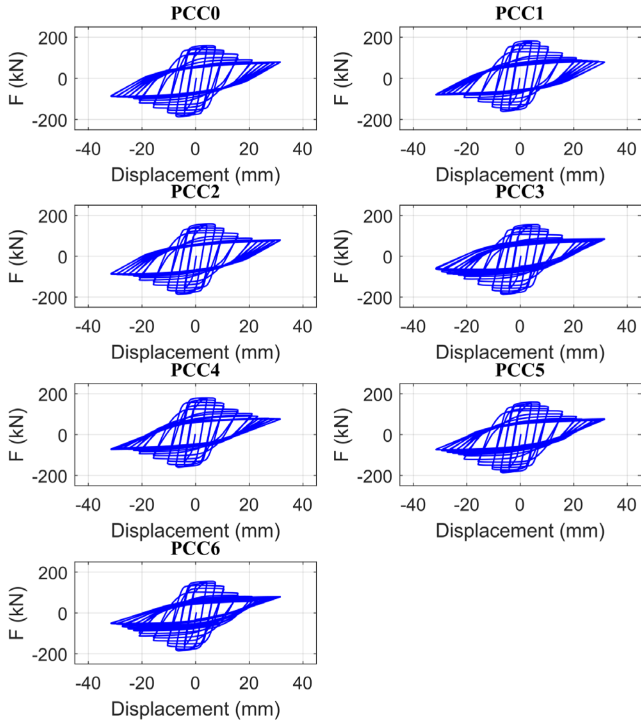
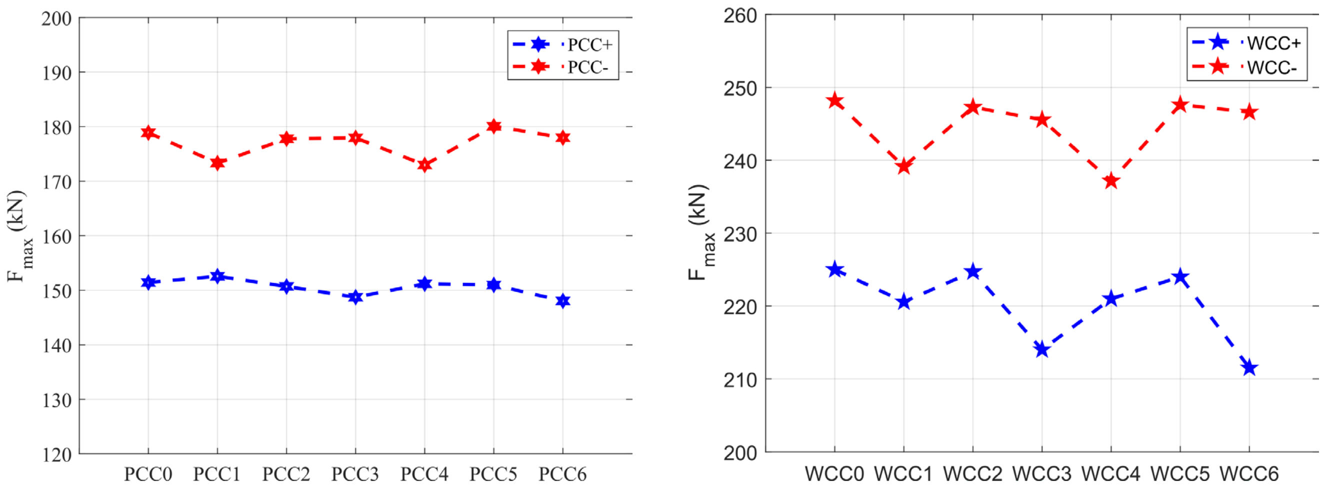
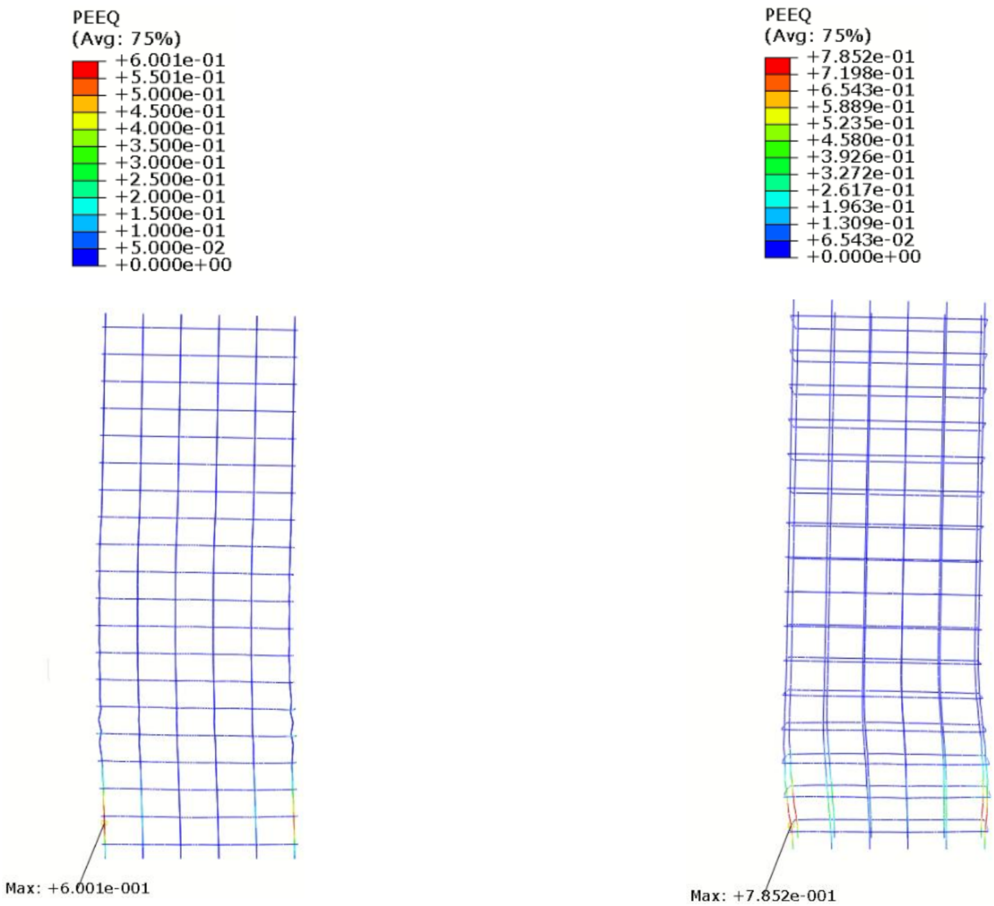


Fig. 13 Hysteretic loading curves for poorly confined columns



(a) (b)

Fig. 14 Absolute F_{max} values to according to direction: (a) PCC; (b) WCC



(a) (b)

Fig. 15 $PEEQ_{max}$ values undrilled column models: (a) WCC; (b) PCC

- The support area of the column is subjected to the greatest stress under cyclic loading. When the core hole location is sufficiently distant from this critical area, the core hole will not have a significant impact on the results. It should be noted that this distance may vary depending on the column's confinement conditions. However, since it is practically impossible to core from this critical area given the column's longitudinal reinforcement overlap area and stirrup density, the core location should be determined by considering the change in the column's axial load capacity.
- Based on the findings of this study and previous research conducted under axial loading conditions, the centroid of the column cross-section is recommended

as the optimal core location for symmetrically loaded columns. In contrast, for eccentrically loaded columns, the optimal core hole position is suggested to be within the middle third of the cross-section on the side opposite to the applied eccentric load.

In this study, results are presented for well and poor confinement conditions for a single column model with a specific cross-sectional area, and the evaluations are based on this model. This is a significant limitation of the study. The results obtained in this study should be supported by experimental or numerical studies covering column models of different sizes. Therefore, further studies should be conducted for eccentric loading at different axial load levels to obtain more comprehensive results.

Acknowledgements

The research in this paper was founded by Karabük University Scientific Research Projects Coordination (Project Number: KBÜBAP-25-DS-038).

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