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Numerical Analysis of Sectional Shape Effect on Behavior of Short Concrete Columns

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Abstract

This paper numerically investigates the effect of sectional shape on the structural behavior of short concrete columns when subjected to axial loading. Seven concrete columns that possess the same cross-sectional area, longitudinal reinforcement ratio, tie-bar diameter, and spacing are analysed via Abaqus software. The concrete compressive strength is equal for all columns. The loading is applied at the plastic centroid of the cross-section. The results show that the plus-shaped cross-sectional column sustains the highest load, while the T-shaped section bears the lowest loading. The plus-shaped, square, rectangular, and circular columns endure a higher loading than the T-shaped ones by 12.3 %, 10.7 %, 10.7 %, and 8.7 %, respectively. Concerning the longitudinal displacement, the T-shaped column exhibits the highest shortening, while the octagonal section shows the minimum shortening. Failure of all columns occurs due to the yielding of the longitudinal bars, followed by a fracturing of the concrete. All columns roughly show the same cracking load, while the T-shaped section exhibits a higher displacement than others at the cracking state, followed by an L-shaped column. However, all other columns show the same longitudinal displacement at the cracking load.

Keywords: short column, section shape, numerical analysis, loading capacity, longitudinal displacement.

الخلاصة

يتناول هذا البحث دراسة عددية حول تأثير شكل المقطع على السلوك الإنشائي للأعمدة الخرسانية القصيرة عند تعرضها لحمل محوري. تم تحليل سبعة أعمدة خرسانية تمتلك نفس مساحة المقطع العرضي ونسبة التسليح الطولية وقطر الاطواق ومسافة التباعد بينهم باستخدام برنامج اباكوس. كانت قوة انضغاط الخرسانة متساوية لجميع الأعمدة. تم تسليط الحمل على نقطة المركز اللدن للمقطع العرضي للعمود. أظهرت النتائج أن العمود ذو الشكل الزائد يتحمل أعلى حمل، في حين أن العمود على شكل حرف T يتحمل أقل حمل. وتتحمل الأعمدة ذات الشكل الزائد والمربعة والمستطيلة والدائرية أحمالاً أعلى من الأعمدة على شكل حرف T بنسبة ١٢,٣%، ١٠,٧%، ١٠,٧%، و٨,٧% على التوالي. فيما يتعلق بالإزاحة الطولية، يظهر العمود على شكل حرف T أعلى تقاصر، في حين يظهر العمود ذو شكل مثمن الحد الأدنى من التقاصر. حدث فشل جميع الأعمدة بسبب خضوع القضبان الطولية، تلاه تهشم الخرسانة. تُظهر جميع الأعمدة نفس حمل التشقق تقريبًا، بينما يُظهر العمود على شكل حرف T إزاحة أعلى من الأعمدة الأخرى في حالة التشقق، يليه العمود على شكل حرف L. ومع ذلك، تظهر جميع الأعمدة الأخرى نفس الإزاحة الطولية عند حمل التشقق.

1. INTRODUCTION

Short columns are widely used in facilities and often bear axial loading while sometimes sustaining bending due to eccentricity or lateral loading [1]. Columns are considered one of the most significant structural elements in structures because they carry the weights of all elements above them [2]. Therefore, their failure leads to the collapse of the entire construction [3]. Failure of short columns occurs due to material yielding either concrete crushing or rebar yield [4].

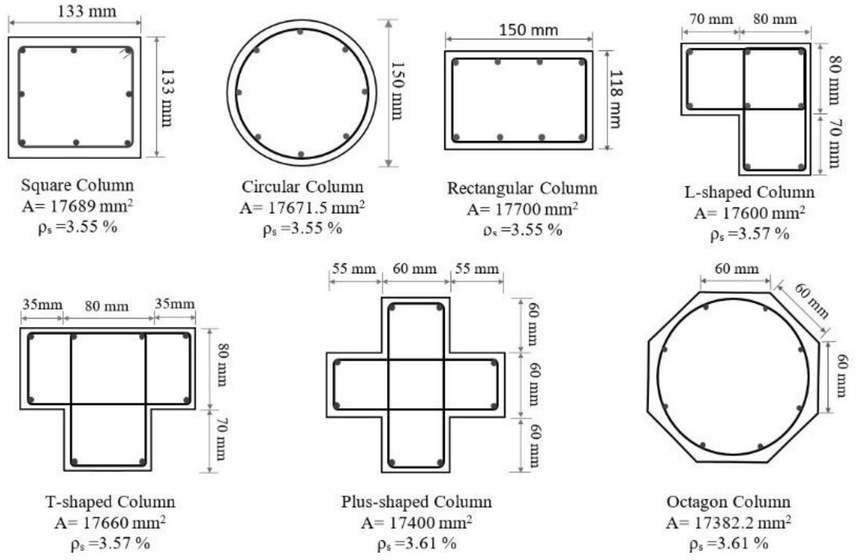
The behavior of the column upon loading depends on its cross-sectional area, concrete compressive strength, reinforcement ratio, and rebar-yielding stress [5]. The column shortens longitudinally and expands laterally upon subjecting to the axial concentric loads [6]. The lateral expansion may occur when the applied stress overreaches 70 % of the column loading capacity [7]. Upon reaching maximum loading, the longitudinal rebars tend to buckle in an outward direction [5]. Therefore, lateral ties are used to prevent buckling. The ties provide confinement for concrete [8]. When a short concrete column is subjected to compressive stress, the concrete expands laterally to sustain the tensile force, and longitudinal bars tend to buckle. The presence of lateral ties provides confinement to concrete that enhances its strength and prohibits the buckling of longitudinal bars [9]. The steel ties are activated when the concrete begins to expand laterally. Stress is transferred from the concrete to the ties. Since the resistance of steel is higher than the concrete strength, it resists those stresses and provides good confinement to the concrete in the core of the column.

The tie configuration depended on the shape and size of the column and the number of longitudinal bars [10]. Various column shapes could use in the facilities according to their locations and architectural design [11]. As mentioned earlier, column resistance depends on its cross-sectional area besides its related parameters. However, the effect of column section shape on load capacity requires inspection. Some research studied the influence of section shape on concrete-filled steel tube (CFST) columns subjected to concentric loading [12]. Almamoori et al. [13] found that the octagonal CFST column exhibited the highest compressive stress, followed by the plus-shaped CFST column. The L-shaped and T-shaped sections showed the lowest loading capacity comparatively. The authors used lightweight concrete to fill the steel tubes. Ibanez et al. [14] considered three cross-sectional shapes to use as CFST; circular, square, and rectangular. They adopted two concrete compressive strengths; C30 and C90. The results showed that the circular column exhibited higher load capacity than the other two shapes. However, square and rectangular columns sustained the same loads approximately. The CFST columns with normal-strength concrete provided more ductile behavior than high-strength concrete columns.

However, there are a lack of information on the efficiency of the sectional shape of reinforced concrete (RC) columns on its structural behavior. Thus, there is a need to study the forms of the column sections in terms of their ability to bear the applied loads and the mode of failure. This paper investigates the effect of cross-sectional shape on the loading capacity, longitudinal displacement, and crack pattern of RC short columns. All columns have an equal length and cross-section area and are equally reinforced longitudinally and transversely. The columns are numerically analyzed via Abaqus software. The changes are only in the shape of the cross-section of the columns. Comparisons are performed for cracking and maximum load, besides the corresponding longitudinal displacements, crack pattern, and rebar stresses.

2. RC SHORT COLUMNS SECTIONS

Seven cross-sectional shape short columns are adopted in this study to investigate their structural behavior under axial loading. The columns have approximately equal cross-sectional areas, as shown in Figure 1. The column is reinforced by eight longitudinal bars of 10 mm diameter. Steel ties of a 5.5 mm diameter are used as transverse reinforcement. Ties are placed at 110 mm spacing center-to-center, and the first and last ties are located 25 mm from the top and bottom of the column ends. The column length is 600 mm to ensure that the behavior is for short columns. The concrete cover is 10 mm in all directions. A single tie for each layer is used in square, circular, rectangular, and octagonal columns. While two ties for each layer are used in L-, T-, and plus-shaped columns.



Square Column
A= 17689 mm^2
ρ_s =3.55 %

Circular Column
A= 17671.5 mm^2
ρ_s =3.55 %

Rectangular Column
A= 17700 mm^2
ρ_s =3.55 %

L-shaped Column
A= 17600 mm^2
ρ_s =3.57 %

T-shaped Column
A= 17660 mm^2
ρ_s =3.57 %

Plus-shaped Column
A= 17400 mm^2
ρ_s =3.61 %

Octagon Column
A= 17382.2 mm^2
ρ_s =3.61 %

Figure 1. Cross-sectional shapes applied for columns

2.1. Experimental Data for Simulation columns

A practically implemented RC column was selected to capture the data required to simulate the adopted columns in this study. A column, performed by Razvi and Shaikh [15], has a (150 x 150) mm cross-section and 960 mm length, was longitudinally reinforced by 4 bars of 10 mm diameter having 460 MPa yield stress and transversely by 6 mm ties at 95 mm spacing between them with 360 MPa yield stress. The concrete cover was 10 mm, and the compressive strength was 32 MPa. The column was tested under axial concentric static load and showed longitudinal cracks when approaching the failure. The longitudinal bars reached yield, the concrete crushed, whereas the ties remained sound upon failure. The column experimentally recorded a failure load of 658 kN. It was simulated by Abaqus software. The simulated column approached the ultimate loading, where the maximum load was 676 kN. The data used to simulate this column was used for the columns adopted in this paper.

2.2. Numerical Simulation of Columns

The column components simulated in Abaqus include concrete, steel reinforcing bars, and steel plates that support the column at the top and bottom. The concrete column and steel plates are discretized into C3D8R elements. C3D8R is a 3-dimensional continuum element that has 8 nodes, where the node has 3 degrees of freedom with reduced integration [16]. The rebars are discretized by T3D2 truss elements which it has 2 nodes with 3 degrees of freedom per node. The rebars are assigned as embedded substances inside the host concrete region. The steel plates are constrained as rigid bodies to prohibit distortion upon loading. The lower supporting plate is designated as fixed support by preventing translation and rotation in all directions. The loading is applied at the upper steel plate. Displacement control loading is applied by subjecting downward displacement to capture the load at each increment in displacement. All constituents are seeded into 20 mm mesh size, as shown in Figure 2. The interaction between steel plates and concrete is chosen as a surface-to-surface contact in an initial step. Two contact properties are selected; tangential behavior with a friction coefficient of 0.45 and normal behavior with hard contact to prohibit the penetration between the two surfaces [17]. The analysis is performed using a static general step of loading.

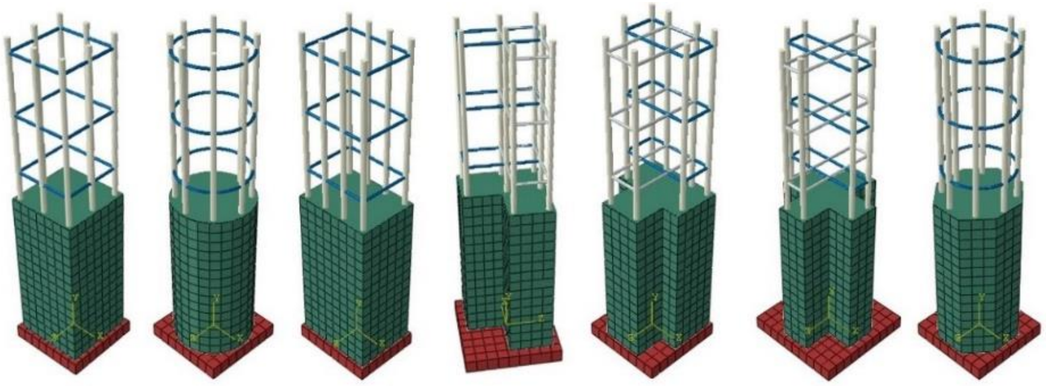


Figure 2. The meshing of column elements

2.3. Concrete Material Modelling

The concrete compressive strength used for columns is 40 MPa. The elastic behavior is simulated by the elastic modulus and Poisson's ratio. The concrete Damage Plasticity (CDP) model is applied to define the plastic behavior of concrete after cracking [17], [18]. Hognestad formula is adopted to explain the stress-strain relationship of concrete in compression, as shown in Figure 3. Euro code2-2004 [19] methodology is used to simulate the stress-inelastic strain of concrete, as described in the following equations:

$$f_c = 2f'_c\,[\frac{\varepsilon_c}{\varepsilon_{co}} - \left(\frac{\varepsilon_c}{\varepsilon_{co}}\right)^2] \qquad (1)$$

Where: f_c is the concrete compressive stress at the corresponding strain in MPa, ε_c is the concrete strain at compression, and ε_{co} is the strain at compressive strength.

$$E_c = 3320\sqrt{f'_c} + 6900 \qquad (2)$$

$$\varepsilon_{pl.} = \varepsilon - \frac{f_c}{E} \qquad (3)$$

$$d_c = 1 - \frac{f_c}{f'_c} \qquad (4)$$

E_c is the elastic Modulus of concrete in MPa. $\varepsilon_{pl.}$ is the plastic strain, and dc is the damage parameter. Table 1 illustrates the properties of concrete and rebars used to simulate the columns in Abaqus. The values of the parameters are derived from the simulation of the experimental column performed by Razvi and Shaikh [15].

Table 1 The properties of materials used to simulate the short columns in Abaqus

<table>
<tr><th>Material</th><th colspan="6">Properties</th></tr>
<tr><td rowspan="4">Concrete</td><td colspan="2"><i>Elastic modulus, Ec</i></td><td>27897.5 MPa</td><td><i>Poisson's ratio</i></td><td colspan="2">0.18</td></tr>
<tr><td colspan="2"><i>compressive strength</i></td><td>40 MPa</td><td><i>Tensile strength</i></td><td colspan="2">3.5 MPa</td></tr>
<tr><td><i>Dilation angle, ψ</i></td><td><i>Eccentricity ε</i></td><td colspan="2"><i>biaxial to uniaxial stress ratio, fbo/fco</i></td><td><i>Shape Parameter K</i></td><td><i>viscosity parameter μ</i></td></tr>
<tr><td>30 °</td><td>0.1</td><td colspan="2">1.16</td><td>0.67</td><td>1E-10</td></tr>
<tr><td rowspan="3">Steel rebars</td><td colspan="3">Diameter = 10 mm</td><td colspan="3">Diameter = 5.5 mm</td></tr>
<tr><td><i>Es</i></td><td><i>Yield stress</i></td><td><i>Poisson's ratio</i></td><td><i>Es</i></td><td><i>Yield stress</i></td><td><i>Poisson's ratio</i></td></tr>
<tr><td>200 GPa</td><td>500 MPa</td><td>0.30</td><td>200 GPa</td><td>350 MPa</td><td>0.30</td></tr>
</table>

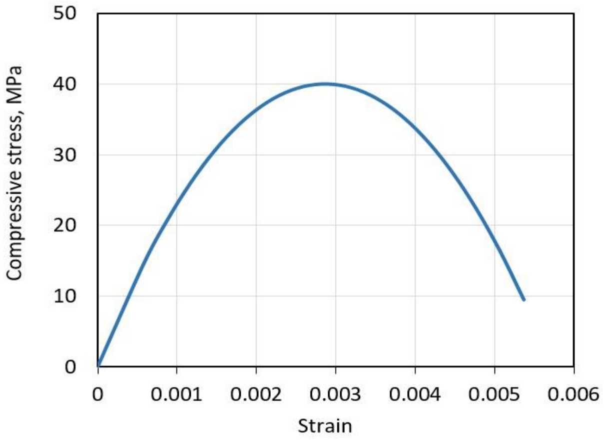


Figure 3. Stress-strain relationship of used concrete in compression

3. ANALYSIS RESULTS

The results of the FEA of columns are illustrated in Table 2. The results include cracking load (Pcr), a load of yielding of longitudinal bars (Py), and maximum loading capacity (Pu) along with the corresponding longitudinal displacement (Δ). It is meaningful to mention that all columns are simulated by Abaqus similarly to all parameters. However, the only change occurred in the shape of the cross-section of the column.

2.1.Effect of column cross-sectional shape on loading and longitudinal displacement

According to the analysis results and at the ultimate state, the plus-shaped column sustains the highest load, followed by the square and rectangular section columns. For comparison, T-shaped and L-shaped columns bear the lowest load, respectively. That result agrees with the findings of Almamoori et al. [13]. The plus-shaped column load was higher than the T-shaped column by 12.3 %. Square and rectangular columns sustained higher loading than the T-shaped ones by 10.7 %. A circular column load was higher than the T-shaped column by 8.7 %. At the first cracking state, whole columns sustained the same loading approximately, as shown in Figure 4.

Table 2 Analysis results of Short columns

Column shape	**First cracking**		**Yielding of long. bar**		**Ultimate state**	
	P_{cr} kN	Δ_{cr} mm	P_y kN	Δ_y mm	P_u kN	Δ_u mm
Circular	456.78	0.90	1007.30	2.42	1027.50	3.14
L-shaped	455.93	1.18	930.65	3.44	974.61	4.58
Plus-shaped	457.28	0.88	1017.29	2.48	1061.66	2.81
Rectangular	461.45	0.89	1033.84	2.65	1046.54	2.83
Square	462.36	0.89	1015.56	2.48	1046.76	2.84
T-shaped	448.73	1.64	918.64	4.82	945.37	5.66
Octagonal	453.86	0.89	1022.16	2.49	1031.92	2.75

Δcr = longitudinal displacement at cracking load

Δy = longitudinal displacement at yielding of bars
Δu = longitudinal displacement at ultimate load

Despite the same reinforcement ratio, cross-sectional area, and compressive strength, a variation in the maximum load occurs according to the column's cross-sectional shape. The reason may be due to the type of external confinement provided by the column's sectional form. That means the plus-shape, square, and rectangular sections provide better external confinement for columns than the T-shaped and L-shaped sections. While the octagonal and circular sections supply medium external confinement.

Concerning longitudinal displacement, the T-shaped and L-shaped sections show the highest shortening, respectively, followed by the circular shape. The T- and L-shaped column displacements were higher than the octagonal column one by 105.8 % and 66.5 %, respectively. The square, rectangular, and Plus-shaped column sections approximately show equal displacement where the variance was about 3 %, while the octagonal column recorded the lowest longitudinal displacement, as shown in Figure 5.

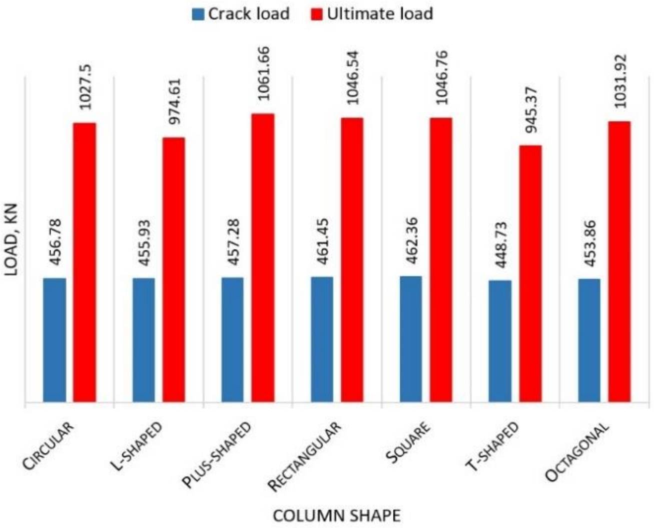


Figure 4. Loading capacity of columns according to the cross-section shape at cracking and ultimate state

The longitudinal rebars in all columns reached yielding just before arriving at the maximum load, which indicates that the failure occurred due to rebar yield before concrete fracture. On the other hand, all ties do not reach yielding at the ultimate state. For circular, Octagonal, rectangular, square, and plus-shaped columns, all longitudinal bars arrive at the yielding, while steel ties sustain about (70-80) % of yielding stress. In L- and T-shaped columns, the bars on the outer perimeter of long legs yield, while the inner bars sustain only 60 % of the yielding stress. The ties bear about 60 % of yielding stress. Figure 6 illustrates the stresses in the rebars of columns.

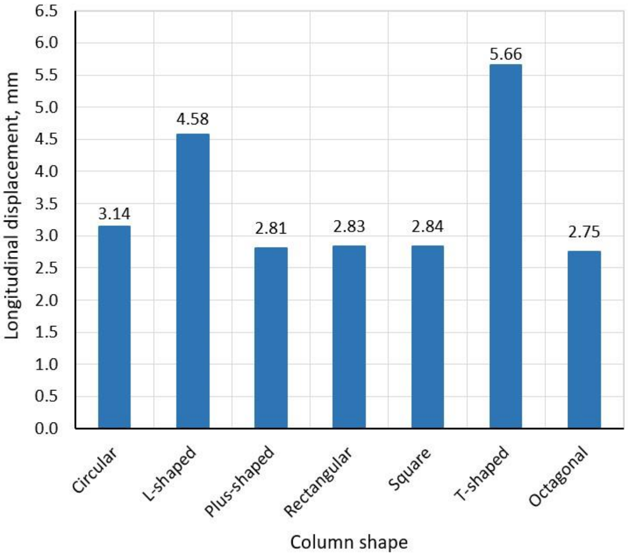


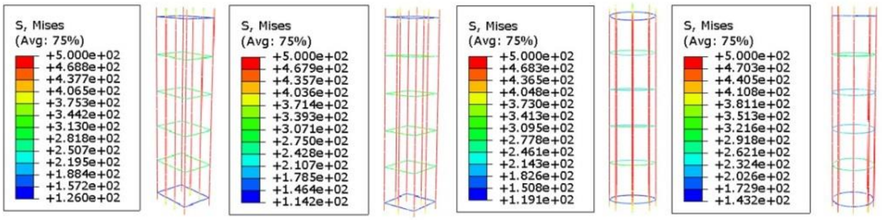
Figure 5. Longitudinal displacement of the short columns

3.2. Columns behavior under loading and Crack pattern

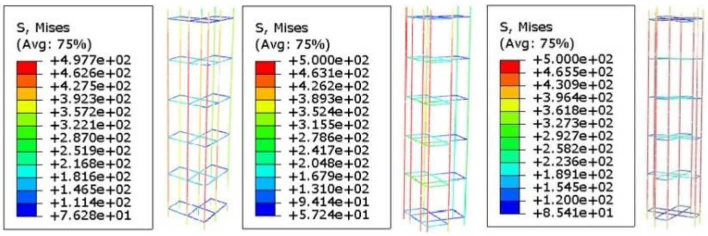
The first crack occurred at equal loading in all columns since the first crack in structures is related to the plastic state of concrete in compression and tension, which started at stress equal to 40% of the compressive strength or at the tensile strength. However, the columns recorded different displacements at the cracking state, where the T-shaped section recorded the highest shortening, followed by the L-shaped form. Other columns showed the same shortening. Then, the loading and displacement were altered according to the column shape.

In general, circular, square, rectangular, and octagonal columns showed the same behavior upon loading, while L and T-shaped columns exhibited different behavior. The square column failed without ductility, while all other columns exhibited ductile behavior upon loading, as shown in Figure 7.

The crack pattern of circular, rectangular, L, and T-shaped sections was similar at failure. The cracks extended near the lower support upward to about mid-length. The square and plus-shaped columns exhibited different patterns, where the cracks were focused at the middle of the column between the upper and lower quarter of the length. In contrast, the octagonal column presented different cracking. The cracks concentrated up to a quarter length near the upper and lower supports, as illustrated in Figure 8.



Rectangular Square Octagonal Circular



L-shaped T-shaped Plus-shaped

Figure 6. Stresses in longitudinal rebars and transverse ties

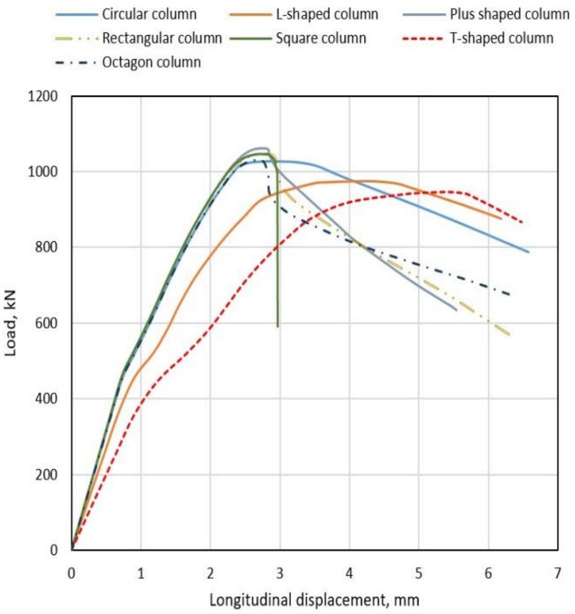


Figure 7. Load-longitudinal displacement relationship for columns

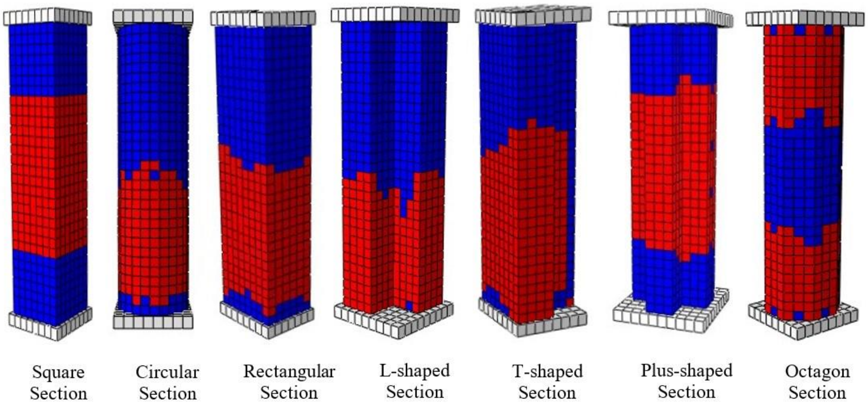


Figure 8. A crack pattern of short columns

4. CONCLUSIONS

This paper numerically studies the effect of section form on the short concrete column's behavior upon axial loading. Seven columns of similar cross-sectional area and reinforcement are analyzed via Abaqus software. The following conclusion can withdraw;

1) Despite the similarity, changes occurred in the maximum load due to the column's cross-sectional shape. The plus-shaped column sustained the highest load, followed by the square and rectangular columns, while T- and L-shaped columns bore the lowest load, respectively. At the first cracking state, all columns afforded equal loading approximately.

2) At peak state, the T-shaped and L-shaped sections showed the highest shortening, while the octagonal column recorded the lowest displacement.

3) The failure occurred due to rebar yield before concrete fracture in all columns.

4) Different crack patterns occurred in columns. In the octagonal column, the cracks focused up to a quarter length near the upper and lower supports, while in the circular, rectangular, L, and T-shaped sections, the cracks propagated near the lower support toward the mid-length. The plus-shaped and square sections showed cracks at the mid-length of the column.

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