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RESEARCH ARTICLE - ENGINEERING

Columns Cross-Section Shape Effect on Punching Shear in Reinforced Concrete Flat Slabs

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Abstract

Punching shear is one of the possible failures that must be taken into consideration in designing concrete slabs and foundations. Several factors control the occurrence of this failure mechanism, such as slab thickness, concentrated loads, and the cross-section area of the supporting columns. The cross-section shape of columns may also affect the punching shear in flat slabs. Therefore, this research was specified to study the effect of the columns' cross-section shape on the punching shear in flat slabs by conducting a simulation analysis for two multi-story concrete buildings with a flat slab but with different structural stability systems, building layout, and column distribution, where five cross-section shapes (square, rectangular, circular, hexagonal, and octagonal) were tested. ETABS 2016 software was adopted for modeling and analysis to identify the optimum column shape leading to minimizing punching shear. Although the cross-section area and the reinforcement area of the columns were fixed while changing the models' column shapes, it was found, in both buildings, that hexagonal columns performed better than others under punching shear and provided the lowest punching shear ratio. In contrast, circular columns gave the lowest resistance. Octagonal, square, and rectangular columns, respectively, follow the hexagonal columns in resisting punching shear.

Publisher: Middle Technical University

Keywords: Punching Shear; Column Shape; Flat Slabs; Punching Shear Ratio; Punching Check.

1. Introduction

A common type of slab is the flat slab, which has advantages like buildability, economy, ease, and speed of building. On the other hand, punching shear and deflection are flat slabs' primary downsides [1]. A local process of failure that results in creating a truncated cone shape produces punching. It has a fragile character because there are few warning signals when it arises, and without integrity reinforcement, it might cause the entire building to collapse gradually [2]. Several treatments can be adopted to reduce or avoid punching failure, such as increasing the cross-section area of the supporting columns, increasing the slab thickness, and using drop panels. Also, some research has been done on the effect of column shapes on punching shear. However, studying the effect of non-commonly used columns, such as hexagonal and octagonal columns, was not investigated and compared with other column sections in terms of punching. Therefore, this research studied the effect of changing the cross-section shapes of two multi-story buildings with different structural and stability systems, from rectangular and square columns to circular, hexagonal, and octagonal columns, keeping the same cross-section area of the columns and their reinforcement area and under the same loading and analysis conditions. The models were created and analyzed using ETABS 2016 software due to the availability of the slab design feature that was recently added to the software, starting from the 2016 version, which allows the researcher/designer to analyze and design slabs, including identifying the punching check, without having to use another program like SAFE. ACI 318-11 code was used to analyze the two models, and the analysis considered the wind and seismic loads, in addition to the dead and live loads. R. Joseph and P. Lakshmi studied the impact of column shape and compressive strength on punching shear stress in concrete flat plate systems in 2018. This analytical study examines how the shear stress at slab-column connections is affected by two parameters: concrete compressive strength and column shape. The study has also been done on the variance in shear stress at different flat plate column locations (corners, interior, and edges). The variance in column shape is discovered to induce variation in the shear stress at slab-column connections for flat plate systems with varying column shapes. When comparing square-shaped columns to rectangle-shaped columns, a shear stress reduction of about 15% is achieved. Additionally, shear stress is more intense at corner and edge connections than it is at interior connections [3]. In 2019, Lubnah Mohammed tested two methods to avoid punching shear in flat slabs; increasing the column dimensions and using drop panels. Two square flat slabs of 5m and 6m were examined, and the examination included interior, corner, and edge columns. Larger column dimensions can prevent punching shear failure in a flat slab, while a drop panel expands the critical shear parameter and prevents punching shear failure [4]. The impact of slab thickness and column dimensions on the punching shear stress in flat plate structures was reviewed by A. Zaib and S. Ahmad in 2020. The goal of this research was to investigate how the column dimensions and the slab thickness affect the punching shear stress that develops at the column slab joint. Different models with different dimensions were taken into consideration for this.

Nomenclature & Symbols			
C1-B2	Building No. 1 Column at Gridline B2	HC1	Hexagonal Column of Building No. 1
C1-B3	Building No. 1 Column at Gridline B3	OC1	Octagonal Column of Building No. 1
C1-C2	Building No. 1 Column at Gridline C2	SC2	Square Column of Building No. 2
C1-C3	Building No. 1 Column at Gridline C3	RC2	Rectangular Column of Building No. 2
C2-C2	Building No. 2 Column at Gridline C2	CC2	Circular Column of Building No. 2
C2-C3	Building No. 2 Column at Gridline C3	HC2	Hexagonal Column of Building No. 2
C2-D2	Building No. 2 Column at Gridline D2	OC2	Octagonal Column of Building No. 2
C2-F2	Building No. 2 Column at Gridline F2	D	Diameter
SC1	Square Column of Building No. 1	$D_{across\ flats}$	Diameter Across Flats
RC1	Rectangular Column of Building No. 1	Ø	Reinforcement Bars Diameter
CC1	Circular Column of Building No. 1		

The six-story flat plate reinforced concrete structures made up the model. Punching shear stresses at three places (corner, edge, and interior) of the column slab joint in flat plate structures were obtained after push-over analysis of the suggested models. Based on the aforementioned findings, it was inferred that the increase in punching shear is precisely proportional to the increase in column depth while keeping width constant. More so, it was seen that punching shear stress decreases as slab thickness increases, making the relationship between the two inverse [5]. In the same year, and per the Indian and international standards, F. Shukla and A. Shah reviewed the impact of slab thickness and column dimensions on the punching shear stress in flat plate structures. In this study, the shape of the columns Circular, L, T, and Cross was studied in Indian, American, European, and British codes to determine the impact these shapes have on punching shear stress. The 12 models considered varied panel sizes (5m x 5m, 8.33m x 8.33m, 5m x 8.33m), as well as the column shapes for a 10-story building while keeping the floor plan area constant (25m2). Based on an analysis of the structures, it was found that, while Eurocode 2 codes are more conservative, L and T-shaped columns are better suited to resisting punching shear stresses [6]. Additionally, a numerical simulation analysis using the ABAQUS program was conducted in 2022 by J. Xue, W. Zhang, J. Xu, Z. Yuan, F. Zhao, and C. Zhang, and the impacts of different parameters on the functionality of slab-column connections were researched. A more complex shear stress distribution and stress concentration phenomenon were observed to result from changing the shape of the column section. But compared to a comparable square column with the same section area, the column with the unusual shape had a larger punching capacity. Inverted T-shaped steel can successfully increase the ultimate bearing capacity of the connections as a new punching shear resistance measure [7].

2. Structural Modeling

Two buildings with different structural and stability systems were involved in this study. The first building is a simple four-story building with a flat slab with edge beams and regular column distribution (square-shaped columns), while the second building is a four-story building with a complete flat slab and irregular column distribution (rectangular section columns). The second building also contains various shapes of shear walls. The layout and 3-D view of the original two models adopted for this study are shown in Figs. 1 and 2.

Each of the two buildings was modeled and analyzed five times. At each round, the columns' shape is reconfigured, taking into consideration keeping the exact cross-section area and the reinforcement area to identify only the column shape impact on the punching shear capacity. In the first building, whose original columns were square, the columns were reconfigured into rectangular, circular, hexagonal, and octagonal cross-sections. On the other hand, the columns were reconfigured into square, circular, hexagonal, and octagonal cross-sections for the second building, whose original columns were rectangular. The columns' geometry and reinforcement details are shown in Tables 1 and 2. Also, Table 3 shows the material and section properties of the two models. To keep the exact reinforcement area in all rounds of analysis, non-common rebar sizes needed to be considered.

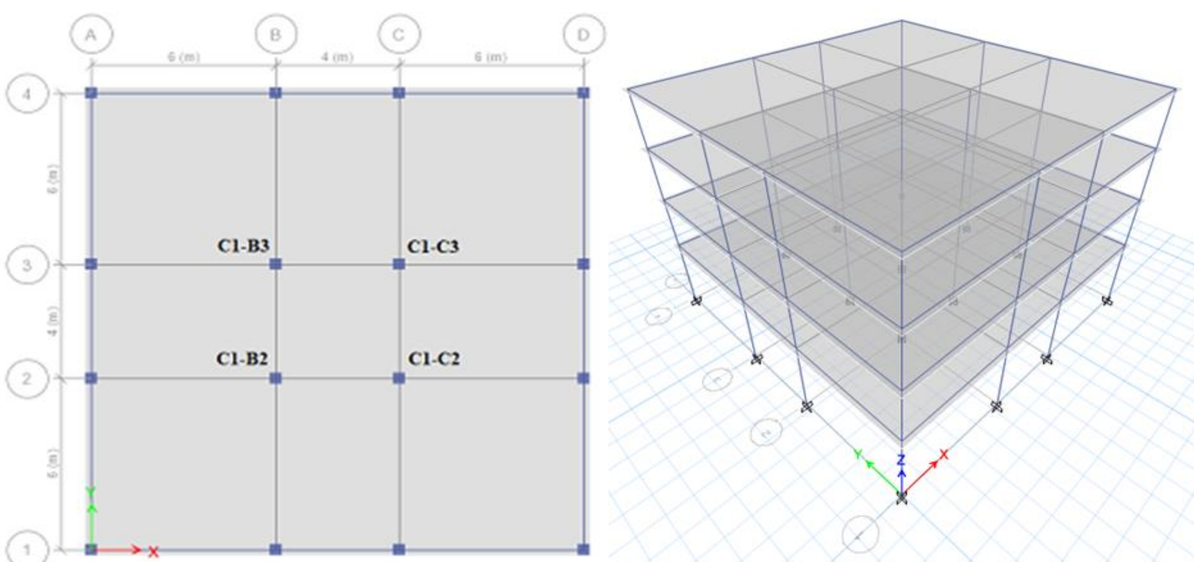


Fig. 1. Layout and the 3-D view of building No. 1

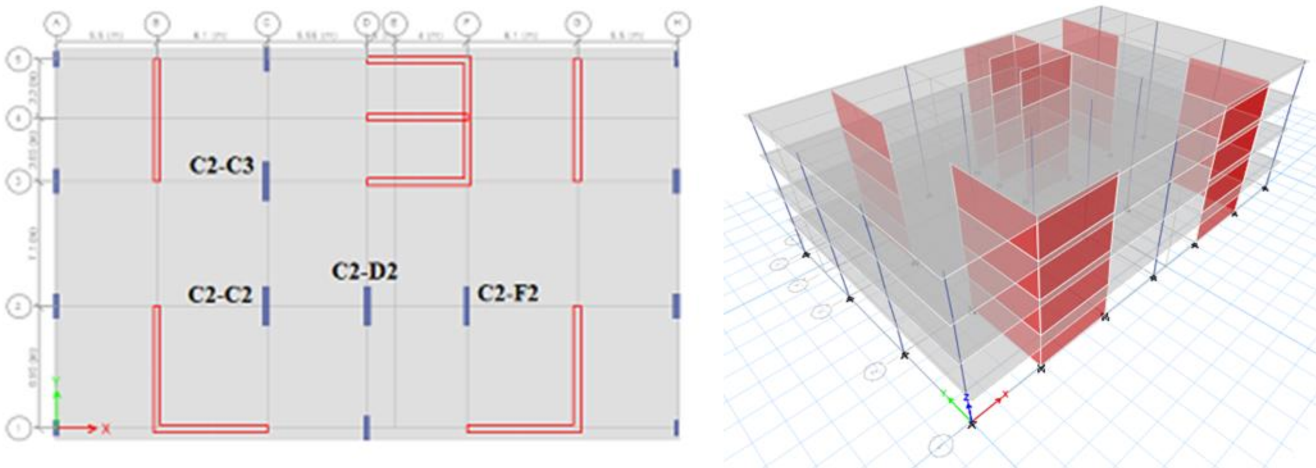


Fig. 2. Layout and the 3-D view of building No. 2

Table 1. Geometry and Reinforcement Details of Building No.1 Interior Columns

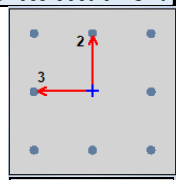
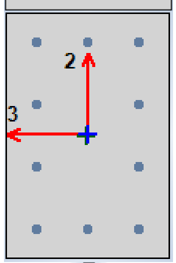
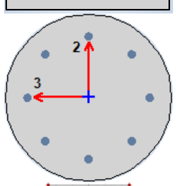
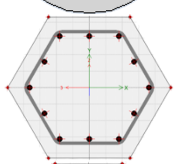
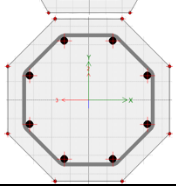
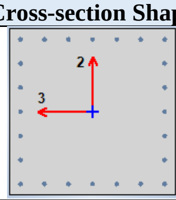
Column Code	Cross-section Shape	Cross-section Dimensions and Area	Reinforcement Details
SC1		400×400 mm ($160×10^3$ mm^2)	8Ø20 ($2.513×10^3$ mm^2)
RC1		492×325 mm ($159.9×10^3$ mm^2)	10Ø17.888 ($2.513×10^3$ mm^2)
CC1		D= 451.4 mm ($160.034×10^3$ mm^2)	8Ø20 ($2.513×10^3$ mm^2)
HC1		$D_{across\ flats}$= 429.8 mm ($160.05×10^3$ mm^2)	12Ø16.33 ($2.513×10^3$ mm^2)
OC1		$D_{across\ flats}$= 439.4 mm ($159.937×10^3$ mm^2)	8Ø20 ($2.513×10^3$ mm^2)

Table 2. Geometry and Reinforcement Details of Building No.2 Interior Columns

Column Code	Cross-section Shape	Cross-section Dimensions and Area	Reinforcement Details
SC2		948×948 mm ($898.704×10^3$ mm^2)	24Ø22 ($9.123×10^3$ mm^2)

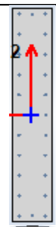
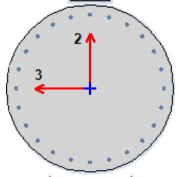
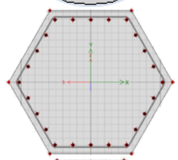
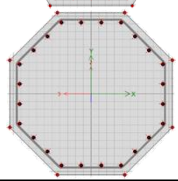
RC2		2250×400 mm (900×10^3 mm^2)	24Ø22 (9.123×10^3 mm^2)
CC2		D= 1070 mm (899.202×10^3 mm^2)	24Ø22 (9.123×10^3 mm^2)
HC2		$D_{across\ flats}$= 1018.4 mm (898.269×10^3 mm^2)	24Ø22 (9.123×10^3 mm^2)
OC2		$D_{across\ flats}$= 1043 mm (901.1×10^3 mm^2)	24Ø22 (9.123×10^3 mm^2)

Table 3. Design properties and loading details

Property	Value
Concrete compressive strength	25 MPa
Reinforcement modulus of elasticity	200 GPa
Slab thickness	200 mm
Dead load	2.2 kN/m^2
Live load	3.0 kN/m^2

ETABS 2016 software was adopted for this study, taking advantage of the Concrete Slab Design newly added tool that provides the punching check, avoiding the researcher using another software, such as SAFE, for slab design. Also, the section designer tool allowed the author to ideally configure the hexagonal and octagonal cross-sections for the columns, which is an excellent feature in ETABS. It's worth mentioning that the wind and seismic loads were involved in the analysis. Concrete of 25 MPa compressive strength and reinforcement of 200 GPa modulus of elasticity were used. Wind and seismic load details are shown in Figs. 3 and 4.

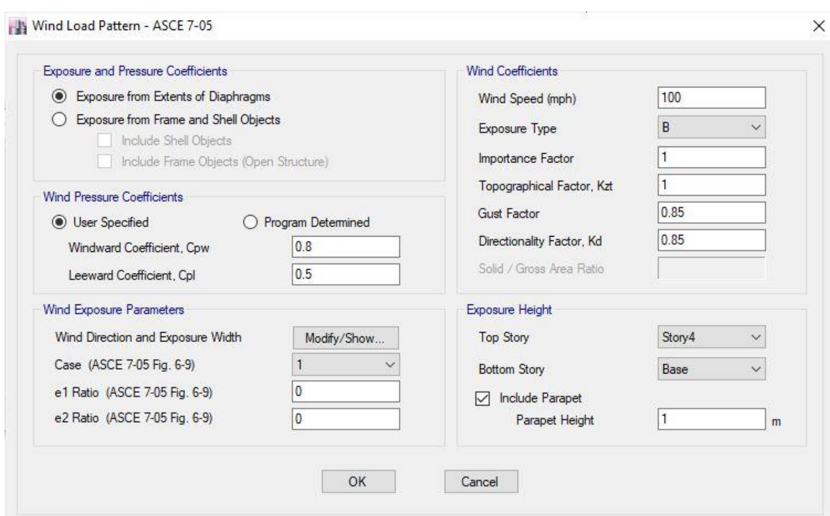


Fig. 3. Wind load pattern details

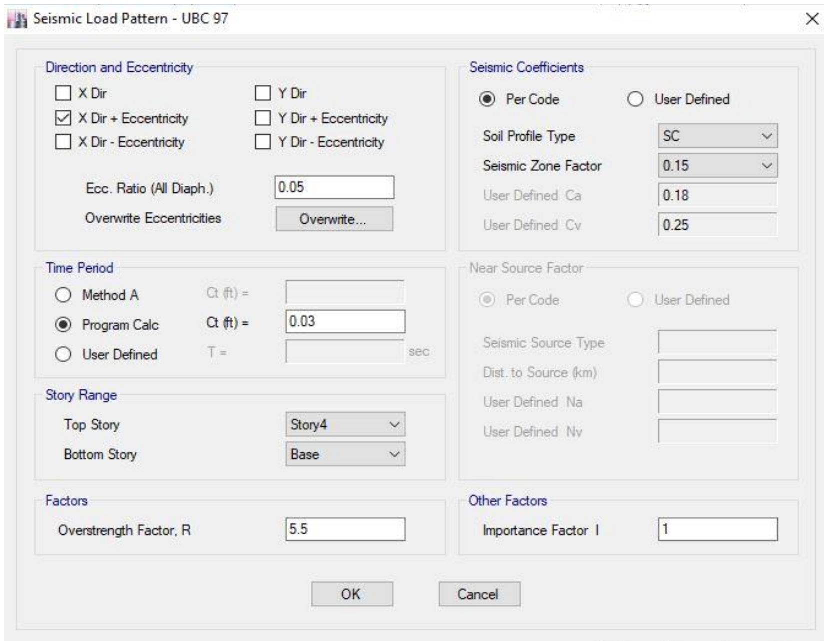


Fig. 4. Seismic load pattern details

3. Results and Discussion

The ACI 318-11 was the design code adopted for this research. Punching shear ratio values were obtained after the analysis and design processes. Figs. 5 and 6 are examples of the punching check and ratios obtained by ETABS. Punching shear ratios were displayed as a ratio of the maximum calculated shear concerning capacity. The results of the two models, including all stories, are shown in Figs. 7 and 8.

$$\rho=\frac{\sigma}{\sigma_o} \quad (1)$$

$$\sigma=\frac{V}{b.d} \quad (2)$$

Where:

ρ Punching shear ratio
σ Maximum calculated punching shear
σ_o Punching shear capacity
b Length of the perimeter
d Effective depth

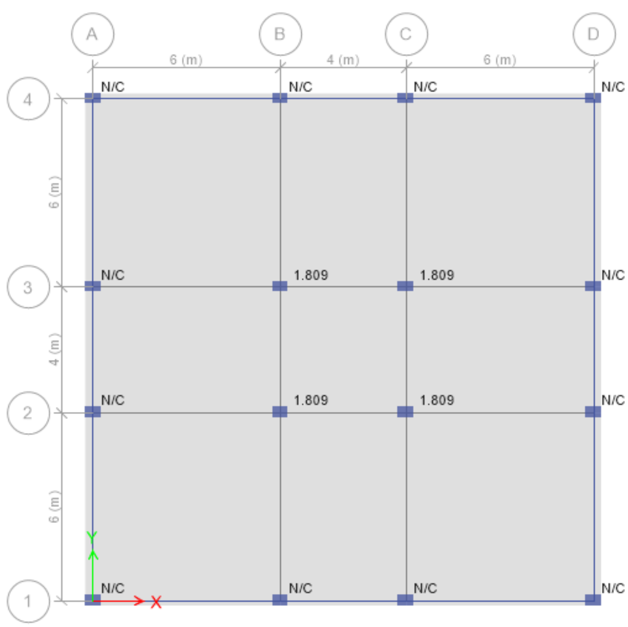


Fig. 5. Punching shear ratios of the rectangular columns – Story 1 – Building No. 1

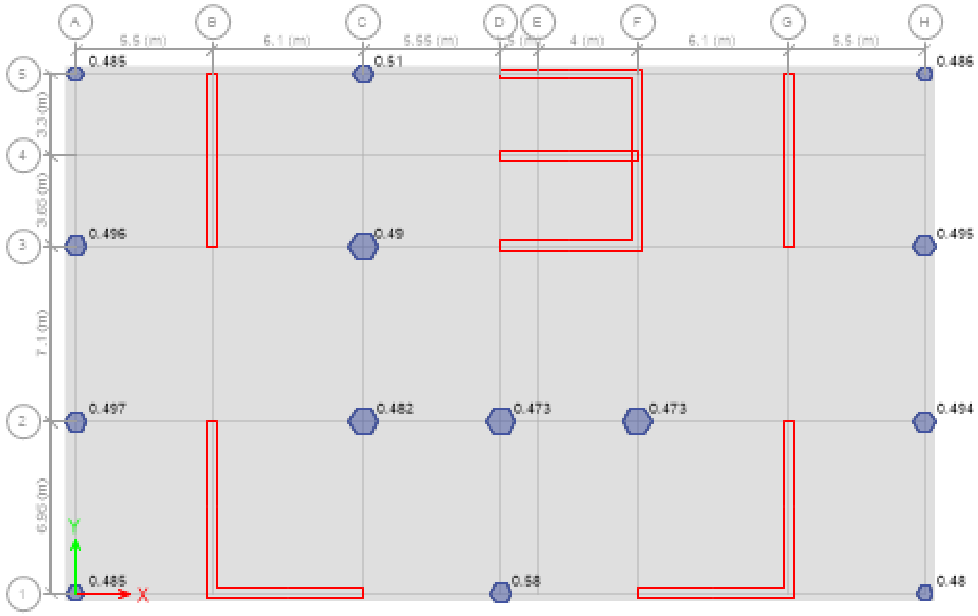
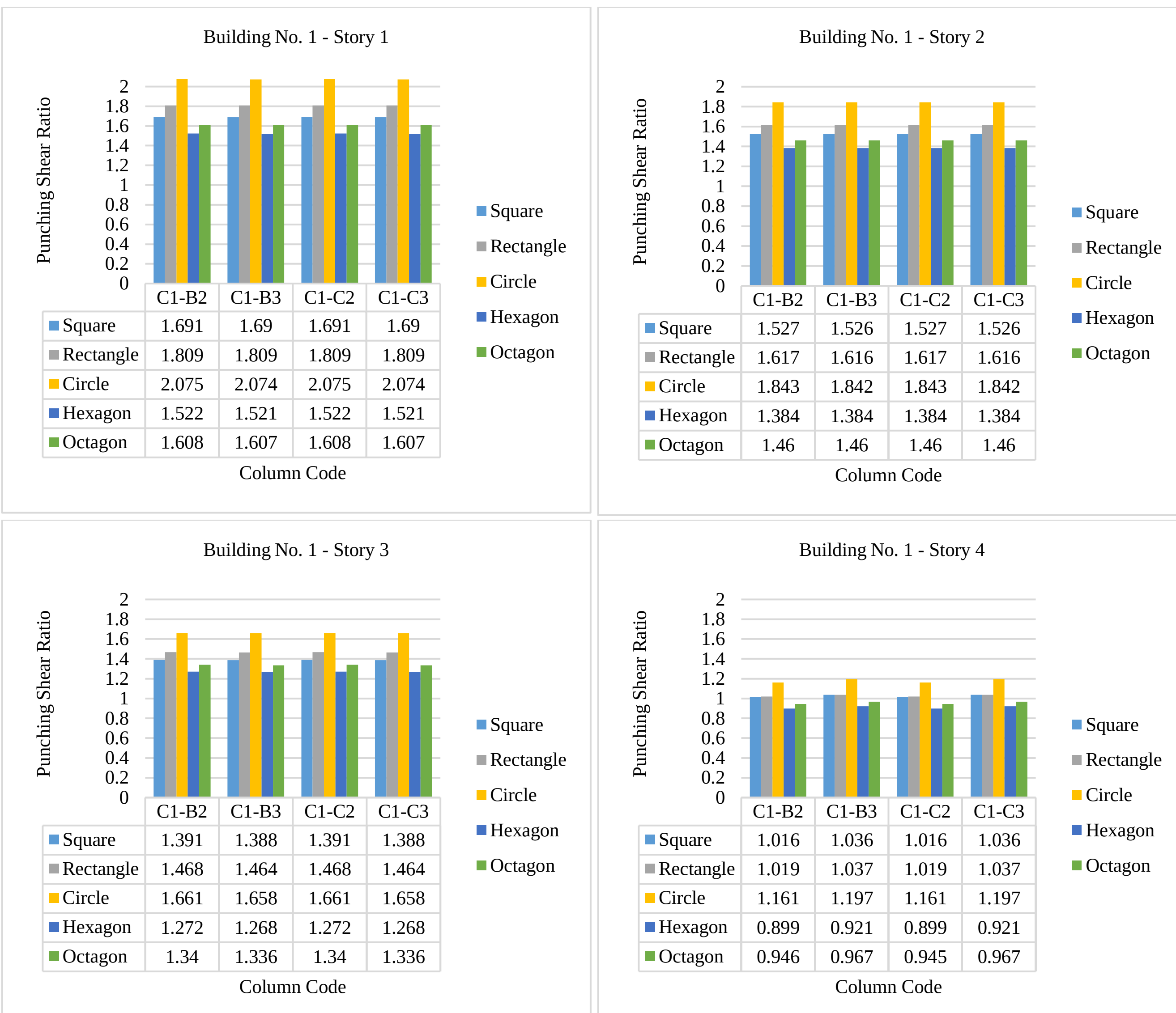


Fig. 6. Punching shear ratios of the hexagonal columns – Story 1 – Building No. 2



Building No. 1 - Story 1

	C1-B2	C1-B3	C1-C2	C1-C3
Square	1.691	1.69	1.691	1.69
Rectangle	1.809	1.809	1.809	1.809
Circle	2.075	2.074	2.075	2.074
Hexagon	1.522	1.521	1.522	1.521
Octagon	1.608	1.607	1.608	1.607

Building No. 1 - Story 2

	C1-B2	C1-B3	C1-C2	C1-C3
Square	1.527	1.526	1.527	1.526
Rectangle	1.617	1.616	1.617	1.616
Circle	1.843	1.842	1.843	1.842
Hexagon	1.384	1.384	1.384	1.384
Octagon	1.46	1.46	1.46	1.46

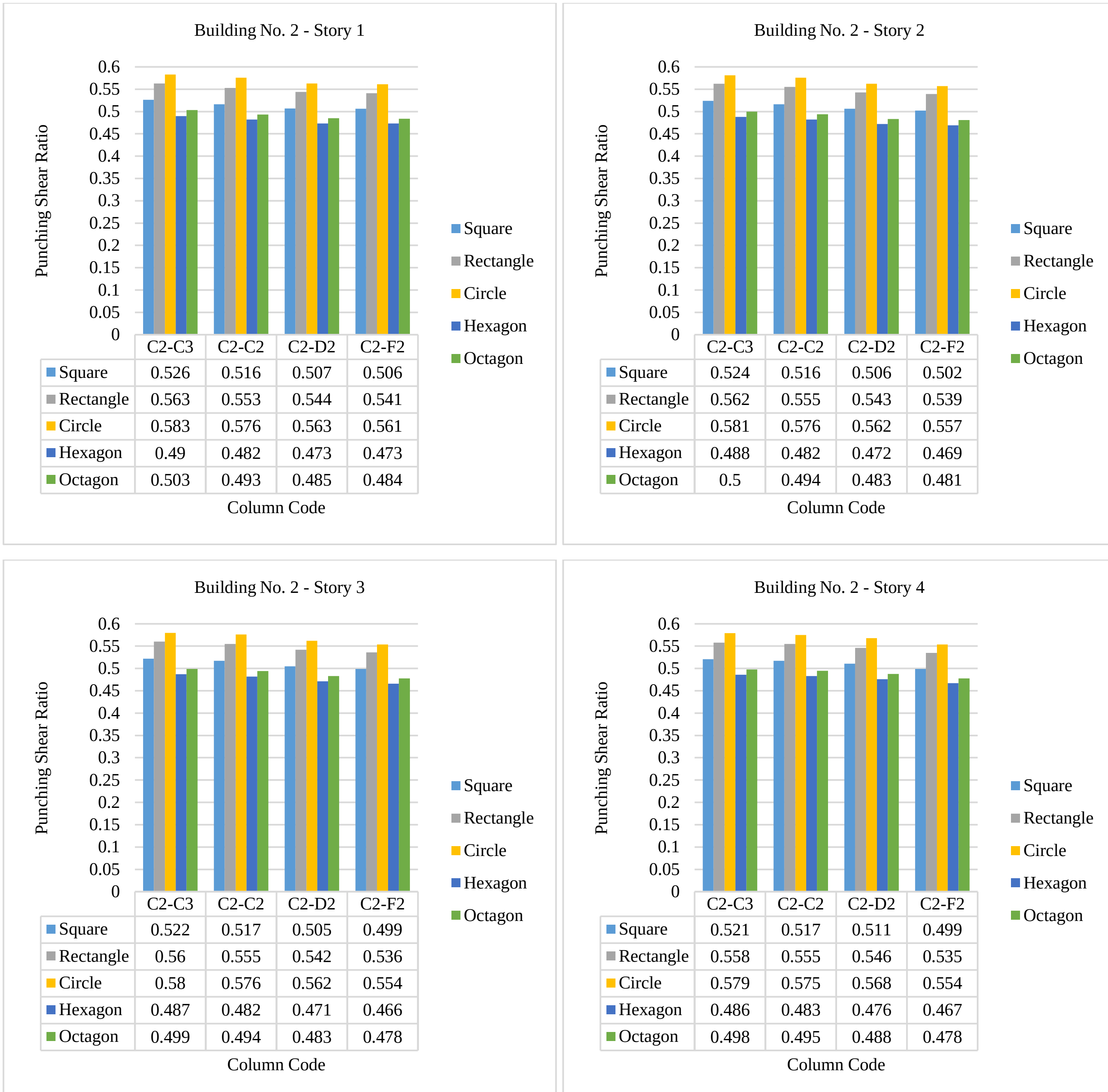
Building No. 1 - Story 3

	C1-B2	C1-B3	C1-C2	C1-C3
Square	1.391	1.388	1.391	1.388
Rectangle	1.468	1.464	1.468	1.464
Circle	1.661	1.658	1.661	1.658
Hexagon	1.272	1.268	1.272	1.268
Octagon	1.34	1.336	1.34	1.336

Building No. 1 - Story 4

	C1-B2	C1-B3	C1-C2	C1-C3
Square	1.016	1.036	1.016	1.036
Rectangle	1.019	1.037	1.019	1.037
Circle	1.161	1.197	1.161	1.197
Hexagon	0.899	0.921	0.899	0.921
Octagon	0.946	0.967	0.945	0.967

Fig. 7. Punching shear ratios of building No. 1



Building No. 2 - Story 1

	C2-C3	C2-C2	C2-D2	C2-F2
Square	0.526	0.516	0.507	0.506
Rectangle	0.563	0.553	0.544	0.541
Circle	0.583	0.576	0.563	0.561
Hexagon	0.49	0.482	0.473	0.473
Octagon	0.503	0.493	0.485	0.484

Building No. 2 - Story 2

	C2-C3	C2-C2	C2-D2	C2-F2
Square	0.524	0.516	0.506	0.502
Rectangle	0.562	0.555	0.543	0.539
Circle	0.581	0.576	0.562	0.557
Hexagon	0.488	0.482	0.472	0.469
Octagon	0.5	0.494	0.483	0.481

Building No. 2 - Story 3

	C2-C3	C2-C2	C2-D2	C2-F2
Square	0.522	0.517	0.505	0.499
Rectangle	0.56	0.555	0.542	0.536
Circle	0.58	0.576	0.562	0.554
Hexagon	0.487	0.482	0.471	0.466
Octagon	0.499	0.494	0.483	0.478

Building No. 2 - Story 4

	C2-C3	C2-C2	C2-D2	C2-F2
Square	0.521	0.517	0.511	0.499
Rectangle	0.558	0.555	0.546	0.535
Circle	0.579	0.575	0.568	0.554
Hexagon	0.486	0.483	0.476	0.467
Octagon	0.498	0.495	0.488	0.478

Fig. 8. Punching shear ratios of building No. 2

It is clear that building No. 1 is not qualified in terms of resisting the punching shear, and it needs a structural treatment to increase the punching resistance, such as increasing slab depth, expanding the column's cross-section area, using drop panels, …, etc. However, there is no harm in adopting the obtained punching shear ratios to identify the effect of column shape on punching shear, where the lower the punching shear ratio, the better. It was found that the punching shear on the upper floors is less than on the lower floors. This is self-evident because the more we go down toward the foundation, the more axial loads on the columns increase, which indicates that the modeling was done correctly. The punching shear ratios of building No.1 columns are almost the same in the same analysis round, which is logical because they all have the same dimensions, supporting equal segments of the slab, and the loads are equally distributed on them due to the symmetry of their positions relative to the slab. The slight variation in the readings is due to wind and seismic loads. In contrast, there is an apparent variation in punching shear ratios of building No. 2 columns for opposite reasons. Each column supports a different slab area due to the different span lengths, resulting in a different amount of load for each column.

4. Conclusions

Through the results shown in Figs. 7 and 8, we notice that the column of the hexagonal cross-section gave the higher punching shear resistance, while the columns of the circular section gave the highest punching shear ratio. Octagonal, square, and rectangular columns, respectively, follow the hexagonal columns in terms of their preference for punching shear resistance. It is noticeable that the variation in the punching shear ratio among the five shapes of columns in building No. 1 is higher than that in building No. 2 as the difference in punching shear ratio between the circular column and the hexagonal column doesn't exceed 9.4% for the second building, while it reached 55.3% in the first building, which might be due to the different structural and stability systems of the two buildings and the layout and column distribution of the two buildings. The configuration of shear walls has a significant effect on structural behavior [8].

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