Different configurations of cores and shear walls in tall buildings

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Abstract. A core system for buildings has been recognized as an effective tool for managing the response of the building when an earthquake happens by decoupling the building structure from potentially damaging earthquake-induced forces. A challenging issue in this context is the application of the configuration of the core system. A review of recent studies shows that the configuration of cores has not been substantial investigated. This study presents seismic design concepts in which different configurations of cores are applied to a building. Nine steel buildings were modeled with rectangular core, octagon core, circle core, lozenge core, cross core, multi core, irregular core 1, and irregular core 2. All structural models are subjected to components of the 1940 El Centro earthquake and are evaluated and compared with the response of a structure without core. All models were also compared with and without opening in cores. The performance of the structural models under seismic excitation was evaluated by conducting linear dynamic time history analysis. Seismic results are investigated in terms of joint displacement and structure internal member forces. Results show that the presence of irregular core 1 significantly reduces the seismic response of the structure in this plane.

1. Introduction
Tall structures have always been admired by humans since ancient times. Meanwhile, earthquakes happen several times a day in different parts of the earth. Oliveto¹ reported that, almost earthquakes 10000 happen every year, around 60 of them lead to noticeable damages.

The design of tall structures is based on four criteria, namely, strength, serviceability, stability, and human comfort. Nevertheless, these circumstances governing how to design tall buildings are always human comfort and maximum space between columns. The effect of oscillatory movement results in an extensive chain of responses in the structure and its occupants when lateral loads are applied to a tall building. The selected structural system has to be sufficiently strong to endure anticipated loads without failure and sufficiently stiff to resist lateral movement and horizontal load-induced motions within boundaries with smallest expenditure. Cores and shear walls are used in multistory buildings as horizontal resistance elements against wind or seismic load.

Anshuman et al.² worked on solving the problem of how to use a shear wall in a multistory building considering the elastic and elastoplastic behavior. Mohr et al.³ used experimental testing and numerical simulation to investigate the performance of coupled shear walls that are representative of
current design practices. Many studies considering different core wall arrangements, such as perforated shafts and no planar walls attached through girders have been conducted. Reinforced concrete (RC) core walls are commonly used in modern building construction as the primary lateral load-resisting system.

Firoozabad et al.\textsuperscript{4} investigated about shear wall usage and results in seismic performance of buildings. The top story displacements compared to investigate the result of shear wall usage on seismic performance of structures. All designs checked with IS codes, and SAP 2000 software was used to design their performance. Authors concluded that; different position of shear walls can reduce the top story drift at least twice and the quantity of shear walls cannot guarantee the seismic behaviour of buildings.

Anshul Sud et al.\textsuperscript{5,6} studied a five-story RC building with five different configurations of shear walls. They were analysed for seismic excitation for evaluation them in base shear, storey displacement, member forces and joint movements. There was a major drop in lateral displacement in the frame with shear wall at core and centrally in exterior. There was just 70% to 85% decrease in bending moments for interior and perimeter columns correspondingly. Shear and axial forces in columns had declined by 86% and 45% respectively. In this study the best place for shear wall was recommended.

Considerable research has been conducted on structures equipped with cores to mitigate seismic vibrations. However, information on different configurations of structures and its response to earthquakes is lacking. The development of data processing, standards, and software would provide more valuable information for future analyses and designs of tall buildings.

The focus of this article is to investigate the response of tall buildings with different types of core configurations and to identify the efficient core system for tall buildings subjected to vertical and lateral loads. In this study, a 25-story 3D structure without core and with eight different types of core systems was modeled and subjected to components of the 1940 El Centro earthquake. The time history seismic response of the structure was determined. The displacement, axial force, shear force, and moment force of the structure were compared and evaluated.

2. Structural developments in tall buildings

Structural developments in tall buildings have been rapidly increasing worldwide. Ali and Moon\textsuperscript{7} reviewed the evolution of the structural systems of tall buildings and the technological driving force behind tall building developments. This review paper focuses on the conventional method like such as outrigger systems, diagrid structures, and auxiliary damping.

In 1969, Fazlur Khan classified the efficiency of the structural system of tall buildings, as shown in Fig1.\textsuperscript{8-10}
Ali and Moon\textsuperscript{7} presented a general review of the structural systems of tall buildings. A system-based broad classification has been proposed. Various structural systems with emphasis on innovations have been described.

From past records of earthquakes, we observed a raise in ordering for the resistance structure against seismic excitation it may happens by using the shear wall in structures. Chandiwala\textsuperscript{11} investigated about the moment force at specific columns; consist of seismic load, by considering various lateral load-resisting systems. Various numbers of story, with distinct shear walls positions for zone III EQ in India, has been studied. It can be concluded that the best place to implement option I shear wall at the end of L section. Mehair Yacoubian et al.\textsuperscript{24} investigated about the effect of the podium in high rise and tall building and he revealed that it can make a huge difference. Daniel Moroder et al.\textsuperscript{25} also did some experimental test about the pres-Lam core walls and showed that there was very little difference in terms of general result although there was high influenced by friction which had been produced between panels.

Hameed et al.\textsuperscript{12} investigated tall buildings with 16 different seismic excitation structural subsystems, which have used the entire world. Analysis reveals that the structures with composite super columns by portal subsystem are the most best and economical system.

Kyoung Sun Moon\textsuperscript{13} investigated the finest design of currently common tall buildings. The tall building system with perimeter diagonals, consisting of braced tubes and the new developed diagrids, are comparatively checked to the best design. The structural effectiveness of outrigger system, which based on the numbers and positions of trusses, was investigated and reported by Smith and Coull.\textsuperscript{14}

Tall buildings will be made since they are economic. Choosing the best system for a tall building is the most important step in a project. The efficiency of the structure is highly depends on the design of it.

Anshuman et al.\textsuperscript{2} investigated and determined the solution for shear wall location in multistory buildings. The earthquake load, shear forces, bending moment, and story drift applied to a building of 15 story in zone IV were computed. Elastic and elastoplastic analyses revealed that the best performance in shorted direction top deflection was for the usage shear walls in the 6th and 7th frames and 1st and 12th. Other studies showed that the inelastic performance was minor. In mid-rise to high-rise buildings the coupling beam must be all required significant yielding members in component system. Lehman et al.\textsuperscript{15} concentrated on concrete walls and conducted many tests on these kind of walls. The results were used to evaluate and verify the system. In their studies they found out that yielding happened in the coupling beams and wall piers, not in the same way they designed. wide damage in the compression pier, consisting of concrete core damage and bar buckling, cause an unstable and sudden failure at 2.27% drift that lead to in reduce the lateral and axial capacities. 5% was the maximum end rotation. The maximum axial capacity after termination of the lateral load was 0.48Agf'c.

Mcginnis et al.\textsuperscript{16} discussed about the reinforced concrete coupled shear wall designing and tests. They widely used unbounded posttensioned floor slab in RC coupled shear wall. In this study, we expand the multi-story by utilizing 2 C-shaped shear. Designing were verified by testing the 15% scale test in the laboratory. Mcginnis et al.\textsuperscript{16} compared the test result with the predicted design model. The experimental and design prediction behavior matched well.

There is a significant coupling in tall core wall system between the core and gravity framing. Therefore, studies have been shown to evaluate the importance of this coupling.\textsuperscript{17} Orakcal and Wallace\textsuperscript{18} decreased the data just in lateral load versus displacement for flexure and shear. They also omitted the test wall foundation and strong floor. Based on the review conducted by Sarkisian et al.\textsuperscript{19}, the next results are noted.

Earthquake engineering problems and earthquake-resistant design have undergone remarkable development. Building codes to which ordinary building designs are based have also developed remarkably, particularly in the case of resistant construction structures, through stringent requirements to achieve high ductility.
Core systems are widely used in tall buildings. One of the advantages of the core is that they have high in-plane stiffness and strength, which it can be utilized to resist large horizontal loads and support gravity loads in the same time, making them quite beneficial in many structure designs. In this study, a 25-story building structure is modeled as a 3D structure in SAP2000 software.

3. Vertical distribution of lateral force

Current codes for seismic and EQ loads are mainly based on first-mode dynamic solution of lumped multiple-degree-of-freedom elastic systems, it could be expressed as follows: 20-23

\[ F_i = V_i \left( \frac{n_i \psi_i}{\sum_{i=1}^{n} n_i \psi_i} \right) \]  

(1-1)

Where \( F_i \) shown as lateral load force in level \( i \); \( V_i \) exposes the base shear first-mode; the lumped seismic weight at the \( i \)th level is shown by \( w_i \); and \( \psi_i \) is the amplitude of the first mode at the \( i \)-th. The lateral force distribution in first-mode deflected shape of elastic lumped mass which was based on dynamic excitation in code shown as follow:

\[ \psi_{i1} = \frac{h_i^L}{L} \]  

(1-2)

The total height of the structure is shown by \( L \); height of level \( i \) above the foundation and base level is shown by \( h_i \), with \( k \) is fundamental period of the building. Studies in elastic response revealed that in buildings when the foundamental period is 0.5 or less than that the first-mode shape is near to a straight line (\( k = 1 \)) and it would be near to a parabola (\( k = 2 \)) when the fundamental period is 2.5 s or longer. The following code lateral force distribution was written:

\[ F_i = C_{V_i}V \]  

\[ C_{V_i} = \frac{V_i}{\sum_{i=1}^{n} V_i} \]  

(1-3)

the lateral force applied at level \( i \) is \( F_i \). \( C_{V_i} \) is shown as the vertical distribution factor; the total design base shear is \( V \), which replaces \( V_i \) since it is the dominant part of the total force \( V \); \( w_i \) and \( w_j \) are the total effective seismic weights at levels \( i \) and \( j \), respectively; \( h_i \) and \( h_j \) are the heights of level \( i \) and \( j \) from the ground, respectively; and \( n \) is the number of stories. For structures with natural period between 0.5 s and 2.5 s, \( k \) is determined by linear interpolation.

3.1 Shear wall and core in tall buildings

The primary function of shear walls and cores is to resist lateral loads. Shear walls fulfill their lateral load-resisting function by vertical cantilever action. Shear walls and core structures are generally quite stiff, and interstory displacement situations are uncommon and usually simply contained. At the base of the wall core and shear wall would may works like a rigid body rotating around a plastic hinge. Thus, generally deformation in a structure is a result of wall rotation. Interstory drift problems, mostly happening in first few floors.

In this study, an attempt has been made to evaluate the effectiveness of different shapes of cores on the performance of the structure against imposed loads. For this purpose, eight different configurations of cores are considered, namely, rectangular core, circle core, cross core, lozenge core, octagon core, irregular core 1, and irregular core 2, are applied to a 25-story building. In this study, another attempt has been made to evaluate the maximum displacement of two types of cores. The first group consists of buildings without opening in cores, and the second group consists of buildings with opening in cores.
A 25-story steel frame structure is modeled, as shown in Fig. 2. The height of each story is 3.2 m, for a total height of the building at 80 m. The plane area of the building is 42 m × 42 m.

![Figure 1. A 25-story building.](image)

This structure is considered for evaluation of its elastic response under earthquake excitation, which is equipped with core systems. The geometric sections and material properties are considered similar to compare the earthquake excitation response of different building models. Floors are solid slab concrete. The thickness of each slab was 180 mm. The entire beams were characterized as IPE200. Column type was characterized as tube section with different sections for every five floors (Table 1).

| Column type | C1               | C2               | C3               | C4               | C5               |
|-------------|------------------|------------------|------------------|------------------|------------------|
| Tube section| 360 × 180 × 10    | 340 × 240 × 12   | 340 × 170 × 12   | 320 × 220 × 12   | 320 × 160 × 12   |

Shear wall material was characterized as thin shell-type with 400 mm membrane and bending thickness. Live load of 1.4 kN/m² and dead load of 4 kN/m² were applied to each floor of the structure. Different core models of the structure are shown in Fig. 3.
Figure 1. Structures with different shapes of cores.

3.2 Pushover analysis and time history analysis

The pushover analysis is controlled by using the monastically rising the lateral loads, which shows the inertia forces to the nodes having mass in the available seismic direction, the gravity load is subjected to ground movement. The main aim of pushover analysis is to predict the “capacity curve,” which represents the relation between roof displacement and base shear.

Time history is one of the techniques to analysis and design of tall buildings. Modern seismic codes, such as EUROCODE and ASCE, propose the linear time history analysis. The most accurate method of modeling the seismic response of a tall building, nonlinear time history analysis, is computationally demanding. As such, nonlinear time history analysis supposes to be impossible in the optimization of tall structures.

In this study, the 1940 El Centro earthquake was used as lateral excitation and subjected to structure in all principle axes to consider as an earthquake on the model.

4. Results and discussion

Most building codes recommend two methods for the analysis of buildings subjected to seismic loads, namely, static and dynamic analyses procedures. Dynamic analysis is used as the evaluation of seismic excitation response and is especially more precise than static analysis in terms of computational effort and interpretation of results.

The time history response of structure is simply the response of the structure evaluated as a function of time, including inertial effects. Analysis is conducted using the finite element SAP2000 software to evaluate the response of the steel structure under earthquake excitation.
4.1. Comparison response of a structure with rectangular core and without core subjected to the El Centro earthquake

Fig. 4 shows the displacement of the right top node subjected to earthquake excitation in the X(horizontal) and Y(vertical) directions. Displacement in the X- and Y-directions is reduced on the structure with rectangular core. The reduction is 59% and 58% for the X- and Y-directions, respectively.

![Graph showing displacement comparison](image)

**Figure 4.** Displacement in the X- and Y-direction responses of the top node of the structure.

The variation of internal force magnitude during earthquake excitation for a structure without core and with rectangular core is compared in Fig. 5. As shown in the graph, a significant reduction of axial force from a structure without core to a building with rectangular core was observed. Axial force value is reduced by 38%.

As shown in Fig. 5, the earthquake-induced shear force to the left lower corner column is effectively reduced by using a rectangular core. The major shear force magnitude is reduced by 82%. Earthquake excitation often induces devastating forces that can severely damage a structure, such as bending moment envelopes that are produced during earthquakes and are subsequently transmitted to a fixed support structure.

![Graph showing force comparison](image)
Figure 5. Internal force of the left lower corner column of the structure.

Fig.5 shows how a rectangular core applied to a structure efficiently reduced the moment. The rectangular core system reduced the major moment by 90% as compared with a structure without core. The same reduction trend for displacements and internal forces was observed with different types of cores.

a. Effect of the shape of cores on the displacement of the top nod

Table 2 and Fig.7 show the percentage of the reduction values of the displacement amplitude of the top nod subjected to the El Centro earthquake. The 25-story structure displacements during earthquake excitation are reduced from 563 mm to 142 mm and from 479 mm to 148 mm in a structure equipped with irregular core 1 in the X- and Y-directions, respectively.

Maximum horizontal peak displacement at all floors is shown in Fig.6. Evidently, displacement in structures equipped with cores is reduced to a considerable amount when compared with a structure without core. The high reduction is due to the displacement throughout the different configurations of cores.

b. Effect of the configuration of cores on internal force

Table 3 and Fig.8 show the percentage of the reduction values of axial force, shear force, and bending moment on the lower left corner column of the structure with maximum effective load combination and equipped with different shapes of cores.

Table 2. Percentage of reduction of displacement.

| System         | Max X displacement | Reduction (%) | Max Y displacement | Reduction (%) |
|----------------|-------------------|---------------|-------------------|---------------|
| Without core   | 563               | –             | 479               | –             |
| Rectangular core| 230               | 59.14         | 183               | 61            |
| Octagon core   | 240               | 57.37         | 177               | 63            |
| Circle core    | 196               | 65.18         | 150               | 68            |
Table 3. Percentage of reduction of internal force at the lower left column.

| System       | Max axial (kN) | Reduction (%) | Max moment (kN·m) | Reduction (%) | Max shear (kN) | Reduction (%) |
|--------------|----------------|---------------|-------------------|---------------|---------------|---------------|
| Without core | 9,411          | –             | 139               | –             | 87            | –             |
| Rectangular  | 8,571          | 8.92          | 27.48             | 80.2          | 12.4          | 85.7          |
Fig. 8 shows a chart of the peak internal force of the lower left column for all nine models. The chart shows that the moment of the lower left column was reduced to a considerable amount in a structure installed with irregular core 1 when compared with a structure without core.

| Core Type   | Axial Force | Shear | Moment |
|-------------|-------------|-------|--------|
| Octagon core| 8,615.1     | 8.45  | 16.4   | 88.2 | 7.15 | 91.7 |
| Circle core | 8,359       | 11.17 | 14.9   | 89.28| 6.25 | 92.8 |
| Cross core  | 8,457       | 10.13 | 14     | 89.9 | 6.9  | 93.2 |
| Multi core  | 7,279       | 22.65 | 6.56   | 95.28| 9.3  | 89.3 |
| Lozenge core| 8,710       | 7.44  | 15.59  | 88.7 | 6.31 | 92.7 |
| Irregular core 1 | 8,340 | 11.4  | 12.8   | 90.7 | 5.2  | 94.0 |
| Irregular core 2 | 8,397 | 10.77 | 14     | 89.9 | 5.69 | 93.0 |

Fig. 9 shows the displacement at all floors with and without opening in the rectangular core system. The graph shows that the displacement value is increased by 14% in the structure without opening compared with the structure with opening. The same reduction trend was observed for different types of cores.

5. Conclusions
Cores and shear walls are used in multistory buildings as horizontal resistance elements against wind or seismic load. Cores for horizontal force resistance have been developed as additional systems for high-rise buildings. The main goal of this study is to model different shapes of cores in a 25-story building and evaluate its effects in mitigating seismic vibrations.
The core system is a feasible device because it is easy to manufacture and costs less. Improvement in data processing based on an updated version of information, standards, and software would contribute more accurate results and provide better evaluation of core systems. In a 25-story building, the result shows that buildings with rectangular core in the X(horizontal) and Y(vertical) directions can have allowable lateral displacements. The following results can be concluded:

1. The numerical results of the nine models clearly indicate that irregular core 1 in this plane effectively reduced the seismic response of the building.
2. The structure equipped with irregular core 1 is the most effective core in reducing structural seismic response in this plane. When irregular core 1 was used, the overall response reduction on displacement is 72.5%. Therefore, the results showed that the structure equipped with irregular core 1 effectively reduced the seismic response of the building and can protect the building by minimizing or even eliminating structural or nonstructural damage during severe earthquake.

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