Journal of Brilliant Engineering 3 (2026) 41142
Brilliant Engineering
journal home: www.acapublishing.com/journals/4/ben

Research Article

Seismic Performance of Reinforced Concrete Buildings with Hollow Block Slabs and Flat Beams: Combined Effects of Shear Walls, Beam Depth Ratio and Column Type

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Keywords

*FFT analysis,
Square column,
Whiplash effect,
Hollow block slab,
Time-history analysis,
Comparative energy response characteristics.*

Abstract

In this study, the dynamic response and seismic performance of RC buildings with hollow block slab and flat beam system have been investigated. Six different building models with 10 stories have been designed to investigate the effect of factors such as the existence of shear walls, the ratio of b/d for beams, and the cross-sectional area of columns (square vs. rectangle). All of the buildings have been modeled in ETABS software according to the rules of Turkish Building Earthquake Code (TBEC-2018), using the seismic loads corresponding to Erzurum region and ZD soil type. The linear time history analysis has been conducted to study inter-story drift, acceleration amplification, frequency shifting, and comparative energy response characteristics. It has been observed that due to the flexibility nature of hollow blocks, a whiplash effect is created, causing up to ten times amplification of accelerations at the top stories. The use of square columns and shear walls has reduced the inter-story drift ratio about 25-30 percent and peak story acceleration about 15 percent. FFT analyses have revealed that square columns provided more stable and symmetric dynamic response characteristics within the investigated structural configurations. creating a stable mode shape in their dynamic response. Moreover, comparative energy response analyses (Ed/Ein) have shown that using square columns and shear walls can increase the damping factor by up to 5.42 percent. The results indicated that the combined use of square columns and shear walls improved the seismic response characteristics of the investigated structural systems.

1. Introduction

Proper knowledge about load transfer mechanisms plays a crucial role in designing structurally sound buildings. In reinforced concrete (RC) structures, slabs serve a dual purpose: they act as architectural finishes and structural elements that transfer vertical gravity loads and horizontal seismic forces. Given that slabs are considerably thinner than their plan dimensions, they are generally represented as 2D structural elements in analyses [1-2].

There are several types of slab systems; however, asmolen (hollow block) slabs are widely used due to their advantageous characteristics, including low self-weight, flat ceiling finish, easy formwork, and better insulation against temperature and noise [3-7]. The system consists of nervures filled with lightweight materials such as bricks, aerated concrete, and expanded polystyrene (EPS); While this allows for efficient material utilization, the construction of hollow block slabs may negatively affect load transfer mechanisms and induce seismic torsional irregularities due to low in-plane stiffness and weak diaphragm action [8-11]. For instance, it was found that due to a small slab thickness (5-7 cm), such slabs may develop insufficient in-plane rigidity. Therefore, they can lead to story drifts, irregular deformations, and concentrated damage zones located at the interfaces of slabs-beams and slabs-shear walls [8, 12-14]. Moreover, the increase in structural mass caused by the use of hollow block slab system can aggravate these problems.

Another important architectural element in RC buildings is flat beam systems. Flat beams are characterized by the following features: narrow depth and wide breadth. Such architectural flexibility allows creating flat ceilings. However, this configuration may cause some issues concerning seismic behavior, namely: decreased flexural rigidity and large displacements caused by horizontal loads [15]. It was found that joints between beam and column and shear stresses as well as torsional behavior of flat beams significantly differ from regular ones; therefore, incorrect detailing and design can cause brittle failure [16]. Furthermore, the use of wide and shallow beams can lead to strong beam and weak column inconsistencies.

Vertical load-resisting elements such as columns and shear walls play an important role in determining seismic behavior of RC buildings. Square-shaped columns are popular among engineers due to the balance in geometrical proportions. If properly strengthened, square columns demonstrate excellent seismic performance [17-18]. Recent studies have focused on improving the seismic behavior of columns through innovative strengthening systems and high-performance materials [19 – 21]. Still, insufficient interrelation between slab-beam-column structure can affect seismic behavior.

The country has considerable seismic activity owing to interaction of tectonic plates like Arabian, Eurasian, and African [22-26]. This situation makes Turkey one of the countries at the highest risk of experiencing strong earthquakes; many areas can be characterized by PGAs above 0.5g [27]. The 6 February 2023 earthquake in Kahramanmaraş showed that common structural systems are not capable of ensuring safety if they are not designed properly.

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Received 21 Apr 2026; Revised 06 May 2026; Accepted 11 May 2026
https://doi.org/10.36937/ben.2026.41142
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Although there are many publications about seismic behavior of hollow block slab systems and flat beams, there are very few studies investigating the combined effect of these elements. The majority of existing publications are dedicated to the study of either hollow block slab systems or flat beam systems; the influence of shear walls, beam depth-to-breadth ratios (b/d), and columns on seismic performance of the system has not been investigated in sufficient detail.

In seismic zones where the structural safety becomes the most important issue, an exhaustive analysis of structural systems commonly used in practice should be carried out. Thus, the need for further investigation related to in-plane stiffness deficiency, weak diaphragms, and larger displacements is apparent, especially for systems without shear walls.

Based on the above-presented facts, the current study aims to explore seismic behavior of multi-storey RC buildings with hollow block slabs and flat beams with various configurations. In order to achieve the proposed objectives, six analytical models with different parameters such as existence of shear wall, beam depth-to-width ratios (b/d), and type of columns will be constructed. Seismic responses of the models will be analyzed according to TBEC (2018) standards utilizing numerical simulation in ETABS [28].

The main contribution of this study is the comparative seismic assessment of hollow block slab systems with different structural configurations under the same analytical framework.

2. Structural Systems and Research Scope

This research deals with seismic performance of multi-storey buildings constructed using hollow block slab and flat beam systems. The former is commonly used in practice; however, they are deficient in terms of diaphragms' behaviour, stiffness, and lateral load transfer [8, 12, 14]. The existence of holes and thin topping slabs in hollow block slab system results in decreased in-plane stiffness, and the decrease in beam depth leads to reduced overall stiffness and higher inter-story drift under seismic actions [9,15]. Thus, lateral load transfer becomes difficult in such configurations due to irregular distribution of internal forces in the building.

Field data show that many buildings designed with hollow block slab and flat beam systems suffer significant damage after the 6 February 2023 Kahramanmaraş earthquakes. Due to the use of large width to depth ratios of beams and insufficiently confining columns, weak column-strong beam mechanism was formed which is contradictory to the capacity design philosophy [8,14]. The formation of said mechanism led to discontinuous lateral load transfer, stress concentration around beam-column joints, and brittle failure patterns under seismic loads. In addition, limited stiffness in the in-plane direction prevented the development of rigid diaphragm behaviour, resulting in greater torsional irregularities.

Therefore, the seismic behaviour of reinforced concrete buildings constructed by means of hollow block slab and flat beam system will be numerically studied considering different configurations. The impact of several structural parameters such as presence of shear walls, ratio of depth and width of beams (b/d), and type of columns will be examined by conducting comparative analysis.

Despite the fact that this study has some limitations, several valuable conclusions can be drawn from the obtained results. In particular, the analyses are conducted only for idealized building designs with fixed plan geometries and pre-determined number of storeys. Moreover, soil-structure interaction effect, advanced material models, and construction deficiencies are not accounted for. Finally, numerical analysis only yields results in absence of experimental studies. Nonetheless, this study aims at providing valuable insight on the problem under discussion and contribute to the literature. Although the analytical models allow comparative evaluation of different structural parameters, the current model matrix has certain limitations regarding the complete isolation of individual parameter effects.

2.1. Description of structural systems

The combined use of hollow block slabs and flat beam arrangements in RC structures is highly common due to their aesthetic and structural advantages. However, the low in-plane stiffness of hollow block slabs due to the voids formed in such a slab and the thin topping layers along with low flexural stiffness of the flat beams caused by the low depths can cause high interstory drifts and irregular force transfer during earthquake loading conditions [8, 12, 15]. Moreover, the field observations after the 6th February 2023 Kahramanmaraş earthquakes indicate that the combination of these two systems might encourage the formation of the weak column-strong beam mechanism that leads to the damage and even collapse of the structure [8,14].

As can be seen from Fig. 1, the vertical loads are primarily transferred to the columns via ribbed beams and flat beams, but the lateral loads are expected to be transferred via diaphragm action of the slab. However, the discontinuous and flexible nature of the slab in hollow block slab arrangements prevents this diaphragm action, which causes non-uniform lateral force distribution. Moreover, flat beams, having lower depths, provide less stiffness to the system.

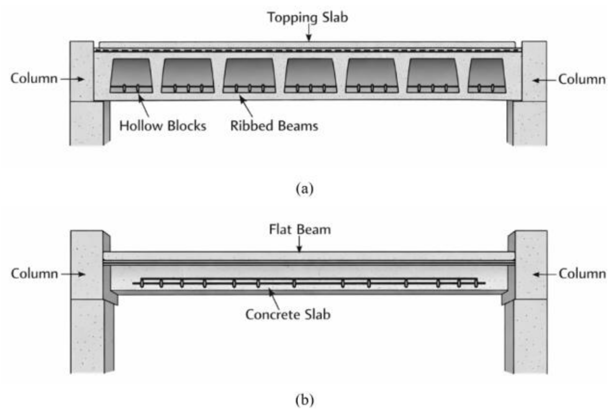


Figure 1. Structural system type; a) Hollow block slab system; b) Flat beam system

2.2. Definition of analytical models

Six models were developed in this study for evaluating the seismic behavior of RC buildings with hollow block slab and flat beam system construction. All six models were created using the same plan geometry, materials, and vertical zoning, consisting of basement, ground level, and eight regular floors (ten floors in total). Models were designed in such a way that the differences between them would be along three basic parameters, namely whether the model has shear walls or not, beam depth-to-width ratio (b/d), and column shape. As a result, both cases when the model does or does not have shear walls, two b/d ratios (10/30 and 10/40), and various types of columns were analyzed.

Table 1. Structural properties of analytical models

Model	Group	Shear Wall	b/d Ratio	Column Type
KKP1030	1	Yes	10/30	Square
KKP01030	1	No	10/30	Square
NKP1030	1	Yes	10/30	Rectangular
KKP1040	2	Yes	10/40	Square
KKP01040	2	No	10/40	Square
NKP1040	2	Yes	10/40	Rectangular

2.2. Investigated parameters

Table 2 summarizes the cross-section properties of the analysis models. For all models, the beam width is kept fixed at 70 cm while two depths of beams, namely 30 cm and 40 cm are considered. As a result, the b/d ratio will become 10/30 and 10/40 respectively. The structure systems of all the models include hollow block slab systems while columns may consist of two shapes; square cross-section or variable cross-section. In order to ensure consistency of the models' stiffness properties, an average value of effective radius of gyration for variable cross-section columns is assumed to be equal to that of square columns.

Beam cross-sections have been selected based on field observations from earthquake-stricken regions. Field observations show that hollow block slab systems with flat beams having a depth of 30 cm and 40 cm are commonly utilized especially in older buildings and are often damaged or collapsed. Therefore, cross-sections with these values are selected in the analysis models to simulate real building systems. Structural dimensions were obtained using relevant building codes such as TBEC (2018), Eurocode 2 (EN 1992-1-1) and Eurocode 8 (EN 1998-1) [28-30].

Table 2. Cross-sectional and structural properties of the analytical models

Model	Beam Dimensions (cm)	Slab Type	Column Dimensions (cm)	Shear Wall	b/d Ratio
KKP1030	70×30	Hollow Block Slab	60×60	Yes	10/30
KKP01030	70×30	Hollow Block Slab	60×60	No	10/30
NKP1030	70×30	Hollow Block Slab	Variable	Yes	10/30
KKP1040	70×40	Hollow Block Slab	60×60	Yes	10/40
KKP01040	70×40	Hollow Block Slab	60×60	No	10/40
NKP1040	70×40	Hollow Block Slab	Variable	Yes	10/40

3. Numerical Modeling and Analysis Procedure

This section presents the numerical modeling approach and analysis procedure adopted in the study. The material and geometric properties of the structural models, seismic input parameters, modeling assumptions, and analysis methods are described in detail. All analytical models were developed to ensure consistency and comparability, allowing a systematic evaluation of the effects of key structural parameters on seismic behavior.

3.1. Material Properties

The properties of materials used in analytical models were set based on the relevant guidelines of seismic design codes. In this study, C25/30 concrete and B420C steel reinforcing bars were chosen in all structural components according to TBEC (2018) requirements and related international codes of EN 1992-1-1; EN 1998-1 [29-30].

It is commonly known that many existing buildings in Turkey were built under older seismic codes which required lower material strength. According to the Seismic Code of 1975, the minimum concrete compressive class was around C14, while the minimum reinforcement was S220 [31]. The minimum requirements changed to the following in the 1997 code: C20/25 concrete and S220 reinforcement [32]. Later, the Seismic Code of 2007 imposed higher requirements: C20/25 concrete and S420 reinforcement [33].

Relatively low material properties, together with structural disadvantages like hollow block slabs or flat beams, led to higher structural vulnerability and damages during previous earthquakes. Therefore, to assess the real potential of hollow block slab structures and flat beams, the material properties were set based on the newest code in this case (TBEC, 2018). Such an approach allows estimating the behavior of structures with no effect from material properties at the same time.

3.2. Structural system type

These analyses have been performed based on the structure that is a reinforced concrete frame structure having hollow blocks and flat beams. Sometimes reinforced concrete shear walls were combined with the structure to enhance the capacity of resisting lateral loads, while some other cases without shear walls were also considered. According to TBEC (2018), the structure may be classified into a frame-shear wall system where the seismic load will be carried out by moment-resisting frames and shear walls [28].

All these structures consist of basement, ground story, and eight-story buildings for mid-rise residential constructions. Such a choice of configurations is related to the real-life building constructions, especially hollow block slab and flat beams configurations. Moreover, the main aim of this analysis is to study the effect of square columns in enhancing the seismic performance of frame structures.

3.3. Seismic parameters

Seismic input parameters have been defined according to the Turkish Building Earthquake Code (TBEC, 2018). Site-specific seismic hazard parameters were considered. The analyses have been carried out for Oltu in Erzurum Province, which is a highly seismic province. The soil class was determined as ZD, representing medium-stiff soil properties.

The ZD soil class was adopted to define the site-specific seismic hazard parameters according to TBEC (2018), while fixed-base support assumptions were used to neglect soil-structure interaction effects [28]. Seismic demand parameters such as spectral accelerations, design spectrum factors, and ground motions were obtained from the Turkish Seismic Hazard Map using the geographical coordinates of the location. Seismic demand parameters are important to define the design response spectrum and conduct seismic analyses. Seismic parameters used in the study are provided in Table 3.

Table 3. Seismic parameters used in the analyses

Soil class	ZD
Earthquake level	DD-2
Latitude	40.54867
Longitude	41.99144
S_s	0.628
S_1	0.160
PGA (g)	0.271
PGV (cm/s)	14.916
S_{DS}	0.815

The seismic parameters used in this study include standard spectral and ground motion descriptors defined in TBEC (2018). Here, S_s and S_1 represent the short-period and 1.0-second period spectral acceleration coefficients obtained from the seismic hazard map. Based on these values, the design spectral coefficients S_{DS} and S_{D1} are calculated to define the elastic design response spectrum. In addition, PGA (Peak Ground Acceleration) and PGV (Peak Ground Velocity) represent the maximum expected ground acceleration and velocity, respectively, characterizing the intensity of ground motion.

Following the definition of seismic input parameters, the building-specific seismic design parameters were determined in accordance with TBEC (2018). The building importance factor was taken as I = 1.0, and the building usage class (BKS) was defined as 3. Accordingly, the seismic design class (DTS) was determined as 1, and the building height class (BYS) was identified as 4.

The structural behavior factor was selected as R = 6, and the overstrength factor was taken as D = 2.5. For existing reinforced concrete buildings, the target performance level was defined as Controlled Damage (KH), in line with the performance-based assessment provisions of TBEC (2018). These parameters ensure a consistent and code-compliant evaluation of the seismic performance of the analytical models.

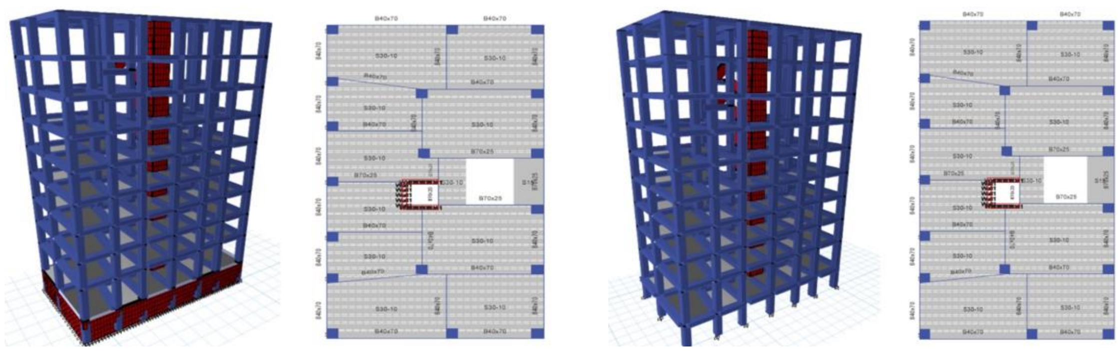
3.4. Modeling assumptions

The analysis models were created using the finite element-based structural analysis tool ETABS. Beams and columns were modeled using frame elements that have specific cross-sectional properties, in keeping with the standard practice in structural analysis [34]. The structural masses were specified taking into account the weight of the structural elements, including self-weight, and other dead loads, in accordance with EN 1991-1-1, while gravity and seismic loads were also considered, in line with TBEC (2018) [28].

Floor slabs were modeled using rigid diaphragm constraints to ensure numerical consistency and comparative evaluation between different structural configurations. Therefore, the analyses reflect the global seismic response of the investigated systems rather than directly modeling the low in-plane stiffness and weak diaphragm behavior of hollow block slabs [30,35].

Fixed boundary conditions were applied at the foundation, as depicted in the numerical models provided in Fig. 2 below. The soil-structure interaction was neglected in order to make the analyses straightforward and possible for a direct comparison of structural performances.

Linear elasticity was assumed regarding the material, geometry and loading behavior within the scope of the current research. This assumption conforms to the response spectrum method of analysis and has been widely accepted to assess the global seismic performance of buildings [30,36]. Furthermore, previous research works have shown that such assumption produces satisfactory results for comparing the structural performance of the buildings under various parameters [37-38].



(a) (b)

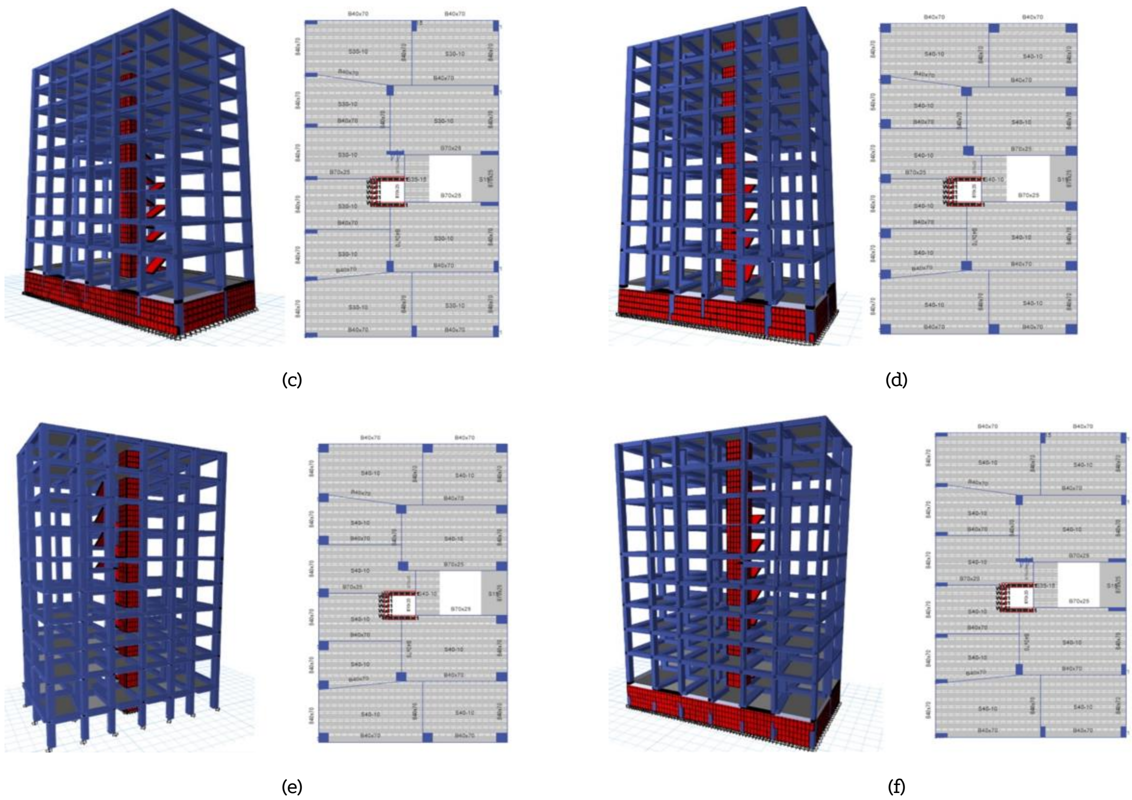


Figure 2. Finite element models and plan views of the analyzed structural systems: (a) Model 1 (KKP1030); (b) Model 2 (KKP$_0$1030); (c) Model 3 (NKP1030); (d) Model 4 (KKP1040); (e) Model 5 (KKP$_0$1040); (f) Model 6 (NKP1040)

3.5. Analysis method

The seismic behavior of the proposed models was evaluated using linear dynamic analysis techniques. The vibration behavior of the structures subjected to seismic loading can be mathematically described by Eq. (1), which represents the basic principle involving the mass, damping, and stiffness components of structural dynamics [36,39]. First, modal analysis was performed for determining the characteristics of the free vibration of the structures such as period, mode shape, and mass participation factor. Modal parameters were used to check whether enough modes are considered in the study.

$$M\ddot{u}(t)+C\dot{u}(t)+Ku(t)=-Mr\ddot{u}_g(t) \tag{1}$$

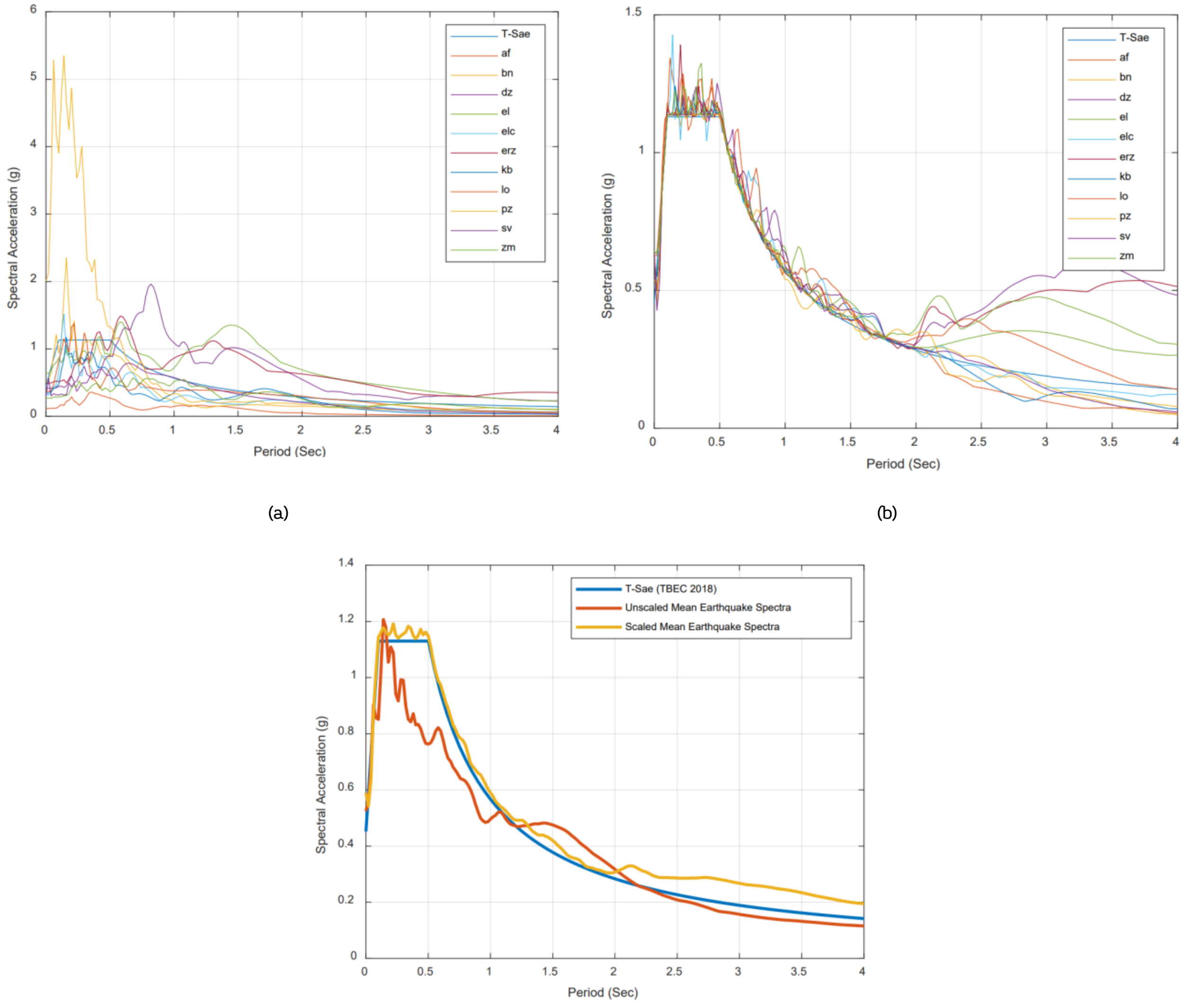
where M, C, and K are the mass, damping, and stiffness matrices of the structural system, respectively; u(t) is the displacement vector; $\ddot{u}(t)$ and $\dot{u}(t)$ denote the acceleration and velocity vectors; r is the influence vector; and $\ddot{u}_g(t)$ represents the ground acceleration time history.

Following this, time history analyses were performed utilizing a series of actual earthquake recordings. The attributes of the ground motions used are provided in Table 4. The actual earthquake recordings considered have been selected in such a way that a range of seismic properties are represented, from different magnitudes and faulting types to near field and far field effects.

Table 4 Seismic properties of the selected ground motion records used in the analyses [40]

No	Earthquake	Abbreviation	Date	Station	PGA (g)	Mw
1	Erzincan	erz	13 March 1992	Erzincan Merkez	0.488	6.6
2	Gölcük	zm	17 August 1999	Yarımca Petkim	0.235	7.6
3	Düzce	dz	12 November 1999	Bolu Merkez	0.819	7.1
4	Afyon	af	3 February 2002	Afyon Merkez	0.115	6.5
5	Bingöl	bn	5 January 2003	Bingöl Merkez	0.511	6.3
6	Sivrice	sv	24 January 2020	Sivrice	0.298	6.8
7	Elbistan	el	6 February 2023	Göksun	0.648	7.6
8	Pazarcık	pz	6 February 2023	Pazarcık	2.070	7.7
9	Loma Prieta	lo	17 October 1989	Loma Prieta	0.550	6.9
10	Kobe	kb	17 January 1995	Kobe	0.908	7.2
11	El Centro	elc	15 October 1979	Imperial Valley	0.177	6.5

The unscaled and scaled response spectra for the selected earthquake ground motions have been provided in Fig. 3(a) and 3(b), respectively, whereas Figure 3(c) provides the plot comparing the mean response spectrum with the target design spectrum as prescribed by TBEC (2018) [28]. The ground motions have been scaled in the time domain so as to be compatible with the target design spectrum. The scaling has been done in such a way that the mean response spectrum is made to match with the target response spectrum in the fundamental period range of the structure ($0.2\ T_1 – 1.5\ T_1$) [30,35]. The selected ground motions were scaled to achieve spectral compatibility with the TBEC (2018) target spectrum within the period range of 0.2T1–1.5T1. The reported seismic response values represent comparative trends obtained from the adopted earthquake record set. Amplitude-based scaling factors were applied to achieve compatibility between the selected ground motions and the target design spectrum within the specified period range.



(c)

Figure 3. Response spectra of selected earthquake records: (a) unscaled spectra; (b) scaled spectra; (c) comparison of mean spectrum and target design spectrum (TBEC 2018).

Moreover, the time history of acceleration values for the chosen ground motion before and after scaling are provided in Fig. 4. This scaled data was used as the input ground motion in the analysis. Earthquake records used in this work are taken from Çelebi and Demir (2026) [40], yet the aim of the current study is quite different, focusing on the evaluation of the seismic performance of hollow block slab and flat beam construction.

The damping coefficient for all the modes was considered as 5%, which is a usual value for RC structures [36]. Results obtained from the analysis, like displacements, inter-story drift ratio, and internal forces, were used to assess the influence of structural parameters (beam depth, column type, shear wall presence, etc.) on the seismic behavior of the building.

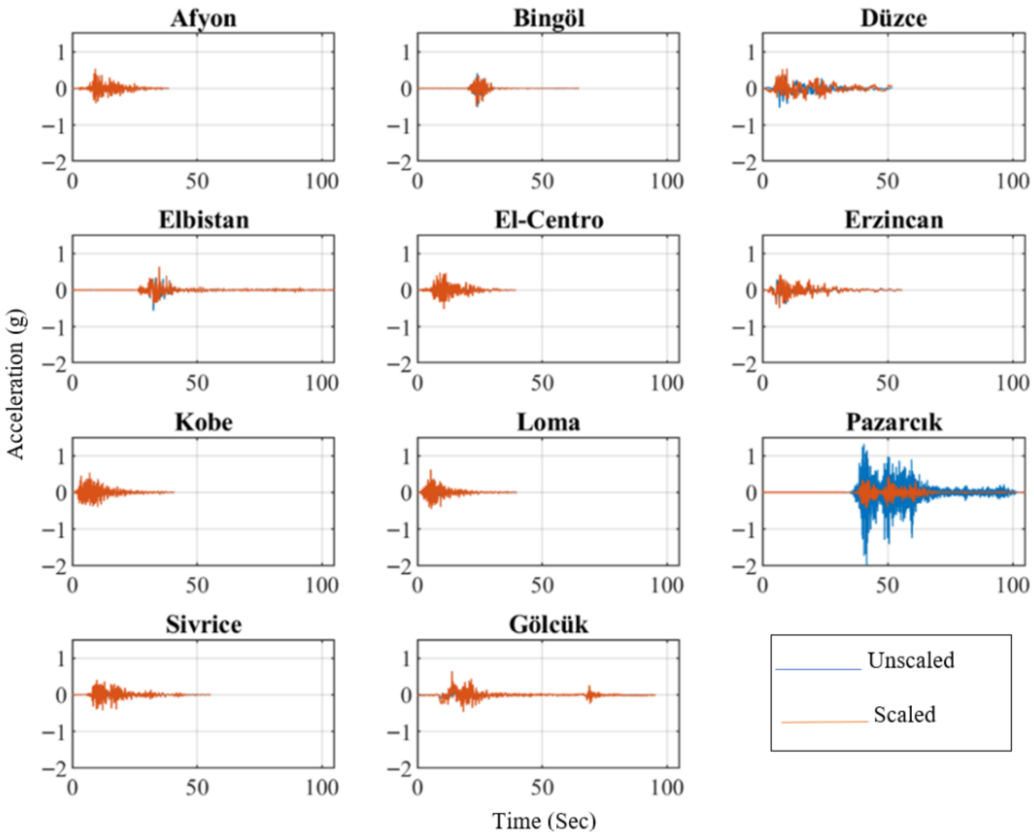


Figure 4. Acceleration time histories of selected ground motions: comparison of unscaled and scaled records.

4. Discussion

Seismic response of RC buildings with hollow block slab and flat beam construction is an intricate matter depending on the relationship between structural stiffness and resistance to lateral forces. In this paper, a thorough comparison analysis of six different structures will be presented using a wide range of parameters including mode shapes, dynamic time history (base shear force, top displacement, and acceleration), comparative energy response characteristics, and stress distribution. It will become evident from the outcomes that the inherent weaknesses of hollow block slab system such as lower in-plane stiffness and inadequate diaphragm action can either be compensated for or aggravated depending on the inclusion of shear wall structures, b/d ratio of beams, and column dimensions. Using frequency-domain approach (FFT) along with time domain findings, further discussion will follow in the upcoming sections concerning the efficacy of these structural considerations in satisfying design standards for significant seismic loading, e.g., TBEC (2018) criteria for Erzurum-Oltu city [28].

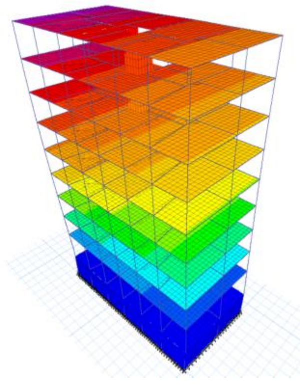
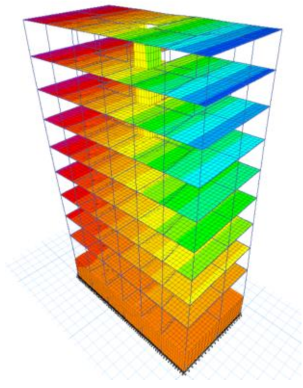
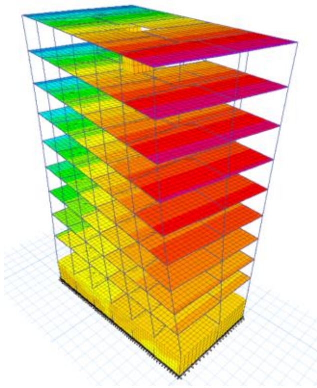
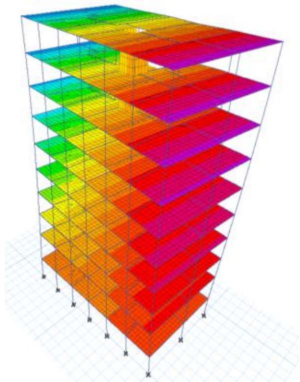
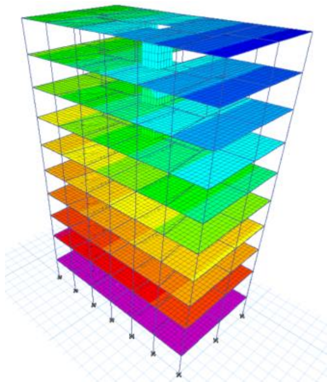
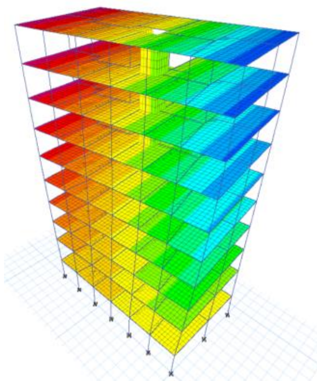
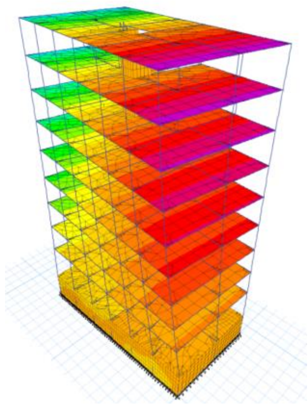
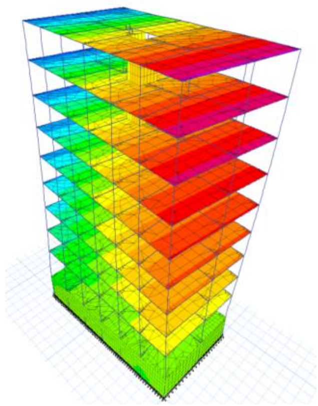
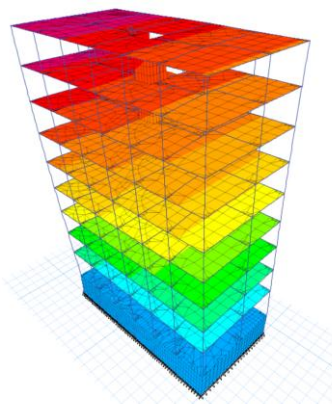
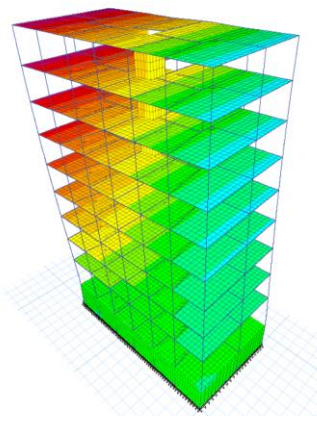
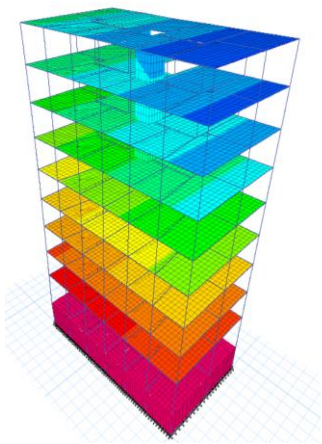
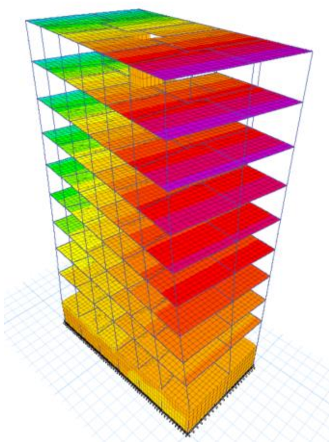
4.1. Modal characteristics and dynamic properties of the structural systems

The periods of natural vibration as well as the mode shapes provide crucial information on the stiffness and mass distribution characteristics of the considered models. Table 5 presents the findings for modal analysis carried out for the first three periods of natural vibrations (T_1, T_2, T_3), while Fig. 5 shows the corresponding deformed mode shapes.

Table 5. Natural vibration periods and mass participation ratios of the investigated structural models for the first three modes.

Models	T_1 (s)	T_2 (s)	T_3 (s)	U_x (%)	U_y (%)
KKP1030	1.046	1.034	0.977	92.03	89.96
KKP_01030	1.123	1.105	1.058	98.26	98.69
NKP1030	1.245	1.054	1.036	91.02	89.27
KKP1040	1.041	1.025	0.977	91.44	89.91
KKP_01040	1.128	1.096	1.062	98.43	98.85
NKP1040	1.277	1.081	1.064	91.77	90.38

In cases where the structure is devoid of any shear walls (KKP_0 series), there is a marked increase in T_1, suggesting significant lateral flexibility. It is evident from the above analysis that the hollow block slab system technique, which is flexible by itself owing to its use of flat beams, becomes highly flexible without any shear wall reinforcement. An increase in the depth of the beam from 30 cm to 40 cm (transition from Group 1 to Group 2) causes a corresponding decrease in natural periods for all structures, suggesting that increasing the b/d ratio to 10/40 will lead to increased stiffness of the frames, which will be critical for resisting seismic forces. On the other hand, the shear wall structures (KKP/NKP) have translation-dominated first modes, while the KKP_0 structures show torsion-translation coupling. This is because of the poor effectiveness of the diaphragms owing to their small thickness.

Models	**First Mode**	**Second Mode**	**Third Mode**
KKP1030			
KKP$_0$1030			
NKP1030			
KKP1040			

KKP$_0$1040

NKP1040

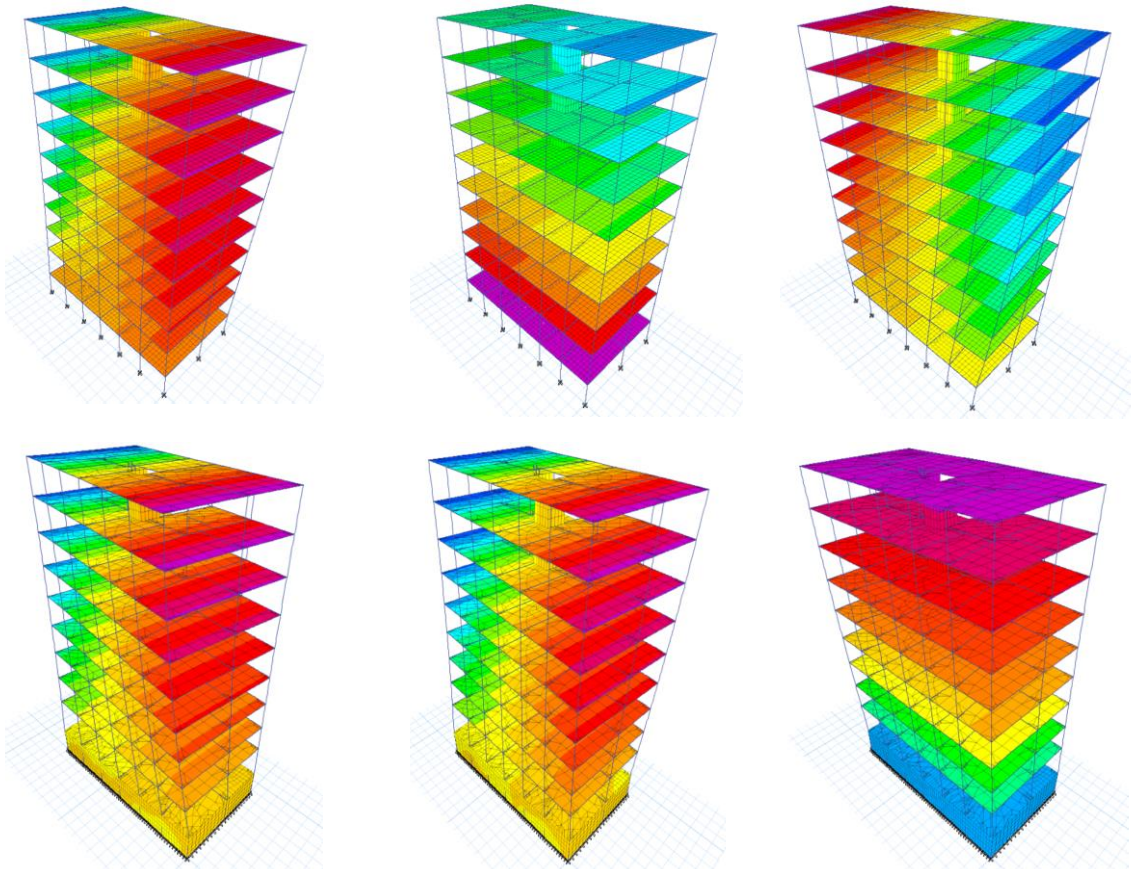


Figure 5. Translational and torsional mode shapes for different structural configurations

Periods for square (KKP) and rectangular (NKP) columns remained similar due to the balanced radius of gyration used in modeling. However, Fig. 5 reveals that square columns provide a more symmetrical stiffness distribution, leading to better-decoupled mode shapes.

5.2. Seismic demand and force distribution

The global seismic response parameters, including maximum base shear, peak top displacement, and peak acceleration, are compared for all six models in Fig. 6.

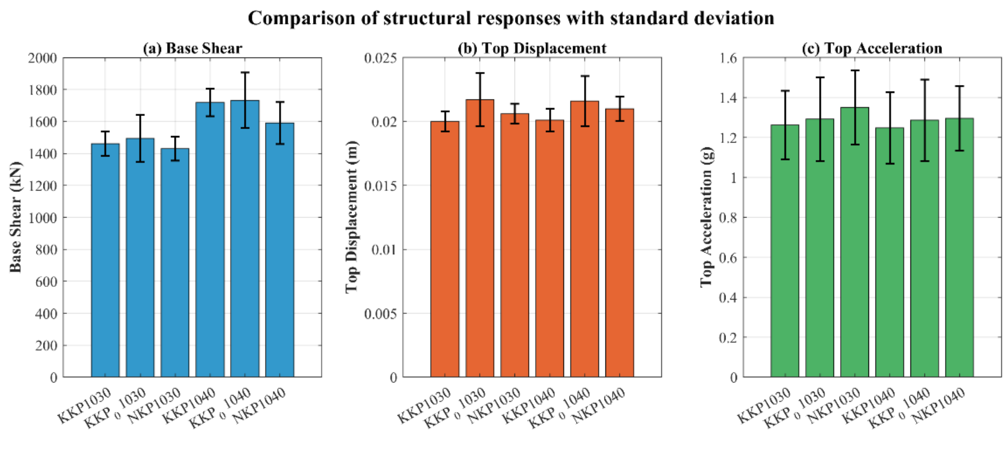


Figure 6: Comparison of maximum base shear, top displacement, and peak acceleration values for all models.

The highest base shear forces were registered in models using shear walls together with the beam-connecting frame (KKP and NKP). This result is attributed to higher structural stiffness, according to Garg et al. (2021) [41], who recognized shear walls as the one of the effective approaches to increase the stiffness of the flat slab system. At the same time, the comparatively low base shear in KKP0 models was caused by their excessive flexibility making them fall into the long-period/low-acceleration range of the curve. Maximum top displacements of KKP0 models prove how vulnerable such configurations are. This result is consistent with the findings of Jiang et al. (2023) [42], indicating that wide-flat beams could not provide satisfactory control over the lateral drift. Furthermore, such requirements can be justified in light of the lack of lateral rigidity of analogous constructions discovered by Yenidoğan (2024) [8] in their field investigation conducted after the February 6th earthquakes. Raising the beam depth to 40 cm and using square columns significantly decreased the displacement demands. Last but not least, using square columns together with shear walls improves torsional stability mentioned by Bayrak et al. (2023) [43].

Deflections resulting from vertical load effects in the presence of peak seismic demands determined through non-linear time-history analyses are summarized in Fig. 7. One may conclude that the use of square columns (KKP) proves to be a highly efficient option compared to traditional rectangular columns (NKP) when dealing with the problem of deflection in the context of the serviceability of flat-beam constructions. First of all, the maximum deflections in NKP models amounted to 0.37 cm, almost reaching the critical values established by TS 500 [44], while the KKP model kept deflections below 0.14–0.17 cm. Such an achievement is about 55% smaller than previous results, which shows that square columns can ensure greater stiffness balance in two principal directions, similarly to the torsional stability benefits reported by Bayrak et al. (2023) [43]. Second, raising the beam depth to 40 cm (Group 2) and implementing square columns (KKP1040) ensures that the deflections do not exceed the restrictive L/480 limit, thus addressing the "flexibility and joint-stiffness" problems emphasized by Jiang et al. (2023) and Jain et al. (2016) [42]. Here, L represents the effective span length of the flat beam system considered in the analytical models.

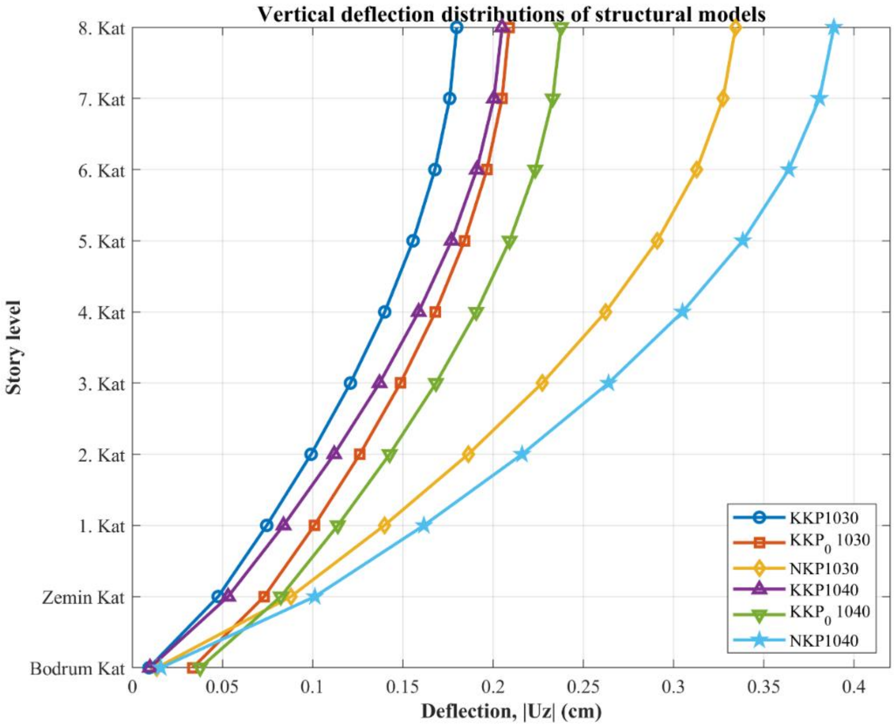


Figure 7. Comparative deflection response of structural models under simultaneous vertical and non-linear time-history loads

The values of maximum story displacement at the building height (Fig. 8) substantiate the effectiveness of the proposed design modifications and their numerical success. The frame model (KKP_0) shows an essential displacement of 0.024 m in the X-direction and confirms the sensitivity of hollow block structures to flexibility-induced instabilities, as noted by Sarkis et al. (2023) [45]. It can be seen that while shear wall inclusion decreases this value by 40% in both X and Y directions, the use of square columns (KKP) provides similar performance with a decrease of 37.5%. The significant effectiveness of square columns proves that the balanced stiffness distribution provided by square columns contributed positively to the seismic response of the investigated models. Thus, numerical results reveal that the use of square columns, specifically those applied in flat beam construction, is contributed to keep displacement levels below the values regarded as safe according to ASCE 7-22 and TBEC-2018 [28,46]. Overall, these findings validate the theory of stiffness balancing formulated by Garg et al. (2021) [41], proving that square column application showed favorable seismic response characteristics in the analyzed models. [47].

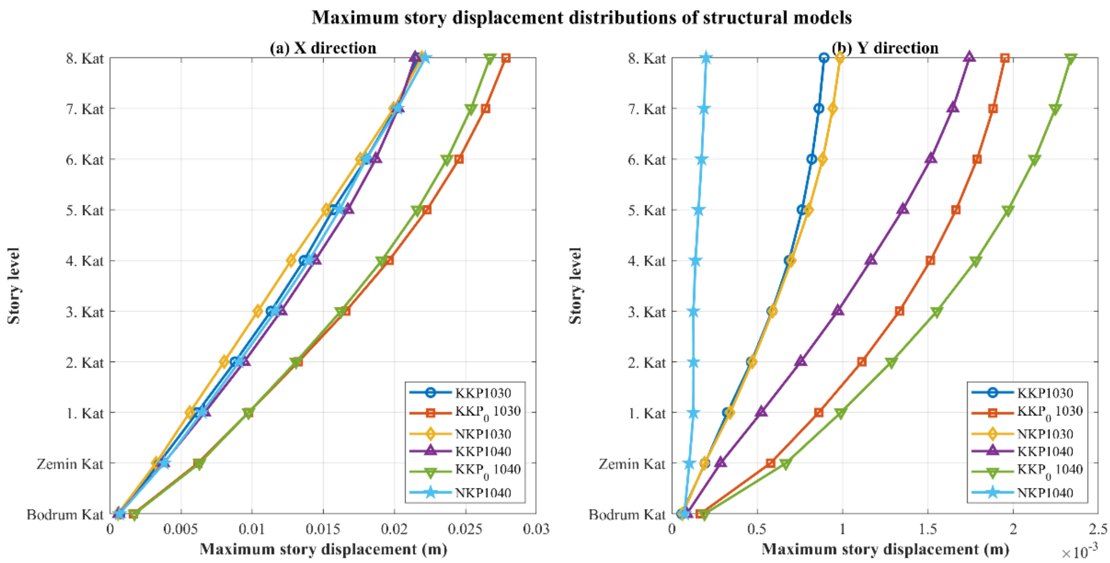


Figure 8. Maximum story displacements; a) X direction, b) Y direction

Fig. 9a and Fig. 9b depict the probability distribution of the maximum story shear force computed through the combination of gravity loads and seismic loading calculated based on the time history of the linear dynamic analysis. From the numerical data, one can note the crucial importance of the structural layout on the process of load sharing under seismic action. For the X-direction, it is seen that the KKP layouts (square column sections with shear walls) have considerable attraction capacity for loads, increasing the story shear up to 12,000 kN compared to KKP_0 layouts. This result agrees well with the stiffness-based protection theory put forward by Garg et al. (2021) [41].

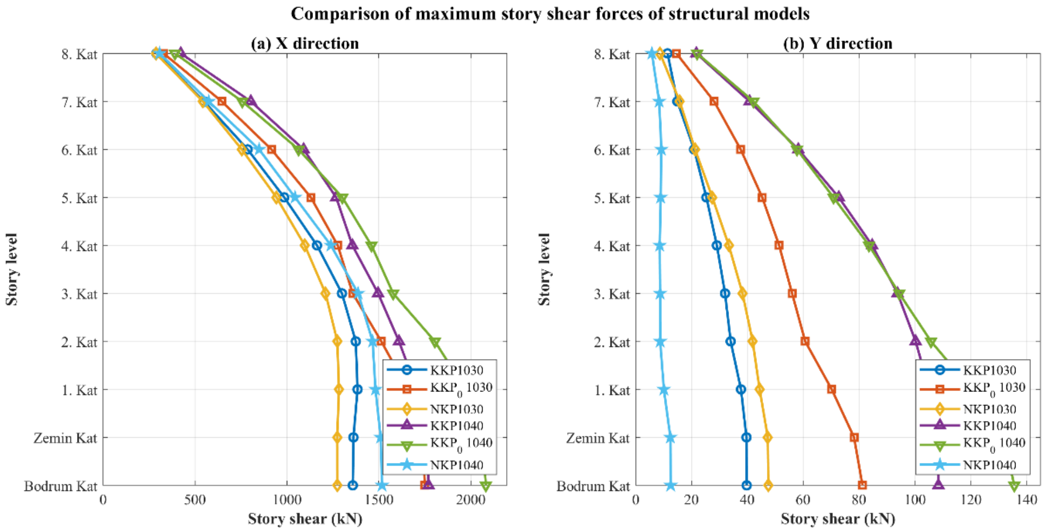


Figure 9. Distribution of maximum story shear forces under combined gravity and non-linear time-history loads: (a) X-direction, (b) Y-direction

Analyzing data along the Y-axis reveals that the performance of the square-column-based model (KKP) is virtually equal to that of the shear-wall-integrated NKP structures. Indeed, the balanced ability to withstand loads evenly in both primary directions offered by square columns helps to address potential issues with torsion-induced instability discussed by Sarkis et al. (2023) [45] in their work on hollow-block structures. The conclusion that deeper flexural members lead to greater overall base shear resistance confirms that using square columns helps to distribute seismic loads uniformly in accordance with ASCE 7-22 and TBEC-2018 standards [28, 46].

Drift ratios in all stories of the building (see Fig. 10 below) support the effectiveness of proposed engineering approaches as primary indicators of structural failure. According to the data, integration of shear walls and square columns helps to reduce inter-story drift ratios by 25-30 percent; the most prominent changes are observed in the upper stories (floors 4-8). Individually, shear walls result in improvements between 25-30 percent, whereas square columns provide equally effective results: between 23-27 percent. As mentioned before, the effectiveness of square columns supports the approach of achieving equal two-way stiffness described by Bayrak et al. (2023) [43] as the best alternative to shear walls when dealing with seismic demand from both the X and Y directions. In turn, such levels of improvement ensure that the model with only frame structures does not exceed the performance requirements set by TBEC-2018 and ASCE 7-22 (0.008) [28, 46]. It can be assumed that the use of square columns is contributed to preserve the structure at the "Immediate Occupancy" level of performance and minimize the risk of potential problems caused by P-Delta instability discussed by Sarkis et al. (2023) [45]. Thus, implementation of both square columns and shear walls represents the best solution to avoid structural damage due to lateral rigidity deficiency reported by Mıstıkoğlu (2024) and Yenidoğan (2024) [8, 47].

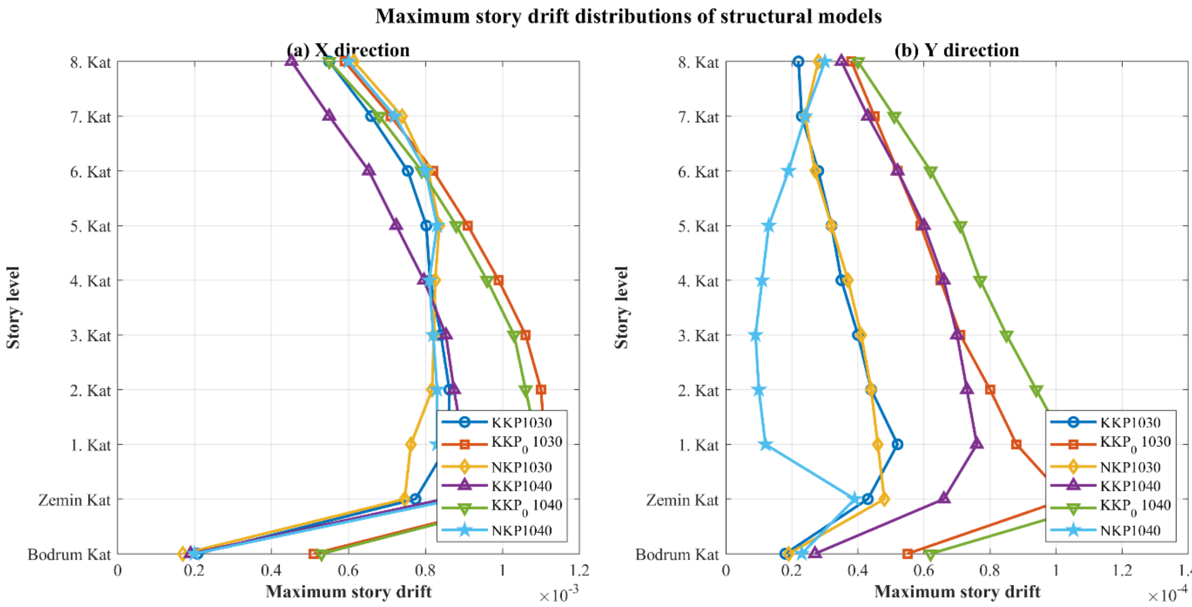


Figure 10. Distribution of interstory drift ratios across the building height for different structural configurations; a) X direction, b) Y direction

5.3. Dynamic response analysis

In this regard, the current subsection evaluates the dynamics of the structure's behavior with the aid of acceleration distributions, FFT calculations, and comparative energy response characteristics under extreme seismic forces. Seismic acceleration responses are considered for the basement story, the 4th story, and the 8th story to examine the wave propagation and effects caused by the height of a building. Although acceleration data provide certain information concerning the stiffness of a structure and the demands at the floor level, FFT graphs can be used to determine dominant natural frequencies and possible period shifts caused by structural changes proposed in this study. Besides, the energy-based analysis of input and damping capabilities of the structure is performed. It should be noted that energy analysis will help compare the efficacy of square columns and shear walls in reducing the seismic loads' influence on the building. The reported energy-related responses should be interpreted within the assumptions of linear dynamic analysis and viscous damping behavior rather than hysteretic energy dissipation.

Fig. 11 illustrate acceleration time histories for the basement, 4th, and 8th floors. The significant lateral flexibility of structures comprising hollow blocks and flat beams leads to the whiplash effect, wherein seismic accelerations are drastically amplified at the upper floor levels. More specifically, the model of frame without any improvements (Fig. 11b) experiences approximately 10 times higher input acceleration than that recorded at the base with an ultimate floor acceleration value of 1.5g. Similarly, the KKP$_0$1040 model shown in Fig. 11e demonstrates the same tendency; although beams are deeper, the lack of shear walls does not prevent high inertial forces. Thus, this study proves that stiffness is mainly responsible for dynamic stability, which is supported by Sarkis et al. (2023) [45]. On the other hand, combining the proposed square columns with shear walls greatly alleviates this problem, since the accelerations are decreased by approximately 15% (Fig. 11a and 11d). Moreover, acceleration spikes are less random for models KKP1030 and KKP1040 with square columns (Fig. 11a and 11d); in addition, a combination of increased beam depths and square columns produces more balanced acceleration values (Fig. 11d). This conclusion can be explained by the equivalence of stiffness in two directions, which allows controlling inertia according to Garg et al. (2021) [41]. Finally, using 40 cm deep beams in all Group 2 models (11d, 11e, 11f) creates harmony in diaphragm-frame interaction according to Pang et al. (2019) [48]. Yet, the most optimal seismic behavior is reached when 40 cm beams and square columns are combined.

The frequency spectra and predominant vibration forms obtained using FFT analysis based on acceleration-time data are illustrated in Fig. 12. One can clearly see that the obtained results correspond mathematically to the periods of oscillations given in Table 4 ($T = 1/f$) and act as a signature of dynamic changes in the lateral stiffness characteristics of the considered structures. Specifically, the fact that frame-only KKP0 models display a significant presence of low frequencies denotes the flexible behavior and the lack of sufficient lateral stiffness in hollow block systems under seismic loads. After adding square columns and/or shear walls to the frame-only models, a pronounced shift of spectral peaks towards higher frequencies (frequency shift) is detected, which aligns with the spectral shift due to an increase in stiffness in the frequency-domain literature [49]

While shear walls contribute to increasing the fundamental frequency and thus taking the structure away from the damaging low-frequency range of earthquakes, the addition of square columns causes the resulting frequency spectrum to be significantly narrower than for NKP models. This finding implies that square columns help eliminate the detrimental impact of the torsion effect, hence stabilizing dynamic mode shapes. Concerning the frequency-domain damage assessment technique [49-50], wide spectral windows and distribution of amplitudes observed in KKP0 models suggest a higher susceptibility to plastic deformations. Meanwhile, the narrow peaks in frequency spectra calculated for structures containing square columns and shear walls prove that a system absorbs energy elastically under seismic forces, hence contributing to improved damage resistance. Finally, the application of story transmissibility functions and frequency-time decompositions in accordance with the literature recommendations [50] demonstrates numerical evidence of the important "disciplining" contribution made by square columns and shear walls.

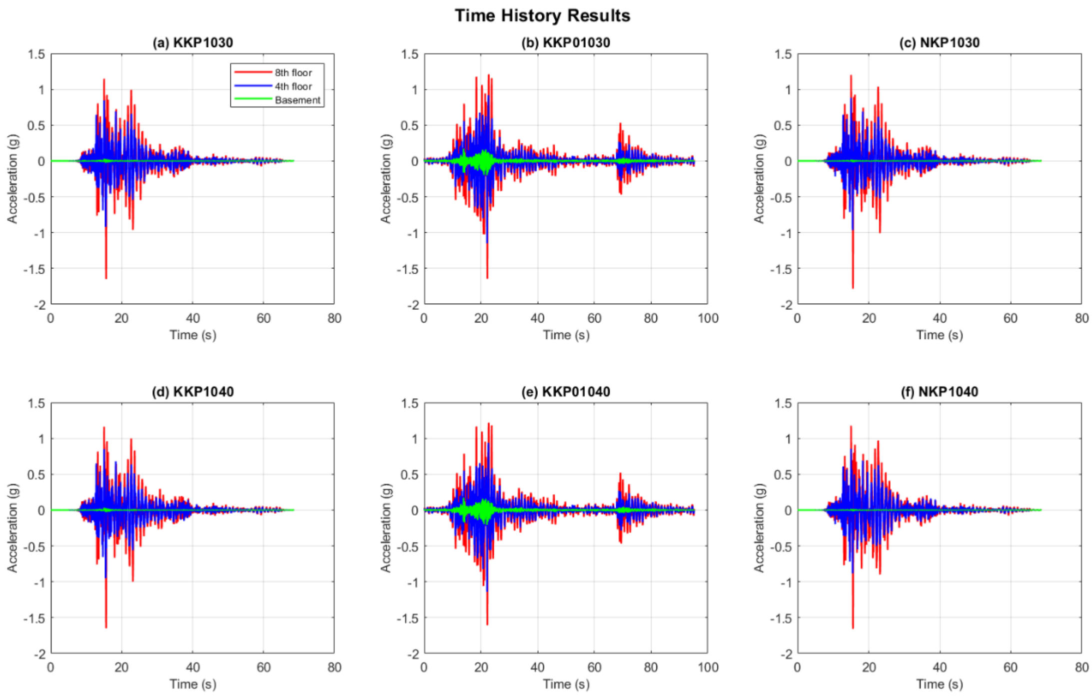


Figure 11. Acceleration-time histories at basement (green), 4th (blue), and 8th (red) floor levels for different structural configurations; a) KKP1030, b) KKP$_0$1030, c) NKP1030, d) KKP1040, e) KKP$_0$1040, f) NKP1040

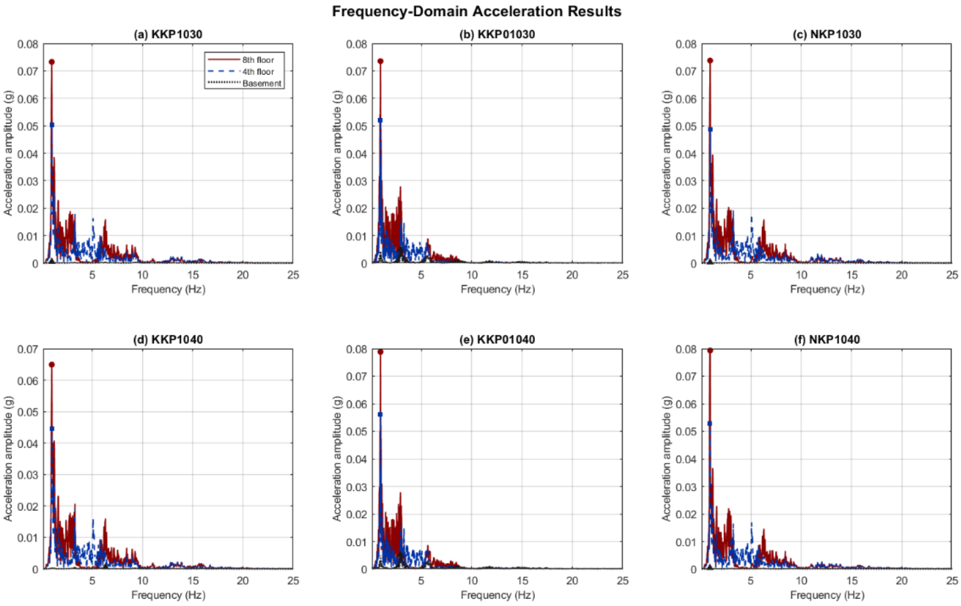


Figure 12. Fast Fourier Transform (FFT) power spectra and dominant frequency shifts for different structural configuration; a) KKP1030, b) KKP$_0$1030, c) NKP1030, d) KKP1040, e) KKP$_0$1040, f) NKP1040

Comparative energy response characteristics of the structures subjected to gravitational and earthquake forces is illustrated in Fig. 13 through time histories of input (Ein) and damping (Ed) energies. Comparison of average Ed/Ein ratio is utilized here as a basis for validating proposed structural modifications in order to dissipate seismic energy effectively. It is found that implementation of shear wall in the models with 30 cm joist depth results in increase of damping efficiency by 5.42%, whereas utilization of square column increases it by 1.58%. In case of Group 2 models, characterized by 40 cm joist depth, such improvements are equal to 2.21% for shear walls and 0.67% for square columns. Significantly higher values of Ed/Ein ratio close to 0.901, observed for pure-frame models (KKP01030 in Fig. 13b and KKP01040 in Fig. 13e), indicate high dependence of structure on damping ability in order to meet the needs of earthquakes because of insufficient lateral stiffness; thus, increasing likelihood of plastic behavior occurs. Lower energy ratios obtained for models equipped with square columns and shear walls (namely KKP1030 with 0.887 in Fig. 13a and KKP1040 with 0.839 in Fig. 13d) prove that higher structural stiffness provides more uniform energy distribution among its components. Despite the similarity of comparative energy response characteristics in normal-column structures (NKP1030 in Fig. 13c and NKP1040 in Fig. 13f), the increasing trends of energy levels in square-column models confirm constant damping process due to geometric symmetry. Thus, the above analysis proves that use of square columns and shear walls in the structure provides higher comparative energy response and improves structural behavior during earthquakes.

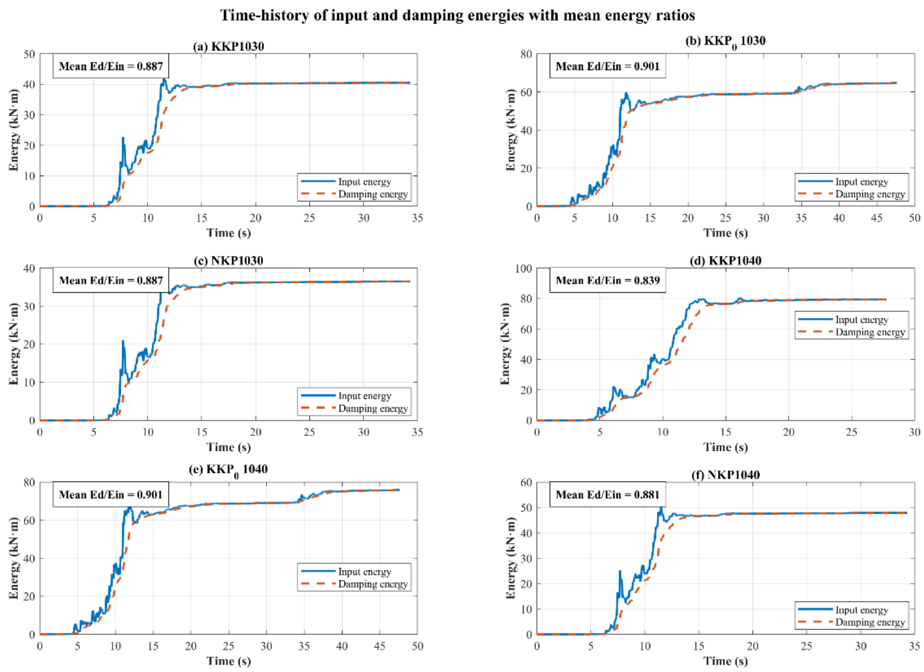


Figure 13. Time-history of input and damping energies with mean energy ratios (E_d/E_{in}) for different structural configurations: (a) KKP1030, (b) KKP$_0$1030, (c) NKP1030, (d) KKP1040, (e) KKP$_0$1040, (f) NKP1040

6. Conclusions

This paper presents a comprehensive assessment of the structural benefits and drawbacks of integrating square columns and shear walls to improve the seismic performance of reinforced concrete buildings featuring hollow block slabs and flat beams. Through linear time history analysis based on various beam depths and square column geometries, it is found out that the lateral stiffness and geometric symmetry are very important criteria to ensure structural integrity within the seismic engineering restrictions. Technically, it can be concluded that the analyzed models with square columns exhibited more balanced bidirectional stiffness characteristics, which increases the seismic resistance of RC buildings without the presence of shear walls.

The main findings of this linear analysis include the following:

- The combination of square columns and shear walls helped to lower inter-story drift ratios by 25-30% with pronounced impact on the upper stories (from the 4th to the 8th floors). Using shear walls individually provided a 30% improvement in inter-story drift while square columns alone gave 23-27%. This result suggests that geometric symmetry may positively influence stiffness distribution.

- When square columns and shear walls were used, there was a significant decrease in the value of the amplification factor (to five times the base acceleration) because frame systems have up to ten-fold increase. The presence of square columns and shear walls helped reduce the whiplash effect to the level that did not lead to a peak floor acceleration of 1.5 g. This indicates that the proposed construction solution reduces the damage caused to the non-structural elements of the building.

- The Fast Fourier Transform analysis showed the transition to a higher frequency when square columns and shear walls were used. In addition, the analysis showed that the peak response frequency with square columns was narrower than with the rectangular ones, which suggests that square columns provided more balanced biaxial stiffness characteristics and reduced weak-axis torsional coupling effects within the investigated structural configurations.

- For frame with 30 cm joists, using shear walls improved damping effectiveness by 5.42%, while square columns – by 1.58%. Based on numerical results, it can be stated that stiffness and geometric symmetry help improve uniform distribution of seismic energy in the structure to avoid excessive energy accumulation.

- The combination of square columns with shear walls and an increased beam depth (40 cm) provides the optimal design for ensuring the seismic resistance since it allows avoiding potential P-Delta instability and working within predictable engineering limitations.

As for further research topics, it seems reasonable to estimate fragility characteristics of buildings with the studied combinations of materials to identify the probability of damage at various seismic intensities. Moreover, performing SSI calculations for hollow block buildings with square columns can be useful in analyzing their performance in terms of soil classes. Finally, studying the economic optimality of implementing square columns compared with adding shear walls would provide valuable results related to reinforcement ratio and usable floor space.

Declaration of Conflict of Interests

The authors declare that there is no conflict of interest. They have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledge

This study was produced from the Master's thesis titled 'Seismic Behavior of Multi-Storey Reinforced Concrete Buildings with Hollow Block Slabs and Flat Beams', completed at Atatürk University.

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How to Cite This Article

Çelebi, O. and Yalçın, A Seismic Performance of Reinforced Concrete Buildings with Hollow Block Slabs and Flat Beams: Combined Effects of Shear Walls, Beam Depth Ratio and Column Type, Brilliant Engineering, 3(2026), 41142.
https://doi.org/10.36937/ben.2026.41142