A Comparative Study of the Seismic Response of Different Concrete Slab Systems for a Multistory Building in Madinah

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ABSTRACT

Seismic analysis is considered as an important aspect of the design of high-rise buildings, particularly in earthquake prone areas. The structural system choice can have a considerable impact on the building seismic response. The goal of this study is to compare the seismic behavior of multiple slab systems used in a multi-story building in Saudi Arabia's Madinah region. This study's goal is to determine the most effective and efficient slab system performance in a seismic zone. The ETABS V20.3 program was used in this work to model and assess the seismic response of three different types of slab systems: flat, solid, and hollow blocks slab types. Many earthquake aspects, including story displacement, base shear, story drifts, column forces, and bending moments, are estimated for each system. The study examines and assesses each system's seismic response, and the conclusions are given and discussed. According to the findings, the choice of slab system has a considerable impact on the seismic reaction of the building. The hollow block system has the least base shear value and bending moments, while the flat slab system has the greatest. The values in the solid slab system are in the middle. In terms of story displacement and column forces, the study additionally indicates that the hollow block type system performs effectively in terms of story drifts, however, the solid slab system outperforms the others. The study's findings can assist designers and engineers to determine the best slab system for multistory buildings in seismic-prone areas by providing important insight and suggestions.

Keywords-story displacement; base shear; column forces; story drift

I. INTRODUCTION

Design and rapid urbanization, driven by increasing population densities, have increased the construction of high-rise structures to meet the growing demand for residential and commercial areas [1]. While these tall structures represent architectural achievements, they are also vulnerable to a wide range of natural and anthropogenic hazards. Seismic disturbances stand out as one of the most crucial challenges [2]. The shear uncertainty and force of earthquakes can wreak havoc, resulting in casualties, property destruction, and far-reaching economic consequences [3, 19]. High-rise structures are intrinsically more vulnerable to the dynamic and uncertain forces generated during seismic occurrences due to their tall stature and significant mass [4, 20]. If not treated properly, the lateral and vertical forces created during such disturbances can cause large strains, potentially leading to structural deficiencies or even catastrophic collapses [5, 21]. As a result, the importance of seismic analysis and design is paramount, as they are critical in guaranteeing the structural integrity and safety of these structures [6, 22]. The slab system and design are essential to this seismic design approach [8, 23]. The slab, as a fundamental horizontal structural component, plays an important role in load distribution and provides the structure with the necessary rigidity [9, 24]. The slab system used can have a significant impact on a building's seismic behavior, modifying its overall mass, stiffness, and intrinsic vibrational frequencies [10, 25]. Slab systems, which range from flat and solid to waffle shapes, each have their own set of advantages and drawbacks, particularly when examined through the lens of architectural flexibility, structural efficacy, and serviceability [11, 26]. In seismically active areas, the importance of carefully selecting the most appropriate and efficient slab system is emphasized [12, 27]. Beyond simply conforming to the architectural and functional requirements of the structure, the slab system must be improved to enhance seismic resistance [13]. This delicate balancing act necessitates a harmonic blend of attractive design, structural robustness, and strict adherence to local building and seismic standards [14].

Developments in structural engineering and material sciences have brought in a variety of improved slab systems and building approaches, many of which promise increased seismic resistance [15]. Base isolation techniques, for example, which are based on the principle of disconnecting the structure from the ground, can significantly reduce the seismic forces transferred to the structure [16]. Concurrently, energy dissipation devices can effectively harness and diffuse seismic energy, reducing strains on the structure [3]. To summarize, as our urban environments become increasingly congested with skyscrapers, the importance of seismic analysis and design in high-rise buildings grows [18]. Safeguarding these structures during seismic disturbances is a societal obligation, not only a technical challenge. The careful selection of a slab system designed for seismic zones is critical in this endeavor, ensuring that cities and their inhabitants are protected from earthquakes.

II. OBJECTIVES OF THE CURRENT WORK

- Assess and compare the seismic performance of three different slab systems: flat slab, solid slab, and hollow block slab.
- Investigate the effects of seismic loads for high-rise buildings using the parameters of bending moment, story shear force, drift, base shear, displacement, deflection, and punching shear.
- Examine the short- and long-term deflections caused by seismic stresses in these slab systems, as well as the material properties in tall structures.
- Determine the most suitable slab system for tall structures in seismic zones, taking safety and construction feasibility into account.

III. METHODOLOGY

A. *Structural Model Analysis*

For comparison, three slab systems were considered: flat, solid, and hollow block slab. For assessing the seismic performance, structural models for each of the slab types have been constructed using modal analysis techniques. Important characteristics such as base shear, story shear force, bending moment, story drift, story deflection, and punching shear have been determined using the structural analysis approach.

B. *Result Comparison*

In the comparison of the structural analysis results for the three slab systems, parameters such as construction cost, seismic performance, and building time were investigated. The primary objective of this research was to find the best slab system for high structures in seismically active areas.

C. *Sensitivity Analysis*

To examine and assess the impact of different design features on the seismic performance of each type of slab, a study was conducted. The investigation attempted to identify the important design characteristics that have a substantial impact on the seismic performance of slab structures.

D. *Result Validation*

To assess the accuracy of the structural analysis results, a comparison was made between the seismic performance for each type of slab and the results from the literature review. This enabled an evaluation of the output's consistency and dependability.

E. *Conclusion*

The most acceptable slab option for high-rise buildings in seismically prone areas was established through comparative and sensitivity research. The seismic performance of the various slab systems was taken into consideration as a part of the decision. This choice is intended to provide the most effective slab construction for more effective earthquake resilience in such locations.

IV. BUILDING SPECIFICATIONS

TABLE I. SPECIFICATIONS OF REINFORCED CONCRETE SLAB SYSTEMS

Specifications	**Slab system type**		
	Flat	**Solid**	**Hollow block**
Total number of storys	7	7	7
Height of a typical floor (m)	3	3	3
Height of the first floor (m)	4	4	4
Total depth of slab (cm)	22	12	28
Maximum span length (m)	3.6	3.6	3.6
Cross-section of beams (cm^2)	50×30	50×30	50×30
Cross-sections of columns (cm^2)	(60, 80, 90, 100, 110)×30		
Size of ribs (cm)	-	-	15
Spacing of ribs (cm)	-	-	55
Compressive strength of concrete (Mpa)	24	24	24
Longitudinal steel rebar	Fy420	Fy420	Fy420
Lateral steel rebar	Fy240	Fy240	Fy240

V. BUILDING DESING LOADS

The multi-story building was designed in accordance with the Saudi building codes for concrete structures. The loads were defined in accordance with SBC 301 for live and dead loads for the specific application and occupancy. The seismic loads were defined using the Static Equivalent Method (SEM) and the Response Spectrum Method (RSE) in accordance with SBC 304C.

A. Dead Loads

- Self-weight of concrete with a density of 24 kN/m^3.
- Superimposed deadloads for the residential and commercial occupancy of 2 kN/m^2.
- Superimposed load of the helicopter pad of 1.2 kN/m^2.

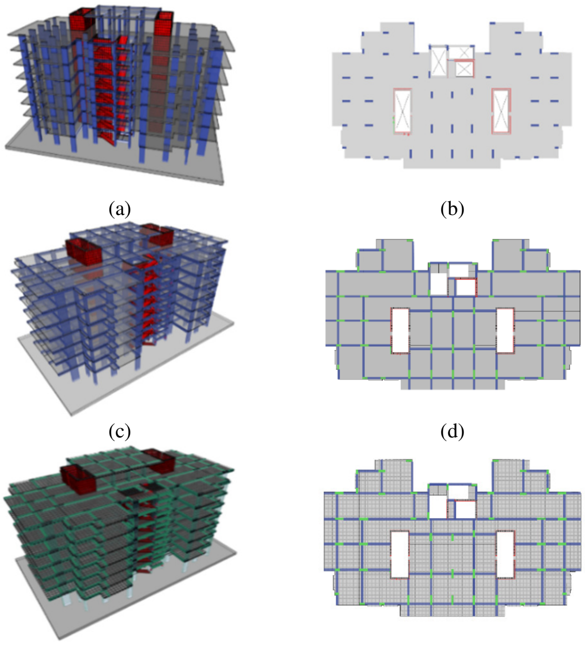
B. Live Loads

- Service live load of floor slabs of 3 kN/m^2.
- Service live load of staircases of 5 kN/m^2.
- Helicopter landing and take-off load of 2.87 kN/m^2.

C. Seismic Loads

- Spectral response acceleration, SDS = 0.254
- Spectral response acceleration, SD1 = 0.073
- Transition period = 4
- Site class: B
- Seismic occupancy importance factor, I = 1.25
- Response modification factor(s), R = 4
- System overstrength factor = 2.5

VI. STRUCTURAL ANALYSIS MODELS



(a) (b)

(c) (d)

(e) (f)

Fig. 1. ETABS Software Model: (a)-(b) Flat, (c)-(d) solid, (e)-(f) hollow block slab.

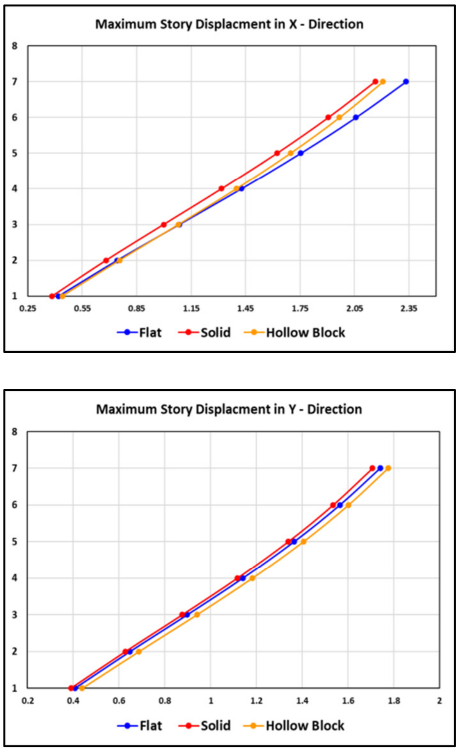
VII. SLABS STRUCTURAL RESPONSE COMPARISON

A. Story Displacement Comparison

Among the three slab systems, the flat slab has the greatest x-direction story displacement, with a maximum displacement in story 7 of 2.334 mm. In the solid slab system, the least amount of displacement of 2.164 mm is found in story 7, as illustrated in Figure 2. The hollow block slab has the maximum story displacement in the y-direction of 1.776 mm in story 7. The least displacement is found to be 1.707 mm in story 7 for the solid slab system.

TABLE II. SPECIFICATIONS OF REINFORCED CONCRETE SLAB SYSTEMS

Story	**Flat Slab**		**Solid slab**		**Hollow block slab**	
Unit	**mm**		**mm**		**mm**	
Direction	**x**	**y**	**x**	**y**	**x**	**y**
7	2.334	1.741	2.164	1.707	2.207	1.776
6	2.058	1.565	1.906	1.535	1.967	1.603
5	1.754	1.365	1.623	1.339	1.697	1.406
4	1.427	1.141	1.317	1.117	1.399	1.183
3	1.085	0.898	0.998	0.876	1.080	0.940
2	0.743	0.648	0.681	0.628	0.755	0.687
1	0.42	0.407	0.384	0.390	0.440	0.439



(a)

(b)

Fig. 2. Maximum story displacment in (a) x and (b) y direction.

B. Base Shear Reactions Comparison

The hollow block slab has the highest base shear reactions according to the RSE analysis, with 712.33 kN in the x- and 921.26 kN in the y-direction. As demonstrated in Figure 3, the solid slab system has the lowest base shear values of 623.72 kN and 799.91 kN in the x- and y-direction, respectively.

C. Story Drift Comparison

The flat slab system exhibits the maximum story drift in the X-direction due to the response spectrum, with a ratio of 0.000114 between stories 3 and 4, as shown in Figure 4.

TABLE III. BASE SHEAR COMPARISON FOR RESPONSE SPECTRUM

Unit	kN	
Direction	x	y
Flat	641.055	839.706
Solid	623.719	799.906
Hollow block	712.331	921.262

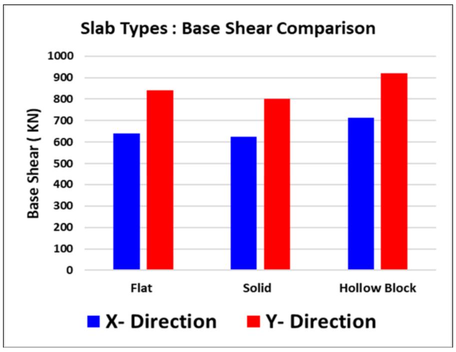


Fig. 3. Base shear comparison of slab types.

TABLE IV. MAXIMUM STORY DRIFTS FOR RESPONSE SPECTRUM IN THE X-DIRECTION

Slab type	**Flat**	**Solid**	**Hollow block**
Unit	mm/mm	mm/mm	mm/mm
Story	x - direction		
7	0.000092	0.000086	0.000073
6	0.000102	0.000095	0.000082
5	0.00011	0.000102	0.000091
4	0.000114	0.000107	0.000097
3	0.000114	0.000106	0.000099
2	0.000108	0.0001	0.000096
1	0.000085	0.000078	0.00008

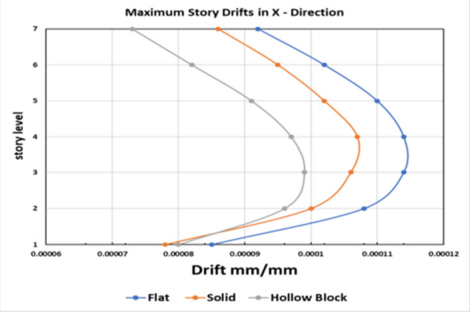


Fig. 4. Maximum story drifts in the x - direction.

Because of the geometry of the multistory building, the values of story drifts in the y-direction are nearly the same for all types of slabs, as illustrated in Figure 5.

D. *Maximum Column Forces*

Maximum column force reactions are evaluated in relation to the maximum applied design loads on reinforced concrete columns at the bottom of each column for each floor. Column C32 was chosen because it has the highest resultant force values of any slab type. It has a tributary area of 0.64 m^2 and stretches from story 1 to story 7. The hollow block slab had the highest axial load at 1239.65 kN in story 6, whereas the solid slab had the lowest at 725.16 kN in level 5. In story 1, the hollow block slab has the highest shear force of 1278.1 kN, whereas the solid slab has the lowest shear force of 1077.57 kN in story 1 as shown in Table VI.

TABLE V. MAXIMUM STORY DRIFTS FOR RESPONSE SPECTRUM IN THE X-DIRECTION

Slab type	**Flat**	**Solid**	**Hollow block**
Unit	mm/mm	mm/mm	mm/mm
Story	x - direction		
7	0.000061	0.000059	0.000058
6	0.000069	0.000068	0.000066
5	0.000077	0.000076	0.000075
4	0.000083	0.000083	0.000081
3	0.000085	0.000085	0.000085
2	0.000083	0.000082	0.000083
1	0.00007	0.000067	0.000072

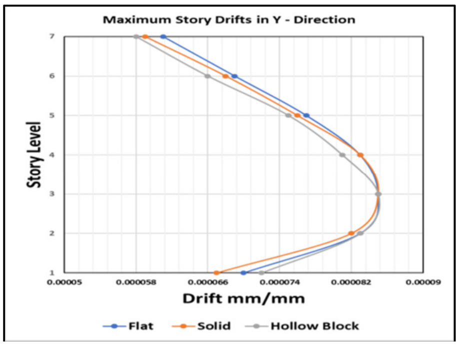


Fig. 5. Maximum story drifts in the y - direction.

E. *Maximum Bending Moment*

At the bottom of each column, the maximum bending moment reactions are calculated. For all slab types, one column with the greatest resulting bending moment was chosen. As indicated in Table VII, the maximum bending moment resultant value is found in the Hollow Block slab at 3116.21 kN-m in story 1, while the lowest value is found in the Solid slab at 2630.64 kN-m in story 1.

TABLE VI. COLUMN MAXIMUM DESIGN FORCES

Slab type	**Flat**			**Solid**			**Hollow block**		
Force	P	V2	V3	P	V2	V3	P	V2	V3
Unit	kN	kN	kN	kN	kN	kN	kN	kN	kN
Story 7	-797.32	27.71	-50.69	578.42	-98.08	-7.89	964.00	-70.10	263.42
Story 6	-929.53	-22.84	-338.78	697.34	13.91	347.09	1239.66	15.60	415.52
Story 5	-900.26	-57.67	207.20	725.16	104.63	-88.25	1212.96	77.28	-250.12
Story 4	-676.19	-16.25	613.24	547.07	66.88	-518.17	789.00	37.14	-765.33
Story 3	-403.65	31.93	471.59	258.67	-20.06	-477.52	243.00	-31.42	-601.25
Story 2	-291.74	29.56	28.30	108.58	-55.33	-51.37	9.21	-42.11	12.39
Story 1	-429.41	-25.48	-1239.70	255.21	0.77	1077.57	290.56	18.31	1278.10

TABLE VII. COLUMN MAXIMUM DESIGN MOMENTS

Slab type	**Flat**		**Solid**		**Hollow block**	
Story	**M2**	**M3**	**M2**	**M3**	**M2**	**M3**
	(kN-m)					
7	-716.42	76.92	442.08	-181.45	883.31	-124.14
6	-1439.98	-7.70	1149.57	-10.89	1495.66	7.38
5	-813.73	-83.36	777.12	148.77	697.55	112.89
4	667.95	-44.28	-467.03	119.29	-887.78	66.90
3	1622.07	33.43	-1385.84	-11.50	-1750.41	-38.04
2	1536.32	52.03	-1315.40	-85.55	-1363.79	-67.10
1	-3115.16	-50.78	2630.64	-0.03	3116.21	38.13

VIII. CONCLUSIONS

Previous research has explored the effects of seismic loads on several concrete slab systems, such as the flat slab system, the solid slab system, and the hollow block slab system, with the aim of better understanding the reaction of multistory building designs that use these diverse slab systems. In comparison to previous research findings, the current study considered several critical Saudi building code factors, including story displacement, story drift, column force, base shear, and bending moments. The solid slab system demonstrated the least displacement, being 7.3% less than that of the flat slab method. Furthermore, the solid slab system displayed 13.2% less base shear than the hollow block slab system.

In addition, compared to the hollow block slab system, the solid slab system displayed the lowest axial column forces, with a 42% reduction. When compared to the hollow block slab system, it had the lowest bending moments, with a 16% reduction. The hollow block slab system showed the lowest story drift, with a 15% reduction when compared to the flat slab system. Despite these findings, it is critical to recognize the study's limitations. The study was limited to Saudi construction restrictions and did not account for possible changes in seismic conditions between locations.

IX. POSSIBLE FUTURE RESEARCH DIRECTIONS

Considering the current results and the constantly evolving discipline of structural engineering, the following areas identify as promising for future research:

- Long-Term Durability and Effects: A more comprehensive investigation of the long-term resilience of various slab systems is necessary. This requires assessing their durability, especially when subjected to frequent seismic disturbances over a long period of time.
- Analysis of Dynamic Response: A thorough investigation into the dynamic properties of these structural systems is required. Understanding their nonlinear responses under a range of earthquake conditions could reveal insight into their adaptability and robustness.
- Construction Material Innovations: With the rapid technical advances in construction materials, there is an exciting opportunity to investigate the integration of innovative materials or hybrid systems. Such research could potentially reveal construction approaches that considerably improve structural seismic performance.

These directions not only correspond to the current research environment, but, also aim to address some of the most pressing difficulties in seismic engineering.

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