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Dynamic Analysis of Structures Considering Waffle Slab with and without Drops and Beams

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Abstract

The seismic performance of a structure is a fundamental and vital aspect of structural engineering, carrying significant importance in ensuring safety and stability. This study investigates the dynamic behavior of structures employing waffle slab designs with and without drops and beams, focusing on varying panel sizes. Commercial buildings, each comprising 12 stories with heights of 3.5 m, were analyzed using the response spectrum method in seismic zone III, utilizing ETABS software. Parameters such as lateral displacement, story shear, story drift, and overturning moment were assessed across different seismic zones. The analysis revealed that waffle slab designs consistently reduce displacement, with waffle slabs featuring beams showing a significant reduction of approximately 67.48% at an 8-m span compared to those without drops and beams. Waffle slabs with drops generally decrease story shear, while waffle slabs with beams tend to increase it. Overall, waffle slab designs incorporating beams demonstrate superior performance in terms of displacement reduction and story shear across all span lengths, indicating their effectiveness in enhancing structural performance and stability. Hence, structures utilizing waffle slabs with beams can be deemed more efficient in meeting structural requirements compared to those employing waffle slabs with drops or without drops and beams.

Keywords: Dynamic analysis, waffle slab, drop panels, beams, response spectrum method, multistory structures, comparative study

INTRODUCTION

Buildings and bridges require a floor slab to provide protection for occupants and for the vehicles to pass through, respectively. Concrete is the ideal material of choice for the slab because its mass and stiffness can be used to reduce deflections and vibrations of the floor system and to provide the required fire protection. Slabs can be simply supported, continuous, or cantilevered. Slabs are supported on beams, which are, in turn, supported by columns. They are classified in many ways such as one-way, two-way, flat plates, flat slabs, waffle slabs, and ribbed (joist) slabs. This research aims to comprehend how the structure behaves when a waffle slab design with solid head/drop panel and beams. It involves a step-by-step process of modeling and analyzing structures with waffle slabs with different panel sizes consisting 12 stories.

The dynamic behavior of a structure under both gravitational and lateral loads depends on various factors in seismic Zone III. Structures designed primarily for gravitational loads may not withstand the horizontal ground vibrations during an earthquake. Therefore, it is vital to ensure the structure's adequacy against horizontal ground vibrations. Consequently, this research focuses on examining the behavior of multi-story reinforced concrete framed buildings with and without drops and beams concerning different responses such as lateral displacement and story shear.

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WAFFLE SLAB

Waffle slab is an arrangement of intersecting beams spaced at regular intervals in perpendicular directions, linked to a slab with a nominal thickness cast monolithic with the concrete slab as shown in Figure 1. These slabs are commonly used to cover spacious areas without the need for many columns, making them a preferred choice for venues such as public assembly halls. They are suitable for large panels with spans greater than 8 m and are more often used as floor or roof systems for large assembly halls and auditoriums. Waffle slabs offer large column-free areas and are ideally suited for concealed architectural lighting as shown in Figure 1; the coffered soffits are aesthetically superior to other floor systems. It is more economical to space the grid beams at larger intervals, in the range of 1 m to 2.5 m. The drop panel is defined as the slab's thickened part above the supporting column. This structural element is employed to resist punching shear forces, which are most pronounced at the intersection of a column and the slab. It serves to counteract the predominant punching shear forces that occur at the junction of the column and the slab. Drop is used to resist stresses induced due to bending moment and shear.

LITERATURE REVIEW

Technical papers on the waffle slab have been presented in various literature. The review paper addresses multiple aspects, including the dynamic analysis of multi-level reinforced concrete (RC) buildings featuring waffle slabs in seismic zones. The following section discusses some previous studies on dynamic analysis of structures considering waffle slabs.

Grace and Kennedy [1] examined the dynamic response and fatigue behavior of rectangular and skew prestressed concrete waffle slabs, often used in bridge decks and semiconductor manufacturing floors. The research derives a solution for dynamic response based on orthotropic plate theory and validates it through experiments on two waffle slab models. A parametric study revealed that prestressing boosts natural frequencies and prolongs fatigue life, enabling designers to avoid resonance and economize on dynamic load allowances.

Rodriguez et al. [2] investigated a two-story model structure with waffle-flat-plate reinforced concrete experienced simulated severe earthquake loading. The test structure, typical of Mexico City architecture, suffered severe flexural and shear damage in columns and notable flexural distress in waffle slabs. Its low lateral stiffness, not accurately accounted for in building codes, suggested inadequate seismic performance, emphasizing the necessity for added bracing or structural walls for better resilience.

Hoffman et al. [3] explained waffle flat slabs, using a two-way joist system, that they offer economical construction with uniform depth and void spaces for lighting or ventilation fixtures. Common configurations include combining joists with solid column heads or wide beam sections for shear transfer and reinforcement concentration. Standard reusable form sizes, within code limitations, ensure industry-wide compatibility. Custom forms are necessary for nonstandard sizes. Higher concrete shear strength is permissible within dimensional limits. Waffle slab forms are available in various depths and span lengths, providing flexibility in design and construction.

Figure 1. Waffle slabs.

Abdul-Wahab and Khalil [4] presented findings from experiments on reinforced concrete waffle slabs, focusing on square rib layouts. Tests on eight models with varying rib spacing and depth were conducted, along with examining the "equivalent thickness" concept. Results of rigidity tests were compared to predictions from three methods. Conventional theory gave satisfactory predictions but had complex procedures. The "equivalent thickness" approach provided moderately higher rigidity values. An alternative simplified method based on the "effective modulus of elasticity" is proposed, yielding safe and close predictions.

Mosalam and Naito [5] presented experimental findings on perforated waffle-slab systems designed for heavy gravity loads, focusing on an industrial facility. Two reduced-scale specimens, modeling half the height of an interior column, were tested. Lateral loading was applied for seismic evaluation, revealing high deformation ductility with minor damage. Failure was characterized by stable plastic hinging at the column-waffle slab junction. The study emphasizes modeling the structural response at this junction, particularly discussing moment transfer between the column and floor joists using curvature distributions.

Benavent-Climent et al. [6] examined the seismic performance of interior connections in older reinforced concrete waffle-flat-plate structures under moderate gravity loads, typical of earthquakes in the Mediterranean region. A scaled test model representative of a six-story building was subjected to gravity and cyclic loading until failure. Results suggest that ACI (American Concrete Institute) 318-05 code predictions for connection strength are adequate but recommend against varying prescribed parameters. Additionally, the lateral drift at initial yielding exceeds Eurocode 8 limits. Ultimate drift and energy dissipation capacities are also discussed.

Ibrahim et al. [7] addressed the lack of specific design recommendations for waffle slabs. They highlighted how current practices generalize rib contributions and apply flat slab guidelines. Additionally, it explores the insufficient understanding of how openings affect waffle slab responses. Through numerical simulations using ANSYS, the study investigates both plain and open waffle slabs, verifying the model against experimental data. The objectives include deriving design coefficients for waffle slab components and assessing their deviation from ACI code suggestions, alongside examining how openings influence these coefficients. Ninety-six linear and nonlinear ANSYS models were employed, evaluating parameters such as column size, solid portion dimensions, and opening characteristics. The study proposed simple multipliers to adjust ACI-recommended moment coefficients accordingly.

Nie et al. [8] introduced a novel composite waffle slab design comprising steel girders and prefabricated RC slabs, aimed at reducing concrete cracking and accelerating construction. Experimental tests confirm excellent ductility and load-bearing capacity. A mixed finite-element model is proposed to predict slab behavior, followed by parameter analyses. Simplified formulas for ultimate capacity are derived, providing practical design recommendations for engineers.

Alraie and Barik [9] investigated the impact of continuity on reduction factors for bending moments and shear forces in grid slabs. While international codes like the Syrian code provide reduction factors for simply supported slabs, they do not cover cases with continuity. Using SAP 2000 software, the study investigated various levels of continuity in grid slabs. Different slab sizes and percentages of continuity are analyzed, demonstrating that considering continuity leads to more economical designs.

Latha and Pratibha [10] studied grid slabs, featuring regularly spaced ribs integrated with the slab, were investigated. These slabs are commonly utilized in architectural designs for large spaces, where internal columns are undesirable, such as in public assembly halls and auditoriums. The study focused on square voided patterns. A 12-story structure with symmetric and asymmetric configurations was considered. Both conventional slabs and grid slabs were analyzed and compared under gravity and lateral load conditions according to Indian Standards (IS) codes. The analysis was performed using ETABS software, with static analysis conducted for regular and plan irregular structures and dynamic analysis for vertical irregular structures. Results were compared for parameters, including deflection, story shear, displacement, and story stiffness between conventional slabs and grid slabs.

Nishanth et al. [11] explained that earthquakes significantly influence structural analysis and design. Manual processes for analysis and design are time-consuming, whereas software enables quicker outcomes. This study aimed to analyze and design a commercial building with different slab arrangements: conventional slab, flat slab with drop panels, grid/waffle slab, and load-bearing wall structures. Analysis considered seismic and wind forces using ETABS software, adhering to IS 456-2000 standards. M30 concrete grade and Fe-500 steel were used, with load combinations from IS: 875-part 5 (2015). Concerns such as story drift, base shear, and displacement were assessed. Results, presented through tables and bar charts, indicated increased story displacement with height. The grid slab demonstrated stability and cost-effectiveness compared to other arrangements under wind and seismic loads.

Nithyambigai et al, [12] investigated waffle slabs, lighter than solid slabs due to their voids. Economical for long spans (5–6 m) with light to moderate live loads, they reduce concrete usage and dead load while increasing load-bearing capacity. This allows for smaller column and footing sizes. Literature review revealed variations in beam spacing, depth, and analytical findings. The project cast and tested waffle slab systems with various grid beam spacings to assess load-carrying capacity.

Lee et al. [13] explained in response to the CO_2 emissions associated with building materials, this study proposed an eco-friendly and cost-effective design model (EEODM) for waffle slabs in large structures like stores and malls. The EEODM aimed to minimize CO_2 emissions and costs for long-span waffle slabs. Through analysis of 20 slab types, qualitative scales CEEA (CO_2 emission efficiency analysis) and CEA (cost-efficiency analysis) were introduced to assess environmental and economic feasibility. A new design standard was proposed based on these analyses. Application of the EEODM to Gimpo International Airport's waffle slab showed reduced emissions and costs compared to existing sections.

Besjak et al. [14] studied the new Integrated Terminal Building at Mumbai’s Chhatrapati Shivaji International Airport that combined international and domestic operations, increasing capacity to 40 million passengers per annum upon its completion in 2014. The primary design feature was its expansive long-span roof, covering 70,000 m^2 without expansion joints, supported by only 30 columns. By optimizing truss depth and configuration, large column-free spaces were achieved, along with cantilevers of up to 40 m. Mega-columns also served as hoist mechanisms for construction. The building featured the world's largest cable wall system, and structural studies included finite element analysis for connection optimization. Additionally, modular construction was prioritized for efficiency and an accelerated construction schedule.

Teodosio et al. [15] studied in response to the lack of consideration for environmental and economic factors in residential foundation slab design, this study developed MOUNDS, a tool predicting embodied energy, carbon emissions, life cycle cost, and deflection of waffle and stiffened rafts. MOUNDS considered these criteria across various soil reactivities. Analyzing Australian residential slab design codes, it determined waffle rafts as more sustainable and serviceable, especially in slight-to-moderate reactive sites. In highly reactive sites, differences were minimal, not meeting serviceability limits. This study employed machine learning to link and predict the multidisciplinary relationship between environmental, economic, and structural aspects of residential slabs, aiding decision-making in design phases.

A literature review was conducted to gather information on structural analysis methods. In the analyzed papers, comparisons between flat slabs, grid slabs and conventional slabs were made for various factors such as geographical zones, building heights, irregularities (plan and vertical), span lengths, and slab thickness, all in accordance with Indian standards. ETABS and STAAD PRO software were frequently used for analysis. Different methods of analysis, including equivalent static analysis, nonlinear static analysis, response spectrum method, and time history method, were applied in modeling and assessing these structures.

Overall, the literature suggested that regular structures with waffle slabs tend to perform well. However, there is limited research on waffle slabs with drops and beams, across varying in span sizes. Based on the available literatures, this study focuses on analyzing and comparing waffle slabs for both with and without drops and beams in different panel sizes including parameters such as lateral displacement, story shear, story drift and overturning moment.

AIMS AND OBJECTIVES

The specific objectives of the research are:

- To study the dynamic behavior of structures considering waffle slabs with and without drops and beams, across varying panel size by using response spectrum method in seismic Zone III using ETABS software.
- To compare the results of critical parameters such as as lateral displacement and story shear.

SYSTEM DEVELOPMENT

The current study demonstrates the dynamic behavior of commercial buildings featuring waffle slabs, with and without drops and beams. The buildings were designed with different panel sizes (i.e., 8 m × 8 m, 10 m × 10 m, 12 m × 12 m and 15 m × 15 m) and consisted of 12 stories, with each story having a height of 3.5 m. Design parameters were based on IS 456:2000 standards, and structural analysis was performed using the response spectrum method for both gravitational and lateral loading conditions, following IS 875:2000 (all parts) and IS 1893:2016 guidelines. The analysis was conducted in various seismic zones using ETABS software [16–18].

Linear dynamic analysis was carried out for each building model using the response spectrum method to assess structural responses to seismic excitation. Key performance indicators, including as lateral displacement, story shear, were evaluated for each structural system and building height across all seismic zones. This comprehensive analysis aimed to provide insights into the behavior of the buildings under seismic loads, allowing for informed design decisions and ensuring structural safety in different seismic regions.

The analysis and design process involves the following steps:

1. Modeling
2. Analysis phase (in accordance with IS methods)
3. Design phase

STRUCTURE DESCRIPTIONS

In the current study, the commercial building of structures of considering waffle slab with and without drops and beam is considered with different panel sizes (i.e., 8 m × 8 m, 10 m × 10 m, 12 m × 12 m, and 15 m × 15 m) and consisted of 12 stories, with each story having a height of 3.5 m are designed. Some basic structure description to design the waffle slab are shown in Table 1 and sectional view of waffle slab is shown in Figure 2.

LOADING CONDITIONS

The careful consideration of loading condition is the main aspect of structural analysis. The analysis and design processes are done based on the loading conditions on the basis of IS code. The loading conditions are calculated for a structural analysis purpose and are detailed in Tables 2 and 3.

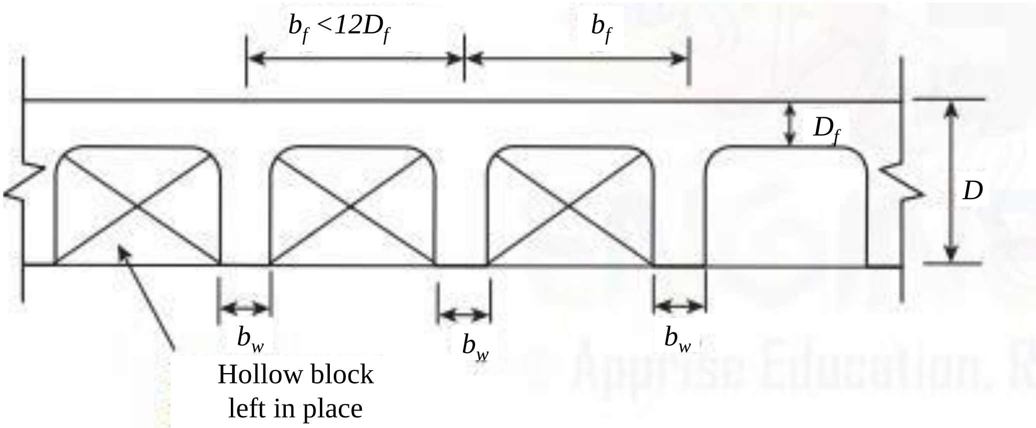

Figure 2. Sectional view of waffle slab.

Table 1. Structure descriptions.

S.N.	Specification	Value				
Geometry Definition						
1	Panel sizes	8 m × 8 m, 10 m × 10 m, 12 m × 12 m, and 15 m × 15 m				
2	Floor to floor height (each story height)	3.5 m				
3	Bottom story height	2 m				
4	Number of stories	12				
5	Total height of building	40.5 m				
6	Thickness of partition walls	150 mm				
7	Beam size	0.45 m × 0.9 m				
8	Column sizes	1 m × 1 m, 0.85 m × 0.85 m				
Size of Ribs						***IS Code Recommendation***
9	Panel size	8 m	10 m	12 m	15 m	
10	Center to center spacing between two ribs (bf)	1.0 m	1.05 m	1.1 m	1.2 m	1 m to 1.5 m; >12 × depth of topping
11	Width of rib (bw)	75mm	100 mm	125 mm	150 mm	> 65 mm
12	Depth of rib (Dw)	215 mm	260 mm	325 mm	420 mm	<4 × Width of Rib
13	Depth of topping (Df)	85 mm	90 mm	95 mm	100 mm	>50 mm; less than spacing of ribs /10
14	Total depth of rib (D)	300 mm	350 mm	420 mm	520 mm	Depth of rib + depth of topping
Size of Drops/Solid Head						
15	Drop panel size	4 m × 4 m	5 m × 5 m	6 m × 6 m	7.5 m ×7.5 m	Span length/2
16	Drop panel thickness	300 mm	350 mm	420 mm	520 mm	Equal to total depth of rib
Material Properties						
17	Grade of concrete			M30		
18	Grade of steel (HYSD rebar)			Fe500		
19	Density of concrete			25 kN/m^3		
20	Density of lightweight brick			10 kN/m^3		

DEAD LOAD

Dead loads are gravitational load refers to the self-weight of various structure and its components indicated in Table 2 (1) according to IS 875 (Part 1): 2015.

LIVE LOAD

Live loads are gravitational loads resulting from the use and occupancy of the building or structures. This includes the weight of all movable loads such as people, tools, miscellaneous equipment, movable partitions, storage materials, etc. The live loads considered in the structure, according to IS 875 (Part 2): 2015 Code, are tabulated in Table 2 (2).

WIND LOADS

Wind loads are lateral load refers to the force exerted by wind on a structure and calculated according to the provisions specified in IS 875 (Part 3): 2015. Wind load parameters are provided in Table 2 (3).

The design wind pressure is calculated as:

Pd = - kd × ka × kc × 0.6 Vz2

EARTHQUAKE LOADS

Earthquake loads are lateral load and generated by the response of the structure to the design spectrum as specified in IS 1893 (Part 1): 2016. The building site is considered in all earthquake zone. The masses considered in the structure that generate earthquake loads include the dead weight of permanent construction and 50% of the live load, as tabulated in Table 2 (4).

RESPONSE SPECTRUM METHOD

The response spectrum method is a linear dynamic analysis technique that directly derives a structure's peak responses during an earthquake from the seismic forces acting upon it. The maximum response is then plotted against the un-damped natural period, considering different damping values. This response can be expressed in terms of maximum relative velocity or maximum relative displacement. In this study, we employ the response spectrum method to analyze 12 different models with varying slab arrangements. We examine parameters like as lateral displacement and story shear.

PLAN AND 3D VIEW OF MODEL

The plan layout and three-dimensional (3D) views of commercial buildings were designed with different panel sizes like 8 m × 8 m, 10 m × 10 m, 12 m × 12 m, and 15 m × 15 m and consisted of 12 stories, with each story having a height of 3.5 m are detailed in Figures 3 to 14. These structural models were designed by using ETABS software.

Table 2. Loading conditions.

S.N.	Loads	Specification	Value	IS Code
1	Dead load	Self-weight factor	1.0 kN/m^2	IS 875 (Part 1)
		Floor finish load	6.32 kN/m^2	
2	Live load	Live load	3 kN/m^2	IS 875 (Part 2)
3	Wind load	Terrain category	2	IS 875 (Part 3)
		Windward coefficient (Cp)	0.8	
		Leeward coefficient (Cp)	0.5	
		Internal pressure coefficient (Cpi)	+/-0.5	
		Wind speed	55 m/s	
		Risk coefficient (K1)	1	
		Terrain, height, and structure size factor (K2)	As per building height	
		Topography factor (K3)	1	
		Directionality factor (Kd)	0.9	
		Area averaging factor (Ka)	0.8	
		Combination factor (Kc)	0.9	
		Structural class- (for 20 m to 50 m building height)	B	
4	Earthquake load	Seismic zone	III	IS 1893 (Part 1)
		Zone factor	0.16	
		Response reduction factor	5	
		Importance factor	1.5	
		Soil type	Medium	
		Damping ratio	5%	

DESCRIPTION OF MODELS

Below is the complete list of all 12 models shown in Figures 3 to 14.

Model 1: Structure of 8 m span of waffle slab without drops and beams consisting of 12 stories

Model 2: Structure of 8 m span of waffle slab with drops consisting of 12 stories

Model 3: Structure of 8 m span of waffle slab with beams consisting of 12 stories

Model 4: Structure of 10 m span of waffle slab without drops and beams consisting of 12 stories

Model 5: Structure of 10 m span of waffle slab with drops consisting of 12 stories

Model 6: Structure of 10 m span of waffle slab with beams consisting of 12 stories

Model 7: Structure of 12 m span of waffle slab without drops and beams consisting of 12 stories

Model 8: Structure of 12 m span of waffle slab with drops consisting of 12 stories

Model 9: Structure of 12 m span of waffle slab with beams consisting of 12 stories

Model 10: Structure of 15 m span of waffle slab without drops and beams consisting of 12 stories

Model 11: Structure of 15 m span of waffle slab with drops consisting of 12 stories

Model 12: Structure of 15 m span of waffle slab with beams consisting of 12 stories

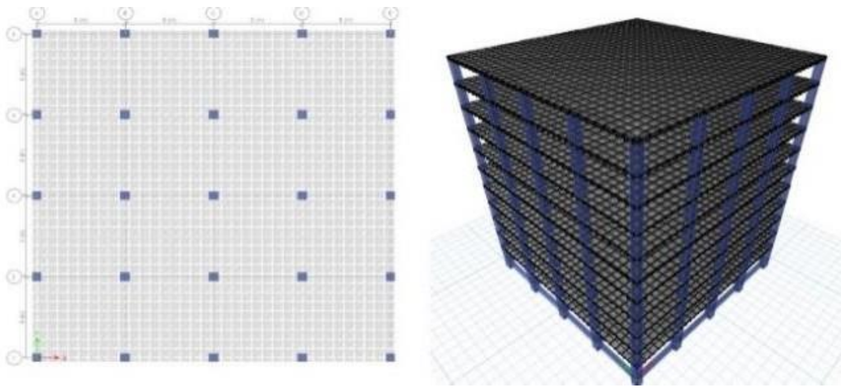

Figure 3. Model 1.

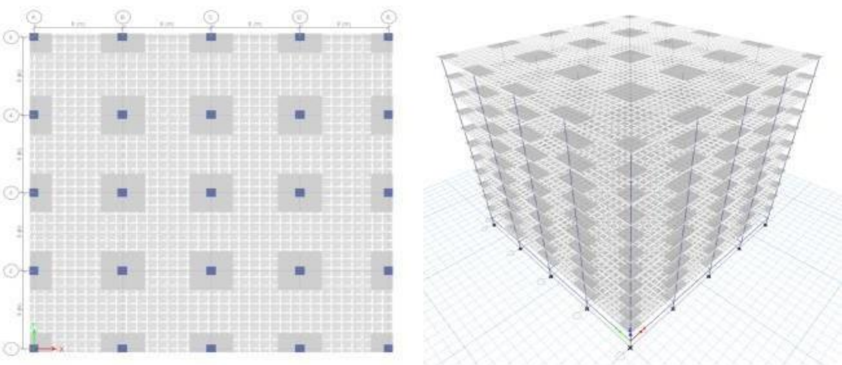

Figure 4. Model 2.

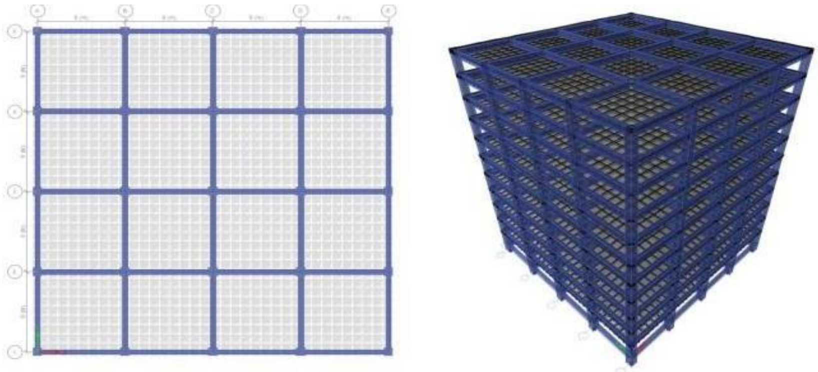

Figure 5. Model 3.

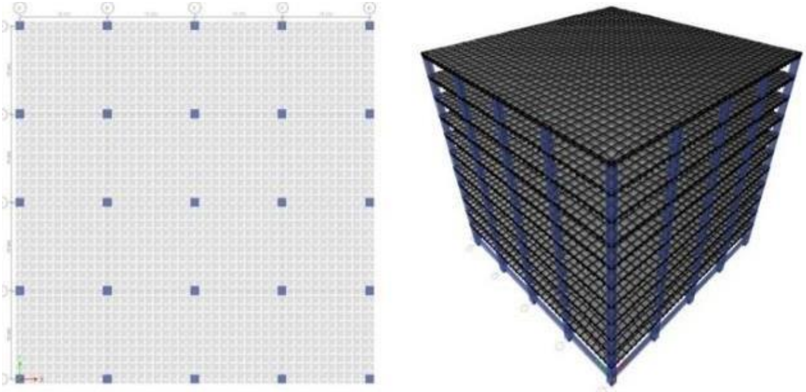

Figure 6. Model 4.

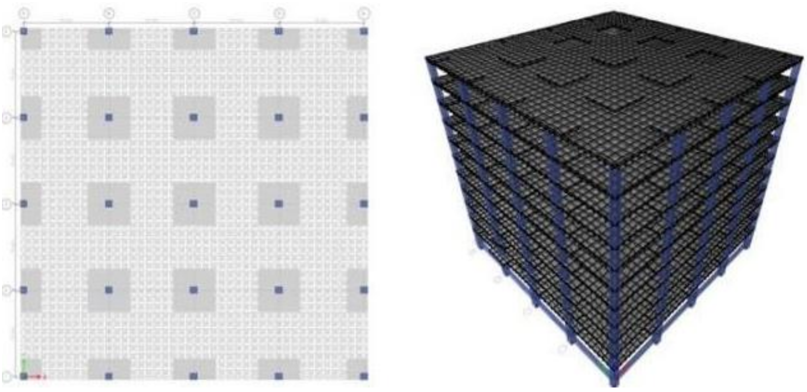

Figure 7. Model 5.

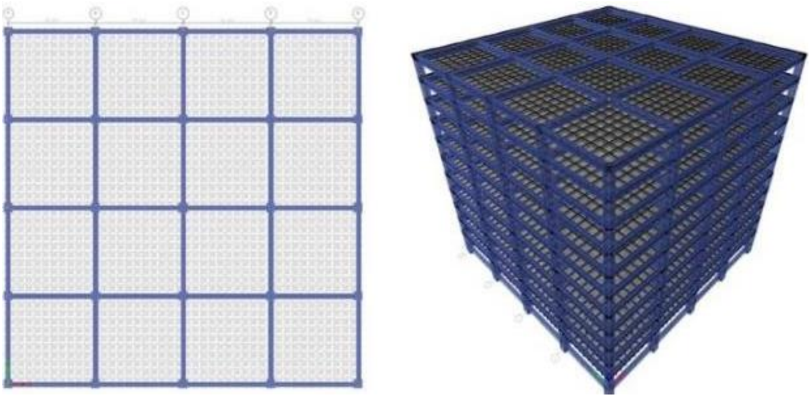

Figure 8. Model 6.

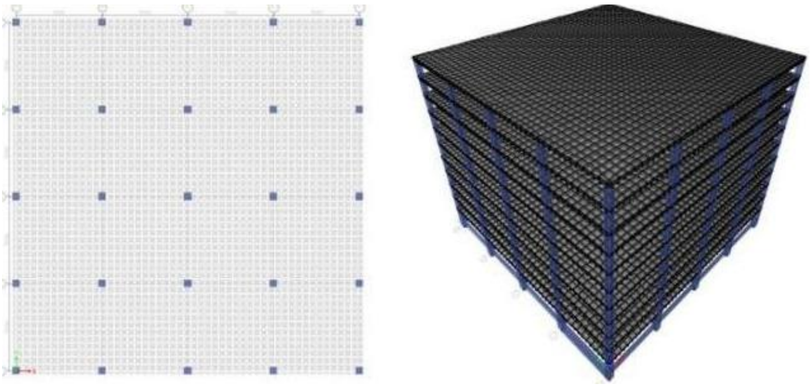

Figure 9. Model 7.

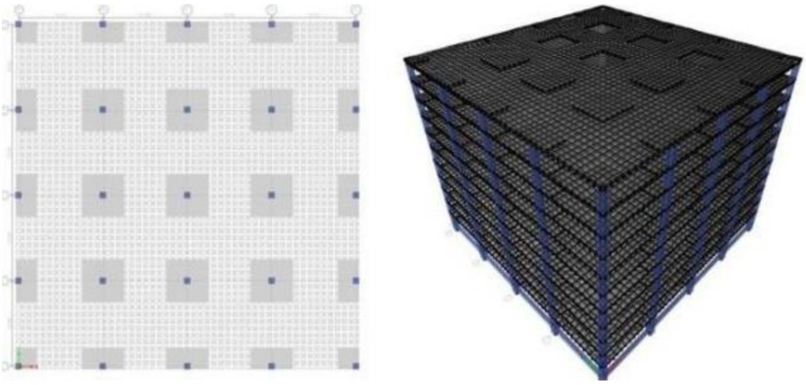

Figure 10. Model 8.

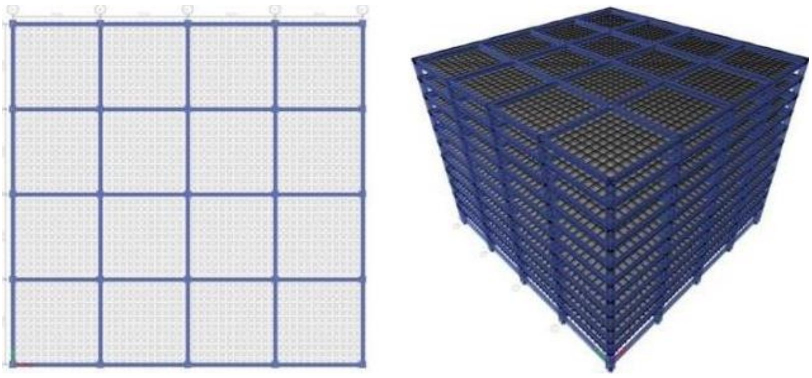

Figure 11. Model 9.

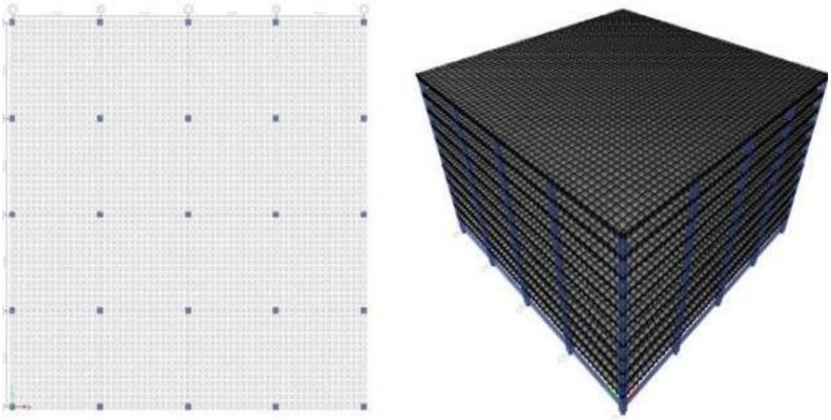

Figure 12. Model 10.

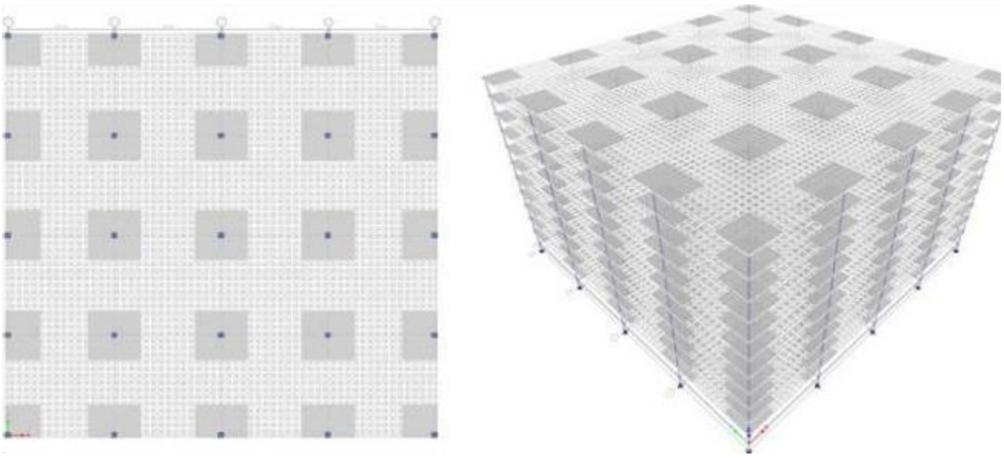

Figure 13. Model 11.

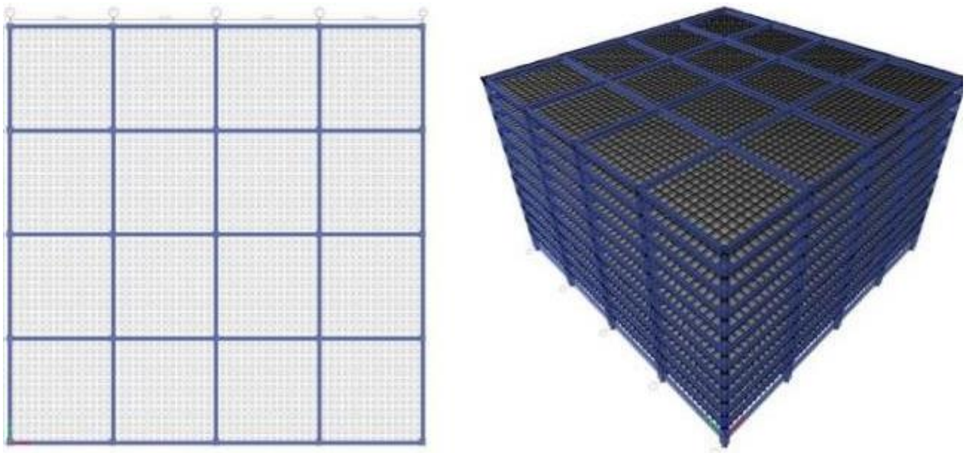

Figure 14. Model 12.

RESULTS AND DISCUSSION

In the current study, a dynamic analysis is conducted on a prospective 12-story building, which incorporates both Waffle Slab SYSTEMS with and without drops, across varying span sizes. The investigation utilizes the response spectrum method across seismic Zone III to obtain results. The evaluation of seismic performance entails classifying bifurcations, considering factors such as lateral displacement and story shear.

Lateral Displacement

For the study, lateral displacements were considered which were caused due to dynamic forces. The displacements have been compared here so as to evaluate the displacement controlling capability of structure of waffle slab with and without drops and beams during dynamically activated condition as shown in below.

Lateral Displacement Comparison for 8 m Span

The comparison for lateral displacements from models using waffle slab systems with and without drops and beams for 8 m × 8 m is detailed in Table 3, and Figure 15 visually represents these findings for enhanced clarity.

Lateral Displacement Comparison for 10 m Span

The comparison for lateral displacements from models using waffle slab systems with and without drops and beams for 10 m × 10 m is detailed in Table 4, and Figure 16 visually represents these findings for enhanced clarity.

Table 3. Comparison of lateral displacement for the studied structure for 8 m span.

No. of Floors	Story Height (m)	Without Drops and Beams	With Drops	With Beams
Story 12	40.5	69.271	63.036	22.509
Story 11	37	61.292	59.579	21.858
Story 10	33.5	53.193	55.373	20.837
Story 9	30	45.029	50.24	19.407
Story 8	26.5	36.949	44.178	17.579
Story 7	23	29.187	37.318	15.382
Story 6	19.5	22.048	29.917	12.853
Story 5	16	15.645	22.459	10.23
Story 4	12.5	9.994	15.25	7.489
Story 3	9	5.351	8.739	4.74
Story 2	5.5	2	3.54	2.212
Story 1	2	0.25	0.493	0.374
Base	0	0	0	0

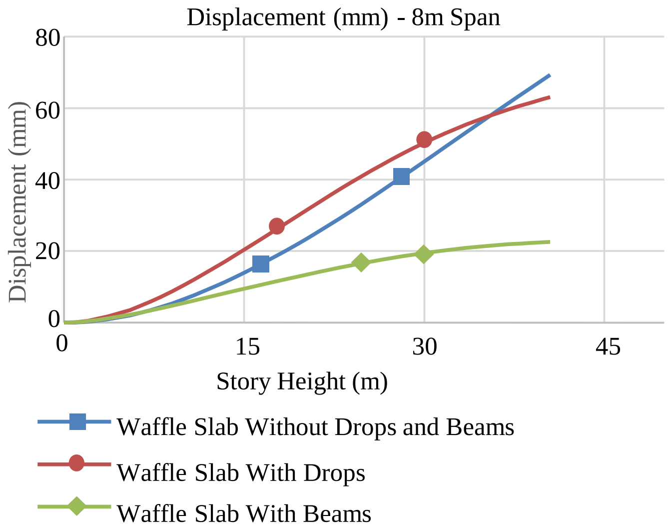

Figure 15. Comparison of lateral displacement for the 8 m span.

Table 4. Comparison of lateral displacement for the studied structure for 10 m span.

No. of Floors	Story Height (m)	Without Drops and Beams	With Drops	With Beams
Story 12	40.5	73.127	62.652	34.666
Story 11	37	65.462	59.986	33.641
Story 10	33.5	57.539	56.455	32.055
Story 9	30	49.361	51.88	29.839
Story 8	26.5	41.055	46.252	27.006
Story 7	23	32.86	39.671	23.604
Story 6	19.5	25.112	32.334	19.691
Story 5	16	18.011	24.771	15.62
Story 4	12.5	11.644	17.25	11.384
Story 3	9	6.326	10.211	7.165
Story 2	5.5	2.415	4.33	3.322
Story 1	2	0.313	0.645	0.56
Base	0	0	0	0

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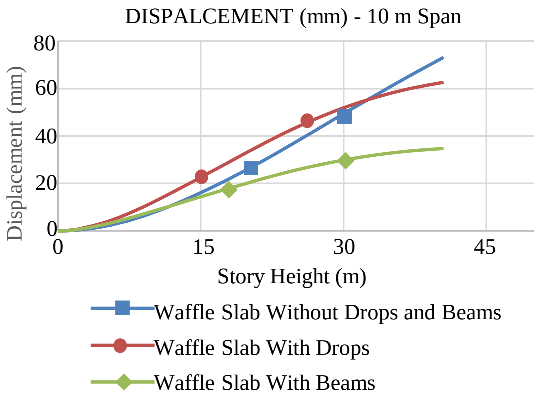

Figure 16. Comparison of lateral displacement for the 10 m span.

Table 5. Comparison of lateral displacement for the studied structure for 12 m span.

No. of Floors	Story Height (m)	Without Drops and Beams	With Drops	With Beams
Story 12	40.5	74.94	60.147	52.351
Story 11	37	68.199	58.1	50.792
Story 10	33.5	61	55.128	48.39
Story 9	30	53.274	51.083	45.039
Story 8	26.5	45.108	45.973	40.757
Story 7	23	36.729	39.888	35.614
Story 6	19.5	28.494	32.977	29.702
Story 5	16	20.724	25.797	23.544
Story 4	12.5	13.604	18.462	17.148
Story 3	9	7.524	11.341	10.79
Story 2	5.5	2.941	5.08	5.008
Story 1	2	0.359	0.825	0.849
Base	0	0	0	0

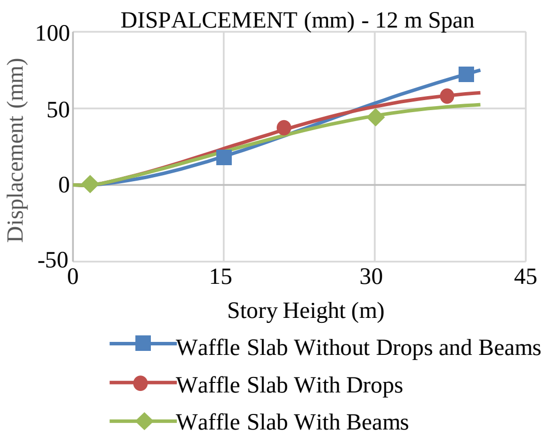

Figure 17. Comparison of lateral displacement for the 12 m span.

Lateral Displacement Comparison for 12 m Span

The comparison for lateral displacements from models using waffle slab systems with and without drops and beams for 12 m × 12 m is detailed in Table 5, and Figure 17 visually represents these findings for enhanced clarity.

Lateral Displacement Comparison for 15 m Span

The comparison for lateral displacements from models using waffle slab systems with and without drops and beams for 15 m × 15 m is detailed in Table 6, and Figure 18 visually represents these findings for enhanced clarity.

Table 6. Comparison of lateral displacement for the studied structure for 15 m span.

No. of Floors	Story Height (m)	Without Drops and Beams	With Drops	With Beams
Story 12	40.5	76.727	54.64	77.005
Story 11	37	71.252	53.169	74.716
Story 10	33.5	65.064	50.781	71.19
Story 9	30	58.012	47.394	66.27
Story 8	26.5	50.138	43.046	59.984
Story 7	23	41.647	37.811	52.433
Story 6	19.5	32.896	31.78	43.753
Story 5	16	24.35	25.573	34.711
Story 4	12.5	16.305	19.029	25.318
Story 3	9	9.231	12.363	15.975
Story 2	5.5	3.721	6.043	7.459
Story 1	2	0.523	1.113	1.281
Base	0	0	0	0

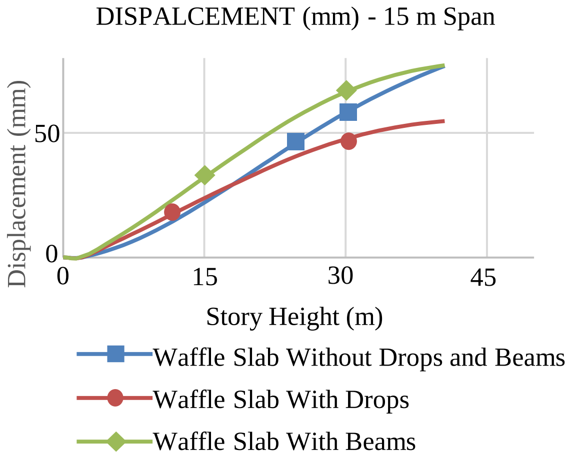

Figure 18. Comparison of lateral displacement for the 15 m span.

Maximum Displacement Comparison for All Structures

The comparison for maximum displacements from models using waffle slab systems with and without drops and beams for the structures of all sizes of span is detailed in Table 7, and Figure 19 visually represent these findings for enhanced clarity.

Based on the provided displacement data for various waffle slab configurations across different spans (8 m, 10 m, 12 m, and 15 m) reveals significant findings. For the 8 m span, the inclusion of waffle slab with drops (WSD) decreased displacement by approximately 8.98% compared to waffle slab only (WS only), while waffle slab with beams (WSB) showed a remarkable reduction of about 67.48%. Similarly, at spans of 10 m, 12 m, and 15 m, both WSD and WSB configurations exhibited considerable decreases in displacement compared to WS only, with WSB consistently showing greater reductions. These findings underscore the effectiveness of waffle slab configurations, particularly those with beams, in mitigating displacement in structural applications.

Table 7. Comparison of maximum displacement for the studied all types of structures.

8 m WS Only	8 m WSD	8 m WSB	10 m WS Only	10 m WSD	10 m WSB	12 m WS Only	12 m WSD	12 m WSB	15 m WS Only	15 m WSD	15 m WSB
69.271	63.036	22.509	74.94	60.147	52.351	73.127	62.652	34.666	76.727	54.64	77.005

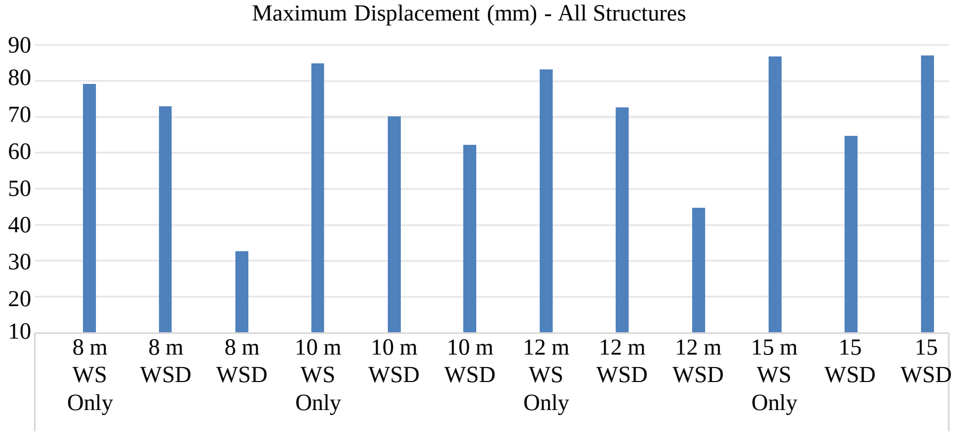

Figure 19. Comparison of maximum displacement for the studied all types of structures.

Story Shear

The next parameter under investigation in our parametric study is story shear, a pivotal aspect of structural analysis quantifying the lateral force encountered by each story of the building. This metric is crucial for understanding the structure's response to lateral loads, such as those from seismic activity or wind. Additionally, we scrutinize the maximum story shear experienced at the base of the building, commonly termed base shear, representing the total lateral force exerted on the entire structure at its foundation.

Story Shear Comparison for 8 m Span

The comparison for story shear from models utilizing waffle slab systems with and without drops and beams for the 8 m × 8 m configuration is meticulously outlined in Table 8. To enhance clarity and facilitate better comprehension, Figure 20 visually illustrates these findings, providing a graphical representation of the story shear values across the various models.

Table 8. Comparison of story shear for the studied structure for 8 m span.

No. of Floors	Story Height (m)	Without Drops and Beams	With Drops	With Beams
Story 12	40.5	312.5675	243.2626	305.4625
Story 11	37	568.9575	462.8855	596.9973
Story 10	33.5	778.0184	657.9034	864.4577
Story 9	30	952.034	831.6175	1107.7519
Story 8	26.5	1097.2011	984.0978	1325.795
Story 7	23	1218.3325	1115.5179	1518.2035
Story 6	19.5	1319.6414	1226.6451	1684.055
Story 5	16	1400.9351	1315.928	1822.6422
Story 4	12.5	1460.5299	1380.8109	1928.6338
Story 3	9	1499.1247	1422.0585	2000.0205
Story 2	5.5	1518.1005	1441.7891	1441.7891
Story 1	2	1519.5794	1443.3082	2038.6704
Base	0	0	0	0

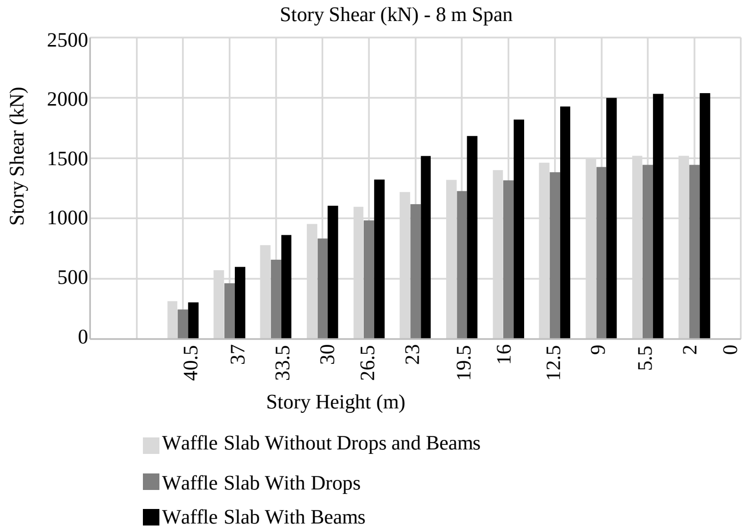

Figure 20. Comparison of story shear for the studied structure for 8 m span.

Table 9. Comparison of story shear for the studied structure for 10 m span.

No. of Floors	Story Height (m)	Without Drops and Beams	With Drops	With Beams
Story 12	40.5	370.314	428.2312	477.6702
Story 11	37	705.5891	828.6704	866.994
Story 10	33.5	1008.1087	1195.9173	1189.932
Story 9	30	1280.6546	1530.0778	1462.5379
Story 8	26.5	1522.4484	1829.6109	1692.0665
Story 7	23	1731.4083	2092.0943	1882.7581
Story 6	19.5	1909.5602	2318.1626	2041.6275
Story 5	16	2053.2372	2505.2113	2167.51
Story 4	12.5	2158.9896	2647.6417	2259.2693
Story 3	9	2227.1423	2743.0926	2318.3601
Story 2	5.5	2260.1872	2791.6274	2347.2652
Story 1	2	2262.0226	2793.8425	2348.8924
Base	0	0	0	0

Story Shear Comparison for 10 m Span

The comparison for story shear from models utilizing waffle slab systems with and without drops and beams for the 10 m × 10 m configuration is meticulously outlined in Table 9. To enhance clarity and facilitate better comprehension, Figure 21 visually illustrates these findings, providing a graphical representation of the story shear values across the various models.

Story Shear Comparison for 12 m Span

The comparison for story shear from models utilizing waffle slab systems with and without drops and beams for the 12 m × 12 m configuration is meticulously outlined in Table 10. To enhance clarity and facilitate better comprehension, Figure 22 visually illustrates these findings, providing a graphical representation of the story shear values across the various models.

Story Shear Comparison for 15 m Span

The comparison for story shear from models utilizing waffle slab systems with and without drops and beams for the 15 m × 15 m configuration is meticulously outlined in Table 11. To enhance clarity and facilitate better comprehension, Figure 23 visually illustrates these findings, providing a graphical representation of the story shear values across the various models.

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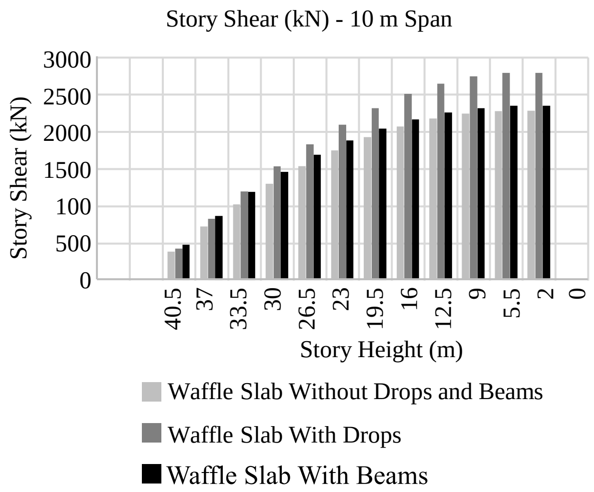

Figure 21. Comparison of story shear for the studied structure for 10 m span.

Table 10. Comparison of story shear for the studied structure for 12 m span.

No. of Floors	Story Height (m)	Without Drops and Beams	With Drops	With Beams
Story 12	40.5	4951	626.7331	626.7331
Story 11	37	1042.7789	1206.3152	1249.9887
Story 10	33.5	1497.2813	1737.8773	1728.6659
Story 9	30	1909.4808	2221.6862	2140.1875
Story 8	26.5	2277.6204	2655.4641	2491.1612
Story 7	23	2598.5281	3035.6027	2784.7514
Story 6	19.5	2873.2241	3361.6665	3027.9225
Story 5	16	3097.31	3630.125	3219.0698
Story 4	12.5	3265.5163	3834.3395	3357.6915
Story 3	9	3376.2927	3971.1092	3446.3764
Story 2	5.5	3431.4192	4040.6764	3489.4397
Story 1	2	3433.7309	4043.1815	3491.2327
Base	0	0	0	0

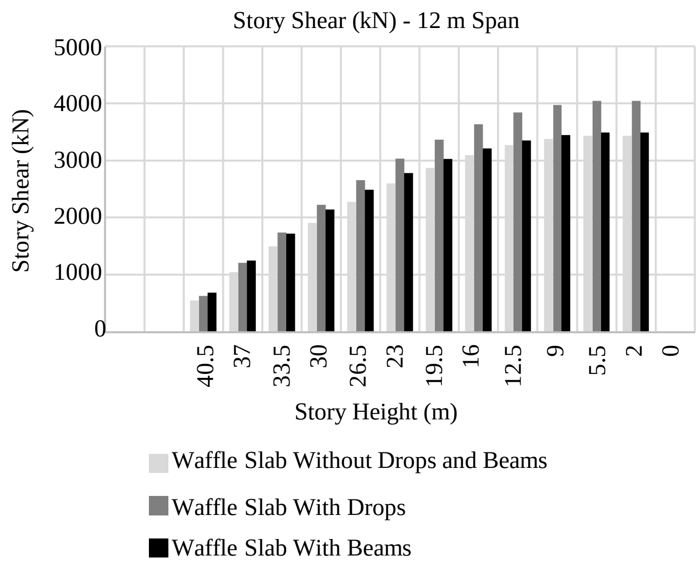

Figure 22. Comparison of story shear for the studied structure for 12 m span.

Table 11. Comparison of story shear for the studied structure for 15 m span.

No. of Floors	Story Height (m)	Without Drops and Beams	With Drops	With Beams
Story 12	40.5	889.4048	1005.8048	1073.3157
Story 11	37	1713.5486	1924.753	1969.2194
Story 10	33.5	2472.3676	2767.9088	2749.3025
Story 9	30	3164.4231	3535.66	3433.8878
Story 8	26.5	3786.1788	4224.3101	4027.0578
Story 7	23	4332.9329	4828.0555	4528.6479
Story 6	19.5	4804.0379	5344.3456	4943.9009
Story 5	16	5196.0208	5768.1898	5269.6056
Story 4	12.5	5499.5716	6090.8685	5505.635
Story 3	9	5708.0926	6307.3707	5656.1284
Story 2	5.5	5818.2885	6417.9128	5728.8216
Story 1	2	5821.6915	6420.8859	5730.9381
Base	0	0	0	0

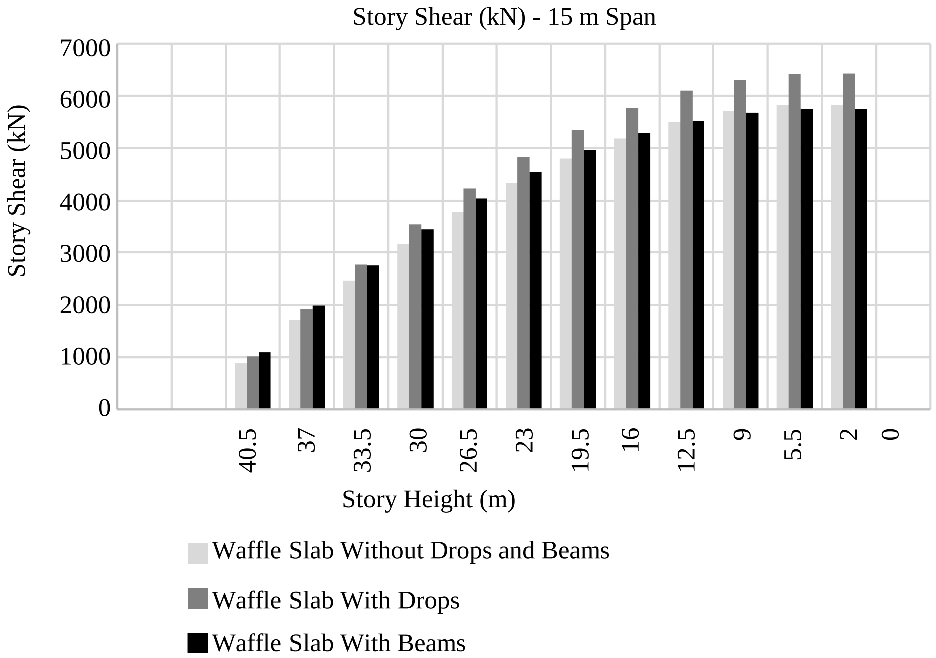

Figure 23. Comparison of story shear for the studied structure for 15 m span.

Table 12. Comparison of maximum shear for the studied all types of structures.

8 m WS Only	8 m WSD	8 m WSB	10 m WS Only	10 m WSD	10 m WSB	12 m WS Only	12 m WSD	12 m WSB	15 m WS Only	15 m WSD	15 m WSB
1519.5794	1443.3082	2038.6704	2262.0226	2793.8425	2348.8924	3433.7309	4043.1815	3491.2327	5821.6915	6420.8859	5730.9381

Maximum Shear Comparison for All Structures

The comparison for maximum shear from models utilizing waffle slab systems with and without drops and beams for the all-panel sizes configuration is meticulously outlined in Table 12. To enhance clarity and facilitate better comprehension, Figure 24 visually illustrates these findings, providing a graphical representation of the story shear values across the various models.

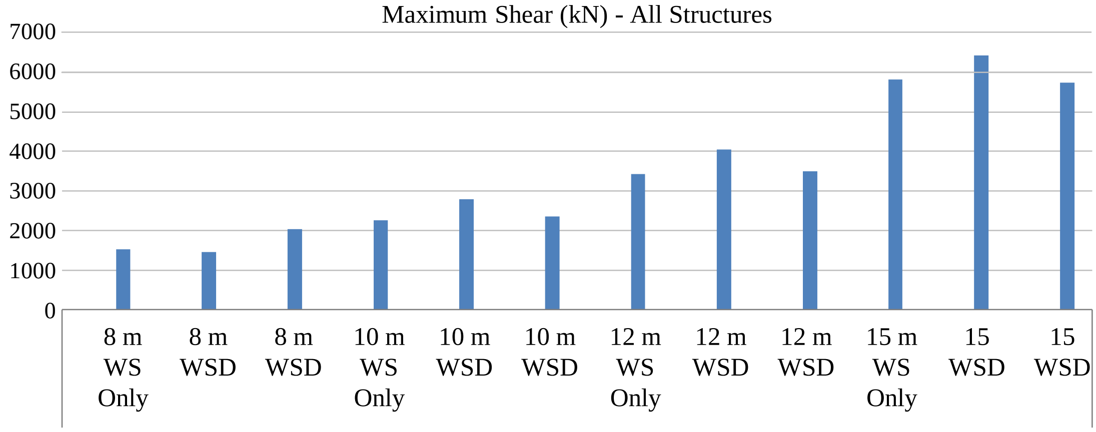

Figure 24. Comparison of maximum shear for the studied all types of structures.

In summary, for various span lengths:

1. Waffle slab with drops (WSD) generally reduces story shear by about 5% to 19% compared to waffle slab only (WS Only).
2. Waffle slab with beams (WSB) typically increases story shear by approximately 10% to 34% compared to WS Only.
3. Across all spans, WSD decreases story shear, while WSB increases it, highlighting the impact of waffle slab enhancements on structural behavior.

CONCLUSIONS

On the basis of above results and observations of lateral displacements and base shear of the studied structure considering waffle slabs with and without drop and beams, the following conclusions are drawn:

1. Waffle slab design consistently reduce displacement across all spans, with waffle slab with beams showing a significant reduction of about 67.48% at 8 m span compared to waffle slab without drops and beams.
2. The effectiveness of waffle slab design in displacement reduction varies across different span sizes, with reductions ranging from approximately 8.98% to 29.05% for waffle slab with beams and 26.69% to 67.48% for waffle slab with drops.
3. Waffle slab with drops generally reduces story shear compared to waffle slab without drops and beams, with approximately 5% lower shear at 8m span, while waffle slab with beams tends to increase it by around 34%.
4. Across all spans, waffle slab with drops leads to reductions in story shear, averaging about 14% across different spans, while waffle slab with beams tends to result in increases, averaging around 15%.
5. The findings highlight the influence of slab designs on structural behavior, with the effectiveness of enhancements varying depending on span length and type, underscoring the importance of optimizing configurations for specific project requirements.

Based on the above conclusions, the structure with waffle slab designs incorporating waffle slab with beams performs better and is more efficient in terms of displacement reduction and story shear to the structure with waffle slab with drops or waffle slab without drops and beams. WSB consistently shows significant reductions in displacement and story shear across all span lengths, highlighting its effectiveness in enhancing structural performance and stability. Therefore, the structure with waffle slab with beams can be considered to perform well and be more sufficient in meeting structural requirements.

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