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Effects of slab types on the seismic behavior and construction cost of RC buildings

Betonarme binaların yapım maliyeti ve deprem davranışında döşeme tipinin etkisi

***Yazar(lar) (Author(s))**: Gökhan TUNÇ[1], Abdul Basir AZIZI[2], Tuğrul TANFENER[3]*

ORCID[1]: 0000-0002-8307-1060

ORCID[2]: 0000-0002-0847-8557

ORCID[3]: 0000-0002-9315-8100

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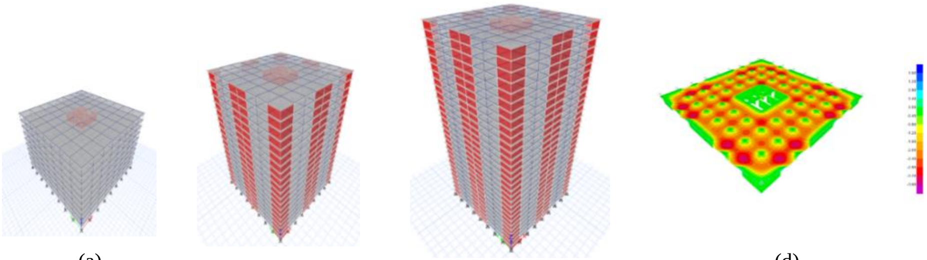
Effects of Slab Types on the Seismic Behavior and Construction Cost of RC Buildings

Highlights

- *A total of thirty-six building models with different types of slabs (two-way slabs with beams, flat, waffle and ribbed), number of floors (10, 20 and 30), and span length (6, 7.5, and 9 m) were analyzed and designed.*
- *A two-way slab with beams was the most economical slab type for 6-meter spans, while a waffle slab was the most economical one for spans larger than 7.5 meters.*
- *A flat slab was found to be the most expensive slab type in all cases.*
- *Out of all slab types, a two-way slab with beams exhibited better earthquake performance, while a waffle and flat slab provided relatively poor earthquake performances.*

Graphical Abstract

This study assesses the effects of different slab types on multi-story reinforced concrete buildings by investigating their structural behaviors while trying to optimize their overall cost.



(a) (b) (c) (d)

Figure. Building models: (a) 10 story, (b) 20 story, (c) 30 story, (d) Deflected shape of a floor slab

Aim

The aim of this article can be summarized as: (a) to investigate different slab types in terms of their earthquake performances, and (b) to evaluate their impacts on overall building cost.

Design & Methodology

A total of thirty-six reinforced concrete (RC) building models were constructed with four slab types using FE software packages of ETABS, and SAFE. The structural behavior of the building models with various slab types subjected to earthquake loads was examined and discussed.

Originality

Different types of slab construction tend to result in variation in seismic behavior and cost. Therefore, it is important to carefully evaluate all slab alternatives in order to find an optimal choice that will not compromise the building's integrity while providing an economical solution. This study covers a wide range of slab types and span dimensions for mid-to-high rise RC buildings with and without shear walls.

Findings

A two-way slab with beams was the most economical slab type for 6-meter spans, while a waffle slab was the most economical one for spans larger than 7.5 meters. A flat slab was found to be the most expensive slab type in all cases. Out of all slab types, two-way slabs with beams exhibited better earthquake performances while waffle and flat slabs provided relatively poor performances.

Conclusion

A two-way slab with beams is recommended for 10, 20 and 30 story buildings with 6 and 7.5-m spans. A waffle slab can be considered a viable option for taller buildings. However, due to their larger displacements and period values, adopting a span length from 7.5 to 9 meters, and introducing more columns and shear walls, is recommended.

Declaration of Ethical Standards

The author(s) of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

Effects of Slab Types on the Seismic Behavior and Construction Cost of RC Buildings

Araştırma Makalesi / Research Article

Gökhan TUNÇ[1*], Abdul Basir AZIZI[2], Tuğrul TANFENER[3]

[1,2] Atılım University, Department of Civil Engineering, Ankara, Turkey

[3] Prota Engineering, Ankara, Turkey

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ABSTRACT

Reinforced concrete-framed buildings are commonly preferred to other types of buildings in Turkey. In these types of buildings, a two-way slab with beams, flat, waffle, and ribbed slab types are widely used. In building design, determining the best slab type that will perform well under gravity and lateral loads, with the least cost, is required. However, the proper selection of slab type has generally been overlooked by designers due to the emphasis on other structural members, such as beams, columns and structural walls. For this reason, the structural contribution of floors to building design has not been adequately examined. This shortcoming must be inspected in detail starting from the very first step of the design stage of a building. This study assesses the effects of different slab types on multi-story reinforced concrete buildings by investigating their structural behaviors while trying to optimize their overall cost. For this purpose, a total of 36 structural models were constructed, analyzed, and designed according to the current Turkish Building Codes and Standards. The type of slab system (a two-way slab with beams, flat, waffle and ribbed), the number of floors (10, 20 and 30), and span length (6, 7.5, and 9 m) were selected as the key parameters in these analyses. The buildings were assumed to be office buildings located in a seismically-active zone in Istanbul. The results indicated that a two-way slab with beams was the most economical slab type for 6-meter spans, while the waffle slab was the most economical for spans larger than 7.5 meters. Based on these results, the flat slab was found to be the most expensive slab type in all cases. Out of all slab types, the two-way slab with beams exhibited better earthquake performance, while the waffle and flat slabs provided relatively poor earthquake performances.

Keywords: Multi-story buildings, reinforced concrete buildings, seismic behavior, slab types.

Betonarme Binaların Yapım Maliyeti ve Deprem Davranışında Döşeme Tipinin Etkisi

ÖZ

Türkiye'de betonarme çerçeveli binalar diğer tür yapı taşıyıcı sistemlerine göre en çok tercih edilmektedir. Bu tür binalarda kullanılan yaygın döşeme türleri ise kirişli, kirişsiz, kaset ve nervürlü olanlarıdır. Bir bina tasarımında, yatay ve düşey yükler altında en iyi performansı gösteren ve aynı zamanda en az maliyet gerektiren döşeme türünün belirlenmesi istenir. Ancak, kirişler, kolonlar ve perde duvarlar gibi diğer yapı elemanlarına analitik çalışmalarda öncelik verildiğinden, döşeme türünün uygun seçimi genellikle tasarımcı tarafından göz ardı edilir. Bu nedenle, döşemelerin bina tasarımına ve yapısal davranışına sağlayacakları katkılar yeterince irdelenmemiş olur. Ortaya çıkan bu eksikliğin ise binanın tasarım aşamasından itibaren detaylı olarak irdelenmesi gerekmektedir. Bu çalışmada çok katlı betonarme binalar üzerinde farklı döşeme türlerinin etkileri incelenirken aynı zamanda toplam maliyetin de optimumda kılınması hedeflenmiştir. Bu amaç doğrultusunda toplamda 36 bina modeli hazırlanarak, analiz ve tasarımları mevcut Türkiye bina yönetmelik ve standartlarına uygun olarak yapılmıştır. Bu kapsamda yapılan analitik çalışmalarda incelenen parametreler şu şekildedir: döşeme türleri (kirişli, kirişsiz, kaset ve nervürlü), toplam kat sayıları (10, 20 ve 30) ve tip döşeme açıklıkları (6, 7.5 ve 9 metre). Binaların tümünün iş yeri kullanımına uygun olarak İstanbul'un deprem tehlikesi içeren bir bölgesinde yer aldığı kabul edilmiştir. Yapılan analitik çalışmalara göre 6 metre açıklığa sahip binalarda en ekonomik sonucun kirişli, 7.5 metre açıklığa sahip olanlarda ise kaset döşemelerde olduğu görülmüştür. Ele alınan tüm modeller içerisinde en maliyetli çözümü üreten döşeme türü kirişsiz döşeme olarak belirlenmiştir. İncelenen tüm döşeme türleri arasında, kirişli döşemeye sahip binaların en iyi deprem performansına, kaset ve kirişsiz döşeme türlerine sahip binaların ise en olumsuz deprem performansına sahip oldukları görülmüştür.

Anahtar Kelimeler: Çok katlı binalar, betonarme binalar, deprem davranışı, döşeme türleri.

1. INTRODUCTION

A reinforced concrete slab is a planar bearing structural element used to create flat horizontal surfaces for floors and roof decks. Structural engineers have a wide choice of concrete floor systems. Different types of slab construction tend to result in variation in seismic behavior and cost. Therefore, it is important to carefully evaluate all slab alternatives in order to find an optimal choice that will not compromise the building's integrity, while providing an economical solution. This article,

*Sorumlu Yazar (Corresponding Author)
e-posta : gokhan.tunc@atilim.edu.tr

which is partially derived from an MS study conducted at Atilim University, Ankara, will investigate the effects of different slab types on seismic behaviors and costs of reinforced concrete tall buildings [1]. The preliminary research findings of this study were presented at a conference in France [2]. This article further elaborates these initial findings and provides an extensive overview of the topic.

The aim of this article can be summarized as (a) to investigate different slab types in terms of their earthquake performances, and (b) to evaluate their impacts on overall building cost. For this purpose, a total of 36 reinforced concrete (RC) structural models were constructed with four slab types—a two-way slab with beams, flat slab, waffle slab and one-way ribbed slab (ribbed slab)—using software packages ETABS, and SAFE [3, 4]. The buildings were designed according to the recommendations and regulations of the current related code and standards [5, 6]. All 36 buildings were assumed to be office buildings located in a severe seismic zone in Istanbul, Turkey. For lateral loads, only earthquake loads were considered since the current earthquake code, TBEC 2018, generated much larger forces than those in the Turkish Standards (TS 498) wind code [7].

Slabs in RC tall buildings cover large areas and generally consume more construction materials than any other structural element [8-11]. In a typical RC building, slabs can account for more than 50% of a building’s total embodied energy, or the energy required for extraction, processing, manufacturing, and delivery of construction materials to a construction site. Out of this 50% embodied energy, about 30% comes from steel rebars [12]. The cost optimization of floor slabs is much more important than the optimization of the number of columns and their sizes [9] since the volume of concrete for columns is limited to 2.5 to 14% of the concrete volume of floor slabs [10]. Therefore, reducing the weight of floor slabs has the potential to reduce the volume of concrete and its environmental impact, thus resulting in savings in construction cost [13].

There are several reinforced concrete slab types that exist in building construction. In this study, the most common ones, namely a two-way slab with beams, ribbed, waffle and flat slab types, will be studied. A Two-way slab with beams (columns anchored with beams) provides high diaphragm rigidity, adequate lateral displacement, and durability. Therefore, these types of slab systems are recommended for buildings located in earthquake prone areas [14-16]. Ribbed and waffle slab types have many advantages. Due to the presence of voids in these slabs, the dead weight will decrease; consequently, the concrete below the neutral axis will also decrease [17]. Yet, both of these slab types have disadvantages when employed in seismic areas since they exhibit low rigidity and ductility [18]. Similarly, flat slabs also provide less rigidity, resulting in higher periods of vibration [14, 19, 20]. A flat slab, however, possesses many advantages over a two-way slab with beams due to their shorter construction time, architectural advantages, and economic benefits [21-23]. However, since there are no beams in flat slabs, they are more vulnerable to punching shear failure [24-26]. If perimeter beams and/or RC walls are provided in these slab types, then their structural behaviors would be enhanced, specifically in earthquake prone areas [15, 25, 27].

In 2017, Idrizi and Idrizi [28] investigated the advantages of mid-rise RC buildings with waffle slab instead of a two-way slab with beams. Their study revealed that adopting waffle slab in a building resulted in a 20% savings in concrete volume and a 27% savings in steel reinforcement. The study concluded that a lighter and flexible building can be obtained by adopting a waffle slab type. Bakale and Viswanathan [29] conducted a comparative study on seismic behaviors of different slab types, namely a two-way slab with beams, flat plate, flat slab, and ribbed slab, in buildings with regular and irregular features. According to their study, in regular buildings, the story displacement was identical in both orthogonal directions for each slab type, except for the ribbed slab that caused more displacements perpendicular to the ribs. The story displacements of the regular and irregular buildings with flat slab was 37% and 24% more than those of the buildings with a two-way slab with beams. The story shear forces of the regular and irregular buildings with flat plates were 17 and 11% more than those of the buildings with flat slab.

Bikçe et al. [30] investigated the cost and seismic behavior of lightweight hollow block slab (ribbed slab) and a two-way slab with beams using theoretical analytical structural models and physically built models. The results from the theoretical and physical structural models indicated that lightweight hollow block slab costs 10.5% to 21.9% more than a two-way slab with beams, and that larger values of base shear forces and periods were associated with lightweight hollow block slab. Zakaria et al. [31] assessed the seismic performance of RC buildings with grid slab (a two-way slab with secondary beams) and hollow block slab types. In this study, it was observed that grid slab was the most appropriate slab type for buildings under seismic loads due to their lower values of base shear forces and periods, which ranged from 9% to 12% in the base shear forces, and 5% to 6% in the periods.

Eşki et al. [32] investigated the structural behavior of low-rise RC buildings with different slab types, namely a two-way slab with beams, flat, and ribbed slab types under earthquake loads. For this purpose, a total of three 5-story buildings were modeled and designed according to the Turkish Earthquake Code, 2007 (TEC 2007) [33]. Their study concluded that the highest and lowest base shear forces were obtained in buildings with a flat slab and a two-way slab with beams, respectively. The higher periods of vibration were associated with ribbed slab, while the lower periods of vibration were associated with flat slab. The maximum average lateral displacement was obtained in ribbed slab, while the minimum average lateral displacement was observed in flat slab. Gürsoy and Uludağ [34] assessed the earthquake behavior of a 5-story low-rise RC building with different slab types, namely a two-way slab with beams, ribbed, waffle, flat, and slab with plane beams (wider beams with shallower depths). Three different span lengths (5, 6, and 7m) and three different site classes (Z1, Z2, and Z3 according to TEC 2007, where Z1 is considered a rock type soil) were considered in their analysis. Their results showed that a two-way slab with beams was the most rigid slab type, with minimum rooftop displacement and periods for all spans and site classes. Therefore, a two-way slab with beams was recommended for areas prone to high seismicity. Higher periods of vibration were associated with flat slab. Due to their large concrete volume and lower rigidity, this slab type was not recommended for spans larger than 5 meters. A two-way slab with beams required less concrete than a flat slab.

Öztürk and Öztürk [35] also studied the effects of different slab types, namely a two-way slab with beams, grid and flat slabs, on the structural behavior of multi-story buildings. Their results showed that larger displacements and higher base shear forces and periods were always associated with flat slab, while smaller displacements and lower base shear forces and periods were associated with a two-way slab with beams. Therefore, they recommended that a two-way slab with beams be used in regions prone to high seismic activities.

2. STRUCTURAL MODELS

A total of 36 structural models with four slab types (a two-way slab with beams designated by 2WSlBms, flat, waffle, and ribbed), three span lengths (6, 7.5 and 9 m), and three sets of story numbers (10, 20 and 30) were constructed in ETABS [3]. The most commonly built RC buildings in Turkey are mid-to-high rise structures with total floor numbers varying from 10 to 30. In this study, three sets of floor numbers, 10, 20 and 30, were selected. As for the span lengths, it is very common to see lengths between 6 to 9 meters. Therefore, as with the number of floors, three sets of span lengths were studied: 6, 7.5 and 9 meters. The buildings were all assumed to have square-shaped floor layouts. The overall in-plan dimensions of the buildings were determined based on the three span lengths. In order to have an even number of spans, 6 and 9-meter span buildings were treated together with an overall dimension of 72 meters; this dimension was kept at 60 meters for the 7.5-meter span structures. The 60-meter dimension is probably most commonly observed in an RC building. However, in order to better understand the impact of a slab on a building's seismic behavior, the slightly longer in-plan dimensions of 72 meters by 72 meters was studied. The buildings' slabs were designed according to the requirements of TS 500 using another software package, SAFE [4]. The goal was to evaluate the impact of span length and floor number on the overall seismic behavior of buildings with four different slab types. In the following subsections, further details will be given with respect to the structural models. All 36 buildings were assumed to be office buildings located in Istanbul, Turkey, with the same floor height of 4 meters.

2.1. Plan Feautures

The layouts of the buildings are shown in Figs. 1.a.1 through 1.c.4. The layouts with the same span lengths were identical to each other for each set of floor numbers (i.e., ten-story, twenty-story, and thirty-story), except for the ten-story case where shear walls did not exist along the building's perimeter (i.e., shear walls were used only in the core wall, see Fig. 3.a). A total of three distinct square- shaped layouts were used in this study for each of the four slab types (2WSlBms, flat, waffle, and ribbed). Each of these layouts corresponded to a span length of 6, 7.5 and 9 meters. In order to better understand the significance of varying slab types in terms of the buildings' structural behaviors and costs, a minimum overall layout dimension of 60 meters was used for the 7.5-meter span, while a 72-meter dimension was used for the 6 and 9 meter spans. Table 1 summarizes the slab details and designations of all the buildings. In the text, these designations are used interchangeably along with their full descriptions.

Figures 1.a.1 through 1.a.4 illustrate the layouts of the buildings with 72-meter dimensions and 6-meter spans for a two-way slab with beams (2WSlBms), flat, waffle and ribbed slabs, respectively. The layouts include a core wall with an opening to house elevators, staircases, and electrical and mechanical shafts since this type of layout arrangement is commonly used in Turkey. Figures 1.b.1 through 1.b.4 show the layouts for the four slab types in a square-shaped building with an overall dimension of 60 meters and a span of 7.5 meters. The final four layouts are for the same four slab types for buildings with an overall dimension of 72 meters and a span of 9 meters (see Figures 1.c.1 through 1.c.4).

During the member size selection process, three important factors were considered: (a) slab thicknesses were selected to be slightly over the minimum requirements of TS 500 so that their deflections would not be an issue, (b) punching shear was used in determining the flat plate thickness so that no column capital or dropped panel would be needed, and (c) shear wall areas followed the requirements of a study conducted by Tunc and Al-Ageedi and kept continuous along the gridlines [36]. Figures 2a through 2f display the ratios of shear wall area to total floor area in the "x" and "y" directions for each case. As illustrated in these figures, a higher wall area ratio was used in the "y" direction and the maximum ratio varied from 0.6% in the 10 story building, to 2% in the 20 story building, to 2.6% in the 30 story building. The smallest wall areas were used for the layouts with a 6-meter span, while the largest wall areas were used for layouts with 7.5-meter spans. The 9-meter span layouts required less wall area compared to the 7.5-meter layouts due to the decision to avoid excessive wall areas.

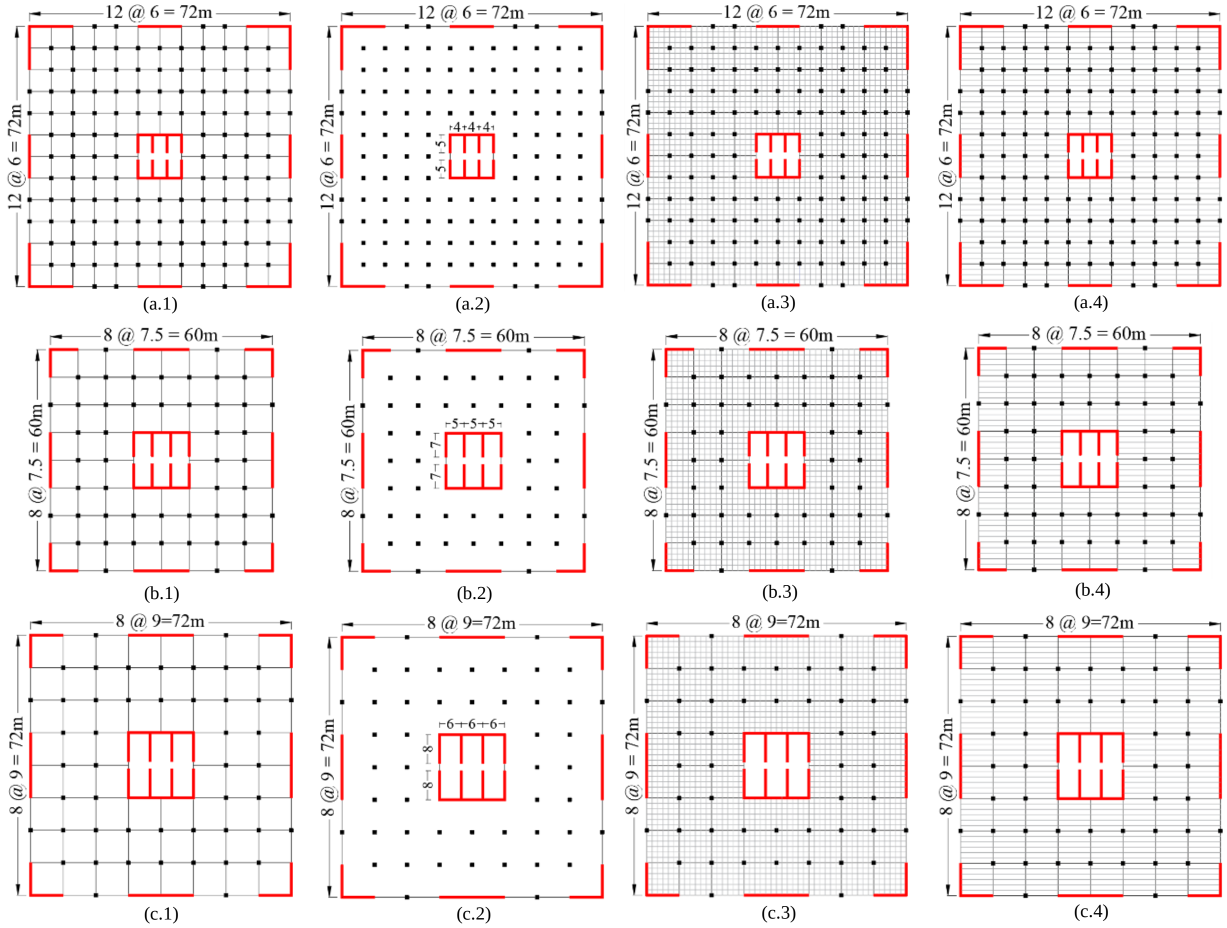

Figure 1. Floor layouts: (a) 72 m by 72 m with a 6-meter span, (a.1) 2WSlBms, (a.2) flat, (a.3) waffle, (a.4) ribbed; (b) 60 m by 60 m with a 7.5-meter span, (b.1) 2WSlBms, (b.2) flat, (b.3) waffle, (b.4) ribbed; (c) 72 m by 72 m with a 9-meter span, (c.1) 2WSlBms, (c.2) flat, (c.3) waffle, (c.4) ribbed

Table 1. Slab details and designations of buildings

Slab Type	Number of Floors								
	10			20			30		
	Overall in-plan dimensions (m x m)			Overall in-plan dimensions (m x m)			Overall in-plan dimensions (m x m)		
	72 x 72	60 x 60	72 x 72	72 x 72	60 x 60	72 x 72	72 x 72	60 x 60	72 x 72
	Span (m)			Span (m)			Span (m)		
	6	7.5	9	6	7.5	9	6	7.5	9
2WSlBms	10B6-7272	10B7.5-6060	10B9-7272	20B6-7272	20B7.5-6060	20B9-7272	30B6-7272	30B7.5-6060	30B9-7272
Flat	10F6-7272	10F7.5-6060	10F9-7272	20F6-7272	20F7.5-6060	20F9-7272	30F6-7272	30F7.5-6060	30F9-7272
Ribbed	10R6-7272	10R7.5-6060	10R9-7272	20R6-7272	20R7.5-6060	20R9-7272	30R6-7272	30R7.5-6060	30R9-7272
Waffle	10W6-7272	10W7.5-6060	10W9-7272	20W6-7272	20W7.5-6060	20W9-7272	30W6-7272	30W7.5-6060	30W9-7272

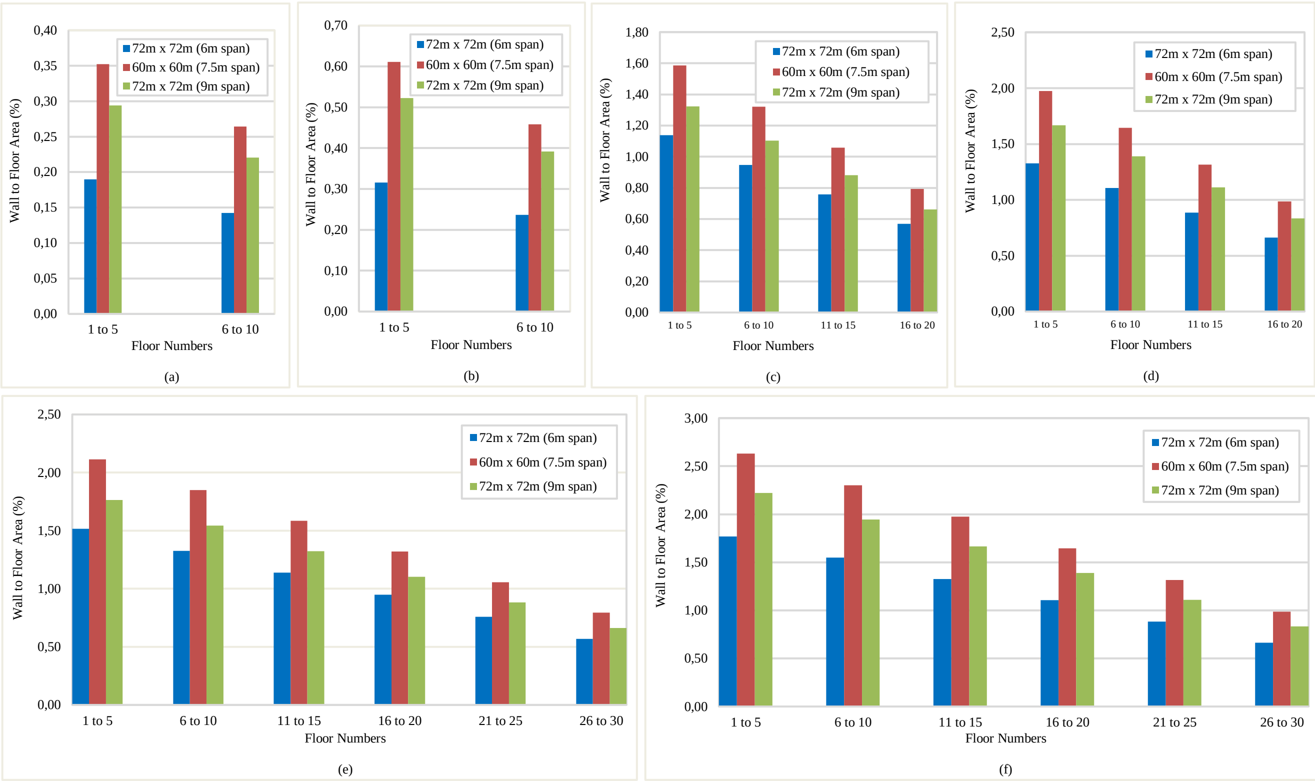

Figure 2. Shear wall area to floor area in %: (a) 10 story building in the "x" direction, (b) 10 story building in the "y" direction, (c) 20 story building in the "x" direction, (d) 20 story building in the "y" direction, (e) 30 story building in the "x" direction, (f) 30 story building in the "y" direction

2.2. Dimensions of Structural Members

The minimum requirements of TS 500 and TBEC 2018 were taken into consideration while dimensioning all structural members. Following a common practice in the construction of RC buildings, the cross-sectional dimensions of columns and the thicknesses of shear walls were reduced every 5 floors. Unlike the dimensioning procedure followed for the columns and shear walls, the beam dimensions and floor thicknesses were kept constant along each building's height. The cross-sectional dimensions of the coupling beams were the same for all structural models, with a width of 0.4 meters and a depth of 0.6 meters. The depth of coupling beam was found to be adequate for the 10 and 20 story buildings, and therefore kept the same for the 30 story buildings so that results could be compared to one another.

Table 2 lists the details of each layout for the three sets of floor numbers (i.e., ten, twenty, and thirty-story). The topping thicknesses for both ribbed and waffle slabs were assumed to be the same as 0.1 meter. For the ribbed slab type, the joists were parallel to the "x" direction, with a width of 0.2 meters and a clear spacing of 0.7 meters. For the waffle slab types, the joists were in both the "x" and "y" directions, with a width of 0.15 meters and a clear spacing of 0.7 meters. In Table 2, the depth of joists for both ribbed and waffle slab types, including the topping thicknesses, are identified as the overall depth of the slab.

The cross-sectional dimensions of the columns and the thicknesses of the shear walls were kept identical for all four different slab types used in each span length. This decision was justified, since the volume of the concrete used for columns generally constitutes 2.5 to 14% of the volume of the concrete used for floor slabs [10].

Concrete class C35 was used for all structural members, with a Poisson's ratio of 0.2. As per TS 500, the modulus of elasticity for C35 concrete was assumed to be 33,000 MPa. The steel rebars were B420C with a minimum yield strength of 420 MPa, a modulus of elasticity of 2x105 MPa, and a Poisson's ratio of 0.3.

2.3. Seismic Loads

In this study, the local site class was assumed to be ZB for all structural models based on the assumption that the soil was semi-stiff soil with an average shear wave velocity, Vs30, of 760 m/sec to 1,500 m/sec measured in the top 30 meters of soil layer. As per TBEC 2018, the seismic importance factor was set to one, since all the buildings were office buildings, which led to an occupancy class of three (BKS=3). A live load participation factor of 0.3 was used in the total seismic weight calculations. The short and 1 second periods for the mapped spectral acceleration coefficients, SS and S1, were extracted from the Earthquake Hazard Map, AFAD 2020, for a region in Istanbul as 0.711 and 0.206, respectively [37].

A high ductile system was selected for all the buildings. As shown in Figs. 1.a.1 through 1.c.4, the shear walls in

Table 2. Structural member sizes of the structural models

Span (m)	Total Story Number	Column Dimensions (cm)			Shear Wall Thick.ness (cm)	Beam Dimensions (cm)				Slab Thickness (cm)			
		Story Numbers	Interior	Exterior		2WSlBms	Flat	Ribbed	Waffle	2WSlBms	Flat	Ribbed	Waffle
6	10	1 to 5	70 x 70	60 x 60	40	30 x 50	40 x 50	50 x 40	50 x 25	15	20	30	25
		6 to 10	60 x 60	50 x 50	30								
	20	1 to 5	90 x 90	80 x 80	60	30 x 50	40 x 50	50 x 40	50 x 25	15	20	30	25
		6 to 10	80 x 80	70 x 70	50								
		11 to 15	70 x 70	60 x 60	40								
		16 to 20	60 x 60	50 x 50	30								
	30	1 to 5	120 x 120	100 x 100	80	30 x 50	40 x 50	50 x 40	50 x 25	15	20	30	25
		6 to 10	100 x 100	90 x 90	70								
		11 to 15	90 x 90	80 x 80	60								
		16 to 20	80 x 80	70 x 70	50								
		21 to 25	70 x 70	60 x 60	40								
		26 to 30	60 x 60	50 x 50	30								
7.5	10	1 to 5	80 x 80	70 x 70	40	40 x 60	40 x 60	50 x 50	50 x 30	18	25	40	30
		6 to 10	70 x 70	60 x 60	30								
	20	1 to 5	100 x 100	90 x 90	60	40 x 60	40 x 60	50 x 50	50 x 30	18	25	40	30
		6 to 10	90 x 90	80 x 80	50								
		11 to 15	80 x 80	70 x 70	40								
		16 to 20	70 x 70	60 x 60	30								
	30	1 to 5	140 x 140	120 x 120	80	40 x 60	40 x 60	50 x 50	50 x 30	18	25	40	30
		6 to 10	120 x 120	100 x 100	70								
		11 to 15	100 x 100	90 x 90	60								
		16 to 20	90 x 90	80 x 80	50								
		21 to 25	80 x 80	70 x 70	40								
		26 to 30	70 x 70	60 x 60	30								
9	10	1 to 5	90 x 90	80 x 80	40	40 x 70	40 x 70	50 x 60	50 x 40	22	30	50	40
		6 to 10	80 x 80	70 x 70	30								
	20	1 to 5	130 x 130	100 x 100	60	40 x 70	40 x 70	50 x 60	50 x 40	22	30	50	40
		6 to 10	110 x 110	90 x 90	50								
		11 to 15	90 x 90	80 x 80	40								
		16 to 20	80 x 80	70 x 70	30								
	30	1 to 5	160 x 160	150 x 150	80	40 x 70	40 x 70	50 x 60	50 x 40	22	30	50	40
		6 to 10	150 x 150	140 x 140	70								
		11 to 15	140 x 140	120 x 120	60								
		16 to 20	120 x 120	100 x 100	50								
		21 to 25	100 x 100	80 x 80	40								
		26 to 30	80 x 80	70 x 70	30								

the “x” direction were all solid, while those in the “y” direction were coupled. The response modification factor (or coefficient), R, was 7 in the “x” and 8 in the “y” directions. The overstrength coefficient, D, was 2.5. The response spectrum method (RSM) was used for the 10, 20 and 30 story buildings. The damping ratio was 5% and, as stated in TBEC 2018, the concrete was assumed to be cracked.

2.4. Finite Element Modeling

All structural models were constructed, analyzed and designed using the commercially available software packages ETABS and SAFE. ETABS is an engineering software product that caters to multi-story building analysis and design under static or dynamic loading conditions. Modeling tools and templates, code-based load prescriptions, analysis methods and solution techniques are all coordinated with the grid-like geometry unique to this class of structure. SAFE is a software tailored to the engineering of elevated floor and foundation slab systems. Slab modeling, analysis, and design procedures feature a suite of sophisticated tools and applications, coupled with post-tensioning, punching-shear, and beam detailing, while integrating the influence of soil types, ramps, columns, braces, walls (rectilinear or curvilinear), and other interfacial elements. Interoperability with ETABS allows users to import models, loading, and displacement fields into SAFE for more advanced local assessments of slab systems within larger structures.

The structural models were subjected RSM analyses, as described in TBEC 2018 (Fig.3). Self-weight, superimposed and live gravity loads were applied to the buildings. The structural members’ self-weights were automatically included by the program. A 200 kg-f/m^2 of

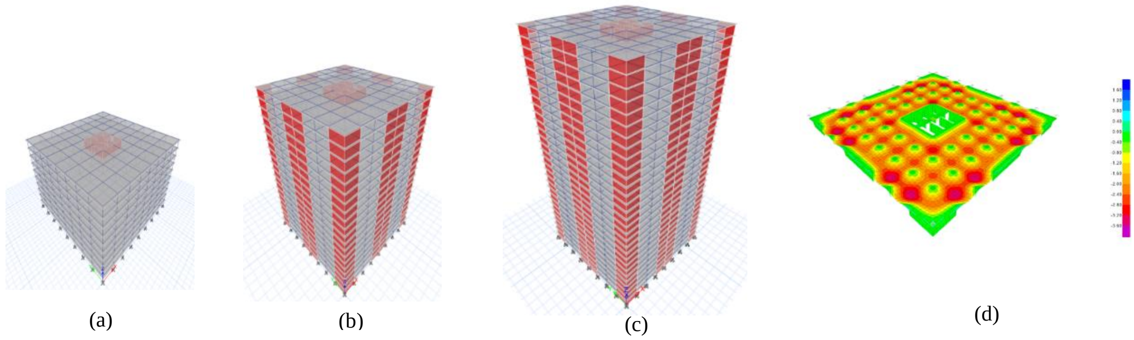

Figure 3. Structural models: (a) ETABS-10 story, (b) ETABS-20 story, (c) ETABS-30 story, (d) SAFE-Deflected shape of a floor slab in a 30 story building

superimposed dead load, and a 350 kg-f/m^2 (including partition walls) of uniformly distributed live loads were assumed to exist in all buildings. The supports at the bases of all the buildings were restrained against translation and rotation through fixity. Since the presence of any openings in the floor layout might adversely affect the rigid diaphragm approach, a semi-rigid diaphragm was used in the modeling of all the floor slabs. Slabs were modeled and designed in SAFE using the requirements of TS 500. Maximum slab reinforcement was obtained based on the results at the top and bottom of the slabs within each design strip, along with a corresponding load combination.

3. RESULTS

The structural behavior of the structural models with various slab types are evaluated in terms of their structural responses and overall costs. The results are examined and discussed for each set of story numbers (i.e., 10, 20 and 30 stories) with a consideration of their (a) fundamental periods, (b) base shear forces, (c) maximum lateral displacements, and (d) overall costs. In the cost estimation stage, the volume of concrete and the quantity of steel rebars are determined for each element (i.e., beams, columns, and slabs) separately. In determining the total cost, the cost of steel rebars (B420C) was assumed to be 2,602 Turkish Liras (TL) per ton, and the cost of concrete (C35) was assumed to be 245 TL per cubic meter. The formwork cost, labor fees, and the expense associated with the foundation were not included in determining the total cost. The costs of each building is calculated in the United States Dollars (USD). At the time of this study (March 2021), 1 USD equaled 6.5 TL.

In the cost analysis, a minimum reinforcement ratio was valid for almost all columns due to the minimum column capacity requirement in TBEC 2018. Therefore, the attempt to adjust columns sizes for each slab type was aborted and identical column sizes were used in each set, regardless of their slab types. Beam reinforcements were determined based on the maximum and minimum positive and negative moments at their mid-spans and supports, respectively.

3.1. Ten Story Buildings

The results of the ten-story structural models are presented in the following subsections.

3.1.1. Layouts with 6-meter spans

The first three periods of buildings with a 6-meter span resulted mode shapes in the "x", "y", and rotational direction, "z", as illustrated in Fig. 4a. The first periods were always in the "z" direction, while the second and third were in the "x" and "y" directions. The largest fundamental period occurred in the building with waffle slab, while the smallest period occurred in the building with a two-way slab with beams. Similarly, the second and third largest periods were obtained in the buildings with flat and ribbed slabs, respectively. Based on the data in Fig. 4b, the building with flat slab had the highest base shear value, while the building with waffle slab had the lowest value. The highest base shear was attributed to the flat slab's relatively larger thickness, which resulted from punching shear and the limiting of excessive deflection. Even though the topping thickness was identical for the buildings with ribbed and waffle slabs, due to different gravity and lateral load transferring mechanisms (i.e., one-way for ribbed slab and two-way for waffle slab) the cross-sectional dimensions of beams and joists in waffle slab became smaller than those in ribbed slab. This outcome resulted in higher base shear forces for the building with ribbed slab, compared to the building with waffle slab. The building with waffle slab exhibited maximum rooftop displacement, while the building with a two-way slab with beams experienced minimum displacement (Fig. 4c). Based on the results, it was determined that the building with a two-way slab with beams generated the most economical solution, while the building with flat slab was the least economical choice (Fig. 4d).

3.1.2. Layouts with 7.5-meter spans

Like the buildings with 6-meter spans, the first mode shapes of the buildings with 7.5-meter spans were in the "z" direction, while the second and third were in the "x" and "y" directions (Fig. 5a). The buildings with waffle and flat slabs had period values that were relatively close to each other, and generated the largest fundamental periods. The building with a two-way slab with beams exhibited the minimum period. Based on the data in Fig. 5b, the building with flat slab had the highest base shear force, while the building with waffle slab had the lowest shear force. The building with flat slab had the maximum rooftop displacement, while the building with a two-way slab with beams exhibited the minimum value (Fig. 5c). Unlike the two-way slab with beams type used in buildings with a 6-meter span, the most economical slab type for 7.5-meter span buildings was the waffle slab (Fig. 5d). However, the flat slab was still the most expensive type of slab.

3.1.3. Layouts with 9-meter spans

Like the buildings with the 6 and 7.5-meter spans, the first mode shapes of the buildings with 9-meter spans were in the "z" direction, while the second and third were in the "x" and "y" directions (Fig. 6a). The buildings with waffle slab had the largest period value, while the building with a two-way slab with beams had the smallest value. As shown in Fig. 6b, the building with flat slab had the highest base shear force, while the building with waffle slab had the lowest shear force. The building with flat slab had the maximum rooftop displacement, while the building with a two-way slab with beams exhibited the minimum value (Fig. 6c). Like the buildings with 7.5-meter spans, the waffle slab was the most economical solution, while the flat slab was the most expensive one (Fig. 6d).

3.1.4. Comparison of layouts with 6 and 9 meter spans

The results of the buildings with 6 and 9 meters were investigated in detail, since their total in-plane dimensions were identical. For this purpose, the variation of periods, base shear forces, maximum rooftop displacements and overall cost of the structural models were compared. Fig.7a illustrates that the buildings with 6-meter spans experienced higher periods compared to those with 9-meter spans. Higher base shear forces were obtained in buildings with 9-meter spans (Fig. 7b). Increasing the span length from 6 to 9 meters resulted in an increase in the base shear value by 9.5%, 9.1%, 16.4%, and 18.6% for the buildings with waffle, ribbed, two-way slabs with beams, and flat slabs, respectively. Fig. 7c shows that layouts with 6-meter spans had higher rooftop displacements compared to layouts with 9-meter spans.

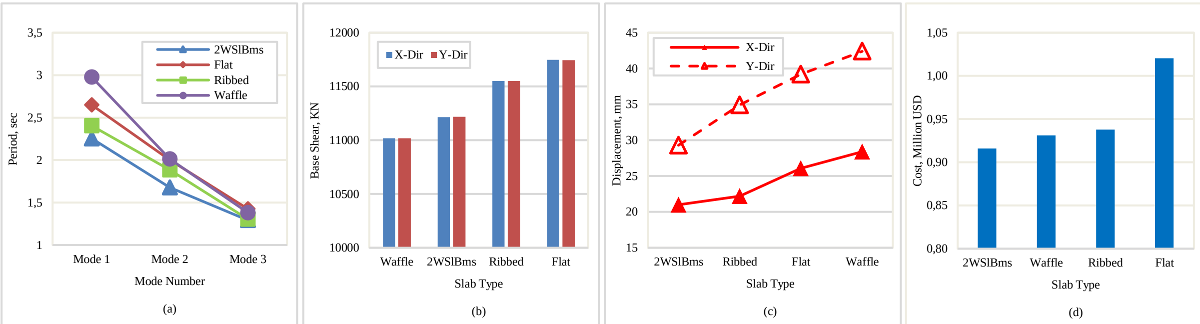

Figure 4. 10 story building with 6-meter span: (a) periods, (b) base shear, (c) max. rooftop displacement, (d) overall cost

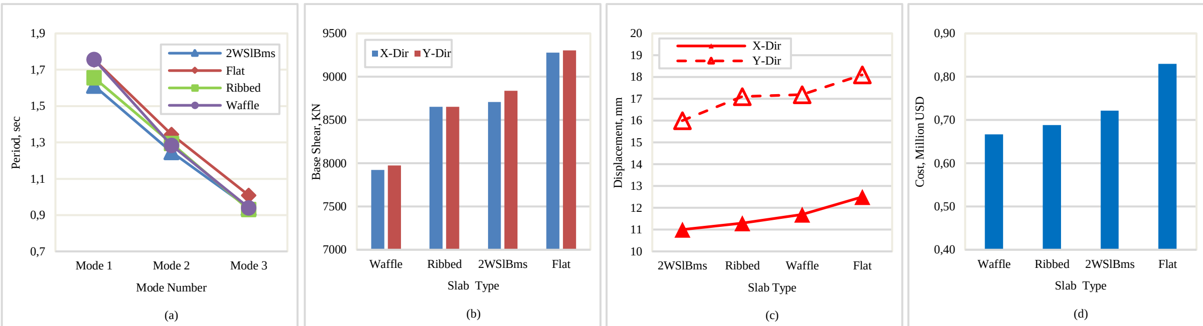

Figure 5. 10 story building with 7.5-meter span: (a) periods, (b) base shear, (c) max. rooftop displacement, (d) overall cost

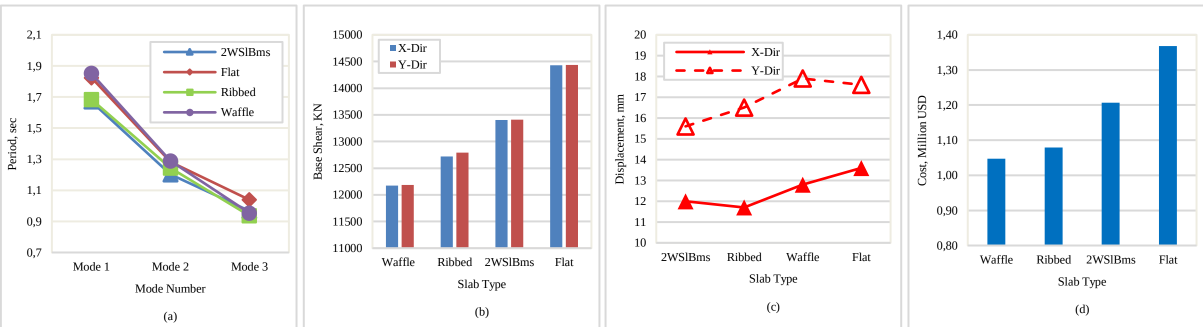

Figure 6. 10 story building with 9-meter span: (a) periods, (b) base shear, (c) max. rooftop displacement, (d) overall cost

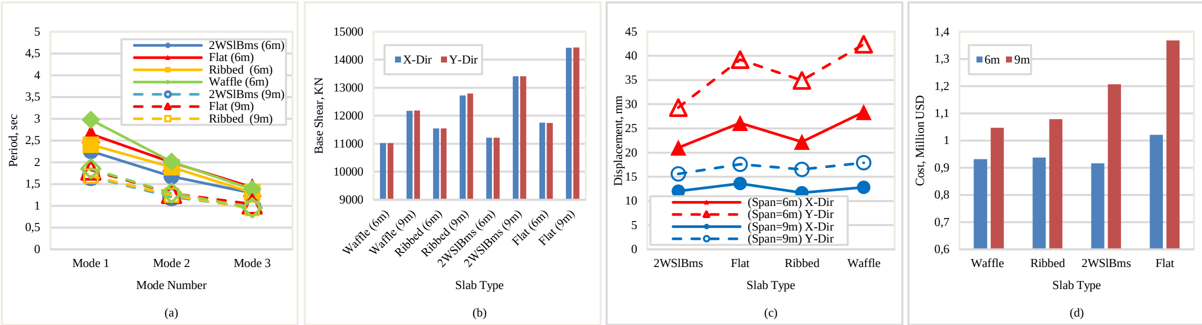

Figure 7. 10 story buildings with 6 to 9 m. spans: (a) periods, (b) base shear, (c) max. rooftop displacement, (d) overall cost

As expected, higher construction costs are associated with buildings with 9-meter spans (Fig. 7d). The cost surplus with respect to the 6-meter span layouts was 11.2% for the building with waffle slab, and 13.1, 24.1, and 25.4% for the buildings with ribbed, two-way slabs with beams and flat slabs, respectively.

3.2. Twenty Story Buildings

3.2.1. Layouts with 6-meter spans

Unlike the mode shapes of the ten-story buildings, the twenty-story buildings' first and second mode shapes were in the "x" or "y" directions, while the third was in the "z" direction (Fig. 8a). Like the outcome of the ten story buildings, the largest periods were associated with buildings with flat and waffle slabs, while the smallest period was achieved in the building with a two-way slab with beams. As displayed in Fig. 8b, the largest base shear force was obtained in the building with flat slab, while the lowest shear force appeared in the building with waffle slab. The building with flat slab had the maximum rooftop displacement, while the one with a two-way slab with beams exhibited the minimum value (Fig. 8c). The flat slab was the most expensive slab type, while the two-way slab with beams was the most economical option (Fig. 8d).

3.2.2. Layouts with 7.5-meter spans

The first and second mode shapes were in the "x" or "y" directions while the third was in the "z" direction (Fig. 9a). The largest period value was obtained in the building with flat slab, while the lowest value was obtained in the building with a two-way slab with beams. The maximum and minimum base shear forces were extracted from flat and waffle slabs, respectively (Fig. 9b). As illustrated in Fig. 9c, the building with flat slab had the maximum rooftop displacement while the building with a two-way slab with beams exhibited the minimum value. Unlike the buildings with 6-meter spans, the waffle slab turned out to be the most economical solution, while the flat slab was the most expensive type of slab (Fig. 9d).

3.2.3. Layouts with 9-meter spans

The first and second periods were in the "x" or "y" directions, while the third was in the "z" direction (Fig. 10a). The buildings with flat and waffle slabs had relatively closer values and generated the largest periods, while the building with a two-way slab with beams generated the smallest period. Fig. 10b illustrates that the building with flat slab had the maximum base shear force, while the building with waffle slab exhibited the minimum force. The building with flat slab had the maximum rooftop displacement, while the building with a two-way slab with beams had the minimum rooftop displacement (Fig. 10c). Like the buildings with 7.5-meter spans, the waffle slab type was the most economical solution, while flat slab was the most expensive one (Fig. 10d).

3.2.4. Comparison of layouts with 6 and 9 meter spans

As Fig. 11a illustrates, the buildings with 6-meter spans experienced higher periods compared to those with 9-meter spans. Higher base shear forces were obtained in the buildings with 9-meter spans (Fig.11b). Increasing the span length from 6 to 9 meters resulted in an increase in the base shear force by 9.4%, 7.4%, 13.3%, and 15.7% for the buildings with waffle, ribbed, two-way slabs with beams and flat slabs, respectively. Fig. 11c shows that the buildings with 6-meter spans had higher rooftop displacements compared to those with 9-meter spans. The higher cost was associated with buildings with 9-meter spans (Fig. 11d). The cost surplus with respect to the layouts with 6-meter spans was 7.3% for the buildings with waffle slab, and 8.0%, 20.6%, and 22.9% for those with ribbed, two-way slabs with beams and flat slabs, respectively.

3.3. Thirty Story Buildings

3.3.1. Layouts with 6-meter spans

Similar to the twenty-story buildings, the first and second mode shapes were in the "x" and "y" directions while the third was in the "z" direction (Fig. 12a). The largest periods were obtained in the buildings with flat and waffle slabs, while the smallest period was in the building with a two-way slab with beams. As illustrated in Fig. 12b, the largest base shear force was recorded in the building with flat slab, while the lowest shear force was in the building with waffle slab. The building with flat slab had the maximum rooftop displacement while the building with a two-way slab with beams exhibited minimum displacement (Fig. 12c). Based on the data presented in Fig. 12d, flat slab was the most expensive choice, while a two-way slab with beams was the most economical option.

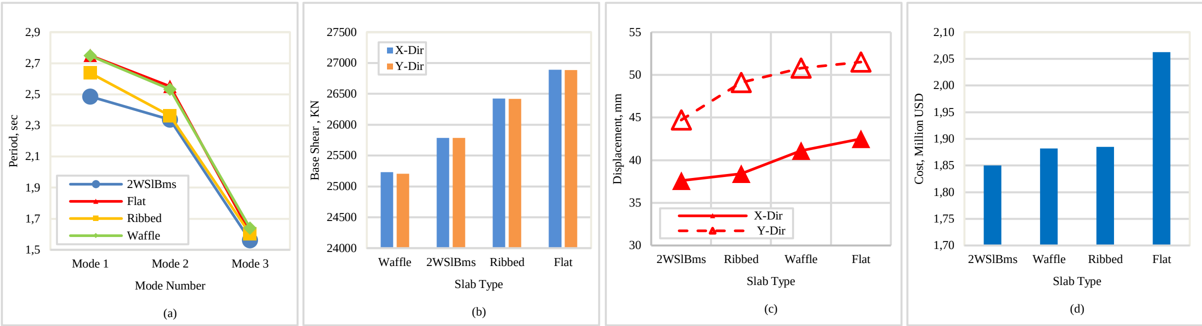

Figure 8. 20 story buildings with 6-meter span: (a) periods, (b) base shear, (c) max. rooftop displacement, (d) overall cost

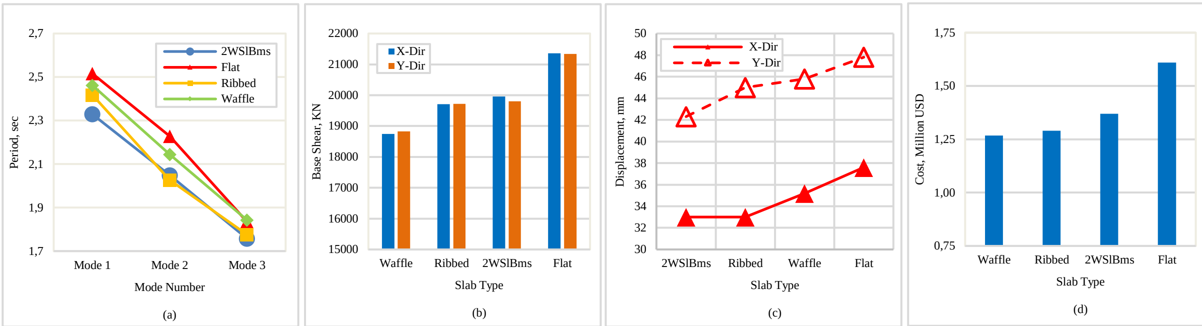

Figure 9. 20 story buildings with 7.5-meter span: (a) periods, (b) base shear, (c) max. rooftop displacement, (d) overall cost

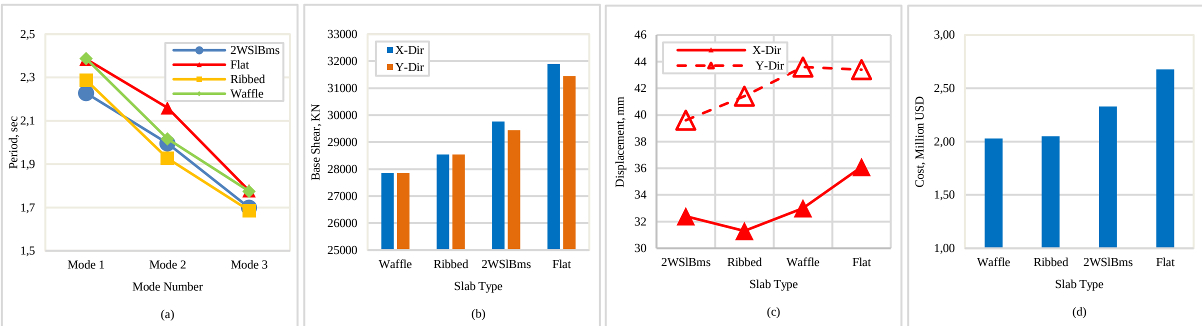

Figure 10. 20 story buildings with 9-meter span: (a) periods, (b) base shear, (c) max. rooftop displacement, (d) overall cost

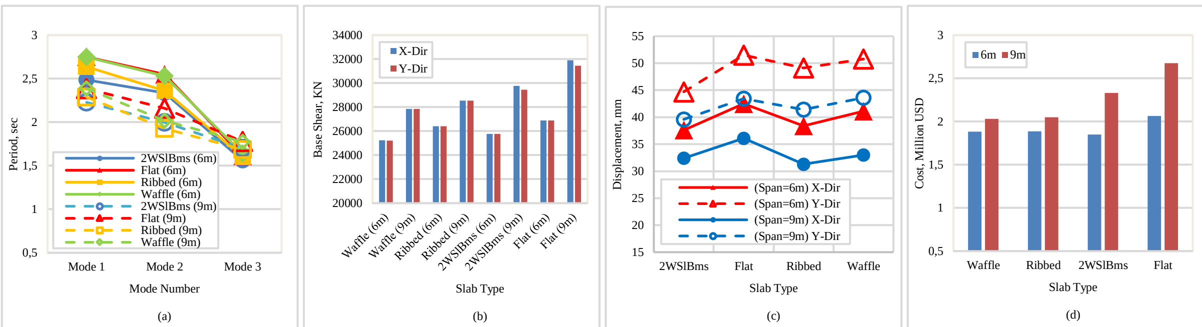

Figure 11. 20 story buildings with 6 vs 9 m. spans: (a) periods, (b) base shear, (c) max. rooftop displ., (d) overall cost

3.3.2. Layouts with 7.5-meter spans

Fig. 13a illustrates the first three mode shapes of the buildings with 7.5-meter spans. The first and second periods were in the "x" and "y" directions, while the third was in the "z" direction. The buildings with flat and waffle slabs generated the largest periods with relatively close periods, while the smallest period was achieved in the building with a two-way slab with beams. The maximum and minimum base shear forces were recorded in the buildings with flat and waffle slabs, respectively (Fig. 13b). The building with flat slab had the maximum rooftop displacement, while the building with a two-way slab with beams exhibited the minimum value (Fig. 13c). Unlike buildings with 6-meter spans, here, waffle slab was the most economical solution, while flat slab was the most expensive choice (Fig. 13d).

3.3.3. Layouts with 9-meter spans

Like the 6 and 7.5-meter span buildings, the first and second mode shapes were in the "x" and "y" directions,

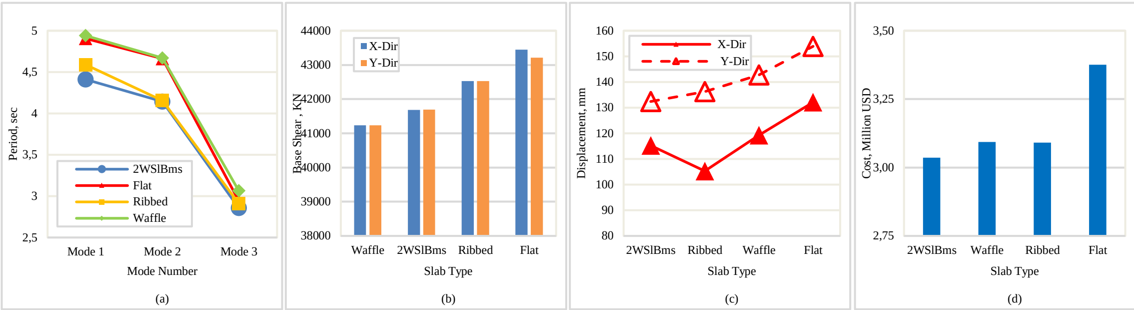

Figure 12. 30 story buildings with 6-meter span: (a) periods, (b) base shear, (c) max. rooftop displ., (d) overall cost

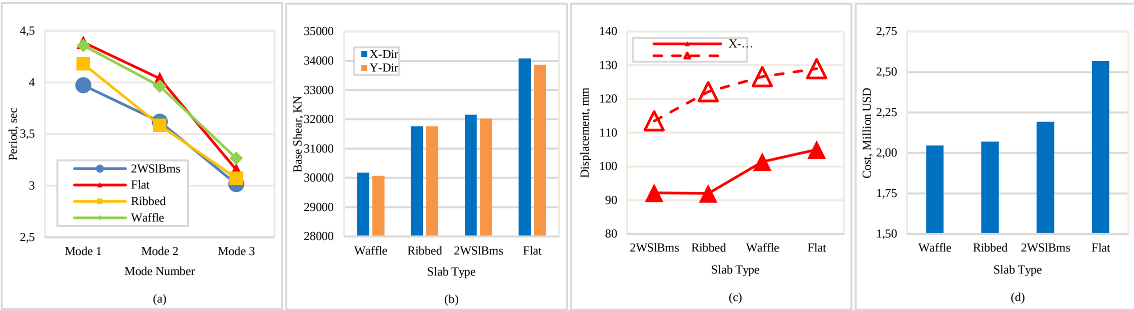

Figure 13. 30 story buildings with 7.5-meter span: (a) periods, (b) base shear, (c) max. rooftop displ., (d) overall cost

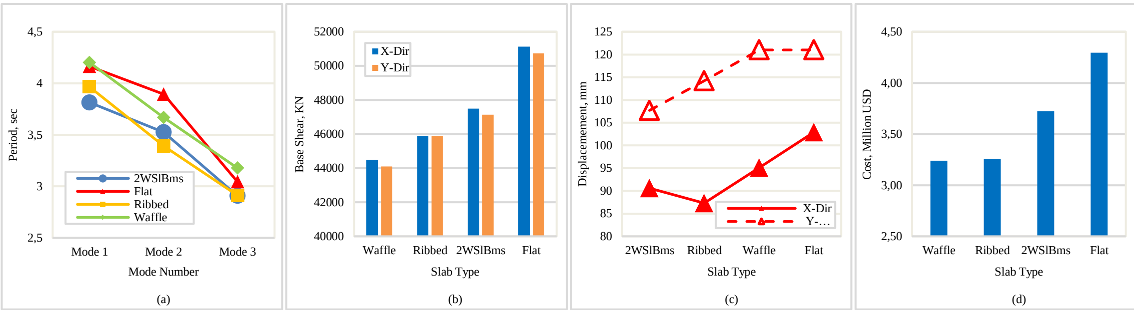

Figure 14. 30 story buildings with 9-meter span: (a) periods, (b) base shear, (c) max. rooftop displ. (d) overall cost

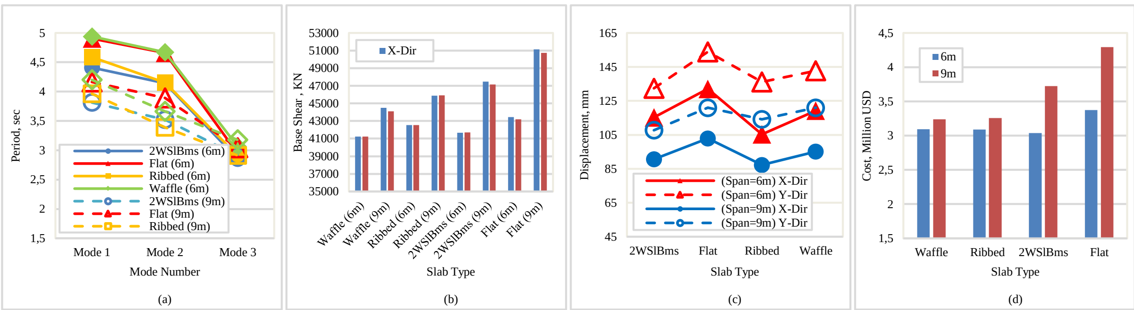

Figure 15. 30 story buildings with 6 vs 9-m spans: (a) periods, (b) base shear, (c) max. rooftop displ., (d) overall cost

while the third was in the z direction (Fig. 14a). The buildings with flat and waffle slabs generated the largest periods with relatively close values, while the building with a two-way slab with beams had the smallest period. Fig. 14b shows that the building with flat slab generated the maximum base shear force, while the building with waffle slab had the minimum value. The building with flat slab demonstrated maximum rooftop displacement, while the building with a two-way slab with beams exhibited the minimum value (Fig. 14c). Like the buildings with 7.5-meter spans, here, waffle slab provided the most economical solution, while flat slab was the most expensive type of slab (Fig. 14d).

3.3.4. Comparison of layouts with 6 and 9 meter spans

Fig. 15a illustrates that the buildings with 6-meter spans experienced higher periods compared to those with 9-meter spans. The higher base shear forces were recorded in buildings with 9-meter spans (Fig. 15b). Increasing the span length from 6 to 9 meters resulted in an increase of 7.3% in the base shear forces of the buildings with waffle and ribbed slabs. For buildings with a two-way slab with beams and flat slabs, the base shear forces increased by 12.2% and 15.0%, respectively. Fig. 15c shows that buildings with 6-meter spans had higher rooftop displacements compared to buildings with 9-meter spans. Higher cost was associated with buildings with 9-meter spans (Fig. 15d). The cost surplus with respect to layouts with 6-meter spans was 4.5%, 5.0%, 18.4%, and 21.4% for buildings with waffle, ribbed, two-way slabs with beams and flat slabs, respectively.

The overall results of the 36 structural models are listed in Table 3. The table helps us understand the variation among the analyses results in determining the conclusions and recommendations listed in the next section.

- The two-way slab with beams generated the minimum periods in all buildings. However, both waffle and flat slabs had the largest period values in the buildings with 6-meter spans, while flat slab alone had the largest value when the span increased to 7.5-meters and 9-meters.
- Keeping the total dimensions of a layout identical but increasing its span length resulted in smaller periods of vibration due to the larger cross-sectional sizes of beams, columns and slabs.
- The largest base shear forces were always associated with buildings with flat slab, while the smallest forces were associated with buildings with waffle slab.

Table 3. Analyses results of 10, 20 and 30 story structural models

Floors	Plan Dim. (mxm)	Span (m)	Slab Types	Base Shear (kN)		Max. Rooftop Displacement (mm)		Natural Period of Vibration (sec)			Cost (in Millions of USD)
				X-Dir.	Y-Dir.	X-Dir.	Y-Dir.	Mode 1	Mode 2	Mode 3	
10	72x72	6	2WSlBms	11,215.65	11,219.29	21.0	29.3	2.255	1.676	1.292	0.915
			Flat	11,747.82	11,745.47	26.1	39.2	2.65	2.001	1.425	1.020
			Ribbed	11,550.81	11,550.86	22.2	34.9	2.405	1.885	1.304	0.938
			Waffle	11,017.63	11,018.07	28.4	42.4	2.978	2.013	1.381	0.931
	60x60	7.5	2WSlBms	8,708.94	8,837.11	11.0	16.0	1.612	1.247	0.941	0.722
			Flat	9,279.43	9,303.66	12.5	18.1	1.756	1.344	1.009	0.829
			Ribbed	8,651.22	8,651.47	11.3	17.1	1.656	1.295	0.931	0.688
			Waffle	7,923.69	7,973.14	11.7	17.2	1.757	1.285	0.941	0.668
	72x72	9	2WSlBms	13,405.00	13,408.26	12.0	15.6	1.671	1.202	0.967	1.206
			Flat	14,428.97	14,436.81	13.6	17.6	1.825	1.282	1.039	1.368
			Ribbed	12,718.64	12,792.54	11.7	16.5	1.685	1.243	0.937	1.078
			Waffle	12,173.70	12,187.28	12.8	17.9	1.852	1.289	0.954	1.048
20	72x72	6	2WSlBms	25,784.73	25,784.97	37.6	44.7	2.486	2.337	1.561	1.851
			Flat	26,893.19	26,886.54	42.5	51.5	2.75	2.551	1.612	2.063
			Ribbed	26,424.6	26,420.37	38.4	49.1	2.637	2.361	1.603	1.885
			Waffle	25,233.22	25,203.75	41.1	50.8	2.748	2.532	1.64	1.882
	60x60	7.5	2WSlBms	19,960.68	19,803.93	33.0	42.3	2.329	2.049	1.758	1.369
			Flat	21,363.4	21,336.39	37.6	47.8	2.516	2.228	1.835	1.609
			Ribbed	19,709.01	19,714.92	33.0	45.0	2.418	2.027	1.776	1.291
			Waffle	18,739.59	18,824.83	35.2	45.8	2.462	2.145	1.843	1.268
	72x72	9	2WSlBms	29,761.15	29,448.35	32.4	39.6	2.228	1.997	1.699	2.331
			Flat	31,899.31	31,448.37	36.1	43.4	2.385	2.16	1.777	2.677
			Ribbed	28,540.14	28,544.98	31.3	41.4	2.288	1.927	1.686	2.051
			Waffle	27,851.73	27,852.35	33.0	43.6	2.387	2.017	1.775	2.029
30	72x72	6	2WSlBms	41,683.13	41,689.35	115.2	132.4	4.410	4.142	2.855	3.035
			Flat	43,450.27	43,210.31	132.1	153.9	4.905	4.661	2.942	3.375
			Ribbed	42,527.95	42,525.46	105.3	136.2	4.588	4.153	2.909	3.091
			Waffle	41,232.98	41,230.29	119.3	142.8	4.940	4.669	3.064	3.094
	60x60	7.5	2WSlBms	32,161.93	32,023.59	92.2	113.5	3.972	3.620	3.015	2.192
			Flat	34,077.07	33,860.94	105.0	129.0	4.388	4.038	3.154	2.568
			Ribbed	31,763.51	31,763.61	92.0	122.2	4.179	3.584	3.072	2.071
			Waffle	30,177.53	30,069.41	101.4	126.6	4.358	3.964	3.264	2.046
	72x72	9	2WSlBms	47,487.59	47,138.55	90.6	107.7	3.814	3.525	2.907	3.723
			Flat	51,135.19	50,733.50	102.9	121.0	4.164	3.893	3.043	4.294
			Ribbed	45,891.21	45,896.52	87.3	114.2	3.964	3.392	2.912	3.257
			Waffle	44,492.32	44,106.43	95.1	121.0	4.201	3.666	3.177	3.242

4. CONCLUSIONS AND REMARKS

The results of the parametric studies of the thirty-six buildings, along with recommendations for future study, are presented in the list given below.

- The base shear forces of 6-meter span buildings with a two-way slab with beams, ribbed and flat slabs were 1.7%, 4.1%, and 5.8% higher than those with waffle slab.

- The base shear forces of 7.5-meter span buildings with ribbed, two-way slabs with beams, and flat slabs were 6.1%, 7.1%, and 12.8% higher than those with waffle slab.
- The base shear forces of 9-meter span buildings with ribbed, two-way slabs with beams, and flat slabs were 3.3%, 7.3%, and 13.8% higher than those with waffle slabs.
- Increasing the span length from 6 to 9 meters caused an increase in the base shear forces of the buildings with ribbed, waffle, two-way slabs with beams and flat slabs by 8.0%, 8.8%, 14.0%, and 16.4%, respectively.
- The buildings with flat slabs had maximum rooftop displacements, while those with two-way slabs with beams exhibited minimum displacements, except for the 6-meter span building with waffle slab.
- When total layout dimensions were kept identical and span length was increased from 6 to 9 meters, rooftop displacements decreased due to the larger cross-sections of beams, columns and slabs. This decrease was in the range of 43% to 58% for the ten-story, and 11% to 22% for the twenty and thirty-story, buildings.
- The most economical slab type for buildings with 6-m spans was a two-way slab with beams. Waffle slab was the most economical slab for buildings with 7.5 and 9-meter spans. In all cases, flat slab was found to be the most expensive type of slab.
- Two-way slabs with beams are recommended for 10, 20 and 30 story buildings with 6 and 7.5-m spans. However, as span length increased, the cross-sections of beams and slabs became more critical, suggesting the use of a slab system with more load transfer options such as ribbed or waffle. Therefore, for larger spans, such as 9-m, ribbed or waffle slabs are recommended if more columns and walls are used.
- A waffle slab could be considered as a viable option for taller buildings since it is the lightest system, and thus can reduce the building's weight and base shear forces. However, due to their larger displacements and period values, adopting a span length from 7.5 to 9 meters, and introducing more columns and shear walls, is recommended to make a lighter building, which would also improve displacements and periods.
- A flat slab produces larger displacements and base shear forces, which leads to the most expensive solution for all span lengths. Therefore, due to its poor structural performance, it is not recommended in seismically active areas.
- Based on the results of the analyses, in order to enhance the structural behavior of buildings, shear walls are recommended to be used with ribbed, waffle and flat slabs.
- This study was limited to the following parameters: (a) the number of floors, (b) span length, and (c) different slab types (two-way slabs with beams, flat slab, ribbed slab, and waffle slab). However, in future studies, the impact of the following parameters might also be considered when evaluating the overall cost and seismic behaviors of RC buildings: (a) varying in-plan aspect ratios, (b) buildings with different floor geometries such as trapezoidal, triangular, or elliptical shapes, (c) varying floor-to-floor heights, (d) the presence of basement floors, (e) various framing types (such as post-tensioned (PT) slabs, composite slabs and hollow-core slabs), (f) soil-structure interaction, (g) plan and vertical irregularities, (h) the presence of shear walls with different configurations, and (i) material nonlinearity in FE analyses.

DECLARATION OF ETHICAL STANDARDS

The author(s) of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

AUTHORS' CONTRIBUTION

Gökhan TUNÇ: Wrote the manuscript and evaluated the results.

Abdul Basir AZIZI: Constructed the structural models, performed the structural analyses and evaluated the results.

Tuğrul TANFENER: Constructed some of the structural models and evaluated the results.

CONFLICT OF INTEREST

There is no conflict of interest in this study.

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