SEISMIC BEHAVIOR OF A HIGH-RISE RC BUILDING WITH DIFFERENT TYPES OF SLABS

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ABSTRACT

In Turkey, high-rise reinforced concrete (RC) buildings become more popular with the population increase and economic growth. In design of high-rise buildings, shear wall and moment resisting frame structural (dual) systems are commonly used. Dual systems typically have sufficient rigidity and ductility depending on the location and total area of shear walls, and the type of the slab system has an influence on the structural behavior and performance. In this study, the influence of different slab types on the structural behavior of a 33-story office building with frame and shear wall structural (dual) system is investigated. The structure has three rigid basement stories. 3D model of the building is developed by using Finite Element software (ETABS) with four different types of slab systems designed in accordance with the Turkish Earthquake Code 2007 (TEC 2007). In the structural models, the building layout and structural system are kept same for each model, while the type of slab system was changed. Investigated slab systems are (a) two-way slabs, (b) ribbed slab system in one direction, (c) flat plate system, and (d) flat slab system with spandrel (edge) beams. The slab systems are defined as shell elements in the numerical model. Elastic design spectrum given in TEC 2007 is used in the dynamic analysis. The fundamental periods, base shear force and story drift profiles of the models are determined from the numerical analyses. Results are given in tables and figures, comparatively and some recommendations are provided for the proper selection of slab types.

Keywords: building; drift; high-rise; seismic behavior; slab type

1. INTRODUCTION

In parallel with urbanization and rapid population growth, big cities and metropolises have arisen around the world. Because of the extensive need for living and working areas and the increasing land costs, design and construction of high-rise buildings are becoming widespread. The definition of high-rise building shows variations with time and location. For example, the buildings exceeding 22 meters are defined as high-rise buildings in Germany while the limit is considered as 12-stories in the United States (Taranath, 2012). The structures with a height of 60 meters from the ground (about 20-story) are defined as high-rise buildings in the ‘Seismic Code for Tall Buildings in Istanbul 2008’ (IYBDY 2008). Extensive research studies were performed regarding the determination of earthquake-induced behaviors and earthquake performances of high-rise buildings structural systems and components, leading to the development and publication of recommended design guidelines (Tall Buildings Initiative, 2011). The presence of a new section for high-rise buildings in the most recent version of TEC 2017 is an indication of how important this issue is in Turkey. The high-rise buildings are mainly composed of a core in the middle, frames, and shear wall-frame structural systems in Turkey. As slab systems, mostly two-way slabs, ribbed slabs and flat plates are used. Design of slabs, which are supposed to carry the loads perpendicular to their plane as gravity loads, is carried out in such a way that they will show rigid diaphragm behavior under lateral (earthquake) loads. In case of the presence of rigid basements in the building, the design of the first basement ceiling slab is vitally important to meet the in-plane effects that will occur. A similar situation is a matter for the slabs in and around the

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core walls. To decrease lateral displacements (limit the drifts) is important in order to reduce the non-structural element damages (Dowrick 2009, Moehle 2015) in buildings.

In this study, design of the structural system of a 33-story reinforced concrete high-rise building was performed as a shear wall-frame structural system where core walls are located in the middle. While the dimensions of the shear walls and the columns vary along the height of the buildings; the dimensions are the same for all four different slab systems. The linear elastic behavior of the structural systems under vertical and lateral (earthquake) loads having four different types of slab system was investigated by means of the elastic design spectrum given in TEC 2007. The slabs were also included in 3D structural system models accordingly to examine the effects of slab systems on building structural system behavior. The numerical results regarding the buildings with different slab systems are summarized in tables and figures, and the results are discussed.

2. SLAB SYSTEMS IN HIGH RISE BUILDINGS

When deciding on a slab system in a high rise building, criteria such as the architectural functions and arrangements, piping layout and some other considerations are essential. There are also many relevant factors, such as obtaining a flat slab ceiling, providing flexibility in the arrangement of partition walls, proper laying of the piping, uniform lighting, sound and thermal insulation, and gaining from floor-height. Reinforced concrete slab systems include two-way slab, one-way ribbed slab, two-way ribbed (waffle) slab, and flat plate. There are some requirements in the codes on slab systems that can be used depending on the structural systems and earthquake zones. For example, in the case of ribbed slabs or flat plate slabs, use of shear wall structural system is required depending on earthquake zone and number of stories (TEC 2007). Limiting the weight of building and the resulting inertia forces to a minimum is also important in deciding on a slab system. The gravity loads, which are perpendicular to the plane of slabs, are transmitted to the beams by which they are supported. However, the loads are directly transferred to the columns or shear walls in case of a flat plate slab. In the case of conventional buildings, span length of frames and slabs usually go up to 6.0m to 7.0m, while for different structures, such as parking lot, it may be designed up to 8.0m to 8.5m. In this context, if there are no important constraints such as limiting the story height, the use of two-way slabs may be preferable in high rise buildings to increase the stiffness of the structural system. If the slab system is a type of ribbed (one or two-way) slab system or flat plate system, the location of shear walls is important. Generally, shear walls and core are assumed to be located outside and at the center of the building, respectively. In high-rise buildings having rigid basement floors at periphery, the in-plane effects and their transfer to the structural system are important. In this study, four different slab systems including two-way slab, one-way ribbed slab, flat slab and flat slab system with spandrel (edge) beams and two-way slab with rigid basement system are considered and analyzed.

3. THE 33-STORY HIGH RISE BUILDING STUDIED

A reinforced concrete high rise building with a shear wall-frame structural system consisting of a core walls in the middle, and columns and shear walls located at the periphery of the building is studied. The building has 33 stories including three basements, ground floor and 29 stories. The building is designed as office building (Uzun, 2014). The story heights in the building are as follows: 5.0m in the basement, 4.5m in the ground floor and 3.5m in the upper stories. The total building height is 116.50m and it has a regular frame configuration in both directions. The building has dimensions of 29.00m × 36.00m in the plan. It was assumed that the high-rise building will be built in the first-degree seismic zone and the soil class was Z2 according to TEC 2007. The concrete and reinforcement grades are planned to be C50 and S420, respectively. Properties of the structural system are given below. The column dimensions are shown in Table 1. The shear walls around the elevator shaft and stairs, which are located at the center of the building are planned to have a thickness of 0.50m throughout the height.
of the building, and other shear walls outside the core wall zone have dimensions of 4.50m × 0.50m (4.50m × 0.40m from the height of +71.00m). The beams are planned to be 0.50m/0.60m in the core wall zone, and 0.45m / 0.60m in the zones outside the core wall. The surrounding shear wall is not taken into consideration in the basements in the structural models.

The four different slab systems considered are as follows:

- Two-way slab system: Type I
- One way ribbed slab system: Type II
- Flat plate system: Type III
- Flat slab system with spandrel (edge) beams system: Type IV

### Table 1: Column sizes through the height of the building

<table>
<thead>
<tr>
<th>Column</th>
<th>-10.50m - +36.00m</th>
<th>+36.00m - +71.00m</th>
<th>+71.00m - +106.00m</th>
</tr>
</thead>
<tbody>
<tr>
<td>S01-S04-S35-S38</td>
<td>0.70×0.70</td>
<td>0.60×0.60</td>
<td>0.60×0.60</td>
</tr>
<tr>
<td>S05-S10-S29-S34</td>
<td>0.50×1.30</td>
<td>0.50×1.00</td>
<td>0.45×0.90</td>
</tr>
<tr>
<td>S06-S07-S08-S09</td>
<td>0.90×0.90</td>
<td>0.80×0.80</td>
<td>0.70×0.70</td>
</tr>
<tr>
<td>S30-S31-S32-S33</td>
<td>0.70×0.70</td>
<td>0.60×0.60</td>
<td>0.60×0.60</td>
</tr>
</tbody>
</table>

### 3.1 Two-way slab system

For Type I slab system, the thickness of two-way slabs is considered as 0.17m. The ground floor slab plan and its ETABS model are given in Figure 1. The columns and beams are assigned as frame elements in the modeling phase, and the shear walls are defined as shell elements. The slabs are included in the model as shell elements, and the slabs in the zone where elevator and stairs are located are also included in the model.

![Figure 1](image1.png)

a) Ground story two-way slab system layout a) for Type 1 and b) its ETABS model

### 3.2 Ribbed slab system in one direction

For the Type II slab system, the ground floor ceiling formwork plan and ETABs model are given in Figure 2. The ribs are 0.20m/0.35m in size, and the distance between the ribs is 0.40m. The plate thickness connecting the ribs is 0.10m (Figure 3). The directions of the ribs are designed so that they transfer the loads to the main beams located on the short axis as much as possible. In the modeling phase; the columns, frame beams, and ribs are defined as frame elements, and the slab elements between the ribs and shear walls are defined as a shell elements. The slabs where the elevator and
stairs are located are formed as a ribbed slab. The beams around the perimeter are designed as regular RC beams to provide a closed cantilever system along the height of the building.

Figure 2. Ground story slab system layout a) for Type II and b) its ETABS model

Figure 3. Section of ribbed slab system (in cm)

3.3 Flat slab system

In Type III slab system where flat plate system is used, the plate thickness is 0.25m. The ceiling formwork plan for this system is given in Figure 4. The loads, perpendicular and in the direction of the slab plane, are directly transferred to the vertical structural system elements. In the modeling phase, the columns are defined as frame elements, and the slabs and shear walls are defined as a shell elements. The slabs located on the core wall in the elevator and stairs zone are included in the model as a flat plate. Two-way slab arrangement of the core wall zone is also possible, and it may be more suitable. There is no perimeter beams around the building in this model.

The only difference between Type IV and Type III slab systems is the presence of perimeter beams around the building. These beams are designed as 0.45m / 0.60m in size, and the slab thickness is designed as 0.25m. The ground floor ceiling formwork plan is given in Figure 5. In the calculation of building weights, the floor load is defined as 2.0kN/m² for all slabs, and regarding live loads, it is defined as 5.0kN/m² on the corridor and the stairs, 3.5kN/m² on the slabs. The total weights calculated for all four different models are given below.

Type I: 479.77MN, Type II: 490.85MN, Type III: 445.66MN, Type IV: 483.27MN

Hence, the structural weight of the flat plate system (Type III) is minimum, and it is maximum for the ribbed slab system (Type II).

The periods and the mass participation ratios of the first three modes obtained for four different configurations of the structural system are given in Table 2. The first mode periods are in the y-direction since the x-direction of the building is more rigid. The presence of shear wall around the building increased the torsional stiffness, causing the relevant period to decrease.
The three-dimensional structural system models of the building are created using ETABS (2000) software. The ETABS structural system model for Type I is given in Figure 6.

Figure 4. Ground story flat slab system layout a) for Type III and b) its ETABS model

Figure 5. Ground story flat slab system layout a) having spandrel beams (Type IV) and b) its ETABS model

Figure 6. ETABS model of the building Type I
As shown in Table 2, the lateral stiffness is maximum in Type I, and minimum in Type III. Because of the lack of beams on the perimeter and in the inner zone of core wall, the stiffness is minimum in Type III slab system despite the perimeter beams in the core wall zone. In Type IV model where the flat plate system and the beams around the building are present, there is a noticeable effect of the surrounding beams on the stiffness of the building. Hence, it is obvious that forming the surrounding beams in the flat plate systems will make a significant contribution to the behavior of the building.

Although the total structural weight increased in Type II, it is seen that due to the presence of the perimeter beams and the plane girders in the core wall zone, the stiffness is very close to the lateral stiffness of the two-way slab system in Type I. It is seen that the mass participation ratios do not reach to the minimum required value of 90%, when three modes of mass participation ratios are considered. Therefore, the first 33 modes are taken into account in the seismic analyses.

Table 2: First three free vibration periods and corresponding mass participation of building having four type of slab system

<table>
<thead>
<tr>
<th>Slab Types of Building Models</th>
<th>Mode</th>
<th>Period (s)</th>
<th>Cumulative Mass Participating Ratios (%) X</th>
<th>Cumulative Mass Participating Ratios (%) Y</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type-I</td>
<td>1</td>
<td>2.575</td>
<td>0.00</td>
<td>72.47</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>2.035</td>
<td>65.63</td>
<td>72.47</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>1.914</td>
<td>65.63</td>
<td>72.47</td>
</tr>
<tr>
<td>Type-II</td>
<td>1</td>
<td>2.699</td>
<td>0.00</td>
<td>72.63</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>2.014</td>
<td>65.68</td>
<td>72.63</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>1.995</td>
<td>65.97</td>
<td>72.63</td>
</tr>
<tr>
<td>Type-III</td>
<td>1</td>
<td>3.681</td>
<td>0.00</td>
<td>70.80</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>2.568</td>
<td>0.00</td>
<td>70.80</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>2.232</td>
<td>64.82</td>
<td>70.80</td>
</tr>
<tr>
<td>Type-IV</td>
<td>1</td>
<td>3.168</td>
<td>0.00</td>
<td>71.56</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>2.187</td>
<td>65.19</td>
<td>71.56</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>2.165</td>
<td>65.19</td>
<td>71.56</td>
</tr>
</tbody>
</table>

4. SEISMIC BEHAVIOR OF THE HIGH RISE BUILDING

The seismic response spectrum analysis is performed using the elastic design spectrum given in the Turkish Earthquake Code 2007 (TEC 2007). The office building (importance factor, I= 1.0) is assumed to be in the first-degree seismic zone (A= 0.40), and the soil class is Z2 (T= 0.15s, T= 0.40s). The behavior coefficient of the structural system is taken into consideration as R= 7 for high ductility shear wall-frame structural system. Internal forces are determined under vertical and horizontal loads and in the x and y directions using the loads given in TS498 (1997), load combinations given in TS500 (2000), and the structural system is dimensioned accordingly (Uzun, 2014). There are no structural irregularities that are considered in the structural system models. The variation of the base shears in x and y directions, respectively along the height of the building is given in Figures 7 and 8 for all models. The base shear V is given in TEC 2007 as follows:

\[ V = A \times I \times S(T) \times W / (R_a) \]  

where S(T) spectrum coefficient, W total weight of the building and R is earthquake load reduction coefficient, where R=0 is considered.
As can be seen from the figures, maximum base shear occurs in Type II which is the largest ribbed slab system, and the minimum base shear appears at the flat plate system (Type III). Although the free vibration period is significantly low in the flat plate system, the weight of the building is also low in this system.

The floor displacements of the building under design seismic loads, occurring under the effects of reduced seismic loads in the x and y directions are given in Figures 9 and 10.
The largest lateral displacements in both principal directions are observed in Type III model where the flat slab is defined. Since displacements are inversely proportional to the stiffness, the Type III is expected to have the lowest stiffness. The perimeter beams increase stiffness in the two-way slab system, as the lateral displacements in Type IV are larger than those in the ribbed slab system. As expected, minimum lateral displacement appears in the two-way slab system which has the maximum stiffness (Type I). Since the rigidity of the building is less in the y-direction, the lateral displacements are larger in this direction. The variation of the drift ratios for the x and y directions under seismic effects is given in Fig. 11 and Fig. 12. As can be seen from the figure, the drift ratios in the flat plate system are high for both directions. They are close to the limit of the interstorey drift ratio (0.02) in the y-direction, because of the lack of beams in the core wall zone. Hence, especially in the flat plate system, more shear walls should exist to increase the overall stiffness of the structural system.
5. CONCLUSIONS

In this study, the structural system of a reinforced concrete high-rise building having 33 stories is designed under vertical and lateral (earthquake) loads according to TEC 2007, TS498 and TS500 (2000). The seismic behavior of the high-rise building for four different slab systems is investigated. These cases include two-way slab, one-way ribbed slab, flat plate and flat slab system with spandrel (edge) beams. The three-dimensional models of the building structural systems are developed using ETABS software, and the slabs are included in the model as well. Through the analyses, the behavioral effects of different slab systems are determined quantitatively, and the results are provided
in tables and figures. The following results may be reported within the scope of considered structural system properties:

- The use of two-way slab system is a suitable choice, since the frame system stiffness is high due to the larger dimensions of the frame beams.
- In the case of the ribbed slab system, the behavior is acceptable depending on the frame beam sizes around the perimeter of the building. Presence of frames in the core wall zone plays an important role on the behavior of structural system.
- Since stiffness is relatively low in case of a flat plate system, the largest lateral displacements occurred in this model. It can be stated that the lack of beams in the core wall zone is responsible for this result. It is obvious that the presence of the beams in the core wall zone will improve the behavior. Furthermore, behavior can be improved, if spandrel beams around the perimeter of the building are used in the case of a flat plate system.
- For safe transfer of in plane forces from floors to the structural system, it is recommended to use two-way slab system at the ground story bottom floor slabs, especially if perimeter shear walls exist at basement. For future work, it is planned to investigate in-plane forces at transfer floors.

6. REFERENCES

TEC 2007. Specifications for the Buildings to be Built in Disaster Regions, Ministry of Public works and Settlement of Republic of Turkey,. Official Gazette.