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Research Article

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Earthquake Failure of Buildings with Overhangs

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Keywords

Earthquake,
Overhangs,
Turkish Building Earthquake Code,
Torsional irregularity,
Structural irregularity.

Abstract

The behavior of buildings during an earthquake is a complicated issue. The interaction of the structural system and the plan geometry play a decisive role in the earthquake behavior of buildings. Overhangs create irregularity in plan geometry that cause an increase in the storey area on the storeys above the ground storey. In this study, the effect of overhangs on earthquake performance of buildings was analyzed. A regular RC building with no overhangs was designed as the reference building model (Model A) for numerical analysis. The reference model building has four different overhang variants. All overhang direction options were compared with the reference model. The numerical models were analyzed by software STA4CAD v14.1. The analysis results were evaluated based on Turkish Building Earthquake Code 2018 (TBEC-2018). The effects of overhangs direction on torsional irregularity were also assessed. The study emphasizes that the cantilever directions are the most significant parameter in an earthquake rather than the negative effect of the cantilever on the earthquake performance. The obtained results revealed that among the models having overhangs, the maximum torsional irregularity coefficients were observed in Model E as 1.30, which has overhangs on three sides and the minimum torsional irregularity coefficients were obtained Model D as 1.12, which has overhangs on two opposite sides. The lowest torsional irregularity coefficient was observed in Model A as 1.09.

1. Introduction

Turkey is located in a seismically active region and, unfortunately, suffers from earthquakes at frequent intervals. An earthquake struck Kahramanmaraş with a magnitude 7.8 in the early hours on February 6, 2023. The earthquake caused serious loss of lives and property in 11 provinces in the south-eastern region of Turkey. It is the deadliest earthquake in Turkish history. It caused more casualties than the Erzincan earthquake, which had Turkey's largest loss of life. When the buildings destroyed after the earthquake were examined, it was seen that the cantilevered buildings were seriously damaged or completely destroyed.

The commonly used construction system in Turkey is reinforced concrete (RC) skeleton buildings. Many reasons can be asserted for this condition such as its cheapness, availability, sufficiency in qualified personnel, etc. The interaction of the structural system and the plan geometry play a decisive role in the earthquake behavior of buildings. If designs that take the earthquake behavior into account are not applied, the number of collapsed buildings and the loss of life increase. Damage levels are directly related to structural irregularities or material quality and faulty workmanship.

Overhangs are one of the significant design features that are commonly used in buildings. However, they cause irregularity in the plan and difference in the stiffness on vertical direction. Overhangs adversely affect earthquake behavior of buildings. This subject has been examined by various researchers. Tuxhari et al. (2023) evaluated observed

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irregularities in buildings after The Durrës earthquake of 11.26.2019. They emphasized volumetric shape irregularities and significance of the early collaboration of the architect and structural engineer [1]. Morey and Potnis (2023) examined earthquake behavior of the cantilever balcony (slab) of fifteen-storied rectangular and C-shaped buildings through numerical analysis with Etabs software. They suggested the optimum sizes for the cantilever balcony [2]. Gürsoy and Doğan (2020) analyzed the effect of floor discontinuity on earthquake behavior of buildings. They investigated the size of gap on floor and its position [3]. Meral (2023) investigated the effects of frame discontinuities on earthquake performance of reinforced concrete buildings. They concluded that reference regular buildings are more affected by discontinuities than buildings with heavy overhangs [4]. Başgöze and Güncü (2023) examined disaster risk analysis of buildings in Erzincan region in Turkey. They deduced from their analysis that improper construction, soil quality, and heavy overhang are the significant parameters that affect the risk range of reinforced concrete buildings [5]. There are many studies examining disasters in literature [6-7].

In this study, the effect of overhangs on earthquake performance of buildings was analyzed by different positions of overhang direction. For numerical analysis, a regular RC building with no overhangs was designed as the reference building model (Model A). All overhang direction options were compared with the reference model to emphasize the effect of overhang direction on torsional irregularity.

2. Seismicity of Turkey

Turkey is located in a seismically active region and frequently suffers from earthquakes, which cause considerable loss of life and property, and negatively impact the national economy. It is expected that it will face with earthquakes in the future as well which will presumably turn to disasters by the collapses of the structures. Therefore, designing earthquake-resistant buildings to defend the structures against significant earthquake loads is a vital need.

Turkey is located on Anatolian Peninsula on the Alp Himalayan earthquake belt, a seismically active region worldwide. Turkey is exposed to great compression from Arabian, African and the Eurasian plate. The African and Arabian plates travel to the North and make a compression to the North Anatolian Fault. After this event, North Anatolian Fault begins to travel towards the west of Turkey. The Turkey Earthquake Hazard Map is shown in Figure 1.

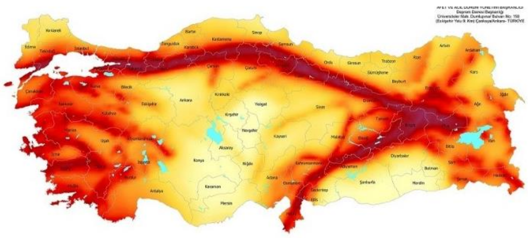

Figure 1. Turkey Earthquake Hazard Map [8]

Turkey has been exposed to various devastating earthquakes throughout history. Due to the 7.7 and 7.6 magnitude earthquakes that took place in Kahramanmaraş on February 6, 2023, many buildings in 11 provinces in Turkey, especially in Kahramanmaraş, were destroyed, many of them were severely damaged, and serious casualties were experienced. The list of major earthquakes is given in Table 1.

Table 1. List of major earthquakes in Turkey [adapted from 9]

Date	Magnitude(M)	Region	Loss of life	Devasted/Heavily damaged/destroyed immediately
1939	7.9	Erzincan	32968	116720
1942	7.0	Tokat	3000	32000
1943	7.2	Samsun	4000	40000
1944	7.2	Bolu	3959	20865
1966	6.9	Muş	2396	20007
1970	7.2	Kütahya	1086	19291
1999	7.8	Kocaeli	17480	73342
2011	7.2	Van	644	17005
2023	7.7 and 7.6	Kahramanmaraş	50783	202000

3. Structural Irregularities

Irregular buildings are described in the TBEC-2018 as the buildings whose design and construction should be avoided due to their negative seismic behavior. Irregularities are divided into two main groups based on TBEC-2018 [10]. These are irregularities in plan and irregularities in vertical direction. The structural irregularities in the plan are torsional irregularity, floor discontinuity, and projections in plan. Structural irregularities in vertical direction are week storey, soft storey, and discontinuity in vertical structural members. in plan consist of three different types of structural irregularity. (TBEC-2018) Torsional Irregularity is one of the most significant irregularities that cause devastating damage in earthquakes in Turkey.

3.1. Torsional Irregularity

The case where torsional irregularity factor ηbi which is defined for any of the two orthogonal earthquake directions as the ratio of the maximum storey drift at any storey to the average storey drift at the same storey in the same direction, is greater than 1.20, as Eq. (1)

$$\eta bi = (\Delta i)_{max} / \Delta\, i)_{avg} > 1.20 \tag{1}$$

The distance between the center of gravity and the center of rigidity should be kept as minimum as possible in any storey of the building. The rigidity center is described as the center of vertical structural elements. The gravity center is the center of the whole building. earthquake loads affect the structure's center of gravity, but the structure's rigidity center responds these loads. If the eccentricity between these two centers is great, a torsional moment will occur around the center of rigidity, and the structure begins to rotate around the rigidity axis. This torsion moment creates additional shear forces (Figure 2).

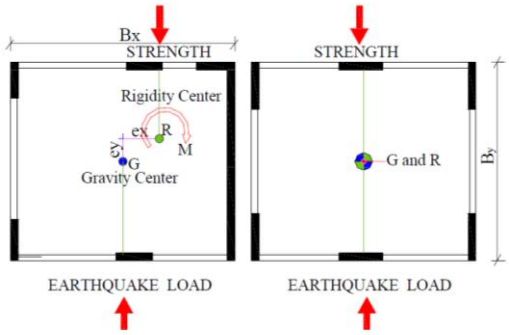

Figure 2. Gravity and rigidity center [11]

In almost all buildings in Turkey, the upper floors of the ground floors are designed as overhangs. Open or closed overhangs cause differences in mass distribution between storeys and eccentricity between gravity and rigidity center. In the latest Kahramanmaraş earthquake on February 6, 2023 with a magnitude of 7.7 and 7.6, various buildings with overhangs expose to destroying effects of the earthquake. They were heavily damaged or destroyed (Figure 3-4).

Figure 3. Overhang **b**uildings in Malatya after on February 6, 2023, Kahramanmaraş earthquake

Figure 4. Overhang buildings in Hatay after on February 6, 2023, Kahramanmaraş earthquake

4. Numerical Analysis

First, this study designed a regular reference RC building model. After, five different models were derived considering different directions of overhangs. Totally, six different 20-storey building models were analyzed in order to examine the earthquake behavior of overhangs. The reference model was regular on both in terms of plan geometry and rigidity distribution. The regular reference model was designed as 25 m by 25 m in plan and had a 5@5 m beam span in both the X and Y directions. It has a rigid core in the center and L-shaped shear walls on the corners of the model. The floor plans were identical in all storeys (Figure 5). The reference model coded as A and other variants with overhangs coded as B, C, D E and F, respectively (Figure 6). The dimension of overhang is taken as 1.50 m. While the model B has a one-sided overhang, the model C has an asymmetric two-sided overhang. Model D has a two-sided symmetric overhang, and Model E has tree sided overhang. On the other hand, Model F has overhangs on all sides.

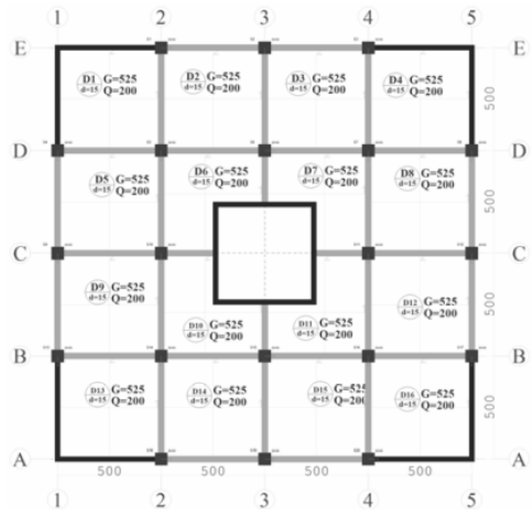

Figure 5. The reference model.

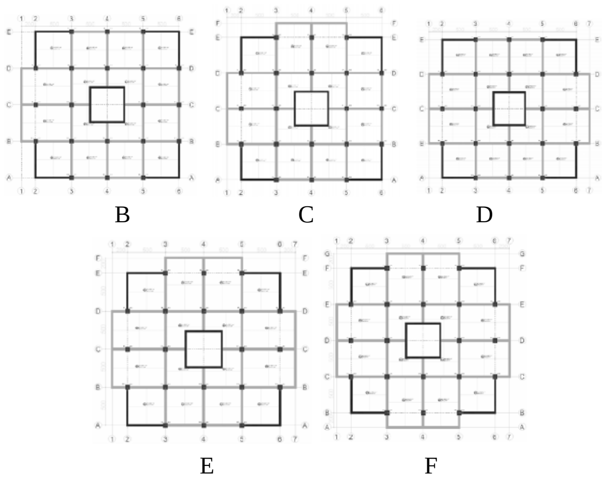

Figure 6. Models with overhang

The model parameters used in the numerical analysis and Turkish Building Earthquake Code parameters were given in Table 2. The changes in the torsional irregularity coefficients in each storey of 20 storey model were analyzed comprehensively.

Table 2. Parameters used in numerical analysis.

Parameters	Dimensions/type
Storey number	20
Storey height	3.00 m
Beam span	5.00 m
Beam dimensions	30/50 cm
Columns	60*60 cm
Shear walls	30*500 cm
Overhang	1.50 m
Soil class	ZB
Building importance factor	1
Concrete class	C30
Steel class	S420

5.Results and Discussion

In this study, the effects of irregular rigidity distribution between ground and upper storeys due to the overhangs were examined comprehensively. It was questioned how overhangs affect the torsional irregularity coefficients despite the regular plan geometry. The irregularity in the plan geometry caused destructions due to the torsional irregularity in the earthquakes in Turkey. For this reason, the effects of overhang and overhang direction were analyzed in detail and the obtained maximum torsional irregularity coefficients from the analysis were compared.

The analysis shows that since torsional irregularity in A, D and F models does not exceed the limit value of 1.20, which is the limit value of the Turkish Building Earthquake Code (TBEC-2018), torsional irregularity does not exist in these models. The lowest torsional irregularity coefficients were observed in models A, D, and F, respectively. The torsional irregularity coefficients are 1.09, 1.12 and 1.14 on the ground floors of models A, D, and F, respectively, while on the twentieth floor, which is the top floor, they are 1.07, 1.12, and 1.17, respectively. It can be concluded from the analysis that the torsional irregularity coefficient in A and D models tended to decrease as the number of floors increased. All three of the models A, D, and F are symmetrical with respect to both the X and Y directions. While the A model does not have an overhang, the D model has two overhangs in the symmetrical direction, while the F model has an overhang in all four directions (Figure 7-8).

A remarkable finding obtained from the analysis results is that torsion irregularity was detected in the B, C and E models. Torsional irregularity was observed from the fourteenth floor of the B model, the sixth floor of the C model, and the third floor of the E model. Torsional irregularity coefficients were determined as 1.17, 118, and 1.20 on the third floor of B, C and E models, respectively. Moreover, the torsional irregularity coefficients were determined as 1.18, 120 and 1.22 on the sixth floor of the B, C and E models, respectively. On the twentieth floor of the B, C and E models, the torsional irregularity coefficients were determined as 1.22, 126 and 1.30, respectively. On the other hand, it has been observed that the torsional irregularity coefficient increases in the B, C and E models as the number of storey increase. The highest torsional irregularity coefficient was obtained as 1.30 on the top floor of the E model, which has overhangs in three directions. While the B model has an overhang in one direction, the C model has two asymmetrically positioned overhangs, and the E model has overhangs in three directions (Figure 7-8).

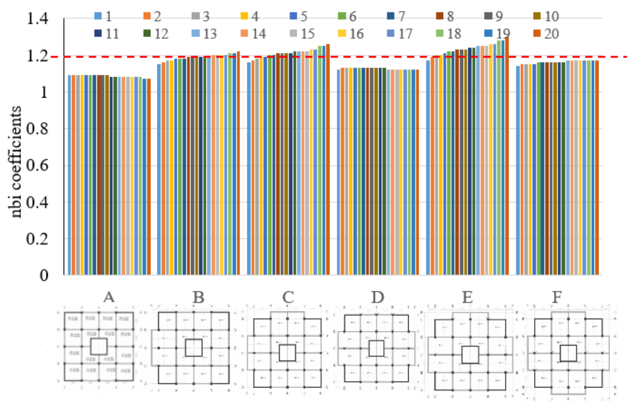

Figure 7. The changes in torsional irregularity coefficient based on each model

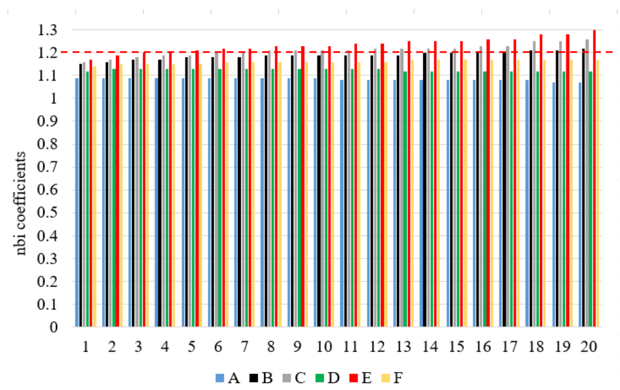

Figure 8. The changes in torsional irregularity coefficient based on each storey

6. Conclusions

In this study, overhangs and the effects of overhang direction on torsional irregularity coefficients were analyzed in detail. Based on the attained results from the numerical analysis, the following conclusions could be drawn up:

- It can be concluded from the analysis that A model which has no overhang presents the best earthquake performance among the models. It has the lowest torsional irregularity coefficients. In A model, the maximum irregularity coefficient is 1.07.
- In the earthquake behavior of structures, the direction of the overhang is more significant than the presence of the overhang. For instance, torsional irregularity was not observed in the A, D, and F models. While the A model has no overhang, and the D model has two symmetrical-sided overhangs, the F model has overhangs in four directions. The symmetrical positioning of the overhangs in the plan geometry is a significant factor in the earthquake behavior of buildings. The maximum torsional irregularity coefficients are 1.09, 1.13, and 1.17.
- The overhang direction is quite significant in terms of the torsional irregularity coefficient. The minimum torsional irregularity coefficient among the models having overhangs was observed in model D which has two-sided symmetrical overhangs.
- B, C, and E models have torsional irregularity. While the B model has an overhang in one direction, the C model has two asymmetrically positioned overhangs, and the E model has overhangs in three directions. The model E exhibits the worst earthquake performance. The highest torsional irregularity coefficient was obtained as 1.30 on the top floor of the E model. It has three-sided overhangs. The overhangs have caused the building to become heavy and disrupted the plan geometry's symmetry.
- It was noticed that the torsional irregularity coefficient increases in the B, C, and E models as the number of storey increases. All three are models with torsional irregularity.
- Architectural design decisions are significant in the earthquake behavior of structures. The interaction of architectural design and structural configuration should be carefully considered in the initial part of the design.
- This study analyzed seismic behavior of high-rise buildings with different overhang orientations. In the further studies, the seismic performance of the cantilevered buildings will be evaluated by considering the different storey heights and the different structural system arrangements.

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