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Effect of Slab Discontinuity on Seismic Performance of Framed Reinforced Concrete Buildings

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ABSTRACT: Turkey is a country where earthquakes occur frequently. Earthquake motion causes a vibration in buildings. The resulting vibration is transferred to the vertical carrier elements by the slabs. If the slabs transfer the in-plane earthquake load to the vertical carrier elements without deformation, rigid diaphragm behavior is achieved. The rigid diaphragm behavior ensures that the building moves as a whole. Therefore, horizontal loads acting on the building are transferred safely to the foundation. However, due to architectural aesthetics and the purpose of use of the building, large opening may occur in the slabs. These opening cause discontinuity in the slabs. In-plane horizontal loads acting on the slab cannot be properly transferred to the vertical carrier elements. Stress concentrations may occur in slabs due to openings. For this reason, the rate of opening in the slabs is limited in the earthquakes codes of many countries. In the Turkish Building Earthquake Code, it is stated that the ratio of the amount of opening in the slab to the total plan area cannot be more than 1/3. However, some parameters such as the location of the opening and the height of the building affect the slab discontinuity.

In this study, a regular building was modeled as 3, 5 and 8 storey. The rate of opening in the buildings was fixed and the opening shapes were changed. A total of 12 models were created. The created models were analyzed with the equivalent earthquake load method and mode superposition methods. With the help of the results obtained, the earthquake performances of the buildings were compared. As a result, it was observed that the earthquake force acting on the building decreased in the buildings where the openings were regular. In buildings where the openings were irregular, earthquake loads increased due to the torsion effect.

KEYWORDS: Slab discontinuities, Rigid diaphragm, Equivalent seismic load, mode superposition.

I. INTRODUCTION

Earthquake is a disaster that has been extensively researched due to its devastating effect on society and the environment compared to other natural disasters. While a large part of Turkey is at risk of earthquakes, the lack of earthquake-resistant structures also causes serious casualties[1]. In 2020, one of the major earthquakes Sivrice, district of Elazığ, Turkey the 6.8 Mw earthquake occurred that caused 38 loss of life and 1607 injures. In total 76 buildings were collapsed and 800 buildings had heavy damage and need to be demolished[2]. Another major earthquake, the 6.6 Mw earthquake that occurred in the Seferihisar district of Izmir, Turkey in 2020, caused 115 loss of life and 1034 injuries and loss of properties. When the damage to the buildings is examined in İzmir, the number of buildings with heavy damage and need to be demolished is 376, and the number of buildings with moderate damage is 410. In addition, there are 4182 buildings with minor damage[3]. These statistics show the importance of buildings to withstand earthquake loads safely. One of the important issues in building design is to safely resist external forces such as earthquakes. Architectural, economic and service concerns during the architectural design of the buildings caused the buildings to be asymmetrical and irregular geometry[4], and negatively affected the earthquake behavior of the buildings. The causes of damage to buildings in earthquakes are sometimes directly related to the architectural design created by these concerns. As a result of arranging the architectural design without considering the carrier system, it becomes difficult to provide a safe carrier system[5]. When earthquake act on building, very important problems are encountered in the behavior of the carrier system. When a mistake is made in the selection of the structural system, the structure will not show the expected positive behavior in earthquakes. In order for the structures to behave safely under external loads, the structural system of the structure should be regular and the structure should be symmetrical. Structures with a regular load-carrying system



provide convenience in application and calculation, as well as increase the detection and accuracy of the forces and moments that occur. For this reason, regular structural design is the most practical solution for a safe structural design[6]. Structural elements are required to carry their own weight safely, also to transfer the loads from external forces to the bearing elements in a safe manner. Slab discontinuities that disrupt the integrity of the buildings cause problems in the transfer of earthquake loads to the bearing elements[7]. External forces that create vertical forces such as earthquakes are transferred to vertical bearing elements in buildings through slabs. In this situation, the working principle of slabs is assumed as rigid diaphragm[8]. However, in some situations the slabs cannot be assumed as rigid diaphragm. For example, such structures which has core-wall (elevator shear wall) structure with very rigid vertical load-bearing elements, and buildings with irregular floors and large gaps in plan. When the slab works as a rigid diaphragm, it will move as a rigid mass without deforming under vertical loads. When the floor works as a flexible diaphragm, it will deform as well[9]. Since it is accepted that the slabs, which are horizontal elements in the buildings, withstand the earthquake load, it is important that the slabs transmit lateral load to the supports; columns, beams or shear walls. In beamless slabs where the slab is directly supported on the column or shear wall, or in cases where there are openings in the slab, the presence of openings in these support edges will make force transmission difficult and cause stress concentrations in some points. A2 type irregularity defined under the heading of plan irregularities in TBEC-2018(Turkish Building Earthquake Code); includes slab discontinuities. In the code the slab discontinuity defined as: The structures that have the case where the sum of the gap areas, including the stair and elevator shafts, is more than 1/3 of the total floor area. When compared with different earthquake codes, it is seen that 1/5 in Eurocode-8 and 1/2 ratio in American IBC-2009 are accepted as limit values for slab openings[10,11]. Another situation that causes A2 type irregularity, the presence of local slab openings that make it difficult to transfer earthquake loads to the vertical structural system elements safely. Lastly, sudden decreases in in-plane stiffness and strength of the slab causes the slab discontinuity irregularity[12]. For these reasons, it is important for the health of the design that there are no openings in slabs in the design of the buildings and that the irregularity of the structures is prevented. However, irregularities occur in the plan for reasons such as architectural aesthetics and purpose of use. In this study, seismic performance of structures with slab discontinuities was investigated. The seismic performances of buildings with different storey numbers and different slab discontinuities were investigated using the equivalent seismic load method and the mode superposition method.

II. MATERIAL AND METHOD

In order to examine the effect of slab discontinuity on seismic performance, 30x40 m building model was created in the SAP2000 program[13]. The building was modeled as 3, 5 and 8 storeys. The axis dimensions of the building were taken as 3 m in the x direction and 4 m in the y direction. The storey height was taken as 3 m. It was assumed that the building was located in Konya and the ground class was ZC. The foundations of the building were defined as fixed support. The building was accepted as a residential type of building. Column dimensions were taken as 50x50 cm. The beam dimensions were taken as 30x60 cm. The wall loads acting on the beams were taken as 8 kN/m. The slabs were taken as 15 cm thick. The additional dead loads acting on the slabs were taken as 2 kN/m² and the live load was taken as 3.5 kN/m². The plan of the building is given in Figure 1. In order to create slab discontinuity in the building, 36% of the total building area was considered opening. The slab opening were taken in different ways and the effect was examined. 4 different model plans were created, including the control model. Different storey plans were given in Figure 2. These plans were analyzed with different storey numbers. The storey numbers were defined as 3, 5 and 8. A total of 12 models were obtained. The models are given in Table 1.

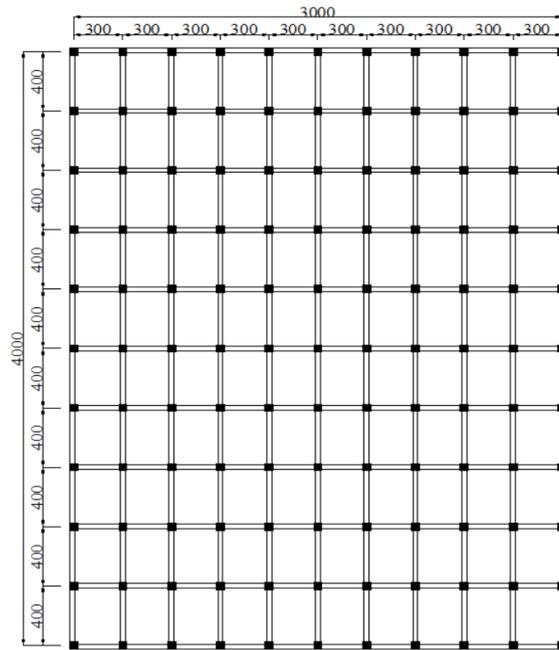
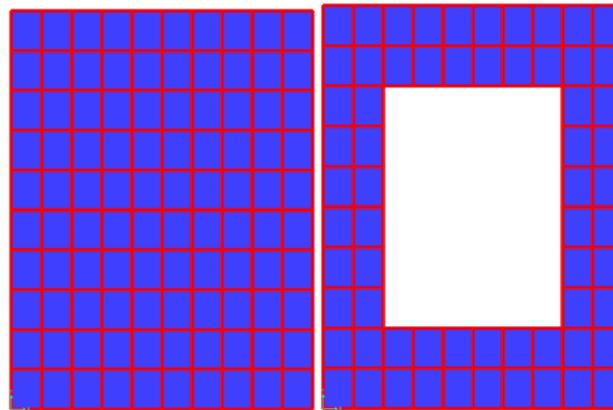
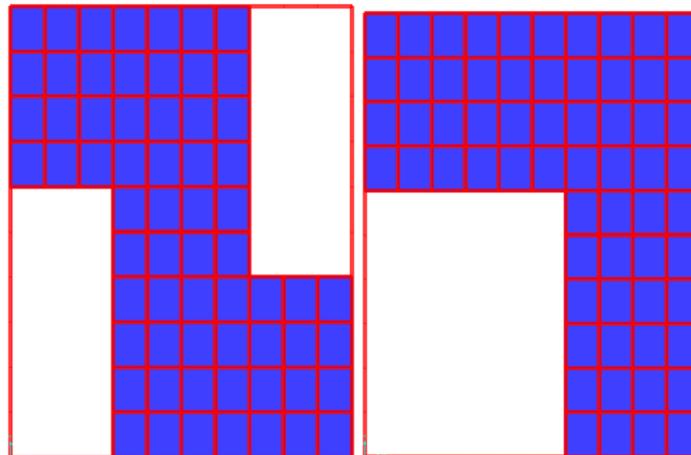


Figure 1. The plan of the building (dimensions are in cm.)



(a)

(b)



(c)

(d)

Figure 2. The plan of models; (a) N1, (b) N2, (c) N3, (d) N4



Table 1. Number of storey and rate of opening for each model

Model	Number of Storey	Rate of Opening (%)
N1	3	-
N2	3	36
N3	3	36
N4	3	36
N5	5	-
N6	5	36
N7	5	36
N8	5	36
N9	8	-
N10	8	36
N11	8	36
N12	8	36

During the modeling of the buildings, the concrete class and reinforcement steel were taken as C30 and S420, respectively. The necessary parameters for seismic analysis are given in Table 2.

Table 2. Seismic analysis parameters

Parameters	Value
GroundSeismic Motion Level	DD-2
SoilClassification	ZC
Latitude	37.875394°
Longitude	32.479438°
S _s	0.308
S ₁	0.074
S _{DS}	0.400
S _{D1}	0.109
PGA	0.134
PGV	6.727

The seismic analyzes were conducted with two different methods. These methods were equivalent earthquake load method and mode superposition methods.

III. RESULTS AND DISCUSSIONS

The natural vibration periods and mass participation ratios obtained as a result of the seismic analysis of the building are given in Table 3.

Table 3. Natural vibration periods

Model	T(s)		Massparticipationratio(%)	
	X	Y	X	Y
N1	0.54	0.58	0.97	0.97
N2	0.52	0.56	0.97	0.96
N3	0.52	0.56	0.89	0.96
N4	0.53	0.56	0.71	0.88
N5	0.79	0.86	0.95	0.94
N6	0.77	0.83	0.95	0.94
N7	0.76	0.83	0.88	0.94
N8	0.77	0.82	0.68	0.70
N9	1.15	1.25	0.92	0.92
N10	1.13	1.23	0.92	0.92
N11	1.11	1.22	0.81	0.92
N12	1.13	1.25	0.64	0.68



In Figure 3, the base shear force acting on the building is given. The results for the equivalent earthquake load method (EEL) and the mode superposition (MS) method are given in Figure 3 separately. Due to the decrease in the weight of the building, the base shear force decreased in the samples with openings. However, the base shear forces obtained by the equivalent earthquake load method were higher than the base shear forces obtained by mode superposition in the samples with decreasing mass participation ratio due to slab discontinuity. In case of irregular openings in buildings, it is not appropriate to use elastic calculation methods to calculate the base shear force acting on the building.

As can be seen in Table 3, as the number of storeys increased, the building natural vibration periods also increased. However, in regular buildings, the rate of mass participation to vibration changes very little. In this case, we can say that the equivalent earthquake load method can be used for regular buildings. In buildings with slab discontinuity, the mass participation rate decreases as the number of storeys increases. For this reason, using the equivalent earthquake load method in irregular buildings may not give accurate results. Since the symmetry is not broken in the building in both directions in N2, N6 and N10 samples, and in the y direction in N3, N7 and N11 samples, mass participation rates were high. The regular distribution of slab discontinuity in buildings does not change the vibration of the building. In other words, if the opening in the building did not change the center of gravity, the behavior of the building was not affected.

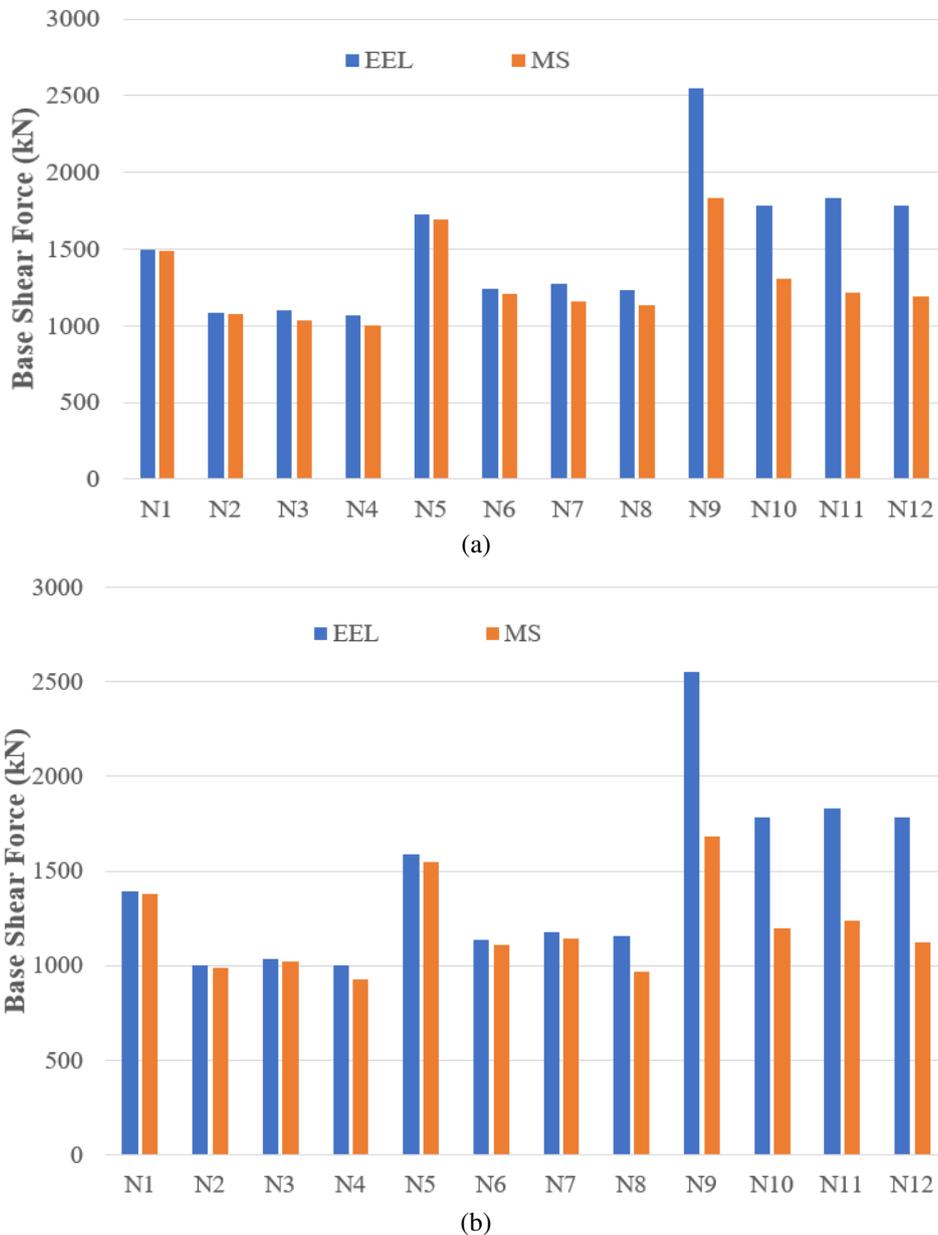


Figure 3. Base shear force; (a) x direction, (b) y direction



Increasing the number of storeys increased the base shear force acting on the samples. The base shear forces of N5 and N9 samples, which had a regular plan, were close for both methods. The regularity of the buildings provided rigid diaphragm behavior. Therefore, the mass participation rate increased and the base shear forces were close. However, higher base shear forces were obtained in the equivalent earthquake load method in irregular buildings. Since the irregularity increased in N8 and N12 samples, the earthquake effect caused torsion effect. Therefore, the base shear force obtained by the equivalent earthquake load method in the N12 sample was 50% higher than the base shear force obtained by the mode superposition method. Even if there was no irregularity in the buildings, the base shear force obtained as the number of storey increased in the equivalent earthquake load method increased compared to the mode superposition method. The reason for this is that in case of an increase in the number of storeys, the predominant natural vibration period in the building was not the 1st Mode. It is the distribution of mass participation rates to modes and not being collected in a single mode.

IV. CONCLUSIONS

In this study, seismic analyzes of models with different slab openings were conducted. Equivalent earthquake load method and mode superposition method were used for seismic analysis. Some important details obtained as a result of the study are given below:

- The regular distribution of the openings in the slabs does not affect the seismic behavior of the building. On the contrary, by reducing the weight of the building, it causes less seismic load.
- As the mass participation rate in the predominant vibration period of the building increases, the results obtained by the equivalent earthquake load method in the building approach the results obtained by mode superposition.
- If the distribution of the openings in the building is irregular, the torsion effect occurs in the building. Therefore, the mode superposition method gives more realistic results when calculating the seismic load acting on the building.
- Even in the case of an increase in the number of storey in buildings without openings, the seismic load acting on the building can be calculated using the equivalent earthquake load method. The absence of openings in the building ensures the emergence of the rigid diaphragm effect.
- As the number of storeys in irregular buildings increases, the mode superposition method gives more accurate results in the seismic load calculation.
- As the number of storeys in irregular buildings increases, the mass participation rate decreases in the predominant vibration period, so the results obtained with the equivalent earthquake load method do not reflect the realistic behavior.

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