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Research Article

Analytical investigation of the measures to be taken against weak storey irregularities

Sinan Cansız[1]*

[1] Civil Engineering Department, Istanbul Arel University, Istanbul (Turkey), sinancansiz@hotmail.com.edu.tr

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Abstract: Due to the earthquakes that have occurred in recent years, heavy damage has occurred in many structures in the world. When the damages occurred after the earthquakes have been examined, it has been observed that the damage occurred frequently in certain structures. These structures are generally structures with different shear capacity due to different story heights. This type of damage is defined as weak-soft storey irregularity in earthquake codes. For this reason, the use of reinforced concrete walls is recommended in the earthquake codes that have been updated in recent years. In addition, it is recommended by many researchers to strengthen the structures with various cross-frames on the storey where weak storey occur in such structures. For this purpose, a pushover analysis of structures with various storey heights and storey numbers supported by various cross-frames has been carried out. For this purpose, seismic analysis of 60 reinforced concrete structures has been made with the Seismo-Build program. In this study, the effectiveness of cross frames used in buildings with reinforced concrete wall and weak storey irregularities has been investigated.

Keywords: weak storey, soft storey, RC wall, push-over analysis, irregularities of building.

1. Introduction

Reinforced concrete structures, which are frequently used in the world, have the potential to be damaged in earthquakes. It is known that reinforced concrete structures are weak against ground motions due to limited displacement capacity. The limited ductile behavior of concrete due to its structure also affects this situation. Especially after the earthquakes in the 1990s, the importance of the ductility capacity of structures has been emerged. After these earthquakes, the Performance-based design principle has been found its place in many national and international earthquake codes (ASCE 41-17, 2017 and TBEC, 2018). In this approach, which takes into account the design of the buildings according to the performance that should provide after the earthquake, the damage conditions of the buildings are limited in line with certain targets (Aksoylu et al. 2020, Erdem and Karal 2022). For this purpose, reinforced concrete walls, which are the most important elements against earthquake effects, come to the fore in earthquake resistant building design because they affect the rigidity of the structure. For this reason, it is important to use reinforced concrete walls in buildings to be built in earthquake zones (Gunes et al. 2020). Reinforced concrete shear walls affect the behavior of buildings to resist ground motion. The effect of reinforced concrete walls on building behavior is summarized in Figure 1.

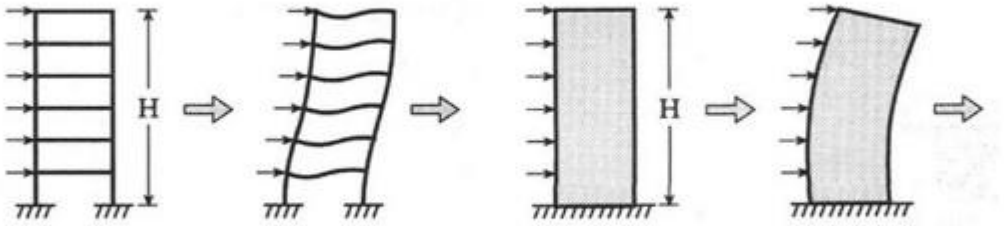


Figure 1. Frame and reinforced concrete wall behavior.

Structures are frequently preferred with reinforced concrete wall in earthquake zones as they provide extra rigidity to the structure during severe ground motions. With the development of innovative architecture, it is seen that different styles of buildings are preferred. Especially in buildings to be built in commercially valuable locations, high ground storey height is preferred. In addition, there are large gaps in the ground storeys of such buildings due to the presence of commercial areas (Jolly, 2020 and Livian et al. 2018). Since it is not done on infill walls, weak-soft storey irregularity occurs between the storey of the building (Inel and Ozmen 2008). In such structures, it is seen that the damage intensifies in the weak-soft storey during the earthquake (Pokhrel et al. 2019). When the structures that have been collapsed or damaged after the earthquakes in recent years are examined, many structures prove this situation (Samant et al. 2010 and Jara et al. 2020).

Figure 2. Weak-soft storey damage after earthquakes.

Weak-soft storey irregularity can occur in unsupervised buildings in recent years. For this reason, many researchers have been made various suggestions (Baek and Lee 2015). Generally, it is recommended to use reinforced concrete walls in buildings as well as supporting them with cross frames (Searer et al. 2010). Supporting with cross steel frames is preferred especially in buildings with weak-soft storey irregularities where the ground storey is used for commercial purposes. For this purpose, the type of measure applied in the building with weak storey irregularity is shown in Figure 3.

Figure 3. Sample of building with weak-soft storey irregularity supported by cross frames.

It is known that approximately 80% of the lateral displacement due to earthquake motion in structures with weak-soft storey irregularities occurs in the weak storey. For this reason, the necessity of taking precautions on these floors is recommended by many researchers (Gursoy et al. 2015). In the studies carried out in recent years, it is seen that the irregularity is carried to other storeys according to the type of measures taken in the designs made to prevent weak storey irregularities. Therefore, it is important that the measures to be taken are made according to certain criteria. When the studies in the literature are examined, studies on the investigation and prevention of weak storey formation are concentrated. Many researchers have been confirmed that there are architectural design errors, static project errors and uncontrolled structures in studies on the causes of weak-soft storey formation (Alvarez and Anaya 2019, Noorifard et al. 2020).

In other studies, on this subject, researches have been conducted on the fracture mechanisms of the weak-soft storey (Dya and Oretaa 2015, Campbell and Duran 2020). Serious studies have also been carried out on the interaction of steel frames and reinforced concrete elements. Analytical models have been created considering the concrete-steel interaction models used in these studies. (Madouni et al. 2018, Talbi et al. 2022). In addition, it has been observed that a limited number of studies have been carried out on measures that reduce the weak-soft storey effect in recent years (Abidi, 2012, Agha et al. 2015, Guavara, 2012). For this reason, this study investigates the effect of measures to reduce the weak-soft storey effect and sheds light on future studies.

2. Methodology

According to the Turkish Building Earthquake Code (2018), if the strength ratio between neighboring storeys is less than 0.8, weak storey irregularity occurs. This coefficient, which is defined as the strength irregularity coefficient, is shown in equation 1-2.

$$\eta_{ci} = \left(\sum A_e\right)_i / \left(\sum A_e\right)_{i+1} < 0.80 \quad (1)$$

$$\left(\sum A_e\right)_i = \left(\sum A_w\right)_i + \left(\sum A_g\right)_i + \left(0.15 \sum A_k\right)_i \quad (2)$$

Where; η_{ci} coefficient of strength irregularity, $(\sum A_e)_i$ effective shear area on the storey, $(\sum A_w)_i$ cross-sectional area of the column in the storey, $\left(\sum A_g\right)_i$ cross-sectional area of the RC wall in the storey and $(\sum A_k)_i$ cross-sectional area of infill wall column in the storey are presented.

Similarly, if the stiffness irregularity coefficient is more than 2, soft storey irregularity occurs. The stiffness irregularity coefficient, which is also expressed as the ratio of the relative storey drifts of two neighboring stories, is shown in equation 3-4.

$$\eta_{ki} = \left(\frac{\Delta_i^x}{h_i}\right)_{ort} / \left(\frac{\Delta_{i+1}^x}{h_{i+1}}\right)_{ort} > 2.0 \tag{3}$$

$$\eta_{ki} = \left(\frac{\Delta_i^x}{h_i}\right)_{ort} / \left(\frac{\Delta_{i-1}^x}{h_{i-1}}\right)_{ort} > 2.0 \tag{4}$$

Where; η_{ki} the coefficient of stiffness irregularity, Δ_i^x the maximum reduced relative story drift and h_i story height are expressed. In the study, the high floor of the buildings has been chosen as the weak floor. Weak floor formation has been allowed by choosing the floor height of the ground floor of the building higher than the limit value.

Within the scope of the study, a structure with symmetrical design and reinforced concrete wall that continues from the basement to the last floor is modeled. For this purpose, Seismo-Build program has been used (Seismo-Build, 2022). In order to determine the effect of the reinforced concrete walls used in the building on the measures to be taken, the reinforced concrete wall less structure has been modeled for comparison purposes. The floor plan of the analyzed building is shown in Figure 4. While there are reinforced concrete walls in the core of all structures indicated by the WB index, all the structures indicated by the B index are modeled as without reinforced concrete walls.

All columns and beams used in the building have been selected within the limits of ASCE 41-17 code. Modeling has been done by taking 1.57% as the percentage of longitudinal reinforcement in the columns. While 8ϕ20 longitudinal reinforcement is used for all square cross-section columns, 12ϕ20 longitudinal reinforcement is chosen for rectangular columns. ϕ10/10 lateral reinforcement arrangement is preferred for all columns. Similarly, the reinforcement arrangement of the beams has been chosen within the limits of the ASCE 41-17 code. The beams are modeled as body reinforcement by using 0.46% reinforcement percentage. All beams has been selected in size 300/500. In all models created, C30-S420 material has been defined and chosen. The floor plans of the buildings are shown in Figure 4.

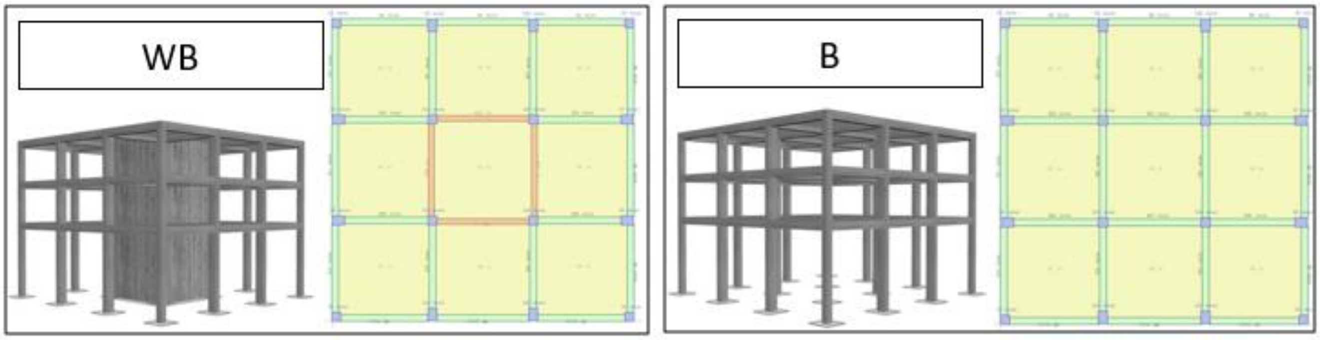


Figure 4. Floor plan of buildings.

When the studies in the literature are examined, it comes to the fore that the most effective measure to be taken for weak-soft storey irregularity is supported by cross frames. In the researches on the effectiveness of the measures to be taken, the shape and location of the cross frames affect the behavior of the structure. For this purpose, the 3D image of the cross frames created against weak-soft storey irregularity in reinforced concrete structures and their positions in the plan are shown in Figure 5. Full interaction in the combination of steel frames with reinforced concrete has been selected and modeled in the seism-build program.

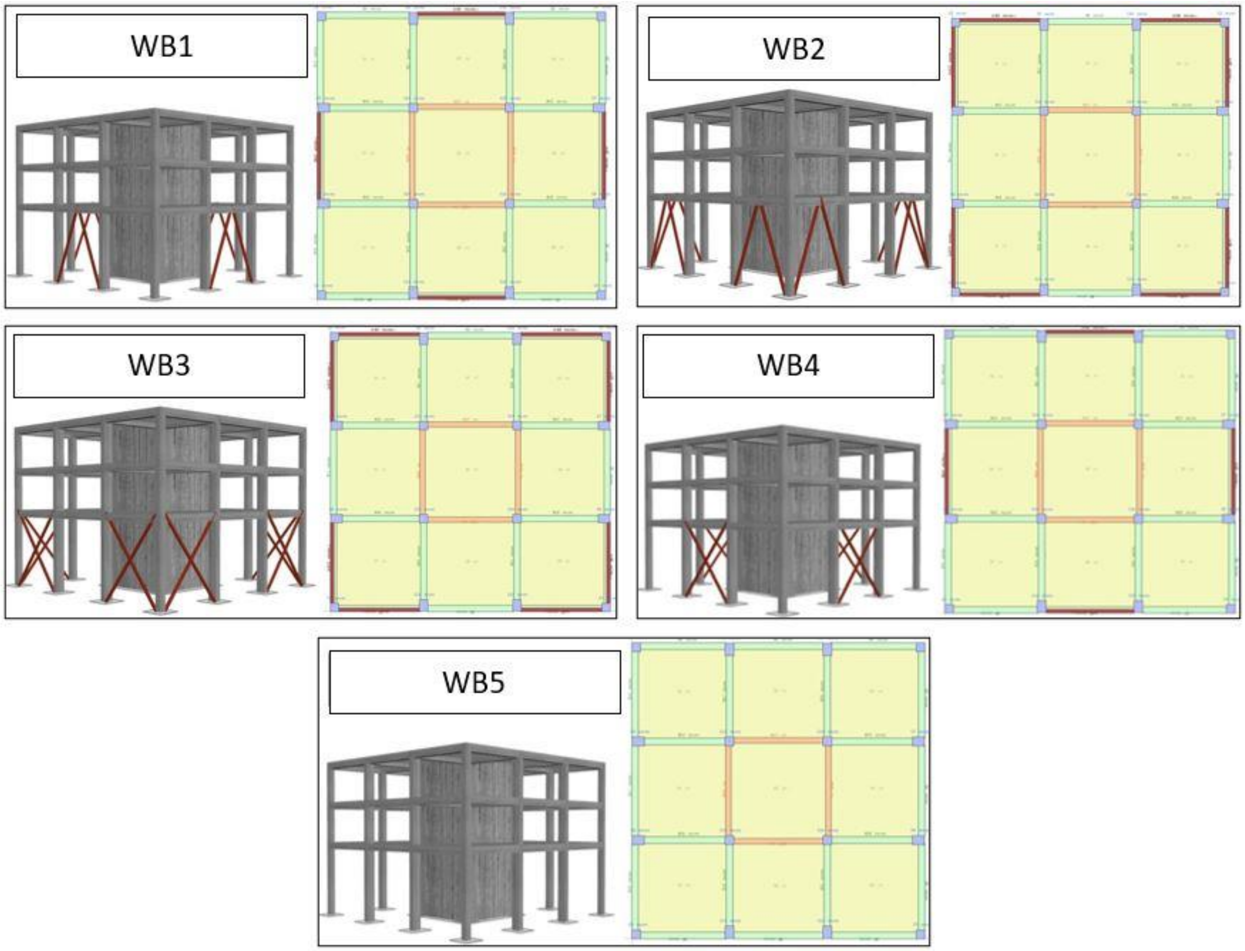


Figure 5. Location and 3D view of cross frames.

The characteristics of the models created within the scope of the study are presented in Table 1 and Table 2.

Table 1. Features of structures containing reinforced concrete wall.

Specimen name	Number of stories	Ground story height (m)	Type of the precautions	Group
WB1-H4-K3	3	4	WB1	W-H4-K3
WB2-H4-K3	3	4	WB2	
WB3-H4-K3	3	4	WB3	
WB4-H4-K3	3	4	WB4	
WB5-H4-K3	3	4	WB5	
WB1-H5.5-K3	3	5.5	WB1	W-H5.5-K3
WB2-H5.5-K3	3	5.5	WB2	
WB3-H5.5-K3	3	5.5	WB3	
WB4-H5.5-K3	3	5.5	WB4	
WB5-H5.5-K3	3	5.5	WB5	
WB1-H7-K3	3	7	WB1	W-H7-K3
WB2-H7-K3	3	7	WB2	
WB3-H7-K3	3	7	WB3	

WB4-H7-K3	3	7	WB4	
WB5-H7-K3	3	7	WB5	
WB1-H4-K6	6	4	WB1	W-H4-K6
WB2-H4-K6	6	4	WB2	
WB3-H4-K6	6	4	WB3	
WB4-H4-K6	6	4	WB4	
WB5-H4-K6	6	4	WB5	
WB1-H5.5-K6	6	5.5	WB1	W-H5.5-K6
WB2-H5.5-K6	6	5.5	WB2	
WB3-H5.5-K6	6	5.5	WB3	
WB4-H5.5-K6	6	5.5	WB4	
WB5-H5.5-K6	6	5.5	WB5	
WB1-H7-K6	6	7	WB1	W-H7-K6
WB2-H7-K6	6	7	WB2	
WB3-H7-K6	6	7	WB3	
WB4-H7-K6	6	7	WB4	
WB5-H7-K6	6	7	WB5	

Table 2. Features of structures without reinforced concrete walls

Specimen Name	Number of Stories	Ground Story Height (m)	Type of the Precautions
B1-H4-K3	3	4	B1
B2-H4-K3	3	4	B2
B3-H4-K3	3	4	B3
B4-H4-K3	3	4	B4
B5-H4-K3	3	4	B5
B1-H5.5-K3	3	5.5	B1
B2-H5.5-K3	3	5.5	B2
B3-H5.5-K3	3	5.5	B3
B4-H5.5-K3	3	5.5	B4
B5-H5.5-K3	3	5.5	B5
B1-H7-K3	3	7	B1
B2-H7-K3	3	7	B2
B3-H7-K3	3	7	B3
B4-H7-K3	3	7	B4
B5-H7-K3	3	7	B5
B1-H4-K6	6	4	B1
B2-H4-K6	6	4	B2
B3-H4-K6	6	4	B3
B4-H4-K6	6	4	B4
B5-H4-K6	6	4	B5
B1-H5.5-K6	6	5.5	B1

B2-H5.5-K6	6	5.5	B2
B3-H5.5-K6	6	5.5	B3
B4-H5.5-K6	6	5.5	B4
B5-H5.5-K6	6	5.5	B5
B1-H7-K6	6	7	B1
B2-H7-K6	6	7	B2
B3-H7-K6	6	7	B3
B4-H7-K6	6	7	B4
B5-H7-K6	6	7	B5

The storey height, which is the main factor of weak-soft storey irregularity in buildings exposed to earthquakes, has been chosen as the basic variable. In addition, the effect of the number of storeys has been chosen as a variable for the purpose of research.

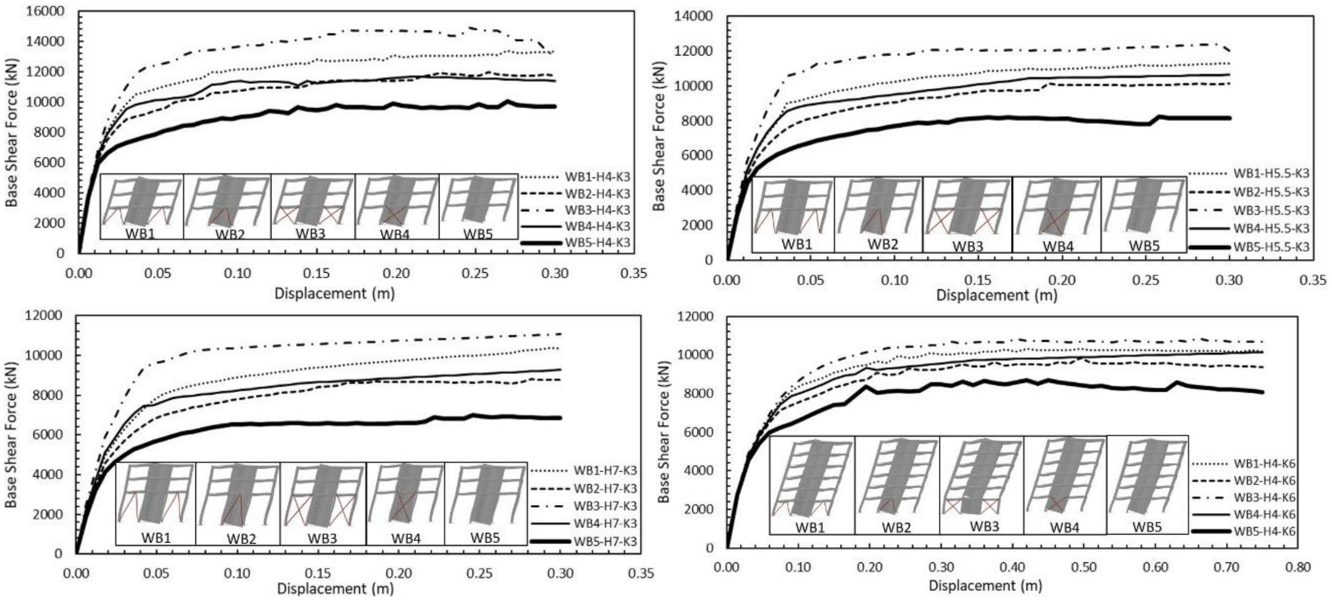
The analytical models created within the scope of the study will be tried to be made with experimental support. The analytical models produced within the scope of this study will be a preliminary study for experimental studies to be carried out in the coming years.

3. Analytical results and analysis

In buildings with weak-soft storey irregularities, the number of storeys is an important factor along with the storey height of the building. For this purpose, the effects of the measures taken on models with different storey numbers and different storey heights have been examined. Pushover analysis of the structures modeled according to ASCE-41-17 regulations has been carried out using the Seismo-Build program. In all structures, Push-over analysis has been examined up to the order of 30 cm. This displacement value corresponds to the collapse prevention performance level according to the ASCE 41-17 regulation.

3.1. Results for structures with reinforced concrete walls

The use of reinforced concrete wall in buildings with weak-soft storey irregularities and other measures to be taken in this direction make a significant contribution to the behavior of the building. For this purpose, reinforced concrete walls have been used and the push over analysis curves of the structures with different number of storeys and different weak storey heights are presented in Figure 6.



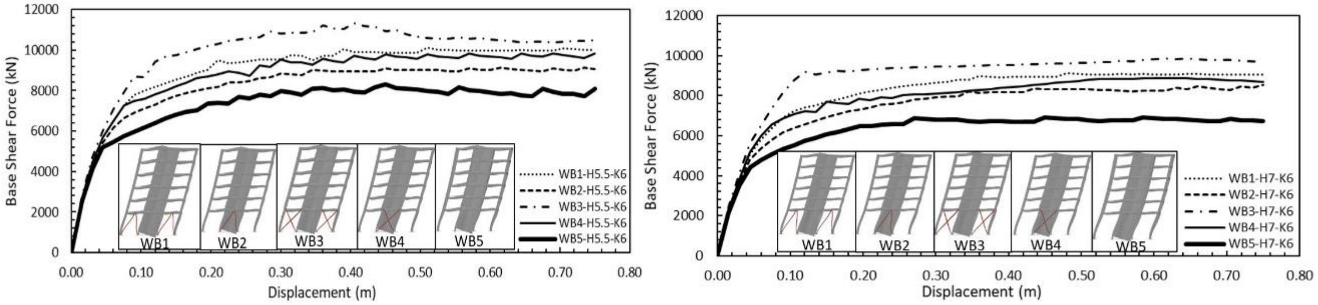


Figure 6. Pushover analysis curves for structures with reinforced concrete walls.

When the push over analysis curves have been examined, the curves of 5 different structures have been compared. Views of the measures taken are shown below the pushover analysis curves. In addition, the deformation shapes that occur in the ultimate limit state of the structures are processed under the push over analysis curves. Here, no measures have been taken for weak storeys in buildings named WB5. In all other structures, the effect of cross frames placed in different positions and shapes has been investigated. It is seen that the lowest base shear force is in the WB5 type structures, where no precautions are taken. In addition, it has been determined that the highest base shear force is in the WB3 type structures where precautions are taken.

When the deformations in the ultimate limit state are examined, it is seen that the measures taken reduce the weak story behavior compared to the WB5 type non-preserved structures. The change in the base shear force caused by the measures taken in such structures containing reinforced concrete wall compared to structures without precautionary measures is summarized in Table 3.

Table 3. Increases in base shear force in structures with RC wall.

Group of Structure	Increase in Base Shear Force (%)				
	WB1	WB2	WB3	WB4	WB5
H=4 S.N=3	33.41	19.36	48.61	16.66	0.00
H=5.5 S.N=3	37.36	23.19	50.57	29.21	0.00
H=7 S.N=3	48.53	26.08	58.49	32.83	0.00
H=4 S.N=6	18.75	13.03	24.68	16.46	0.00
H=5.5 S.N=6	21.60	9.74	36.20	18.36	0.00
H=7 S.N=6	31.50	22.99	42.43	28.05	0.00
Average	31.85	19.06	43.49	23.59	0.00

When Table 1 is examined, it is seen that the highest increase in base shear force is in WB3 type structures. The lowest increase has been found in WB2 type structures. It is seen that the effect of inverted V type cross frames used in WB1-WB2 type structures on the behavior of the structure is more limited than WB3-WB4 type X cross frames. From this point of view, it is thought that WB3-WB4 (X frame) type measures are more successful in preventing weak storey behavior. In addition, the increase in the measures taken in the storey plan has a positive effect on the building behavior. With the number of measures increased in WB3-WB4 type measures, the percentage of increase in the base shear force doubles. In WB1-WB2 type measures, the increase is seen as 1.5 times.

3.2. Results for structures without reinforced concrete walls

To see the positive contribution of reinforced concrete walls to the behavior of weak-soft storeys, all models without reinforced concrete walls have been examined. The curves of the pushover analysis of structures with weak-soft storey behavior without reinforced concrete walls are shown in Figure 7.

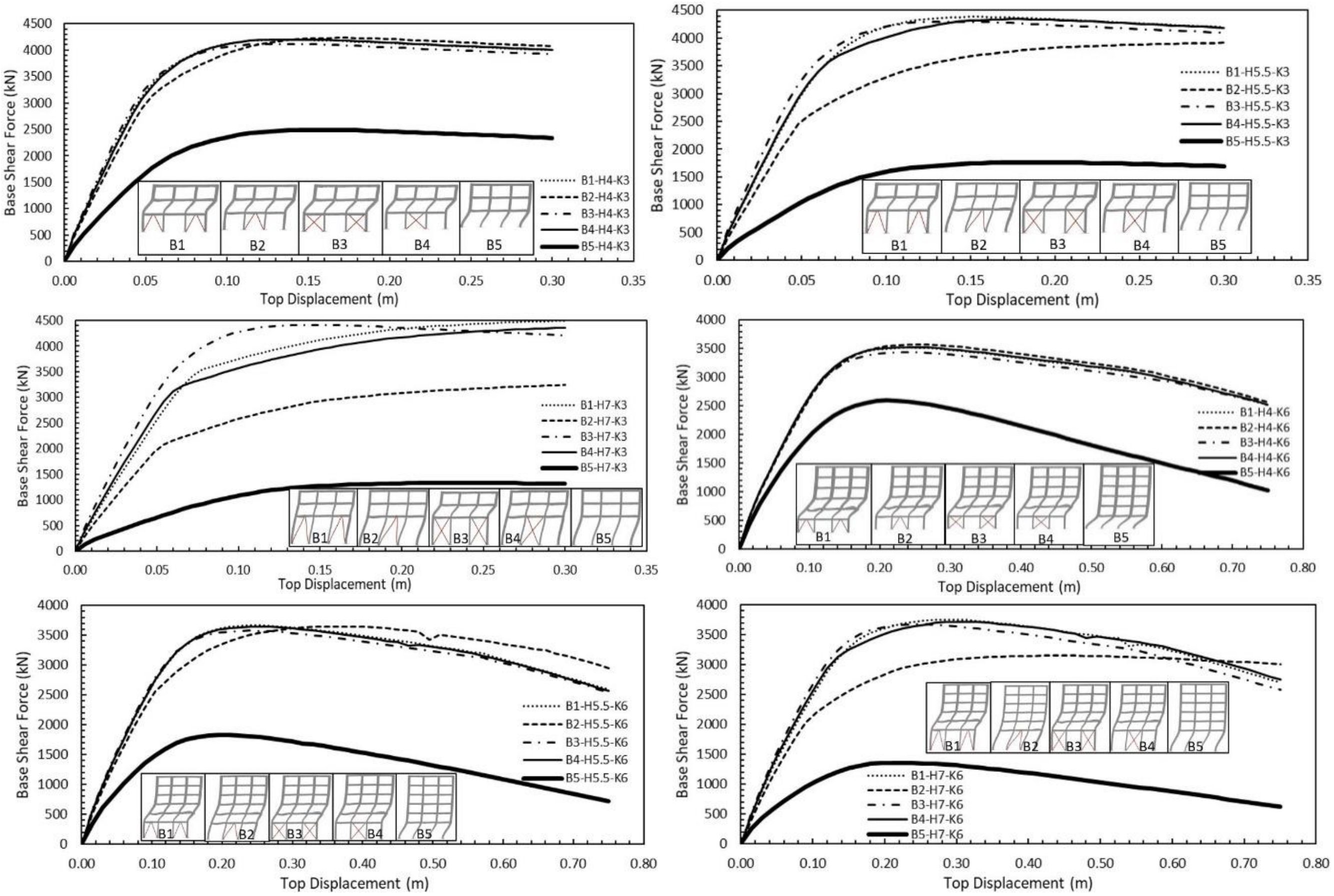


Figure 7. Pushover analysis curves for structures without reinforced concrete walls.

When the push over analysis curves of reinforced concrete non-walled structures is examined, it is seen that the measures taken in buildings with low storey heights contribute equally. In addition, as the height of the weak storey increases, the effect percentages of the measures taken change. It is observed that the B2 type measure is weaker than other measures in weak storey prevention, especially in buildings where the weak storey effect is the highest.

When the deformations occurring in the structure in the ultimate limit state are examined, it is seen that the maximum displacement on the ground storey is independent of the storey height and the number of storey in all buildings without precautions. In addition, as the number of measures taken against weak storey irregularities increases, it is observed that the weak storey irregularity is carried to other storeys. It has been observed that if adequate precautions are taken against weak storey irregularities, the deformation in the structure completely prevents weak storey irregularities.

Examples of such structures are B2-H5.5-K4, B4-H7-K3, B2-H7-K3, B2-H5.5-K6 and B2-H7-K6. It is seen in Figure 7 that the deformation distribution is more homogeneous among all storeys in these structures. It has been determined that the measures taken in reinforced concrete non-walled structures make a very positive contribution to the shear force demand. However, if the measures taken are excessive, it is seen that the weak storey irregularity in the building is formed on the other storeys. For this reason, it is seen that the measures taken in buildings that do not contain reinforced concrete walls make a limited contribution to preventing weak storey irregularities.

Table 4. Increases in base shear force in structures without RC wall.

Group of Structure	Increase in Base Shear Force (%)				
	B1	B2	B3	B4	B5
H=4 S.N=3	68.44	69.81	65.38	68.67	0.00
H=5.5 S.N=3	148.83	122.41	144.04	146.45	0.00
H=7 S.N=6	237.60	143.45	231.77	227.87	0.00
H=4 S.N=6	35.40	37.58	32.33	35.85	0.00
H=5.5 S.N=6	100.16	99.37	95.51	99.21	0.00
H=7 S.N=6	176.57	131.95	170.43	173.75	0.00
Average	127.83	100.76	123.24	125.3	0.00

When Table 3 is examined, it is seen that the effect of the measures taken in the groups in which the effect of weak storey irregularity is increased (H=7 and H=5.5) is very high. It is seen that the buildings with an average floor height of 5.5 m increase of 2 times and the buildings with a floor height of 7 m provide an increase of 4 times. From this point of view, it is seen that the measures that are successful in increasing the shear demand have limited success in preventing the appearance of weak storey deformation. For this reason, the number and quality of the measures to be taken in structures without reinforced concrete walls are important.

4. Conclusions and comments

One of the main reasons of reinforced concrete structures are heavily damaged during earthquakes is the effect of weak-soft storey irregularities. Various measures have been proposed with many studies in this area in recent years. Within the scope of this study, the effect of the measures that can be taken to reduce the weak-soft storey irregularity has been investigated. The results obtained in the study are listed as items.

1. The use of reinforced concrete wall in buildings with weak-soft storey irregularities has a positive effect on the behavior of the building. In buildings with weak-soft storey irregularities, the deformation that occurs during an earthquake is concentrated on a single storey. For this reason, it has been observed that the weak storey effect is more limited in buildings with reinforced concrete walls. In addition, it may cause the transfer of weak-soft storey behavior to other storeys, depending on the number of measures used to reduce the weak-soft storey effect. In this respect, the use of reinforced concrete walls prevents the transfer of weak-soft storey behavior to other storeys as a result of the precautions to be taken. It is important to design reinforced concrete buildings in such a way as to prevent the weak-soft storey effect in structures to be designed under the impact of earthquakes. It has been observed that these measures are more effective with the use of reinforced concrete walls. For this reason, it is recommended that reinforced concrete walls be preferred in buildings.

2. It has been observed that the measures taken with X (WB3-WB4) type cross frames give better results than the measures taken with V (WB1-WB2) type cross frames. In particular, there is a significant increase in the base shear force for each cross member placed in the side spans. It is found that the effects of "Inverted V" type cross frames used in WB1-WB2 type structures on the behavior of the structure are less than those of " X" type cross frames of WB3-WB4 type. Therefore, it is assumed that the WB3-WB4 type (X-frame) measures are more successful in preventing weak projectile behavior. In addition, increasing the measures in the storey plan has a positive effect on the building behavior. As the number of measures of type WB3-WB4 increases, the percentage of increase in base shear force doubles. For measures of type WB1-WB2, the increase is 1.5 times. With the measures taken in reinforced concrete wall structures, an increase of approximately 30% is achieved in the base shear force. One of the most important results is that weak storey behavior is prevented in structures with reinforced concrete wall due to the emergence of equal deformation at all storeys in the ultimate limit state of the building.

3. The contribution of the measures taken against weak-soft storey irregularity in reinforced concrete non-walled structures to the base shear force is very high. It can be seen that the effect of the measures is very high in the groups where the effect of the weak storey is increased (H=7 and H=5.5). It can be seen that the buildings with an average floor height of 5.5 m have a 2-fold increase and the buildings with a floor height of 7 m have a 4-fold increase. From this point of view, it can be seen that the measures taken to increase the shear stress are only partially suitable for preventing the occurrence of weak storey deformations. For this reason, the number and quality of measures to be taken in structures without reinforced concrete walls are of great importance.On average, it is seen that the base shear force has increased 3 times in all structures. On the other hand, the deformation shapes of reinforced concrete non-walled structures in the ultimate limit state are formed in a way that reflects the weak-soft storey behavior. In this situation, it is seen that the measures taken carry the weak-soft storey behavior to other storeys. It is important that the number of measures to be taken in buildings that do not contain reinforced concrete walls is enough to equalize the harmful effects of the weak-soft storey effect with the other storeys.

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