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EFFECTS OF SOFT STORY LOCATIONS ON THE NONLINEAR TIME HISTORY ANALYSIS OF MULTI-STORY REINFORCED CONCRETE BUILDINGS

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Abstract

The current paper included studying the effects of soft storey locations on dynamic response of reinforced concrete (RC) buildings under the impacts of earthquakes. Soft storey is essential to provide the building with a functional space such as vehicle garages or open meeting rooms. Further analytical investigation was necessary to understand the impact of these flexible floors on the building's response during earthquakes, as conducting experimental research to address this issue is highly difficult. The research encompassed the effects of soft storey location in two types of buildings, one with equal spans and the other with unequal spans, on the nonlinear time history response. Each building consists of a 10-stories (G+9) RC residential structure subjected to earthquake effects. The analysis was carried out using program sap2000 v23. An analogous diagonal strut was used to illustrate the infill panels. The study included the effect of soft storeys on the natural period, the change in base shear with time, and the change of displacement and acceleration along time for each building. The obtained results showed that including a soft storey in the analysis for buildings having either equal or unequal spans increased the time period, displacement, and storey drift, causing a decrease in the acceleration and base shear forces. Building with the soft storey on the fifth floor (at the mid-height of the building) showed a better dynamic response compared with that using the soft storey on the ground and last floors.

Keywords:

Dynamic;
Locations;
Strut;
Soft storey;
Time history.

1 Introduction

Vertical irregularities in buildings are a very common feature in urban areas. These buildings usually include one or more open floor that are used as parking garages, open retail stores, restaurants, and halls. These stories have much lower lateral stiffness than the stories with infill walls. This type of building has a relatively higher tendency to collapse during an earthquake. This open story is called the soft story, and it's the level where there is less lateral stiffness by more than 70% of that with infill panels [1]. The lateral stiffness of a soft story depends on the columns and shear wall, if they exist. When non-linear time-history analysis of buildings under the effect of earthquake shows the development of plastic hinges at the upper or lower ends of beams or columns, this is an indication of the onset of failure. When these columns are subjected to large lateral forces, relatively large deformations and displacements occur, as shown in Figure (1). The infill panels normally are used to reduce the lateral displacement that results from the impact of earthquakes. When predicting the nonlinear response of buildings subjected to seismic loads, nonlinear time history analysis is frequently recognized as a precise and practical method. The consideration of soft stories and where they are located in the building is one of the crucial issues of structural engineering. As a result, researchers have started to change the placement of these stories and the characteristics of the utilized materials in order to examine the best place for the soft floor considering different parameters. Here are some of the related research papers in this area. Ivánková et al. [3] investigating the effects of bracing high-rise buildings subjected to wind load in most critical directions and earthquake loading. Four models for the building were considered. Model 1 is the original one. In the second model the building was stiffened by a wall in the x-direction. In the third one, the stiffening wall was added in the y-direction. Model 4 is a combination of models 2 and 3. It was

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observed that stiffening the building by walls causes a reduction in the displacements in the direction of applied load.

Muqeeb et al. [4] studied the impact of soft-story location on the dynamic behaviour of a 14-story concrete building. Ten models were analysed using ETABS software [5], based on linear static analysis (ESA), pushover analysis (PA) and response spectrum analysis (RSA). With the presence and absence of infill panels in all stories and different locations of soft story. Several variables were studied, including the natural period, base shear, and relative displacement between stories. The results showed that the presence of infill panels causes a reduction in the value of the natural period, displacement, and story drift and an increase in the base shear. The study showed that, in case the building is exposed to lateral forces such as earthquakes, the existence of the soft story on the ground level is more dangerous for the building than if it were on the upper floors.

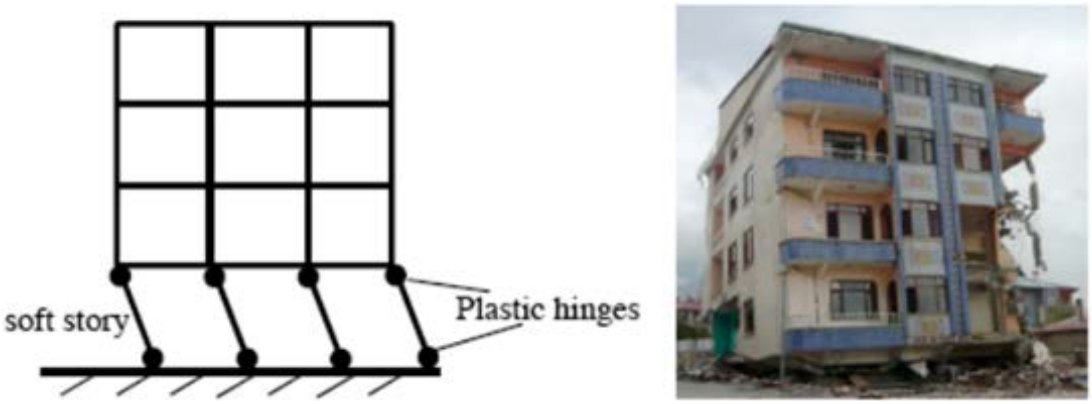

Fig. 1: The development of plastic hinges in the soft story [2].

Halde and Deshmukh [6] used the static analysis (ESA) approach to analyse five different models, each with different soft story placement, and diagonal struts were employed to represent the infill panels in accordance with the FEMA-356: (2000) code [7]. The impact of changing the position of the soft story on the dynamic behavior of the building was looked into by using SAP2000 software [8]. The findings showed that the center location's usage of infill panels should be avoided since the outcomes demonstrated that the displacement of the building utilizing the fill walls decreased in contrast to the bare frame. It was noted that the maximum value of moments and shear appears in the soft story of all models. Singh et al. [9] used the response spectrum analysis to analyse reinforced concrete buildings having different numbers of stories (3, 6, and 9) in addition to the ground floor with and without infill panels to compare the effects of some basic factors. Using STAAD Pro V8i [10] software, the diagonal struts were employed to represent the infill panels based on FEMA (2000) 356 code [7]. The results showed that, when infill panels were used, there was a decrease in the natural period by about 40%, a drift between stories from 25% to 40%, roof displacement from 15% to 35%, and an increase in base shear from 80% to 100%. Additionally, it was found that the presence of infill panels has less impact on low-rise buildings than on high-rise buildings. Mahesh et al. [11] varied the soft story placement from the first to the sixth floor to examine the effects of infill panels and soft story location on the stiffness and dynamic response of a six-story reinforced concrete building during an earthquake of the Gorkha-2015 type. Using ETABS [5] program, a linear time history analysis was carried out and the infill panels were represented by the diagonal strut, which is advised by FEMA Code 356:2000 [7]. The findings demonstrate that the use of infill panels reduces displacement and the percentage of displacement variation between stories while increasing stiffness and shear. Soft stories on the first or bottom stories greatly increase the displacement between stories, whereas soft stories on higher floors have less effect. According to the researcher, soft stories are more suited for upper levels than bottom stories since they have less effect on the structural response of the building. Athamnia et al. [12] used nonlinear dynamic analyses to examine a 12-story insulated RC structure using various ground-story heights utilizing SAP2000 [8] for the non-linear time history analysis. The nonlinearity of the beam and column members was modelled with plastic hinges at both ends of the components. Four structural models were studied using different heights for the soft story: (3 m, 3.5 m, 4 m, and 4.5 m). From the analysis, the effect of the soft story on the drift, floor acceleration, displacement, shear forces, and distribution of plastic hinges was determined. The findings demonstrated that the performance of the RC building is more impacted

by raising the soft story height and that the use of lead rubber bearings (LRB) has a favorable impact on the building by minimizing displacement and drift between stories as well as the production of plastic hinges. Pavithra and Prakash [13] presented an analytical study to determine the optimal location of a soft story in a 15-story RC building under the influence of seismic loads, using the Response Spectrum Analysis method and based on the analytical program ETABS [5]. The study was conducted on six models with a change in the location of the soft story. From the outcomes, it was determined that the ideal location for the soft story is on the upper floor since a reduction in the seismic response of the building and a decrease in the value of the maximum lateral displacements were obtained in this case. Inamdar and Shaikh [14] evaluated the seismic response for 10-story RC building using the ETABS program [5] to carry out a response spectrum analysis. A comparison was made between three buildings that included a building without infill panels, a building containing infill panels in all stories, and others that contained soft story on the ground floor. The study showed that the existence of soft stories leads to a decrease in the value of base shear, increased moments, and lateral displacement, and the magnitude of lateral displacement increases as the number of soft stories at the lower floors increased. Ahiwale and Khartode [15] considered the twelve-stories RC building, and they used SAP 2000 [8] software to carry out a pushover analysis to assess the structure's performance. The nature of the capacity curve, the structural performance, and the plastic hinge growth pattern are presented from the analytical results. The findings showed a plastic hinge formation in the columns at ground floor level. As a result, alternative solutions are to include RC shear walls, steel bracing, and infill panels to improve the response of the building with soft stories. Abd-Alghany et al. [16] investigate the seismic performance of RC structures with soft stories using ETABS [5]. This study considers three characteristics: the irregularity in the building, the height of the soft story, plan dimensions, and the soft story's placement along the building height. An effort was made to find the appropriate position of the soft story along the building height in order to reduce its impact. Using the response spectrum method and equivalent static load technique, the findings showed how the studied parameters affect the stiffness, displacement, and story drifts. A high-rise structure of 20 stories was employed and each story’s height is 3 m, with the first story's height being varied. The findings demonstrated that factors like increasing the height of a soft story or increasing the building's ratio of length to width significantly affect its stiffness and resistance. The study also showed how shear walls may increase stiffness and decrease displacements when they are present.

The methodology of the current study involves performing a non-linear time history analysis of RC buildings under the effects of the El Centro earthquake for different building models with various distributions of soft story locations. The presented results included the variation of acceleration, displacement and base shear along the period of earthquake as well as the formation of plastic hinges for each model. The software (SAP2000, V23) [8] was used to perform the nonlinear time history analysis. This software possesses the capacity to do both static and dynamic linear and nonlinear analyses of reinforced concrete structures. To account for the nonlinear behavior of structural elements, several forms of plastic hinges can be utilized, and addressing the material's nonlinear characteristics such as concrete cracking, concrete crushing, and steel yielding.

2 Building Description

In this study, two reinforced concrete buildings consisting of 10 stories were analyzed. The first building was designed based on ACI 318 cod [17], with equal spans. The dimensions of the building’s plan are (18 x 30 m), and each story is three meters high, the building's overall height is (30 m). The second building was designed with unequal spans, adopting the same code. The plan dimensions are (18 x 22 m). The two models are shown in Figures (2) and (3), while Table (1) summarizes the main building information while Tables (2) and (3) display the sectional properties of the columns and beams. Table (4) describes the models for the analyzed buildings. The implemented nonlinear hinge properties are based on fiber (P-M2-M3), which was assumed to occur at the end of each column and beam. The plastic hinge was assumed to occur when the combined forces (P-M2-M3) at a particular section of the member exceeded its capacity.

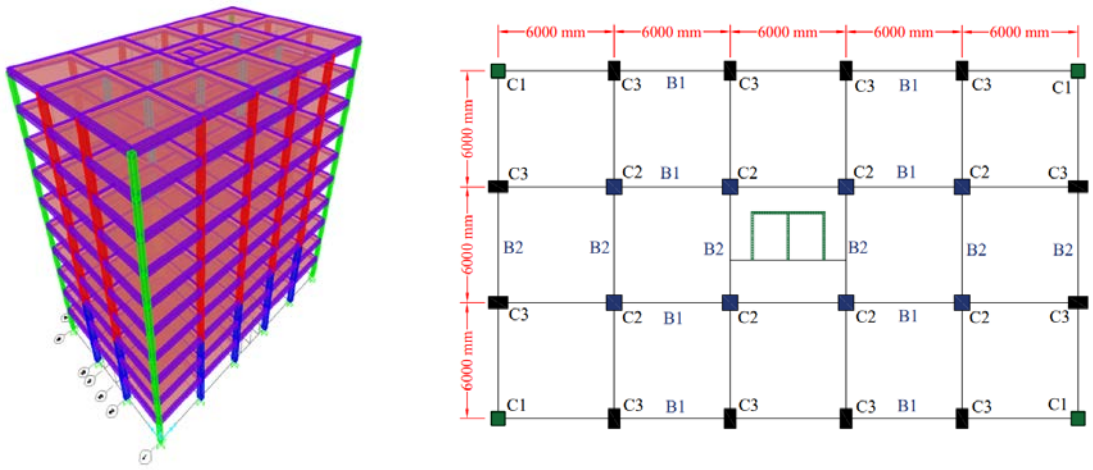

Fig. 2: Plan and three-dimension of the equal spans building modeled by SAP2000.

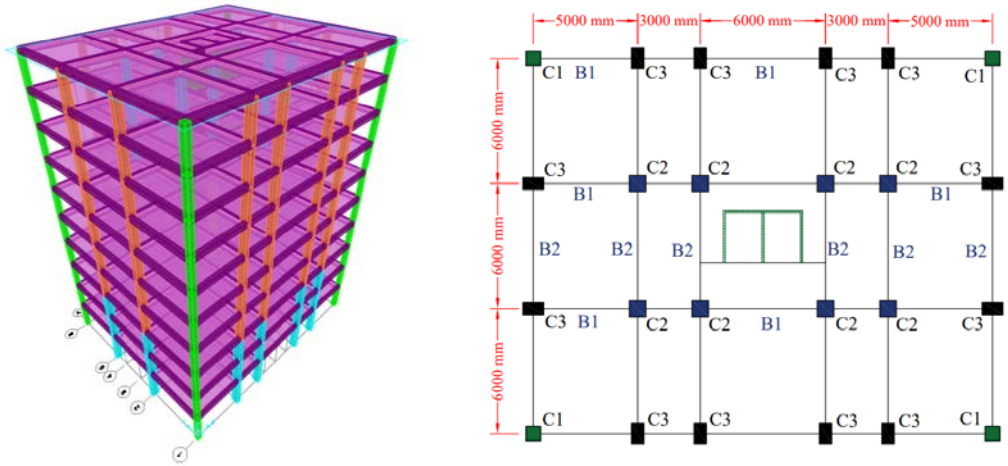

Fig. 3: Plan and three dimensions of the unequal span building modeled by SAP2000.

Table 1: fundamentals of building's data.

Contents	Description
Number of story	10
Height of the Building	30 m
Each story's height	(3) m
Shear Wall Thickness	200mm
Thickness of slab	150mm
Dead load	3 kN/m^2
Live load	3 kN/m^2
partition load	12 kN/m
Concrete compressive strength (fc')	28 MPa
Concrete tensile strength (ft)	3.28 MPa
Yielding of steel (fy)	400 MPa
Compressive strength of infill material	8 MPa
Poisson ratio for the concrete	0.2
Poisson ratio for the infill panels	0.15
Damping	5%

Table 2: Sectional properties of the columns and beams in buildings with equal spans.

Story number	Corner Column (C1)		Internal Column (C2)		Edge Columns (C3)	
	Dimension (b×h) m	Reinforcement	Dimension (b×h) m	Reinforcement	Dimension (b×h) m	Reinforcement
(1,2,3)	0.4*0.4	8φ25	0.65*0.65	16φ28	0.4*0.65	12φ28
(4,5,6,7)	0.4*0.4	8φ16	0.55*0.55	12φ25	0.4*0.6	12φ16
(8,9,10)	0.4*0.4	8φ25	0.5*0.5	16φ25	0.4*0.6	14φ25
	Beams (B1)		Beams (B2)			
(1,2,3)	0.3*0.6	3φ25 Top 3φ25 Bottom	0.3*0.6	4φ25 Top 4φ25 Bottom		
(4,5,6,7)	0.3*0.6	3φ25 Top 3φ25 Bottom	0.3*0.6	4φ25 Top 4φ25 Bottom		
(8,9,10)	0.3*0.6	3φ25 Top 3φ25 Bottom	0.3*0.6	4φ25 Top 4φ25 Bottom		

Table 3: Sectional properties of the columns and beams in buildings with unequal spans.

Story number	Corner Column (C1)		Internal Column (C2)		Edge Columns (C3)	
	Dimension (b×h) m	Reinforcement	Dimension (b×h) m	Reinforcement	Dimension (b×h) m	Reinforcement
(1,2,3)	0.4*0.4	8φ25	0.4*0.65	16φ25	0.35*0.65	14φ25
(4,5,6,7)	0.4*0.4	8φ16	0.4*0.6	12φ16	0.35*0.6	10φ20
(8,9,10)	0.4*0.4	8φ25	0.4*0.55	14φ25	0.35*0.6	12φ25
	Beams (B1)		**Beams (B2)**			
(1,2,3)	0.3*0.5	4φ20 Top 4φ20 Bottom	0.3*0.5	4φ25 Top 4φ25 Bottom		
(4,5,6,7)	0.3*0.5	4φ20 Top 4φ20 Bottom	0.3*0.5	4φ25 Top 4φ25 Bottom		
(8,9,10)	0.3*0.5	4φ20 Top 4φ20 Bottom	0.3*0.5	4φ25 Top 4φ25 Bottom		

Table 4: Description of the analyzed Models.

Building models with equal spans		Building models with unequal spans	
Model 1	without soft story	Model 5	without soft story
Model 2	soft story in ground floor	Model 6	soft story in ground floor
Model 3	soft story in fifth floor	Model 7	soft story in fifth floor
Model 4	soft story in the last floor	Model 8	soft story in the last floor

3 Results and Discussions

The predicted natural period, base shear, and lateral roof displacements for the four analyzed models are presented in Figs. (4-8). The values of the natural periods for the two buildings are displayed in Fig. (4), which demonstrates that the natural periods of the structures increased as a result of including the soft stories in both buildings with equal and unequal spans. By using the soft story in the ground and fifth floors, less increase was obtained in the first natural period of the buildings compared with that when the last story was made soft. The percentage of these increases for frames with unequal spans is higher than that for frame with equal spans. The average increase was (27%, 30%, and 1.26%) for the models 2, 3, and 4 for buildings with equal spans, respectively, while the average increase was (56%, 53%, and 1.23%) for the models 6, 7, and 8 for buildings with unequal spans, respectively. In general, the inclusion of the soft story in buildings with equal and unequal spans causes an increase in its natural periods, particularly when the soft story is in the ground or fifth story. These may be attributed to the reduction in mass of the structure by eliminating the infill panels from a particular story.

The impact of including the soft story on the dynamic performance, in terms of variation of acceleration with time, for both building models, with equal and unequal spans, are presented in Fig. (5). The figure demonstrates that in the two buildings, the largest roof acceleration occurred when the soft story was either on the fifth or top story. From Figure (6), it can be seen that the impact of the soft story on increasing the lateral roof displacement of buildings with equal spans is greater than that of buildings with unequal spans. The obtained results from the nonlinear time history analysis of buildings with equal spans showed an increase in the maximum positive roof displacement of (15%) for model (2)

compared with the that without a soft story. The models (3 and 4) showed a miner reduction in the maximum positive roof displacement by an order of (6% and 2.6%) respectively.

As demonstrated in Fig. (7), the inclusion of the soft story has no appreciable impact on the base shear variation of the two buildings. Fig. (8) shows that the maximum lateral displacement all along the height of the building with soft floor is higher than that of the building with full infill panels. It can be noticed that for buildings with equal spans, the response in terms of maximum story displacement for model (1) without a soft story and model (5) with a soft story at the uppermost floor is almost identical, particularly the positive displacement. A similar response was obtained for the building with an unequal span indicating that including the soft story in the last story has only a minor impact on the maximum story displacement.

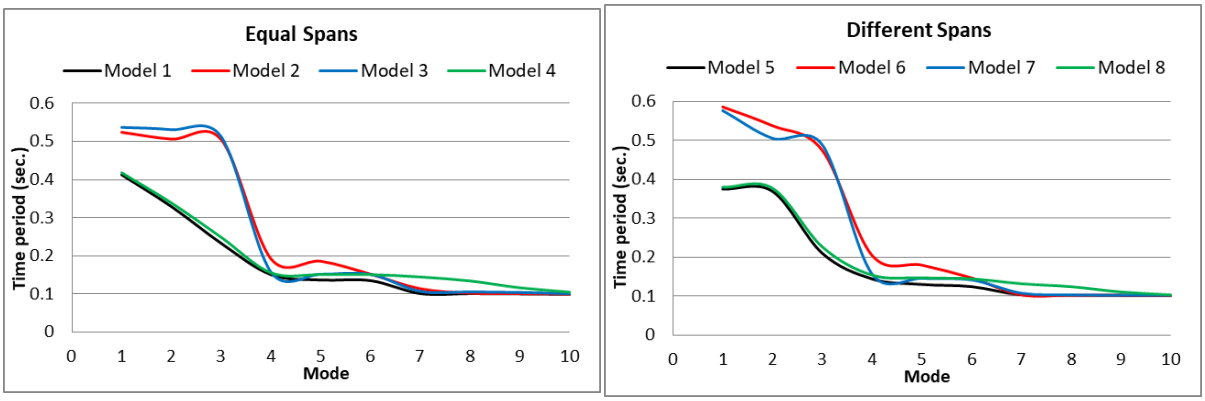

Fig. 4: Natural period for the different building models.

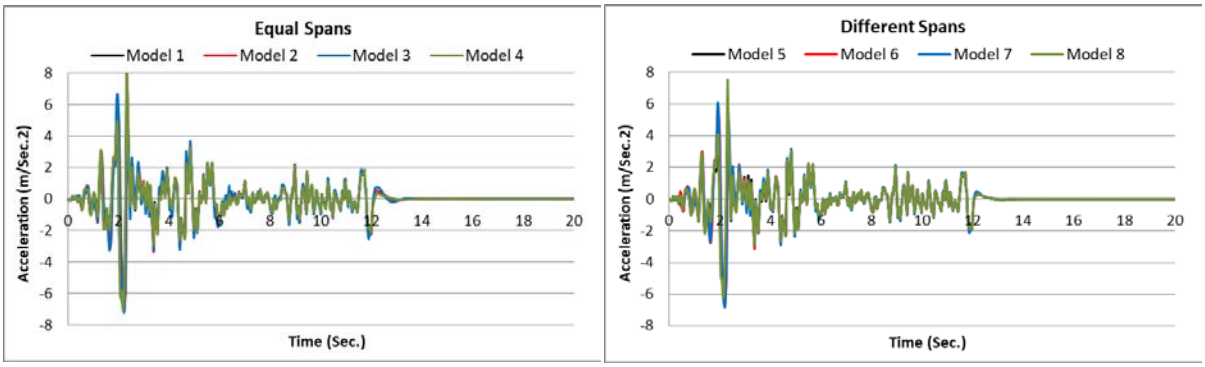

Fig. 5: Effect of location of soft story on the roof Acceleration for different building models.

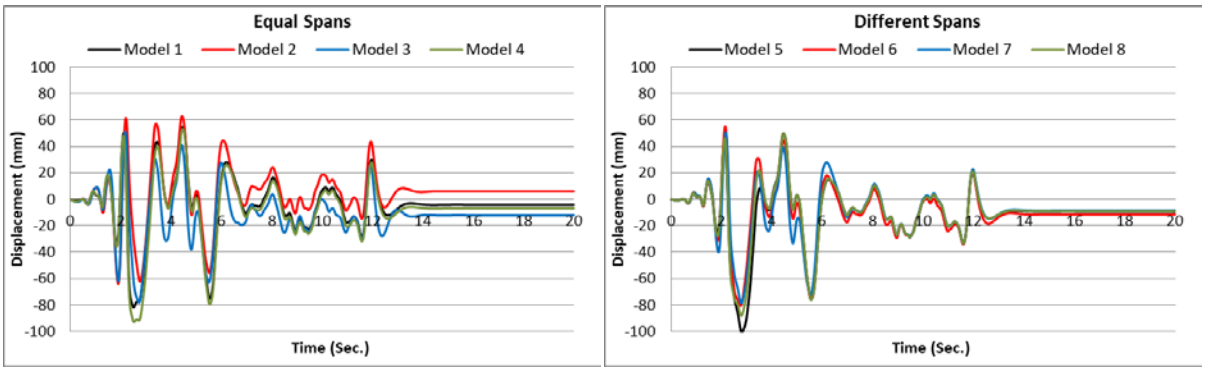

Fig. 6: Effect of location of soft story on the roof Displacement for different building models.

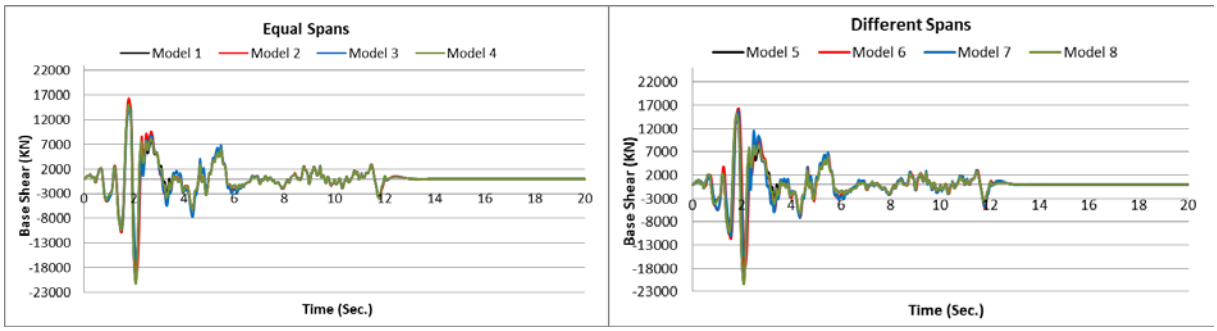

Fig. 7: Effect of location of soft story on the base shear for different building models.

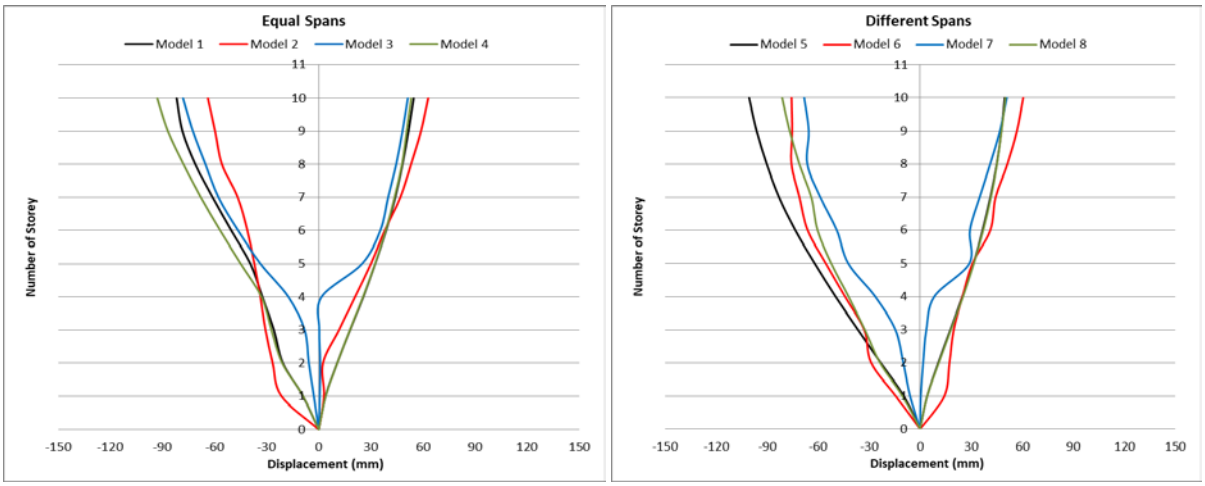

Fig. 8: Maximum Story Displacement for different building models.

4 Formation of Plastic Hinges

This paragraph discusses how the positions of soft story and infill panels affect the development of plastic hinges for beams and columns. The type, state, and location of the plastic hinges are shown in the Figs. (9-16) in the three-dimensional model of the buildings and in the (Y–Z) plane as well. The two types of structures without soft floors produced a lesser number of plastic hinges. This was explained by the higher lateral stiffness of the structures without soft floors. In contrast to a building with equal spans, the building with unequal spans has encountered a greater number of plastic hinges at the soft floor, especially for model (6) with a soft ground floor. In all models, the developed plastic hinge in the struts is caused by the tension axial force that has been induced in the strut members. The majority of the struts did not acquire plastic hinges from compression forces.

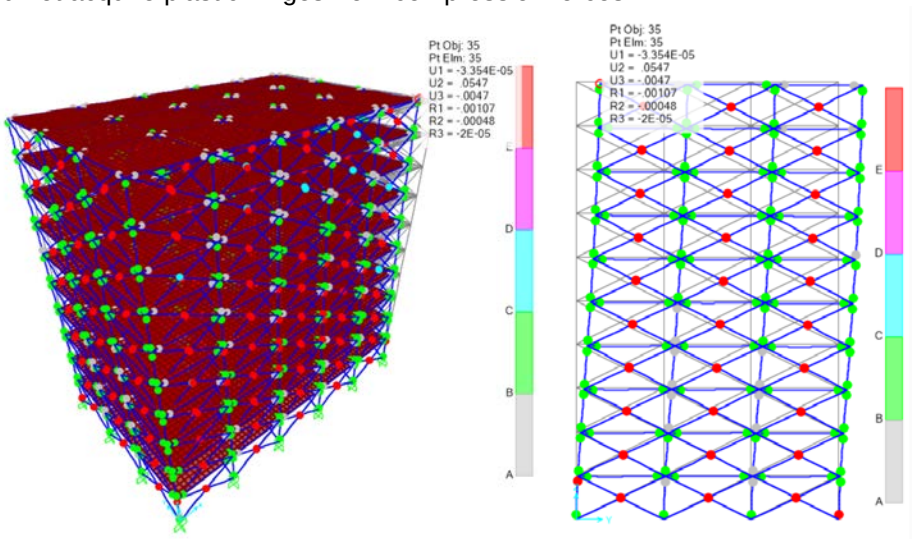

Fig. 9: Developed plastic hinges in model (1) at max displacement (0.054m) at time (4.47Sec).

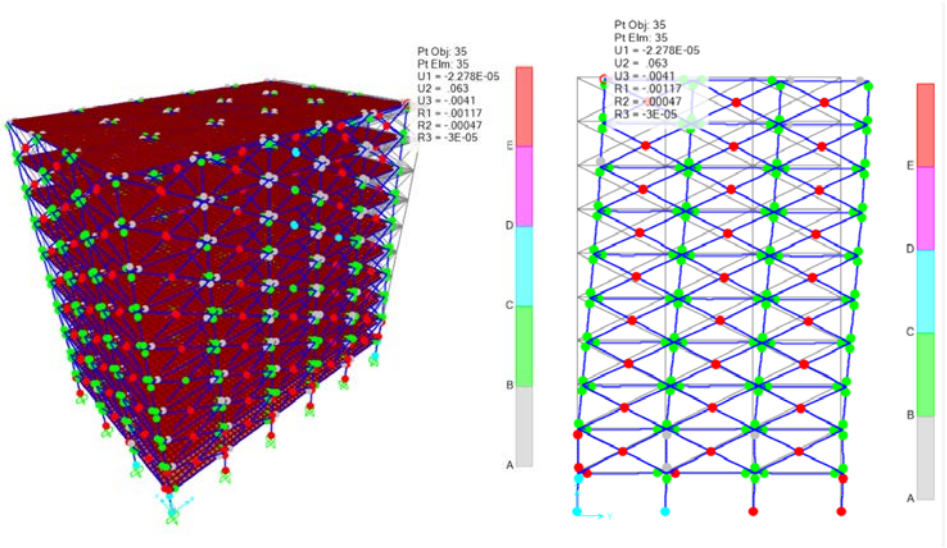

Fig. 10: Developed plastic hinges in model (2) at max displacement (0.063m) at time (4.45Sec).

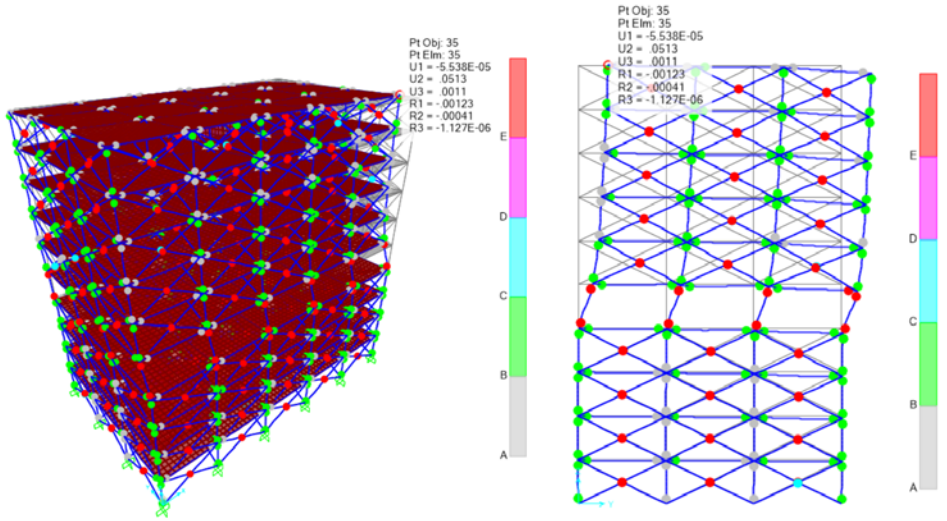

Fig. 11: Developed plastic hinges in model (3) at max displacement (0.051m) at time (2.19Sec).

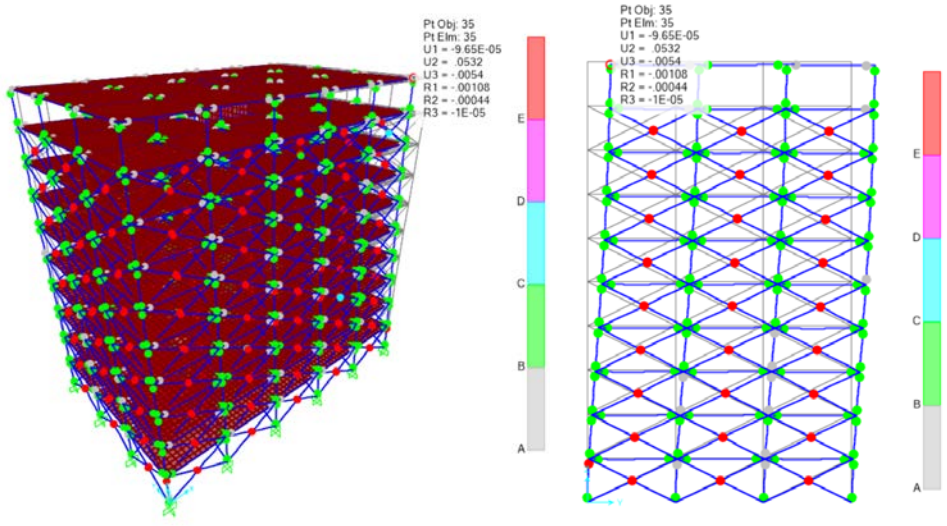

Fig. 12: Developed plastic hinges in model (4) at max displacement (0.053m) at time (4.47Sec).

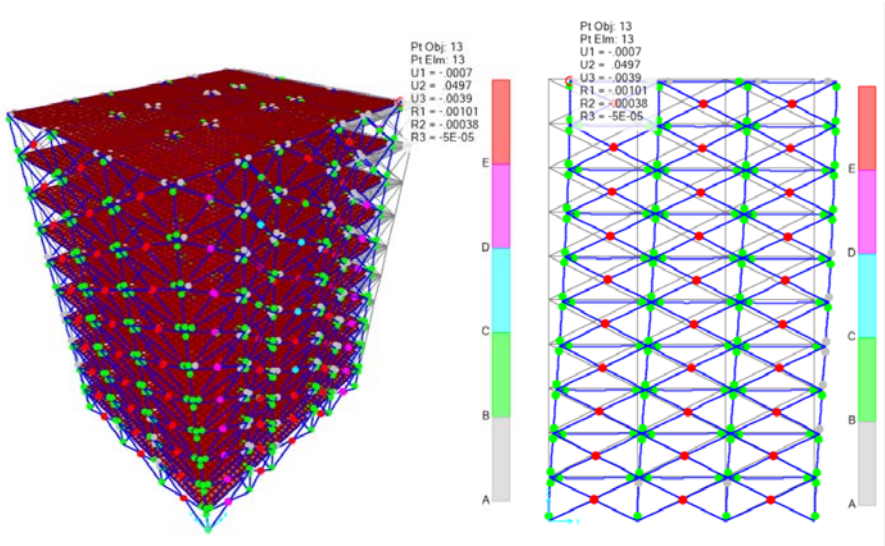

Fig. 13: Developed plastic hinges in model (5) at max displacement (0.049) at time (4.46 Sec).

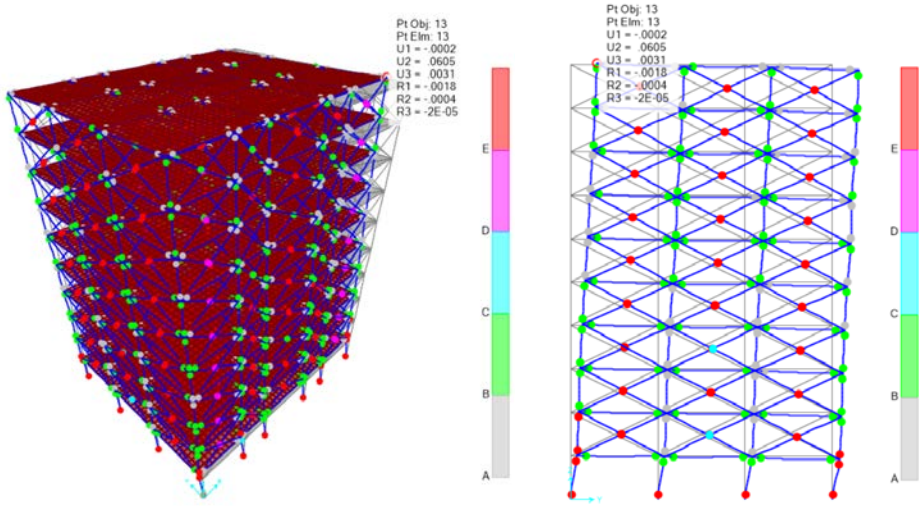

Fig. 14: Developed plastic hinges in model (6) at max displacement (0.060m) at time (2.19Sec).

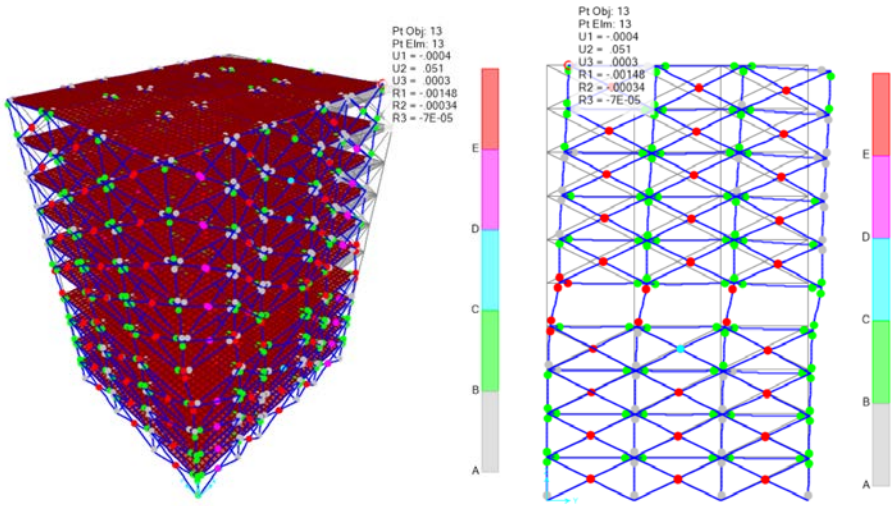

Fig. 15: Developed plastic hinges in model (7) at max displacement (0.051m) at time (2.17 Sec).

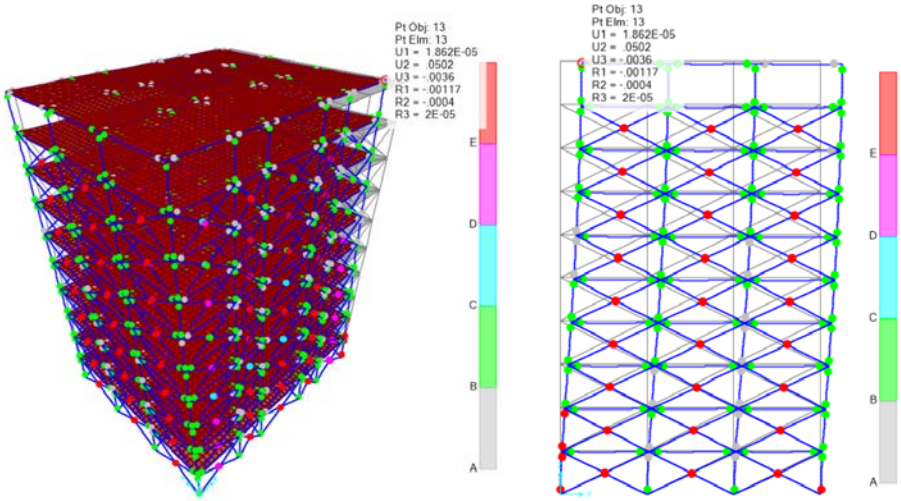

Fig. 16: Developed plastic hinges in model (8) at max displacement (0.050m) at time (4.46 Sec).

5. Conclusions

The findings from a nonlinear time history analysis of ten-story RC buildings were examined to show the consequences of using three distinct places for soft stories, namely the ground, fifth, and last floors. The building with a soft story on the fifth floor had a virtually comparable and equivalent response in both types of buildings. We assessed the compatibility in terms of natural period, maximum displacement, acceleration, base shear, variation of floor displacement, and the formation of plastic hinges in the beams and columns of the two buildings. For buildings with equal spans, including a soft story in the ground or a fifth story, the first three natural periods increased from an average value of 0.41 seconds to 0.53 seconds, while for buildings with unequal spans, the average value increased from 0.37 seconds to 0.58 seconds. When the building has a soft floor at any level, the base shear slightly decreases while the roof lateral displacement significantly increases for both types of buildings. The highest increase in roof displacement and story drift occurred when using a soft story on the ground floor. For the particular buildings under consideration, it can be stated that, compared to other locations of soft stories, the building with soft stories on the fifth level exhibits the best dynamic performance. For a building having the soft story in either the round or fifth story, the main plastic hinges are developed in the columns of that story.

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