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Soft-story effects on the behaviour of seismically isolated buildings under near and far-fault earthquakes

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ABSTRACT

In this study, the effects of soft-story on the seismic behaviour of 3-story and 8-story isolated buildings under near and far-fault earthquakes were investigated. Four different structural models with two different 1st story height were designed: One with 1st story height of 3m and 2nd with 1st story height of 4.5m to capture soft story effect. The prototype fixed base buildings were converted to seismically isolated buildings by introducing rubber isolators at base level. Analyses were conducted by using two different isolation systems (QW7.5Tb3 and QW7.5Tb4). The modelling of conventional fixed base prototype seismically isolated buildings and their modal analyses were conducted on finite-element program SAP2000, whereas, modelling of seismically isolated buildings and nonlinear time-history analyses were conducted using 3D-BASIS program. The four accelerations records has been used for the time-history analysis. Floor accelerations, story shears and inter-story drift ratios were the key structural responses considered. The analysis results showed seismic isolations can be used as a viable mitigation method for the buildings with soft-stories under near and far-fault earthquakes. Based on the results obtained, it is interesting to note that all types of buildings whether with soft story or with typical story height show the same acceleration trend and close values (except top floor) for all types of isolation systems and earthquakes considered. In addition, both 3 and 8-story buildings suffered increase in interstory drifts beyond the limits defined UBC 97 under earthquakes containing long period pulses.

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1. Introduction

A soft story known as weak story can be defined as a story in a building that has open parking or commercial space and substantially less resistance or stiffness or inadequate ductility (energy absorption capacity) than the stories above or below it (Hejazil et al., 2016). In such buildings, the dynamic ductility demand during probable earthquake gets intense in the soft stories and the upper stories tend to remain elastic, and thus the whole building down with them (Setia and Sharma, 2012). Many studies have been conducted on the dynamic behaviour and seismic vulnerability of reinforced concrete structures with soft stories (Alekar et al., 1997; Kanitkar and Kanitkar, 2004; Lee and Ko, 2007; Mastrandrea and Piluso, 2009).

It has been observed from previous research (Pinarbasi and Konstantinidis, 2007; Ribakov, 2010; Komur, 2016) that a popular earthquake resistant design concept is the use of base-isolation devices that are placed between the superstructure and the substructure. The base isolation possess high lateral flexibility and high axial rigidity, reduces substantially the absorption of the earthquake's energy by the superstructure and shift the fundamental period of the structure toward higher values (Berton et al., 2008). Although base isolation reduces the possibility of damage (less inter-story drifts, shear forces and floor accelerations) of a building, it causes to large displacements in the structure relative to the ground. This, in turn, increases the potential of impact or pounding of a building with adjacent structures (Pant and Wijeyewickrema, 2012).

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One of the important factor that affects evaluation of the seismic performance of a building is the type of earthquake ground motion. Compared to far-fault (FF) ground records, near fault (NF) ground motions often possess distinct characteristics such as producing high input energy at the beginning of the earthquake and have strong influences on the structural dynamic response, especially for long-period structures. In addition, for structures subjected to NF ground motions, the isolator displacements tend to be considerable while the isolators experience acceptable deformations under FF ground motions (Providakis, 2008; Bayraktar et al., 2009; Li et al., 2016). In the literature review, a number of research studies have been performed for investigating the influence of concrete strength on the structural performance. A recent work by Tavakoli et al. (2015) demonstrated the NF motion induces noticeable base shear so that reduction in base shear values was very low after utilizing lead-rubber isolating bearing in high-rise and intermediate structure models in comparison with FF motion. In another study, Chopra and Chintanapakdee (2001) compared certain aspect of the response of single degree freedom systems to NF ground motions with their response to FF ground motions in the context of the acceleration, velocity and displacement sensitive regions of the response spectrum. It was found that for the same ductility factor, NF ground motions impose a larger strength demand in their acceleration-sensitive region compared to FF motions.

A review of the literature indicates that in contrast to seismic behaviour of seismically isolated reinforced concrete buildings, no study has been conducted so far to investigate the effect of soft story on the seismic response of a seismically isolated building under near and far fault earthquakes. In this study, three story and eight story isolated buildings with 1st story height of 3m and 2nd with 1st story height of 4.5m were employed to capture soft story effect on the seismic response of seismically isolated buildings under near and far fault earthquakes. Analyses were conducted by using two different isolation systems (QW7.5Tb3 and QW7.5Tb4) and the four accelerations records. Floor accelerations, story shears and inter-story drift ratios were the key structural responses considered.

2. Methodology

In this study, the effects of soft-story on the behaviour of 3-story and 8-story isolated buildings under near and far-fault earthquakes were investigated. The superstructure and isolation system were designed according to TEC 2007 and UBC 97, respectively.

2.1. Design of the superstructures

3-story and 8-story isolated buildings with 5 bays in each orthogonal direction have been used in this study. These structures are intended to represent typical residential low-rise and high-rise reinforced concrete buildings in urban areas. Two different 1st story height was used: One with 1st story height of 3m and 2nd with 1st story height of 4.5m to capture soft story effect. The buildings are symmetrical about both principal axes and have typical column-beam sections without any shear walls. Typical plan of 3 and 8-story buildings, and 3D views of the buildings are shown in Fig. 1, Fig. 2 and Fig. 3, respectively. It was assumed that the building importance factor was 1, and that the soil type according to UBC 97 was Class C. Materials properties are assumed to be 30 MPa for the concrete compressive strength and 420 MPa for the yield strength of both longitudinal and transverse reinforcement. The height of the slabs is taken to be 14 cm.

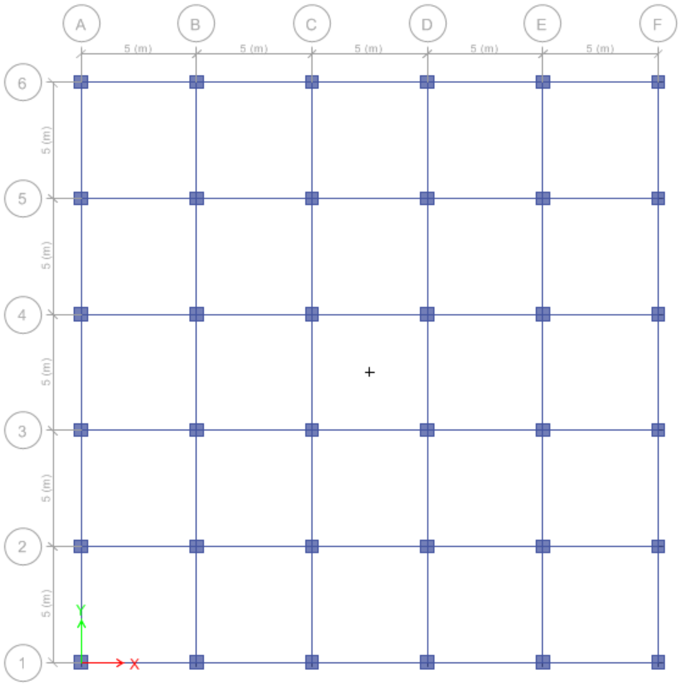


Fig. 1. Typical floor plan of 3 and 8-story buildings.

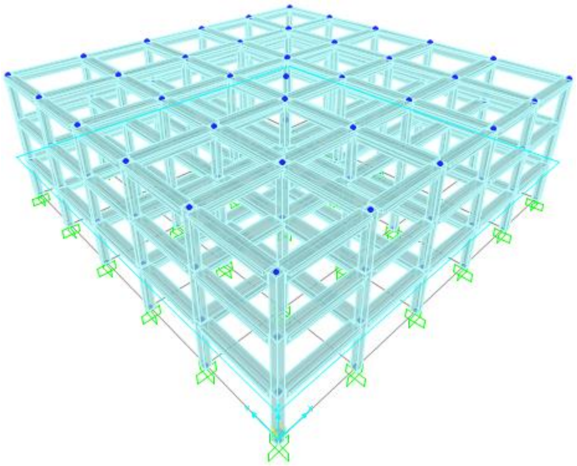


Fig. 2. 3D view of prototype 3-story building.

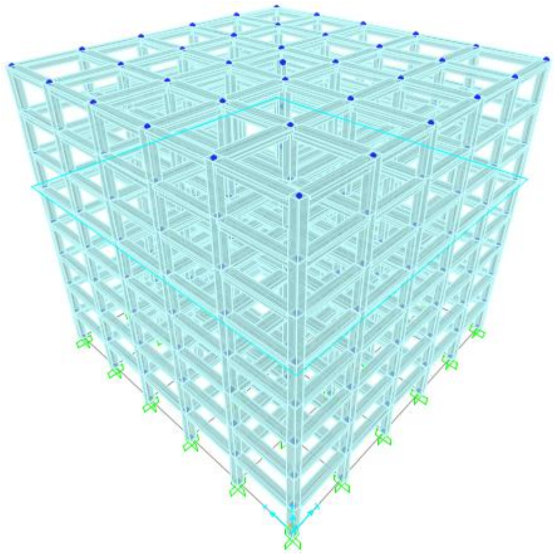
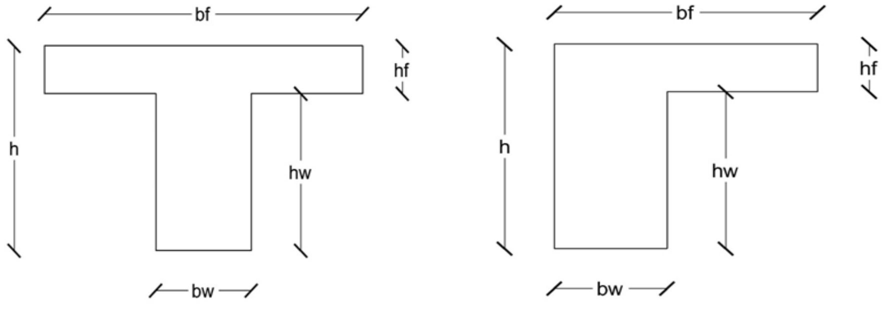
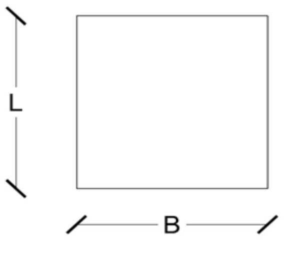


Fig. 3. 3D view of prototype 8-story building.



Interior T-Beam **Edge L-Beam**



Column

Fig. 4. Details of the frame section the buildings.

Regarding loading on the buildings, story masses were usually used which are lumped at centre of gravity (at master joint). Figure of frame sections of the buildings is shown Fig. 4. Details of the column and beam sections are also tabulated in Table 1. The prototype fixed base buildings were converted to seismically isolated buildings by introducing rubber isolators at base level (also called base isolation). A translational mass of 500 kNs^2/m was assumed to be lumped at the centre of mass of each floor.

Each floor had 3 degrees of freedom i.e. 2 translations and 1 rotation. Rigid diaphragm was introduced at each floor level to distribute the lateral forces to structural elements of the frame.

Table 1. Section size of the members.

X - section	Symbol	Dimensions for 3-story building (mm)	Dimensions for 8-story building (mm)
T - beam	h	600	600
	h_w	460	460
	b_w	300	300
	b_f	1000	1000
	h_f	140	140
L - Beam	h	600	600
	h_w	460	460
	b_w	300	300
	b_f	700	700
	h_f	140	140
Column	L	400	550
	B	400	550

2.2. Design of the isolation systems

Analyses were realized by using two different isolation systems (QW7.5Tb3 and QW7.5Tb4). Here, in QW7.5Tb3 isolation system QW7.5Tb4 indicates characteristic strength of isolation system normalized with weight of the building (W) to be 7.5% and T_{b3} indicates isolation period to be 3 seconds. It is worth-mentioning that characteristic strength of the isolation system is a measure of level of damping in the isolation system. The parameters concerning isolation systems were summarized in Table 2. To calculate parameters for each isolator, Q (characteristic strength), K_1 (pre-yield stiffness), K_2 (post-yield stiffness), and F_y (Yield force) should be divided by total number of isolators used in the isolation system. In Table 2, α is post-yield to pre-yield stiffness ratio and D_y is yield displacement of isolation system. A constant value of 0.015 m was adopted for both the isolation systems.

Table 2. Parameters related to modelling of nonlinear isolation system.

Super-structure	Isolation System	T_b (s)	Q (kN)	α	K_2 (kN/m)	K_1 (kN/m)	D_y (m)	F_y (kN)
3-story	QW7.5Tb3	3	1471.5	0.082	8772.982	106873.0	0.015	1603.09
	QW7.5Tb4	4	1471.5	0.048	4934.802	103034.8	0.015	1545.52
8-story	QW7.5Tb3	3	3310.875	0.082	19739.209	240464.2	0.015	3606.96
	QW7.5Tb4	4	3310.875	0.048	11103.305	231828.3	0.015	3477.42

2.3. Seismic ground motions

The modelling of conventional fixed base prototype seismically isolated buildings and their modal analyses were conducted on finite-element program SAP2000, whereas, modelling of seismically isolated buildings and nonlinear time-history analyses were conducted using 3D-BASIS program which has been particularly developed, by Nagarajaiah et al. (1991), for nonlinear dynamic analysis of three dimensional base isolated structures. The four accelerations records has been used for the time-history analysis. The properties of these acceleration records are shown in Table 3.

The fundamental/first mode periods of the buildings with different 1st story heights were obtained through modal analyses and are presented in Table 4.

Analyses were done by using bidirectional earthquake input with strong component of earthquake along one main axis (X-axis) and weak component of earthquake along other orthogonal main axis (Y-axis) of the buildings. The scaled spectrum record for acceleration used in the analysis are shown in Fig. 5. It should not be forgotten that the spectrum shows the responses of a single degree freedom system. As the buildings were a multi degree of freedom system, the response will vary.

Table 3. Parameters related to modelling of nonlinear isolation system.

Historical earthquakes	Date of occurrence	Recording station	Magnitude	Strong component (g)	Weak component (g)
Duzce (Far-Fault)	12/11/1999	IRIGM 498	7.14	0.396	0.337
Landers (Far-Fault)	28/06/1992	Coolwater CLW	7.28	0.412	0.282
Northridge (Pulse-like Near-Fault)	17/01/1994	Rinaldi Receiving Station RRS	6.69	0.825	0.487
Tabas (Pulse-like Near-Fault)	16/09/1978	Tabas Tab	7.4	0.854	0.767

Table 4. Fundamental/First mode period of the buildings.

Building superstructure	Fixed-base natural period (s)
3-story with 1st story of height 3m	0.357
3-story with 1st story of height 4.5m	0.512
8-story with 1st story of height 3m	0.638
8-story with 1st story of height 4.5m	0.727

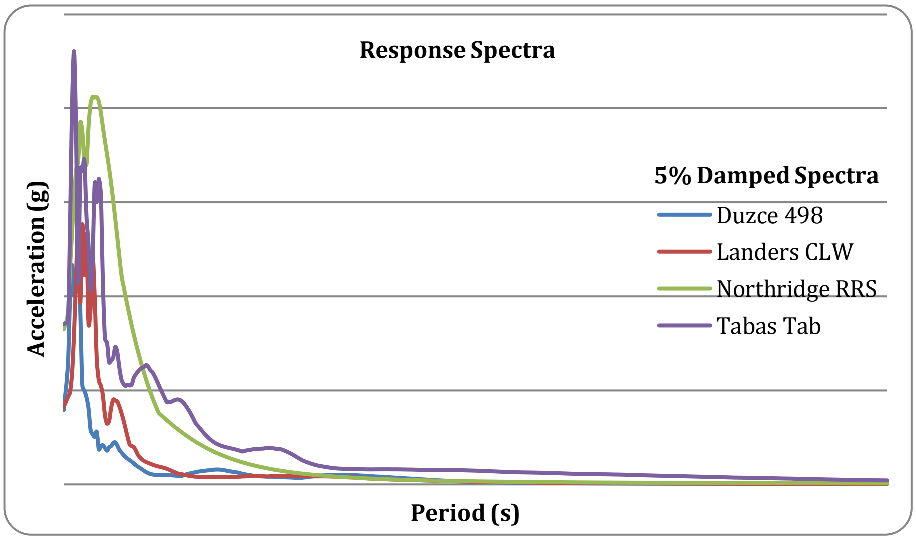


Fig. 5. The scaled record spectra used.

3. Results and Discussion

As the seismically isolated buildings in this study are subjected to bi-directional near and far-fault earthquake excitations, the structural responses in both global X and Y direction have been considered for performance comparison. It is important to mention that the building models used in this study are symmetrical so the results obtained would be same if the axes are reversed. Moreover, the displacements at the isolation level or the base displacements obtained from the analyses of all the building models with similar isolation parameters are almost same so the main focus of attention for this study is the superstructure responses. Floor accelerations, story shears and inter-story drift ratios are the key structural responses considered.

3.1. Floor accelerations

Considering FF earthquakes, for 3-story buildings with isolation system QW7.5Tb3, the accelerations are normally less at 1st floor for building with soft story as compared to building with typical story height at 1st floor (i.e. 3m). However, the accelerations are more at 2nd floor for soft story building (see Fig. 6). It is interesting to note that soft story building shows almost a linearly increasing pattern of accelerations towards top floor, while, the building with typical 1st story height shows about same acceleration at 1st and 2nd floor but accelerations increasing for 3rd floor (i.e. top floor). And, the accelerations at top floor level are generally less for building with typical 1st story than building with soft story at first floor. Under Northridge RRS pulse-like earthquake, floor acceleration increases towards top floor for both of the buildings i.e. building with 3m 1st floor and building with 4.5m 1st floor but the difference of floor accelerations between aforementioned buildings increases towards top floor with soft story building showing more acceleration at top floor level than the other. Tabas Tab NF earthquake bring about a slightly different response with floor acceleration almost same at 1st floor level for both type of buildings under consideration and the difference of floor accelerations between two buildings highest at 2nd floor level. Buildings with isolation system QW7.5Tb4 follow the same trend as described for buildings with isolation system QW7.5Tb3 but typically the floor accelerations are less for building with QW7.5Tb4, as compared to their QW7.5Tb3 counterparts, due to more flexibility at the isolation level.

The response in other orthogonal direction is a bit different as FF earthquakes show less increase in acceleration from 1st to 2nd floor for soft story building as compared to other principal direction X (Fig. 7). For NF earthquakes, the response is also slightly different for Y-direction as compared to X-direction. Nevertheless, this slight difference is not so significant.

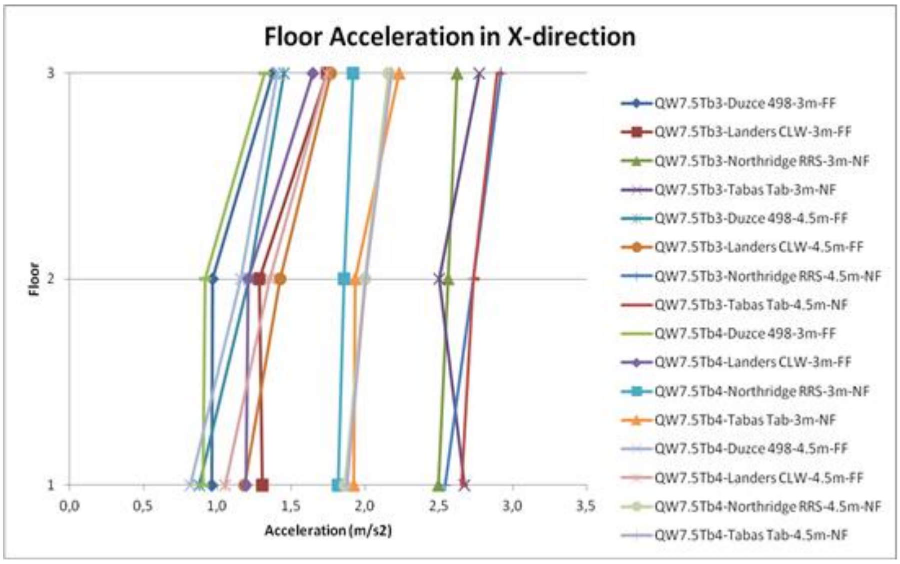


Fig. 6. Floor acceleration in X-direction for 3-story building.

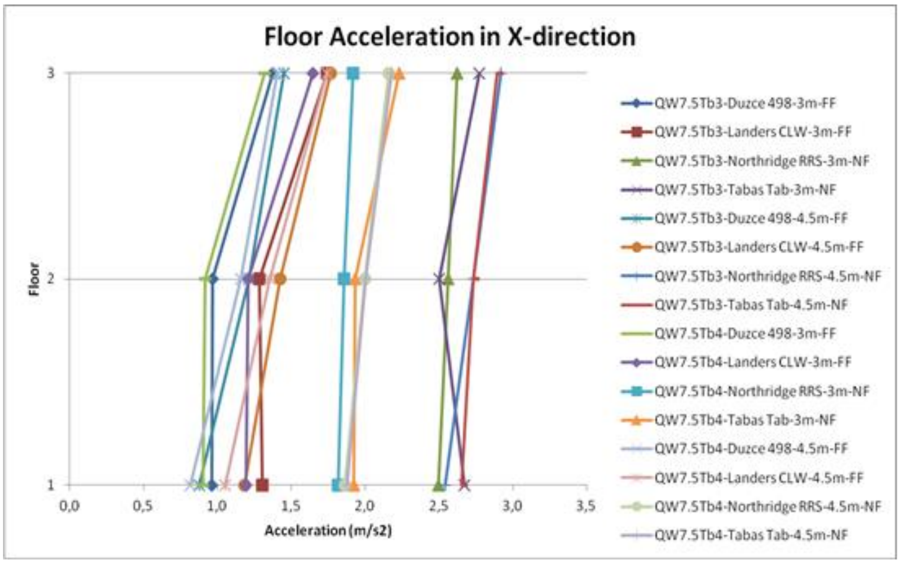


Fig. 7. Floor acceleration in Y-direction for 3-story building.

8-story seismically isolated buildings show different trend in comparison to 3-story building, as evident from Fig. 8. For all types of buildings, floor accelerations are generally more for lower floors with accelerations decreasing towards middle floor levels and then again increases towards top floor, thus, reaching the highest value at top floor level. The only exception to this behavior is Tabas Tab pulse-like earthquake which shows relatively complex floor acceleration trend (see Fig. 8). One important thing to be noticed here that all types of buildings whether with soft story or with typical story height show the same acceleration trend and close values (except top floor where a slight deviation is noted for some earthquakes), for all types of isolation systems and earthquakes considered.

The floor acceleration response in other orthogonal direction is essentially the same (Fig. 9). It can be concluded that 8-story buildings whether having 1st story of height 4.5m or 3m show different response as compared to corresponding 3-story buildings. As flexibility of superstructure increases, the acceleration trend changes and effect of soft story on floor accelerations becomes less distinct.

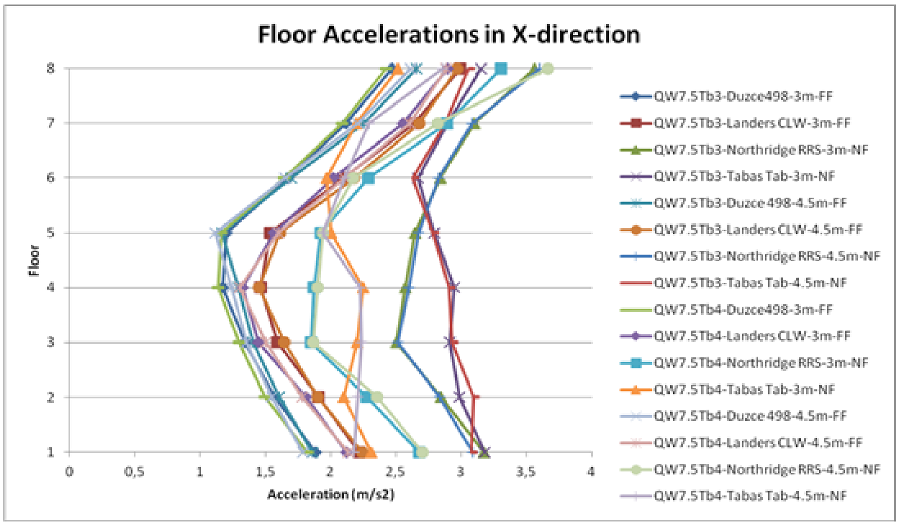


Fig. 8. Floor acceleration in X-direction for 8-story building.

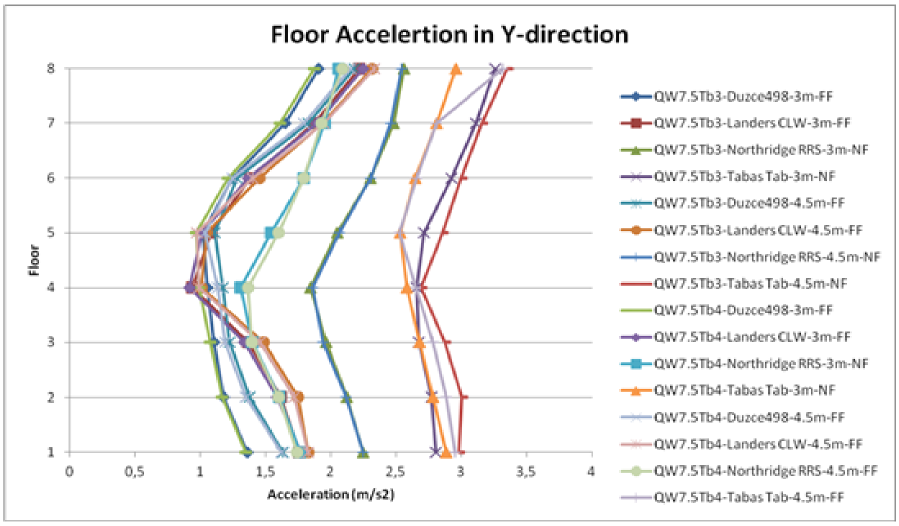


Fig. 9. Floor acceleration in Y-direction for 8-story building.

3.2. Story shears

In 3-story building, the story shear distribution trend is almost same for all earthquakes i.e. FF and NF earthquakes, in similar type of buildings. However, more story shears are observed at 1st and 2nd floor for buildings with soft story but the base shear and shear at top floors are almost same as building with typical 3m story height (see Fig. 10). For NF Earthquakes, comparing buildings with QW7.5Tb3 against the buildings with QW7.5Tb4 isolation system, the difference in story shears and base shears are quite large as compared to the same seismically isolated buildings subjected to FF earthquakes. Overall, for every type of building and earthquake, the shears are more for QW7.5Tb3 as compared to isolation system QW7.5Tb4 which may be down to its flexibility.

Same trend is observed for other orthogonal direction but difference in shears between building with 3m 1st story height and building with 4.5m 1st story height is very small (Fig. 11).

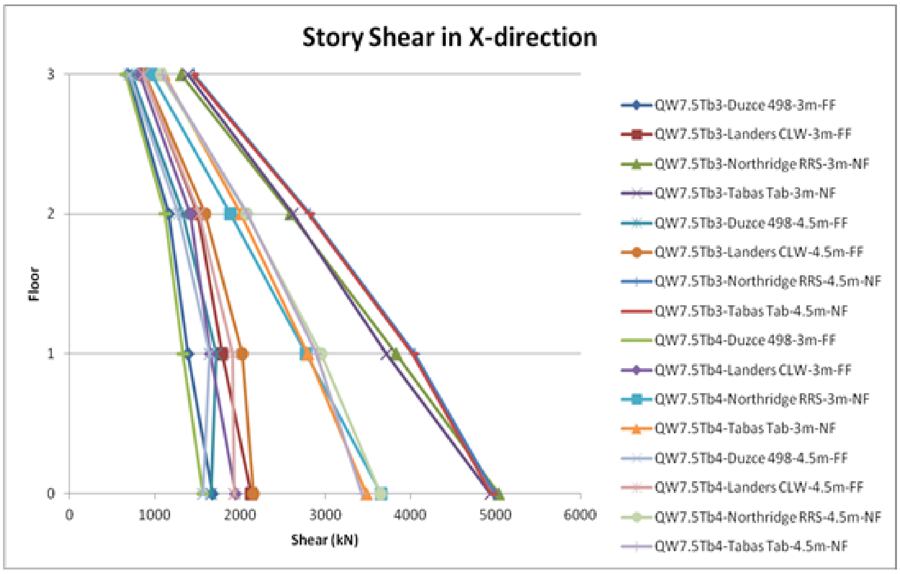


Fig. 10. Story shears in X-direction for 3-story building.

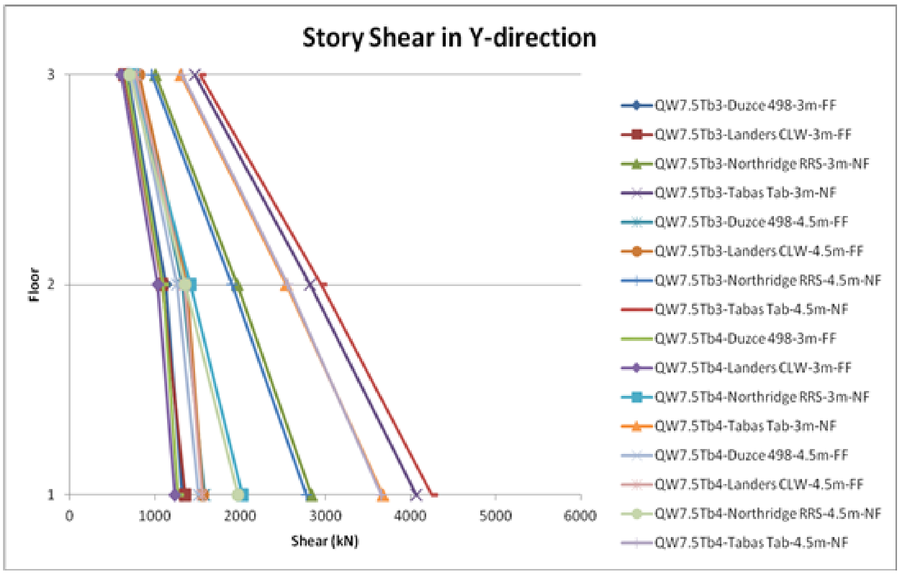


Fig. 11. Story shears in Y-direction for 3-story building.

For 8-story building, the story shears and base shears are more or less same for 3m 1st story building and 4.5m 1st story building. The shear distribution along the height is not as linear as in the case of 3-story buildings. The difference of story shears between all types of buildings becomes less apparent on upper floors with very close values of top floor shear for every type of building, isolation system and earthquake (Fig. 12). Likewise 3-story building, the difference of shears at each floor level, between buildings with QW7.5Tb3 and QW7.5Tb4 subjected to NF earthquakes, is quite large in lower and middle floors as compared to the situation if they are excited by FF earthquakes. Same trend is observed for other principal direction i.e. along Y-axis (Fig. 13).

3.3. Inter-story drift ratios

In 3-story seismically isolated building with isolation system QW7.5Tb3, for (FF) earthquakes i.e. Duzce 498 and Landers CLW, the inter-story drift ratios at each floor level are more for isolated building with 1st story of height 4.5m as compared to the building with 1st story of height 3m. The soft story at 1st floor induces an increase in inter-story drifts at floors above it but this difference decreases from the soft story towards the top floor with the lowest difference in inter-story drift ratios observed at top floor level. In the building with the same isolation system, under pulse like (NF) earthquakes i.e. Northridge RRS and Tabas Tab, overall the inter-story drift ratios are more as compared to that of FF earthquakes (Fig. 14). In this case, the soft story at 1st floor induces more increase in inter-story drift ratios at every floor level as compared to FF earthquakes but the trend observed is same i.e. decrease in difference of inter-story drift ratios towards top floor level.

As the isolation period is increased from 3s to 4s (QW7.5Tb4), an overall decrease of inter-story drift ratios at each floor level is observed as compared to building with isolation system QW7.5Tb3 but the difference of inter-story drift ratios (between a building with 1st story of height 3m and a building with soft story effect 1st story of height 4.5m) remains essentially the same. The same decreasing trend of difference of inter-story drift ratio is observed from soft story towards top floor as was observed for QW7.5Tb3. Likewise QW7.5Tb3, Pulse-like NF earthquake induces more difference in inter-story drift ratios as compared to FF earthquakes (Fig. 14).

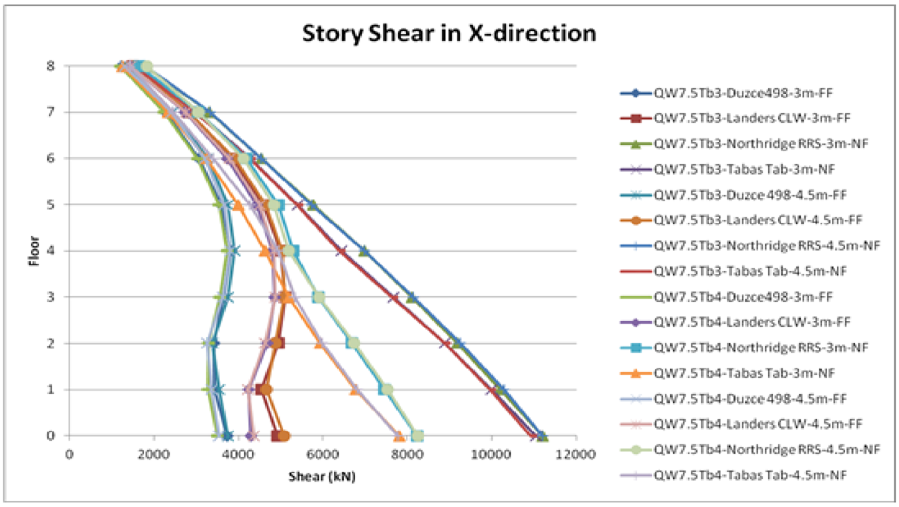


Fig. 12. Story shears in X-direction for 8-story building.

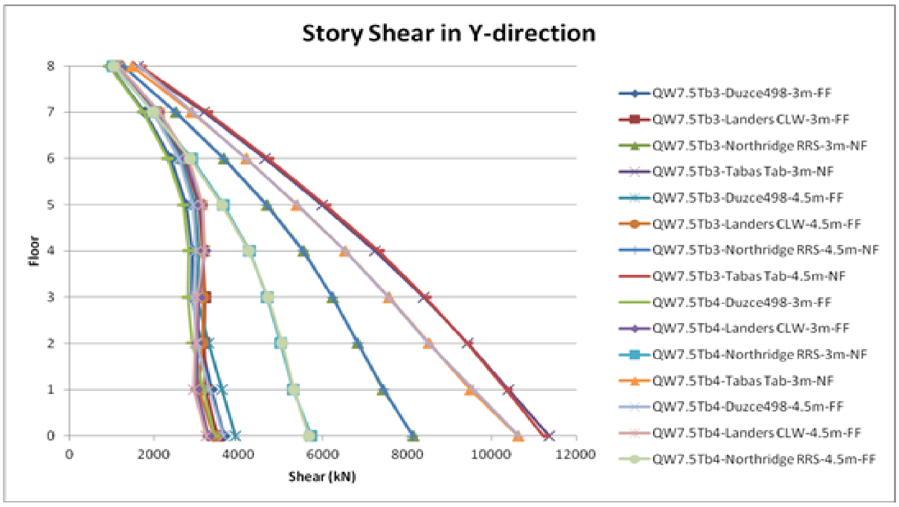


Fig. 13. Story shears in Y-direction for 8-story building.

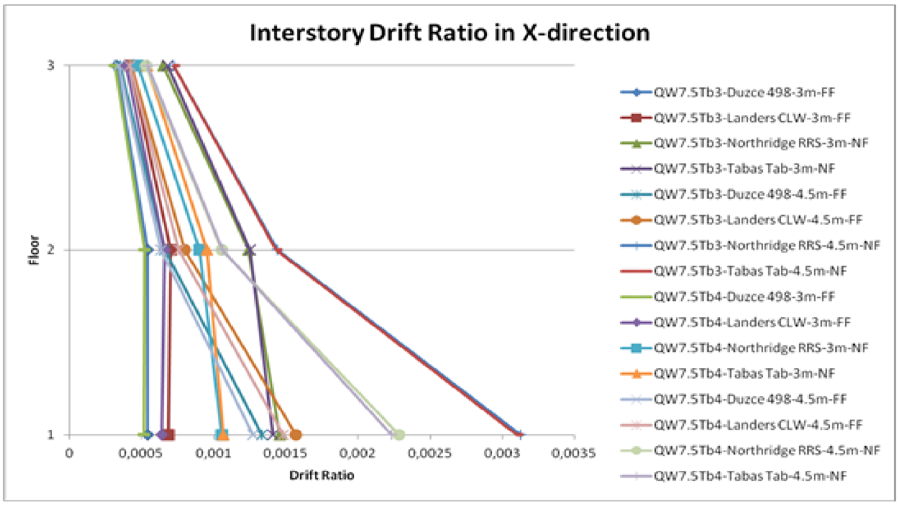


Fig. 14. Inter-story drifts in X-direction for 3-story building.

For 3-story building, in orthogonal Y-direction the inter-story drift ratios follow the same trend as observed in main orthogonal X-direction (Fig. 15). The only exception being the NF earthquake Northridge RRS where a sharp decrease, in difference between inter-story drifts of building with soft 1st story and normal 1st story, is observed from 2nd to 3rd floor for both isolation systems QW7.5Tb3 and QW7.5Tb4.

For 8-story buildings with isolation system QW7.5Tb3, under FF earthquakes i.e. Duzce 498 and Landers CLW, an increase in inter-story drift ratios is observed for building having soft 1st story (4.5m height) as compared to building with normal first story (3m height) with the greatest difference between inter-story drift ratios at 1st floor level but difference becomes very small from 3rd floor towards Top floor level (as evident in Fig. 16). For NF earthquakes Northridge RRS and Tabas Tab, inter-story drift ratios are greatest at 2nd floor level and decreases towards top floor with the least value of inter-story drift ratios seen at the top floor. The difference of inter-story drift ratios, between building with 1st story of height 3m and building with 1st story of height 4.5m, is greatest at 1st floor level but the difference becomes very small from 3rd floor onwards towards top floor level.

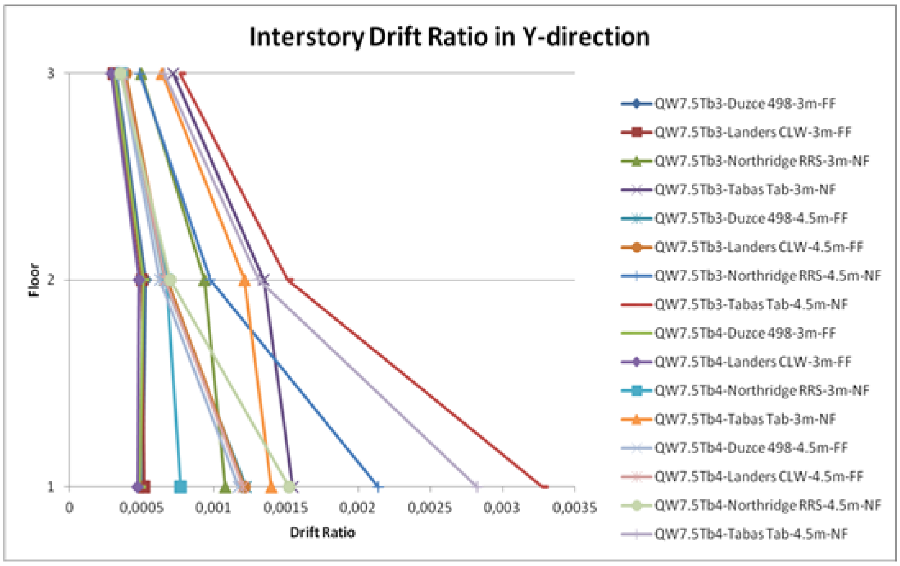


Fig. 15. Story shears in Y-direction for 3-story building.

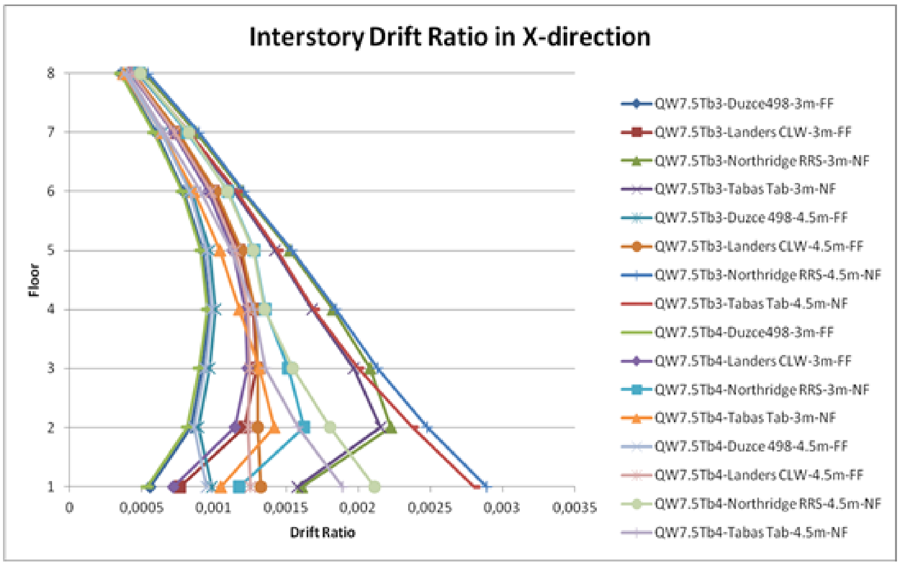


Fig. 16. Inter-story drifts in X-direction for 8-story building.

For the same buildings with isolation system QW7.5Tb4, under FF earthquakes, inter-story drift ratios are overall slightly less than that of building with isolation system QW7.5Tb3. Far-Fault earthquakes induce maximum inter-story drifts at 4th floor level for both QW7.5Tb3 and QW7.5Tb4, while, this value is greatest at 2nd floor level (see Fig. 16). For NF earthquakes, in the building with QW7.5Tb4, the difference of inter-story drifts between building with 3m 1st floor height and building with 4.5m height is highest at 1st floor level with the difference very small from 3rd floor onwards to top floor. An exception to that is Tabas Tab earthquake, where the difference is less at 3rd floor followed by an increase and then decrease towards top floor with the least value of difference observed at top floor level. However, unlike FF earthquakes, for pulse-like earthquakes the difference in inter-story drift ratios at each floor level is quite large between QW7.5Tb3 building with 3m 1st story and QW7.5Tb4 building with 3m 1st story and same trend is observed for buildings with 1st story of 4.5m height. In comparison to 3-story buildings, generally the difference in inter-story drift ratios becomes very small after 3rd story towards 8th story (top level) so a decreasing trend is not so obvious. Similar results are seen on the other orthogonal direction i.e. along Y-axis of the buildings (as obvious from Fig. 17). It can be concluded that soft story influences the inter-story drifts of stories just above it and becomes less pronounced at upper floors.

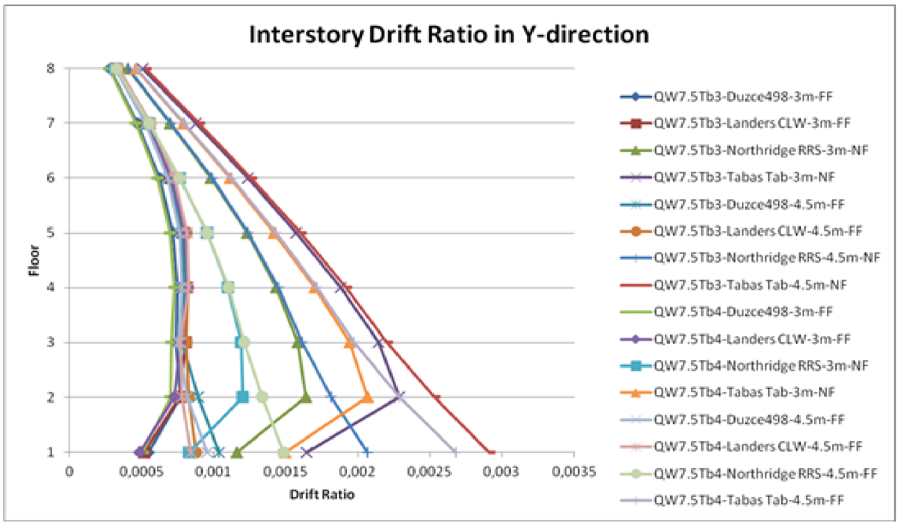


Fig. 17. Inter-story drifts in Y-direction for 8-story building.

In general for all the cases considered, max inter-story drift ratio limit, defined in UBC97, for seismically isolated building is $0.02/R_I$ (if calculated by time-history analysis). Where, R_I is 2 for concrete moment resisting frames. It is important to mention that both 3 and 8-story buildings suffered increase in inter-story drifts beyond this limit, under earthquakes containing long period pulses. Inter-story drifts beyond a certain level may be dangerous for the integrity of the building.

4. Conclusions

Sudden changes in lateral stiffness and strength is one of the most important factors on the structural response of seismically isolated buildings under near and far fault earthquakes.

In general, the results demonstrate that seismic isolations can be used as a viable mitigation method for the buildings with soft-stories under near and far-fault earthquakes. In addition, it can be concluded that soft story influences the inter-story drifts of stories just above it and becomes less pronounced at upper floors. However, both 3 and 8-story buildings suffered increase in inter-story drifts beyond the limits which is defined in UBC97, under earthquakes containing long period pulses. Thus, interstory drifts beyond a certain level may be dangerous for the integrity of the building.

In a future research study, the efficiency of hybrid isolation system with friction sliders and viscous damper for protection of seismically isolated buildings with soft story against near fault earthquakes would be studied.

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