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Research Article

Comparative study on the linear and nonlinear dynamic analysis of typical RC buildings

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Highlights:

- Results in linear dynamic analysis largely affected by dynamic amplification.
- Linear dynamic analysis method is inadequate to reflect intensity of ground motion.
- Nonlinear modelling is recommended to obtain realistic results in dynamic analysis.

Abstract: A careful evaluation has been carried out to reveal advantages and disadvantages of linear and nonlinear modelling in dynamic analysis. 4- and 7- story building models representing characteristics of about 500 existing buildings models in Turkey was used in analyses. In the study, displacement demand parameters such as roof drift ratio and interstory drift ratio obtained from linear and nonlinear analyses were compared using a total of 24 ground motion records including forward directivity effects (Set 2) as well as records (Set 1) recorded in type B and C soils. Although the seismic demands for Set 2 are obtained extremely high in the nonlinear models, the demand differences between Set 1 and Set 2 are not excessive for the linear models. In the region where the T/T_p ratio is close to one, the linear analysis predicts unrealistically high demands compared to the nonlinear analysis. Linear analysis results mostly show an increase or decrease depending on dynamic amplification effects. The effects of ground motion intensity and damage mechanism cannot be observed in linear analysis method. For all these reasons, it is recommended not to prefer linear modeling method when using time-history analysis.

Keywords: Displacement demands, existing reinforced concrete buildings, forward directivity effects, linear analysis, nonlinear time history analysis.

Abbreviation:

IDR - interstory drift ratio
T - first mode period
T_p - predominant period
VSI - velocity spectrum intensity

1. Introduction

Seismic performance evaluation of existing structures requires proper displacement estimates. Linear static, linear dynamic, nonlinear static and nonlinear dynamic analyses are available options for seismic displacement estimates. In most cases, linear static analysis is preferred in design stage while nonlinear static analysis is used for evaluation purposes. However, the response of buildings is complex and yielding on structural members inevitable during strong earthquakes, but these effects are neglected in linear modeling. Moreover, many effects occurring under dynamic loading are not taken into account in the linear static analysis method (Priestley, 1995; Krawinkler, 1996; Mwafy and Elnashai, 2001; Ni, 2014). Thus, nonlinear dynamic analysis is the best choice for determining seismic response of buildings.

Most of seismic codes relies on linear modelling with simplified nonlinear demand estimates and assumed to be an acceptable solution (Miranda, 1993; ACI, 2002; Eurocode 8, 2005; TEC, 2007). However, there are obvious inadequacies of linear methods for seismic assessment of existing structures. The existing building stock of most of developing countries like Turkey is substantially built according to pre-modern seismic codes (Ozmen et al., 2015; Oz et al., 2020; Cirak Karakas et al., 2022). Thus, plastic deformation and stiffness capacity of these buildings are inadequate compared to buildings designed according to modern seismic codes. To make assessments by using linear modelling assumption is highly questionable approach for pre-modern buildings. Investigation of the events that occurred after yield such as the strength and deformation capacity of the structure, the redistribution of critical loading between building elements is possible only with nonlinear analysis methods (Binici et al., 2015; Cakir et al., 2015; Gunes, 2015; Bikçe and Çelik, 2016).

The reflection of nonlinear behavior in modelling is a complex problem. Solving dynamic equilibrium of nonlinear models is also computationally intensive. In nonlinear methods, strength-deformation relationships for each element are defined to consider capacities of elements and rigidity changes that may occur during the analysis are taken into account. Although it is well known that nonlinear time history analysis is the most realistic method for seismic demand predictions and performance evaluations of structures (Demir et al., 2023; Palanci et al., 2023; Demir et al., 2024), nonlinear static analysis known as pushover analysis has been thoroughly utilized in structural and earthquake engineering due to its simplicity (Erduran, 2008; El-Betar, 2017, Benaied et al., 2023).

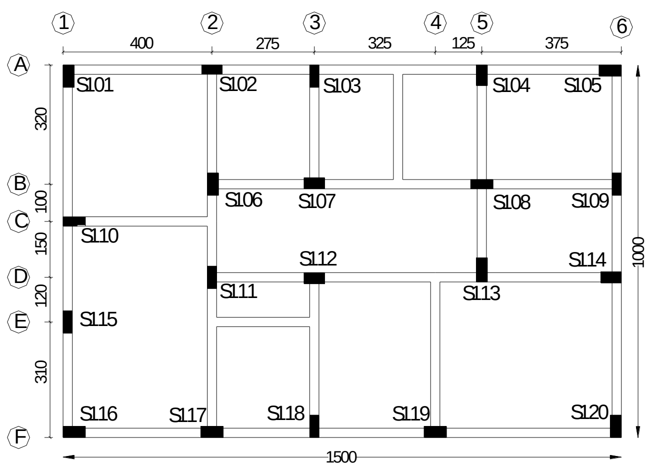
There are some studies concerned with the time history analysis. An equivalent single-degree-of-freedom (SDOF) system approach often used to obtain displacement demands of buildings (Elnashai, 2000; Liao et al., 2001; Hatzigeorgiou, 2010a, 2010b; Demir et al., 2021). Besides, related literature concentrated on SDOF (Amadio et al., 2003; Hatzigeorgiou and Beskos, 2009; Hatzigeorgiou et al., 2011; Moustafa and Takewaki, 2011; Palanci and Senel, 2019) or two-dimensional MDOF systems (Hatzigeorgiou and Liolios, 2010; Zhou et al., 2014; Demir et al., 2020; Das et al., 2024) instead of three-dimensional RC building models. Limited studies have been carried out about time history analysis of 3D RC buildings by researchers (Aydinoğlu, 2003; Çelik, 2011; Ozmen, 2011; Önür, 2011; Kokot et al., 2012; Faisal et al., 2013; Hancilar et al., 2014; Antoniou et al., 2015; Hatzivassiliou and Hatzigeorgiou, 2015; López-López et al., 2016; Moon et al., 2017; Meral, 2024). Moreover, the studies focused on the differences between linear and nonlinear time history analyses are limited (Ozmen, 2011). Some studies contain demands such as distribution of plastic hinge rotation, interstory drifts and maximum story drifts in order to determine structural behavior using nonlinear time history analysis (Memari et al., 2000; Kalkan and Kunnath, 2007; Kayhan et al., 2018; Palanci et al., 2018). Different nonlinear procedures were used to examine for damage cases (Borzi and Elnashai, 2000; Kappos and Panagopoulos, 2004; Causevic and Mitrovic, 2011). The results from static pushover analysis were compared with time–history results for selected RC buildings (Goel and Chopra, 2005; Wilkinson and Hiley, 2006; Li et al., 2017;

Inel et al., 2018). The time history analysis is utilized in different fields such as seismic assessment (Ruiz-García and Miranda, 2006; Bakir et al., 2007; Subramanian and Velayutham, 2014; Eskandari and Vafaei, 2015; Fontara et al., 2015; Koçak, 2015), pounding between adjacent structures (Naserkhaki et al., 2012; Efraimiadou et al., 2013; Kamal, 2022; Kamal and Inel, 2022a, 2022b; Kamal et al., 2022), fragility curves (Borekci and Kirçila, 2011; Korkmaz et al., 2013; Palanci et al., 2017), soil-structure interaction (Eser et al., 2012; Aydemir, 2013a, 2013b; RezaTabatabaiefar et al., 2013; Tabatabaiefar et al., 2015; Cayci and Akpinar, 2021; Cayci et al., 2021; Van Nguyen et al., 2024) and seismic isolation (Meral, 2021; Ozer et al., 2022a, 2022b) for RC buildings. There are also some studies related to the nonlinear static and time history analyses (Tremayne and Kelly, 2005; Gonzales and López-Almansa, 2012; Chaulagain et al., 2013; Çavdar and Bayraktar, 2014; Koçak et al., 2015; Mosleh et al., 2016).

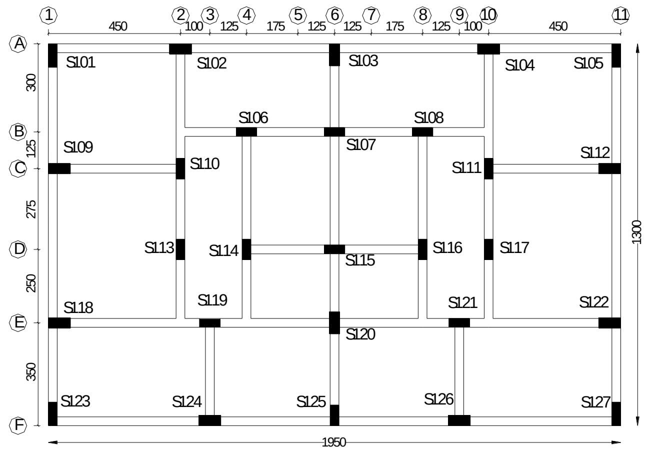
This study aims to compare linear and nonlinear time history analyses for existing low and mid-rise RC buildings to better understand the differences between two assumptions. The three-dimensional low and mid-rise RC building models are created by using the average of about 500 real residential RC buildings designed according to the pre-modern and modern Turkish Earthquake Codes (TEC, 1975, 1998).

2. Modeling approach

Two RC building models, 4- and 7-story, are selected to represent reference low and mid-rise residential buildings located in the high seismicity region of Turkey. All of the selected buildings have typical beam-column RC frame buildings with no shear walls. Outcomes of detailed field and archive investigation including about 500 real residential RC buildings established building models; number of columns, column and beam dimensions, story area or other parameters reflects a typical constructed building (Ozmen et al., 2015). Plan view of the buildings are given in Figure 1.



4-story model



7-story model

Figure 1. Plan views of the considered buildings.

The considered reference buildings are constructed according to pre-modern (TEC) (1975) and modern Turkish Earthquake Codes (TEC) (1998) considering the gravity and seismic loading. Dimensions of buildings based on field and archive investigations (TEC, 1975, 1998). A design ground acceleration of 0.4 g and soil class Z3 that is similar to class C soil of FEMA-356 was assumed for the design (FEMA-356, 2000). Then, using the member size and reinforcements, structures were modelled for nonlinear analysis. The reinforcement ratio for each structural members was calculated separately; no grouping or simplification was made during design stage.

Two different concrete compressive strength values are considered; 16 MPa for the pre-modern code and 25 MPa for the modern code buildings. The yield strength of both longitudinal and transverse reinforcement is assumed to be 220 and 420 MPa for the pre-modern and modern codes, respectively. Strain-hardening of longitudinal reinforcement has been taken into account. Considering typical building parameters and material variability four building models are established. Properties of existing buildings were reflected by reference buildings. Table 1 lists the model properties such as model identifiers, analysis directions, seismic weights, ratios of yield lateral strength to the seismic weight of building, building heights (H), periods of first mode considering cracked section stiffness (T), considered concrete strength about models.

Table 1. Range of some important properties of the building models.

Model ID	Analysis direction	Weight (kN)	Lateral strength ratio	H (m)	T (s)	Concrete strength (MPa)
4-75	X	6216.0	0.177	11.2	0.544	16
	Y		0.177		0.530	
4-98	X	6473.2	0.311	11.2	0.445	25
	Y		0.315		0.403	
7-75	X	18621.7	0.105	19.6	0.769	16
	Y		0.119		0.782	
7-98	X	20065.6	0.225	19.6	0.631	25
	Y		0.242		0.602	

Nonlinear time history analyses have been performed using SAP2000 that is a general-purpose structural analysis program (SAP2000, 2018). Three-dimensional model of each structure is created in SAP2000 to carry out nonlinear analysis. Beam and column elements were defined as nonlinear frame elements with lumped plasticity by defining plastic hinges at both ends of beams and columns. As shown in Figure 2, five points labeled A, B, C, D, and E define force-deformation behavior of a plastic hinge. Plastic hinge properties vary depending on type of element, material properties, longitudinal and transverse steel content, and axial load level on the element. Note that number of plastic hinges to be generated for each building is in the order of 800 and 1800 for the 4- and 7-story buildings, respectively. Plastic hinge length is assumed to be half of the section depth as recommended in 2007 Turkish Earthquake Code (TEC) (2007). Also, effective stiffness values are obtained per the code; 0.4EI for beams and values between 0.4 and 08EI depending on axial load level for columns.

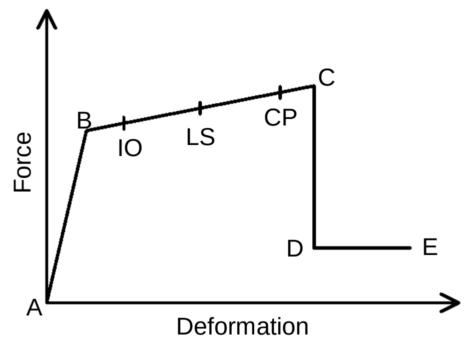


Figure 2. Force-deformation relation for a typical plastic hinge.

Newmark average acceleration method was used during nonlinear time history analyses as time integration approach for solution (Chopra, 1995; Tedesco et al., 1998). Rayleigh (mass and stiffness proportional) damping is considered. Mass and stiffness proportional coefficients are calculated for %5 damping.

3. Ground motion records

The ground motion records selected from destructive earthquakes in the past are used in nonlinear time history analysis. The selected sets provide an opportunity to examine reasons of existing building damages. USGS site classification based on the average shear wave velocity to a depth of 30 m (V_{s30}) is used for soil site classification of the selected records (USGS, 2016). V_{s30} for B soil class is assumed to be between 360 and 750 m/s. In the same way, V_{s30} for C soil class is weaker soil with the lower shear wave velocity is assumed to be between 180 and 360 m/s. The ground motion records are divided into two main groups in order to better understand the effect of seismic input characteristics on dynamic response of structures. The first set represents destructive earthquakes occurred in the past and recorded on soil type B and C. The records in second set content forward directivity effects that were used by past studies (Somerville, 1989, 1997, 2003; Bray and Rodriguez-Marek, 2004). It is well known that structural damages significantly increase by the presence of forward directivity effect (Inel et al., 2010). Table 2 lists major attributes of records considered in this study.

Table 2. Ground motions records selected from real earthquakes.

Sets	Record No	Earthquake	Date	Station	Component	PGA (g)	PGV (cm/s)	Vs30 (m/s)
SET 1 (Soil type B and C)	1	Chi-Chi	20.09.1999	TCU45	W	0.474	36.7	704.6
	2	Gazli	17.05.1976	Karakyr	0	0.608	65.4	659.6
	3	Kobe	16.01.1995	Nishi-Akashi	0	0.509	37.3	609
	4	Loma Pri.	18.10.1989	H.S. Pine	0	0.371	62.4	370.8
	5	Northridge	17.01.1994	Pacoima KC	360	0.433	51.5	508.1
	6	Northridge	17.01.1994	Sepulveda VA	360	0.939	76.6	380.1
	7	Imperial V.	15.10.1979	El C.Array #5	140	0.519	46.9	205.6
	8	Kocaeli	17.08.1999	Duzce	180	0.312	58.8	276
	9	Loma Pri.	18.10.1989	G.Array #3	90	0.367	44.7	349.9
	10	Northridge	17.01.1994	Canoga Park	196	0.42	60.8	267.5
	11	N. Palm Sp.	08.07.1986	N. Palm Sp.	210	0.594	73.3	345.4
	12	Whittier N.	01.10.1987	Santa Fe Spr.	48	0.426	38.1	308.6
SET	13	Cape Men.	25.04.1992	Petrolia	90	0.662	89.7	712.8

14	Duzce	12.11.1999	Bolu	90	0.822	62.1	326
15	Erzincan	13.03.1992	Erzincan	EW	0.496	64.3	274.5
16	Imperial V.	15.10.1979	Brawley Air	315	0.22	38.9	208.7
17	Kobe	16.01.1995	Takatori	90	0.616	120.7	256
18	Kocaeli	17.08.1999	Duzce	270	0.358	46.4	276
19	Kocaeli	17.08.1999	Gebze	0	0.244	50.3	792
20	Landers	28.06.1998	Lucerne	275	0.721	97.6	684.9
21	Loma Pri.	18.10.1989	Los Gatos Lex	90	0.508	72.79	1070
22	Morgan Hill	24.04.1984	C. Lake Dam	285	1.298	80.8	597.1
23	Northridge	17.01.1994	Newhall F.	360	0.59	97.2	269.1
24	Northridge	17.01.1994	Sylmar Ol	90	0.604	78.2	440.5

The average response spectrum of Set 1 and Set 2 ground motion records for 5% damping are plotted in Figure 3 as well as demand spectrum provided in 2007 Turkish Earthquake Code for design earthquake with 10% probability of exceedance in 50 years for a typical high seismicity region with soil class Z3. The code spectrum is provided to visualize the demand of selected records. No special effort has been given to fit the average of selected records to the code spectrum. Moreover, the current earthquake code (2018 Turkish Building Earthquake Code-TEC 2018) adopted the location based seismic demand. Since the response spectrum in TEC 2018 is created according to the soil class, seismic level and location of the building in the existing regulation, the seismic demands obtained from the records selected using this spectrum are only specific to the region, so generalization cannot be made.

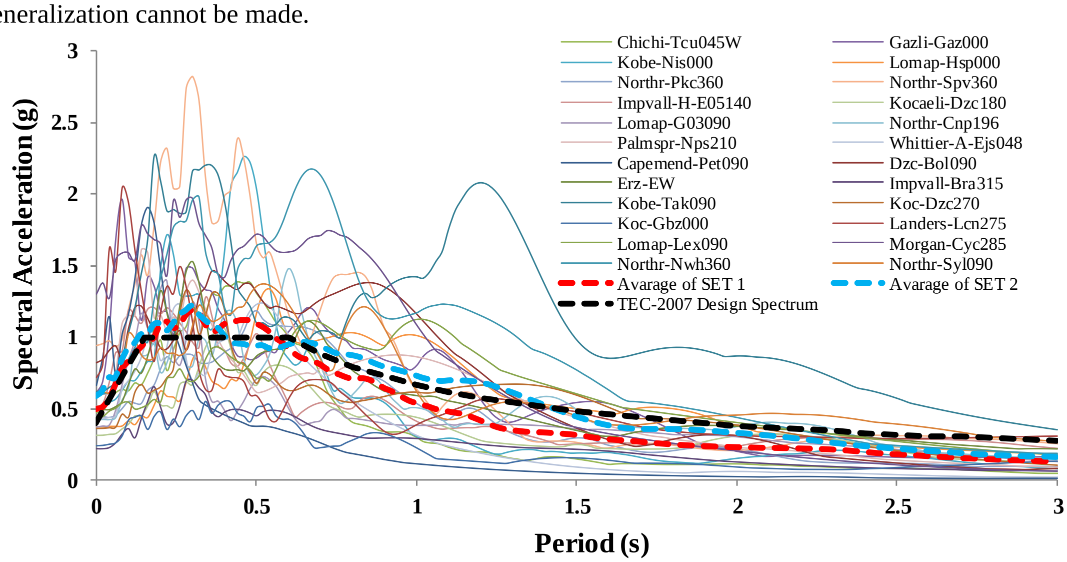


Figure 3. Average response spectrum of ground motion records for 5% damping.

4. Discussion of results

4.1. General

In the study, two different three-dimension RC building sets, consist of 4- and 7-story, were used to represent existing low and mid-rise residential buildings to carry out linear and nonlinear dynamic analysis in time domain under 24 different ground motion records.

The 4- and 7-story buildings designed according to pre-modern (TEC) (1975) and modern Turkish Earthquake Codes (TEC) (1998) were analyzed for X and Y directions separately. Maximum roof displacement demands are given in Table 3. In order to examine the difference between linear and nonlinear models clearly, the averages of demands obtained from X and Y directions considered in the table. Nonlinear models estimate excessively higher seismic demands for Set 2. Contrarily, the difference between Set 1 and Set 2 is not remarkable for linear models. While maximum roof displacement demands for nonlinear 4-story pre-modern code model are calculated 77.3 mm for Set 1 and 145.3 mm for Set 2 in average, it is calculated 96.2 mm and 88.4 mm for linear model respectively. Similarly, significant demand increases in Set-2 also observed in other nonlinear models while it is not apparent in linear models. The results clearly indicate that seismic effects that cause sudden demand increments like forward-directivity is more effective in nonlinear behavior. Linear models on the other hand are more sensitive to dynamic amplification and higher mode effects. Another important point is that the results are strongly dependent on characteristics of ground motion records by the nature of dynamic analysis (Demir et al., 2020; Demir et al., 2023). Thus, the difference between linear and nonlinear models tend to increase or decrease under different seismic inputs. In Figure 4, comparisons of roof displacement demand and velocity spectrum intensity (VSI) parameter of ground motion records are compared for linear and nonlinear analysis results. The VSI parameter is one of the most important ground motion parameters that show the intensity and damage potential of the earthquake (Massumi and Gholami, 2016; Kamal and Inel, 2021). While there is a high correlation between nonlinear analysis results and VSI parameter, it is seen that there is no such relationship for linear analysis. Therefore, it can be said that the linear analysis results do not have a significant correlation with the damage potential of ground motion records. To better observe the dynamic amplification effects, displacement demand ratios of linear and nonlinear analysis are compared with ratio of first mode period (T) to the predominant period of input motion (T_p) ratio are compared in Figure 5. As the predominant period and the structure period get closer, the dynamic amplification factor also increases. But the initial period differs with nonlinear behavior, so it is not possible to occur dynamic amplification for a fixed T/T_p region under destructive earthquakes. It is clear that, linear analysis method estimates unrealistically higher displacement demands in close T/T_p ratio range. The range in which the nonlinear analysis method predicts higher demand is scattered in a large band independent from the T/T_p ratio.

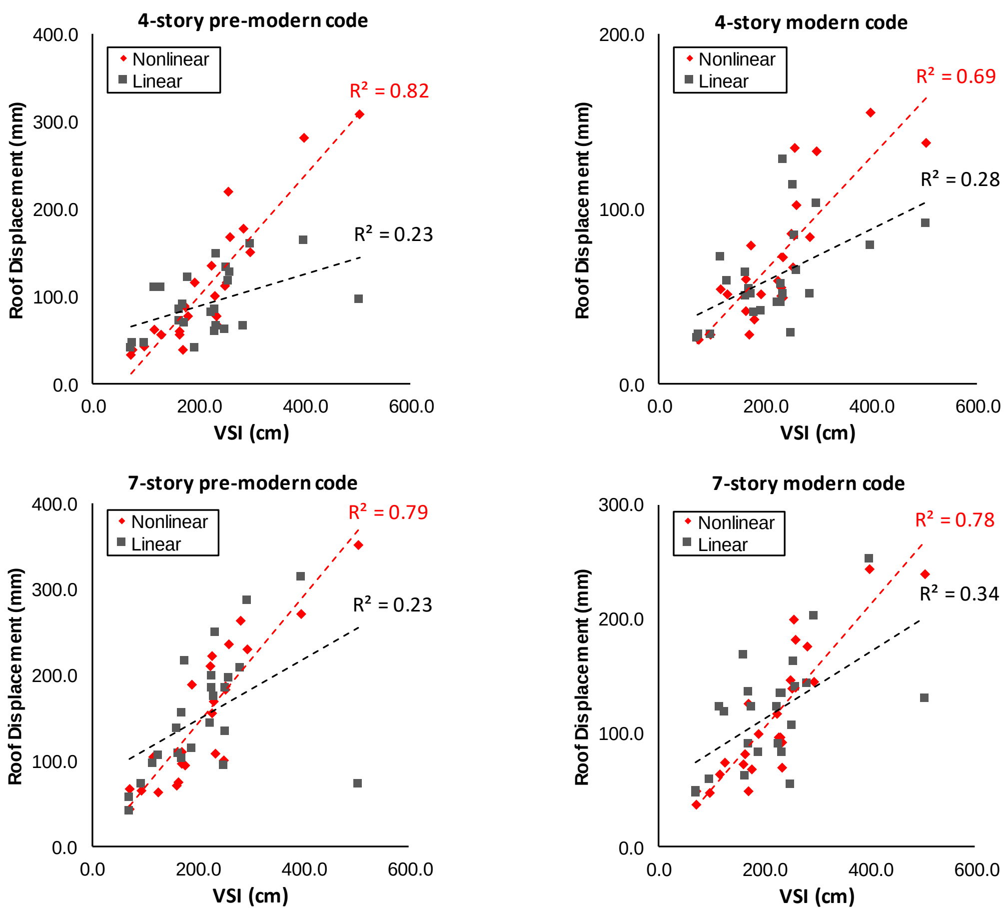


Figure 4. Comparisons of roof displacements and VSI for 4- and 7-story buildings.

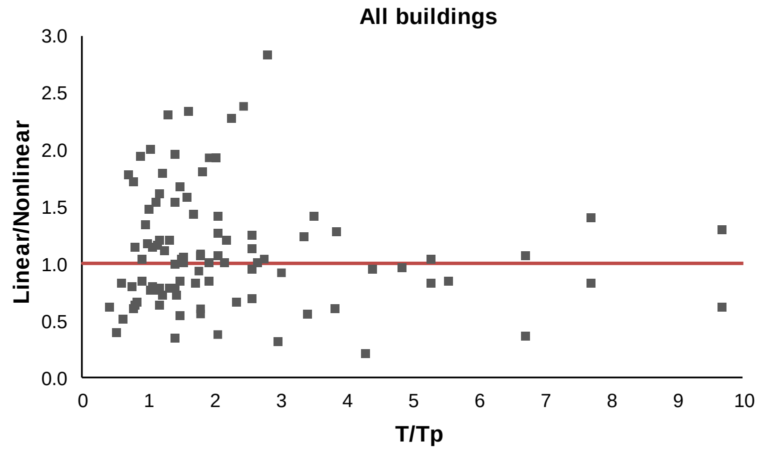


Figure 5. Relationship between T/Tp and displacement demand ratios of nonlinear and linear analysis.

Table 3. Roof displacement demands of the model buildings.

Sets	Record	Roof displacement (mm)							
		Nonlinear				Linear			
		4-Story		7-Story		4-Story		7-Story	
		Pre-mod-ern	Modern	Pre-modern	Modern	Pre-modern	Modern	Pre-modern	Modern
SET 1 (Soil type B and C)	Chichi-Tcu45W	61.7	54.7	104.6	62.3	109.7	73.1	96.2	122.0
	Gazli-Gaz000	80.2	55.0	155.2	95.6	85.0	56.8	199.6	133.6
	Kobe-Nis000	60.9	60.3	76.2	80.3	72.7	50.1	108.3	61.9
	Lomap-Hsp000	115.6	67.1	187.3	138.4	134.3	114.4	135.2	106.1
	Northr-Pkc360	89.4	79.7	97.9	124.7	70.8	51.7	102.7	88.8
	Northr-Spv360	112.6	86.4	100.3	144.8	62.6	28.9	94.8	54.3
	Impvall-E05140	77.3	37.1	95.8	67.8	121.2	41.0	216.8	121.6
	Kocaeli-Dzc180	56.7	41.9	71.6	71.8	86.4	63.8	137.4	166.9
	Lomap-G03090	38.5	28.2	110.6	47.6	91.2	54.1	155.8	134.5
	Northr-Cnp196	77.0	72.9	109.1	90.3	149.0	128.9	250.5	133.1
	Palmspr-Nps210	101.2	50.9	222.2	94.8	60.0	46.3	185.2	89.7
	Whittier-A-Ejs048	56.0	51.6	63.5	73.2	111.4	58.8	106.0	117.7
Set 1 Average		77.3	57.2	116.2	91.0	96.2	64.0	149.0	110.8
SET2 (Forward directivity)	Capamend-Pet090	32.8	26.0	44.7	37.1	40.4	26.0	42.6	47.2
	Dzc-Bol090	220.4	135.5	183.8	197.9	118.4	85.6	185.0	162.2
	Erz-Ew	136.2	59.2	211.3	115.8	81.8	46.2	143.7	122.2
	Impvall-Bra315	43.5	28.5	65.4	46.2	46.6	28.1	73.5	58.4
	Kobe-Tak090	308.5	138.3	353.0	237.6	96.6	91.5	73.5	129.8
	Koc-Dzc270	67.4	49.7	170.6	68.8	67.1	51.0	175.0	82.7
	Koc-Gbz000	39.4	25.1	68.5	47.9	46.9	28.5	57.1	48.2
	Landers-Lcn275	116.3	51.0	189.2	98.7	41.2	42.1	114.3	81.7

Lomap-Lex090	178.0	84.3	264.1	174.9	67.0	51.6	209.4	142.7
Morgan-Cyc285	150.7	133.6	230.9	143.8	160.6	103.7	288.6	201.9
Northr-Nwh360	281.5	155.6	272.6	243.2	165.2	79.2	314.3	251.6
Northr-Syl090	169.1	102.8	236.1	180.3	128.6	64.7	197.0	140.2
Set 2 Average	145.3	82.5	190.9	132.7	88.4	58.2	156.2	122.4
Average of Set 1 and Set 2	111.3	69.8	153.5	111.8	92.3	61.1	152.6	116.6

The roof drift ratio averages of Set 1 and Set 2 are compared in Figure 6. Although the difference between Set 1 and Set 2 is negligible for linear models, it is significant for nonlinear models. The highest roof drift ratios are calculated for nonlinear models under Set 2 as expected. Considering that nonlinear time history analysis is the most realistic method for seismic demand predictions, linear models overestimate seismic demands for Set 1 while their underestimated demands are obvious for Set 2. Another important observation is apparent difference between linear and nonlinear models for the pre-modern code buildings. Moreover, the pre-modern code building demands are higher than the modern-code building demands due to lower stiffness and strength capacity of column and beam members. Figure 6 also illustrates that linear model demands are very close while there are significant differences among displacement demands of nonlinear models for Set 1 and Set 2 records. The displacement demand of Set 2 is 88% higher than that of Set 1 for the 4-story pre-modern code buildings while this difference is 64% for the 7-story pre-modern code buildings. The displacement demand of Set 2 is about 45% higher than that of Set 1 for both 4- and 7-story modern code buildings.

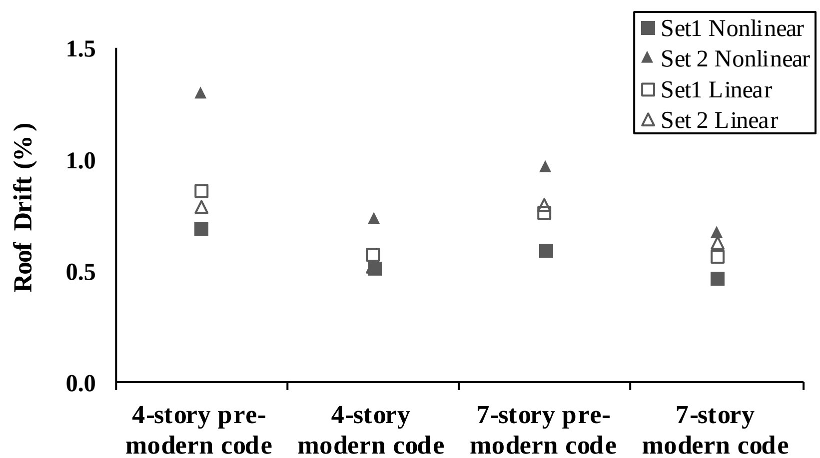
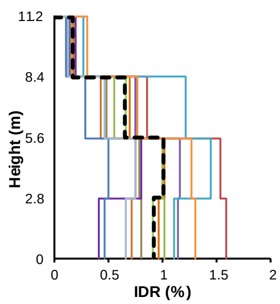


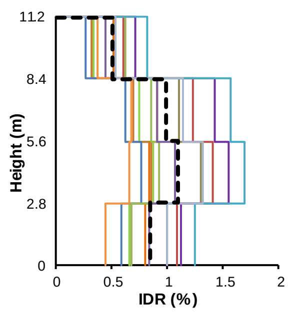
Figure 6. Comparisons of roof drift demands of 4- and 7-story buildings.

4.2. Comparison of interstory drift ratios

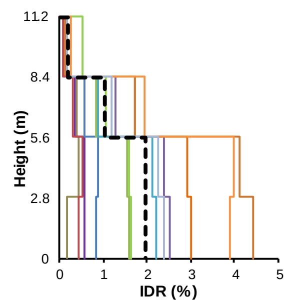
Dynamic behavior of structures under seismic loads is a complex problem. It can be directly influenced by characteristics of input motion as well as the structural parameters. Demand distribution might be differing from each other for different stories and structural members even for under same roof displacement value for different ground motion records. Therefore, assessment of maximum demands can remain insufficient for understanding of structural behavior. Interstory drift ratio (IDR), is a useful indicator of distribution of seismic demands and damage mechanism like peak story drift ratio (PSDR) (Gallegos et al., 2023) . Maximum IDR values were compared under each ground motion record in order to understand characteristics of linear and nonlinear analysis methods. Figures 7 and 8 illustrate the maximum interstory drift ratios calculated for Set 1 and Set 2 ground motion records. The average interstory drift ratio values are plotted in Figure 9 for linear and nonlinear methods. It is obvious that the interstory drift ratios vary in a wide range under different records for both methods. The differences between linear and nonlinear models arise when the distribution of IDR values is examined. Unlike the linear assumption, the maximum IDR values accumulate at the first stories with nonlinear modelling because of plastic deformations. Linear models are not influenced by forward directivity effects hence seismic demands are not concentrated in a specific story. Analysis results indicate that; linear models are more sensitive to higher mode effects. The maximum IDR and roof drift ratios also have better correlation with nonlinear modelling (Figure 10). The figure clearly indicates the difference on distribution of seismic demands for linear and nonlinear modelling. While maximum IDR values are predominant on maximum displacement demands for nonlinear behavior, the correlation decreases for linear models.



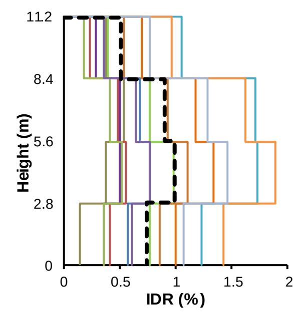
4-story pre-modern code Nonlinear Set 1



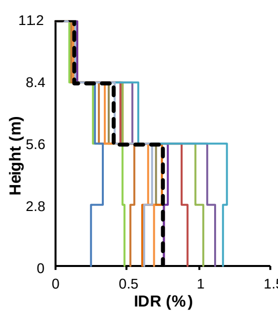
4-story pre-modern code Linear Set 1



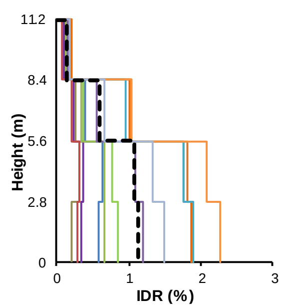
4-story pre-modern code Nonlinear Set 2



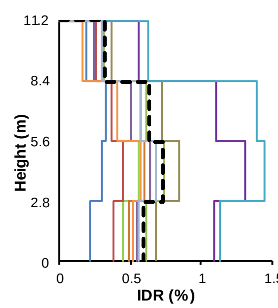
4-story pre-modern code Linear Set 2



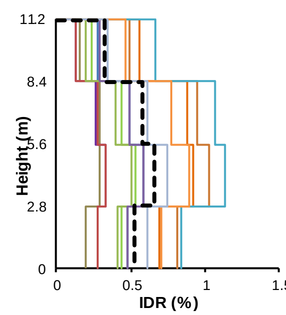
4-story modern code Nonlinear Set 1



4-story modern code Linear Set 1



4-story modern code Nonlinear Set 2



4-story modern code Linear Set 2

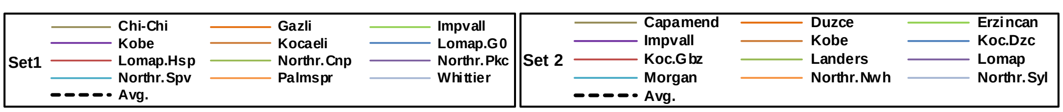


Figure 7. The interstory drift ratios along the building height for 4 buildings models.

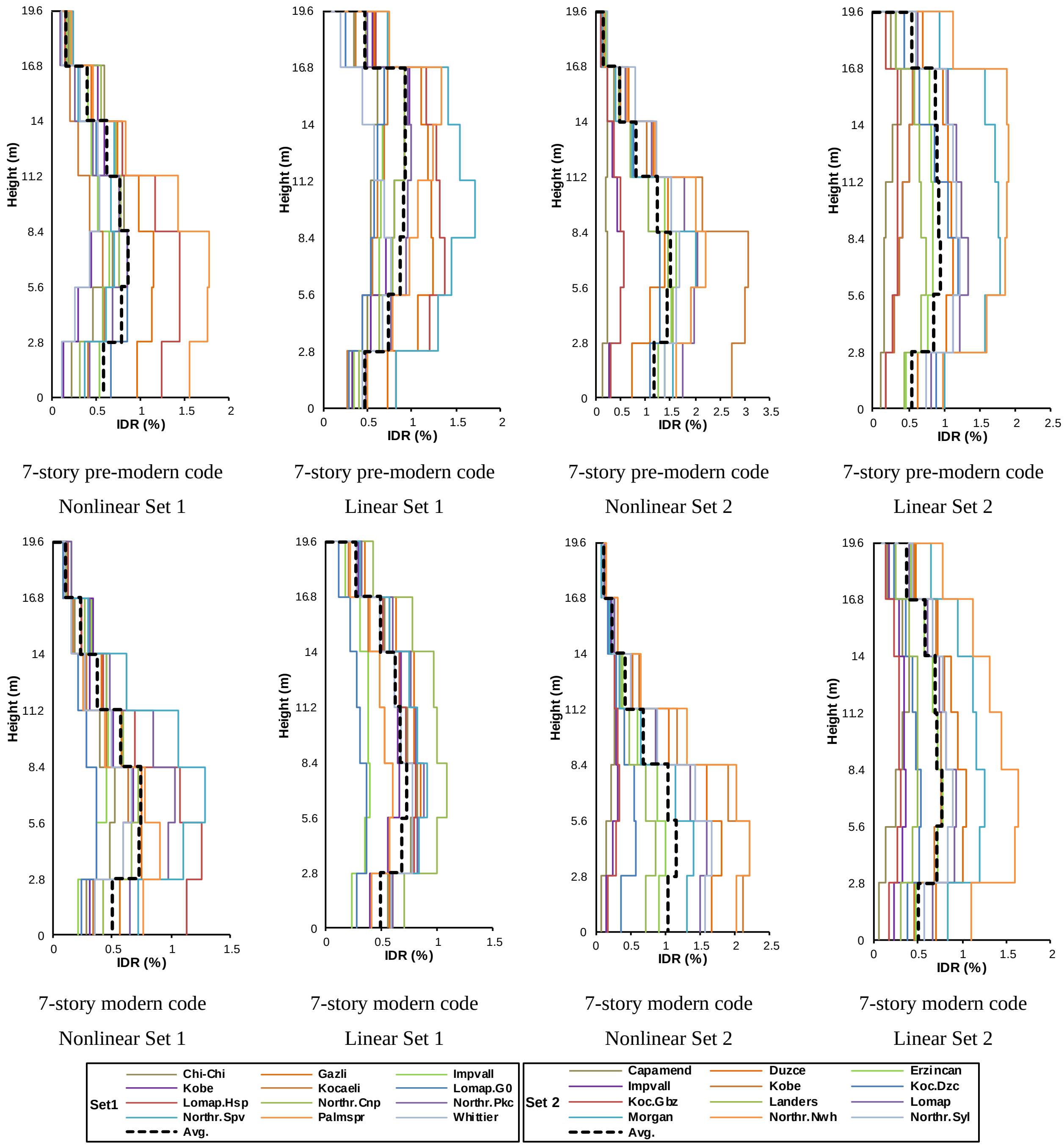


Figure 8. The interstory drift ratios along the building height for 7 buildings models.

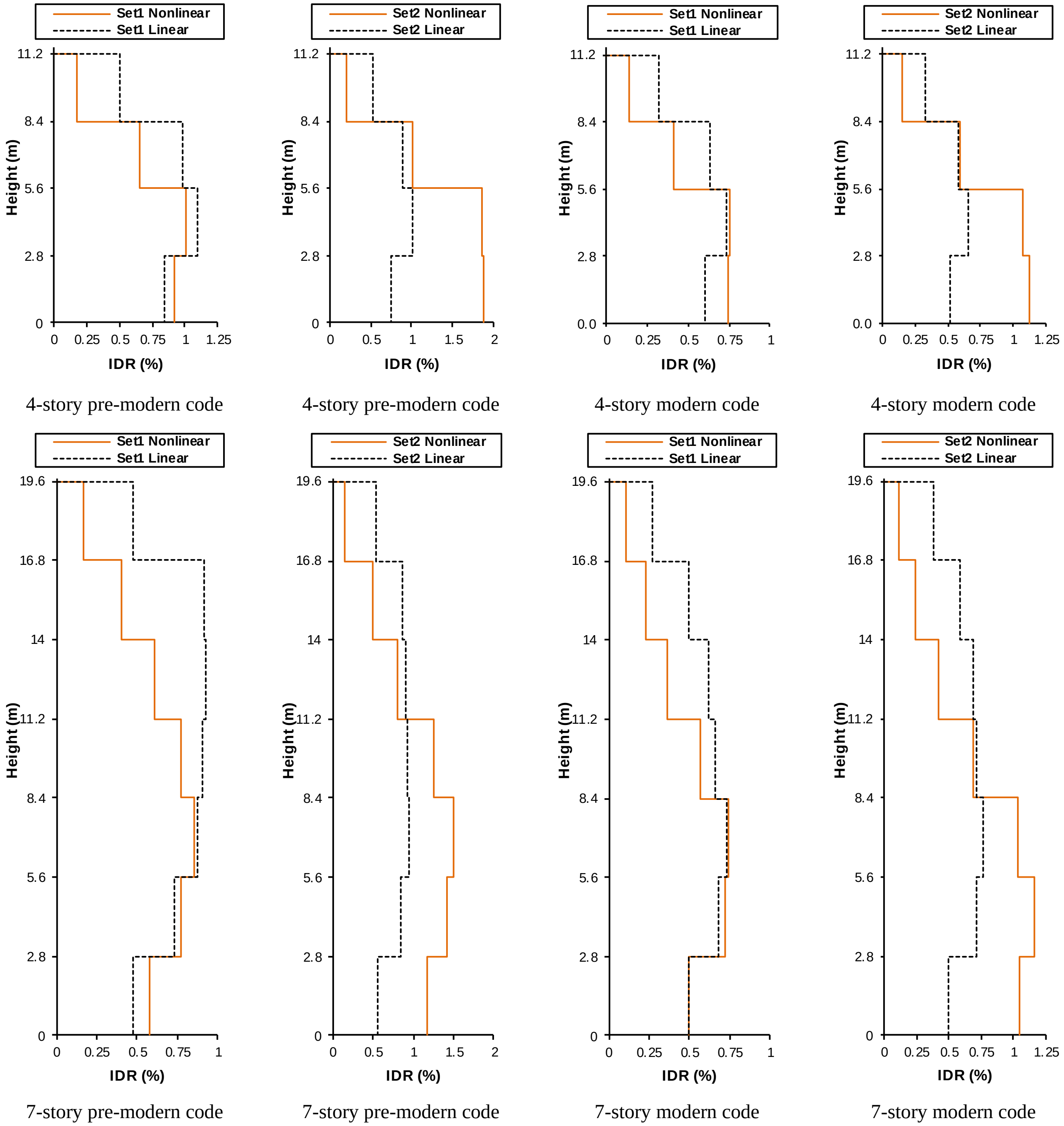


Figure 9. The comparison of the interstory drift ratios of linear and nonlinear time history analyses for the Set 1 and Set 2 ground motions.

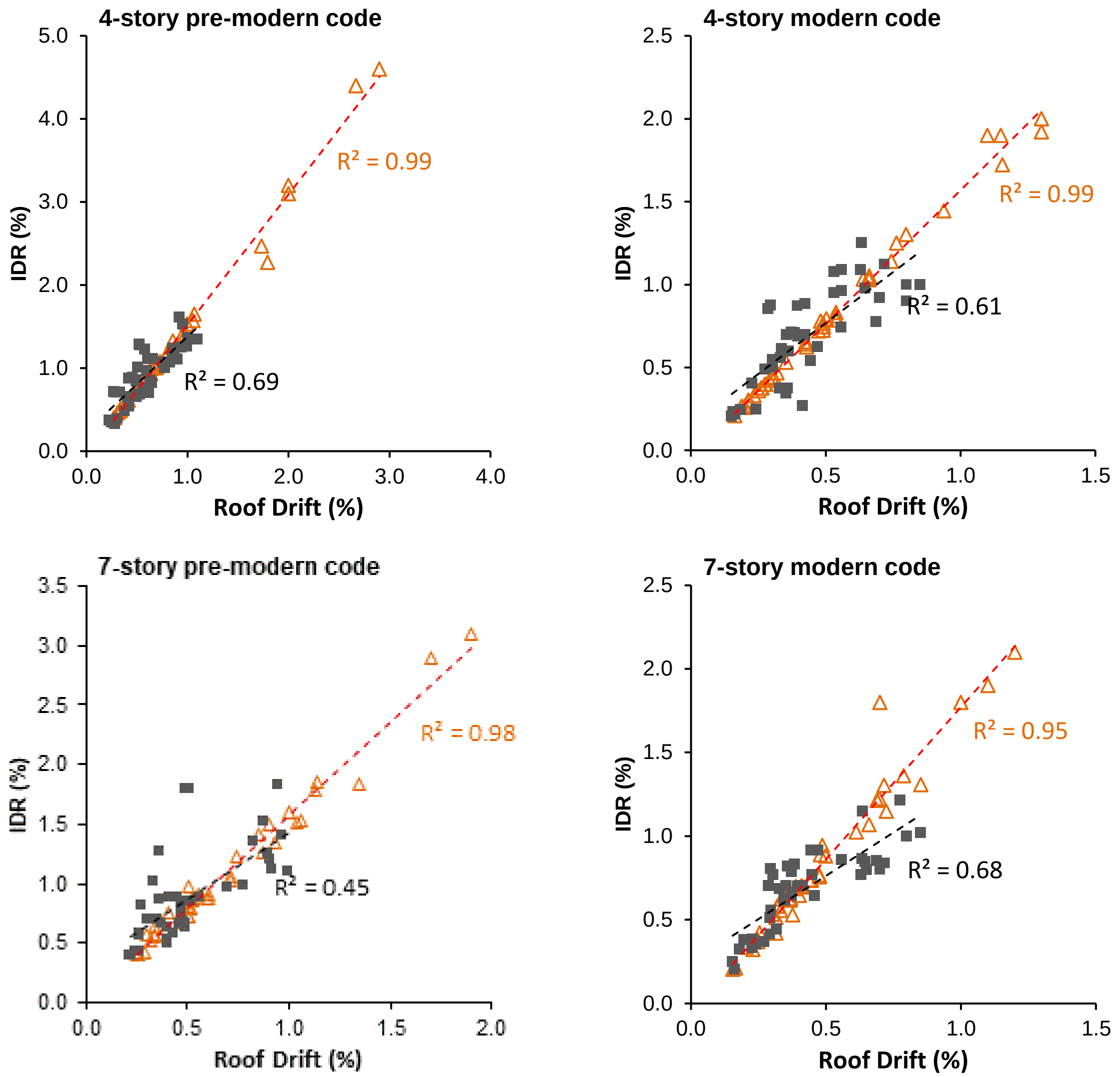


Figure 10. Comparisons of roof drift demand and IDR.

4.3. Comparison of normalized displacement profiles

In this section, the normalized displacement profiles calculated by dividing by the maximum roof displacement value are compared with the dominant mode shape. Figure 11 and Figure 12 show the average normalized displacement profiles and mode shape calculated for each model and acceleration record set.

When the results are examined, the distribution of displacements to the stories is largely consistent with the mode shape when linear models are used for both Set 1 and Set 2 records. For nonlinear analysis results, the normalized displacement profiles are separated from mode shape for all models. Therefore, while using mode shapes as a static pushover pattern is consistent within the linear modeling assumption, it does not seem to be sufficient for reflecting nonlinear behavior.

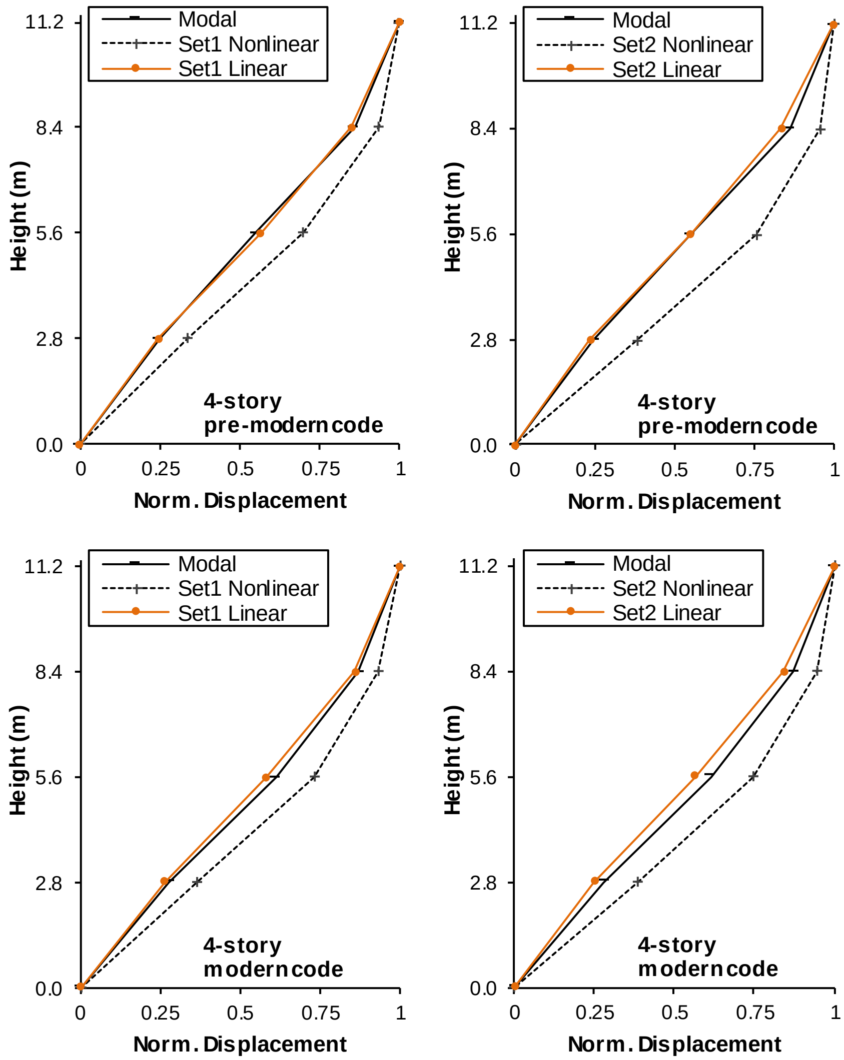


Figure 11. Normalized displacement profile of 4-story models.

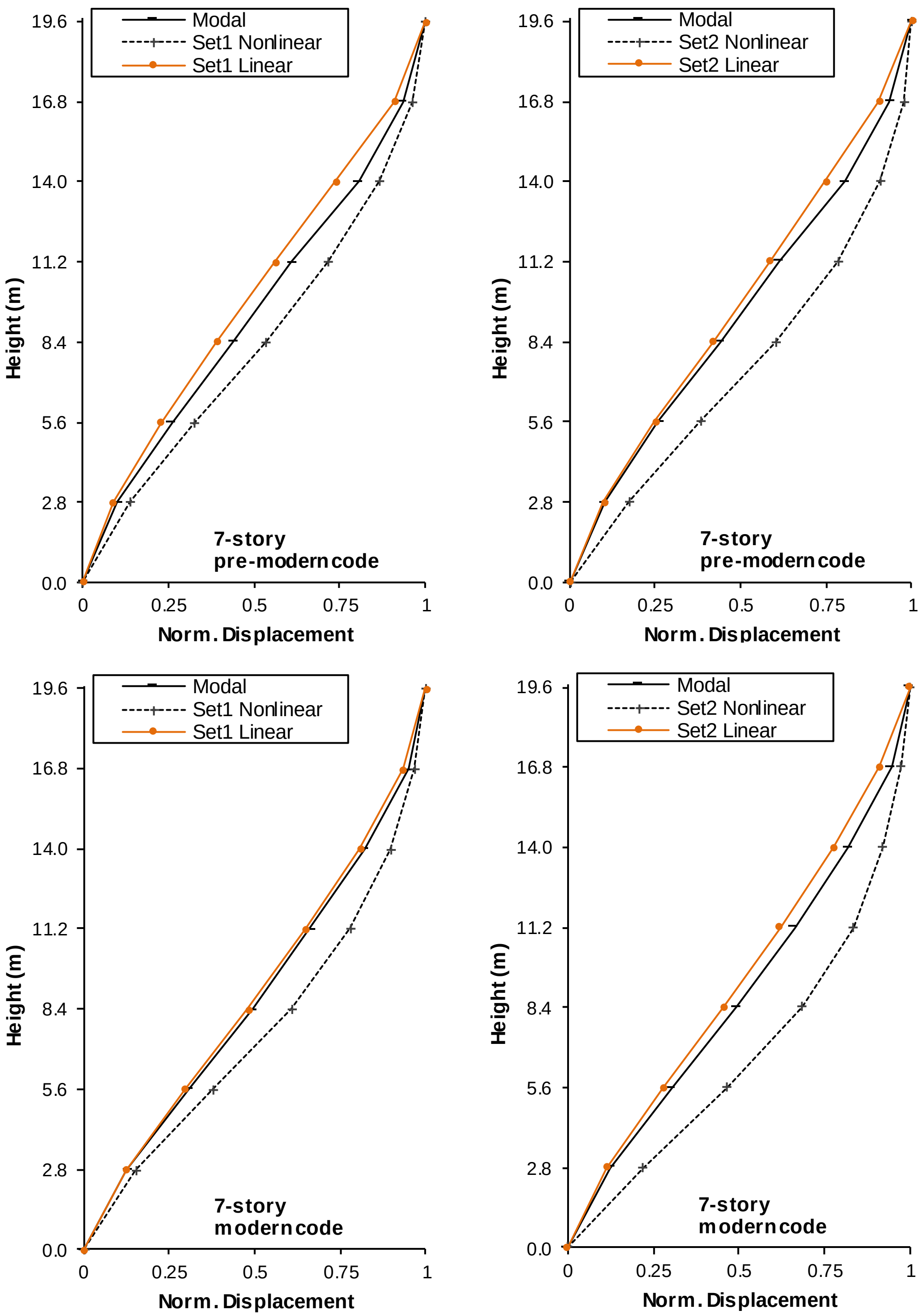


Figure 12. Normalized displacement profile of 7-story models.

5. Summary and conclusions

This study aims to compare linear and nonlinear modelling assumptions to applicability limits on time-history analysis and behavioral differences in dynamic response characteristics for existing mid-rise buildings. The ground motion records used in dynamic analyses are defined in two groups. First set consists of twelve different destructive ground motion records taken from soil type B and C whereas the second set contains forward-directivity effects.

The important findings of this study are summarized as follows:

- The correlation between the roof displacement demands with the linear analysis method and the velocity spectrum intensity parameter of ground motion records was found to be low. In contrast, the correlations calculated for the nonlinear analysis methods were significantly higher. This shows that the nonlinear analysis method better reflects the damage potential of the ground motions.
- Independently from the intensity of ground motion record, the maximum displacement values calculated for the linear analysis method increase as the period of the structure and the predominant period of ground motion record get closer. As the T/T_p ratio is away from each other, the displacement demands for the linear method decrease. However, the nonlinear method is not affected by the T/T_p ratio. This shows that linear analysis methods are significantly affected by dynamic amplification.
- For Set 1, which consists of low-intensity ground motion records, the linear method is generally successful in estimating maximum IDR values. However, the pattern of IDR between stories differs from the nonlinear method. IDR values are significantly higher in the upper stories due to higher mode effects compared to the nonlinear method.
- The differences between the two methods are more obvious for Set 2 records, which consists of intense ground motion records. In the nonlinear method, maximum IDR values are concentrated in the first and second stories and are much higher compared to the linear method.
- In the linear method, since the dynamic properties of the structure are constant and yielding does not occur in the structural members, the formations such as the story mechanism cannot be reflected in the linear method. This causes the differences between the two methods to increase when seismic demands are concentrated on a certain story.
- Therefore, while a very high correlation was calculated between the maximum displacement demands and maximum IDR values for the nonlinear method, it was found to be much lower in the linear method.
- For linear analysis results, the average normalized displacement profiles are largely similar to the mode shape. Nonlinear model patterns, on the other hand, diverge from the mode shape. Therefore, it is evaluated that using the mode shape as a static pushover pattern is insufficient to reflect the nonlinear behavior.
- As a result, it has been concluded that linear modelling is inadequate in reflecting nonlinear behavior when used with dynamic analysis methods. Linear analysis results mostly show an increase or decrease depending on dynamic amplification effects. The effects of ground motion intensity and damage mechanism cannot be observed in linear analysis method. Although the differences between the methods decrease when low-intensity ground motions are used, unrealistic demand values can be calculated as the T/T_p ratio approaches. For all these reasons, it is recommended not to prefer linear modeling approach when using dynamic analysis methods.

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