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Assessment of Nonlinear Dynamic Analysis Method for Irregular Steel Moment Frames in Nine-Story Structures

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Abstract: *Deficiencies in linear static methods and nonlinear software development in the last decade on the one hand, and the rising issue of performance-based engineering (design of buildings based on different performance levels needed against different levels of earthquake intensity) in recent years, has resulted in many efforts in the design and evaluation of buildings based on displacement (deformation) and the direct use of nonlinear analysis to more precisely appraise structures against different levels of earthquakes. The objective of this study was to determine the correlation between MPA results and nonlinear dynamic analysis, taking into account their comparative comparison with US FEMA regulations, and to explore the similarities and differences between each of them. In this research, the Conditional Mean Spectrum was used to evaluate seismic parameters. The response spectrum and design spectrum are the basis of all earthquake load modeling in earthquake engineering. What spectrum to use for this is one of the most critical issues in earthquake engineering. Studies in recent years have revealed that the Conditional Mean Spectrum can be a more suitable target spectrum for earthquake selection. This spectrum gives the average value of the response spectrum at all periods, provided that a particular spectral acceleration happens at the desired period. The results of time history analysis in the form of intermediate displacement and drift diagrams for structures showed that in all cases, the displacements created in the structures are different from the conditional and standard scale method.*

Keywords: *Time history analysis, Equivalent nonlinear static analysis, Irregular steel moment frame, pushover analysis, Seismic modeling, Conditional Mean Spectrum*

INTRODUCTION

Buildings are designed and built for various ideas. To this end, each structure must preserve its stability under the impacts of incoming loads and all factors influencing it, including earthquakes, and be protected from rupture with an acceptable safety margin. The goal of seismic analysis of constructions is to determine the behavior of structures under seismic load. The earthquake response spectrum is one of the most extensively used seismic load specifications.

In modern years, many methods have been proposed to give seismic acceleration spectra. Among these methods, the concept of the "Conditional Mean Spectrum" can be mentioned. Provided that a specific spectral acceleration occurs at the desired periodicity, this spectrum gives the average value of the response spectrum at all cycles. Earthquake spectra in other methods did not depend on the structure being analyzed. However, in this method, the obtained spectrum has a strong relationship with the dynamic characteristics of the analyzed structure (Kashkooli and Banan, 2013).
According to the Seismic Improvement Instructions of Existing Buildings (2006) in Nonlinear Static Analysis, The lateral load caused by the earthquake is applied to the structure statically and gradually increasingly. To the extent that the displacement at a specific point (control point) under the impact of a lateral load reaches a specific value (the target displacement) or the structure collapses. It can be stated that the total capacity of construction depends on the resistance (force capacity) and the spatial displacement capacity of each of its parts. It is required to use nonlinear analysis such as nonlinear dynamic analysis or nonlinear static analysis, or pushover analysis to determine the capacity of the structure beyond the elastic limit. The application of these nonlinear analysis methods presents valuable information for many structural response characteristics (Modab, 2012).
A Newer method of nonlinear static analysis called Modal Pushover Analysis (MPA) has been proposed by Chopra and Goel. This method is based on the assumption that the response of the structure is controlled by a mode the shape of which remains the same over time. In more detail, the functional levels of the frames are obtained based on the preceding directions with the help of Nonlinear static pushover analysis. Then, for economic estimation, the seismic parameters of the frames, such as displacement to the extent of collapsing, the relative displacement of the floors, strength index, ductility, and final weight and volume are obtained. Furthermore, the regulation criteria, such as the expected ratios of frame parts, lateral force distribution at height, strength reduction coefficient, earthquake coefficient, behavior coefficient, and the regulation lateral force and base shear, are compared with each other (Tarta and Pintea, 2012).
It is supposed that when the design of a structure follows the rules of the earthquake regulations, the danger of rupture of the structure eliminates. This mistake arises from people's trust in formal regulations, which are the only common ground for designing and implementing conventional buildings. Whereas the fact is that the impact of an earthquake on a structure and the response of the structure to it, is yet to be well learned. The information that has been gathered until now in this respect is trivial compared to the unknowns of the matter. Hence, from this insufficient information, the regulations pick and suggest only the parts on which there is more unison - not that they have been finalized (Govind et al., 2014).
The design viewpoint in several existing seismic design regulations, such as Iranian Regulation 2800, is based on one-level seismic design. The idea of the design in these regulations is to have the structures continue at a performance level called life safety against earthquakes with a 10% chance of happening in 50 years by providing some design rules and regulations. Obtaining a functional purpose in these regulations is done by doing linear elastic analyzes and employing indirect methods, such as design based on strength. Certainly, these methods do not have high precision for the application of inappropriate tools and too much approximation in the seismic design process, and there is no certainty of the optimal performance of the building or the optimal design (Arvindreddy and Fernandes, 2015).
The existence of high economic losses in the earthquakes of the last two decades designates the need for a more precise design method than the one-level method in conventional building regulations. Loss from earthquakes in the late twentieth century was much higher than anticipated, even where seismic regulations govern buildings, such as the Loma Prieta, Northridge, and Kobe earthquakes.

This demonstrated the invalidity of the rules of the current regulations. In opposition, the philosophy of seismic design based on the performance level, by arranging performance ends for the structure, enables the designer to adjust and design the building to control the amount of damage and keep service at different levels of risk (Himaja et al., 2015).
The vast majority of seismic regulations around the world have introduced earthquakes with a response spectrum equal to or higher than a specific target spectrum for structural analysis. According to studies in this domain, the uniform hazard spectrum (introduced in most regulations as the target spectrum) is not suitable for performance-based design. Because this spectrum reasonably assumes that the spectrum of a particular earthquake has very high spectral values at all periods. In performance-based design, an earthquake is preferred that has the target spectral acceleration only in the desired period. Assuming that probabilistic seismic hazard analysis is performed in only one period, by having spectral acceleration in a particular period, spectral accelerations in other periods can be obtained by having information about magnitude and distance, which is called the Conditional Mean Spectrum. This spectrum gives the average value of the response spectrum in all periods, provided that a certain spectral acceleration occurs in the desired period (Abou-Elfath et al., 2017).
Three different methods are presented to calculate the conditional mean spectrum, and lastly, the results of the examination of the use of these three spectra to the structure are compared.

a. Approximate conditional mean spectrum method (rational tree weight assignment)
Mean conditional values are achieved using each independent seismic relationship but using the results of the overall seismic hazard deaggregation. Then, by assigning a weight (PK) to each seismic relation, the value of the combined conditional mean spectrum is obtained from the k seismic relations.

B. Approximate conditional mean spectrum method (risk deaggregation weight allocation)
The calculation of the mean conditional values is done using the results of seismic hazard deaggregation exclusive to the same seismic relationship. The value of the compound conditional mean spectrum is then determined by assigning weights (PK) to each earthquake relation.

C. Accurate conditional mean spectrum method
The conditional mean value is determined using every possible magnitude and distance (Mj and Rj) and the seismic relationship *k*. These conditional mean values are mixed after assigning weights (Pj, k). This method is recognized as the most accurate method for estimating the conditional mean spectrum (Shahri et al., 2011).
A comparison of the results obtained from the three types of spectra mentioned for different sites shows that the accuracy of the approximate method responses declines for constructs with one source, several sources with one type of mechanism, and several sources with different mechanisms, sequentially. Moreover, the standard deviation changes for calculating the conditional mean spectrum are more sensitive to the type of chosen method (Nourizadeh et al., 2013).
Nabiollah Ali Rahimi Kashkoli and Mohammad Reza Banan in (2012) studied the effect of frame irregularities on the precision of nonlinear static seismic analysis. This study examines the effect of frame break irregularity at height on MPA accuracy for predicting displacement target, displacement description, and base shear.
In this research, 21 irregular designs were considered for five stories of steel moment frames. Each irregular frame is designed for low and high values of the response coefficient R. The results of nonlinear static analysis are compared with nonlinear dynamic analysis and the modified FEMA440 coefficient method is considered. According to FEMA, MPA estimation results have a good

correlation between displacement and drift results for all models under all earthquakes. Govind M, Kiran Shetty, and Anil K Hegde, in 2014, report on nonlinear static pushover analysis, an irregular spatial frame structure with and without a T-shaped column: This analysis is an essential tool for evaluating the seismic performance of new and existing buildings. Pushover analysis is expected to give sufficient information on the seismic demand applied by ground motion design on the structural system and its components. The recent emergence of structural design is for a specific level of earthquake performance, like fast post-earthquake capture - which is called earthquake engineering-based performance. The results are in instructions such as ATC-40 and FEMA-336 and standards such as ASCE-41. Among the different types of analysis, pushover analysis is notable for its optimum accuracy, efficiency, and ease of use. In this study, the RC building (H-shaped column design with and without T-shaped) in seismic zone III ' ETABS software has been used.

N. JAYARAMAPPA, Ashwini. L.K, and G.V. Sai Himaja mention in 2015 the study of nonlinear analysis of frame deposition for irregular buildings that structural system evaluation can resort to nonlinear static analysis. This includes determining power demand and structural deformation and comparing capacities at desired performance levels. The goal of this study is to assess and compare the response of 30 reinforced concrete buildings with and without different filling materials using the nonlinear static method by describing the acceptance criteria. This method is described by FEMA as a 4- and 10-story system frame with and without vertical irregularities in both IS in terms of performance based on the seismic design method. Also, the RCC building frame is done by the conventional design method. Nonlinear static analysis (pushover analysis) is used to obtain the inelastic deformation capability of the frame. It was found that the irregular effect of cement on reducing metabolism in the deformation or displacement of this type of building is greater than others.

Based on what mentioned this research, the seismic evaluation of domestic regulations and their comparative comparison with US FEMA regulations and the similarities and differences and strengths and drawbacks of each was addressed using the conditional mean spectrum. In fact, this study examines the irregularity effect of steel moment frame on height with nonlinear static analysis. Nonlinear dynamic analysis and nonlinear static analysis were also performed for each frame.

Materials and Methods

Structural models

The design of the frames is performed using Sap2000 software.

This software, one of the most powerful ones in developing analysis and design, other than using conventional finite element methods to analyze structures, has several design processors; Including a steel frame design processor (Table 1).

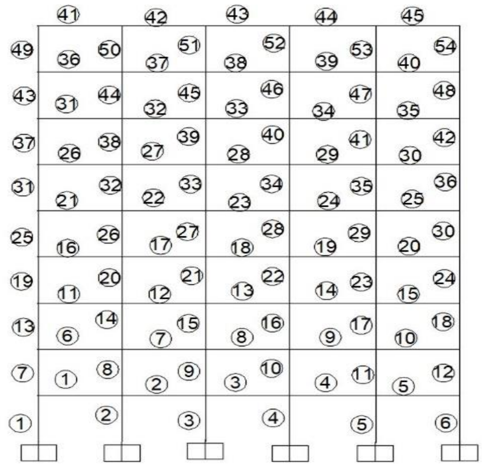
Table 1: Introduction of models

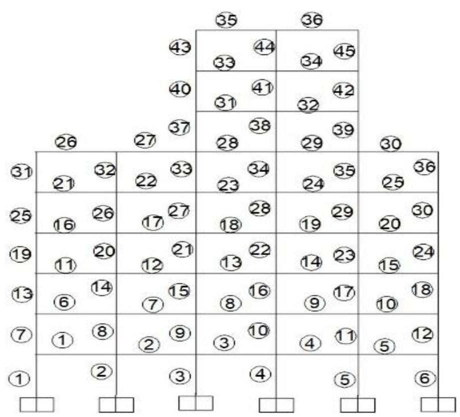
Earthquake coefficient	Live load	Dead load	Model name		
0.05	1.8 t/m	3 t/m	Regular 9-story	9-r	9-story
			The first model: irregular 9-story	9-1 I r	
			The second model: irregular 9-story	9-2 i-r	
			The third model: irregular 9-story	9-3 I r	

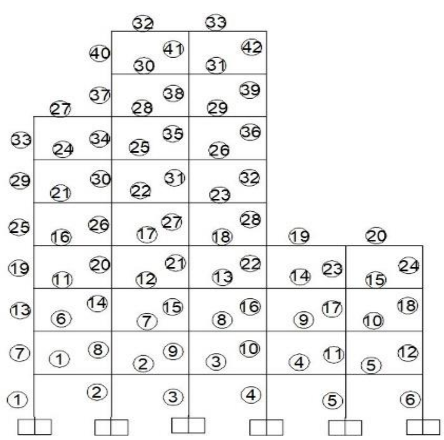
Combinations of dead loads (DL), live loads (LL), and earthquake loads (EL) based on which structural members and joints are designed or controlled according to models 2800 are:

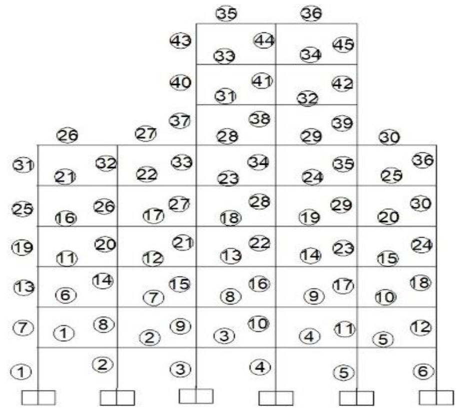
COMB1: DL + LL

COMB2: DL + LL + EL
COMB3: DL + LL ± EL
COMB4: DL + EL
COMB5: DL ± EL


a: 9-r


b: 9-1 ir


c: 9-2 ir



d: 9-3 ir

Figure 1: Figures of the models

Table 2: Specifications of structural sections

Beam and column design sections for 9-r model

Column number	Section	Column number	Section	Column number	Column number
1	w21x44	9	w21x57	17	w24x55
2	w24x62	10	w21x57	18	w21x44
3	w24x62	11	w21x57	19	w21x44
4	w24x62	12	w21x44	20	w21x50
5	w24x62	13	w21x44	21	w21x50
6	w21x44	14	w24x55	22	w21x50
7	w21x44	15	w24x55	23	w21x50
8	w21x57	16	w24x55	24 to 54	w21x44

Beam number	Section
1 to 45	W14x34

Beam and column design sections for 9-1 i r model

Column number	Section	Column number	Section	Column number	Column number
1	w21x44	9	w21x57	17	w24x55
2	w24x62	10	w21x57	18	w21x44
3	w24x62	11	w21x57	19	w21x44
4	w24x62	12	w21x44	20	w21x50
5	w24x62	13	w21x44	21	w21x50
6	w21x44	14	w24x55	22	w21x50
7	w21x44	15	w24x55	23	w21x50
8	w21x57	16	w24x55	24 to 42	w21x44

Beam number	Section

1 to 31	W14x34

Beam and column design sections for 9-2 i r model

Column number	Section	Column number	Section	Column number	Column number
1	w21x44	9	w21x57	17	w24x55
2	w24x62	10	w21x57	18	w21x44
3	w24x62	11	w21x57	19	w21x44
4	w24x62	12	w21x44	20	w21x50
5	w24x62	13	w21x44	21	w21x50
6	w21x44	14	w24x55	22	w21x50
7	w21x44	15	w24x55	23	w21x50
8	w21x57	16	w24x55	24 to 42	w21x44

Beam number	Section
1 to 33	W14x34

Beam and column design sections for 9-3 i r model

Column number	Section	Column number	Section	Column number	Column number
1	w21x44	9	w21x57	17	w24x55
2	w24x62	10	w21x57	18	w21x44
3	w24x62	11	w21x57	19	w21x44
4	w24x62	12	w21x44	20	w21x50
5	w24x62	13	w21x44	21	w21x50
6	w21x44	14	w24x55	22	w21x50
7	w21x44	15	w24x55	23	w21x50
8	w21x57	16	w24x55	24 to 42	w21x44

Beam number	Section
1 to 36	W14x34

Pushover analysis execution

Although the nonlinear dynamic analysis method is a thorough method for analyzing buildings and gives more accurate answers than other existing methods, it is approximately complex and hard. Consequently, the pushover nonlinear static analysis method is adopted. It is required to analyze the nonlinear time history with reliable earthquake records (meaning different seismic properties including amplitude, frequency content, duration, etc.) to predict the performance of the construction under earthquake forces. In most cases, this analysis is intricate, time-consuming, and ineffective. To prevail these limitations, it is required to provide an analysis method that is comparatively simple but indicates the main characteristics of earthquakes and buildings. This method should also consider the change in forces and the distribution of deformations emerging from nonlinear behaviors. Pushover analysis is one of the approaches that can help to reach this goal.

This analysis is a simplified method for assessing the performance of a structure through an earthquake. In this method, the amount of lateral loading of the building according to a planned pattern continues steadily until a target displacement is reached. In this situation, the forces of the members and the deformations are computed. These evaluations are used to control the safety of the system.

Issues concerning the spectrum used

In this study, time history analysis is performed based on the standard spectrum and the conditional mean spectrum being examined. This section gives the figure of the spectra and how to achieve the scale coefficient of the spectra and their values.

The figure of the spectra used

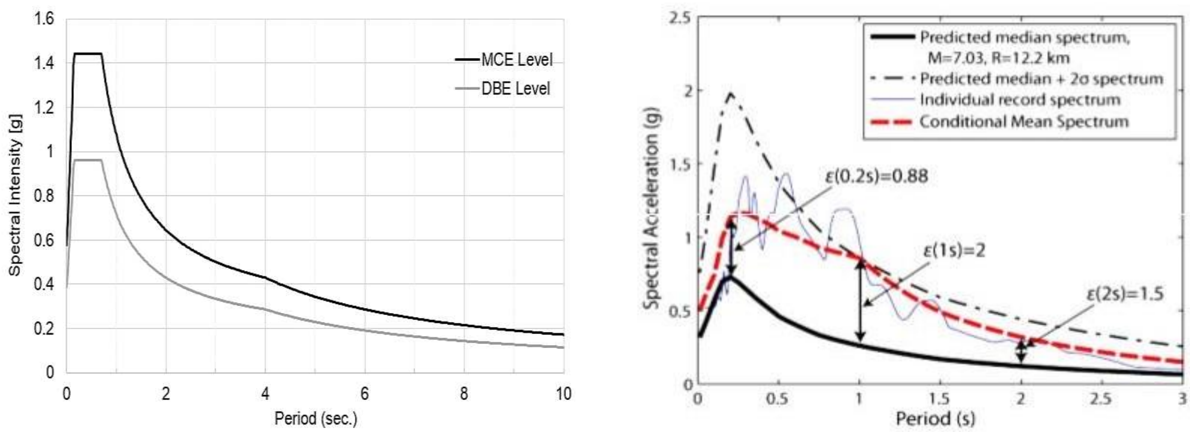


Figure 2: A: Standard design spectrum diagram - [Regulation 2800], B: Conditional average spectrum diagram – [3]

Scale method and scale coefficient

To reach the scale coefficient used in the analysis, considering the height of 3 meters for the 9-story and 15-story models, the value of T is determined using the following formula:

$$T = 0.08\, H^{0.75} \tag{1}$$

Considering soil type II, which is a very high seismic risk area for Tehran, according to the spectra used in Figures (2-a and b), the amount of spectral acceleration is obtained and divided for each of the earthquake records used. The minimum value in the intervals of 0.2T and 1.5T for the heights of 9 and 15 stories is obtained by dividing 1 by the value of the scale factor.

Table 3: Scale coefficients used in this study

Earthquake manes	9 story
68	50.71
125	42.47
169	46.2
174	39.14
721	29.13
725	28.84

Earthquake manes	9 story
68	32.55
125	23.55
169	24.07
174	21.77
721	16.64
725	15.82

752	22.46
767	53.26
829	19.32
848	63.86
900	29.33
953	18.05
960	35.02
1111	40.22
1116	28.93
1148	78.57
1158	29.72
1244	29.13
1485	44.43
1602	20.11
1633	52.97
1787	33.64

752	12.22
767	29.47
829	13.33
848	47.02
900	23.24
953	14.39
960	17.37
1111	21.62
1116	21.87
1148	52.58
1158	19.22
1244	20.97
1485	25.72
1602	10.49
1633	26.29
1787	26.38

The characteristics of the earthquakes used

One of the primary steps in determining seismic responses and fragility curves based on time history analysis is the choice and scale of earthquake records. Various issues such as soil conditions, distance from the source of the earthquake, type of fault, spectral shape (frequency content of the record), etc. should be counted in the choice of records. Besides, the number of records selected should be such as to minimize the average of the results of time history analyzes and variations in the record-to-record response. In this part of the research, twenty-two earthquake records (twenty-two earthquakes with two components) proposed by FEMA P-695 [**Error! Bookmark not defined.**] have been used to compare the response of structures. The multiplicity of records allows for statistical comparison and estimation. In Error! Reference source not found.) Selected records are given. The records are obtained from large-scale events presented to researchers in the PEER database for soil types C and D. Moreover, the type of faults, that produce earthquakes, are of the Strike-Slip Fault type. As stated earlier, to overcome variables and uncertainties between records owing to their inherent differences in size, distance to the source, source type, and soil type, FEMA P-695 requires that all chosen records be normalized to the Peak Ground Velocity (PGV). Normalization to this value is a fairly reliable method to remove unknown variables. The scale coefficient is determined based on the peak velocity in FEMA P-695 and is presented in the last row for each record. This coefficient is multiplied by the record before it is applied to the construction.

Table 4: Records used to analyze time history

ID No.	Record ID	Components IDs according toPEER NGA Database(PEER, 2012)		PGA $_{\text{component-1}}$ (g)	PGA $_{\text{component-2}}$ (g)	Normalization factor
		Component 1	Component 2			
1	953	NORTHR/MUL009	NORTHR/MUL279	0.52	0.42	0.65
2	960	NORTHR/LOS000	NORTHR/LOS270	0.48	0.41	0.83

3	1602	DUZCE/BOL000	DUZCE/BOL090	0.82	0.73	0.63
4	1787	HECTOR/HEC000	HECTOR/HEC090	0.34	0.27	1.09
5	169	IMPVALL/H-DLT262	IMPVALL/H-DLT352	0.35	0.24	1.31
6	174	IMPVALL/H-E11140	IMPVALL/H-E11230	0.38	0.36	1.01
7	1111	KOBE/NIS000	KOBE/NIS090	0.51	0.50	1.03
8	1116	KOBE/SHI000	KOBE/SHI090	0.24	0.21	1.10
9	1158	KOCAELI/DZC180	KOCAELI/DZC270	0.36	0.31	0.69
10	1148	KOCAELI/ARC000	KOCAELI/ARC090	0.22	0.15	1.36
11	900	LANDERS/YER270	LANDERS/YER360	0.24	0.15	0.99
12	848	LANDERS/CLW-LN	LANDERS/CLW-TR	0.42	0.18	1.15
13	752	LOMAP/CAP000	LOMAP/CAP090	0.53	0.44	1.09
14	767	LOMAP/G03000	LOMAP/G03090	0.56	0.37	0.88
15	1633	MANJIL/ABBAR--L	MANJIL/ABBAR--T	0.51	0.50	0.79
16	721	SUPERST/B-ICC000	SUPERST/B-ICC090	0.36	0.26	0.87
17	725	SUPERST/B-POE270	SUPERST/B-POE270	0.45	0.44	1.17
18	829	CAPEMEND/RIO270	CAPEMEND/RIO360	0.55	0.39	0.82
19	1244	CHICHI/CHY101-E	CHICHI/CHY101-N	0.44	0.35	0.41
20	1485	CHICHI/TCU045-E	CHICHI/TCU045-N	0.51	0.47	0.96
21	68	SFERN/PEL090	SFERN/PEL180	0.21	0.17	2.10
22	125	FRIULI/A-TMZ000	FRIULI/A-TMZ270	0.35	0.31	1.44

Results

Pushover analysis results

For the primary evaluation of the modeled buildings, the nonlinear static analysis was performed by applying the target displacement at the control point on two-dimensional models. The diagrams presented in Figure (3) show the results of nonlinear static analysis. According to the diagrams, the capacity curve of the models is somewhat different. But regular structures show more capacity. The yield displacements of the structure are nearly the same.

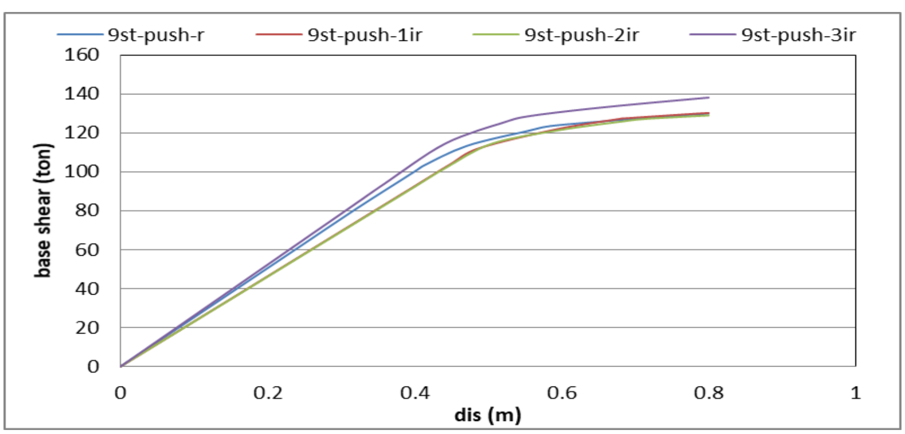


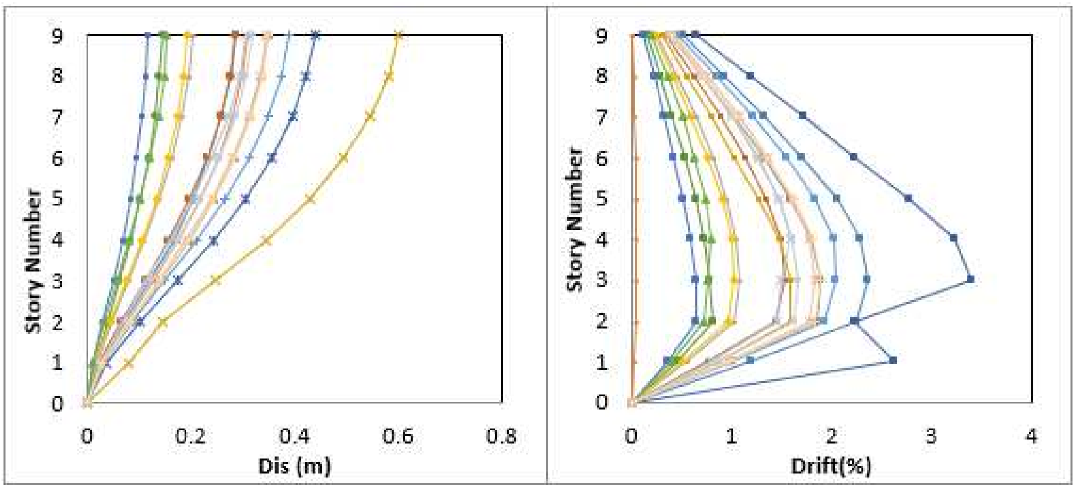
Figure 3: Pushover diagram for 9-story models

Time History Analysis

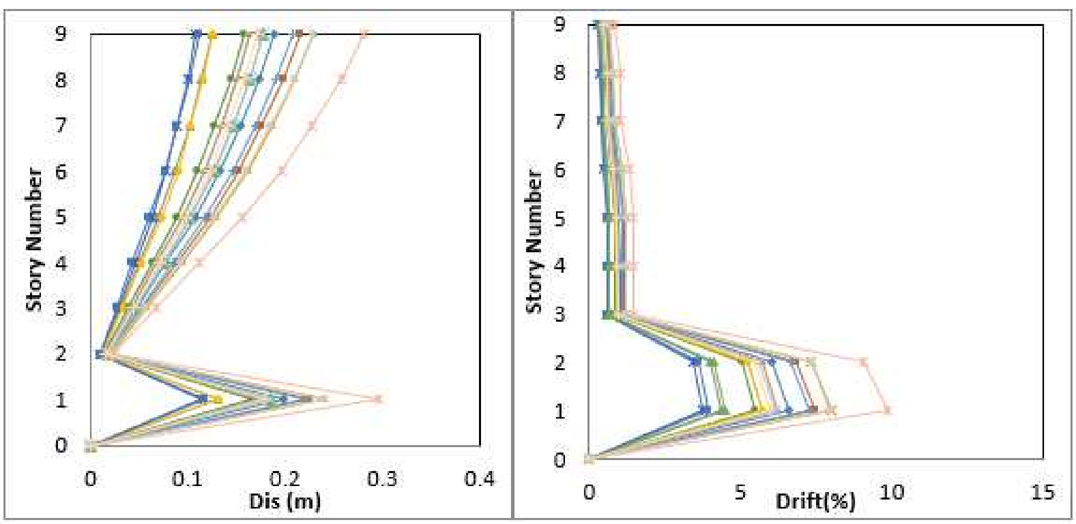
This analysis has been performed for regular and irregular constructions to examine the difference between the responses with the two studied spectra. The results of these examinations are briefed in displacement and base shear diagrams.

Results of time history analysis based on standard spectrum

The records used were scaled according to the standard spectrum. The chosen structures are split into two groups: regular and irregular. Figure (4) displays the relative displacements and displacements between stories. The difference between the model presented for relative displacement in the regular and irregular groups means that the demand for relative displacement in the middle stories is very high compared to the upper stories. This value even reaches 4% for a 9-story structure in the 3rd and 4th floors.



A



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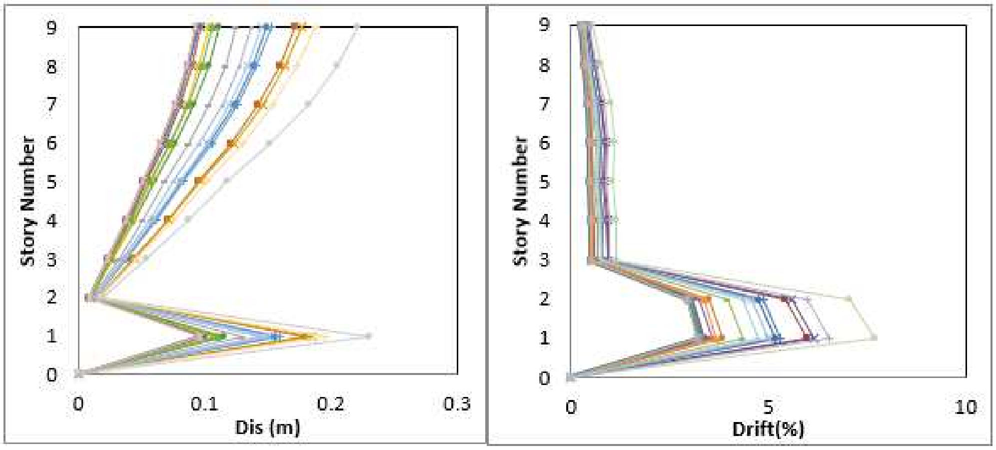

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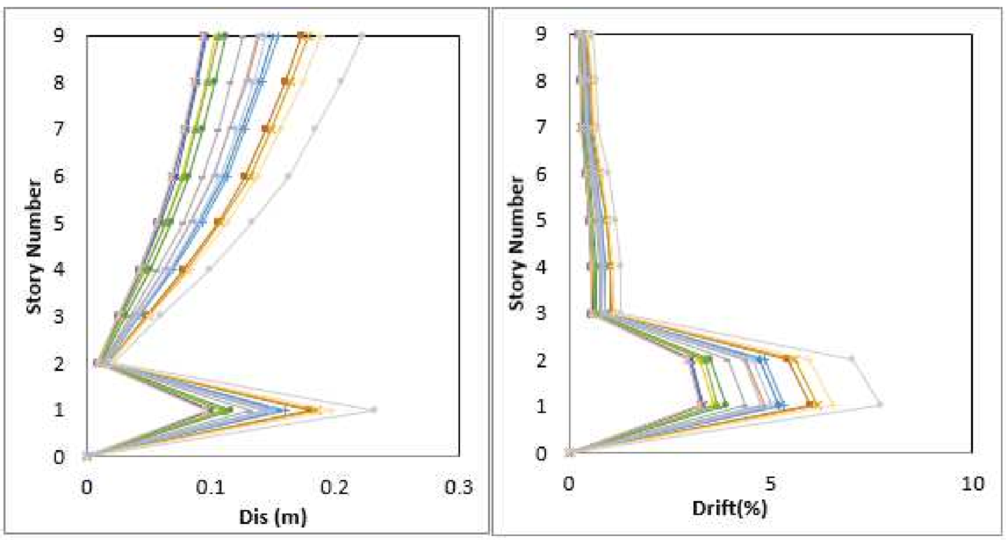
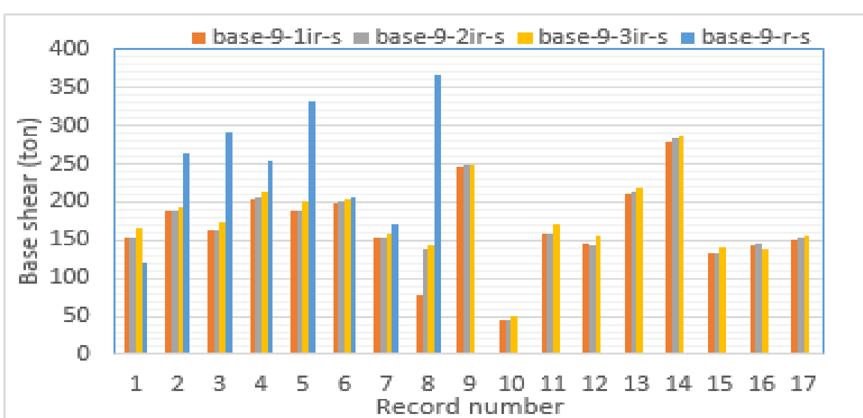


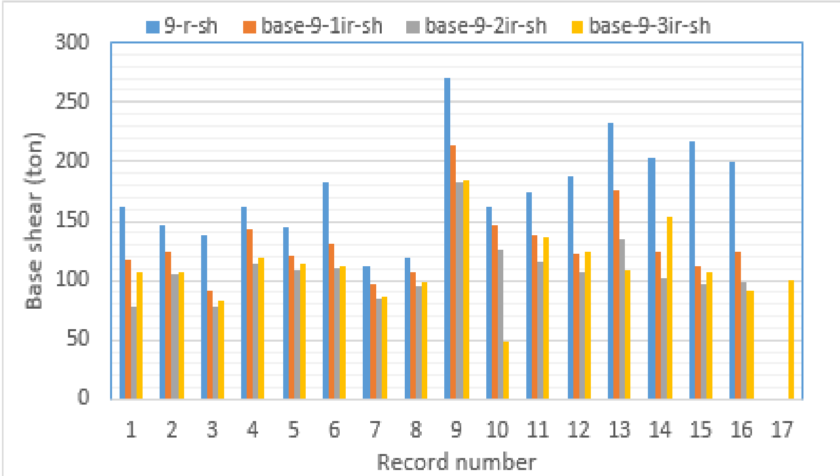
D

Figure 5: A: Displacement and drift diagram for model 9-r. B: Displacement and drift diagram for 9-1ir model. A: Displacement and drift diagram for 9-2ir model. A: Displacement and drift diagram for 9-3ir model

Base shear results



A



B

Figure 6: A: Diagram of nine-story structures of standard base shear, B: Diagram of nine-story structures of base shear of conditional mean spectrum

Mediation of model displacements

The results of time history analysis in the form of the displacement and drift median diagrams for constructions are shown in Figure (7). In all cases, the displacements generated in the structures by the conditional and standard spectral scale methods are different. The displacement demand made in standard-scale buildings is higher than the conditional spectrum. This means that the standard spectrum applies higher and more conservative values to the structure than the conditional mean spectrum. Whereas, the conditional mean spectrum applies smaller values to the structure.

In irregular structures, this difference is less than in regular ones. In such structures, the dominant mode of the period is not the first mode. The reason for this is the difference between the periods of the first mode and the dominant mode. This difference is also more evident in the base sections. The median of the base shear for the conditional mean spectra is less than the values achieved from the standard spectrum. This means that with this scaling method, there is less demand on the structure. By using the conditional mean spectrum for design, even in irregular constructions, the response of the structure can be reduced in higher modes.

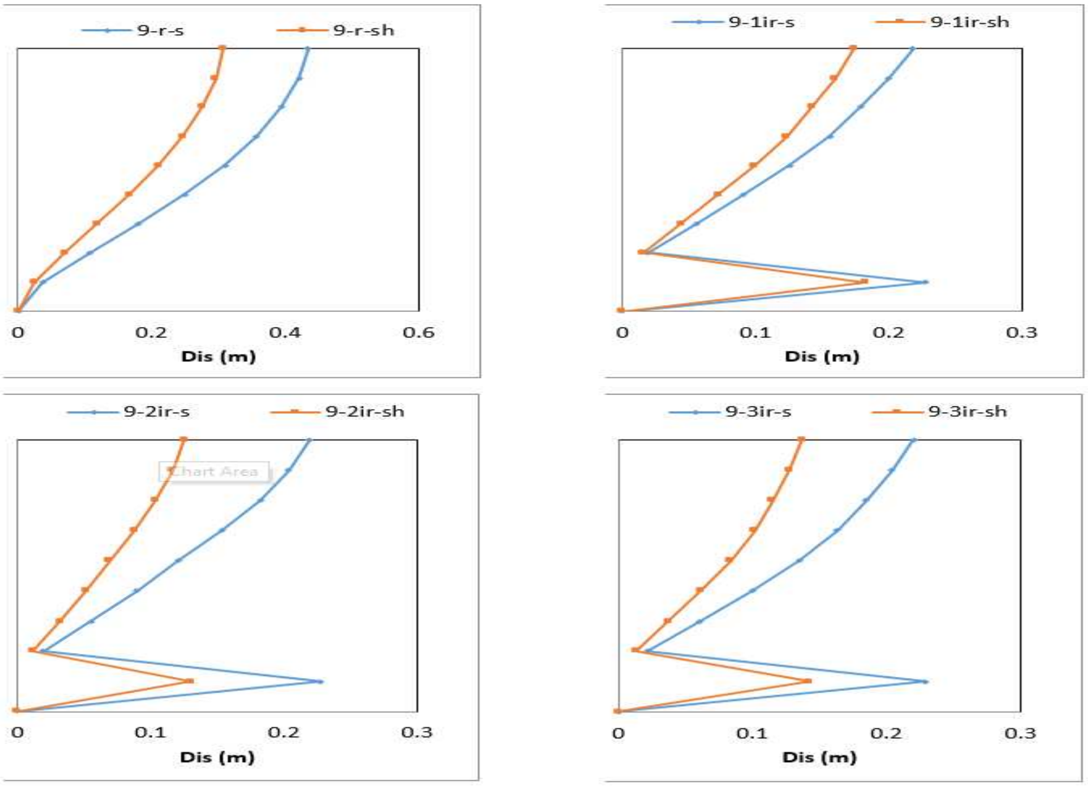


Figure 7: Comparison of displacement median for a nine-story structure

Conclusion

The objective of this research was to evaluate the method of nonlinear dynamic analysis for irregular steel moment frames in 9-story structures.

In this study, after introducing the name and shape of the model and the beam and column sections of the models, the pushover analysis was addressed. Then, the time history analysis was done on a spectrum. The shape of the spectra and the method of scaling the spectra were discussed, and the properties of twenty-two earthquakes used in these analyzes were presented.

According to the results of nonlinear static analysis, the capacity curve of the models is slightly different. But regular structures show more capacity. The yield displacements of the structures are almost identical.

The records used were scaled according to the standard spectrum. The difference between the model presented for relative displacement in the regular and irregular groups means that the demand for relative displacement in the middle stories is quite high compared to the upper ones. To the extent that this value even reaches 4% for a 9-story structure on floors 3 and 4.

The results of time history analyzes in the form of meidan and drift displacement diagrams for structures confirmed that in all cases, the displacements created in structures using conditional and standard spectrum scale methods are different. The displacement demand created in scaled structures with the standard spectrum is higher than the conditional spectrum. This means that the standard spectrum applies higher and more conservative values to the structure than the conditional mean spectrum. Whereas, the conditional mean spectrum applies smaller values to the structure.

Further, this difference is more apparent in the base shears. The median of the base shear for the conditional mean spectra is less than the values taken from the standard spectrum. This means that if this scaling method is used, there is less demand on the structure.

By using the conditional mean spectrum for design, even in irregular structures, the response of the structure can be decreased in higher modes.

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