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ARTICLE

AN INVESTIGATION TO SEISMIC PERFORMANCE OF ORDINARY REINFORCED CONCRETE MOMENT RESISTING FRAMES UNDER INTENSE EARTHQUAKES

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ABSTRACT

In the current research, the seismic performance of three multi-story reinforced concrete frame building has been studied. The three typical reinforced concrete moment-resisting frame buildings were designed according to the current Iranian seismic code (IS 2800-14). Three earthquake records were selected and scaled based on IS 2800-14 requirements. In order to assess the seismic vulnerability of the case study structure, nonlinear dynamic time-history analysis has been conducted. The performance has been evaluated based on both the member and global level criteria.. The numerical results additionally show that the case-study building frames designed by IS 2800-14 satisfy the intended code requirements and meet the inter-story drift ratios but they failed to meet maximum plastic rotation demands suggested by Guide 360 (Instruction for Seismic Rehabilitation of Existing Buildings). Therefore they need to be rehabilated against seismic demands.

KEY WORDS
Seismic Design, Reinforced Concrete Frame, Seismic Performance, Drift, Plastic Rotation

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INTRODUCTION

Earthquakes are known as the most destructive phenomena due to their widespread damage on buildings, bridges and etc. A large number of building structures are affected by earthquakes, hence they should design to resist its effects. This design shall incorporate the seismic behavior of the building structures. Design codes propose different methods of analysis and design of the building structures against seismic loads, like equivalent static, nonlinear static, linear dynamic and nonlinear dynamic methods. The earthquake resistant building design code that implemented in Iran is standard No. 2800 that is revised in 2015.

Equivalent static method uses the behavior factor R to convert the elastic response to inelastic one. Nonlinear analysis methods could be used to obtain exact global and local responses. The basic parameter should be estimated in the nonlinear methods, is the ultimate displacement capacity of lateral bearing system. One of the most important factors having role in estimation of the ultimate displacement capacity is the effective stiffness of the lateral bearing system.

Primary studies that used static nonlinear analysis are based on the simplified first mode based lateral loading patterns in the estimation of capacity curve of building structures, namely Freeman et al. [1], Saiidi and Sozen [2], Fajfar and Flschinger [3]. In the last decade the seismic codes prefer the inelastic displacements in spite of elastic displacements of elements [4]. There are some studies on the seismic behavior of reinforced concrete frames that designed based on Iranian seismic standard 2800 [5].

Purpose of the current paper is to investigate seismic behavior of RC frame building structures with moderate ductility that designed based on 4th edition of Iranian Seismic Design Code (Standard No. 2800). The effect of bay dimension increase, story height increase also number of stories increase, on the seismic behavior of RC frame building structures is investigated. The dynamic nonlinear time history method that incorporates the material and geometric nonlinearities along with difference of velocity and accelerations is used to analyze the behavior of structures studied here.

In the subsequent parts of the paper, the studied samples are introduced and selection method of strong ground motion records, analyze conduction method and etc., along with analysis results are briefly explained.

MATERIALS AND METHODS

Three RC frames are investigated in this study, namely Model 1, Model 2 and Model 3. The geometric properties of these samples are shown in [Fig. 1] and summarized in [Table 1]. [Table 2] summarizes the material properties assumed in this paper.

Gravity loading of samples is conducted based on 6th issue of national building code of Iran and summarized in [Table 3]. Lateral loading is based on the Iranian seismic design standard no. 2800. The selected samples are designed based on equivalent static method considering ordinary ductility requirements of ACI 318-11 code of the United States of America.

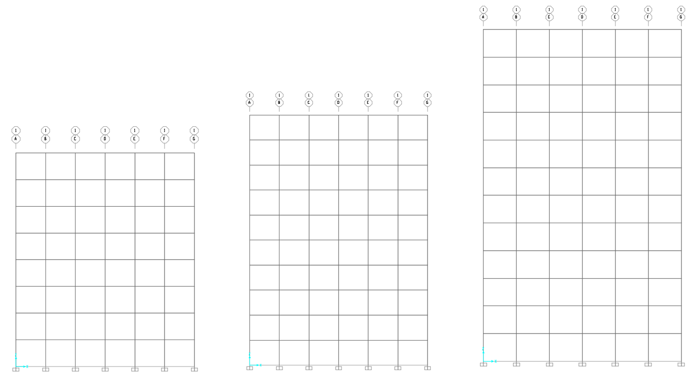


Fig. 1: Elevation view of studied samples.

Table 1: Geometric properties of studies samples

Model name	Number of stories	Story height (m)	Number of bays	Bay length (m)
Model 1	8	3.60	6	4.00
Model 2	10	3.80	6	4.50
Model 3	12	4.20	6	5.00

Table 2: Material Properties

Material Name	Yielding Strength (kg/m^3)	Ultimate Strength (kg/cm^2)	Weight of Unit Volume (kg/m^3)
Steel	4000	4800	7850
Concrete	250	200	2400

Table 3: Gravity loading properties

Load Case	Load Amount (kg/m^2)
Dead	550
Story Live	200
Roof Live	150

To analyzing of the samples, one should use a structural analysis method. Nowadays there are many computer based software uses finite element method to analyze the building structures. In this paper the well-known finite element software SAP-2000 is implemented to analyze and design of samples studied. Due to the symmetry of the samples geometry and loading, just one lateral resisting frame of each sample is considered in the studies. This is a beneficial assumption from numerical cost point of view. Also it is assumed that the roof diaphragms have solid behavior in their plane and the lateral frames carry lateral loads proportional to their stiffness. SAP-2000 implements Beam-Column formulation to simulate the structural behavior of frame elements of the structure. The assumed degree in local and global coordinate system along with global stiffness matrix is shown in the [Fig. 2].

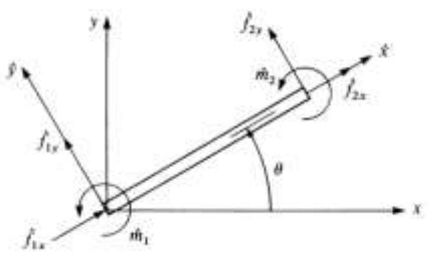


Fig. 2: Local, Globaldegree of freedom beam-column element in the SAP-2000

There are two important challenges in simulation of beam and columns (1) force-deformation relationship, (2) estimation of deformation capacity should conducted with acceptable accuracy. These parameters are introduced in guidelines and technical notes like FEMA 356 and standard 360 of Iran [6].
So the required parameters are extracted from standard 360 and introduced to the SAP-2000. The procedure of defining the nonlinear behavior of plastic hinges of beams and columns in SAP-2000, are shown in [Fig. 3] and [Fig. 4]respectively.

The information required to define the above mentioned hinges are available in the standard 360 of Iran [6] as shown in [Fig. 5].

There are two local and global damage criteria that should be considered in seismic behavior studies of building structures. Local damage criteria are (1) Immediate Occupancy, IO, (2) Life Safety, LS, (3) Collapse Prevention, CP, thatdetermined based on plastic rotation of plastic hinges under earthquake motions. The global damage criterion is maximum inter-story drift ratio determined from a nonlinear time history analysis.

Fig. 3: Definition of plastic hinge properties of beams in flexure

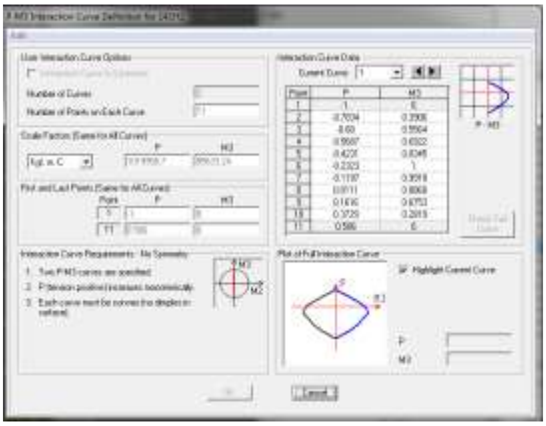


Fig. 4: Definition of plastic hinge properties of columns (Axial-bending interaction diagram)

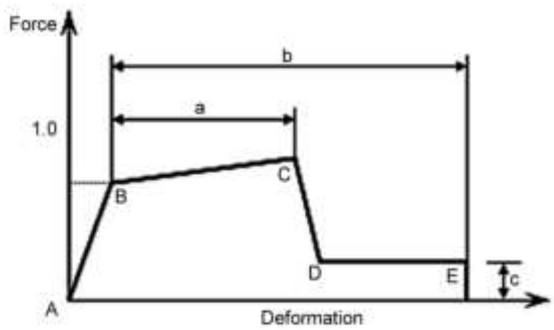


Fig. 5: Force-Deformation relationship provided in standardNo. 360 [6]

In the nonlinear time history analysis, we need to introduce the damping matrix to the finite element software. One of the methods to determine damping matrix is righley method that is based on modal analysis method. The modal analysis method indeed is a eigenvalue problem that solves the characteristic equation of structure as follows:

$$[K - \omega^2 M][\Phi] = 0 \quad (1)$$

In [Eq. 1], K is structural stiffness matrix, ω is natural frequency and M is structural mass matrix determined based of finite element method. Also Φ is modal shape matrix. To solve the eq. 1, one needs to determine the eigenvalues of coefficient matrix[K-ω^2 M], then the eigenvectors could be determined. So one should solve eq. 2 as follows:

$$|K - \omega^2 M| = 0 \quad (2)$$

Generally in dynamic analysis of building structural systems, considering that most of the structural mass is concentrated in story levels, each story is considered as a concentrated mass, and in two dimensional modeling, it is considered as a concentrated mass with one lateral degree of freedom. The gravitational degree of freedom is neglected due to the near solid behavior of structural columns in axial direction that is parallel to gravitational degree of freedom. So, each of samples that investigated here has an important vibration mode shape. The natural frequencies of each model is determined by modal analysis option of SAP-2000 and summarized in [Table 4].

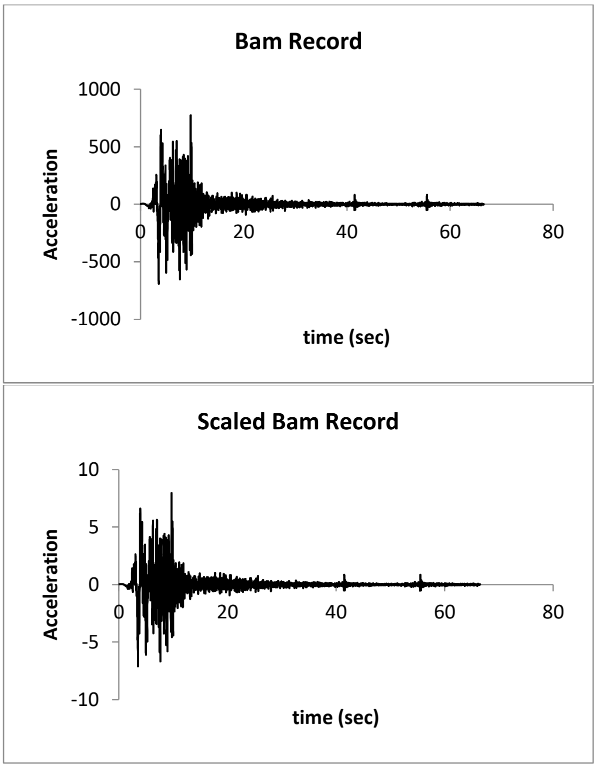


Fig. 6: BAM ecord

To investigate the seismic behavior of the designed samples of part 2, the non-linear time history analysis has been implemented. In the current section, the most important features of this analysis method and its required procedures are introduced. In concise words, to conduct a non-linear time history analysis, one should select some strong ground motion records and scale them to a target spectral acceleration based on seismic codes. This matter is conducted based on Iranian seismic standard no. 2800. Also one should consider and exactly model the material and geometrical non-linear behavior of the structural elements, which have been explained in part 3.

Earthquake resistant building structures design codes like Iranian standard no. 2800, introduce some specifications about selection of strong ground motion time histories to conduct time history analysis. These specifications are (1) site properties, (2) strong ground motion properties [5]. In the other words, the selected strong ground motion should be consistent with site soil conditions and its response spectrum should be conforming to the design spectrum.

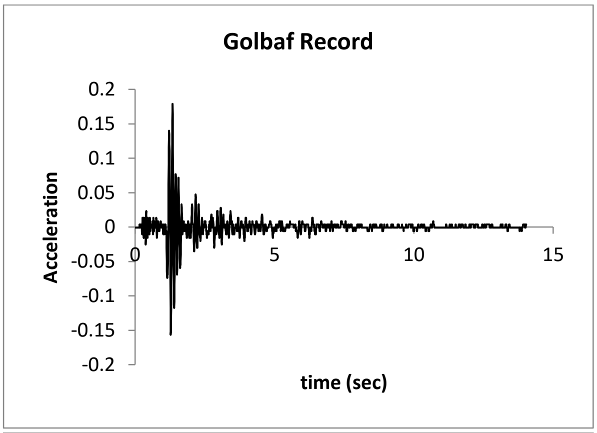
Considering abovementioned tasks, three strong ground motion records have been selected and summarized in [Table 5]. Scaling procedure of these records is based on Iranian standard no. 2800.
[Fig. 6,7, 8] shows the acceleration time history of selected records, before and after scaling, respectively. To study more the features of these records, the Fast Fourier Transform (FFT) and acceleration response spectra of each are obtained by the means of Seismosignal software and are summarized in [Fig. 9 ,10, 11].

Table 4: Natural frequencies of investigated models.

Mode No.	Model 1	Model 2	Model 3
1st Mode	0.5	0.8	1.12
Last Mode	0.05	0.08	0.11

Table 5: Selected earthquake records.

Event name	PGA (g)	Time (s)
Bam	0.98	65
Golbaf	0.54	14
Zarand	0.51	80



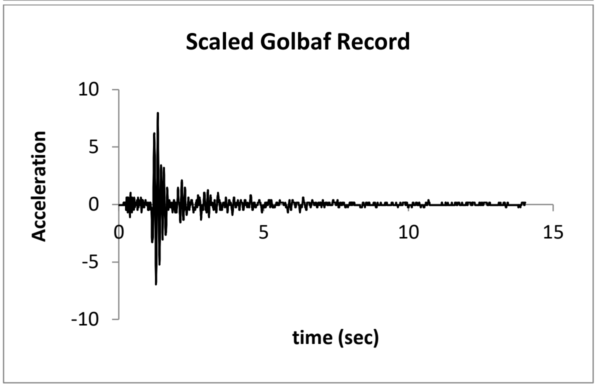
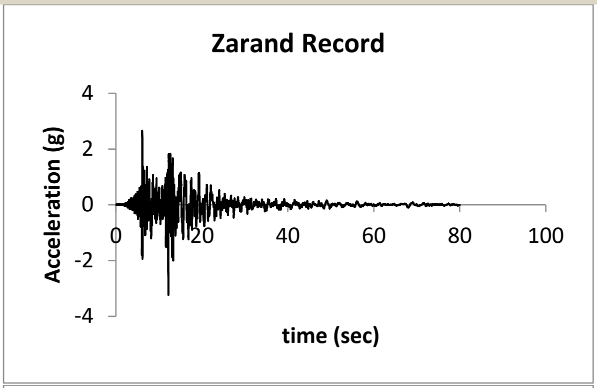


Fig. 7: GOLBAF record



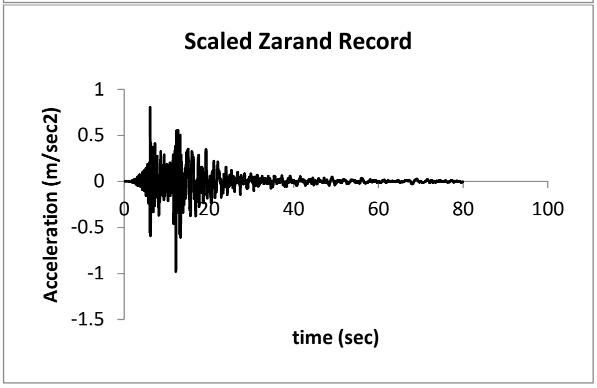


Fig. 8:ZARAND record……

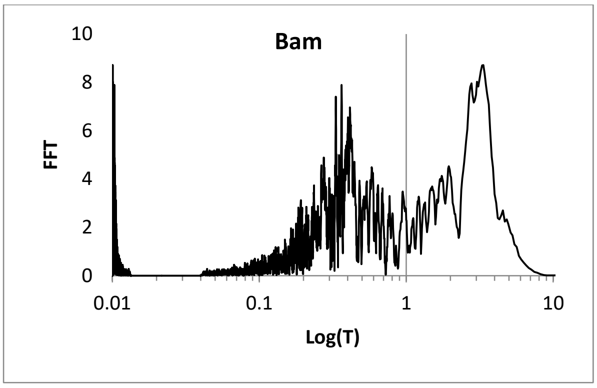


Fig. 9: Bam FFT ……

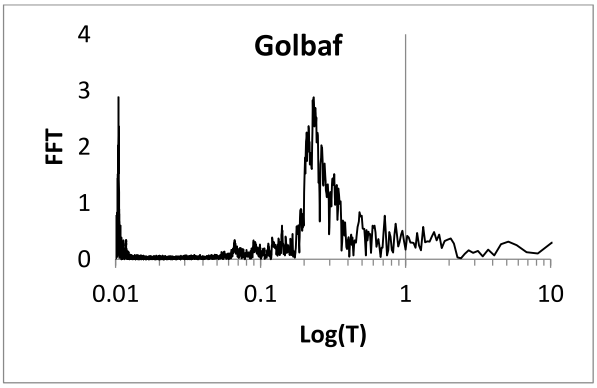


Fig. 10: Golbaf FFT ……

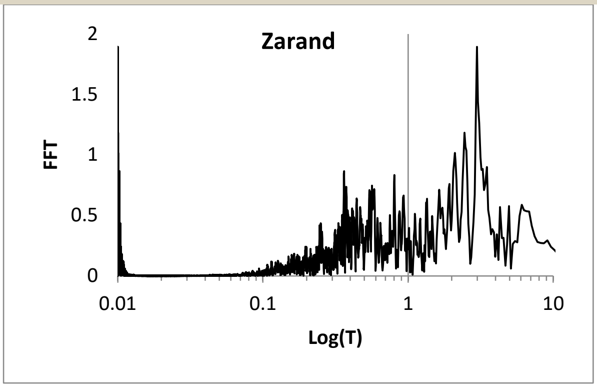


Fig. 11: Zarand FFT

Investigation of the diagrams of FFT shown in [Fig. 9] to [Fig. 11] reveal that the selected records are very different from frequency content point of view. In the FFT of Bam record, most of wave amplitudes are concentrated in periods ranging from 1s to 3s. But for Golbaf record, this rang is between 0.2s to 0.5s and for Zarand event, the governing range is periods above 2s. In the subsequent parts studies will show that the governing periods of the sample structures of current study is between 0.5s to 1.15s. So it is expected that the studied samples will suffer extensive damage under Bam earthquake. It is because the structural periods are in the elastic behavior range and when the samples behave in inelastic behavior range, the periods will be fallen in the range of 1s to 2s that exactly the same with the governing period range of Bam event.

Generally to more deeply studying the selected records, the elastic acceleration response spectrum of selected records are considered. [Fig. 12] compares elastic acceleration response spectrum of three selected records. It should be noted that, for comparison purpose, these spectrums are scaled to Sa max = 1. As it can be seen, the spectrum of Bam event has large spectral accelerations in wide range of periods. The second event is Zarand that has wide period range of large accelerations. Golbaf event is a narrow band one and large accelerations are concentrated to periods of 0.2s to 0.4s and author's experiences show that the Golbaf event could be hazardous for 2 to 5 story building structures, which haven't been studied herein.

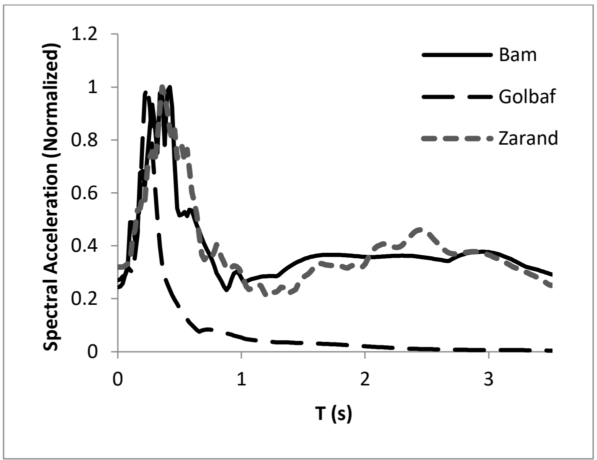


Fig. 12: Elastic acceleration response spectra of one degree of freedom oscillator under selected records

Real damping characteristics of building structures are affected by many parameters and are very hard to known and determine so in practical and research fields, the equivalent viscous damping is used. Studies show that in ordinary building, damping ratio is below 5% of critical damping. In research works, generally the Rayleigh damping method is implemented to obtain damping matrix. The formulation of this method is as follows:

$$C = \alpha_m M + \beta_s K \qquad (3)$$

In this equation, M is structural mass matrix, K is structural stiffness matrix. α_m Is mass proportion coefficient and represents the mass contribution in damping. β_s Is stiffness proportion coefficient and represents the stiffness contribution in damping. To determine α_m and β_s, one need to obtain natural frequencies of important modes of structure and use the following equations:

$$\alpha_m = 2\omega_1\omega_{end}(\xi_1\omega_{end} - \xi_{end}\omega_1)/(\omega_{end}^2 - \omega_1^2) \quad (4)$$

$$\beta_s = 2(\xi_{end}\omega_{end} - \xi_1\omega_1)/(\omega_{end}^2 - \omega_1^2) \quad (5)$$

Non-linear time history analysis conducted using three selected and scaled strong ground motion records. In this section, the seismic performance of studied samples are investigated and compared with together. Generally to investigate the seismic performance of building structures, local and global performance criteria are implemented. The global performance criterion is the inter-story drift ratio distribution along the height of structure and the local performance criterion is the amount of plastic rotations of structural elements that should be compared to acceptance criteria specified by codes like Iranian standard no. 360.

One of the most well-known global performance criteria is the inter-story drift ratio distribution along the height of the building structure. Inter-story drift ratio is the ratio of relative lateral displacement of stories of structure to height of individual story. [Fig. 13] shows this criterion definition briefly. As can be seen, inter-story drift is an index of amount of rotation amount of columns. In this part of study, the results of global performance of structure are summarized. To this end, the non-linear time history analysis is conducted and the time history of displacement of each story of studied samples obtained and shown in [Fig 14]. Inspection of these diagrams shows that the displacement time histories start from zero displacement in time zero. But when the time goes on, the diagrams oscillate around zero displacement but in the end of time, they go a non-zero equilibrium point, and this means that the structure in the end of time is tilted and suffers damage and residual displacements. This is due to cracks in concrete and yielding in steel rebars.

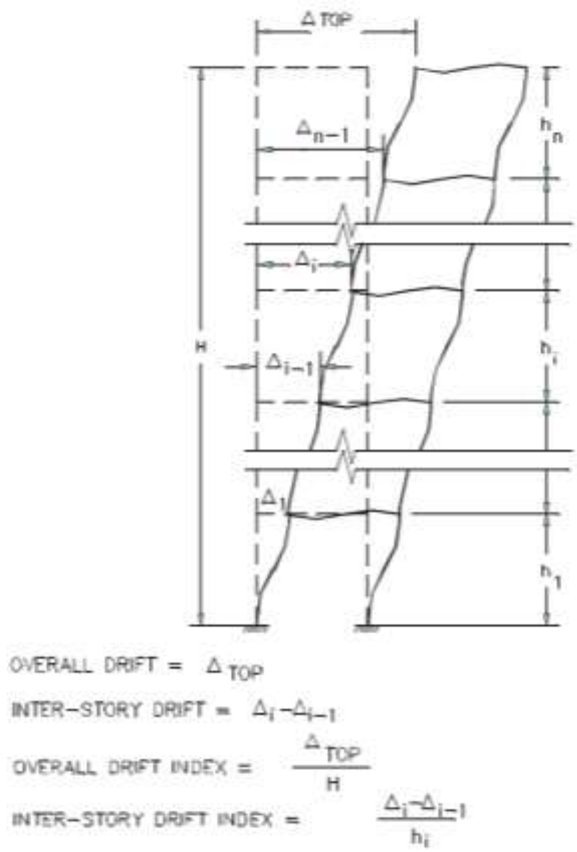


Fig. 13: Drift index definition

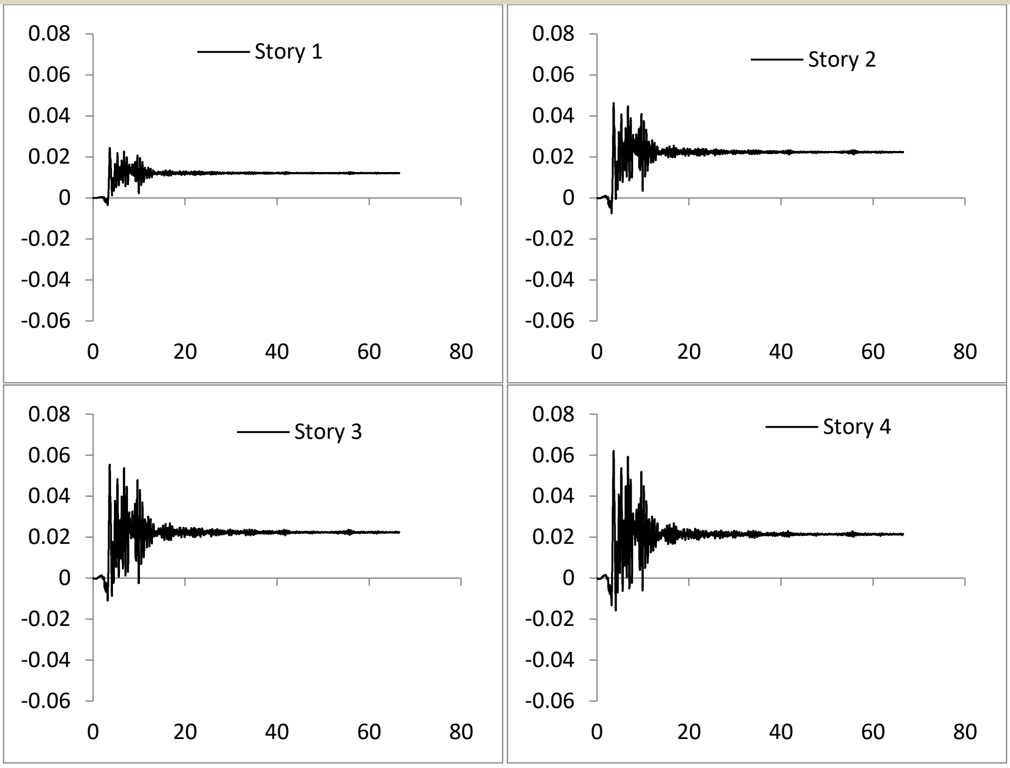


Fig. 14: Time history of displacement sample 1 gravity load 1

Using the displacement time history of stories of the samples, the maximum inter-story drift of each story obtained. A vertical dashed line in [fig. 15] show the accepted lateral drift specified by Iranian standard no. 2800.

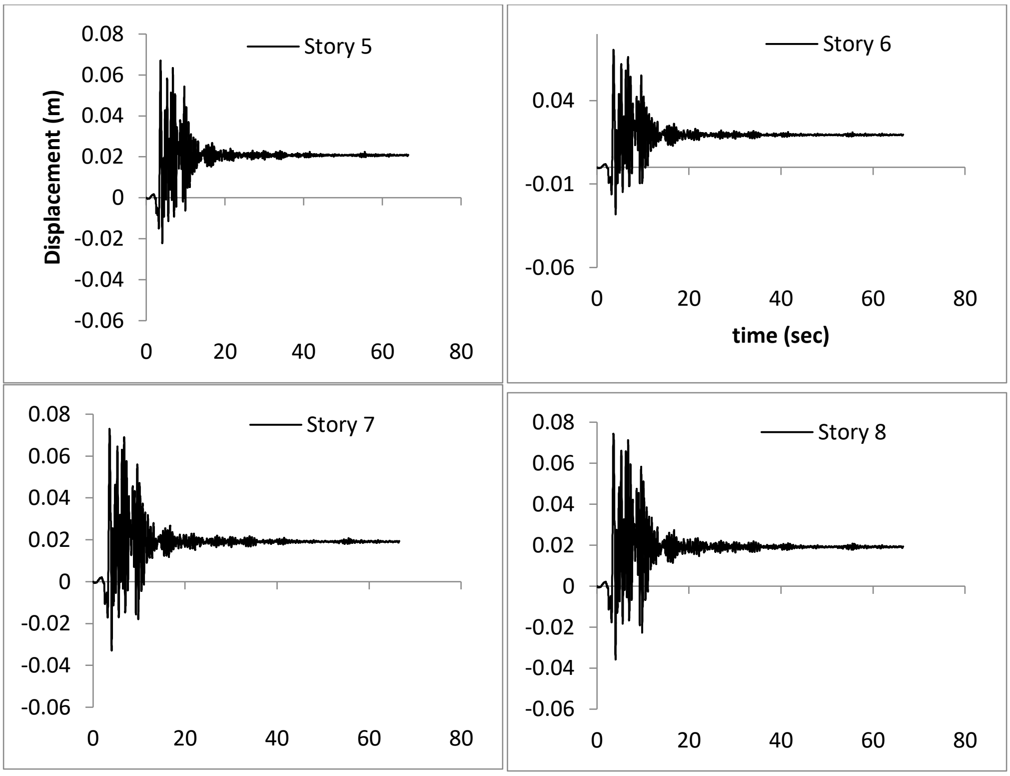


Fig. 14 (Continued): Time history of displacement sample 1 gravity load1

Evaluation of these diagrams reveal that of drift distributions are in acceptable range and as the number of stories increases, the drift ratio distributions are closer to acceptance threshold of Iranian standard no. 2800, hence the risk increases.

The acceptance criteria for the local seismic performances are provided in Iranian standard no. 360 as maximum acceptable plastic rotations in IO, LS and CP performance levels. The values of maximum acceptable plastic rotations are function of reinforcement ratio, confinement, demand to capacity ratio of shear in beams and columns and etc. TheSAP-2000 software is able to compare the plastic rotation demand on elements of structure by the acceptance criteria and report the performance of each element by colored circles in the location of plastic hinges, so the researcher and designer could understand the structures performance. [Fig.16] summarizes the plastic rotation report of SAP-2000 for each of investigated elements.

[Fig. 16] shows the plastic rotation conditions in sample 1 under Bam record. Investigating these figures reveal that all the plastic hinges of beams are exceeded the IO performance index and all except lower story columns are exceeded LS and one of the lower story columns exceeded CP performance index.

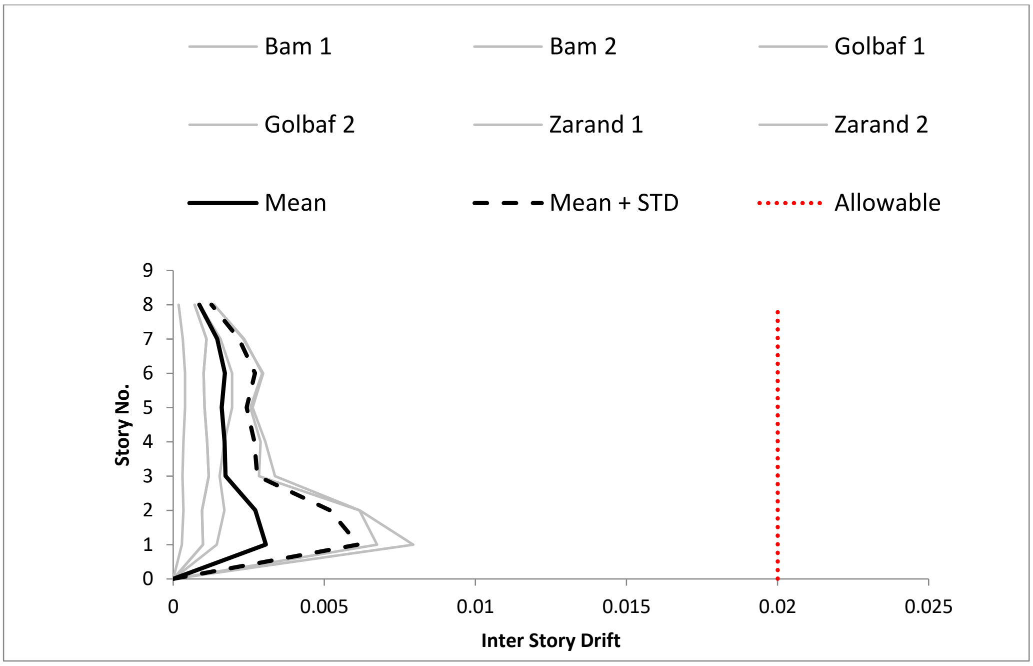


Fig. 15: Inter-story drift distribution forsample 1.

RESULTS

One of the most well-known global performance criteria is the inter-story drift ratio distribution along the height of the building structure. Inter-story drift ratio is the ratio of relative lateral displacement of stories of structure to height of individual story. [Fig. 13] shows this criterion definition briefly. As can be seen, inter-story drift is an index of amount of rotation amount of columns. In this part of study, the results of global performance of structure are summarized. To this end, the non-linear time history analysis is conducted and the time history of displacement of each story of studied samples obtained and shown in [Fig 14]. Inspection of these diagrams shows that the displacement time histories start from zero displacement in time zero. But when the time goes on, the diagrams oscillate around zero displacement but in the end of time, they go a non-zero equilibrium point, and this means that the structure in the end of time is tilted and suffers damage and residual displacements. This is due to cracks in concrete and yielding in steel rebars.

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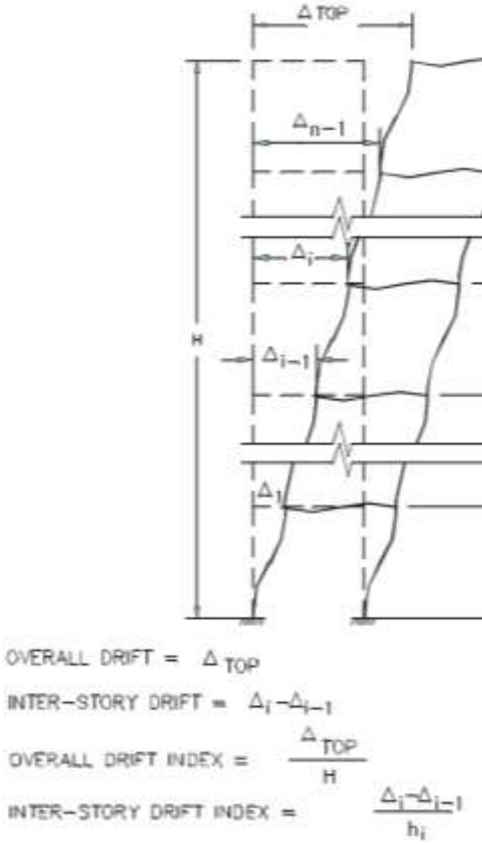

Fig. 13: Drift index definition

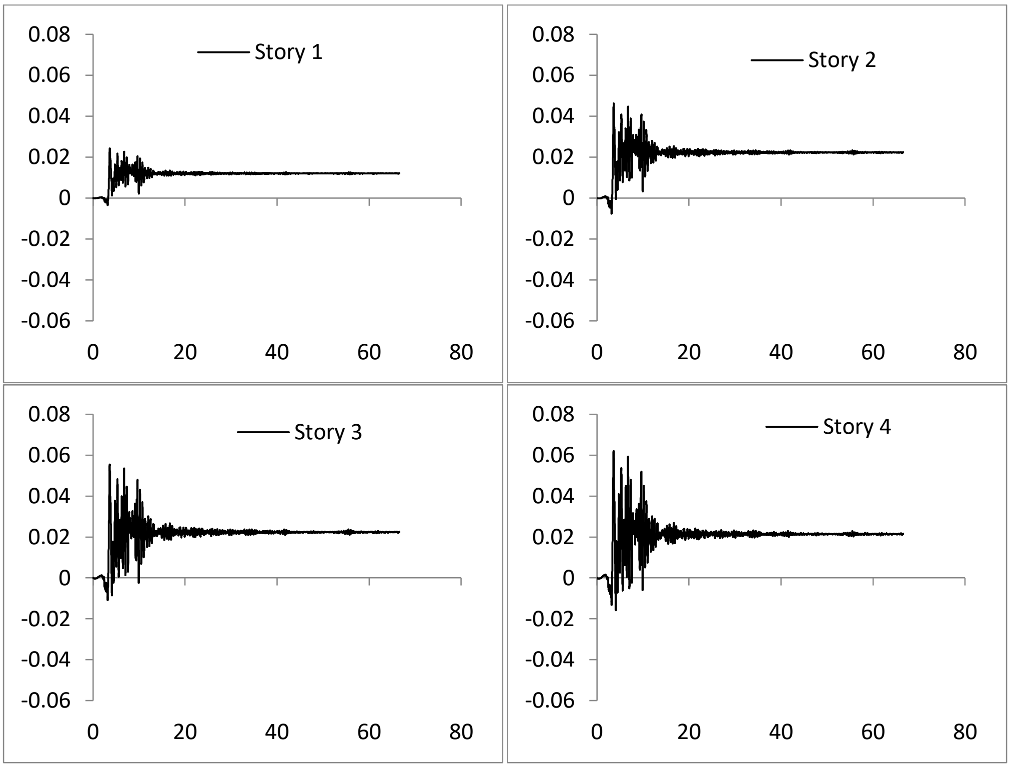

Fig. 14: Time history of displacement sample 1 gravity load 1

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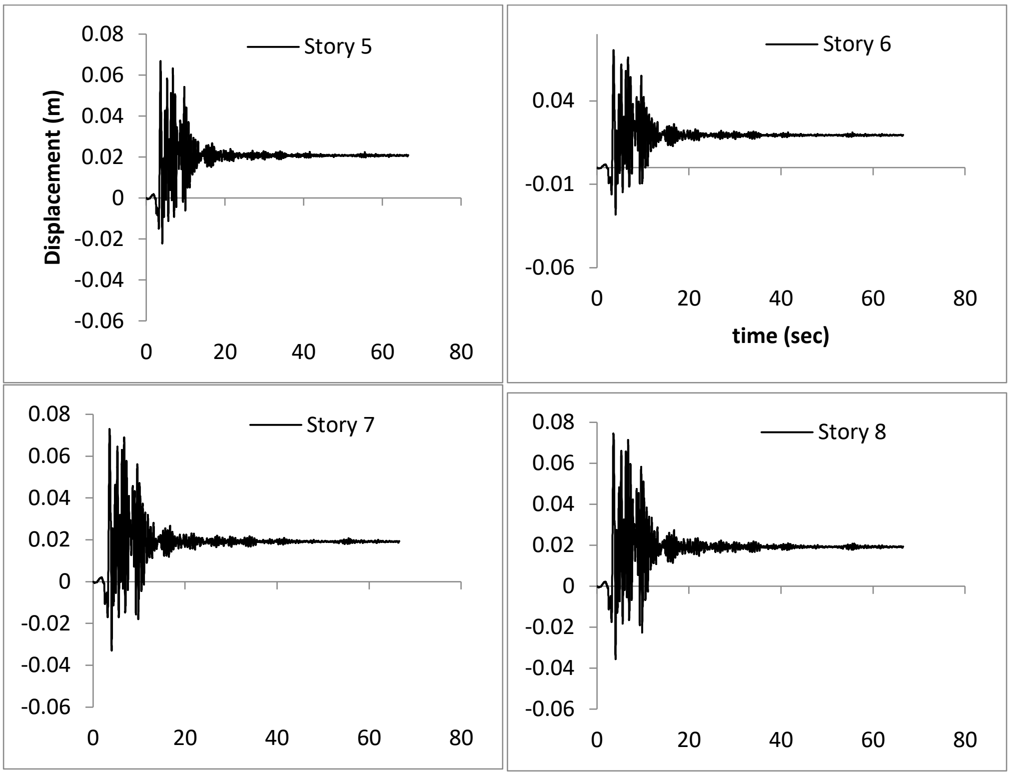

Fig. 14 (Continued): Time history of displacement sample 1 gravity load1

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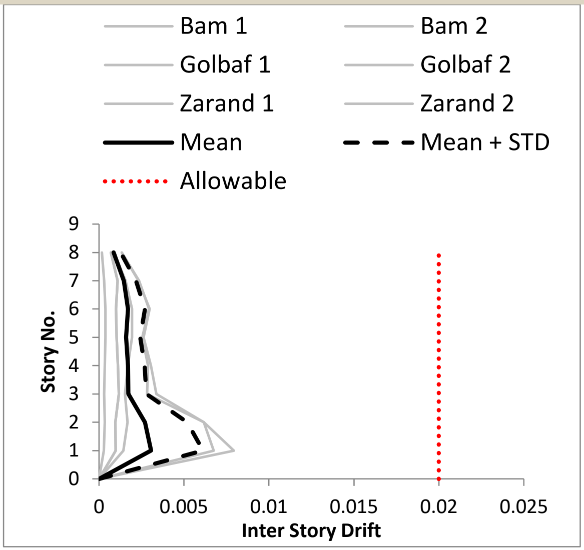

Fig. 15: Inter-story drift distribution forsample 1.

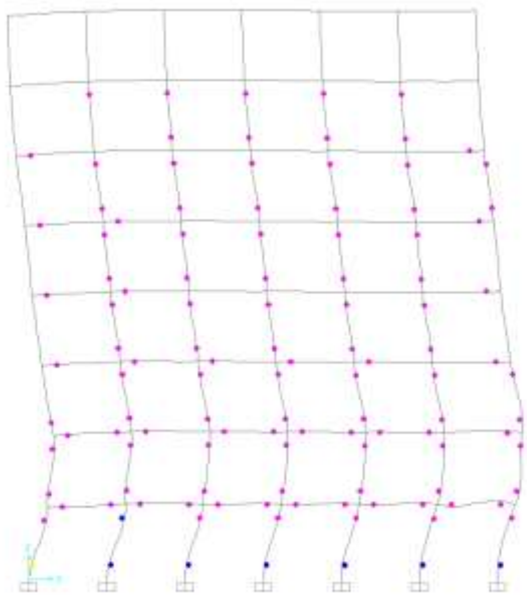

Fig. 16: Plastic hinges in model 1 under Bam record

The wound edge was freshened with B.P. blade to improve vascularity. Buccal fistula was repaired with catgut no. 2 and skin was sutured with silk thread. Another rectangular hard leather piece of size slightly greater than diameter of fistula was placed on outer skin opening of fistula and knot was secured on the outer hard leather piece [Table 1].

CONCLUSION

In this paper the seismic behavior of three sample reinforced concrete moment frames with intermediate ductility having 8, 10 and 12 stories are investigated using non-linear time history analysis under three strong ground motions of Bam, Zarand and Golbaf earthquakes. The samples are designed using equivalent static method of Iranian standard no. 2800. Then their seismic behavior is investigated using non-linear time history analysis. The results of non-linear time history analysis investigated from 2 point of view of local and global performance criteria. Local performance criterion is rotation of plastic hinges and global one is the distribution of inter-story drift along the height of structures.

FFT distribution of selected records is studied and it showed that the Bam record has a high frequency content compared to other two records. So it is expected to samples suffer more damage under this record.

Non-linear time history analysis of individual samples under each strong ground motion acceleration record conducted and the inter-story drift along the height of structures and the plastic rotations of plastic hinges obtained and investigated. Results show that investigated samples have acceptable from global performance but the local criteria of some models are exceeded allowable amounts.

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