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Assessment of Reinforced Concrete Buildings with Shear Wall Based on Iranian Seismic Code (Third Edition)

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Abstract: The aim of his study is to investigate the inelastic behavior of Reinforced Concrete (RC) buildings with sear wall when undergoing severe earthquakes. In this regard, the height-wise distribution of drift, hysteretic energy and damage index in RC buildings with shear wall subjected to strong ground motions were investigated. Three RC frames with shear wall, 8, 12, 15 story frames, in which lateral loading pattern was on the base of Iranian seismic code, were considered and all frames then were evaluated by performing nonlinear dynamic analyses under severe earthquakes. Consequences indicate that in severe earthquakes despite strength uniform allotment in the stories height, an intense concentration of these parameters was observed in one or two stories. This will definitely hinder the serviceability of the maximum capacity of buildings.

Key words: Hysteretic energy, damage distribution, drift, severe earthquake, shear wall

INTRODUCTION

In Reinforced Concrete (RC) buildings which have been designed according to current specifications of earthquake resistant design, the elements are usually determined on the basis of demand strength and then the limitations on the deflection. It seems that the height-wise distribution of these static forces (strength and stiffness) is factually based on the elastic vibration modes. When, these structures are subjected to severe earthquake excitations they are expected to deform well in inelastic range and dissipate the large seismic energy input into the structures. In order to predict the distribution of forces and deformations in these structures under the strong earthquake that can occur at the site, the actual performance of structures during earthquake (hysteretic and ductility) are necessary.

Williams and Sexsmith (1995) reviewed damage based on deformation. It is generally accepted that damage based on cycles of deformation is a low-cycle fatigue phenomenon. Degradation is assumed to evolve by the accumulation of plastic deformation. Karami *et al.* (2004) studied the effect of the conventional lateral loading pattern (i.e., equivalent static method) specified by the different seismic codes (Uniform Building Code, 1997; NEHRP, 1994) on height-wise distribution of ductility demand and drift in a number of steel shear-building frames. It was concluded that the strength distribution patterns suggested by these seismic codes do not lead to a uniform distribution of ductility and deformation in steel shear-building frames subjected to catastrophic earthquake. Therefore, the application of such conventional height-wise distribution of seismic forces will not actually cause the best seismic performance of a structure. Ganjavi *et al.* (2007) considered a number of reinforced concrete buildings based on equivalent static loading patterns (Iranian Code of Practice for Seismic Resistance Design of Building, 1999). They studied the height-wise hysteretic energy, drift and damage distribution subjected to four severe earthquakes.

In this study, three reinforced concrete frames with shear wall were considered. The seismic loading of these frames were applied according to equivalent static method in accordance with Iranian Code of Practice for Seismic Design of Building (2005). The aim of this study is to investigate the distributions of damage index, drift and hysteretic energy in height of RC buildings with shear wall undergone strong ground motions.

EQUIVALENT STATIC LOADING PROCEDURE

In most seismic building codes (Uniform Building Code, 1997; NEHRP, 1994; Iranian Seismic Code, 2005) the height wise distribution of lateral forces is determined from Eq. 1:

$$F_i = \frac{w_i h_i^k}{\sum_{j=1}^{N} w_j h_j^k} \cdot V \qquad (1)$$

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where, w_i and h_i are the weight and height of the ith floor above base level, respectively, N is the number of stories, V is total base shear and k is the power that differs from one seismic code to another.

In some provisions codes such as NEHRP-1994 Code, k increases from 1-2 as the period varies from 0.5-2.5 sec. In some such as UBC-1997, the force at the top floor (or roof) computed from Eq. 1 is increased by adding an additional force (Eq. 2), for a fundamental period T greater than 0.7 sec. In such a case, the base shear V in Eq. 1 is replaced by $v\text{-}F_i$. In this study, the value of k in Eq. 1 base of Iranian Code of Practice for Seismic Resistance Design of Building (2005) is taken as 1 (triangular loading pattern).

$$F_t = 0.07\ TF_i \tag{2}$$

NONLINEAR MODELING

In a nonlinear analysis, the accurate choice of a hysteretic model is crucial in predicting the correct dynamic response of the structure. The model should be able to describe a response similar to the actual hysteretic response of the structure. In this study IDARC 2D software has been used to compute the response of the structures to nonlinear time history (Valles *et al.*, 1996). The formulations are based on macro-models in which most of the elements are represented as a comprehensive element with nonlinear behavior. The load-deformation of the structure is simulated by versatile hysteretic models, which are implemented in the program and are mainly controlled by parameters indicating the stiffness degradation, strength deterioration and pinching of the hysteretic loops. The damage index developed by Park *et al.* (1984) has been considered in the program and is used to estimate the accumulated damage sustained by the components of the structure, by each story level. A global value of the damage index can be used to characterize the damage in the entire RC frame.

PARK-ANG-DAMAGE MODEL IN IDARC PROGRAM

Park-Ang damage index (Park *et al.*, 1984) considered in IDARC is the most usual damage index for damage analysis of reinforced concrete structures. The current Park and Ang three-hysteretic model modified by Kunnath *et al.* (1992) is as follows:

$$DI = \frac{\theta_m - \theta_r}{\theta_u - \theta_r} + \frac{\beta}{M_y \theta_u} E_h \tag{3}$$

where, θ_m is the maximum rotation attained during loading history, θ_u is the ultimate rotation capacity of section, θ_r is the recoverable rotation when unloading, M_m is the yield moment and E_m is the dissipated energy in section.

The element damage is then selected as the biggest damage index of end sections.

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Park *et al.* (1987) suggested these interpretations for the damage index:

$D<0.1$: No damage or localized minor cracking
$0.1 \le D<0.25$: Minor damage-light cracking throughout
$0.25 \le D<0.4$: Moderate damage-severe cracking, localized spelling
$0.4 \le D<1.0$: Severe damage-crushing of concrete, reinforcement exposed
$D \ge 1.0$: Collapsed

The two additional indices, story and overall damage indices are computed using weighting factors based on dissipated hysteretic energy at component and story levels, respectively:

$$DI_{story} = \sum_{i=1}^{n} (DI_i)_{componet} \left[\frac{E_i}{\sum_{i=1}^{n} E_i} \right]_{componet} \tag{4}$$

$$DI_{overall} = \sum_{i=1}^{n} (D_{Ii})_{story} \left[\frac{E_i}{\sum_{i=1}^{n} E_i} \right]_{story} \tag{5}$$

where, DI_i is the damage indices and E_i is the total absorbed energy by the component or the ith story.

STRUCTURAL SYSTEMS AND EARTHQUAKE EXCITATIONS

Structural systems: In present study, three reinforced concrete buildings with shear wall, 8, 12 and 15 story frames were considered. All frames were designed according to the equivalent lateral force procedure for a region with relatively high seismcity (Iran-Tehran) and for the soil type 2 (gravel and compacted sand, very stiff clay). It was also assumed that the structures were located in a region with relatively high seismic risk and relative design base acceleration of A = 0.35 g. Structures have identical plan configurations and were analyzed assuming that the floor diaphragms were sufficiently rigid under in-plane forces. Tri-linear model of Takeda *et al.* (1970) was used in nonlinear analyses. The viscous damping ratio was assumed to be uniformly distributed (damping ratio = 5%). In the design of these samples a basic assumption was considered, that a constant strength ratio (the ratio of the existing strength to the ultimate strength) has been applied in all stories and the frames were moment resisting with medium ductility. IDARC 2D, Ver. 6.1 (Valles and Reinhorn, 2006) Software was used for nonlinear dynamic analysis. A sample of 8 story frame has been shown in Fig. 1. In design and analysis of structures, P-delta effect was considered.

Earthquake excitations: Ten observed ground motions were used for input ground motions. Emphasis was placed on those recorded at a low to moderate distance from the epicenter (less than 30 km), with rather high local magnitudes (i.e., M>6). The recorded ground motions cover a broad variety of conditions in terms of frequency content, peak ground acceleration and velocity, duration and intensity (Table 1). In order to eliminate the influence of peak ground acceleration, all of them were scaled to a ground acceleration of 0.35 g based Iranian Code of Practice for Seismic Resistance Design of Building (2005).

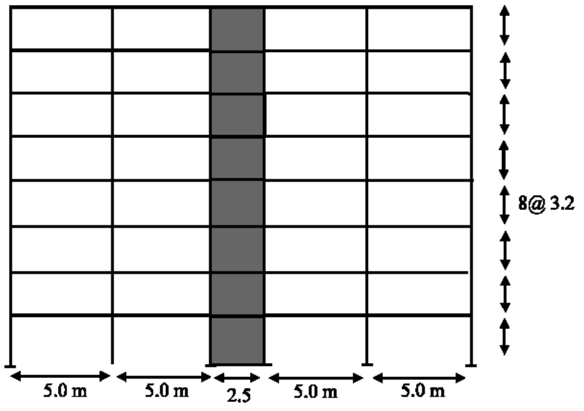

Fig. 1: A sample of an 8 story frame

Table 1: Characteristics of the selected ground motions

Ground motion	Date	Magnitude	PGA [g]
Chi-Chi	20-09-1999	7.62	0.512
El Centro	05-19-1940	7.00	0.313
Gazli	05-17- 1976	6.80	0.608
Lomaprieta 1	18-10-1989	6.93	0.479
Lomaprieta 2	18-10-1989	6.93	0.512
Manjil	20-06-1990	7.70	0.550
Naghan	06-04-1977	6.10	0.720
Northridge 1	17-01-1994	6.70	0.514
Northridge 2	17-01-1994	6.70	0.883
Parkfield	28-06-1966	6.10	0.442

RESULTS AND DISCUSSION

Nonlinear dynamic analyses: In order to study the height-wise distribution of hysteretic energy and story damage indices in the frames, walls, beams and columns were chosen as the considering elements of each story. In this regard the average values of height-wise distribution of hysteretic energy, drift and damage index, subjected to 10 severe earthquakes were calculated and then compared. It should be noted the hysteretic energy of wall, beam and column in each story has been shown as the percentage ratio of hysteretic energy in each wall, beam and column with respect to the total hysteretic energy in each frame.

Hysteretic energy and damage index

Walls: The amount and the form of height-wise distribution of (DI_{wall}) and ($Eh\%_{wall}$) in stories levels for three 8, 12 and 15 story buildings with shear wall subjected to 10 strong ground motions were calculated and the average values of these parameters have been shown in Fig. 2. The qualitative distribution of (DI_{wall}) and ($Eh\%_{wall}$) are identical. The results also show that the maximum values of hysteretic energy, damage indices in 8, 12 and 15 story buildings were in the first story and the minimum ones occurred in the last stories. By considering the mean plot of hysteretic energy and damage indices, it can be found that the differences percentages between maximum and minimum of ($Eh\%_{wall}$) in 8, 12 and 15 story frames are 99.3, 99.7 and 99.7, respectively. These values for damage indices are 99.4, 98.8 and 98.7, respectively. According to Fig. 2, in three buildings, there is a notable difference between the maximum and minimum values of ($Eh\%_{wall}$) and (DI_{wall}), in a way that the high concentration of hysteretic energy and damage indices were observed in the first story.

Beams: Figure 3 shows the plots of damage indices and the percentage of hysteretic energy of beams in story levels for 8, 12 and 15 story frames. The maximum average values of (DI_{beam}) and ($Eh\%_{beam}$) for ten earthquakes in 8 story frame are observed in the second story, while these for 12, 15 story frames occur in the third story. Also, the average of minimum values of ($Eh\%_{beam}$) and (DI_{beam}) for three frames occur in top stories. By considering the average curves and amounts of ($Eh\%_{beam}$) and (DI_{beam}), differences percentages between maximum and minimum of ($Eh\%_{beam}$) in 8, 12 and 15 story frames are 77.4, 99 and 99.7, respectively. These values for damage indices are 66.1, 95.4 and 98.6, respectively.

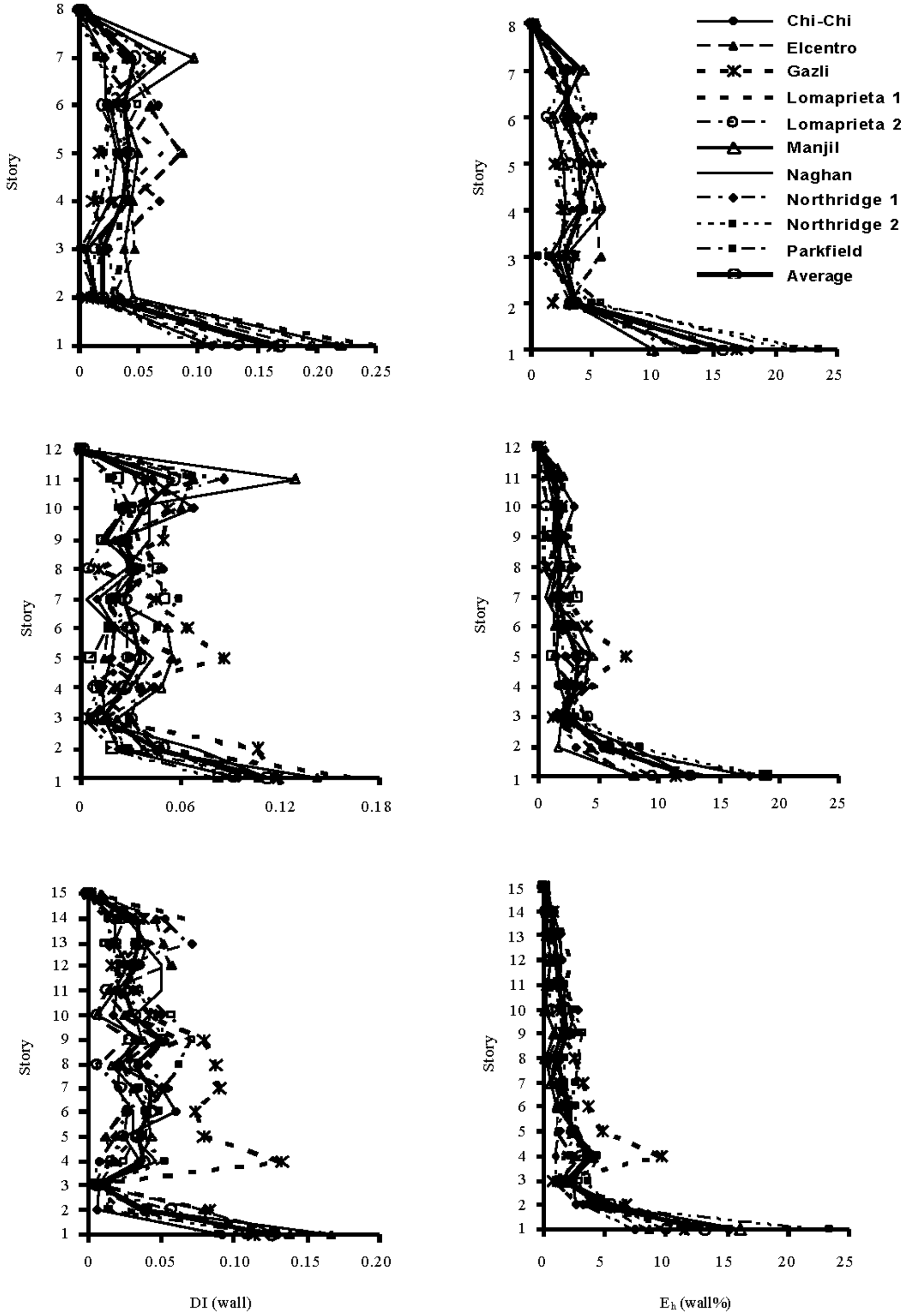

Fig. 2: Effect of ground motion on height-wise distribution of hysteretic energy and damage index of walls in 8, 12 and 15 story buildings

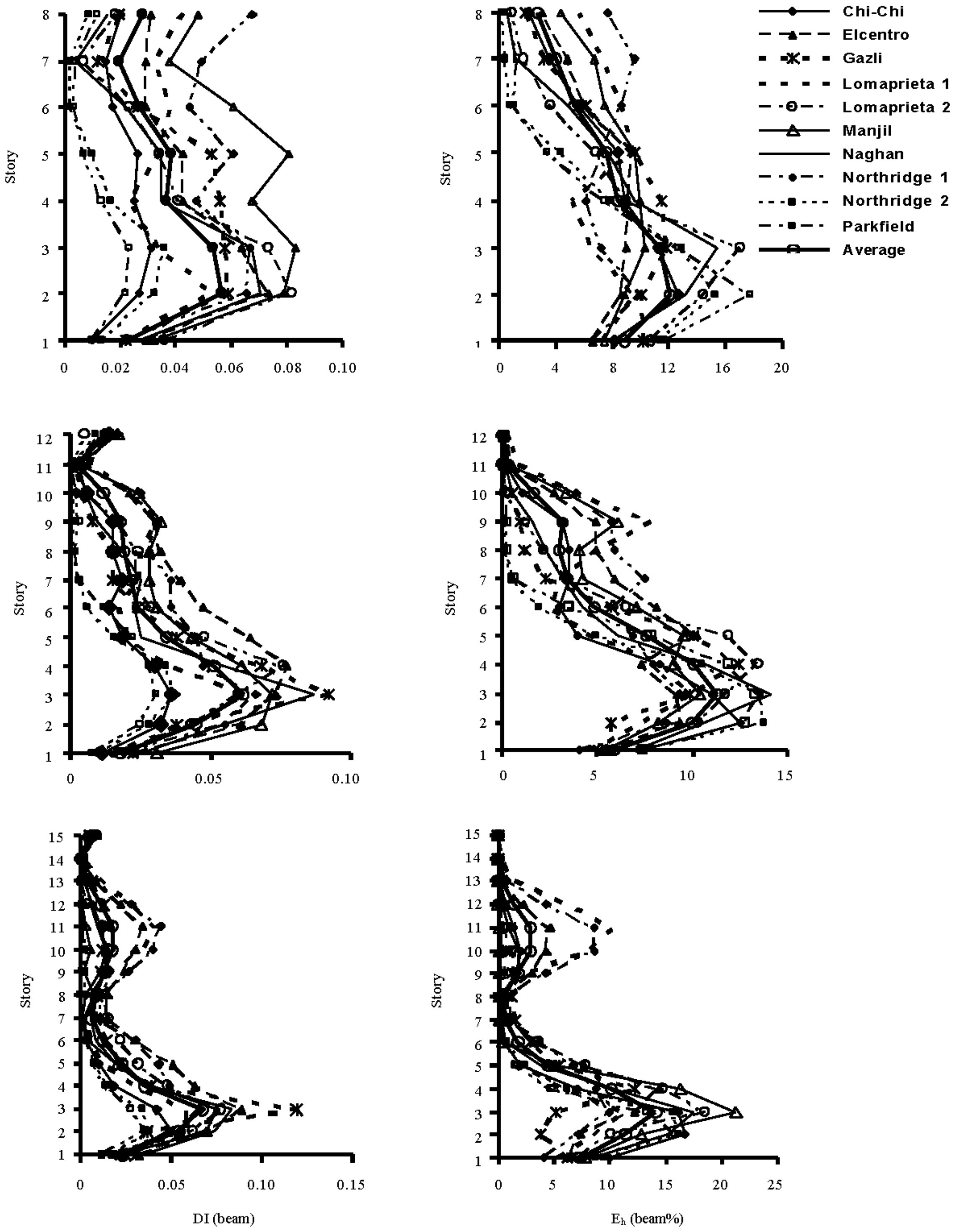

Fig. 3: Effect of ground motion on height-wise distribution of hysteretic energy and damage index of beams, 12 and 15 story buildings

Columns: Obtained results from dynamic analysis indicate that the values of ($Eh\%_{column}$) and (DI_{column}) in columns of all frames in comparison to walls and beams is very small and in most stories is close to zero and even in some stories is equal to zero. Damage index in all columns is below 0.005, which would suggest negligible cracking (Fig. 5).

Frames: Considering the obtained results and performed studies in previous sections, height-wise distribution of ($Eh\%_{frame}$) and (DI_{frame}) in 8, 12 and 15 story buildings subjected to 10 earthquakes have been shown in Fig. 4. According to, the median values' plot of hysteretic energy and damage indices, the maximum and minimum values of three 8, 12 and 15 story frames occurred in the first and

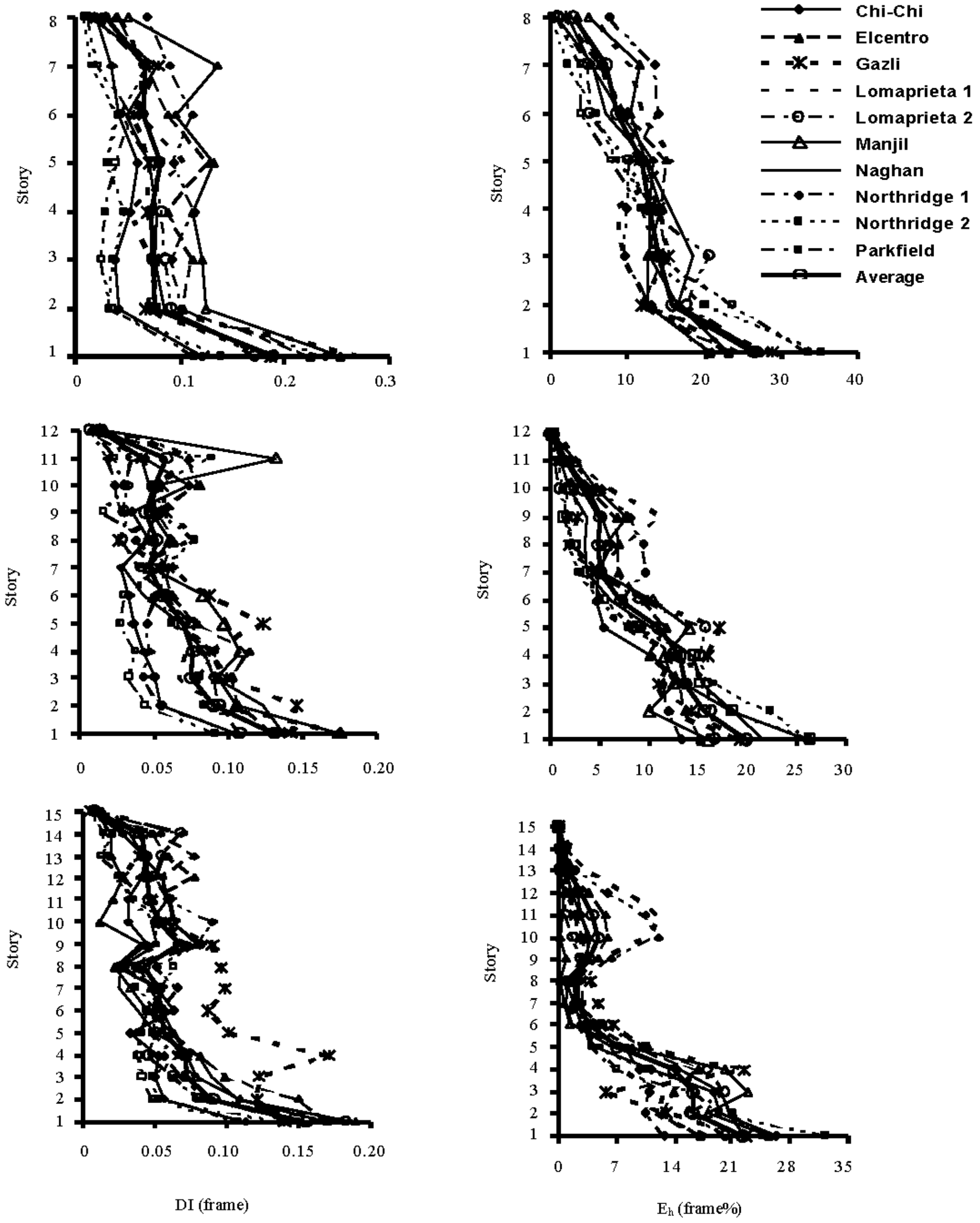

Fig. 4: Comparison of the average values of height-wise distribution of hysteretic energy and damage index of walls, beams, columns and frames in 8, 12 and 15 story buildings

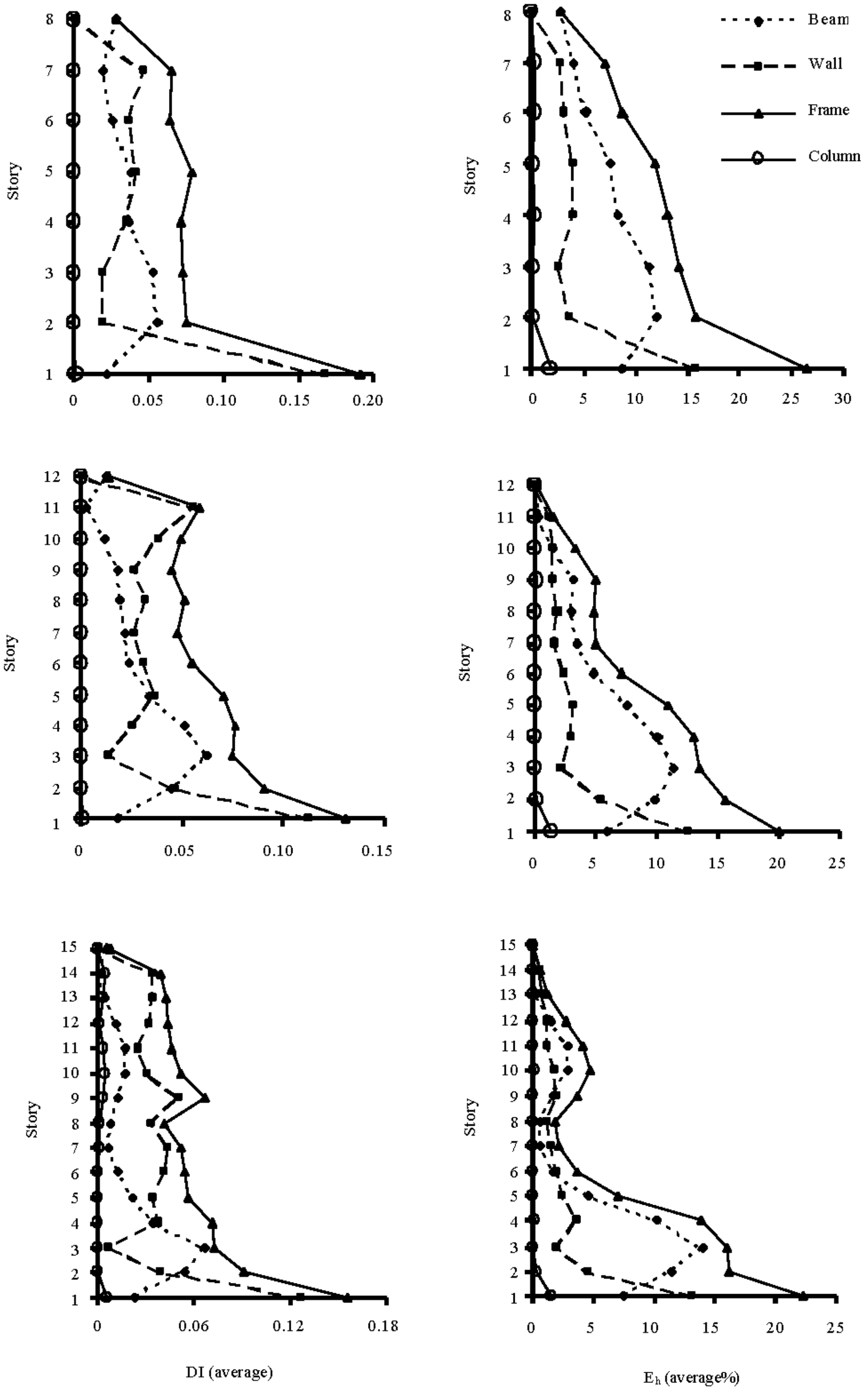

Fig. 5: Effect of ground motion on height-wise distribution of hysteretic energyand damage index in 8, 12 and 15 story buildings

last story, respectively. Although, strength ratios of stories in all frames were considered the same, the differences percentages between the maximum and minimum of $(Eh\%_{frame})$ in 8, 12 and 15 story buildings are 89.1, 99.1 and 99.7, respectively. These values for damage indices are 84.7, 89.5 and 94, respectively. In addition the amount of $(Eh\%_{frame})$ and (DI_{frame}) for the roof are negligible, so it can be explained that most of the elements (wall, beam and column) in this story remain in elastic state and this story experience the least damage compared to other stories.

Comparison of hysteretic energy and damage distribution in the walls, beams and frames in stories levels: Here, values of (Eh%) and DI in beams, walls, columns and frames in stories levels of each frame were compared with each other (Fig. 4). It was observed that in each three building, (Eh%) and DI of the first story was completely affected by $(Eh\%_{wall})$ and (DI_{wall}), while these parameters from the 2th-4th story were affected by $(Eh\%_{beam})$ and (DI beam). This indicates that the influence of beams and walls behavior in various stories is different and the values of $(Eh\%_{column})$ and (DI_{column}) in all frames in comparison with beams and walls, are very small.

Overall structural damage index (Di overall): We have previously discussed the distribution patterns of damage index in stories based on beams, columns and walls damage indices of each story. In order to investigate the overall inelastic behavior of samples, overall damage indices $(DI_{overall})$ of all frames were calculated and then the average values of them were plotted as shown in Fig. 6. It can be observed that the maximum values of $(DI_{overall})$ occurred in 8 story building in Manjil earthquake $(DI_{overall} = 0.144)$. But in 12, 15 story frames maximum amount of $(DI_{overall})$ was observed in Gazli earthquake where overall damage indices are 0.109, 0.125, respectively. Figure 6 shows that structures having different stories, the influence of earthquakes on the structures is completely different. It can be observed that $(DI_{overall})$ is lower than 0.15, i.e., the structures did not undergo severe damage. However, since $(DI_{overall})$ is only a description of general damages exerted to the structure and does not explain the energy dissipation, drift and damage distribution pattern in stories, it is necessary to investigate the drift and damage indicates in stories separately.

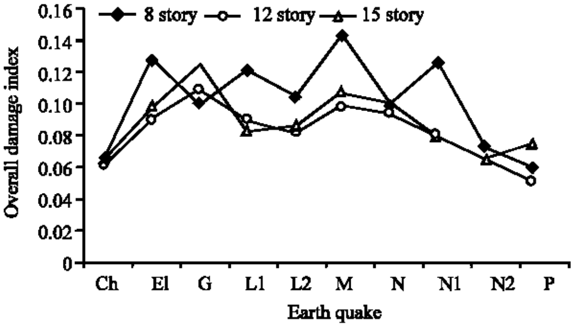

Fig. 6: Effect of ground motion on overall damage index in 8, 12 and 15 story buildings

Drift ratio in stories levels: Taking into consideration of stories drift ratio plots, it is clear that the maximum drift ratios in all frames occurred in the third story, whereas the minimum ones in 12 and 15 story frames and in 8 story frame occurred in the last and first story, respectively (Fig. 7). According to Fig. 3 and 7, it was observed that for RC buildings with shear wall, the way of distribution of (Eh%), DI in beams and drift in levels of each story were relatively similar. The differences percentages between maximum and minimum of drift ratio in 8, 12 and 15 story frames are 45.5, 73.2 and 82.6, respectively.

From the earlier described, it can be concluded that, although the average value of overall structural damage indices of 10 earthquakes indicates that the structures did not undergo severe damage according to Park and Ang damage calibration. A study of drift and damage indices in stories especially in earthquake with high intensity like Manjil and Gazli showed that the structures underwent more damage in one or two stories. Although, strength ratios were considered uniform in stories height, the distribution of Eh%, DI and drift for severe strong ground motions with high intensity were non-uniform and an intense concentration of mentioned parameters occurred in one or two stories in walls, beams and frames. In severe earthquakes, non-uniform distribution of damage and drift imply that considering a matchless strength parameter in seismic loading pattern is not capable of guaranteeing building safety.

This indicates that concurrent consideration of strength, drift and energy parameters is necessary in an optimum seismic design. These findings have been confirmed by the results reported by Karami *et al.* (2004) and Moghaddam *et al.* (2005). They studied the effect of the conventional lateral loading pattern (i.e., equivalent static method) specified by the different seismic codes (Uniform Building Code, 1997; NEHRP Recommended Provisions, 1994) on height wise distribution of ductility demand and drift in a number of steel shear-building and concentric braced-steel frames. It was concluded that the strength distribution patterns suggested by these seismic codes do not lead to a uniform distribution of ductility and deformation in steel shear-building and concentric braced-steel frames subjected to severe earthquakes.

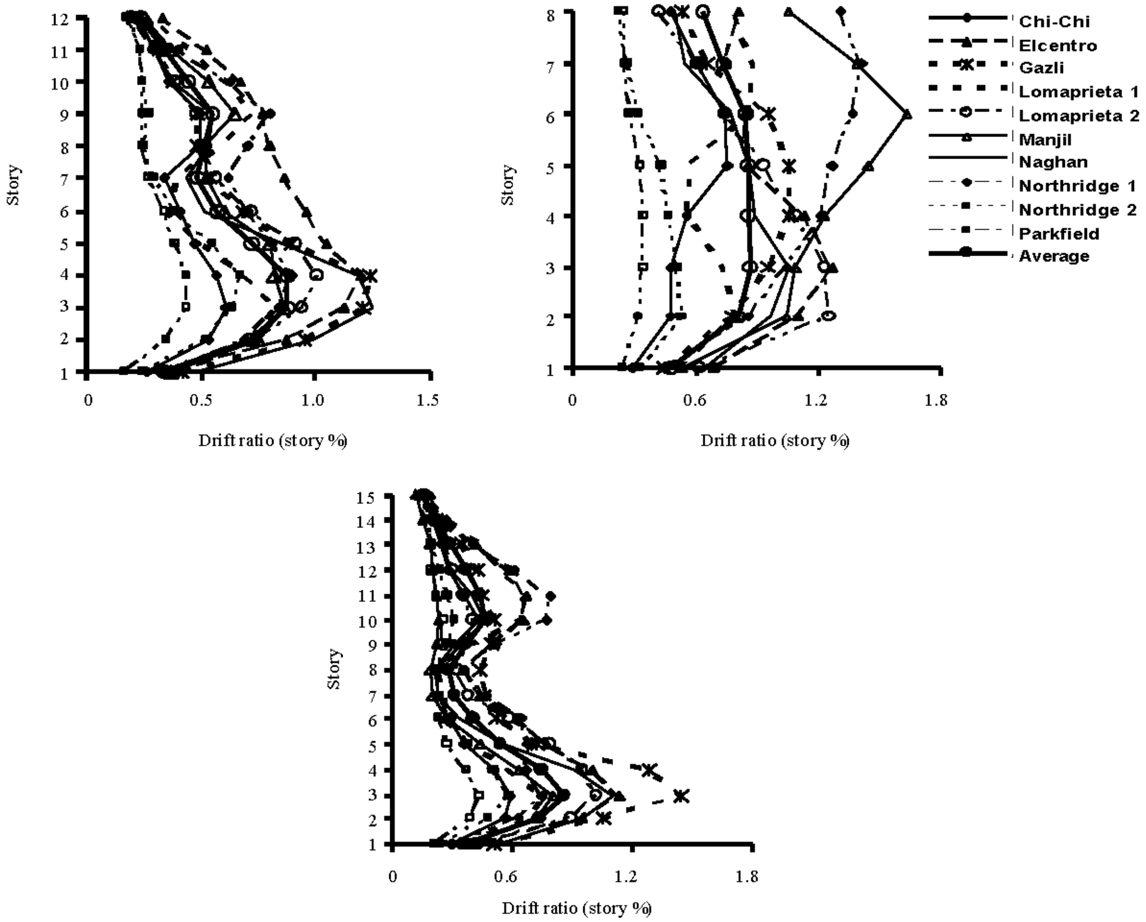

Fig. 7: Effect of ground motion on height-wise distribution of drift in 8, 12 and 15 story buildings

CONCLUSIONS

In this study, seismic behavior of RC buildings with shear wall based on Iranian Seismic Code (2005) (Third edition) subjected to 10 severe earthquakes have been investigated. The following observations and conclusions are presented:

- In RC buildings with shear wall, values of hysteretic energy and damage of columns in each story was very negligible. This confirms strong column and weak beam discussion and indicates that beams yield sooner than columns and experience more damage
- Because of effect of shear wall in the frames, the mean of maximum value of damage indices for 10 earthquakes was small and equaled to 0.188. This represent that structures have not been ruptured and structures are repairable
- Roof floor, of all models experienced the least damage compared to other floors. In addition, the amount of hysteretic energy for roof was negligible, so it can be said that most of the elements of this story stay in elastic state and the small damage observed in the story is only due to drift effect
- A study of drift and damage indices in stories especially in earthquake with high intensity like Manjil and Gazli showed that the structures underwent more damage in one or two stories. Although, strength ratios were considered uniform in stories height, the distribution of Eh%, DI and drift for severe strong ground motions with high intensity were non-uniform and an intense concentration of mentioned parameters occurred in one or two stories in walls, beams and frames. In severe earthquakes, non-uniform distribution of damage and drift imply that considering a matchless strength parameter in seismic loading pattern is not capable of guaranteeing building safety. This indicates that concurrent consideration of strength, drift and energy parameters is necessary in an optimum seismic design

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