INVESTIGATION OF HYSTERETIC ENERGY, DRIFT AND DAMAGE INDEX DISTRIBUTION IN REINFORCED CONCRETE FRAMES WITH SHEAR WALL SUBJECTED TO STRONG GROUND MOTIONS

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ABSTRACT :

In conventional earthquake-resistant design, the loading effect of the earthquake is represented by static equivalent forces, which are calculated from elastic response spectra and are related to the peak ground acceleration (PGA) with the pseudo-acceleration. This approach, however, presents several shortcomings when the inelastic response is of concern. Current provisions for seismic design are based on peak demands without explicit consideration of cumulative damage effects and energy-dissipation capacity resulting from inelastic cyclic response. Studies have shown that most structures subjected to strong ground motions fall into an inelastic state. Thus it is necessary to study the inelastic behavior of structures undergoing such earthquakes. In this study, some reinforced concrete frames with shear wall are considered. The preliminary designs of these frames are based on equivalent static forces accordance to 6 patterns of loadings distribution (UBC; NEHRP; Iranian Seismic Code, Modified Rectangular; First Mode and Three First Modes).The aim of this study is to investigate the distributions of damage in accordance with 6 these patterns. IDARC 2D software has been used to calculate maximum drift, hysteretic energy and structural damage index subjected to severe earthquakes. The results show that the current seismic design based on strength principles, even considering uniform strength distribution, does not lead to a uniform distribution of hysteretic energy, drift and damage index in stories height. However, modified rectangular and three first Modes' patterns show more uniform distribution of damage rather than others.

KEYWORDS: Shear wall, hysteretic energy, damage index, nonlinear dynamic analysis.

1. INTRODUCTION

The preliminary design of most buildings is based on the equivalent static forces specified by the governing building code. The height-wise distribution of these static forces (and therefore, stiffness and strengths) seems to have been based implicitly on the elastic vibration modes (Green, 1981), However, structures do not remain elastic during severe earthquakes and they usually undergo large nonlinear deformation. Therefore, the employment of such arbitrary height-wise distribution of seismic forces may not necessarily lead to the best seismic performance of a structure. Current study indicates that during strong earthquakes the deformation demand in structures does not vary uniformly. Therefore, it can be concluded that in some parts of the structure, the deformation demand does not reach the allowable level of seismic capacity, and therefore, the material is not fully exploited. If the strength of these strong parts decreases, the deformation would be expected to increase (Riddell et al., 1989; Vidic et al., 1994). Many experimental and analytical studies have been carried out to investigate the validity of the distribution of lateral forces according to seismic codes. Lee and Goel (2001) analyzed a series of 2–20 story frame models subjected to various earthquake excitations. They showed that in general there is a discrepancy between the earthquakes induced shear forces and the forces determined by assuming distribution patterns. 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 (2001) studied the effect of the conventional lateral loading pattern (i.e. equivalent static method) specified by the different seismic codes (UBC, 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. In this study three reinforced concrete frames with shear wall were considered. The seismic loading of these frames were applied to equivalent static method accordance to 6 patterns of loadings distribution (UBC, 1997; NEHRP, 1994; Iranian seismic code, 2005; Modified Rectangular; First MODE, and Three First MODE). 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.

2- LATERAL LOADING PATTERNS

In most seismic building codes (Uniform Building Code, 1997; NEHRP, 1994 and Iranian Seismic Code, 2005) the height wise distribution of lateral forces is determined from Eqn. 2.1.

$$F_i = \frac{w_i \, h_i^k}{\sum_{j=1}^{N} w_j \, h_j^k} \cdot V \qquad (2.1)$$

where w_i and h_i are the weight and height of the *i*th 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-94 code, k increases from 1 to 2 as the period varies from 0.5 to 2.5s. In some such as UBC-97, the force at the top floor (or roof) computed from Eqn. 2.1 is increased by adding an additional force (See Eq.2), for a fundamental period T greater than 0.7 s. In such a case, the base shear V in Eqn. 2.1, is replaced by $V - F_t$. In this study, the value of k in Eqn. 2.1 on the base of Iranian Code (2005) and UBC 1997 Codes, is taken as 1 (triangular loading pattern). For Three First Modes, base shear forces in each mode are combined using of the Complete Quadratic Combination (CQC) method. In addition, in modified rectangular loading pattern, uniform distribution of shear force in story height with a concentrated force at the top floor based on Eqn.2.2 was considered.

$$F_t = 0.07 T F_i \qquad (2.2)$$

To compare the results and more precise investigations, total base shear in all patterns has been considered equal.

3. NON LINEAR 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 (Valles et al., 1996) has been used to compute the response of the structures to nonlinear time history. 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 and Ang (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.

3.1. 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:

$$DI = \frac{\theta_m - \theta_r}{\theta_u - \theta_r} + \frac{\beta}{M_y \theta_u} E_h \tag{3.1}$$

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_y is the yield moment; and E_h 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. (Park et al. 1987) suggested these interpretations for the damage index:

$D < 0.10$	No damage or localized minor cracking
$0.10 < D < 0.25$	Minor damage–light cracking throughout
$0.25 < D < 0.40$	Moderate damage–severe cracking, localized spelling
$0.40 < D < 1.00$	Severe damage–crushing of concrete, reinforcement exposed
$D \geq 1.00$	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:

$$DI_{story} = \sum_{i=1}^{n} (DI_i)_{componet} \left[\frac{E_i}{\sum_{i=1}^{n} E_i} \right]_{componet} \tag{3.2}$$

$$DI_{overall} = \sum_{i=1}^{n} (DI_i)_{story} \left[\frac{E_i}{\sum_{i=1}^{n} E_i} \right]_{story} \tag{3.3}$$

Where DI_i are the Damage indices; and E_i are the total absorbed energy by the component or the *i*th story.

4. STRUCTURAL SYSTEMS AND EARTHQUAKE EXCITAIONS

4.1. Structural Systems

In present paper, three reinforced concrete buildings with shear wall, 8, 12 and 15-story frames were considered. The seismic loading of these frames were applied to equivalent static method in accordance with 6 mentioned loading patterns. Soil type II (gravel and compacted sand, very stiff clay) was used in the analyses, and it was also assumed that the structures were located in a region with relatively high seismic risk and relative design base acceleration of A=0.35g. 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 was used in nonlinear analyses (Takeda et al., 1970). The viscous damping ratio was assumed to be uniformly distributed (damping ratio=5%) and the frames were moment resisting with shear wall and with medium ductility. ETABS 2000 (computers and structures 2000) and IDARC 2D, Ver. 6.1(Valles and Reinhorn, 2006) Softwares, were used for initial elastic analysis and design, and for nonlinear dynamic analysis, respectively. In design and analysis of structures, P-Delta effect was considered. A sample of 8-story frame has been shown in Figure 1. It should be noted that the hysteretic energy in each story has been shown as the percentage ratio of hysteretic energy in each story to the total hysteretic energy in each frame**.**

4.2. Earthquake Excitations

7 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 35 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. Real characteristics of earthquake records used in this study are shown in Table 1.

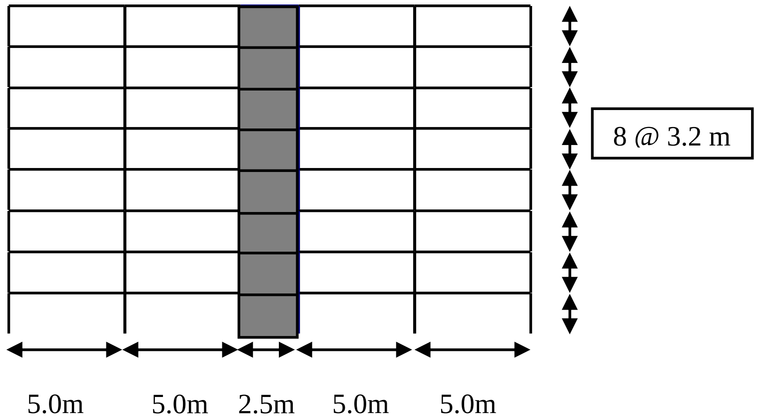

Fig 1. 8- story frame

Table1. 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	0.313
Gazli	05-17- 1976	6.8	0.608
Lomaprieta	18-10-1989	6.93	0.512
Manjil	20-06-1990	7.7	0.55
Naghan	06-04-1977	6.1	0.72
Northridge	17-01-1994	6.7	0.514
Parkfield	28-06-1966	6.1	0.442

5-RESULTS AND DISCUSSIONS

5.1. Hysteretic energy (Eh(%))
Figure 2 illustrates the distribution of average value of hysteretic energy resulted from 7 strong ground motions for 6 loading patterns in 8, 12 and 15-story buildings. In each building, maximum and minimum hysteretic energy is observed for all loading patterns in the first and last stories, respectively. In all patterns, value and the form of height-wise distribution of Eh(%) in all buildings are similar. Also, figure 2 shows that in each three buildings, modified rectangular loading pattern has maximum value of Eh(%) in lower stories and the minimum one in upper stories. While these values in the first mode loading pattern are completely reverse. In other patterns, the values of Eh(%) in upper and lower stories are also between these two patterns. Table 2 shows the Coefficient of Variation (COV) of Eh(%) in each three building for different patterns. These amounts have been obtained from the average results of 7 earthquake records. In 8-story building, modified rectangular and three first modes loading patterns have a better performance than the other patterns. Similar results were obtained for 12 and 15-story frames.

5.2. Structural damage(DI)
Figure 2 indicates the average values of structural damage indices resulted from 7 strong ground motions for 6 loading patterns in 8, 12, 15-story buildings. It seems that by increasing the number of stories, height-wise distribution of damage in all patterns are almost similar to the distribution of the Eh(%). Considering COV of DI in each three buildings, It can be seen that the results are similar to those of hysteretic energy in a way that in each three building, performance of modified rectangular and three first modes loading patterns are better than the other patterns (See Table 2).

5.3. Drift
Amounts and forms of story drift ratios(%) for 6 loading patterns have been shown in figure 3. In 12- and 15-story buildings, maximum drift of upper stories is related to modified rectangular loading pattern but minimum one is related to UBC and 1- mode patterns. This concept is completely reverse in lower stories. Unlike the distribution of Eh(%) and DI that their maximum amounts occur in the first story, the most relative drift for different patterns in 8-story building is observed in the fifth story, but in 12-story building, this amount occurs in the seventh and third stories, and in 15-story building, it occurs in the third story. It means that if the number of stories increases, the maximum relative drift of stories tends to lower stories, also its minimum value occurs in upper stories. Note that the Eh(%) in middle stories, particularly in 12 and 15-story buildings, for all patterns is very close to each other, so the difference of structural damage indices values of patterns in middle stories results from the drift of these stories. Considering COV value of these patterns resulted from the drift, it can be observed that first-mode pattern compared to other patterns, cannot be a suitable pattern for the distribution of shear force (Table 2).

Table2. A comparison of COV of Eh(%), DI and drift for 6 loading patterns in 8, 12 and 15-story buildings

	story	First MODE	Three First MODE	UBC& Iranian Codes	NEHR P	Modified Rectangular
DI	8	1.47	1.07	1.43	1.45	1
	12	2.32	1.51	1.64	1.65	1.53
	15	2.34	2.17	2.32	2.31	2.16
Eh (%)	8	1.6	1.19	1.44	1.46	1.06
	12	3.28	2.12	2.48	2.43	1.95
	15	4.21	3.31	3.97	4	3.15
Drift ratio (%)	8	0.583	0.554	0.508	0.475	0.59
	12	1.66	0.991	1.05	1.02	0.942
	15	2.01	1.61	1.8	1.98	1.55

6. OVERALL DAMAGE INDEX ($DI_{overall}$)

Figure 4 Indicates the average value of overall damage indices for different patterns resulted from several severe earthquakes. It can be observed that for all patterns, $DI_{overall}$ are less 0.2, which means that buildings do not undergo severe damage. Even though this damage index shows only a description of overall damage in structure, local damage maybe more than these values in building members. This damage does not show the distribution value of relative drift, hysteretic energy and structural damage in stories. From figure 4, it can be observed that although in 8- and 12-story buildings, maximum local damage occurs in the first-mode pattern, maximum amount of overall damage is belong to the frames loaded on the base of modified rectangular pattern.

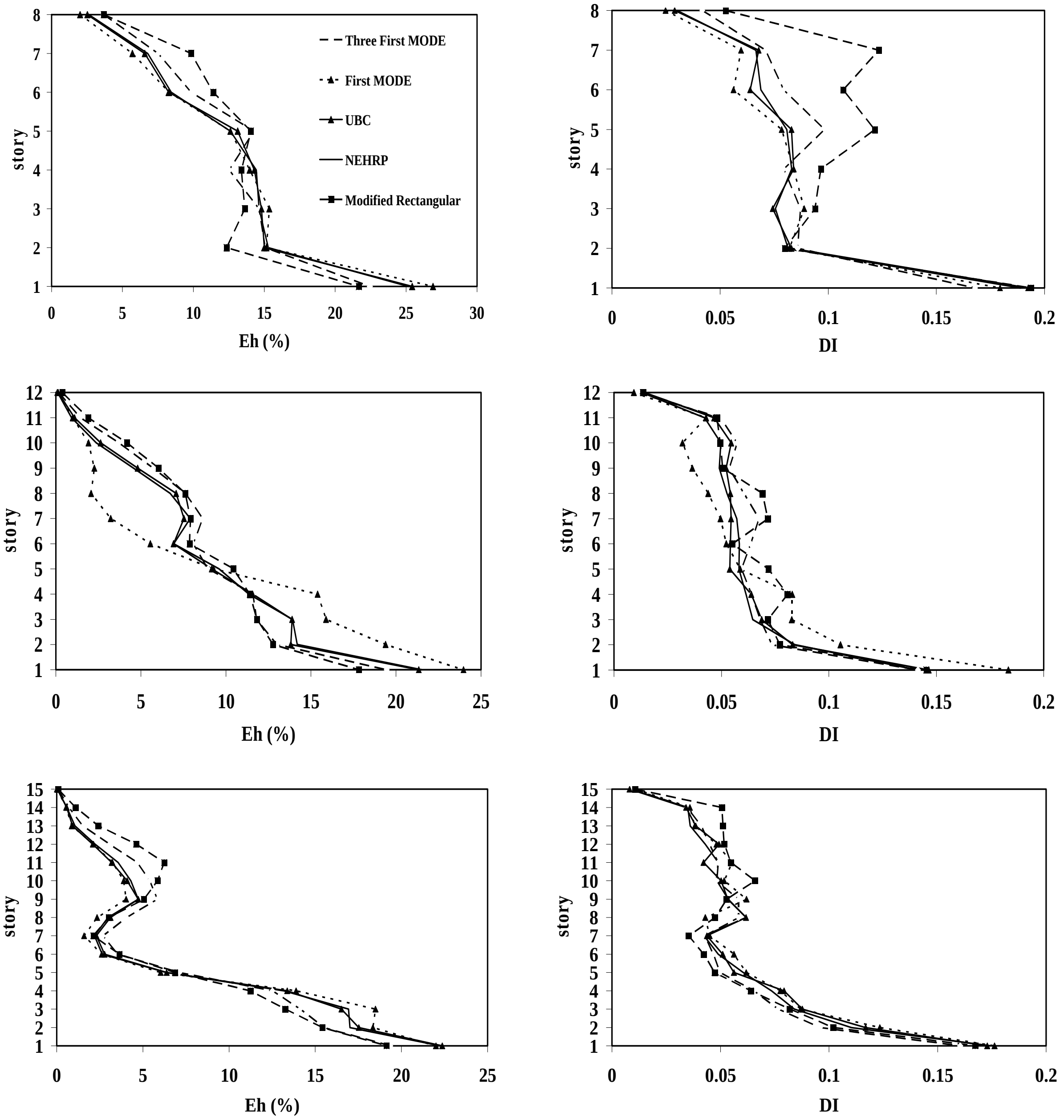

Figure 2 Distributions of average values of hysteretic energy and damage index, resulted from 7 strong ground motions for 6 loading patterns in 8, 12 and 15-story buildings

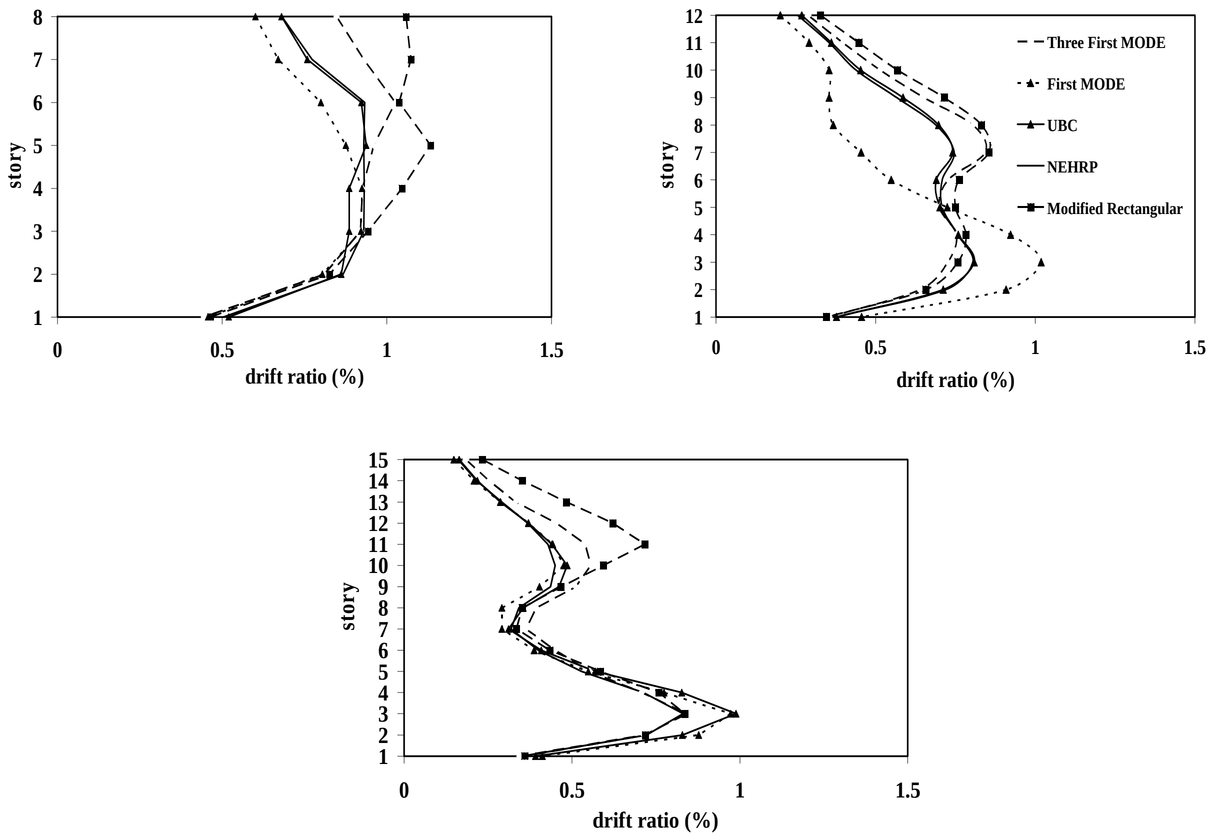

Figure 3. Distributions of average values of drift ratio resulted from 7 strong ground motions for 6 loading patterns in 8, 12 and 15-story buildings

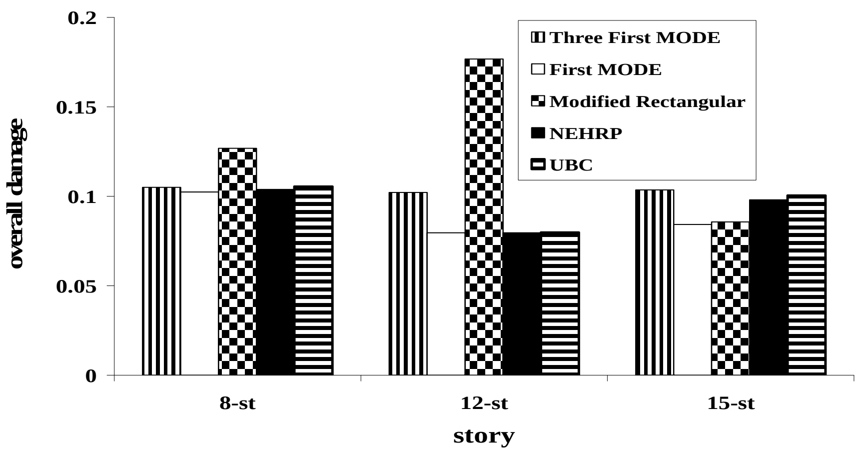

Figure 4 Comparison of the average values of overall damage indices for 6 loading patterns in 8, 12 and 15-story buildings

7- CONCLUSION

This study has examined the sensitivity of different loading patterns on the way of the distribution of Eh(%), DI and Drift of 8,12 and 15-story reinforced concrete buildings with shear wall under 7 severe earthquake. Dynamic analysis results of these models can be stated as follows:

- In each three buildings, the distributions of the hysteretic energy and damage index for all loading patterns are relatively similar, so that maximum and minimum of these values in all patterns occur in the first and the last stories, respectively. Average values of structural damage indices for these patterns in the first story are 0.185, 0.15 and 0.171 respectively. This shows that the buildings have not been damaged significantly and they are repairable. This can be due to the existence of shear wall.

- In each three buildings, for all patterns, the damage index of upper stories is more resulted from the stories drift, while the damage index of the first story can be more resulted from the absorption of Eh(%). With studying the distribution of hysteretic energy, structural damage index and drift and COV values of these amounts can conclude that drift cannot show all characteristics of structural damage, and other factors such as Eh(%) plays a role in structural damage, as well.
- In all loading patterns, maximum and minimum amounts of hysteretic energy, damage index and drift in all three building are related to first mode loading pattern and COV of these values in this pattern in each three buildings is more than those of other patterns, so this loading pattern compared to other patterns cannot be appropriated. While modified rectangular and three first modes patterns has better performance. By increasing the number of stories, COV of each of these patterns will increase.
- Distributions of Eh(%), DI and drift hysteretic energy, damage and drift, resulted form strong ground motions for all patterns are not uniform and a concentration of mentioned parameters is observed in one or two stories.

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