DISTRIBUTION OF DRIFT, HYSTERETIC ENERGY AND DAMAGE IN REINFORCED CONCRETE BUILDINGS WITH UNIFORM STRENGTH RATIO

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ABSTRACT :

Assessment of the behavior of structures during recent earthquakes indicates that much damage has happened to the buildings including those designed according to the engineering principles. The preliminary design of most of buildings is based on equivalent static and spectral dynamic forces specified by the governing seismic codes. The height-wise distribution of these horizontal forces seems to be based implicitly on the elastic vibration modes. 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. The aim of this study is to investigate the effect of the two above-mentioned lateral loading patterns on height-wise distribution of drift, hysteretic energy and damage subjected to severe earthquakes by considering four reinforced concrete buildings. The results indicate that in strong ground motions, none of the lateral loading patterns will lead to uniform distribution of drift, hysteretic energy and damage, and an intense concentration of the values of these parameters can be observed in one or two stories especially in equivalent static method. This will consequently hinder the serviceability of the maximum capacity of structures.

KEYWORDS: RC buildings, drift, hysteretic energy, damage distribution, lateral loading patterns.

1. INTRODUCTION

Structures with inappropriate distributions of strength and stiffness have performed poorly in recent earthquakes, and most of the observed collapses have been related to some extent to problematic configuration or a wrong conceptual design. A soft story has been observed in many collapsed structures because of having non-suitable distribution of structural stiffness. Different types of strength and stiffness distributions are responsible for a deficient structural behavior. Concentrated drift and ductility in some stories are the worst conditions and the consequent results can be catastrophic. Most buildings are preliminary designed on the basis of the equivalent static forces under the governing code. It seems that the height-wise distribution of these static forces (and therefore, stiffness and strength) is factually based on the elastic vibration modes (Green, 1981). However, structures do not remain elastic during severe earthquakes and they usually undergo large nonlinear deformations. Therefore, the application of such conventional height-wise distribution of seismic forces may not actually cause the best seismic performance of a structure. Chopra (2001) evaluated the ductility demands of several shear building elastoplastic models subjected to 1940 El Centro earthquake. The relative story yield strength of these models pertained to the height-wise distribution pattern of the earthquake forces which Uniform Building Code (UBC) clearly specified in 1994. It is perfectly realized that this distribution pattern does not make equal ductility demand in all stories possible, and that the first story has the most ductility demand among all other stories. Moghaddam and Hajirasouliha, 2004 and Karami Mohammadi 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 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. In this study four reinforced concrete frames were considered. The seismic loading of these frames were applied according to two conventional patterns, namely equivalent static and spectral dynamic methods in accordance with the Iranian Code of Practice for Seismic Resistant Design of Buildings (2005). In the design of these samples a basic assumption has been considered, that is, a constant strength ratio (the ratio of the existing strength to the ultimate strength) has been applied in all stories. A great effort was made to achieve optimum conditions for arriving at a consistent value of 0.9 for this ratio in both methods. The aim of this study is to investigate whether or not, reaching optimum condition mentioned above based on different lateral loading patterns specified by the governing seismic codes will result in reduction and optimum damage distribution subjected to severe earthquakes.

2. LATERAL LOADING PATTERNS

2.1. Equivalent Static Method

In most seismic building codes (Uniform Building Code, 1997; NEHRP Recommended Provisions, 1994; ATC-3-06 Report, 1978; Iranian Seismic Code, 2005), the height wise distribution of lateral forces is determined from Eqn. 2.1.

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

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 such as NEHRP-94, k increases from 1 to 2 as the period varies from 0.5 to 2.5 s. In some codes such as UBC-97, the force at the top floor (or roof) computed from Eqn. 2.1 is increased by adding an additional force $F_t = 0.07\,TV$ 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 based on the Iranian Seismic code (2005) is taken as 1 (triangular loading pattern).

2.2. Spectral Dynamic Method

In this method, dynamic analysis is performed assuming linear elastic behavior using maximum response from all vibration modes which have considerable effect on response of the entire building. Maximum response of each mode is obtained using its period from the standard design spectrum. The height-wise distribution of lateral forced in spectral dynamic method is determined from Eqn. 2.*2*.

$$F_{im} = \frac{w_i\ \phi_{im}}{\sum_{j=1}^{N} w_j\ \phi_{jm}} \cdot V_m \tag{2.2}$$

Where ϕ_{im} is the *m*th vibration component in the *i*th floor above the base, V_m the shear force of the *m*th mode and F_{im} is the horizontal force acting on the *i*th floor from the *m*th mode. The maximum story and base shear forces in each mode are combined using one of the common statistical methods, namely: Complete Quadratic Combination (CQC), or Square Root of Sum of Squares (SRSS). In this study the Iranian Standard Design Spectrum (Iranian Seismic Code, 2005) is used for both, equivalent static and spectral dynamic methods.

3. DAMAGE ANALYSIS

3.1. Park & Ang Damage Model

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.
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:

$$DI_{story} = \sum (\lambda_i)_{component} (DI_i)_{component} ; (\lambda_i) = \left[\frac{E_i}{\sum E_i} \right]_{component} \tag{3.2}$$

$$DI_{overall} = \sum (\lambda_i)_{story} (DI_i)_{story} ; (\lambda_i)_{story} = \left[\frac{E_i}{\sum E_i} \right]_{story} \tag{3.3}$$

Where λ_i are the energy weighting factors; and E_i are the total absorbed energy by the component or the *i*th story. 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

4. STRUCTURAL SYSTEMS AND GROUND MOTIONS

4.1. Structural Systems

Reinforced concrete frames of 3, 5, 10 and 15- story structures with identical bays and story heights have been used in present study. The total height to the total building dimension ratio in these samples varies from 0.96 to 4.8 for 3- and 15- story frames, respectively. These models have been chosen to represent three common building behaviors (shear, flexural and shear-flexural behavior). A sample of 5- story frame is shown in Figure1. In order to correctly compare the effects of two lateral loading patterns (equivalent static and spectral dynamic methods) on height-wise distribution of hysteretic energy, drift and damage, analysis and design processes have been completely similar for both patterns. Other details of analysis and design are as follow: The vertical and lateral loadings of the structures were applied according to Iranian Code of Practice for Seismic Resistant Design of Buildings (2005), respectively. Soil type II (gravel and compacted sand, very stiff clay) was used in the analyses, and it was also assumed that the structures are located in a region with relatively high seismic risk and relative design base acceleration of A= 0.35g. The frames are moment resisting with medium ductility**.** IDARC 2D version 6.0 software (Valles et al., 2004) was used for nonlinear dynamic analysis. All the analyses were performed with damping model corresponding to stiffness, and damping ratio of 5%. Tri-linear hysteretic model of Takada was used in nonlinear analyses (Takeda et al., 1970).

4.2. Ground Motions

For input ground motions, 7 observed ground motions are used. Emphasis is placed on those recorded at a low to moderate distance from epicenter (less than 45 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. In order to eliminate the influence of peak ground acceleration, all of them are scaled to a ground acceleration of 0.35g based on Iranian seismic code (2005).

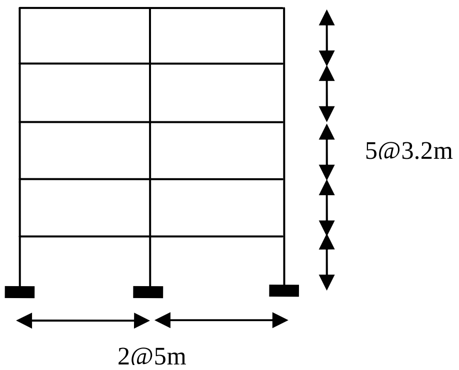

Figure 1. 5- story frame

Table 1. Earthquakes records used in this study

Earthquake	Occurrence Date	Magnitude	PGA (g)
Manjil	20.06.1990	7.7	0.55
Naghan	6.04.1977	6.1	0.72
Tabas	16.09.1978	7.4	0.836
El Centro	19.05.1940	7	0.313
Kobe	16.01.1995	6.9	0.821
Chi-Chi	20.09.1999	7.6	0.821
Northridge	17.01.1994	6.7	0.842

5. RESULTS AND DISCUSSIONS

5.1. Height-Wise Distribution of Hysteretic Energy, Drift and Damage Index in Samples

In order to study the height-wise distribution of hysteretic energy (***Eh***%) and story damage index (DI_{story}) in the frames, the beams and columns were chosen as the consisting elements of each story. According to UBC (1997), if seven or more time-history analyses are performed, then the average value of the response parameter of interest may be used for design. Therefore, in this regard, the average values of height-wise distribution of ***Eh***%, drift, and DI_{story}, subjected to 7 strong ground motions in two lateral loading patterns known as equivalent static (ES) and spectral dynamic (SD) methods, were calculated and then compared (Figures 2 and 3). It should be noted that the hysteretic energy of each story is shown as the percentage ratio of hysteretic energy in each story to total hysteretic energy in each frame (***Eh***%).

5.1.1. 3- and 5- story frames

In the 3- story frame, the amount and the form of height-wise distribution for ***Eh***% are completely identical in both ES and SD methods. The qualitative distribution of drift and DI_{story} in this frame is identical. However, ES method has a larger drift, and consequently, a greater amount of damage is caused in the first and second stories as compared to SD method (Figure 2). It is seen that with an increase in the height to dimension ratio (*h/d*=1.6) in 5- story frame, the distribution pattern of the mentioned parameters in this frame is completely different from those of 3- story frame. The height-wise distribution patterns of these parameters are similar in both SD and ES methods, and the maximum drift and damage occurs in the second story. However, considering an increase in drift and damage values of stories of 3, 4 and 5 from ES method comparing to those of SD method, it can be concluded that the frame loaded by SD method has a better performance in this case.

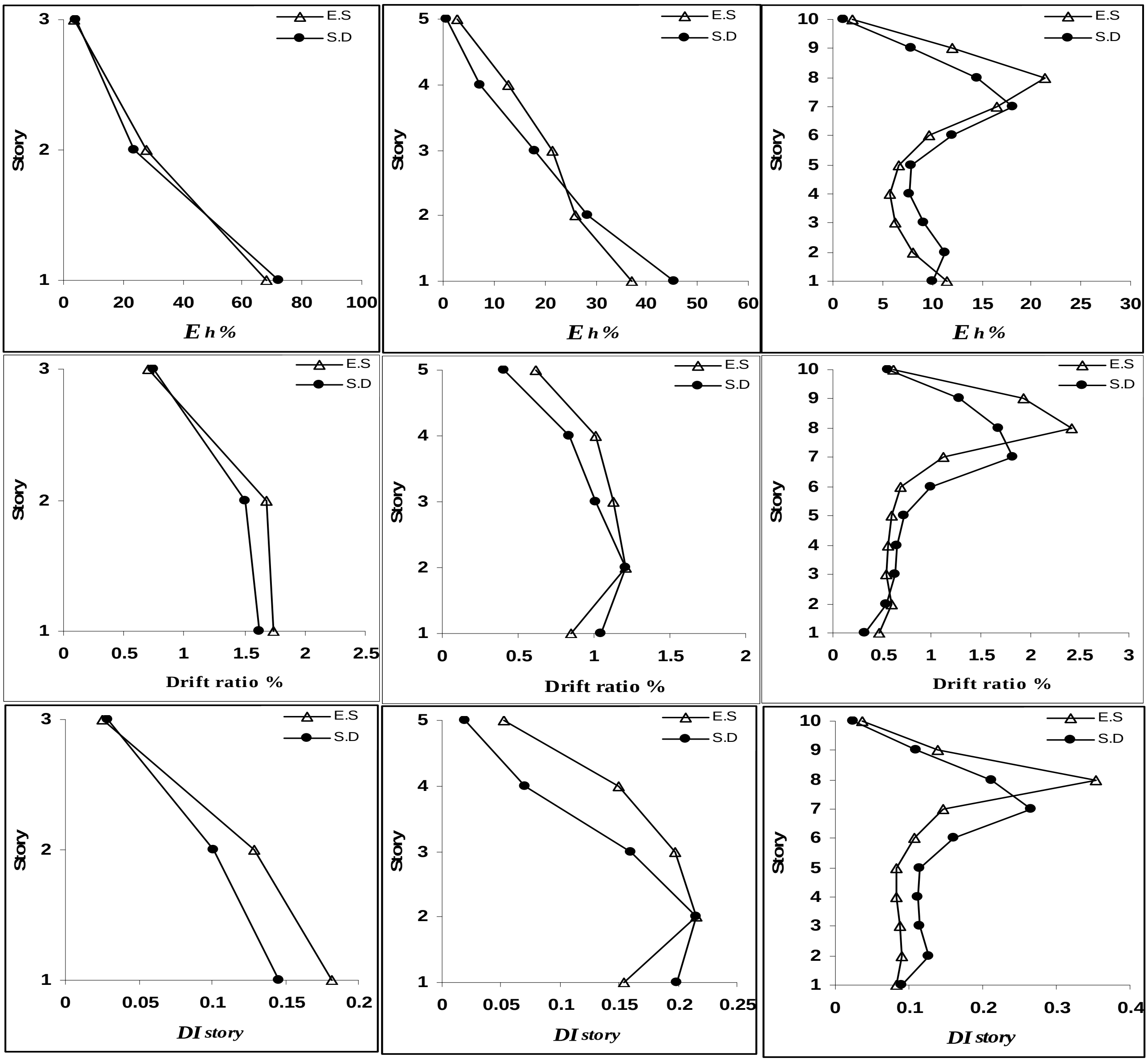

Figure 2 Comparison of the average values of height-wise distribution of hysteretic energy, drift and damage index in 3- 5 and 10- story frames from ES and SD methods

5.1.2. 10- and 15- story frames

As indicated in Figures 2 and 3, distribution patterns of drift, *Eh*% and *DIstory* in 10 and 15- story frames are completely different from those of 3- and 5- story frames, in a way that with an increase in *h*/*d* ratio of these frames (3.2 and 4.8 for 10- and 15- story, respectively) a concentration of the mentioned parameters is observed in either the second or third story below roof. This seems logical considering the effect of higher modes and the involvement of flexural mode. Notable facts are observable from these figures as follow: First, in the lower stories of 10- and 15- story models (the first five or seven stories), the amounts of drift, ***Eh***% and *DIstory* in SD pattern are slightly higher than those of ES pattern, whereas the opposite occurs in the upper stories, and the values from ES pattern are considerably higher compared to SD pattern. In addition, regardless the uniform strength ratio distribution in the elastic method, height-wise distribution of drift, ***Eh***% and *DIstory*, subjected to strong ground motions is non-uniform and an intensive concentration of the mentioned parameters occurs in one or two stories especially in ES patterns. In other words, although ES frames are made of larger beam and column cross-sections compared to those of SD frames, the difference between maximum and minimum of the mentioned parameters in height is much higher in ES frames than to SD frames for both 10- and 15- story frames. An intense concentration of drift, ***Eh***% and *DIstory* occurs in the 8th and 13th story of 10- and 15- story frames, respectively. Thus it can be said that although frames with dynamic spectrum loading patterns do not lead to uniform distribution of drift and *DIstory* in height, they generally show better performance compared to frames with equivalent linear loading pattern. Second, roof floors of all models (3, 5, 10 and 15- story frames) show the least damage compared to other floors from both SD and ES patterns. Also, the amount of absorbed hysteretic energy (***Eh***%) for the roof is negligible and approximately zero in value, so it can be stated that most of the elements of this story remain in elastic state. The minor damage caused in the story is only due to the drift. Thus, applying ***Ft*** in the equivalent static method (Eqn. 2.1) which describes, in someway, the effect of higher modes seems to be prone to discuss. This story, on the other hand, undergoes the least damages compared to other stories.

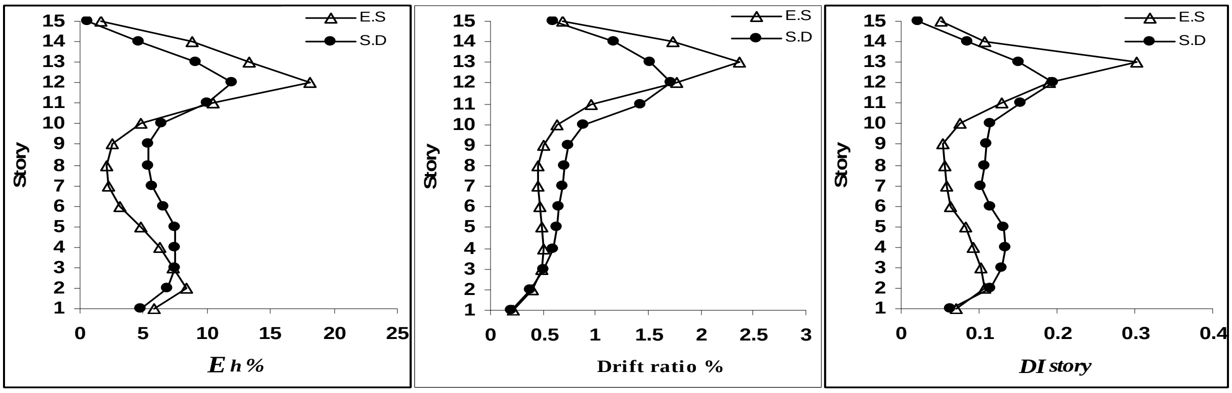

Figure 3 Comparison of the average values of height-wise distribution of hysteretic energy, drift and damage index 15-story frame from ES and SD methods

5.2. Effect of Ground Motion on Height-Wise Distribution of Drift and Damage Index

In the previous section, the average values of drift, ***Eh***% and *DIstory* obtained due to seven earthquakes were used in order to prevent the scattering of the results from various ground motions. None of two earthquakes, even those occurring in the same region, have completely similar characteristics. Thus, considering the fact that the earthquakes chosen in this study cover a broad variety of conditions in terms of intensity, duration, frequency content and peak ground acceleration, the effect of ground motion on height-wise distribution of drift and *DIstory* in 15-story frame is investigated as shown in Figure 4. As shown in this figure, an average value of these parameters from seven earthquakes may be considered. It can be noted from the distribution pattern of drift and *DIstory* that in severe earthquakes such as Northridge, Manjil and Chi-Chi, the concentration of drift and damage index are observed in one or two stories while other stories have a relatively uniform distribution. The fact that most of the elements reach inelastic deformations in such earthquakes leads to a non-uniform damage distribution. In addition, earthquakes with lower intensity (i.e. Naghan and El Centro) compared to those mentioned previously have a relatively uniform distribution of the mentioned parameters in a way that they follow a uniform height-wise distribution of strength ratio in an elastic state. These findings are confirmed by the results reported elsewhere (Moghaddam and Hajirasouliha, 2004; Karami Mohammadi et al., 2004). 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.

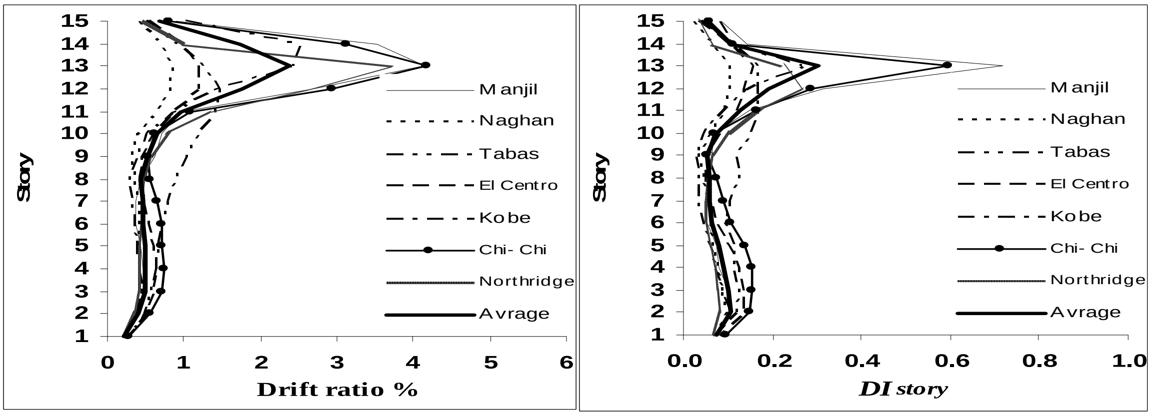

Figure 4 Effect of ground motion on height-wise distribution of drift and damage index in 15- story frame

5.3. Comparison of Overall Structural Damage Index from Spectral Dynamic and Equivalent Static Methods

In Section 4.1., distribution patterns of damage index in stories, based on beam and column damage indices from each story, were discussed. Park & Ang (Park et al., 1984) computed an overall structural damage index $DI_{overall}$ using story damage indices DI_{story} and weighting factors based on dissipated hysteretic energy at component and story levels, as described in Section 3.1. In this section a comparison between the average values of $DI_{overall}$ subjected to seven earthquakes for ES and SD methods has been made as shown in Table 2. This comparison indicates that in all structures, despite having smaller beam and column cross-sections, $DI_{overall}$ resulting from ES patterns are slightly larger than those obtained from SD patterns. This may be due to a somewhat uniform height-wise distribution of damage from SD method compared to that of ES method. Moreover, considering the average values of $DI_{overall}$ from both methods and the relation between $DI_{overall}$ and the state of the building, it can be observed that $DI_{overall}$ is lower than 0.2, i.e., the structure does 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 and drift and damage distribution patterns in stories, therefore it is necessary to investigate the drift and damage indices in stories. As shown in Figure 4, although the average values of DI_{story} are acceptable (less than 0.4), in catastrophic earthquakes such as Manjil and Chi-Chi, having high intensity and damage potential, values of drift ratio and DI_{story} in one story of 15- story frame exceed 4% and 0.7, respectively. This may lead to the formation of a soft story and collapse in the story which in turn causes an overall collapse of the structure. Thus, beside controlling overall structural damage index, the maximum drift, and stories damage indices must be checked.

Table 2. Comparison of the average values of $DI_{overall}$ in spectral dynamic and equivalent static methods

Sample	E.S	S.D	$\frac{(E.S - S.D)}{E.S} * 100$
3-story	0.14	0.12	14.28
5-story	0.15	0.14	6.67
10-story	0.19	0.17	10.5
15-story	0.18	0.16	11.10

6. CONCLUSIONS

- In severe earthquakes with high intensity, despite uniform distribution of strength ratio in elastic loading, height-wise distribution of Eh%, drift and damage are non-uniform, and an intense concentration of mentioned parameters occurs in one or two stories especially in frames with ES pattern. Furthermore, although SD frames have smaller dimensions (cross-section and total bar area) compared to those of ES frames, considering a lower overall structural damage index and rather a uniform distribution compared to ES frames, a better performance by these frames can be concluded.

- Roof floor of all models shows the least damage compared to other floors from both ES and SD patterns. Also, the amount of absorbed hysteretic energy (***Eh***%) for roof is negligible and approximately zero in value, so it can be stated that most of the elements of this story remain in elastic state. The minor damage caused in the story is only due to drift. Thus, applying ***Ft*** in the equivalent static method (Eqn. 2.1) which describes, in some way, the effect of higher modes seems to be prone to discuss. This story, on the other hand, undergoes the least damages compared to other stories.
- Although the average value of overall structural damage indices of 7 earthquakes indicates that the structures do not undergo severe damages according to Park & Ang's damage calibration, a study of drifts and damage indices in stories especially in earthquakes with high intensity like Northridge, Manjil and Chi-Chi shows that the structures undergo severe damages in one or two stories, which it can in turn lead to complete collapse of the building. Therefore, in addition to controlling overall structural damage indices, drift and structural damage indices in stories must also be checked. In strong ground motions, non-uniform distributions of drift and damage indicate that considering a unique strength parameter in seismic loading patterns, even in optimum conditions, is not capable of guaranteeing building safety. Thus, simultaneous consideration of strength, energy and drift (deformation) parameters should be considered in an optimum seismic design.

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