Journal of Applied Sciences

ISSN 1812-5654

Journal of Applied Sciences 7 (22): 3431-3441, 2007
ISSN 1812-5654

Effect of Seismic Loading Patterns on Height-Wise Distribution of Drift, Hysteretic Energy and Damage in Reinforced Concrete Buildings

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Abstract: The aim of this study is to investigate the effect of the two common lateral loading patterns named Equivalent Static (ES) and Spectral Dynamic (SD) 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.

Key words: RC buildings, drift, hysteretic energy, damage distribution, lateral loading patterns

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. However, structures do not remain elastic during severe earthquakes and they usually undergo large nonlinear deformations. 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; Anonymous, 1996) 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 earthquakes. Therefore, the application of such conventional height-wise distribution of seismic forces may not actually cause the best seismic performance of a structure.

Chopra (1995) 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 Esmailzadeh Hakimi (1999) proportioned the relative story yield strength of a number of shear building models in accordance with some arbitrarily chosen distribution patterns as well as the distribution pattern suggested by the UBC. The ductility and displacement demands of these models were calculated. It was concluded that a uniform distribution of ductility will not be achieved by the suggested pattern as was offered by the UBC and other patterns can yield a uniform ductility distribution with a relatively smaller maximum ductility demand.

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Ganjavi *et al*. (2005) considering a number of reinforced concrete buildings based on equivalent static loading patterns (Iranian Code of Practice for Seismic Resistance Design of Building, 1999) studied the height-wise hysteretic energy, drift and damage distribution subjected to four earthquakes. It has been concluded that this can lead to a relatively intense concentration of drift and damage in one or two stories of a building. 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 Resistance Design of Building (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. Although having a uniform distribution of strength ratio in the stories requires minor variations in beam and column cross-section and bar dimensions, 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.

LATERAL LOADING PATTERNS

Equivalent static method: In most seismic building codes (UBC, 1997; NEHRP, 1994; Anonymous, 1978; Anonymous, 1996; Iranian Code of Practice for Seismic Resistance Design of Building, 2005), the height wise distribution of lateral forces is determined from Eq. 1:

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

Where:

w_i and h_i = The weight and height of the ith floor above base level, respectively
N = The number of stories
V = Total base chear
k = The power that differs from one seismic code to another

In some provisions such as NEHRP-94 and ANSI-ASCE 7-95, 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 Eq. 1 is increased by adding an additional force F_t = 0.07 TV for a fundamental period T greater then 0.7 s. In such a case, the base shear V in Eq. 1 is replaced by $V\text{-}F_t$. In this study, the value of k in Eq. 1 based on the Iranian Code of Practice for Seismic Resistance Design of Building (2005) is taken as 1 (triangular loading pattern).

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 Eq. 2:

$$F_{im} = \frac{w_i\, \phi_{im}}{\sum_{j=1}^{N} w_j\, \phi_{jm}} \cdot V_m \qquad (2)$$

Where:

ϕ_{im} = The mth vibration component in the ith floor above the base
V_m = The Shear force of the mth mode
F_{im} = The horizontal force acting on the ith floor from the mth 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 Code of Practice for Seismic Resistance Design of Building, 2005) is used for both, equivalent static and spectral dynamic methods.

DAMAGE ANALYSIS

In a nonlinear analysis, the correct choice of a hysteretic model is crucial in forecasting the exact dynamic response of the structure. The model should be able to describe a response similar to the actual hysteretic response of the structure and parameters such as stiffness degradation, strength deterioration and pinching behavior under cyclic loading are to be considered. In this study IDARC 2D software (Valles *et al*., 1996) has been used to calculate structural damage index and hysteretic energy and to conduct linear and nonlinear static and dynamic analyses on reinforced concrete structures under seismic loading. The software is also capable of conducting comprehensive damage analysis in local and global scale and is able to arrive at a calibrated damage index. This ability is an important step in quantitative evaluation of damage sustainability of reinforced concrete buildings (Valles *et al*., 1996).

The current release of IDARC incorporates three models for damage index: a modified Park and Ang model (Park *et al*., 1984; Kunnath *et al*., 1992), introduced in the previous releases of the program, a new fatigue based damage model introduced by Reinhorm and Valles (1995) and an overall damage qualification based on the variation of the fundamental period of structure.

The Park and Ang and the fatigue based damage models can be used to calculate different damage indices: element, story (subassembly) and overall building damages.

Park and ang damage model: The Park and Ang damage model (Park *et al*., 1984) was incorporated in IDARC since the original release of the program. Furthermore, the Park and Ang damage model is also an integral part of the three parameter hysteretic model since the rate of strength degradation is directly related to the parameter β described below (Park *et al*., 1987b). The Park and Ang damage index for a structural element is defined as:

$$DI_{P\&A} = \frac{\delta_m}{\delta_u} + \frac{\beta}{\delta_u P_y}\int dE_h \tag{3}$$

Where:

δ_m = Maximum experienced deformation
δ_u = Ultimate deformation of element
P_y = Yield strength of element
$\int De_h$ = Hysteretic energy absorbed by the element during response history
β = A model constant parameter

A value of 0.1 for the parameter β has been suggested for nominal strength deterioration (Park *et al*., 1987b). The Park and Ang damage model accounts for damage due to maximum inelastic excursions, as well as damage due to the history of deformations. Both components of damage are linearly combined.

Equation 3 is the basis for damage index computation, although some considerations need to be taken into account.

Direct application of the damage model to a structural element, a story, or to the overall building requires the determination of the corresponding overall element, story, or building ultimate deformations. Since the inelastic behavior is confined to plastic zones near the ends of some members, the relation between element, story or top story deformations, with the local plastic rotations is difficult to establish. For the element end section damages, the following modifications to the original model were introduced in Version 3.0 (Kunnath *et al*., 1992):

$$DI = \frac{\theta_m - \theta_r}{\theta_u - \theta_r} + \frac{\beta}{M_y \theta_u} E_h \tag{4}$$

Where:

θ_m = Maximum rotation attained during loading history
θ_u = Ultimate rotation capacity of section
θ_r = Recoverable rotation when unloading
M_y = Yield moment
E_h = 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:

$$DI_{story} = \sum(\lambda_i)_{component}(DI_i)_{component}; (\lambda_i) = \left[\frac{E_i}{\sum E_i}\right]_{component} \tag{5}$$

$$DI_{overall} = \sum(\lambda_i)_{story}(DI_i)_{story}; (\lambda_i)_{story} = \left[\frac{E_i}{\sum E_i}\right]_{story} \tag{6}$$

Where:

λ_i = Energy weighting factors
E_i = Total absorbed energy by the component or the ith story

The Park and Ang damage model has been calibrated with observed structural damage of nine reinforced concrete buildings (Park *et al*., 1987a). Table 1 shows the calibrated damage index with the degree of observed damage in the structure.

Table 1: Interpretation of overall damage index (Park *et al*., 1987a)

Degree of damage	Physical appearance	Damage index	State of building
Collapse	Partial or total collapse of building	> 1.0	Loss of building
Severe	Extensive crashing of concrete; disclosure of buckled reinforcement	0.4-1.0	Beyond repair
Moderate	Extensive large cracks; spalling of concrete in weaker elements	< 0.4	Repairable
Minor	Minor cracks; partial crushing of concrete in columns	-	-
Slight	Sporadic occurrence of cracking	-	-

STRUCTURAL SYSTEMS AND GROUND MOTIONS

Structural systems: Reinforced concrete frames of 3, 5, 10 and 15-story structures with identical bays and story

Table 2: Some characteristics of reinforced concrete frames

Samples	h/d	Total height (m)	Total weight (KN) ES	Total weight (KN) SD	Column dimensions (cm) ES	Column dimensions (cm) SD	Beam dimensions (cm) ES	Beam dimensions (cm) SD
3-story	0.96	9.6	1170	1156	32*32-37*37	32*32-34*34	32*37-37*42	32*37-35*40
5-story	1.60	16.0	2100	2072	35*35-45*45	35*35-40*40	35*40-45*50	35*40-40*45
10-story	3.20	32.0	4492	4284	40*40-55*55	37*37-52 *52	40*45-55*60	35*40-50*55
15-story	4.80	48.0	7070	6950	40*40-65*65	37*37-65*65	40*45-65*65	35*40-60*65

Table 3: Earthquakes records used in this study

Earthquake	Occurrence date	Magnitude	PGA (g)
Manjil	20.06.1990	7.7	0.550
Naghan	6.04.1977	6.1	0.720
Tabas	16.09.1978	7.4	0.836
El Centro	19.05.1940	7.0	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

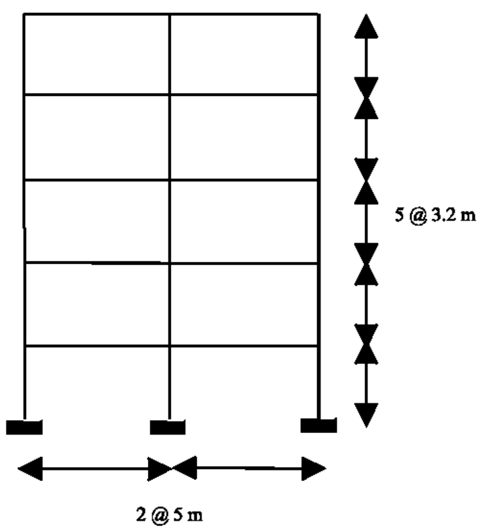

Fig. 1: 5-story frame

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 Fig. 1. 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. Some characteristics of the selected frames are given in Table 2. Other details of analysis and design are as follow: The vertical and lateral loadings of the structures were applied according to Minimum Design Loads for Buildings (Iranian National Building Code for Structural Loadings, 2004) and 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 = 0.35 g. The frames are moment resisting with medium ductility. ETABS (2001) software (Computers and Structures, 2001) was used for linear dynamic elastic analysis and design and IDARC 2D version 6.0 software (Valles and Reinhorn, 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 (Valles *et al.*, 1996).

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 3. In order to eliminate the influence of peak ground acceleration, all of them are scaled to a ground acceleration of 0.35 g based on Iranian Code of Practice for Seismic Resistance Design of Building (2005).

RESULTS AND DISCUSSION

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 (Fig. 2, 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%).

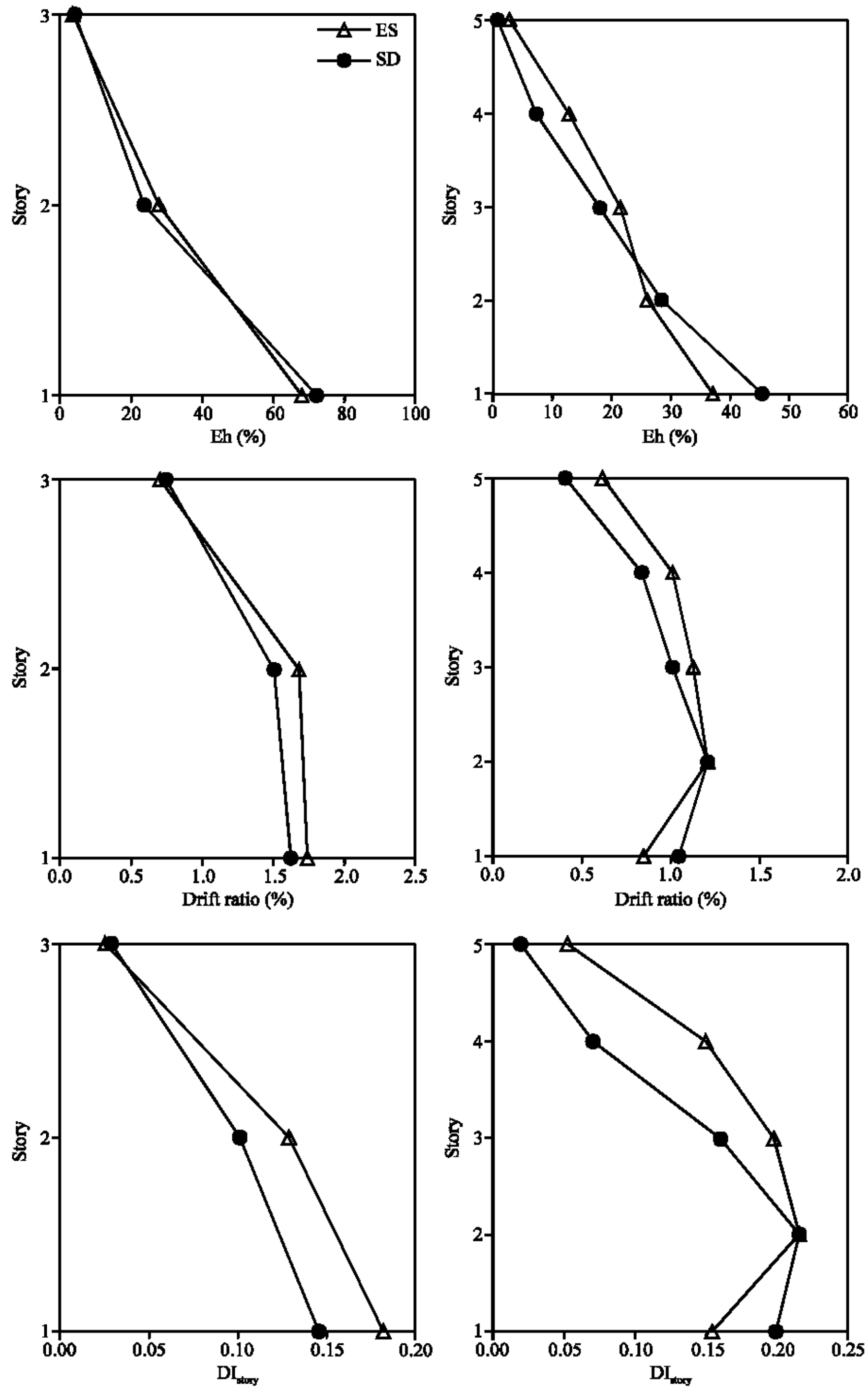

Fig. 2: Comparison of the average values of height-wise distribution of hysteretic energy, drift and damage index in 3-and 5-story frames from ES and SD methods

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 (Fig. 2). It is seen that with an increase in the height to

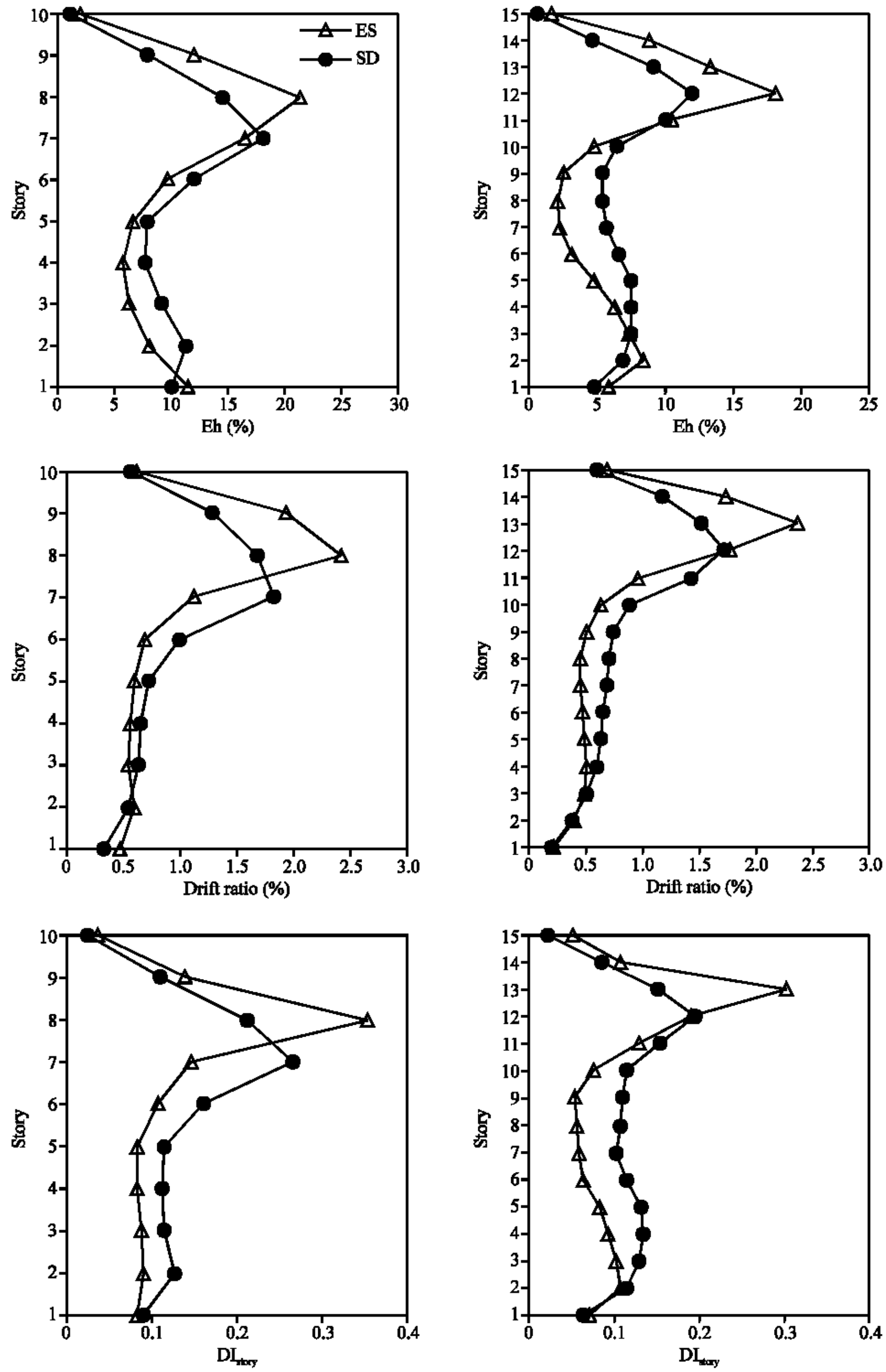

Fig. 3: Comparison of the average values of height-wise distribution of hysteretic energy, drift and damage index in 10- and 15-story frames from ES and SD methods

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,

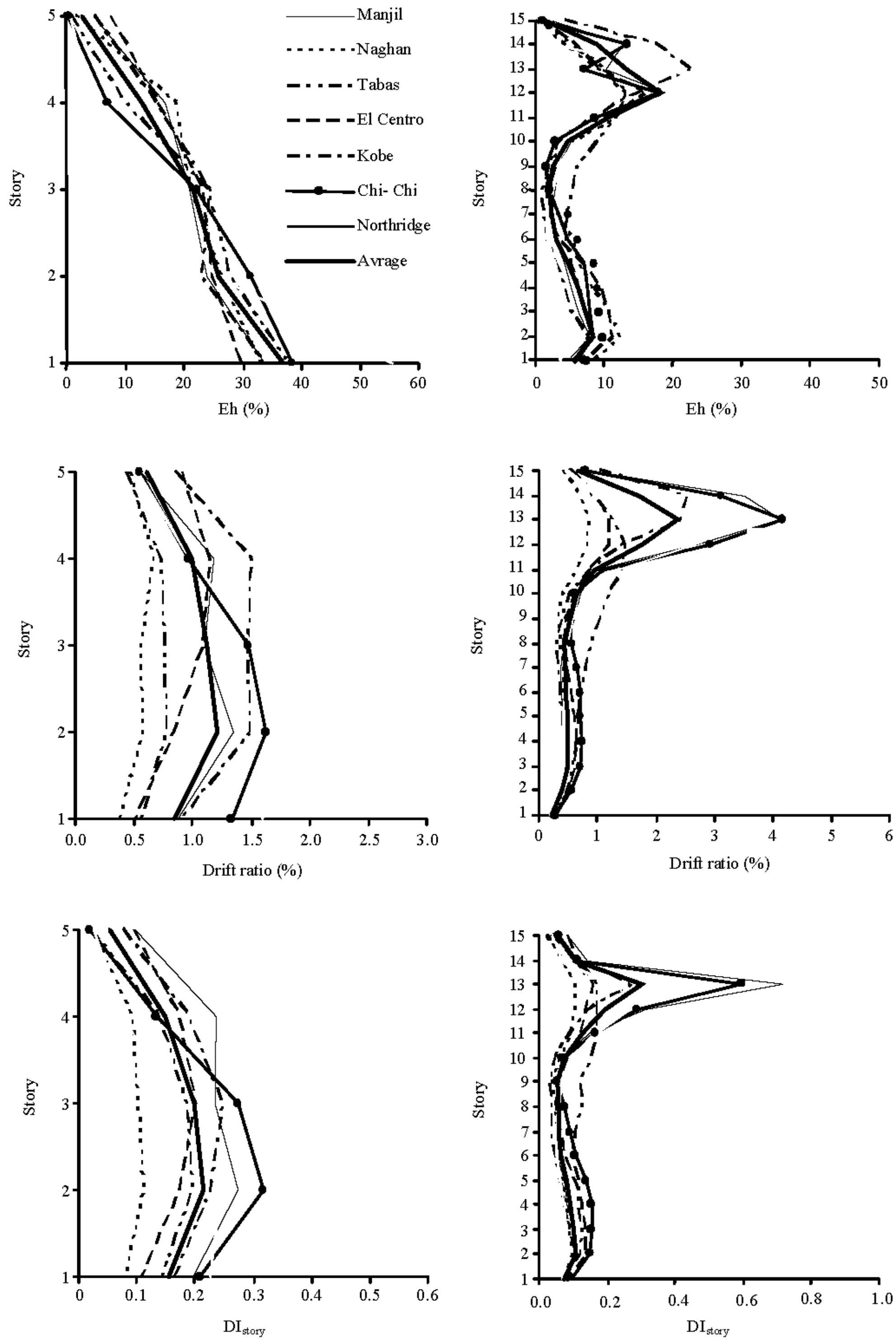

Fig. 4: Effect of ground motion on height-wise distribution of hysteretic energy, drift and damage index in 5-and 15-story frames

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.

10-and 15-story frames: As indicated in Fig. 3, distribution patterns of drift, Eh% and Di_{story} 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 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 Di_{story} 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 DI_{story} 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 (Eq. 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.

Effect of ground motion on height-wise distribution of hysteretic energy, drift and damage index: The average values of drift, Eh% and DI_{story} 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, Eh% and DI_{story} in 5-and 15-story frames is investigated as shown in Fig. 4. This figure indicates that the qualitative distribution of Eh% is similar in different earthquakes and 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 DI_{story} 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 *et al.*, 2003; Moghaddam and Hajirasouliha, 2004). They studied the effect of the conventional lateral loading pattern (i.e., equivalent static method) specified by the different seismic codes (UBC, 1997; NEHRP Recommended Provisions, 1994; Anonymous, 1996) 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.

Comparison of overall structural damage index from spectral dynamic and equivalent static methods: We have already discussed the distribution patterns of damage index in stories, based on beam and column damage indices from each story. 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. A comparison between the average values of $DI_{overall}$ subjected to seven earthquakes for ES and SD methods has been made as shown in Fig. 5. 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.

In addition, from a comparison between total bar areas used in equivalent static (A_{ES}) and spectral dynamic (A_{SD}) shown in Table 4 can be concluded that increasing h/d leads to a considerable lower A_{SD} compared to A_{ES}. For example, A_{SD} is 15.3% lower than A_{ES} in 15-story frame.

Table 4: Comparison of the total bar area in ES and SD methods

Sample	A_{ES} (cm^2)	A_{SD} (cm^2)	$\frac{(A_{SD} - A_{ES})}{A_{SD}} * 100$
3-story	390.8	384.2	-1.72
5-story	823.6	798.2	-3.18
10-story	2012.8	1835.3	-9.67
15-story	3956.7	3430.3	-15.34

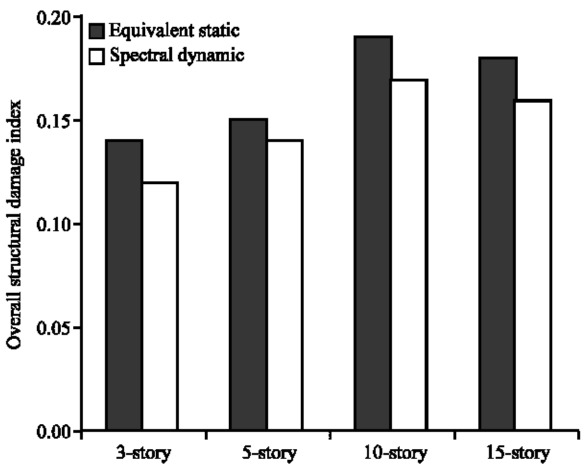

Fig. 5: Comparison of the average values of overall structural damage indices in spectral dynamic and equivalent static methods

Moreover, considering the average values of $DI_{overall}$ from both methods and the relation between $DI_{overall}$ and the state of the building from Table 1, 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 Fig. 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.

CONCLUSIONS

In this study, the effects of two lateral loading patterns (equivalent static and spectral dynamic) on height-wise distribution of hysteretic energy, drift and damage subjected to severe earthquakes with different characteristics have been studied. The results of the study can be summarized as follow:

- 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 equivalent static loading 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 equivalent static and spectral dynamic 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 (Eq. 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 and 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.

ACKNOWLEDGMENTS

We would like to acknowledge Babol University of Technology for partial support of this study. The authors are grateful to Engineer Mehdi Omidvar for helpful discussions.

NOTATIONS

A	=	Design base acceleration.
A_{ES}	=	Total bar area used in equivalent static frame.
A_{SD}	=	Total bar area used in spectral dynamic frame.
DI_{story}	=	Story damage index.
$DI_{overall}$	=	Overall structural damage index.
Eh%	=	Percentage ratio of hysteretic energy in each story to total hysteretic energy.
ES	=	Equivalent static method.
F_i	=	Equivalent static force of the ith floor above base level.
F_m	=	Spectral dynamic force of the ith floor above base level.
F_t	=	Roof additional force in equivalent static method.
M_y	=	Yield moment.
P_y	=	Yield strength of element.
SD	=	Spectral dynamic method.
V	=	Total base shear.
V_m	=	Shear force of the mth mode.
w_i	=	Weight of the ith floor above base level.
$\int dE_h$	=	Total hysteretic energy.
β	=	Constant parameter of Park and Ang model.
δ_m	=	Maximum experienced deformation.
δ_u	=	Ultimate deformation of the element.
ϕ_{im}	=	mth vibration component in the ith floor above base.
λ_i	=	Energy weighting factors.
θ_m	=	Maximum rotation.
θ_u	=	Ultimate rotation capacity.
θ_r	=	Recoverable rotation when unloading.

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