Nonlinear Response Analysis of Multistory Buildings Subjected to Synthetic Motions Compatible with Design Spectrum

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SUMMARY:
In the nonlinear response history analysis of multistory building structures, the input ground motions have considerable effect on the nonlinear seismic response characteristics of structures. As the nonlinear dynamic analysis becomes a more frequently used procedure for evaluating the seismic demand on a structure, it also becomes increasingly important to develop a ground motion scaling method that reduces the scatter in seismic demand estimates. The characteristics of soil and the locality of the site where those ground motions were recorded affect the contents of ground motion time histories. Therefore, it is difficult to select appropriate input ground motions for nonlinear dynamic analysis. The purpose of this study is to evaluate the seismic response demands of multistory buildings by the simulated ground motions compatible with the seismic design spectrum. The simulated ground motions are generated according to the previously recorded earthquake waves in the past major earthquake events. The simulated ground motion time histories have identical phase angles to the recorded ground motions, and their overall response spectra are compatible with the seismic design spectrum with 5% critical viscous damping. The input ground motions applied to this study have identical elastic acceleration response spectra, but have different phase angles. The purpose of this study was to investigate their validity as input ground motion for the nonlinear seismic response analysis of building structures. As expected, the response quantities by simulated ground motions presented better stability than those by real recorded ground motions. It was concluded that the simulated earthquake waves generated in this paper are applicable as input ground motions for a seismic response analysis of building structures. It was also found that the intensity of input ground motions for seismic analysis are suitable to be normalized as elastic acceleration spectra.

Keywords: synthetic motion, design spectrum, nonlinear seismic response, multistory buildings

1. INTRODUCTION

1.1. Background

An earthquake acceleration wave is only to represent the time histories of free field shaking of a specific site caused by an earthquake event. In other words, any one input motion adopted in the seismic response history analysis of building structures is nothing but a ground motion on a specific free field caused by an earthquake event[AIJ, 1992]. A single earthquake event can generate various ground motion time histories with different characteristics. Therefore, any one ground motion does not necessarily represent typical time histories to guarantee the seismic safety of building structures[AIJ, 2004]. It is impossible to predict ground motion characteristics that may occur in the future at a construction site because the property of the ground motion is interrelated with many factors such as fault mechanism, seismic wave propagation from source to site, and the amplification characteristics of ground. The important factors of ground motions affecting structure's response results are peak ground acceleration, frequency contents, duration of ground motion, and shapes of waveform. Though required to set input ground motions for general seismic design including these factors, it is not available at this time[Stewart et al., 2001]. Also, the input ground motions for seismic design need to correspond appropriately to various structural materials and systems. The seismic design guidelines provide an acceleration response spectrum for estimating the design seismic force of a structure.

Accordingly, the input ground motion applied to the dynamic response analysis of structures would be appropriate for the ground motion history which is highly related with design seismic force. For this purpose, new techniques have been studied by many seismic engineers to produce artificial ground motions[Barenberg, 1989; Jun and Inoue, 1991a, 1991b; Preumont, 1984; Tsai, 1972], and general software have been used to simulate the artificial ground motions[Vanmarke and Gasparini, 1976]. However, the results of these studies seem to be inefficient in generating various artificial ground motions reflecting different site conditions and ground motion factors as they require much time and effort.

A difference of input ground motions causes considerable divergence in the analysis of time history responses, therefore appropriate scaling of the input ground motions is necessary in seismic response history analysis. There are two scaling methods: one using peak value of ground accelerations as baseline, the other using ground motion consistent with design spectrum. There is currently no consensus on which approach, scaling or spectrum matching, is preferable for nonlinear seismic response analysis[Aschheim et al., 2007; Han et al., 2007; Hancock et al., 2008; Kurama and Farrow, 2003].

Ground motion scaling procedures using the peak value of input ground accelerations maintains original ground motion history characteristics including the response spectrum of each recorded ground motion. It is, however, recommended to use not less than seven input ground motion records to prevent the response values of structure from being biased by response spectrum characteristics of any one ground motion. Especially when applied for nonlinear seismic response analysis, the scale factor of 2 or below is required for amplification of the ground motion component, because the nonlinear response appear a biased one-directional response characteristics dominated by the peak value of the ground accelerations[Luco and Bazzuro,2007; Moehle,2006]. In addition, it requires relatively large factor to compensate insufficient energy for long period structure as it is difficult to obtain ground motion with sufficient input energy in the long period range for high-rise buildings. In this case, a shortcoming of higher mode magnification effect can occur as a result of unusual scaling up of relatively short period spectrum[PEER, 2009].

The scaling method of input ground motion using design spectrum can be accomplished to perform response history analysis with less ground motions, but it is a question how to effect on nonlinear seismic response because the design spectrum is based on an elastic spectrum. In particular, a question is indicated on the input energy magnification of the artificial motions corresponding to the response spectrum[Naeim and Lew, 1995].

1.2 Purpose

In seismic response analysis of multi-story buildings, the selection of input ground motion and adjustment of input intensity level of the selected ground motion are the most important for estimating the response results of the structure. The purpose of this study is to evaluate nonlinear response characteristics of real buildings through nonlinear time history analysis on multi-story reinforced concrete structures by inputting simulated seismic waves identical as response spectra, which was focused on design response spectrum as scaling method of the input ground motions. This study also is to evaluate its feasibility as input ground motions for the nonlinear time history analysis of actual buildings by identifying relationships between design response spectra and nonlinear seismic response results of the input ground motions.

2. INPUT GROUND MOTIONS

2.1. Selection of Recorded Ground Motions

The ground motions used in this study were selected from the real recordings of ground motions greater than magnitude scale of 6. The characteristics of earthquake such as fault mechanism, wave propagation path, and site characteristics are not considered, and it has been commonly used as input ground motions for seismic design or representative ground motions which caused severe damage to buildings were selected. Table 1 lists these records with the recorded peak ground accelerations and the simulated peak values.

2.2. Characteristics of Simulated Ground Motions

Figures 1 shows comparison between simulated ground motion with original recorded ground motion. Lower figures compare also target design spectra and response spectra of simulated ground motions. In the figure, it is apparent that original recorded ground motions and simulated ground motions have similar trends as phase angle characteristics are same. In addition, it is notable that response spectra of recorded ground motions are adjusted in the proximity of the design response spectrum[Jun, 2010].

Table 1 presents comparison of maximum acceleration value and its occurrence time of recorded ground motions and simulated ground motions which were developed for target response spectrum. The maximum acceleration value of the simulated ground motions adequately developed for design response spectrum is in the range of 300-426cm/sec^2. The occurrence time of the maximum acceleration values of recorded ground motions and simulated ground motions was observed to occur at the almost same time except for El Centro 1940 EW component.

3. NONLINEAR RESPONSE ANALYSIS OF MULTISTORY BUILDINGS

3.1. Analytical Model

The analytical model of multi-story frame structures used in this study was a standard plane frame model for reinforced concrete moment resistant system, it can be generally applied in seismic design of building structure as shown in Figure 2. Modeling of the column member for nonlinear analysis utilized fiber models. The sectional dimensions and reinforcement of column and beam used in the structural model are presented in Table 2, Table 3 and Figure 3, respectively. The characteristics of material are: For steel bar, elastic stiffness E_s=196GPa, yield strength f_y=392MPa; for concrete, elastic stiffness E_c=23GPa, design strength f_{ck}=24MPa.

3.2 Analysis Method

The nonlinear response analysis of ground motions was performed using CANNY-2010 software[Li, 2010]. Nonlinear time history analysis was used for nonlinear dynamic analysis and Newmark β method($\beta = 0.25, \gamma = 0.5$) was used for numerical integration method. A Rayleigh damping was applied in the nonlinear time history analysis and horizontal input ground motion was used to perform nonlinear analysis.

3.3 Nonlinear Seismic Response Results

Nonlinear seismic response is different from elastic seismic response and the response results are very complicated due to characteristics of input ground motion, dynamic property of the structures, and the influence of hysteresis model for structural component. Particularly, hysteresis model for structural member is a critical factor to determine response characteristics of multi-story frame structures. Therefore, the purpose of this analysis is to evaluate the nonlinear responses of each story of structures by changing only the input ground motion characteristics for multi-story frame structures which have same dynamic model and hysteresis characteristics. The nonlinear seismic response analysis was evaluated for story displacement, inter-story deformation and distribution of damage of multi-story frame structures.

Here, the intensity of the input ground motion was scaled to obtain the inelastic response displacement of 71.5cm on the top floor (deformation angle H/100 radian, where H: total building height) followed by evaluation of nonlinear response results of multi-story frame structures. Scaling factors (SF2) for nonlinear response analysis of each input ground motion are shown in Table 1 and Figure 6. In Table 1 and Figure 6, the recorded ground motions show a wide difference of scaling factors between 1.24 and 5.13 depending on the type of the ground motion. For simulated ground motions, the SF2 values were relatively less variable with coefficient range of 1.18-1.65 because the response spectrum was primarily scaled constantly for simulated ground motions.

The seismic responses of the buildings for distribution of story displacement and inter-story drift are shown in figures 7 and 8 for simulated ground motions and recorded ground motions, respectively. In figure 7, the story displacement distribution of lower floor was similar as the roof displacement was adjusted same. In the case of the simulated ground motion waves, the response quantities of story displacement on middle stories showed less than 20% differences, whereas the recorded ground motion waves in the middle stories had approximately 40% differences depending on the type of input ground motion. Both the simulated ground motion and the recorded ground motion resulted in greater difference for nonlinear response compared to elastic response. Figure 8 presents inter-story drift angle distributions according to different input ground motions. It was confirmed that the response results by the simulated ground motions were less variable compared to those by recorded ground motions. Recorded ground motions in particular indicated that the response variations were greater in the middle and lower stories. This could be due to the effect of the higher mode of the recorded ground motions.

Figures 9 and 10 represent the distribution of damage on each floor in 10-story model and 20-story model, respectively. In figure 9 large circle shows the ductility ratio of 10 or more, a small circle indicates that the ductility ratio of 10 or less. In this figure, there is no significant difference in the damage distribution according to the input ground motions because the input ground motion intensity was scaled so that the roof displacement is the same in this analysis. If the input ground motion intensity was adjusted to a constant displacement on the top floor, the distribution of the damage appears similar to on each story.

On the other hand, figure 10 shows that the response variances of the simulated ground motion are smaller than those of the recorded ground motion. Apparently, several waves of the recorded ground motions showed large response values compared to other ground motions. The response values of the recorded ground motions in higher stories show greater variance than those of simulated ground motions. These results may be possible because the recorded ground motions had great effect on response results of the short period range corresponding to higher mode. In case of the simulated ground motion, the decrease of the short period component and amplification of the long period component resulted in relatively small effect on response results of short period structure.

When examined in the basis only results of the analytical model used in this paper, it was found from the presented figures that the response variances of simulated ground motions were smaller than those of recorded ground motions. However, the input intensity of the simulated ground motions, that is, the scaling up of the response spectrum was not always proportional to the response value of each story, and the nonlinear response value was dependent on the property of the ground motions. Furthermore, it needs to be examined how the response distribution of recorded ground motions in the middle stories had greater variance. The small variance of the response distribution of the simulated ground motions on all stories was thought to be caused by the decreased influence of the specific period component included in the ground motions. In the future, more researches need to be performed with various structural models and recorded ground motions. And also, the proposed nonlinear response analysis in this study is necessary to verify if the simulated ground motion histories generated by this study can be used as input ground motion for seismic design.

4. CONCLUSIONS

The seismic safety of building structures can be evaluated by the nonlinear behavior of structures induced by ground motions. The characteristics of input ground motions and dynamic property of the structure are important factors to affect seismic response of structures. Ground motions used in the seismic response analysis of structure include various characteristics depending on fault mechanism of earthquake, wave propagation, and amplification of soil type. As the result of the analysis, it is a difficult task to quantitatively examine all affecting factors. In seismic design, design response spectrum generally represents the response characteristics of structural model. In this study, a simulated ground motion suitable for design spectrum was developed and its feasibility for the input ground motion was evaluated through nonlinear seismic response analysis of the multi-story frame structures. The results obtained from this study can be summarized as follows.

1) The response results of simulated ground motions by each floor presented better stability than those by recorded ground motions.

2) The simulated ground motions scaled to design elastic spectrum was confirmed to show less differences in nonlinear responses by each floor.

3) The simulated ground motions generated in this paper can be applied as the input ground motions for a nonlinear response analysis of the high-rise building structures.

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Table 1 List of Input Ground Motions

Earthquake Name	Recorded motions				Artificial motions			
	Duration time	Peak Accel. cm/sec^2	Occurrence time (sec)	Scale Factor SF2	Duration time	Peak Accel. cm/sec^2	Occurrence time sec	Scale Factor SF2
El Centro 1940 NS	53.48	341.70	2.12	3.842	53.00	324.00	2.08	1.308
El Centro 1940 EW	53.48	210.10	11.44	1.583	53.00	321.60	2.03	1.205
JMA Kobe 1995 NS	30.0	819.10	4.94	2.290	60.00	415.30	5.54	1.653
JMA Kobe 1995 EW	30.0	617.14	8.46	2.307	60.00	401.10	8.47	1.381
Mexico city 1985 NS	180.0	98.00	24.16	2.025	180.0	353.40	39.86	1.179
Mexico city 1985 EW	180.0	167.90	28.08	1.240	180.0	336.60	33.38	1.336
Taft 1952 NS	54.36	152.70	9.10	4.939	60.0	369.30	6.62	1.569
Taft 1952 EW	54.36	175.90	3.70	5.130	60.0	426.30	3.71	1.302
Tohoku Univ 1978 NS	40.94	258.20	7.56	2.684	40.96	299.50	14.88	1.387
Tohoku Univ 1978 EW	40.94	202.50	3.10	3.025	40.96	314.10	3.10	1.291
Hachinohe 1968 NS	36.0	225.00	4.17	3.164	40.96	331.60	4.18	1.434
Hachinohe 1968 EW	36.0	182.90	3.19	3.104	40.96	330.80	5.86	1.427

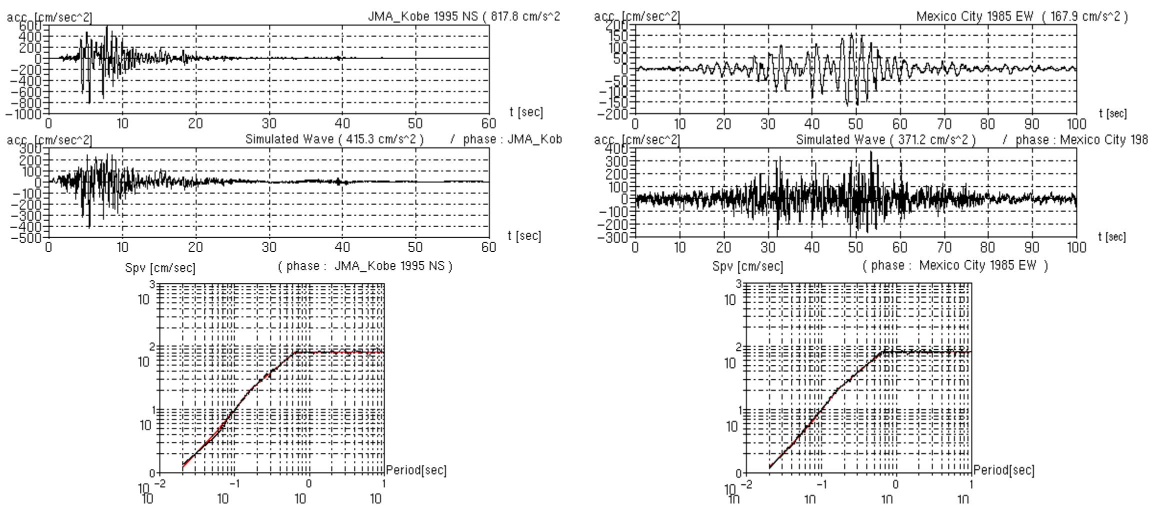

Fig. 1 Comparison of recorded waveform and simulated waveform

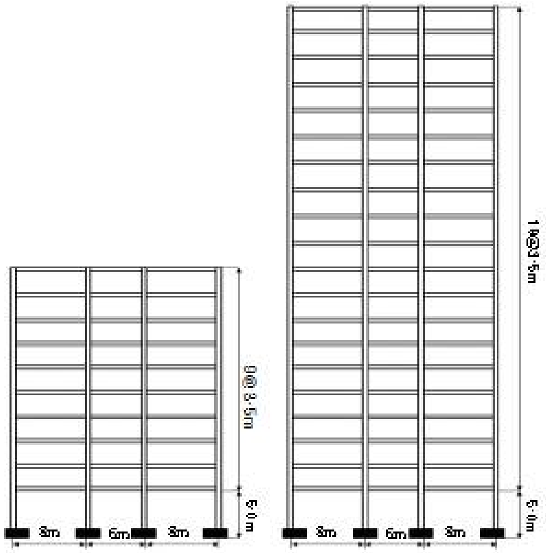

Fig. 2 Analytical model

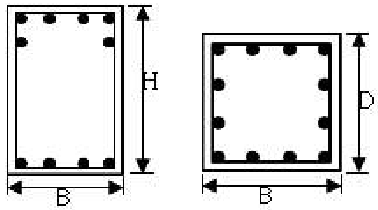

Fig. 3 Section reinforcements

Table 2 20-Story Member List

(a)Column

Floor No.	Dimension BxD(mm)	Reinforcement
1~5	700x700	12-D22
6~10	600x600	12-D22
11~15	500X500	12-D22
16~20	500X500	8-D22

(b) Beam

Floor No.	Dimension BxD(mm)	Reinforcement	
		Upper bar	Bottom Bar
All	400x600	6-D19	4-D19

Table 3 10-Story Member List

(a)Column

Floor No.	Dimension BxD(mm)	Reinforcement
1~3	600x600	12-D22
4~6	500x600	12-D22
7~10	500X500	8-D22

(b) Beam

Floor No.	Dimension BxD(mm)	Reinforcement	
		Upper bar	Bottom Bar
All	400x600	6-D19	4-D19

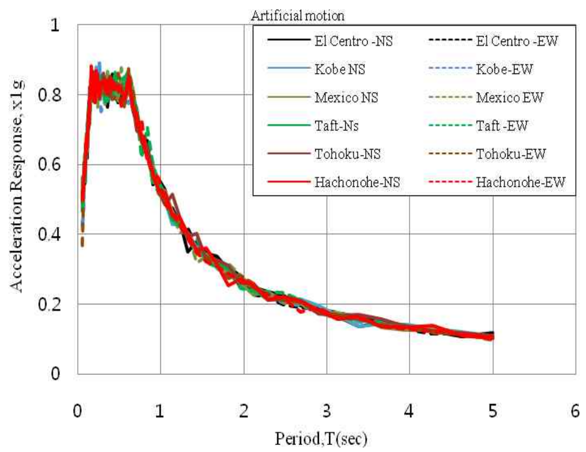

Fig. 4 Acceleration response spectra of simulated motions

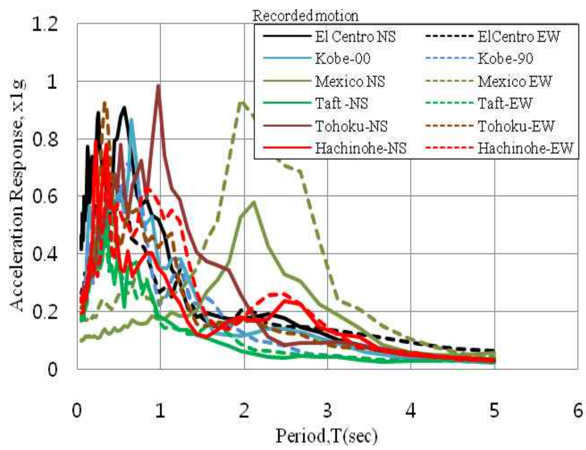

Fig. 5 Acceleration response spectra of recorded motions

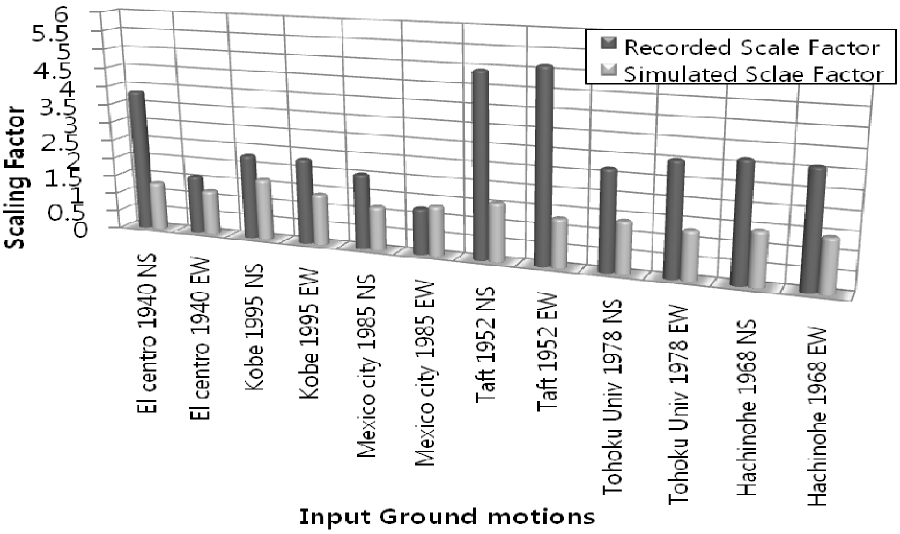

Fig. 6　Scale factor according to the input ground motions

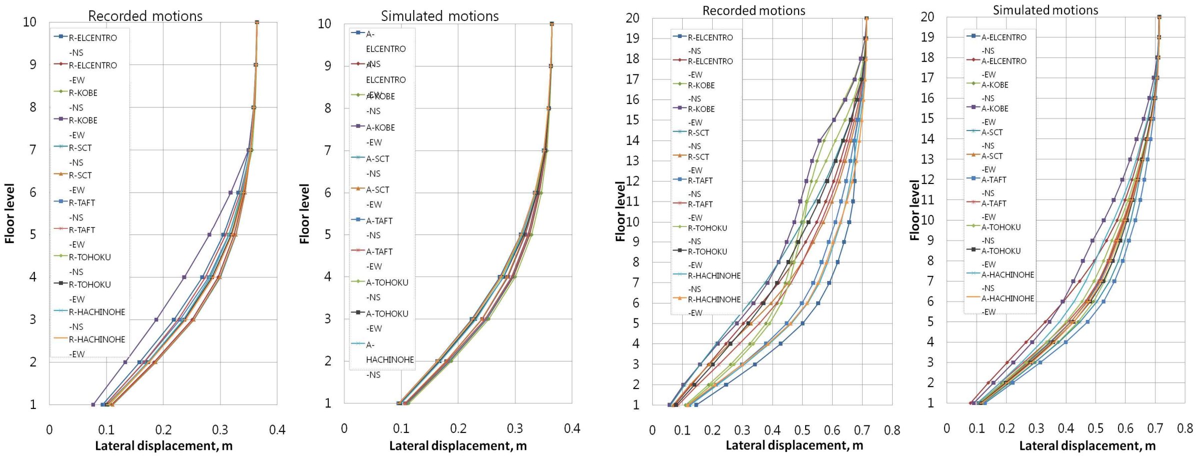

Fig. 7　Story displacement distribution

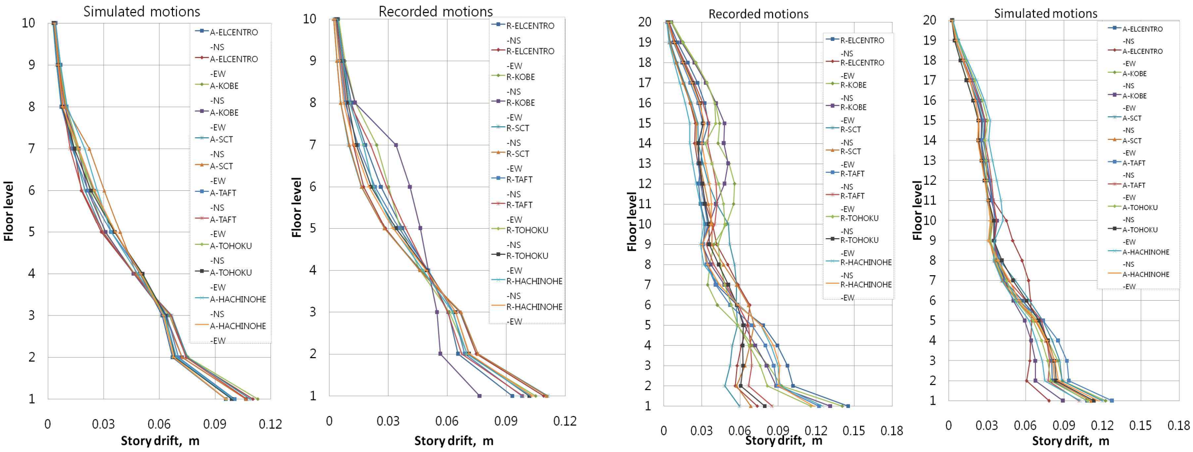

Fig. 8　Inter-story drift distribution

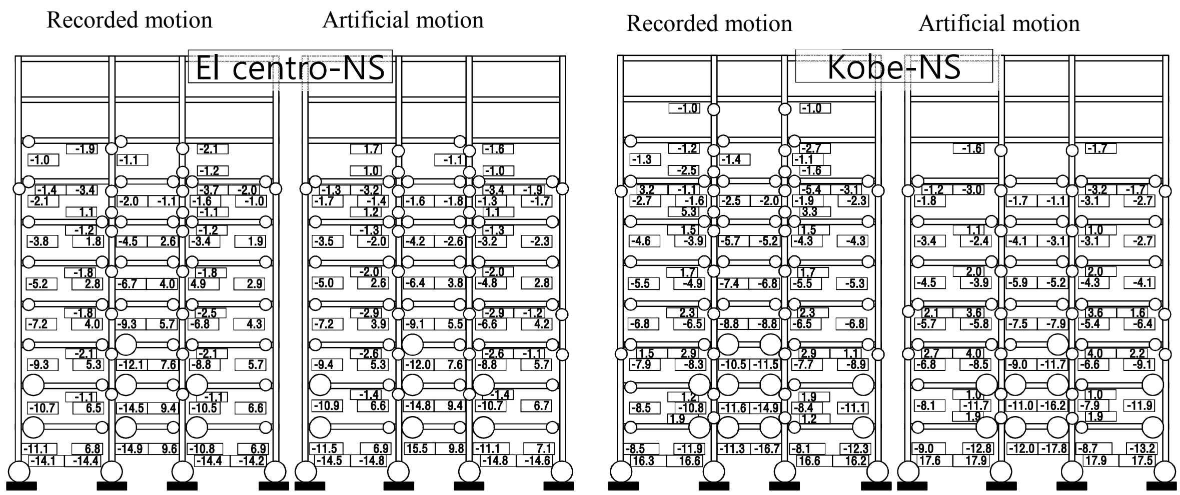

Fig. 9 Distribution of damage in 10-story model

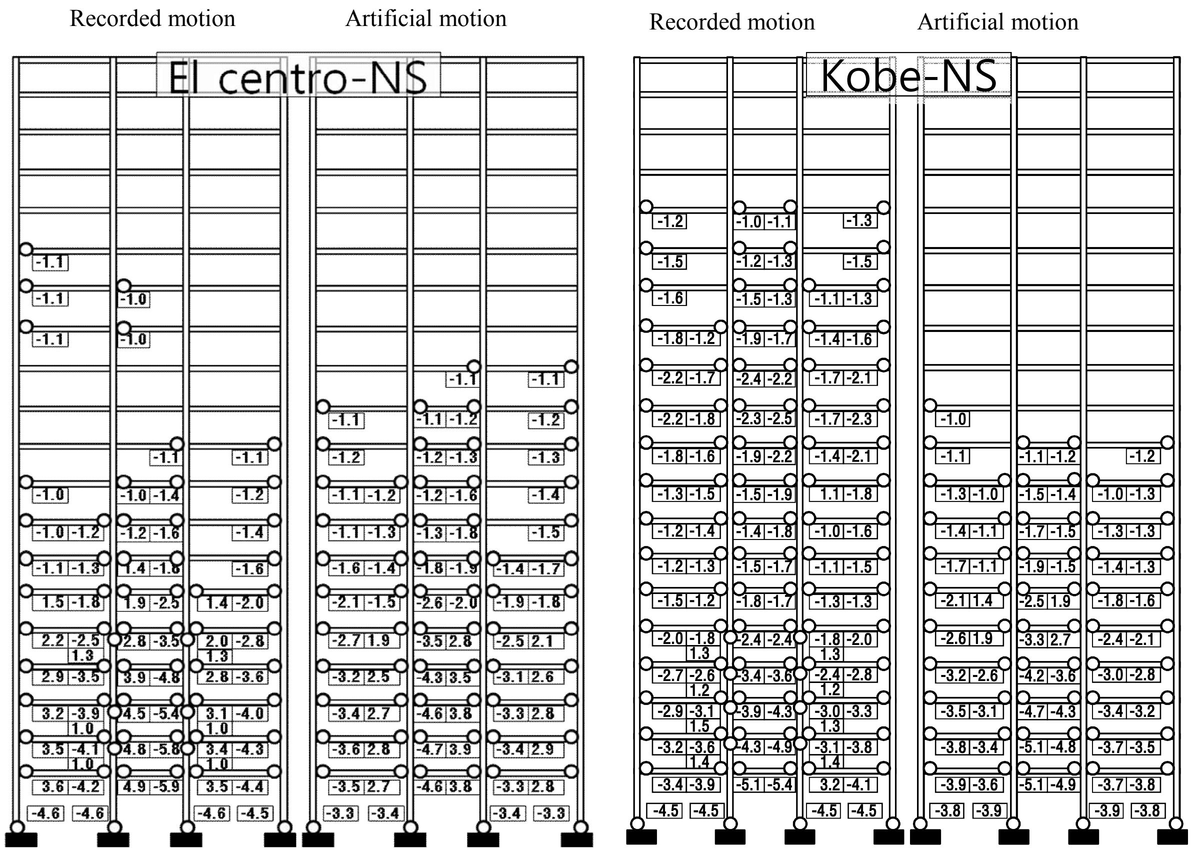

Fig. 10 Distribution of damage in 20-story model