# Generation of Artificial Earthquake Wave Compatible with Design Spectrum

**Dae-Han Jun[1] , Pyeong-Doo Kang[2] and Jae-Ung Kim[3]**

[1] *Associate professor, Dept. of Architectural Engineering , Dongseo University, Busan, Korea*
[2] *Associate professor, Dept. of Architecture & Interior, Gyeongnam Provincial College, Gyeongnam, Korea*
[3] *Professor, Faculty of Architectural Design & Engineering, Dong-A University, Busan, Korea*
*Email: jdh@dongseo.ac.kr, pdkang@kc.ac.kr, jukim@dau.ac.kr*

**ABSTRACT :**
In seismic response analysis of building structures, the input ground motions have considerable effect on the nonlinear seismic response characteristics of structures. 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 seismic response analysis. This study describes a generation of synthetic ground motion time histories compatible with seismic design spectrum, and also evaluates the seismic response results of multi-story reinforced concrete structures by the simulated ground motions. 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 seismic design spectrum with 5% critical viscous damping. The purpose of this study was to investigate their validity as input ground motion for 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.

**KEYWORDS:** Simulated ground motion, Phase angles, Design spectrum, Nonlinear seismic response

## 1. INTTRODUCTION

An earthquake acceleration wave is only to represent time histories of free field shaking of a specific site caused by an earthquake event. In other words, any one ground motion is nothing but a ground motion on a specific free field by an earthquake event. 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 seismic safety of building structures. It is impossible to predict ground motions that may occur in the future at construction site as the ground motion characteristics is interrelated with many factors such as fault mechanism, seismic wave propagation from source to site, and amplification characteristics of soil. 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 considering these factors, it is not available at this time.
In time history response analysis, selection of an appropriate input ground motion is important and input motions should be selected from real records considering magnitude, distance of epicenter, site conditions, and other factors that control the ground motion characteristics. The duration of input ground motion, especially for high-rise buildings, has also been recognized as an important factor to increase the input energy required for long-period buildings. A difference of input ground motions create large divergence in the analysis of time history responses, therefore appropriate scaling of the input ground motions is necessary in seismic response analysis. There are two scaling methods: one using peak value of ground accelerations as baseline, the other using ground motion consistent with design spectrum. Current research results do not provide agreed opinion on which method is appropriate in scaling input ground motion.
This study proposes a new process to easily simulate ground motions with response spectra characteristics close to standard design response spectrum shapes and identical phase angles with the ground motions recorded at the past earthquakes. In particular, this study can provide massive creation of simulated ground motions having design response spectra of various phase angles characteristics of recorded ground motions.

Nonlinear response analysis of single degree of freedom system was performed by simulated ground motions to examine the feasibility of it as the input ground motion.
The purpose of this study was 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 was 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. GENERATION OF SYNTHETIC GROUND MOTION

### *2.1 How to create synthetic ground motion*

The simulation approach used in this study was to manipulate acceleration amplitudes to make acceleration response spectrum of the ground motion which is closely related to the response of structures match design response spectrum, while maintaining same phase angles characteristics of the ground motions recorded at past earthquakes.
Recorded ground acceleration time histories ($\ddot{u}_g(t)$) from the past earthquake can be expressed by discrete and finite Fourier approximate formulae as follows.

$$\ddot{u}_g(t) = \sum_{k=0}^{n-1} a_k \cos(w_k + \phi_k) \tag{2.1}$$

where, $a_k$: k-th Fourier amplitude
$w_k$: k-th Fourier circular frequency
$\phi_k$: k-th Fourier phase angles

From the parameters obtained in the equation (2.1), keep phase angles ($\phi_k$) and adjust Fourier circular frequency ($w_k$), T = 0.02 - 10.0 seconds to synchronize with set target elastic response spectrum followed by Fourier inverse transform to generate synthetic ground motion time histories. Fourier amplitude can be adjusted as shown in the equations below.

$$a_k^{'} = \frac{S_{AT}}{S_A} a_k \tag{2.2}$$

where, $a_k^{'}$ : Adjusted Fourier amplitude
$a_k$ : Fourier amplitude of the original recorded ground motion
$S_{AT}$: Target elastic response spectrum
$S_A$: Acceleration response spectrum of real recorded ground motion or of adjusted ground motion

In equation (2.2), Fourier inverse transform using adjusted amplitude generates synthetic ground motion time histories. After seismic response analysis utilizing this motion to recalculate acceleration response spectrum, verify goodness of fit with design acceleration response spectrum. This calculation process is continued until the response spectrum of final motion is close enough to target response spectrum.

### *2.2 Selection of recorded ground motions*

An ensemble of 8 earthquake waves, recorded from past events, is chosen for use in this study. Ground motions 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.

### *2.3 Selection of design acceleration spectrum*

Target acceleration response spectra to develop simulated ground motions was set in reference to seismic design regulations as follows.

$$
\begin{aligned}
&\text{(i)}\quad T_i<0.16\text{sec}: && S_{AT}(T_i, 0.05)=320+3000T_i \\
&\text{(ii)}\ 0.16\le T_i<0.64\text{sec}: && S_{AT}(T_i, 0.05)=800 \\
&\text{(iii)}\ 0.64\text{sec}\le T_i: && S_{AT}(T_i, 0.05)=512/T_i
\end{aligned}
\tag{2.3}
$$

This is represented in Figure 1. The design acceleration response spectra is defined by the vibration period($T_i$) for damping ratio h = 5%. The variation of the size of the acceleration response spectra may result in different design acceleration response spectra at other site, where the site conditions and seismic activities are different.

## 3. CHARACTERISTICS OF SIMULATED GROUND MOTIONS

### *3.1 Comparison of simulated ground motions with recorded ground motions*

Figure 2 show comparison between simulated ground motion and original recorded ground motion. Lower figures compare 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.

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 322-426 cm/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.

### *3.2 Nonlinear response characteristics of simulated ground motions*

Seismic response characteristics using simulated ground motion wave and recorded ground motion wave was examined by the nonlinear response analysis of a single degree of freedom system. In general, yield strength coefficient ($C_y$) has been widely used as an indicator to represent nonlinear response characteristics of input ground motions. Yield strength coefficient is a normalized coefficient, which is calculated from yield strength of dynamic model in consistent with ductility of the input ground motions of similar strength divided by weight of the structural system. That is, yield strength coefficient ($C_y$) can be expressed as follows when the yield strength of structural model in the single degree of freedom system is $Q_y$, weight of the structural system, $W_T$:

$$C_y = \frac{Q}{W_T} = \frac{Q_y}{mg} \tag{3.1}$$

where, g: gravity acceleration

In the single degree of freedom dynamic model, yield strength coefficient ($C_y$) is expressed as the ratio of yield strength of structural system to gravity acceleration when the mass (m=1) is normalized. This value is used to obtain the yield strength of ductility in consistent with the period of the structural system for the input ground motions. It is called constant ductility response spectrum in the single degree of freedom system. Constant ductility response spectrum is utilized to determine the yield strength of structural system, obtaining consistent ductility to represent damage rate of the structure for each period.

Figure 3 and Figure 4 represent comparison of original recorded ground motions and simulated input ground motions with respect to yield strength coefficient ($C_y$) using bilinear hysteresis model (ratio of initial stiffness and post yield $\alpha$=5%). In the figures, as ductility of 1 means elastic state, the response of recorded ground motions produced large differences depending on the characteristics of the input ground motions. On the contrary, the response of simulated ground motions indicated almost identical response characteristic, which was due to the fact that simulated ground motions was developed close to design response spectrum.

## 4. NONLINEAR RESPONSE ANALYSIS OF MULTI-STORY FRAME STRUCTURES

### *4.2 Analytical model*

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 structure designs as shown in Figure 5. The sectional dimensions and reinforcement of column and beam used in the structural model are presented in Table 2 and Figure 6, respectively. The characteristics of material are: For steel bar, elastic stiffness $E_s$=196 GPa, yield strength $f_y$=392 MPa; for concrete, elastic stiffness $E_c$=23 GPa, design strength $f_{ck}$=24 MPa.

### *4.2 Analysis method*

Nonlinear response analysis of ground motions was performed using CANNY-2004 software[5]. 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. Modeling of the column member for nonlinear analysis utilized fiber models. A Rayleigh damping was applied in the nonlinear time history analysis and horizontal input ground motion was used to perform nonlinear analysis.

### *4.3 Nonlinear seismic response analysis*

Nonlinear seismic response is different from elastic seismic response and the response is very complicated due to characteristics of input ground motion, dynamic property of the structures, and effect of hysteresis model for structural component. 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 nonlinear responses by each story of the building varying characteristics of input ground motions for multi-story frame structures which have identical building model and hysteresis characteristics. Similar to elastic response, story displacement, inter-story drift, story seismic force, and distribution of story shear force were evaluated.

Here, the intensity of the input ground motion was scaled to obtain elastic response displacement of 36.5 cm 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. In Table 1, the recorded ground motions showed substantial range of scaling factors between 0.79 and 6.00 depending on the type of the ground motion. For simulated ground motions, the SF2 values were relatively less variable with coefficient range of 1.32-2.08 because the response spectrum was primarily scaled constantly for simulated ground motions.

Seismic responses of the buildings for distribution of story displacement, inter-story drift, and story seismic force are shown in figures 7-10 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 simulated ground motion waves, the response quantities of story displacement on all stories showed less than 5% differences, whereas recorded ground motion waves in the middle stories had approximately 20% differences depending on the type of input ground motion. Both simulated ground motion and recorded ground motion resulted in greater difference for nonlinear response compared to elastic response. Figure 8 presents inter-story deformation angle distributions with input ground motions. It was confirmed that the response results by 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 stories. This could be due to the effect of the higher mode of the recorded ground motions.

Figure 9 and figure 10 represent distribution of story seismic force and of story shear force on each floor. Each figure shows that the response variances of the simulated ground motion are smaller than those of the recorded ground motion, regardless of types of input ground motions. Apparently, several waves of the recorded ground motions showed large response values compared to other ground motions. As such, these ground motions are classified as unfavorable ground motionss to be chosen as input ground motions for

seismic design, as indicated in other research[8]. Likewise, the response values of the recorded ground motions in middle stories show greater variance than those of simulated ground motions. It is believed that this happened because response results of the short period range corresponding to higher mode had great impact on recorded ground motions. 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 impact on components of short period range.
When analyzed only with results of the analytical model, 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 ground motions on all stories was thought to be caused by the decreased impact of the specific period component included in the ground motions. In the future, more research needs to be performed with various structural models and recorded ground motions, focusing on ground motions showing special response results, to verify if the simulated ground motions generated by this study can be used as input ground motion for seismic analysis.

## 5. CONCLUSIONS

Seismic safety of building structures can be evaluated by nonlinear behavior of structures caused by ground motions. The characteristics of input ground motions and dynamic property of the structure are important factors to influence seismic response of structures. Ground motions used in seismic response of structure include various characteristics depending on fault mechanism of earthquake, wave propagation, and amplification of soil type. As a result, it is a difficult task to quantitatively examine all affecting factors. In seismic design, design response spectrum generally represents its characteristics. In this study, an 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) 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 high-rise building structures.

REFERENCES

1. Architectural Institute of Japan(1992), Seismic Loading-strong motion prediction and building response(in Japanese), Tokyo, p240.
2. Jun, Dae-Han and Inoue, Yutaka(1991), Inelastic response of single-degree-of-freedom systems subjected to artificial ground motions(in Japanese), Journal of Structural Engineering, Vol.37B, 111-118.
3. Jun, Dae-Han and Inoue, Yutaka(1991), Inelastic response of SDOF systems subjected to spectrum-compatible artificial accelerograms, the 3rd EASEC, Shanghai, China, 23-26 April, 711-716.
4. Kurama Y.C. and Farrow, K.T.(2003). Ground motion scaling methods for different site conditions and structure characteristics, Earthquake Engineering and Structural Dynamics, Vol.32, No.15, 2423-2450.
5. Li, Kang-Ning(2004). CANNY:3-dimensional nonlinear static/dynamic structural analysis computer program-User Manual, CANNY Structural Analysis, CANADA.
6. Moehle J.P.(2006). Seismic analysis, design, and review for tall buildings, The Structural Design of Tall and Special Buildings, Vol.15, 495-513.
7. Stewart J.P., Chiou S., Bray J.D., Graves R.W., Somerville P.G. and Abrahamson N.A.(2001), Ground motion evaluation procedures for performance- based design, PEER-2001/09, PEER, University of

California.
8. Zhai, Chang-Hai and Xie, Li-Li(2007). A new approach of selecting real input ground motions for seismic design: The most unfavorable real seismic design ground motions, Earthquake Engineering and Structural Dynamics, Vol.36, No.2, 1009-1027.

**Table 1 Comparison of maximum acceleration values for recorded and simulated ground motions (unit: cm/sec$^2$, sec)**

| Type of ground motion wave | Record ground motion | | | | Simulated ground motion | | | |
|---|---|---|---|---|---|---|---|---|
| | Max | Time | SF1* | SF2** | Max | Time | SF1* | SF2** |
| JMA Kobe 1995 NS | 819.1 | 4.94 | 0.75 | 1.16 | 415.3 | 5.54 | 2.06 | 1.55 |
| JMA Kobe 1995 EW | 617.1 | 8.46 | 0.99 | 1.65 | 401.1 | 8.47 | 2.09 | 2.05 |
| Taft 1952 NS | 152.7 | 9.10 | 5.73 | 4.30 | 369.3 | 6.62 | 2.03 | 1.32 |
| Taft 1952 EW | 175.9 | 3.70 | 6.73 | 6.00 | 426.3 | 3.71 | 1.98 | 2.08 |
| El Centro 1940 NS | 341.7 | 2.12 | 2.21 | 2.48 | 324.0 | 2.08 | 1.96 | 1.92 |
| El Centro 1940 EW | 210.1 | 11.44 | 3.41 | 2.48 | 321.6 | 2.03 | 2.09 | 1.50 |
| Mexico city 1985 NS | 98.0 | 24.16 | 6.00 | 1.10 | 353.4 | 39.86 | 1.94 | 1.70 |
| Mexico city 1985 EW | 167.9 | 28.08 | 3.98 | 0.79 | 336.6 | 33.38 | 2.05 | 1.65 |

*SF1: Scaling Factor for elastic response analysis
**SF2: Scaling Factor for non-linear response analysis

**Table 2 Member section and reinforcement**

(a) Column (C1, C2)

| Story | Size BxD(cm) | Reinforcement |
|---|---|---|
| 1 ~ 3 | 60x60 | 12-D22 |
| 4 ~ 6 | 50x60 | 12-D22 |
| 7 ~ 10 | 50x50 | 8-D22 |

(b) Beam (G1)

| Story | Size BxD(cm) | Upper bar* | Lower bar* |
|---|---|---|---|
| All | 35x60 | 6-D19 | 4-D19 |

* Denotes beam's both ends

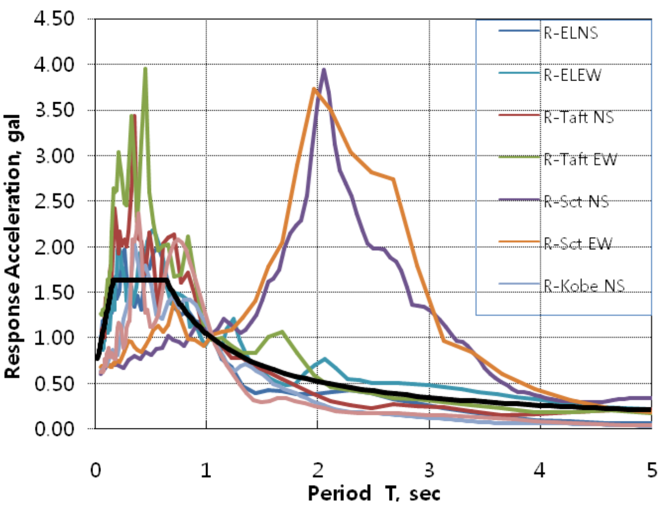


**Figure 1 Response spectra and design spectra of input ground motions**

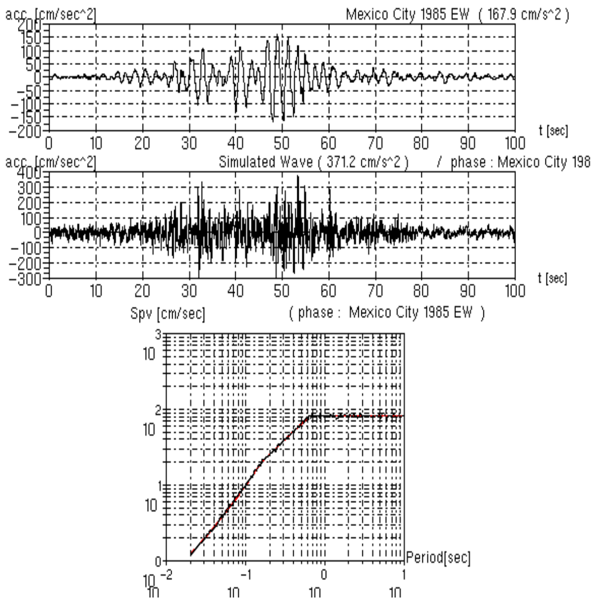


**Figure 2 Mexico city 1985 EW component**

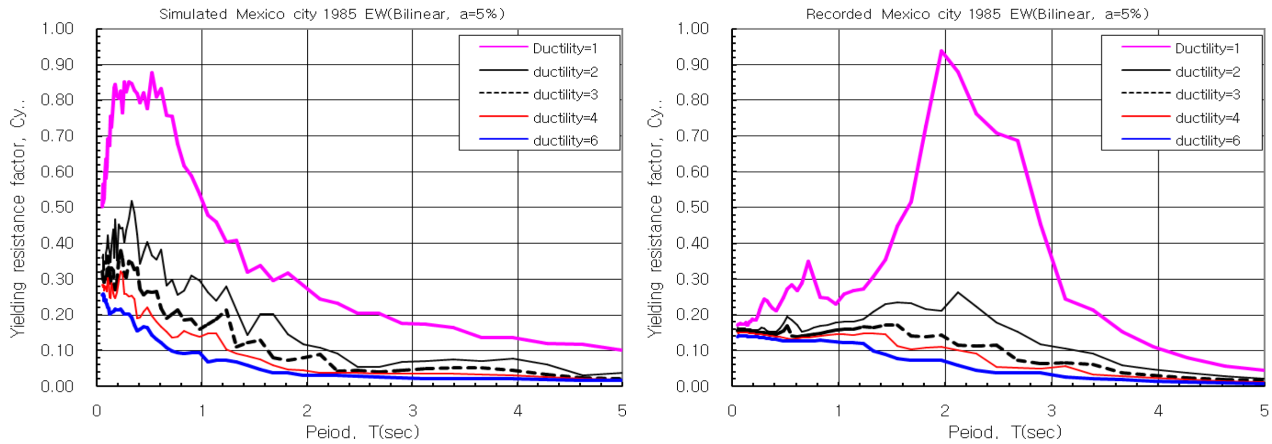


**Figure 3 Mexico city 1985 EW ground motion**

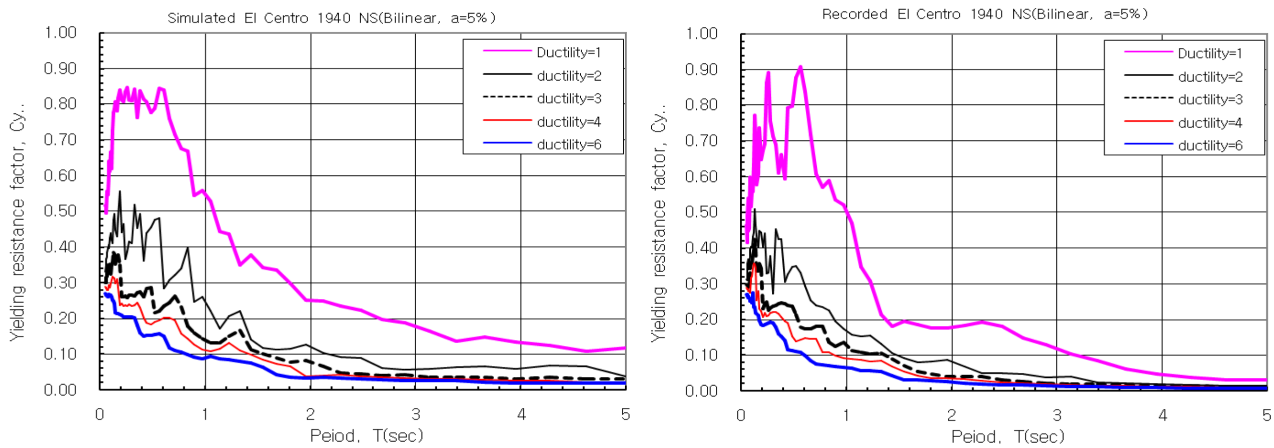


**Figure 4 El Centro 1940 NS ground motion**

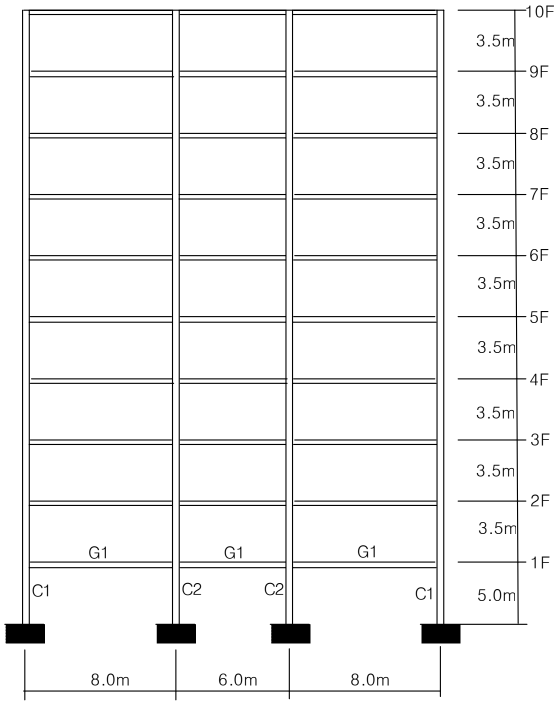


**Figure 5 Structural model**

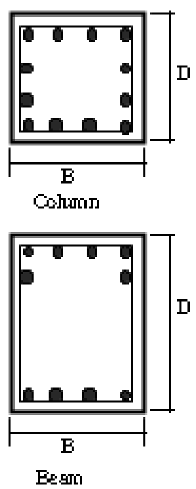


**Figure 6 Member cross section**

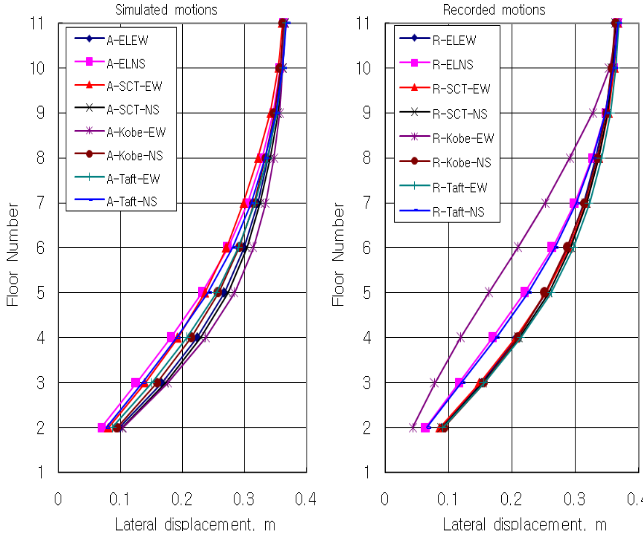


**Figure 7 Story displacement distribution by nonlinear analysis**

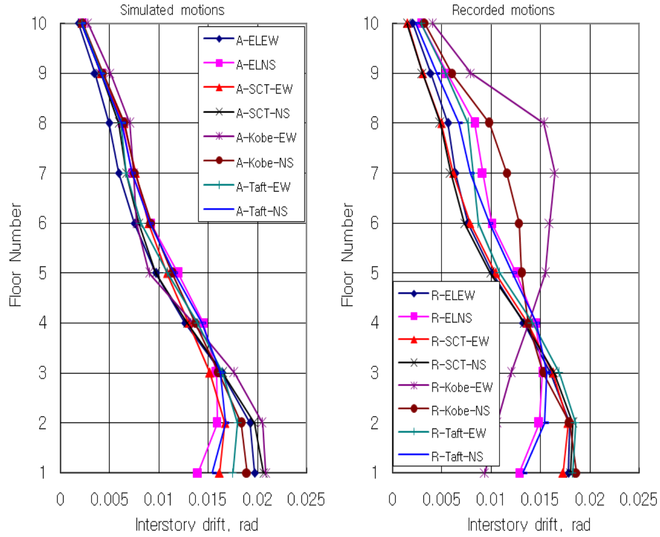


**Figure 8 Inter-story deformation distribution by nonlinear analysis**

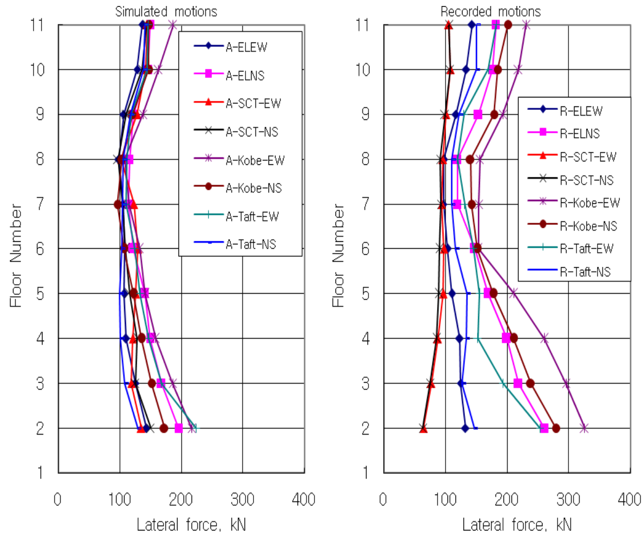


**Figure 9 Story seismic force distribution by nonlinear analysis**

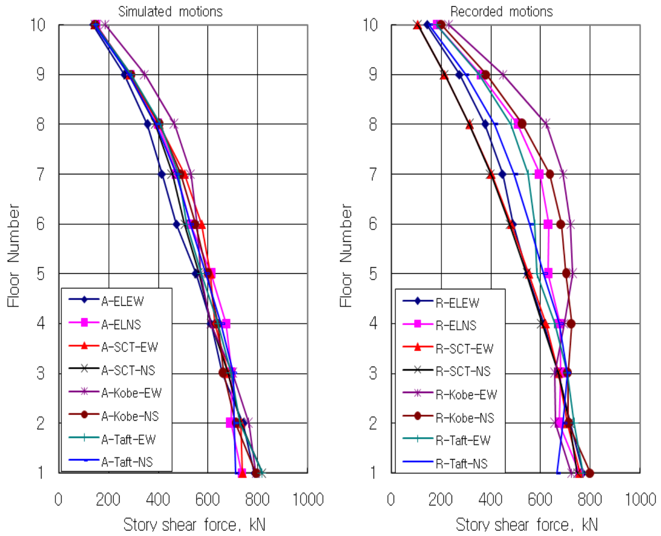


**Figure 10 Story shear force distribution by nonlinear analysis**