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# Determination of inelastic seismic response and evaluation of seismic performance for building structures using pseudo dynamic analysis method

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D.G. Lee, W.H. Choi & J.W. Lee
*Dept. of Architectural Engineering, Sungkyunkwan University, Suwon, Korea*

ABSTRACT: For the performance based seismic design, nonlinear static analysis is usually applied to evaluate the seismic capacity of a building structure effectively. This is a simple and practical analysis method to estimate the stability limit of a structure considering the load redistribution in the inelastic range. However, evaluation of the seismic performance of high-rise buildings or irregular buildings based on the nonlinear static analysis results may have shortcomings because the effects of the higher modes on the structure are not considered. In this study the story force obtained by the pseudo dynamic analysis method was used in the nonlinear static analysis, and the results were compared with those of the nonlinear time history analysis in terms of the plastic hinge formation, and interstory drift. The seismic responses predicted using the proposed method turned out to represent the nonlinear seismic response of a structure more accurately than those by other lateral load patterns.

## 1 INTRODUCTION

Recently, one of the main tendencies in the earthquake engineering research is to predict the behavior of a structure caused by earthquake loads that can occur during the lifetime of a building, and to analyze the seismic performance in a more effective method. The basic concept of the performance based seismic design is to design structures to achieve the desired performance objectives for several levels of ground motion.

In the performance based seismic design, nonlinear static analysis (or pushover analysis) is usually employed to estimate the seismic capacity of a structure effectively. This is a simple and practical analysis method to estimate the stability limit of a structure considering the load redistribution in the inelastic range. There are several parameters that should be considered in the nonlinear static analysis, and the most important one is to choose the vertical distribution of seismic loads that may have significant influence on the characteristics of the nonlinear seismic response of a structure and the seismic performance. In general, the vertical distribution of the seismic loads used in the seismic design is based on the assumption that the first mode shape of a structure mainly governs the elastic seismic response. Therefore, this type of seismic load distribution cannot reflect the effects of the higher modes on the seismic response.

An improved method for the vertical distribution of the seismic loads is proposed in this study to represent the nonlinear seismic responses of a structure for the evaluation of the capacity. Seismic response of example structure was obtained using linear and nonlinear time history analyses for different ground motions and irregularity of the structure. Vertical distribution of the seismic loads by the method proposed in this study and other methods were used in the analysis for the verification of the adequateness of the proposed method by comparing the linear and nonlinear seismic responses of a structure.

## 2 VERTICAL DISTRIBUTION OF THE SEISMIC LOADS

Several methods for the vertical distribution of seismic loads were introduced to account for the effects of higher modes on the seismic response of a structure. ATC-40 distributes the seismic loads according to the first mode shape for regular buildings while Freeman and Requena respectively suggested a method for the load distributions based on the seismic loads combined for all of the modes in the response spectrum analysis. The story forces distributed in portion to the deflected shape of a building structure was proposed by Fajfar and Fischinger. Lee proposed the pseudo dynamic analysis method that employs the story forces derived from the story shear forces obtained by combining the story shear forces for all of the modes using the SRSS method as an alternative to the response spectrum analysis.

Eberhard and Sozen suggested a method for distribution of seismic loads based on the nonlinearity of a structure. It is a method that applies the seismic loads distributed according to the mode shape of a structure in each step of the incremental nonlinear static analysis or pushover analysis. However, this modal adaptive method is very sensitive to the inelastic property of materials and the inelastic responses of a structure, so the application is very limited. Therefore, the seismic design procedures in ATC-40 and FEMA-273, 274 recommend to use the vertical distribution of seismic loads based on the combination of the modal story forces for the nonlinear static analysis. The lateral load patterns according to ATC-40 and FEMA-273, 274 and the proposed method based on the pseudo dynamic analysis method suggested by Lee were used for linear and nonlinear static analysis in this study.

### *2.1 Lateral load pattern TYPE-S based on the first mode shape*

ATC-40 suggested a method to distribute the base shear force for the first mode to each floor level using the first mode shape of a structure. This method can be useful for regular building structures or low-rise buildings and the base shear force ($V_1$) can be obtained by Eq.(1) as follows;

$$V_1 = \alpha_1 \, S_{a1} \, W \tag{1}$$

where $S_{a1}$ = spectral acceleration of the fundamental period of a structure; $W$= total weight of a structure; and $\alpha_1$ = effective mass coefficient. The base shear force ($V_1$) is distributed to each floor level as follows;

$$F_i = \frac{m_i \, \phi_{i1}}{\sum_{i=1}^{N} m_i \, \phi_{i1}} V_1 \tag{2}$$

where $F_i$ is the seismic force to be applied at each floor. When the seismic loads are distributed in this manner the response of a structure will be governed by the effect of the first mode only.

### *2.2 Lateral load pattern TYPE-F based on the combination of modal story forces*

Another methods proposed by Freeman and Requena accounted for the contribution of the higher modes of a structure in the distribution of the seismic loads. The seismic loads are distributed using the load patterns obtained by means of combination of the story force of all modes using the SRSS method as shown in Fig.1.

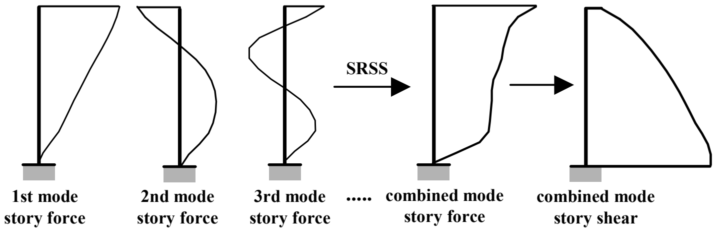


Figure 1 Lateral load pattern TYPE-F based on the combination of modal story forces

The seismic force to be applied at each floor is calculated as follows;

$$F_i = \sqrt{\sum_{i=1}^{N} (\Gamma_j \, \phi_{ij} \, S_{aj} \, m_i)^2} \tag{3}$$

where $\phi_{ij}$ = amplitude of mode $j$ at level $i$, $S_{aj}$ = spectral acceleration for mode $j$, and $\Gamma_j$ is the modal participation factor for mode *j*. The seismic forces calculated by Eq.(3) can be used to obtain the story shear forces as shown in Fig.1.

### *2.3 Lateral load pattern TYPE-V based on the combination of modal story shear forces*

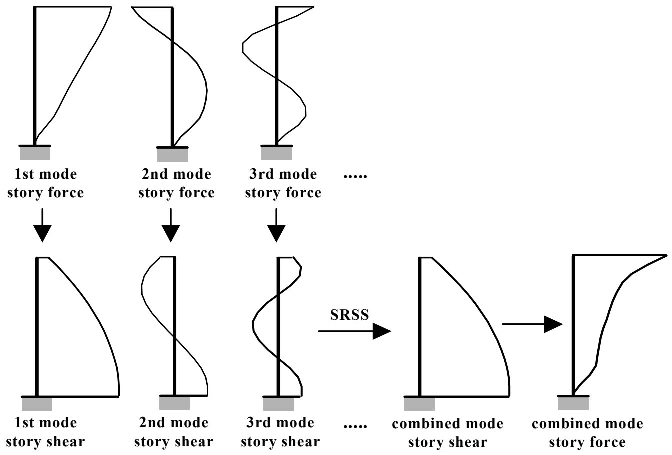


Figure 2 Lateral load pattern TYPE-V based on the combination of modal story shear forces

The bending moments and the shear forces in beams and columns in multistory buildings due to lateral forces mainly depend on the story shear forces, and the axial forces in columns are governed by the overturning moments which are mainly influenced by the story shear forces. The procedure to calculate the lateral load pattern using the pseudo dynamic analysis method is explained in Fig.2. Modal story forces are used to obtain modal story shear forces, which are combined for all of the modes. Story shear forces for the load pattern TYPE-V obtained in this manner may be somewhat different from those of the load pattern TYPE-F. Then the story forces are obtained as the difference of the story shear forces in adjacent levels.

### *2.4 Lateral load pattern to be used for the nonlinear static analysis*

Seismic responses of the example structure were analyzed in this study using the load pattern TYPE-V based on the pseudo dynamic analysis method suggested by Lee for the nonlinear static analysis. Since the story shear forces governs the seismic responses of a structure, and lateral load pattern to be applied in the nonlinear static analysis should be based on the story forces that can accurately lead to the story shear forces for a building structure.

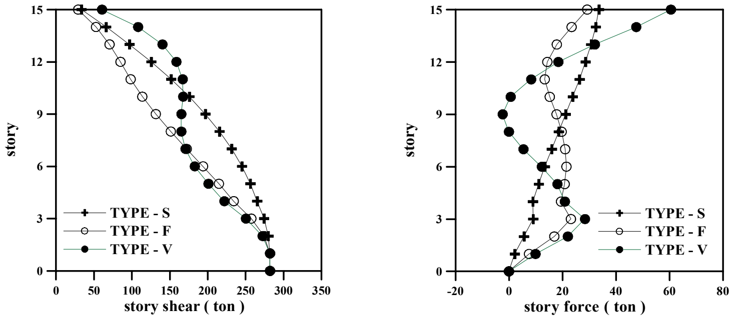


Figure 3 Story shear forces and story forces from three types of lateral load patterns

The story shear forces and the story forces for three types of lateral load pattern applied to the example structure shown in Fig.4 using the response spectrum of the El Centro earthquake (NS, 1940) scaled to have the EPA of 0.4g are plotted in Figs.3. Story forces for the example structure was scaled to have the same base shear force for three types of lateral load pattern. There were noticeable differences in story forces obtained using three types of load pattern leading to similar differences in story shear forces. The difference in the story shear forces will result in difference in nonlinear response of structures.

## 3 EVALUATION OF LINEAR SEISMIC RESPONSE FOR THREE LATERAL LOAD PATTERNS

In general, the contribution of the first mode is less dominant and the effects of higher modes are getting more significant on seismic responses of irregular buildings. Therefore, a 15-story reinforced concrete building illustrated in Fig.4 was employed as an example structure to induce larger contribution of higher modes on the seismic response so that responses will largely depend on the lateral load pattern whether it accounts for the effects of the higher modes or not.

### *3.1 Example structure*

Preliminary design of the example structure was based on the strong column-weak girder concept. The compressive strength of the concrete and tensile strength of the steel were assumed to be 210kg/cm$^2$ and 4000kg/cm$^2$, respectively. For nonlinear analysis of the example structure, the effect of the gravity load of a structure should be considered. So, the dead and live loads were assumed to be 600kg/cm$^2$ and 250kg/cm$^2$, respectively. The section of members and the reinforcement for the beams and columns used in the example structure are listed in Table 1.

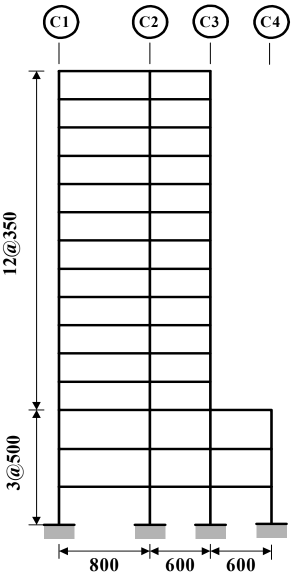


Figure 4 Fifteen story example structure (unit : cm)

Table 1 Sections and the reinforcements of the members

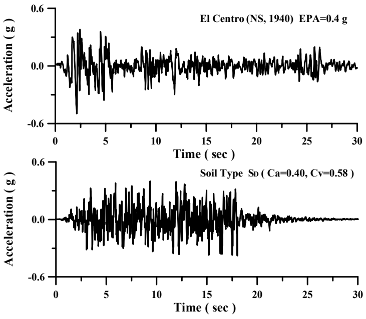
| story | column sections and reinforcements | | | | beam sections and reinforcements |
|---|---|---|---|---|---|
| | C1 | C2 | C3 | C4 | |
| 1–3 | 700×700<br>20-HD25 | 750×750<br>24-HD25 | 750×750<br>24-HD25 | 700×700<br>20-HD25 | 500×700<br>top bottom:<br>5-HD25 |
| 4–6 | 650×650<br>16-HD25 | 700×700<br>20-HD25 | 700×700<br>20-HD25 | - | 500×650<br>top bottom:<br>5-HD25 |
| 7–9 | 600×600<br>12-HD25 | 650×650<br>16-HD25 | 600×600<br>12-HD25 | - | 500×600<br>top bottom:<br>5-HD25 |
| 10–12 | 550×550<br>12-HD25 | 600×600<br>12-HD25 | 550×550<br>12-HD25 | - | 400×600<br>top bottom:<br>4-HD25 |
| 12–15 | 500×500<br>12-HD25 | 550×550<br>12-HD25 | 500×500<br>12-HD25 | - | 400×550<br>top bottom:<br>4-HD25 |

### *3.2 Earthquake loads*

Two earthquake ground acceleration records were used for the response spectrum analysis and the time history analysis of the example structure. The effective peak acceleration (EPA) of the El Centro earthquake (NS, 1940) was scaled to be 0.4g. The seismic coefficients ($C_a$, $C_v$) of zone 4 (Z=0.4) in the seismic design code UBC-97 corresponding to the acceleration response spectra of the scaled earthquake record were estimated. As can be observed in Fig.6, the response spectrum for the El Centro earthquake corresponds to the design spectrum for the soil type $S_D$. The effect of the near-source factor ($N_a$, $N_v$) was not considered in this study. And an artificial earthquake ground acceleration record, which almost coincides with the design response spectrum for the soil type $S_D$ was generated. Earthquake records used in this study were listed in Table 2 and time histories of ground acceleration and corresponding to the acceleration response spectra are shown in Figs.5 and 6, respectively.

Table 2 Scaled earthquake ground motion records used for the seismic analysis

| Earthquake records | PGA (cm/sec$^2$) | PGV (cm/sec) | PGD (cm) | EPA (g) |
|---|---|---|---|---|
| El Centro (NS, 1940) | 487.95 | 47.69 | 15.42 | 0.40 |
| Artificial earthquake | Soil type $S_D$ ( $C_a$ = 0.40, $C_v$ = 0.58 ) | | | 0.40 |



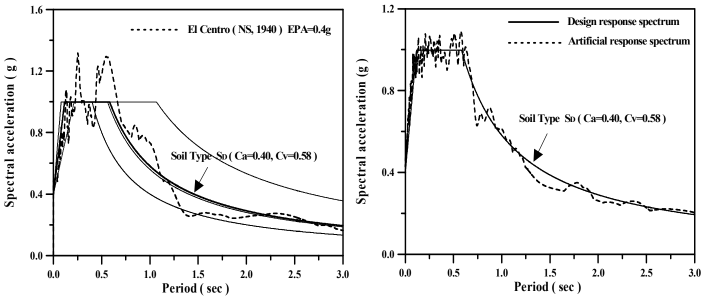


Figure 5 El Centro earthquake and Artificial earthquake

Figure 6 Acceleration response spectra for El Centro earthquake and Artificial earthquake

### *3.3 Response spectrum analysis results for the example structure*

Response spectrum analyses of the 15-story example structure were performed and the mode shapes, natural periods, modal participation factors, effective modal masses and the ratio of the effective modal mass to total mass were calculated and listed in Table 3 for the first five modes. The elastic response spectrum with 5% damping for each earthquake record was used for the response spectrum analysis to obtain modal story forces. And modal story shear forces were obtained from the modal story forces using static theory. Story forces and story shear forces obtained from the response spectrum analysis of the example structure for the El Centro earthquake (NS, 1940) were plotted in Figs.7 and 8.

Table 3 Results of the response spectrum analysis for example structure

| mode | natural period (sec) | modal participation factor | effective modal mass | effective modal mass / total mass (%) |
|---|---|---|---|---|
| 1 | 1.519 | 1.407 | 0.755 | 73.998 |
| 2 | 0.554 | 0.613 | 0.151 | 14.828 |
| 3 | 0.321 | 0.328 | 0.044 | 4.339 |
| 4 | 0.221 | 0.218 | 0.020 | 1.955 |
| 5 | 0.163 | 0.177 | 0.014 | 1.373 |

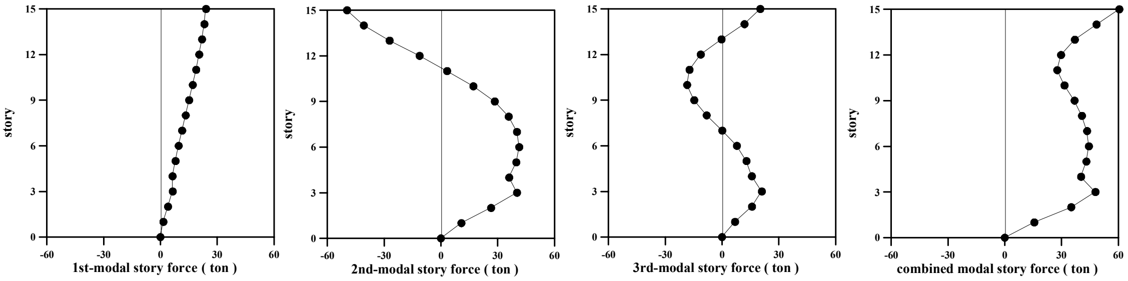


Figure 7 Story forces for the first 3 modes and combined result (El Centro, EPA=0.4g)

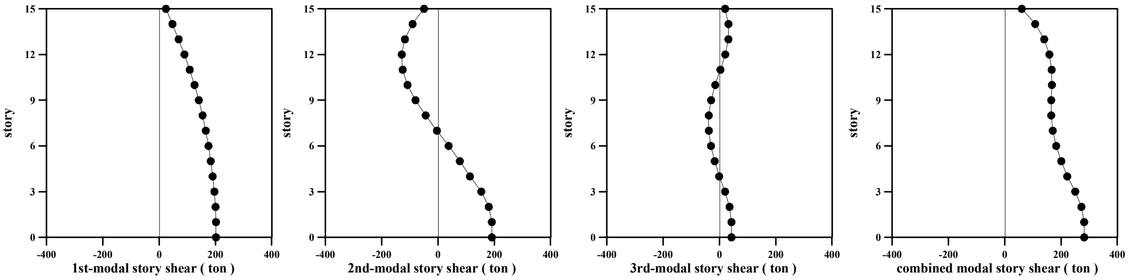
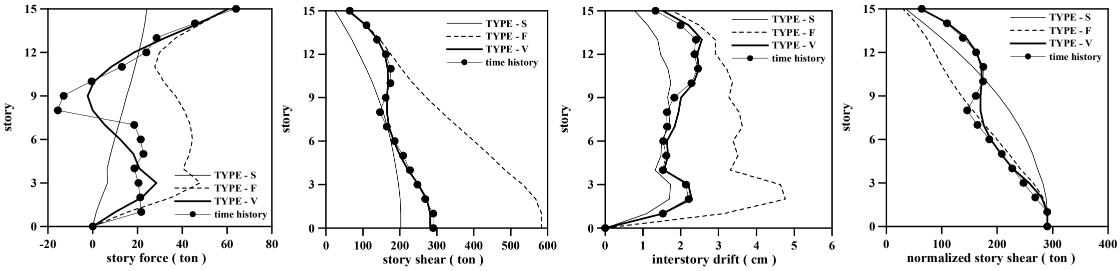


Figure 8 Story shear forces for the first 3 modes and combined result (El Centro, EPA=0.4g)

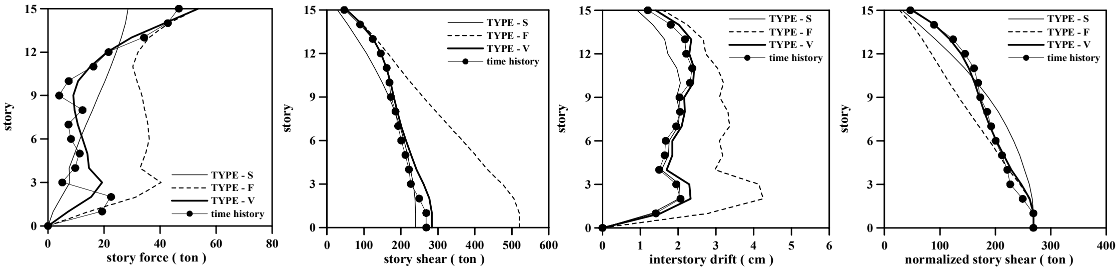
### *3.4 Linear seismic responses to three types of lateral load pattern*

Story forces, story shear forces and the interstory drifts obtained using three types of lateral load pattern were compared to those obtained from the linear elastic time history analysis of the example structure. The proposed lateral load pattern that is based on the combined story shear forces from the response spectrum analysis resulted in the seismic response that is similar to that from the time history analysis. The seismic responses of the example structure obtained using three types of lateral load pattern were compared to those of the time history analysis and distribution of the story shear for three types of load pattern was investigated by normalizing the base shear with the respect to that of the time history analysis as shown in Figs.9 and 10, respectively. Story shear forces can be in a good agreement when the story forces are in a similar pattern. It could be noticed that the proposed load pattern TYPE-V, provide story forces, story shear forces, interstory drifts and normalized story shear closer to those from the time history analysis in all cases of two earthquake records used in this study.



(a) story forces (b) story shear forces (c) interstory drifts (d) normalized story shear

Figure 9 Comparison of the seismic responses from different load patterns (El Centro earthquake)

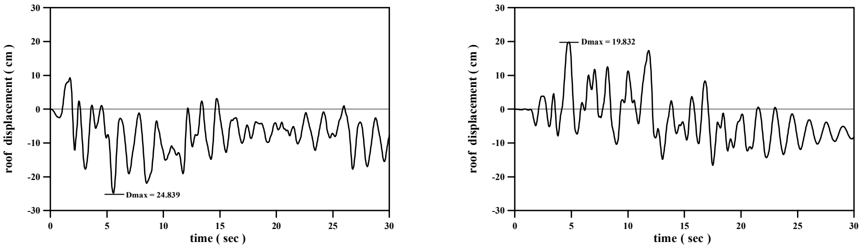


(a) story forces (b) story shear forces (c) interstory drifts (d) normalized story shear

Figure 10 Comparison of the seismic responses from different load patterns (Artificial earthquake)

## 4 EVALUATION OF NONLINEAR SEISMIC RESPONSE FOR THREE LATERAL LOAD PATTERNS

The nonlinear seismic response was evaluated by applying three types of load pattern to the example structure. The gravity load was considered by using the load combination of 1.0D.L+0.5L.L, while the P-Δeffect was not considered in the nonlinear seismic analysis. The maximum displacement at the roof obtained by the nonlinear time history analysis using two earthquake records and the maximum roof displacement was set as the target displacement in the nonlinear static analysis with three types of lateral load pattern. The roof displacement time histories for two earthquake records are illustrated in Fig.11.

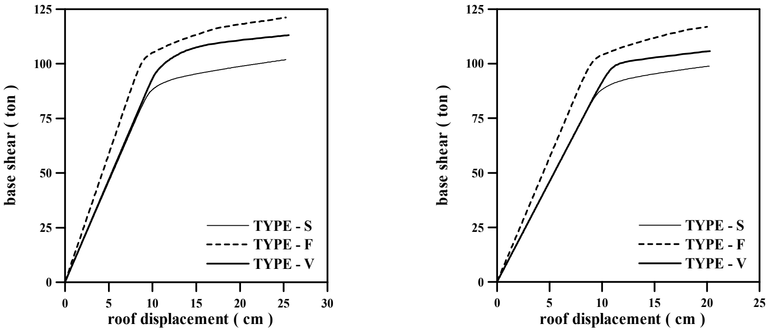


(a) El Centro earthquake (b) Artificial earthquake

Figure 11 Roof displacement time histories for two earthquake records

### *4.1 Relationship between the base shear force and roof displacement*

The maximum displacement obtained by the nonlinear time history analysis was set as the target displacement in the nonlinear static analysis, and the relationship between the base shear force and roof displacement of the example structure was determined for three types of lateral load pattern considered in this study. It can be noticed that the relationship between the base shear and the roof displacement of the example structure can be different for three types of lateral load pattern as shown in Fig.12. The relationship between the base shear force and the displacement can be used as the resistance capacity of a structure. Therefore, the seismic performance of a structure can be sensitive to the lateral load pattern in the nonlinear static analysis.

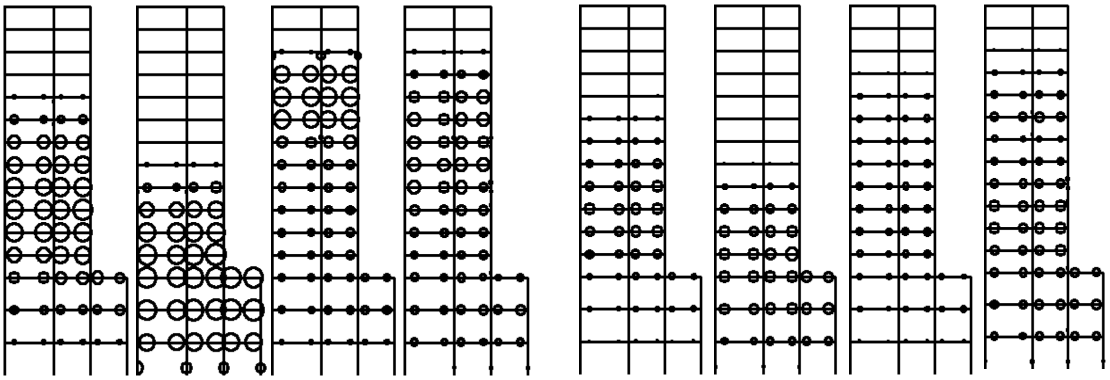


(a) El Centro earthquake (b) Artificial earthquake

Figure 12 The relationship between the base shear and the roof displacement for example structure

### *4.2 Evaluation of the lateral load patterns based on the plastic hinge formation*

Nonlinear response of a structure can be represented by the location and rotation angle of plastic hinges, which is very useful to evaluate the nonlinear seismic response. In general, the plastic hinge formation in the nonlinear time history analysis can be somewhat different from those from the nonlinear static analysis with monotonically increasing load, since the seismic load is a random cyclic load with frequency component in a wide range. Nonlinear static analyses with three types of load pattern and the nonlinear time history analyses were performed using two earthquake records for the example structure and the location and rotation angle of plastic hinges are presented in Fig.13. The plastic hinge rotations are represented by the size of circles in this figure. The plastic response was underestimated by the load pattern TYPE-S and TYPE-F in upper stories while TYPE-F overestimates the plastic deformation in lower stories. As observed in the seismic responses elastic range, the load pattern TYPE-V could represent the nonlinear seismic response of a structure closer to that by the nonlinear time history analysis compared to lateral load pattern TYPE-S and TYPE-F.



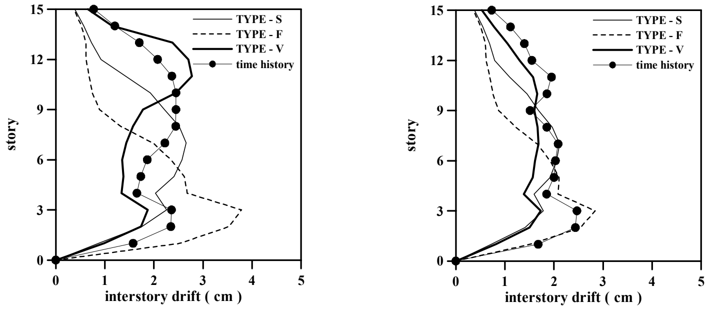
TYPE-S TYPE-F TYPE-V time history TYPE-S TYPE-F TYPE-V time history

(a) El Centro earthquake (b) Artificial earthquake

Figure 13 Plastic hinge formations from different load patterns structures for example structure

### *4.3 Evaluation of the lateral load patterns based on the interstory drift*

In the performance based seismic design, one of the most important parameters that evaluate the seismic performance level is the nonlinear interstory drift of a building structure. According to the previous research it is indicated that the interstory drift from the nonlinear seismic analysis, which reflects the effects of the higher mode, governs the yield mechanism. Nonlinear static analyses with three types of load pattern and the nonlinear time history analyses were performed using two earthquake records for the example structure and the interstory drifts are presented in Fig.14. It was noticed that the proposed method predicts the interstory drifts closer to the results of the nonlinear time history analysis than those by the other lateral load patterns as could be expected from the study on the resistance capacity and the plastic hinge formation.



(a) El Centro earthquake (b) Artificial earthquake

Figure 14 Evaluation of nonlinear interstory drifts from different load patterns for example structure

## 5 CONCLUSIONS

An effective method for prediction and evaluation of the nonlinear seismic response and the seismic performance of a multistory building was proposed in this study. By comparing the linear and nonlinear seismic response for several lateral load patterns, two conclusions could be drawn as follows;

(1) If the story forces used in the linear elastic analysis could represent the story shear forces with accuracy, the results can be in a good agreement with those from the time history analysis of a multistory building structure.

(2) The lateral load patterns for nonlinear static analysis based on the first mode shape or the combination of modal story forces could not represent the nonlinear response including the upper and lower stories of a multistory building structure. When the proposed lateral load pattern based on the combination of modal story shear forces is used for nonlinear static analysis, the significant nonlinear seismic responses such as plastic hinge formation and interstory drift could be predicted and evaluated accurately.

## ACKNOWLEDGEMENT

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