A Simple Analysis Method for Estimation of Required Damping Ratio for Seismic Response Reduction

Hyeong-Gook Kim¹ and Kil-Hee Kim*²

¹ Research Assistant Professor, Department of Architectural Engineering, Kongju National University, Cheonan, Republic of Korea
² Professor, Department of Architectural Engineering, Kongju National University, Cheonan, Republic of Korea

Abstract
This paper proposes a simple analysis method to estimate the additional damping ratio required to achieve a target seismic performance level. The proposed method employs the Newmark and Hall's design response spectrum and the simple version of the N2 method. With the help of combining the characteristic of the two methods, it is possible to approximately estimate additional damping ratios required to achieve target elastic or inelastic seismic responses of a building structure without iteration. To examine the validity and effective range of the proposed method, time history response analysis is conducted, and the results are compared with those of a numerical analysis in which the post-yield stiffness ratio is considered. The analytical results show that the post-yield stiffness ratio and the yield displacement are important factors that affect the validity of the proposed analysis method; it is also found that the proposed simple analysis procedure may be quite efficient in evaluating the performance point and the damping requirements for seismic response reduction of building structures.

Keywords: seismic response reduction; capacity spectrum method; post yield stiffness ratio; ductility ratio; damping requirement

1. Introduction
Since the paradigm for seismic design was changed to performance-based design in the 1980s, deformation has been used as a key indicator in the seismic performance assessment of building structures. The capacity spectrum method (CSM) (ATC-40, 1996; Freeman, 1998) and its improved procedures (Chopra and Goel, 1999; Fajfar, 1999; Iwan and Guyder, 2002; Lin and Miranda, 2004) have been widely used for assessing the seismic performance of building structures due to its visual representation and accuracy. However, structural engineers are confronted with non-convergence and/or multiple solution problems when attempting to determine the seismic performance of building structures. Fajfar (2000) proposed the N2 method as a variant of CSM based on inelastic demand spectra. The N2 method allows structural engineers to determine the seismic performance of building structures without iteration. These methods are obviously one of the powerful tools for the seismic analysis of structures; however, these methods provide the level of deformation and/or acceleration responses of building structures at a damping ratio, but not the value of additional damping required to reduce the seismic response to a target seismic performance level. Kim et al. (2003) proposed a design method for adding viscous dampers using the CSM; it was found as well that their method, even though it has the conventional problems, is effective at estimating the optimal damping ratio. Over the past few years, many studies on analytical approaches to evaluate earthquake-induced structural damages based on the energy input to the structure (Takahashi and Akiyama, 1999; Ogawa et al., 2000; Decanini and Mollaioli, 2001; Li et al., 2009; Yi et al., 2013; Taniguchi and Takekwa, 2015) has been conducted; however, there are few practical applications employing these approaches in structural design.

This paper deals with a simple analysis method to estimate the additional damping ratio required to achieve a target seismic performance level. The proposed method employs the Newmark and Hall's design response spectrum and the simple version of the N2 method. While the former provides relatively accurate elastic seismic responses of a building structure for various damping ratios, the latter which is a variant of CSM based on inelastic spectra provides the approximate inelastic seismic response of a building structure for 5% damping without iteration. With the help of combining the advantage of the two methods, the proposed method can approximately
estimate additional damping ratios required to achieve target elastic or inelastic seismic responses of a building structure without iteration. To overcome the problems of existing procedures in determining additional damping for seismic response reduction, in this paper, the capacity and demand spectrum are assumed to be functions of the ductility ratio. Solving a simultaneous equation for the two functions makes it possible to find the intersection between the capacity and the demand spectra, namely, the performance point of the structural system, and an additional damping ratio required to achieve a target seismic performance using a single process. This procedure can be applied to bilinear SDOF systems with various post-yield stiffness ratios. To examine the validity of the proposed simple analysis method, time history response analysis is conducted, and the results are compared with those of a numerical analysis considering the post-yield stiffness ratio.

2. Design Response Spectrum

2.1 Elastic Design Response Spectrum

Newmark and Hall’s elastic design response spectrum (1982), which considers spectrum amplification factors for the 50-percentile cumulative probability level, is expressed in terms of the undamped natural frequency \( \omega \) and the damping ratio \( \beta \) (%) as

\[
S_D^E(\omega, \beta) = \frac{PGA}{\omega} \times \left\{ \begin{array}{ll}
0.56 - 0.38 \ln(\beta) & (\omega \leq \omega_1) \\
0.31 & (\omega_1 < \omega \leq \omega_2)
\end{array} \right.
\]

(1a)

\[
S_D^E(\omega, \beta) = \frac{PGV}{\omega} \times \left\{ \begin{array}{ll}
0.44 & (\omega \leq \omega_1) \\
0.18 & (\omega_1 < \omega)
\end{array} \right.
\]

(1b)

\[
S_D^E(\omega, \beta) = \frac{PGD}{\omega} \times \left\{ \begin{array}{ll}
0.82 - 0.27 \ln(\beta) & (\omega_1 < \omega \leq \omega_2)
\end{array} \right.
\]

(1c)

In Eq. 1, PGA, PGV and PGD are the peak ground acceleration, velocity and displacement, respectively. The corner circular frequencies \( \omega_1 \) and \( \omega_2 \) can be derived from the relation of \( S_D^E(\omega_1, \beta) = S_D^E(\omega_2, \beta) \) and \( S_D^E(\omega_1, \beta) = S_D^E(\omega_2, \beta) \), respectively.

2.2 Relationship between Linear Elastic and Inelastic Responses

It is assumed that if the natural frequencies of a linear elastic system and a bilinear SDOF system with post-yield stiffness lie within the constant spectral acceleration region of the response spectrum, the energy in the two systems is the same, as shown in Fig.1.(a). This assumption called the law of energy conservation is commonly used to relate the linear elastic displacement with the inelastic displacement (Penzien 1960; Chopra and Goel 1999; Fajfar 2000). The relation between the linear elastic and inelastic displacements can be expressed by

\[
S_D^E = \mu S_D^I
\]

(2)

\[
S_A^E = \mu S_A^I
\]

(3)

in which \( S_D^E \) and \( S_D^I \) are the acceleration responses in the linear elastic and bilinear SDOF systems, respectively. The relation between \( S_D^E \) and \( S_D^I \) in the inelastic spectrum (Vidic et al., 1994), using the Newmark and Hall method, can be approximated as

\[
S_D^E = \frac{\mu}{R} S_D^I
\]

(4)

\[
S_A^E = \frac{\mu}{R} S_A^I
\]

(5)

In Eqs. 2 to 5, in the case of \( \alpha = 0 \), the equations for a bilinear system are the same as those for an elastic-perfectly plastic system. The relation between \( S_D^E \) and \( S_D^I \) in the inelastic spectrum (Vidic et al., 1994), using the Newmark and Hall method, can be approximated as

\[
S_D^E = \frac{\mu}{R} S_D^I
\]

(6)

In Eq. 6, the period dependent strength reduction factor \( R \) (Newmark and Hall, 1982) is given by

\[
R = \frac{1}{T} \cdot \frac{1}{T_c} = \frac{1}{1.33}\left\{ \begin{array}{ll}
1 & (T < T_c)\\
0.125 & (1.33 \leq T < T_c)
\end{array} \right.
\]

(7)

where \( T \) is the period of the structural system, \( T_c \) is the critical period, and \( \mu \) is the ductility ratio. The period dependent strength reduction factor \( R \) is defined as

\[
R = \frac{1}{2} \left\{ \begin{array}{ll}
1 & (T < T_c)\\
0.125 & (1.33 \leq T < T_c)
\end{array} \right.
\]

(8)
T_c = \left(\sqrt{2\mu - 1}\right) / \mu \cdot T_e \quad (9)

T_c is the corner period at which the constant spectral acceleration region is divided from the constant spectral velocity region of the response spectrum.

### 2.3 Inelastic Design Response Spectrum for Bilinear SDOF System with Post-Yield Stiffness

The relation between the displacement and the pseudo-acceleration in the elastic response spectra corresponding to the period \( T \) is defined as

\[
S_D^2 = \frac{T^2}{4\pi^2} S_s^2 \quad (10)
\]

Substituting Eqs. 2-5 into Eq. 10, \( S_D^2 \) and \( S_s^2 \), considering the post-yield stiffness of inelastic systems, can be derived as follows

\[
S_D^2 = \frac{\mu}{\sqrt{\alpha (\mu - 1) + 2\mu - 1}} S_s^2 = \frac{\mu}{1 + \alpha (\mu - 1)} T^2 \cdot S_s^2 \quad (11a)
\]

\[
S_D^2 = S_D^2 = \frac{T^2}{4\pi^2} S_s^2 = \frac{\mu}{1 + \alpha (\mu - 1)} T^2 \cdot S_s^2 \quad (11b)
\]

It can be understood that, in the case of \( \alpha = 0 \), each denominator in Eq. 11 will correspond to \( R \) in Eq. 7 for a natural period range of more than \( T_b = 0.125s \). However, in the case of \( 1/33 \leq T / T_b < 0.125 \), \( R \) can be also expressed as \( (\alpha (\mu - 1)^2 + 2\mu - 1)^{\frac{1}{2}} \) with reference to Fig.1.(a), and Eqs. 2 and 3.

### 3. Simple Analysis Method for Estimation of Required Damping Ratio

#### 3.1 Evaluation of Performance Point

As mentioned above, to find the accurate performance point \( S_D^2 \) of an inelastic SDOF system using a single process, the capacity curve and the demand spectrum are assumed to be functions of the ductility ratio \( \mu \). If \( S_D^2 \) lies in the constant spectral acceleration region of the response spectrum, the ductility ratio \( \mu_{EA} \) corresponding to the intersection between the capacity curve and the demand spectrum for 0.5–20% damping can be derived from the relation between Eqs. 1(a) and 2.

\[
S_D^{E_I} = \delta_y \sqrt{\alpha (\mu_{EI} - 1)^2 + 2\mu_{EI} - 1} \quad (12a)
\]

where \( \delta_y \) is the yield displacement of a bilinear SDOF system. Then, \( \mu_{EA} \) can be expressed in terms of the post-yield stiffness ratio \( \alpha \), as follows.

\[
\mu_{EI} = \frac{\left(\frac{S_D^{E_I}}{\delta_y}\right)^2 + 1}{2}, \quad (\alpha = 0)
\]

\[
\mu_{EV} = \frac{\alpha - 1 + \alpha \left(\frac{S_D^{E_I}}{\delta_y}\right)^2 + 1}{\alpha}, \quad (0 < \alpha < 1)
\]

\[
\mu_{ED} = \frac{1}{\alpha}, \quad (\alpha > 1)
\]

If the performance point \( S_D^2 \) lies in the constant spectral velocity or displacement region, the ductility ratios \( \mu_{EV} \) and \( \mu_{ED} \) can be derived from the relation between Eqs. 1(b), 1(c) and 4, respectively.

\[
S_D^{EV} = S_D^2 = \mu_{EV} \cdot \delta_y \quad (12c)
\]

\[
S_D^{ED} = S_D^2 = \mu_{ED} \cdot \delta_y \quad (12d)
\]

The performance point \( S_D^2 \) of the structure for a prescribed damping, therefore, can be expressed using \( \mu \).

\[
\mu = \left| \mu_{EI}, \mu_{EV}, \mu_{ED} \right| \quad (12g)
\]

\[
S_D^2 = \mu \cdot \delta_y \quad (12h)
\]

Substituting \( S_D^2 \) and \( \mu \) into Eq. 11, the response spectral acceleration \( S_s^2 \) can be estimated.

#### 3.2 Damping Requirement for Performance Target

During the design phase of damping devices, after assessing the seismic performance of a building structure subjected to ground motion, it is necessary to estimate the required damping ratio needed to achieve the prescribed performance target, \( S_D^2 \). A simple analysis method for damping estimation using the elastic design response spectrum is introduced here to determine the damping requirement \( \beta_{req} \) for the prescribed performance target. This method is similar to the above method for estimation of performance point; however, the capacity and demand spectra are assumed here to be functions of the damping ratio \( \beta \). \( \beta_{req} \) for the constant spectral acceleration, velocity, and displacement regions of the response spectrum can be derived from the relation between Eq. 1 and Eqs. 2 to 5.
where $S_D$ and $\mu^T$ are the displacement and the ductility ratio corresponding to the performance target.

Fig. 2. provides a conceptual diagram and flowchart of the proposed analysis procedures. The performance point $S_D$ of a bilinear SDOF system subjected to prescribed ground motions is evaluated using the simple analysis method for estimation of performance point (Step 1); then, with reference to $S_D$, the damping requirement $\beta_{req}$ needed to achieve the prescribed performance target $S_D$ is determined using the simple analysis method for damping estimation (Step 2). Finally, the capacity spectrum, plotted in the ADRS format, is compared with the two demand spectra for 0.5~20% damping and for the damping requirement $\beta_{req}$ (Step 3).

4. Verification

Time history response analysis is conducted using ten artificial ground motions compatible with a design acceleration response spectrum specified at the open engineering bedrock (Otani, 2004), to check the validity and accuracy of the proposed analysis procedures, the results are compared with those of the numerical analysis. The maximum velocity of artificial ground motions was normalized to 50.0 cm/s ($PGA=402.0$ cm/s$^2$, $PGV=50.0$ cm/s and $PGD=37.5$ cm) for level-2 earthquake events proposed by the Architectural Institute of Japan (AIJ, 1993). Artificial ground motions in this study were generated using the envelope function proposed by Jennings et al. (1969). Fig. 3. shows the elastic displacement response spectra obtained using the Newmark and Hall’s method and the mean displacement response spectra of the ten artificial ground motions compatible with a design response spectrum for several damping ratios. Fig. 4. shows a sample of the acceleration time history of the artificial ground motions.

### Table 1. Performance Points Obtained Using Proposed Method and Time History Response Analysis

| Displacement response | $\beta$ (%) | Mean value of time history response analysis | Proposed method |
|-----------------------|-------------|---------------------------------------------|-----------------|
| $S_D$ (cm)            | $S_A$ (g)   | $S_D$ (cm)                                  | $S_A$ (g)       |
| Performance point     | 5.0         | 1.735                                       | 0.779           | 1.939 | 0.868 |
| Target performance    | 9.3         | 1.286                                       | 0.583           | 1.551 | 0.694 |

| Displacement response | $\beta$ (%) | Mean value of time history response analysis | Proposed method |
|-----------------------|-------------|---------------------------------------------|-----------------|
| $S_D$ (cm)            | $S_A$ (g)   | $S_D$ (cm)                                  | $S_A$ (g)       |
| Performance point     | 5.0         | 4.471                                       | 0.543           | 6.028 | 0.581 |
| Target performance    | 8.2         | 3.906                                       | 0.541           | 4.823 | 0.542 |

| Displacement response | $\beta$ (%) | Mean value of time history response analysis | Proposed method |
|-----------------------|-------------|---------------------------------------------|-----------------|
| $S_D$ (cm)            | $S_A$ (g)   | $S_D$ (cm)                                  | $S_A$ (g)       |
| Performance point     | 5.0         | 11.256                                      | 0.194           | 13.130 | 0.202 |
| Target performance    | 11.2        | 9.694                                       | 0.198           | 10.505 | 0.181 |

where $S_D$ and $\mu^T$ are the displacement and the ductility ratio corresponding to the performance target. Fig. 2. provides a conceptual diagram and flowchart of the proposed analysis procedures. The performance point $S_D$ of a bilinear SDOF system subjected to prescribed ground motions is evaluated using the simple analysis method for estimation of performance point (Step 1); then, with reference to $S_D$, the damping requirement $\beta_{req}$ needed to achieve the prescribed performance target $S_D$ is determined using the simple analysis method for damping estimation (Step 2). Finally, the capacity spectrum, plotted in the ADRS format, is compared with the two demand spectra for 0.5~20% damping and for the damping requirement $\beta_{req}$ (Step 3).
motions was set to 60 sec; however, the duration of motion used in the time history response analysis is 25 sec in which significant duration of the artificial ground motions is included.

Table 1. shows the performance points of several SDOF systems defined by natural periods of $T=0.3, 0.5$ and $1.0s$ and post-yield stiffness ratio of $\alpha=0.2$; also shown is the damping requirement necessary to achieve the prescribed performance target corresponding to the prescribed ductility ratio: $\mu=0.8\mu$. The damping requirement $\beta_{req}$ of the systems estimated by the simple analysis method for damping estimation are 9.3, 8.2 and 11.2%, respectively. It was found that the results obtained using the proposed analysis procedure are in fairly good agreement with those obtained using the time history response analysis.

Fig. 5. also shows graphically the performance points of the systems for 5, 9.3, 8.2 and 11.2% damping, evaluated using the proposed analysis procedures. The solid line in each figure indicates the performance point of the bilinear SDOF systems with the same post-yield stiffness ratio and yield displacement. When understanding Fig. 5. care must be taken because the solid lines in Fig. 5. are successive performance points obtained from Eqs. 1 to 12, not the performance points obtained from the time history response analysis. It can be seen that, if the ductility ratio is less than 3 for the systems, the responses evaluated using the proposed analysis method is close to the maximum spectral demands; meanwhile, if the ductility ratio is more than 3, the responses are close to the average spectral demands.

Fig. 6. Application of Simple Analysis Method for Estimation of Performance Point
5. Numerical Example

Fig. 6. and Table 2. show the results of the numerical analysis for three bilinear SDOF systems defined by two natural periods of $T = 0.5$ and 1.0 s, a yield displacement of 3.0 cm, and two post-yield stiffness ratios of $\alpha = 0.01$ and 0.2, subjected to the N-S component of El Centro (1940). The ductility ratios $\mu$ corresponding to the intersection between the capacity and demand spectra for the structural systems with $T = 0.5$ s, $\alpha = 0.01$ and 0.2 are 1.67 and 1.63, respectively. The performance points $S_{DP}$ for the structural systems with $T = 1.0$ s, $\alpha = 0.01$ and 0.2 are 14.96 cm ($\mu = 4.99$). In this example, the performance target $S_{DT}$ of the systems is assumed to be a displacement corresponding to $\mu_T = 0.8\mu$ and the damping requirement to achieve $S_{DT}$ is estimated. The results are shown in Fig. 7. and Table 3. It can be observed that 8.1, 8.4, 11.2 and 11.2% damping are required to accomplish the prescribed performance targets of each system.

Table 2. Results from Numerical Example for Evaluating Performance Point

| No. | $T$ (s) | $\delta_y$ (cm) | $\alpha$ | $S_{DE}^E$ (cm) | $S_{DE}^V$ (cm) | $S_{DE}^D$ (cm) | $\mu_{EA}$ | $\mu_{EV}$ | $\mu_{ED}$ | $\mu$ | $S_{DP}$ (cm) |
|-----|---------|-----------------|----------|----------------|----------------|----------------|----------|----------|----------|------|----------------|
| 1   | 0.5     | 0.01            | 4.60     | 9.35           | 63.45          | 1.67           | 3.12     | 21.15    | 1.67     | 5.01 | 63.45          |
| 2   | 0.5     | 0.20            | 4.60     | 9.35           | 63.45          | 1.67           | 3.12     | 21.15    | 1.63     | 4.90 | 63.45          |
| 3   | 1.0     | 0.01            | 18.38    | 18.70          | 63.45          | 17.85          | 6.23     | 21.15    | 6.23     | 18.70| 63.45          |
| 4   | 1.0     | 0.20            | 18.38    | 18.70          | 63.45          | 10.41          | 6.23     | 21.15    | 6.23     | 18.70| 63.45          |

Table 3. Results from Numerical Example for Estimating Damping Requirement

| No. | $T$ (s) | $\delta_y$ (cm) | $\alpha$ | $\mu_T$ | $S_{DT}$ (cm) | $A$ | $B$ | $C$ | $\beta_{EA}$ (%) | $\beta_{EV}$ (%) | $\beta_{ED}$ (%) | $\beta_{req}$ (%) |
|-----|---------|-----------------|----------|---------|---------------|-----|-----|-----|------------------|------------------|------------------|------------------|
| 1   | 0.5     | 0.01            | 0.01     | 0.8$\mu$| 4.01          | 2.09| 3.19| 6.42| 8.1              | 49.8             | 611.8            | 8.1              |
| 2   | 0.5     | 0.20            | 0.8$\mu$| 3.92    | 2.13          | 3.95| 6.42| 8.4  | 51.8             | 616.3            | 8.4              |                  |
| 3   | 1.0     | 0.01            | 14.96    | 3.19    | 2.41          | 5.53| 24.2| 11.2 | 252.4            | 11.2             |                  |                  |
| 4   | 1.0     | 0.20            | 14.96    | 2.95    | 2.41          | 5.53| 19.1| 11.2 | 252.4            | 11.2             |                  |                  |

Fig. 7. Application of Damping Requirement for Response Reduction of Systems

(a) $T = 0.5$ and 1.0 s with $\alpha = 0.01$

(b) $T = 0.5$ and 1.0 s with $\alpha = 0.2$

Fig. 8. Damping Requirement with Respect to Various Performance Targets

(a) $T = 0.5\ s$ and $\alpha = 0.0\text{~}1.0$

(b) $T = 1.0\ s$ and $\alpha = 0.0\text{~}1.0$
Fig. 8. shows the damping requirement $\beta_{req}$ with respect to the successively given performance targets of the systems subjected to the same ground motion. It can be seen that the damping requirements for the given performance levels, when those levels are lower than the performance point ($\beta_{req} = 5.0\%$), can be found easily; in comparison with the case of the damping requirements in the long-period range ($T = 1.0s$), the damping requirements of systems in the short-period range ($T = 0.5s$) decrease drastically with increases in the performance level.

As confirmed in the numerical example, the proposed analysis procedure is simple and efficient in assessing the seismic performance and damping requirement of building structures without iterative analysis; however, it is recommended to use the proposed analysis procedure for estimating the damping requirement of building structures in the range of 0.5-20% damping.

6. Damping Requirements for Various Peak Ground Parameters

Earthquake records or response spectrum-compatible ground motions have often been used to evaluate the seismic performance of building structures with various purposes and properties. In this chapter, the seismic performance and damping requirement of several bilinear SDOF systems are examined for ten earthquake records. Strong earthquakes with magnitudes of more than 6.5 and with peak ground accelerations higher than 0.2g are used; however, the site classification and characteristic period of the ground motions are not taken into account in the examples. Table 4. lists the ten earthquake records considered. The bilinear SDOF systems employed here are the same as those used for the numerical examples.

Fig. 9. shows the performance points and the damping requirements, including 5% structural damping, for each system subjected to the ten strong earthquake ground motions. It is possible to confirm

Table 4. Earthquake Records Considered in Numerical Implementation

| No. | Earthquake record (year) | Station | M   | PGA (g) | PGV (cm/s) | PGD (cm) |
|-----|--------------------------|---------|-----|--------|------------|----------|
| 1   | Imperial Valley (1979)   | El Centro Diff. Array | 6.5 | 0.35   | 71.2       | 45.8     |
| 2   | Imperial Valley (1979)   | Ec Co Centre FF     | 6.5 | 0.23   | 68.8       | 39.4     |
| 3   | Kocaeli (1999)           | Duzce             | 7.4 | 0.31   | 58.8       | 44.1     |
| 4   | Erzincan (1992)          | Erzincan station EW | 6.8 | 0.47   | 92.1       | 58.1     |
| 5   | Chi Chi (1999)           | TCU078             | 7.6 | 0.34   | 30.9       | 4.9      |
| 6   | Loma Prieta (1989)       | Saratoga W Valley Coll. | 6.9 | 0.33   | 61.5       | 36.4     |
| 7   | Landers (1992)           | Lucerne           | 7.5 | 0.36   | 31.2       | 7.0      |
| 8   | Landers (1992)           | Joshua Tree       | 7.5 | 0.23   | 21.7       | 4.6      |
| 9   | Northbridge (1994)       | Newhall-WPC       | 6.7 | 0.42   | 46.7       | 11.3     |
| 10  | Kobe (1995)              | Takatori          | 6.9 | 0.43   | 59.0       | 19.4     |

(a) Performance points and performance targets of system 1
(b) Damping requirements for performance targets of system 1
(c) Performance points and performance targets of system 3
(d) Damping requirements for performance targets of system 3

Fig. 9. Damping Requirement of Systems for Ten Earthquake Records
how much damping is needed in each system to achieve the prescribed performance target against each strong earthquake ground motion. By considering the effective range of the proposed analysis procedures mentioned above, it can be understood that the results for system 3 show low accuracy, and thus detailed analysis is required. However, the results in the effective range with high accuracy show that the proposed analysis procedures make it easy, using a single process, to assess the seismic performance of building structures and the damping ratio required to achieve performance targets for various levels of ground motion.

7. Conclusion
This paper proposed a simple analysis method using the Newmark and Hall’s design response spectrum and the simple version of the N2 method to assess the seismic performance of bilinear SDOF systems with post-yield stiffness. To overcome the problems in the existing procedures, such as iterative analysis, multiple solutions, and non-convergence, the capacity and demand spectra were assumed to be functions of the ductility ratio. In addition, using the relation between performance targets and spectrum amplification factors, the damping ratios necessary to achieve the performance targets of the systems were estimated. The results of numerical analysis showed that the proposed analysis procedures have fairly good accuracy in evaluating performance points and required damping ratios of bilinear SDOF systems with post-yield stiffness; the proposed analysis method, due to its simplicity, may be useful for structural engineers in the preliminary design phase of building structures. It was confirmed that, if the ductility value is more than 6 for structural systems, detailed analysis should be conducted for reasonable seismic performance assessment in the constant spectral velocity and displacement regions of the response spectrum. Finally, in order for the proposed analysis method to be applied to the practical structural design, it is necessary to study the proposed method considering the effect of strength degradation of structural elements and a rational approach to modify the estimated damping ratio according to structural behavior types, and to extend the method to MDOF systems in the future.

Acknowledgments
This research was supported by Basic Science Research Program through the National Research Foundation of Korea(NRF) funded by the Ministry of Education(2014R1A1A2005431) and by the Functional Districts of the Science Belt support program, Ministry of Science and ICT(2017K000488). This research was also supported by Basic Science Research Program through the National Research Foundation of Korea(NRF) funded by the Ministry of Education (2018R1A2B3001656).

References
1) Applied Technology Council (ATC) (1996) Seismic evaluation and retrofit of concrete buildings. Report No. ATC-40, Redwood City, California, US, November.
2) Architectural Institute of Japan (1993) Recommendations for loads on buildings and commentary (in Japanese), Tokyo.
3) Chopra, A.K. and Goel, R.K. (1999) Capacity-demand-diagram Methods based on inelastic spectrum. Earthquake Spectra. 15(4), pp.637-656.
4) Decanini, L.D. and Mollaoli, F. (2001) An energy-based methodology for the assessment of seismic demand. Soil Dynamics and Earthquake Engineering, 21, pp.523-537.
5) Fajfar, P. (1999) Capacity spectrum method based on inelastic demand spectra. Earthquake Engineering & Structural Dynamics, 28(9), pp.979-993.
6) Fajfar, P. (2000) A nonlinear analysis method for performance based seismic design. Earthquake Spectra, 16(3), pp.573-592.
7) Freeman, S.A. (1998) Development and use of capacity spectrum method. Proc., 6th U.S. National Conference on Earthquake Engineering/EERI, Seattle, Washington, 31 May-4 June 1998.
8) Iwan, W.D. and Guyoader, A.C. (2002) An improved equivalent linearization procedure for the capacity spectrum method. Proc., International Conference on Advanced and New Challenges in Earthquake Engineering Research, Harbin, China, 15-17 August 2002.
9) Jennings, P.C., Housner, G.W. and Tsai, N.C. (1969) Simulated earthquake motions for design purpose. Proc., 4th World Conference on Earthquake Engineering, Santiago, Chile, 13-18 January 1969.
10) Kim, J., Choi, H. and Min, K.W. (2003) Performance-based design of added viscous dampers using capacity spectrum method. Journal of Earthquake Engineering, 7(1), pp.1-24.
11) Li, H.N., Yi, T.H., Gu, M. and Huo, L.S. (2009) Evaluation of earthquake-induced structural damages by wavelet transform. Progress in Natural Science, 19(4), pp.461-470.
12) Lin, Y.Y. and Miranda, E. (2004) Non-iterative capacity spectrum method based on equivalent linearization for estimating inelastic deformation demands of buildings. Journal of Structural Mechanics and Earthquake Engineering, JSCE 73(3-69), pp.113-119.
13) Miranda, E. and Bertero, V.V. (1994) Evaluation of strength reduction factors for earthquake-resistant design. Earthquake Spectra, 10(2), pp.357-379.
14) Newmark, N.M. and Hall, W.J. (1982) Earthquake Spectra and Design. EERI, Berkeley, California.
15) Otani, S. (2004) Japanese seismic design of high-rise reinforced concrete buildings: An example of performance-based design code and state of practices. Proc., 13th World Conference on Earthquake Engineering, Vancouver, Canada, August 2004.
16) Penzien, J. (1960) Elasto-plastic response of idealized multi-story structures subjected to a strong motion earthquake. Proc., 2nd World Conference on Earthquake Engineering, Tokyo, Japan, July 1960.
17) Takahashi, M. and Akiyama, H. (1999) The maximum displacement and energy response of multi-story frames under earthquakes. Journal of Structural and Construction Engineering (AJJ), 515, 59-66 (in Japanese).
18) Taniguchi, M. and Takewaki, I. (2015) Bound of earthquake input energy to building structure considering shallow and deep ground uncertainties. Soil Dynamics and Earthquake Engineering, 77, pp.267-273.
19) Vidic, T., Fajfar, P. and Fischinger, M. (1994) Consistent inelastic design spectra: strength and displacement. Earthquake Engineering & Structural Dynamics, 23(5), pp.507-521.
20) Yi, T.H., Li, H.N. and Sun, H.M. (2013) Multi-stage structural damage diagnosis method based on "energy-damage" theory, International Journal of Smart Structures and Systems, 12(3-4), pp.345-361.