Seismic evaluation of reinforced concrete building retrofitted with energy absorbing devices

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SUMMARY:
This paper presents a proposal for a seismic evaluation method to be applied to reinforced concrete buildings retrofitted with energy-absorbing devices. A structural seismic index "Is" which is used in Japan to indicate the earthquake resistance performance of existing buildings and buildings retrofitted by strengthening with steel braces and other members is a static evaluation. The authors show a way to evaluate statically the dynamic performance of energy-absorbing devices. For this purpose, an improved evaluation method to estimate the structural seismic index adapted to both ductile and stiff structures is formulated. The proposed method is verified using time-history response analysis and validity of the proposed method is assured.

Keywords: Seismic evaluation, Structural seismic index, Energy-absorbing devices, Intensity distribution

1. INTRODUTION

Many buildings which were constructed in conformance to the old Building Standard Law suffered a lot of damage from The Southern Hyogo Prefecture Earthquake in 1995. The structural seismic index "Is" has been used for evaluating buildings which don't meet the sufficient seismic performance demanded by the current law.
A main method for retrofitting buildings has previously been improving their strength with steel braces and other members, but recently a method to improve the energy-absorbing ability of buildings with energy-absorbing devices has been increasingly used. Through this retrofit, the acceleration response of structures is reduced and obstructions to the use of buildings during retrofitting can be relieved. However, for retrofitting with energy-absorbing devices, time-history response analysis is necessary to evaluate a building's dynamic performance. This paper presents a proposal for a static evaluation method for index "Is" with reinforced concrete buildings retrofitted with energy-absorbing devices.
Evaluation of the seismic performance of reinforced concrete buildings by "Is" is based on Literature 1). It shows three levels for the evaluation method. Of those, the second grade of evaluation method is considered in this paper, which is for buildings whose columns are assumed to fracture before its beams. Because many buildings which were constructed before implementation of the current Building Standard Law fall under this type, the second grade has been used commonly. In addition, the fractural mode of buildings is classified as shear fracture type and bending yield type in the second-grade evaluation method. An evaluation method for the shear fracture type was shown in Literature 2). This paper shows an evaluation method for the bending yield type.

2. EVALUATION OF BUILDING RETROFITTED WITH ENERGY ABSORBING DEVICES

2.1. Structural Seismic Index "Is"

The structural seismic index "Is" can be calculated by the following equation[1).]

$$Is = \frac{1}{A_i} \cdot C \cdot F \cdot S_D \cdot T \tag{2.1}$$

Where A_i : Coefficient of distribution for shear force of each story, C : Strength index, F : Ductility index, S_D : Index of building's shape, T : Index of building age.

2.2. Strength Index "C"

The strength index "C" is used to evaluate the building's shear force as a coefficient, and it can be calculated by the following equation[1].

$$C = \frac{{}_f Q_u}{\sum w} \tag{2.2}$$

Where ${}_f Q_u$: Shear force of the building at the limit, Σw : Weight of the building above the story.
For buildings retrofitted with energy-absorbing devices, the strength index "C" can be calculated by the following equation.

$$C = \frac{{}_f Q_u + {}_d Q_u}{\sum w} \tag{2.3}$$

Where ${}_d Q_u$: Shear force of the energy-absorbing devices at the limit.

2.3. Ductility Index "F"

The ductility index "F" can be calculated by the following equation[1].

$$F = \frac{\sqrt{2\mu - 1}}{0.75 \cdot (1 + 0.05\mu)} \tag{2.4}$$

Where μ : Maximum plasticity rate.
For buildings retrofitted with energy-absorbing devices, the ductility index "F" can be calculated by following the equation[3].

$$F = \frac{\sqrt{2\mu - 1}}{0.75 \cdot (1 + 0.05\mu)} \cdot \frac{1}{D_h} \tag{2.5}$$

$$D_h = \sqrt{\frac{1 + 25 {}_f h_{eq}}{1 + 25 h_{eq}}} \tag{2.6}$$

Where D_h : Coefficient of reduction for earthquake-response spectrum[4], ${}_f h_{eq}$: Equivalent viscous damping factor before retrofitting, h_{eq} : Equivalent viscous damping factor after retrofitting.
Equation (2.5) shows that the seismic performance of buildings improves as value of D_h is reduced, because retrofitting with energy-absorbing devices makes the viscous damping factor of structures increase from ${}_f h_{eq}$ to h_{eq} and as a result, the earthquake response is reduced by the ratio of D_h.

2.4. Intensity Distribution

Considering multistory buildings, when the intensity distribution of the building is different from

Ai-Distribution[1], the input of earthquake energy focuses on specific stories[5]. According to literature5), the input of earthquake energy W_0' of each story can be calculate by the following equation.

$$W_{0i}' = \frac{p^{-n} \cdot \sum_{j=1}^{N} s_j}{\sum_{j=1}^{N} s_j \cdot p_j^{-n}} W_{0i} \tag{2.7}$$

Where W_0 : Earthquake energy input when the intensity distribution is equal to Ai-Distribution, s : Energy distribution rate, p : Coefficient of the extent of difference of the intensity distribution from Ai-Distribution.
For calculating Is index, the authors consider the increase (decrease) of earthquake input as a decrease (increase) of the viscous damping performance, and proposes a method to calculate h_{eq} of a multistory building. It can be calculated by the following equation.

$$h_{eqi}' = \frac{\sum_{j=1}^{N} s_j \cdot p_j^{-n}}{p^{-n} \cdot \sum_{j=1}^{N} s_j} h_{eqi} \tag{2.8}$$

This h_{eq}' is applied to equation (2.6).

2.5. Evaluation of Energy-Absorbing Devices

For energy-absorbing devices, oil dampers, visco-elastic dampers, and steel dampers are considered in this paper. For calculating the index “Is”, the device’s shearing force at the limit of the building, ${}_dQ_u$, and the equivalent viscous damping factor after retrofitting, h_{eq} is necessary. h_{eq} can be calculated with ${}_dh_{eq}$, which is the equivalent viscous damping factor of energy-absorbing devices, by the following equation.

$$h_{eq} = \frac{{}_fh_{eq} \cdot {}_fQ_u + \xi \cdot {}_dh_{eq} \cdot {}_dQ_u}{{}_fQ_u + {}_dQ_u} \tag{2.9}$$

Where ${}_fh_{eq}$: Equivalent viscous damping factor of the main structure, ${}_fQ_u$: Shearing force of the main structure at the limit of the building.
ξ is the correction coefficient for taking the unsteady disposition of the earthquake into consideration.
The following paragraphs indicate the method of evaluation for each device[4].
(1) Oil damper[4]
The oil damper has a relief function. As shown in the bottom of Figure 1, the damper section is modelled as a dashpot, and the mounting section is modelled as a shear spring, and the whole section is modelled as both connected in series. Figure 1 also shows the hysteresis loop of them by simple harmonic motion with circular frequency ω, which is the fundamental circular frequency of the main structure. As shown in the picture, stiffness is defined as k, stored stiffness as k', displacement as u, shear force as Q, and quantity of absorbed energy as E. Further, subscript d is put beside parameters about the damper section, subscript b is put beside parameters about the mounting section, and subscript a is put beside parameters about the whole section. Moreover x_u is the maximum displacement, and in this figure it means $u_{a\max}$, which is the maximum displacement of the whole section.
Equivalent mounting section displacement rate λ is defined by this equation: $\lambda = c_d\,\omega/k_b$. c_d : 1st attenuation coefficient, k_b : Stiffness of mounting section. Relief displacement of the damper section is defined as u_{dy}, which is calculated by this equation: $u_{dy}=v_{dy}/\omega$. v_{dy} : Relief velocity of the damper. With u_{dy}, μ_d, which is the relief rate of damper section, and μ_a, which is that of whole section, are defined by following equations.

$$\mu_d = u_{d\max} / u_{dy} \tag{2.10}$$

$$\mu_a = u_{a\max} / \left(u_{dy} \cdot \sqrt{1+\lambda^2}\right) \tag{2.11}$$

In the case of an oil damper which has a relief function, the connection of μ_d and μ_a can be approximated with the following equation.

$$\mu_d = 1 + (\mu_a - 1)\left(1 + 0.25\lambda + 0.15\lambda^2\right) \tag{2.12}$$

Next, the stored stiffness of the whole section, k'_a, is calculated by the following equation.

$$k'_a = \varsigma^2 \cdot \lambda \cdot c_d \cdot \omega / \left\{1 + (\varsigma \cdot \lambda)^2\right\} \tag{2.13}$$

$$\varsigma = p + (1-p) \cdot \exp\left\{-R \cdot (\mu_a - 1)^S\right\} \tag{2.14}$$

$$R = \min\left[0.05 + 0.4\lambda,\ 0.5\lambda^2 + \lambda^4\right] \tag{2.15}$$

$$S = \max\left[-2.5\log\lambda,\ 0.67 - 0.43\log\lambda\right] \tag{2.16}$$

Where p : Attenuation rate after relief.
The quantity of energy absorbed by the whole section, E_a is calculated by the following equation.

$$E_a = E_d = \pi \cdot c_d \cdot \omega \cdot u_{d\max}^2 \cdot \left\{p + (1-p) / \mu_d^{0.886}\right\} \tag{2.17}$$

From the above, ${}_dQ_u$ and ${}_dh_{eq}$ can be calculated by the following equation.

$${}_dQ_u = k'_a \cdot u_{a\max} = k'_a \cdot x_u \tag{2.18}$$

$${}_dh_{eq} = \frac{1}{2\pi} \frac{E_a}{{}_dQ_u \cdot x_u} = \frac{1}{2\pi} \frac{E_a}{k'_a \cdot x_u^2} \tag{2.19}$$

The correction coefficient ξ is 0.8.

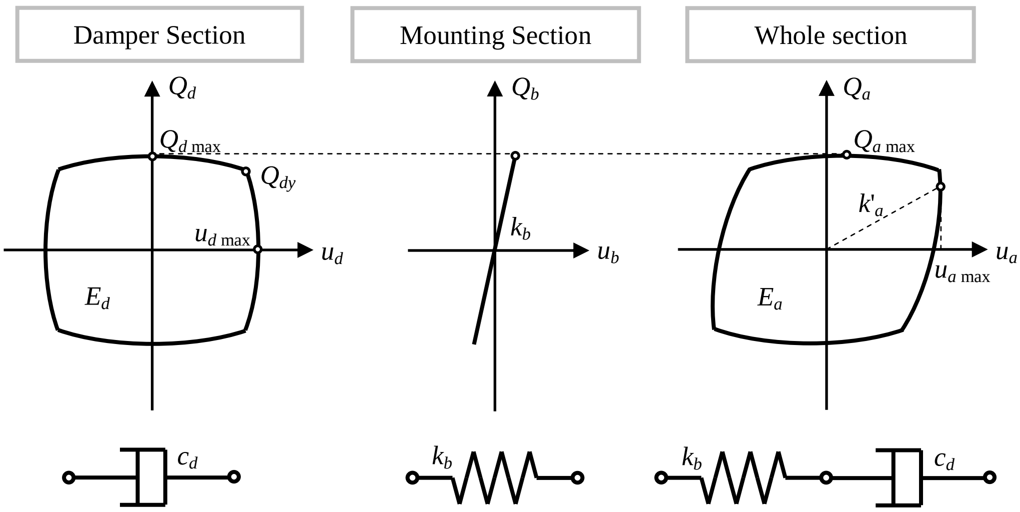

Figure 1. Mathematical models for non-linear response history analysis

(2) Visco-elastic damper[4)]

In the same way as for the oil damper, each section's model is instituted as shown in Figure 2. As shown in the bottom of the figure, the damper section is modelled as a shear spring and dashpot connected in parallel, the mounting section is modelled as a shear spring, and the whole section is modelled as both connected in series. With k_d, which is the shear stiffness of the damper section, the

loss coefficient η is defined by this equation: $\eta = c_d\,\omega / k_d$.
Maximum displacement of the damper section, $u_{d\max}$, is calculated by the following equation.

$$u_{d\max} = \frac{k_b}{\sqrt{(k_b + k_d)^2 + (\eta_d \cdot k_d)^2}} \cdot u_{a\max} \tag{2.20}$$

The stored stiffness of the whole section, k'_a, is calculated by the following equation.

$$k'_a = \frac{\{k_b + (1+\eta_d^2) \cdot k_d\} \cdot k_b \cdot k_d}{(k_b + k_d)^2 + (\eta_d \cdot k_d)^2} \tag{2.21}$$

The quantity of energy absorbed by the whole section, E_a, is calculated by the following section.

$$E_a = E_d = \pi \cdot \eta_d \cdot k_d \cdot u_{d\max}^2 \tag{2.22}$$

From the above, ${}_dQ_u$ and ${}_dh_{eq}$ can be calculated by equations (2.18), (2.19).
The correction coefficient, ξ is 0.92.

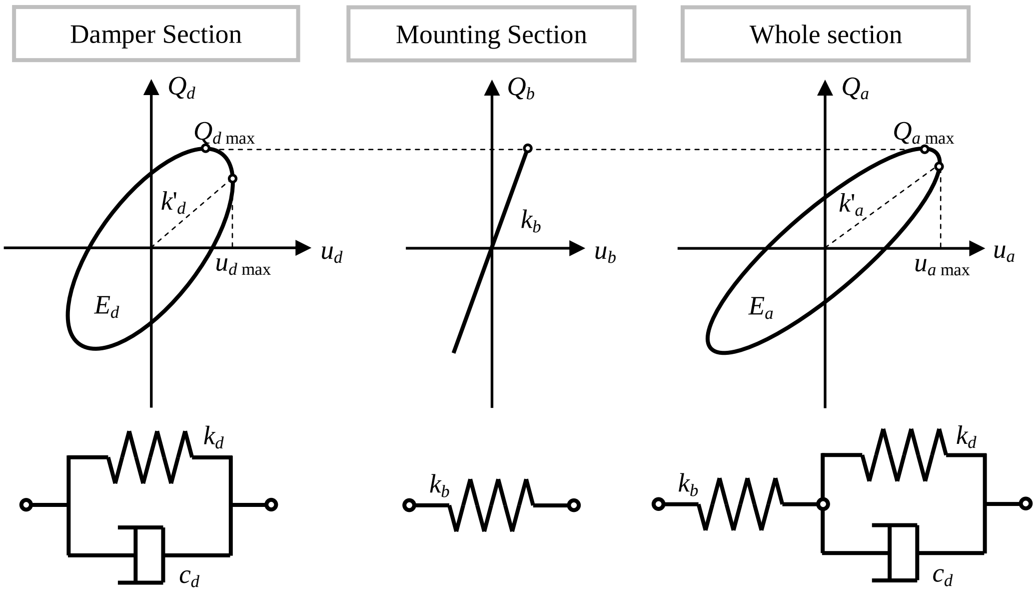

Figure 2. Mathematical models for non-linear response history analysis

(3) Steel damper
Characteristics of the hysteresis of the steel damper is modelled as a bi-linear skeleton curve. In the same way as for the oil damper and visco elastic damper, each section's model is instituted and shown in Figure 3. As shown in the bottom of the figure, the damper section is modelled as a shear spring, the mounting section is modelled as a shear spring too, and the whole section is modelled as both connected in series.
Maximum displacement of damper section, $u_{d\max}$, is calculated by the following equation.

$$u_{d\max} = \frac{k_b \cdot x_u - (1-\gamma) \cdot k_d \cdot x_{dy}}{k_b + \gamma \cdot k_d} \tag{2.23}$$

Where γ : stiffness reduction rate, k_d : incipient stiffness, x_{dy} : displacement at the yield.
The shearing force at the limit of the building, ${}_dQ_u$, is calculated by following equation.

$$ {}_dQ_u = k_d \cdot \{\gamma \cdot u_{d\max} + (1-\gamma)\cdot x_{dy}\} \tag{2.24} $$

The quantity of energy absorbed by the whole section, E_a, is calculated by following section.

$$ E_a = E_d = 4 \cdot k_d \cdot x_{dy} \cdot (1-\gamma)(u_{d\max} - x_{dy}) \tag{2.25} $$

From the above, ${}_dh_{eq}$ can be calculated by equations (2.19).
To take the unsteady disposition of the earthquake into consideration, ${}_dh_{eq}$ can be corrected by the following equation, which calculates the mean value of ${}_dh_{eq}$ when displacement is from 0 to x_u[4].

$$ \xi \cdot {}_dh_{eq} = \overline{{}_dh_{eq}} = \frac{1}{x_u}\int_0^{x_u} {}_dh_{eq}(x)\,dx \tag{2.26} $$

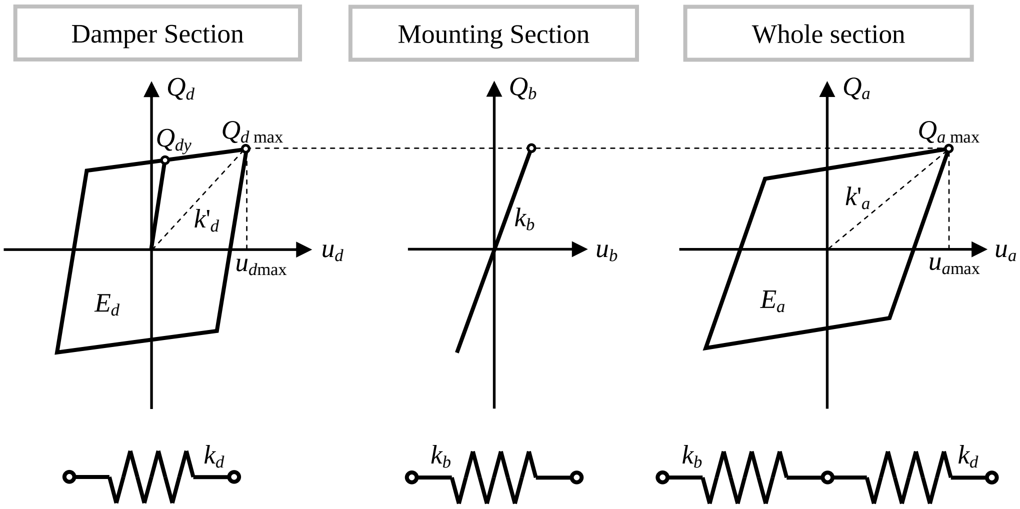

Figure 3. Mathematical models for non-linear response history analysis

3. VERIFICATION OF THE PROPOSED METHOD
3. 1. Instructions

Evaluation of structural seismic index "Is" is based on the premise that when two buildings which have the same seismic performance in "Is" receive the same earthquake input, the maximum displacement of both buildings reach the same extent to the limit[1]. Based on this premise, the proposal method is verified by comparing the maximum displacement of a normal reinforced concrete building and a reinforced concrete building retrofitted with energy-absorbing devices.
As the index for verification, the maximum earthquake response displacement rate, ε, is used. The process of verification is shown in the following sequence.
(1) Determining parameters of normal reinforced concrete building and main structure part of building retrofitted with energy-absorbing devices
(2) Determining the kind of earthquake used in time-history response analysis
(3) Calculating the scale of the earthquake that can make ε of normal reinforced concrete building reach exactly 1.0 by repeating time-history response analysis
(4) Determining parameters of the energy-absorbing devices
(5) Calculating the quantity of the energy-absorbing devices for "Is" value of building retrofitted with energy-absorbing devices estimated to be the same as the normal reinforced concrete building by proposed method
(6) Outputting ε of all stories of the building retrofitted with energy-absorbing devices by trying time-history response analysis
(7) Changing parameters of energy-absorbing devices and going back to (5)

If ε of all stories of the building retrofitted with energy-absorbing devices is lower than 1.0, the earthquake response performance of the retrofitted building can be higher than that of the normal reinforced concrete building.
By the process above, the proposed method can be verified.
Two types of building models were used: 4 stories and 9 stories. The index "Is" of normal reinforced concrete buildings and buildings with energy-absorbing devices are estimated at 0.6. The main structures of buildings with energy-absorbing devices are 4 types.
Structure type A is a 4-story building that doesn't have weak stories and the "Is" of all stories are 0.4.
Structure type B is also a 4-story building that has a weak story at the 3rd story and the "Is" of the 3rd story is 0.3.
Structure type C is a 9-story building that doesn't have weak stories and the "Is" of all stories is 0.4.
Structure type D is also a 9-story building that has a weak story at the 6th story and the "Is" of the 6th story is 0.3.
The ductility index "F" of all stories of all structure models is 1.5. The earthquake inputs which are used in time-history response analysis are El Centro NS, Hachinohe NS, Taft EW.

3. 2. Parameter of Energy Absorbing Devices

In this paper, the proposal method is verified for several parameters of energy-absorbing devices. Parameters of each device used in this paper are shown in following sentence.
(1) Oil damper[4)]
When an arbitrary value is given as the 1st attenuation coefficient c_d, required parameters to define the hysteretic behaviour of the devices are inside stiffness coefficient β (which is a parameter about stiffness of mounting section), relief rate μ_d (which is a parameter about relief velocity), and attenuation rate after relief p.
β is rate of stiffness of the mounting section, and is calculated from k_b and c_d by this equation, $\beta = k_b / c_d$. In this paper, the value of β is set to 4.5, 9.0, 13.5, and 18.0[4)].
μ_d can be calculated by this equation, $\mu_d = x_u\ \omega / v_{dy}$, where x_u is the assumed maximum displacement of main structure, ω is the fundamental circular frequency of the main structure, and v_{dy} is the relief velocity of the damper. In this paper, the value of μ_d is set to 1.0, 2.0, 3.0, and 4.0[4)].
p can be calculated by this equation, $p = c_{d2} / c_d$, where c_{d2} is the attenuation coefficient after relief. In this paper, the value of p is set to 0.02

(2) Visco-elastic damper[4)]
When an arbitrary value is given as the 1st attenuation coefficient c_d, required parameters to define the hysteretic behaviour of the devices are inside stiffness coefficient β (which is a parameter about stiffness of mounting section), and loss coefficient η (which is a parameter about stiffness of damper section).
The value of β is set to 4.5, 9.0, 13.5, and 18.0 in the same way as for the oil damper.
η can be calculated by this equation, $\eta = c_d\ \omega / k_d$, where k_d is the stiffness of the damper section. In this paper, the value of η is set to 0.33, 0.5, 2.0, and 10.0[4)].

(3) Steel damper[4)]
When an arbitrary value is given as incipient stiffness k_d, required parameters to define the hysteretic behaviour of the devices are inside stiffness coefficient β' (which is a parameter about stiffness of mounting section), plasticity rate μ_d (which is a parameter about yield displacement), and stiffness reduction rate, γ.
β' is the rate of stiffness of the mounting section, and can be calculated from k_b and k_d by this equation, $\beta' = k_b / k_d$. The value of β' is set to be sufficiently large in this paper,.
μ_d can be calculated by this equation, $\mu_d = x_u / x_{dy}$, where x_{dy} is the yield displacement of the damper. In this paper, the value of μ_d is set to 1.0, 2.0, 3.0, and 4.0[4)].
γ can be calculated by this equation, $\gamma = k_{d2} / k_d$, where k_{d2} is the stiffness after yield. In this paper, the value of γ is set to 0.02.

The connection between parameters of devices and the hysteresis loops are shown in Figure 4.

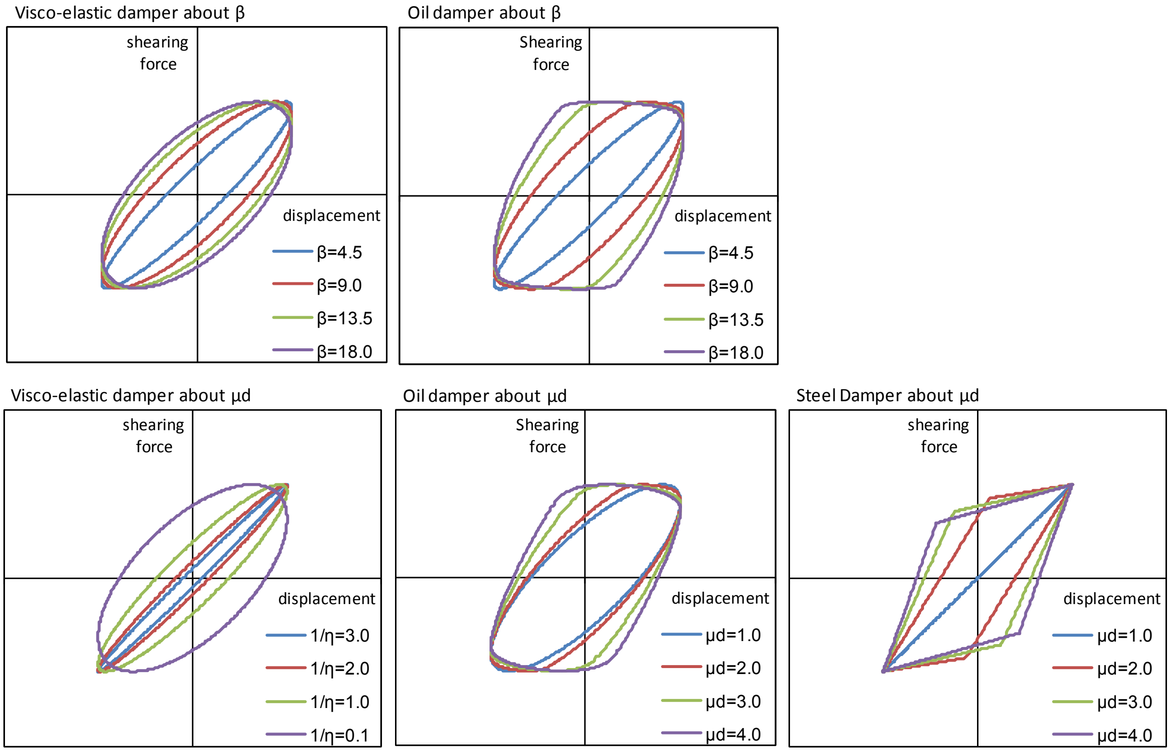

Figure 4. Mathematical models for non-linear response history analysis

3. 3. Result of Time-History Response Analysis

Based on the conditions mentioned above, time-history response analysis is done for every parameter of the energy-absorbing devices, and the results are shown in Figure 5. The abscissa indicates one of the parameters of each device, and the ordinate indicates values of ε about the story which responds the most.
The following is information acquired from the figure of each type of device.

(1) Oil damper
Because there is a low correlation between β and ε, the abscissa of the figure of this damper is set to the relief rate, μ_d.
In almost all cases, the values of ε are close to 1.0. This means that the proposed method provides great precision for evaluation of seismic performance. Concerning structures that don't have weak stories such as type A and C, the values of ε are slightly decreased as μ_d increases. On the other hand, for structures that have weak stories such as type B and D, the values of ε are scattered around 1.0 when the value of μ_d is 4.0.
(2) Visco-elastic damper
Because there is a low correlation between β and ε, the abscissa of the figure of this damper is set to the reciprocal of loss coefficient, η^{-1}.
In almost all cases, the values of ε are close to 1.0. Regardless of the structure type, the results show
(3) Steel damper
The abscissa of the figure of this damper is set to the plasticity rate, μ_d.
Compared to the two previous devices, the values of ε are scattered. However, it shows a tendency similar to the oil damper. Namely, in the case of retrofitting structures that don't have weak stories such as type A and C, it's safer to set a large value for μ_d. On the other hand, for structures that have weak stories such as type B and D, it's safer to set a small value for μ_d.

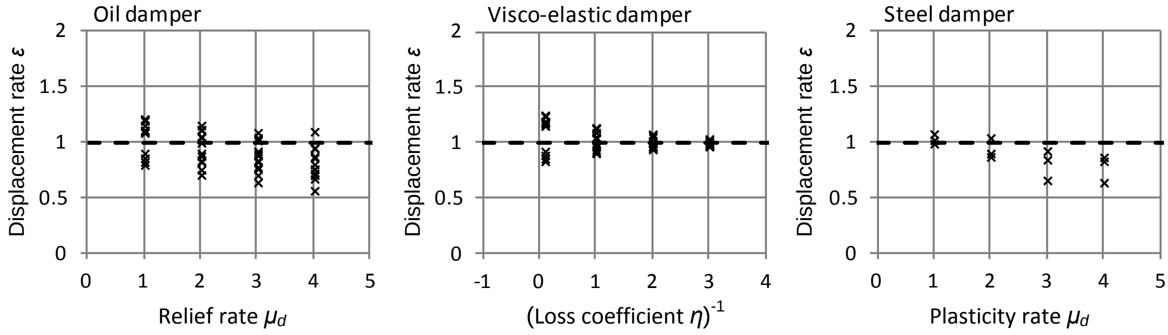

Figure 5. (a) Results of time history analysis about building model A

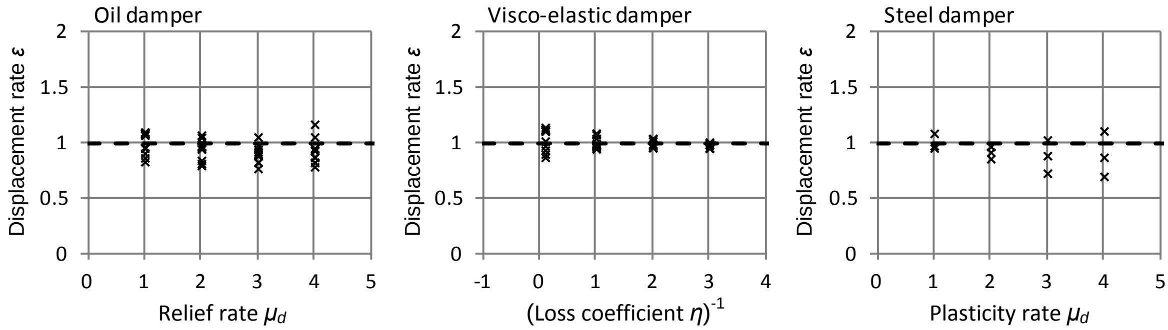

Figure 5. (b) Results of time history analysis about building model B

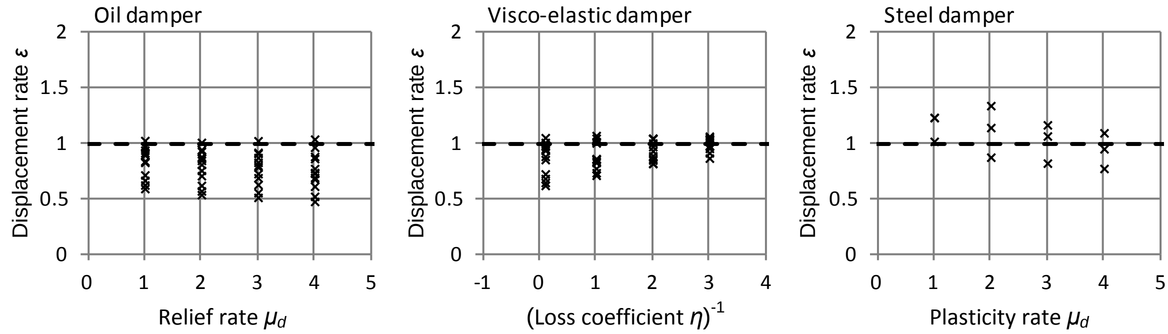

Figure 5. (c) Results of time history analysis about building model C

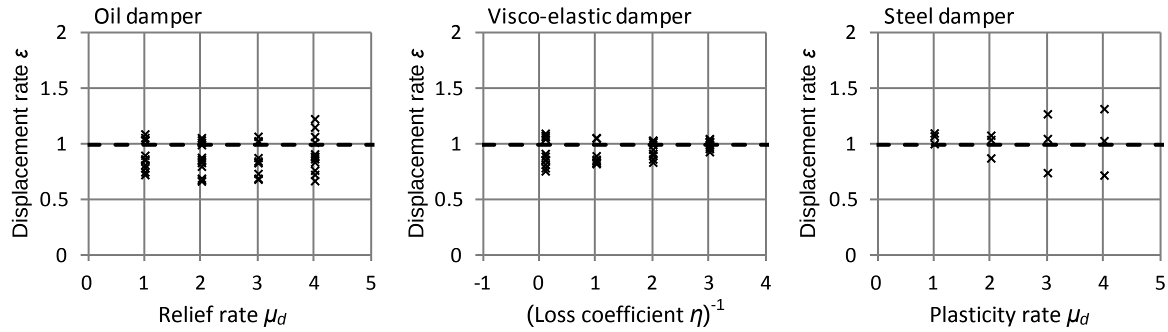

Figure 5. (d) Results of time history analysis about building model D

4. CONCLUSION

This paper proposed a method to evaluate the structural seismic index "Is" for reinforced concrete buildings retrofitted with energy-absorbing devices. Furthermore, the extent of parameters for each energy-absorbing device for guaranteeing the precision of the proposed method was provided by time-history response analysis.

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