CUMULATIVE SEISMIC DAMAGE PREDICTION OF DAMPER IN ELASTO-PLASTICALLY DAMPED BUILDINGS

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ABSTRACT :

This paper discusses simplified theories on cumulative damage evaluation for elasto-plastic (EP) damper under earthquake ground motion. The theories are based on the seismic behavior of single-degree-of-freedom (SDOF) elasto-plastically damped structure, cumulative plastic deformation of damper can be clearly expressed as a function of natural period of structure and duration of earthquake ground motion as well as stiffness parameter and ductility demand. The relationship between cumulative plastic deformation of damper and its maximum deformation is also clarified. Accuracy of proposed evaluation method is demonstrated via numerous time history simulations by using a wide range of multiple-degrees-of-freedom (MDOF) models and earthquake ground motions.

KEYWORDS: passive control, cumulative plastic deformation, maximum ductility factor, elasto-plastic damper, frame

1. INTRODUCTION

1.1. Background

Passively-controlled building structures have become a common practice in Japan, taking full advantage of various energy dissipation devices developed recently. Especially, passively-controlled structure with elasto-plastic (EP) dampers, such as buckling-restrained brace, has gained widespread practical applications. The EP dampers can substantially reduce building drifts and member forces by adding hysteretic damping and stiffness to the structure under earthquake ground motion. The performance of EP damper is closely related to its maximum deformation capacity of EP damper and cumulative plastic deformation capacity, but design method considering such an aspect has not been proposed to-date.

1.2. Objectives

The objective of this paper is to propose a cumulative seismic damage prediction method for elasto-plastic damper under earthquake ground motion, and to verify accuracy of the proposed method. The proposed method is based on the seismic behavior of single-degree-of-freedom (SDOF) elasto-plastically damped structure, cumulative plastic deformation of damper can be clearly expressed as a function of natural period of structure and duration of earthquake ground motion, which haven't been considered exactly by Akiyama et al (1999) and Ogawa et al (2002), as well as stiffness parameter and maximum ductility factor. Cumulative plastic deformation of damper tends to increase strongly with short period structure and long-duration earthquake, as well as with low-stiffness and low-yield-strength damper. The proposed method converts it to the prediction for multiple-degree-of-freedom (MDOF) model of multi-story building, with a consideration for distribution of stiffness balance of damper to frame. The proposed method is validated via numerous MDOF time history analyses of the designed passive control systems, covering wide ranges of building height, frame stiffness distribution, maximum ductility factor, and earthquake type.

2. CUMULATIVE PLASTIC DEFORMATION OF SDOF SYSTEM WITH EP DAMPER

2.1. SDOF System with EP Damper

As shown in Figure 2.1, SDOF model of system with EP Damper consists of mass and two springs, which represent EP damper and frame, connected in a row to the mass. EP damper is modeled as elasto-perfectly-plastic with elastic stiffness K_d, yield deformation u_{dy}, yield strength F_{dy} (= K_d u_{dy}) and maximum ductility factor μ_d, whereas frame behaves linearly with elastic stiffness K_f (Figure 2.2a,b). Thus, maximum displacement of system u is identical to the one of frame u_f, and one of damper u_d, moreover maximum ductility factor μ and yield deformation u_y of system are identical to those of damper μ_d, u_{dy}, respectively. Natural vibration period and damping ratio of frame are defined as T_f and h_0. Elastic stiffness $K_f + K_d$ and natural vibration period T_0 of EP system are given by Eqn. 2.1a-c.

$$K_0 = K_f + K_d \quad , \qquad T_0 = \sqrt{p} \cdot T_f \quad , \qquad p = \frac{K_f}{K_f + K_d} \tag{2.1a-c}$$

where p = ratio of post-yield stiffness to elastic stiffness of system.

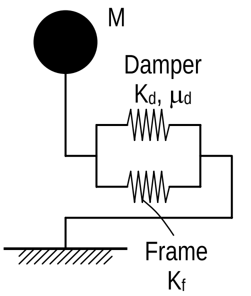

Figure 2.1 SDOF model of system with EP damper

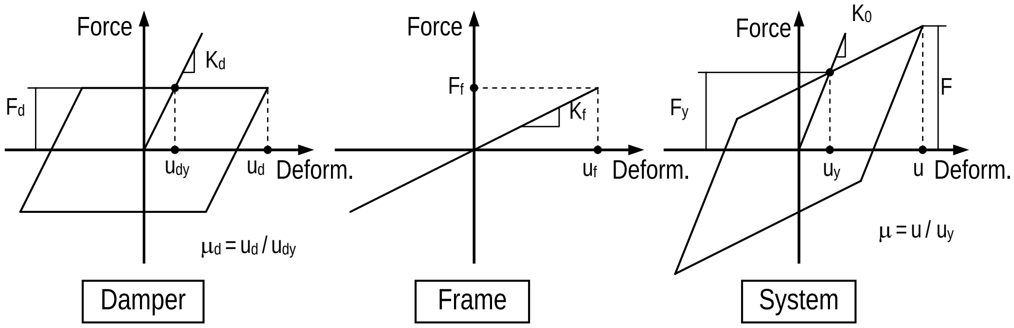

Figure 2.2 Hysteresis curve of damper, frame and system

Cumulative deformation ductility factor of damper η, which is an index of cumulative energy dissipation of damper, is defined as follows.

$$\eta = \sum \Delta\mu \tag{2.2}$$

where $\Delta\mu$ = deformation ductility factor in each half cycle (Figure 2.3).

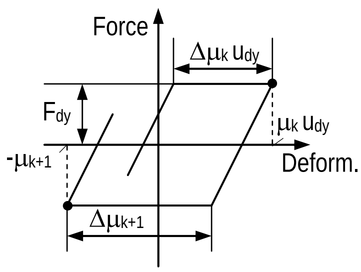

Figure 2.3 Deformation ductility factor of damper in each half cycle

2.2. Trends of Cumulative Plastic Deformation of SDOF System with EP Damper

This section discusses the trends of cumulative plastic deformation of SDOF system with EP damper. From statistical investigation on numerous analysis results of SDOF system with EP damper, cumulative plastic deformation of damper η tends to increase strongly with short period structure and long-duration earthquake, as well as with low-stiffness and low-yield-strength damper. It is found that this trend of η can be estimated by investigating complex effects of key factors such as post-yield stiffness ratio p, maximum ductility factor μ, natural vibration period of system T_0 and duration of earthquake ground motion t_d (Ito and Kasai, 2006). By considering the complex effects of p, μ, T_0 and t_d, the formula for prediction of cumulative deformation ductility factor η of damper is obtained as follows.

$$\eta = \frac{1+\sqrt{p}}{3}\left[(1+\sqrt{p})(\mu-1)^2 + \frac{t_d}{T_0}\frac{0.3\,T_0^{1/3}(\mu-1)^{3/2}\exp(0.55T_0^{1/4}p)}{1-0.18(1-p)\ln(T_0)}\right] \tag{2.3}$$

Moreover, the formula for relationship between cumulative deformation ductility factor η and maximum ductility factor (μ-1) of damper is also obtained by dividing Eqn. 2.3 by (μ-1).

$$\frac{\eta}{\mu-1} = \frac{1+\sqrt{p}}{3}\left[(1+\sqrt{p})(\mu-1) + \frac{t_d}{T_0}\frac{0.3\,T_0^{1/3}(\mu-1)^{1/2}\exp(0.55T_0^{1/4}p)}{1-0.18(1-p)\ln(T_0)}\right] \tag{2.4}$$

Figure 2.4 plots $\eta/(\mu-1)$ against p for different μ, T_0, and t_d by Eqn. 2.4. Eqn. 2.4 can express trends of analysis results, which are the strongly increase of η - value in case of short-period-structure and long-duration-earthquake, as well as behavior of low-stiffness and low-yield-strength damper.

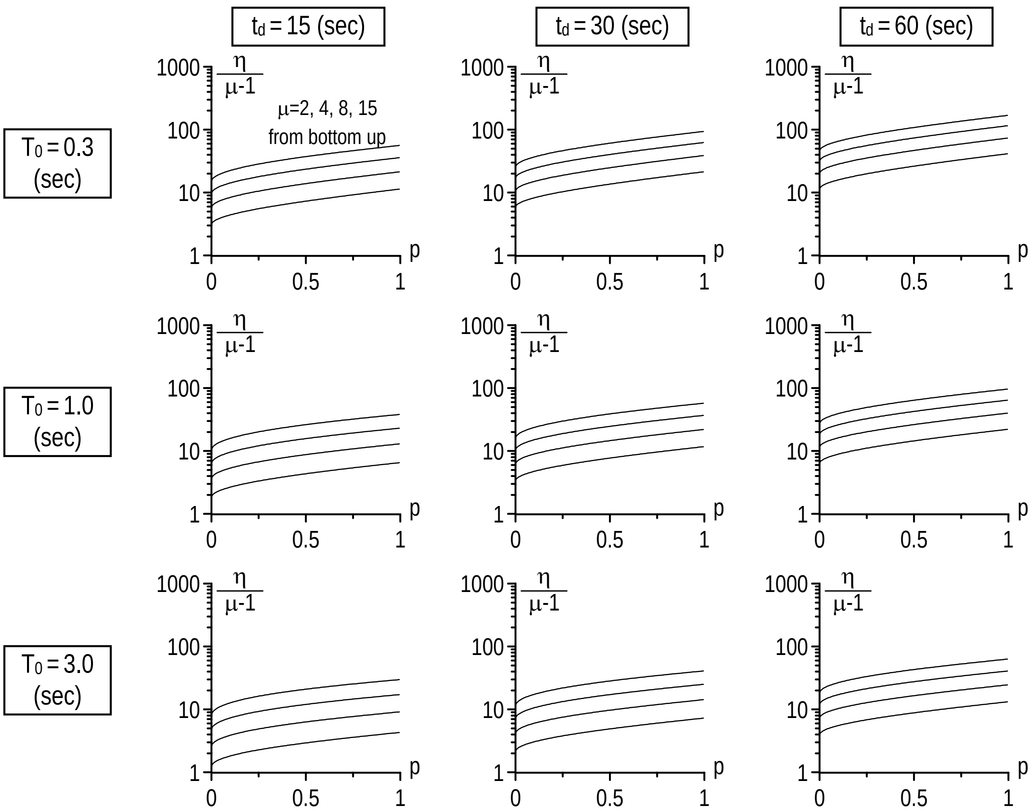

Figure 2.4 Relationship between $\eta/(\mu-1)$ and p for different μ, T_0 and t_d by Eqn. 2.4

3. CUMULATIVE PLASTIC DEFORMATION OF MDOF SYSTEM WITH EP DAMPER

3.1. Frame Models and Design Earthquake

In order to investigate cumulative plastic deformation of damper in multi-story elasto-plastically damped building structure, we will use MDOF shear-beam models created from the member-by-member frame models of 4, 10 and 20-story steel moment-resisting frames that were designed by JSSI (JSSI, 2005, and Kasai and Ito, 2005). In addition to the original frame horizontal stiffness distribution (JSSI-Type), three other types of distribution are considered for each of 4, 10 and 20-story buildings, by maintaining the mass distribution m_i, story height distribution h_i, and natural vibration period T_f identical to those of the JSSI-Type. The three types are called as standard type (S-Type), soft upper story type (U-Type) and soft lower story type (L-Type). Figure 3.1 shows story stiffness distributions of 4 types of frame for 4, 10 and 20-story buildings; they are the normalized value of product of stiffness K_{fi} and story height h_i at i-th story to it of stiffness K_{f1} and story height h_1 at 1st story. The frame stiffness K_{fi} at i-th story of S-Type is designed such that story drift angle may distribute uniformly under the A_i lateral force distribution (BRI, 2004). In U-Type frame, story drift angle tends to be larger at upper stories, whereas in L-Type frame, story drift angle tends to be larger at lower stories. As mentioned above, story stiffness distributions of S, U and L-Type frame are obtained such that natural vibration period of them may be identical to JSSI-Type. Natural vibration period of frame T_f and the total building height H are shown in Table 3.1. The initial damping ratio of frame is h_0 = 0.02.

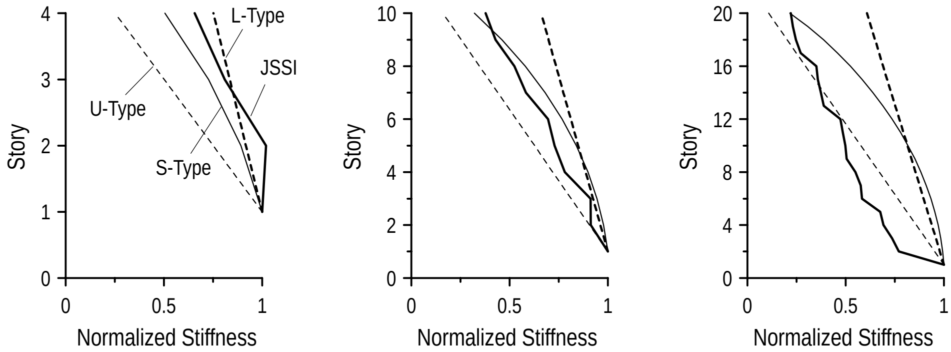

Figure 3.1 4 Types of story stiffness distributions of frames for various building heights

Table 3.1 Natural vibration period T_f and total height H of frame

	T_f (sec)	H (m)	T_f / H
4-story	0.640	18.0	0.036
10-story	2.012	42.0	0.048
20-story	3.704	82.0	0.045

6 artificial and 4 past earthquake ground motions for design are shown in Table 3.2. Design response spectrum and response spectra of 6 artificial earthquake ground motions (Table 3.2) for damping ratio h = 0.02, which are considered as extremely severe earthquake level, are shown in Figure 3.2. Pseudo velocity spectra S_{pv} of 6 artificial earthquake ground motions will be assumed to be period-independent in the range greater than 0.64 sec, pseudo acceleration spectra S_{pa} of 6 artificial earthquake ground motions will be also assumed to be period-independent in the range of shorter vibration period (0.16 - 0.64 sec). The values of duration t_d of those earthquake ground motions are also shown in Table 3.2. The duration of earthquake ground motion t_d is defined as cumulative duration, which is the time interval during which the central 90% of the contribution to the integral of the square of the acceleration takes place (Trifunac and Brady, 1975). As an example, Figure 3.3 shows definition of t_d and its value for El Centro NS ground motion.

Table 3.2 List of earthquake ground motions

Artificial Earthquake Ground Motions	Record Length (sec)	Duration t_d (sec)	Past Earthquake Ground Motions	Record Length (sec)	Duration t_d (sec)
BCJ-L2	120.0	65.3	El Centro NS	53.7	24.4
Hachinohe EW	60.0	49.2	Taft N111E	54.4	28.8
JMA Kobe NS	60.0	14.8	Hachinohe NS	51.0	28.4
Tohoku Univ. NS	60.0	30.4	JMA Kobe NS	30.1	8.1
El Centro NS	53.7	41.4			
Taft N111E	54.4	41.5			

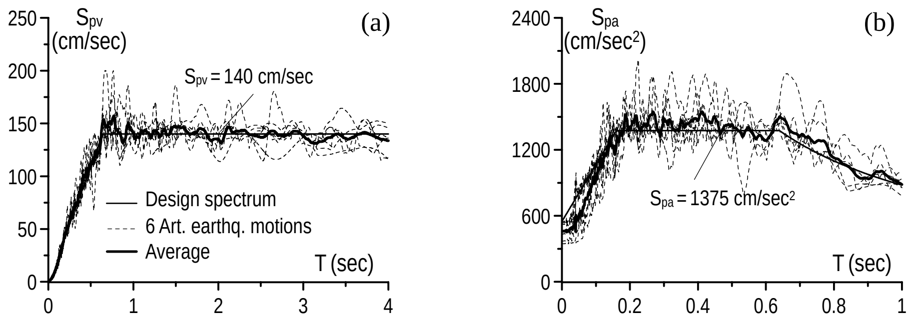

Figure 3.2 Response spectra of 6 artificial earthquake ground motions (h_0 = 0.02)

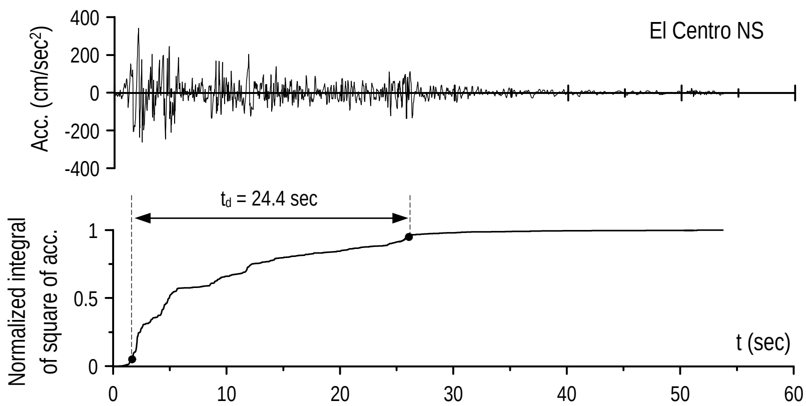

Figure 3.3 Definition of duration of earthquake ground motion t_d

3.2. Passive Control Design and Analysis Model

In order to investigate cumulative plastic deformation of damper in multi-story elasto-plastically damped building structure, time history analysis were carried out for 1440 (= 4×3×4×3×10) MDOF systems with EP dampers designed: 4 types of frame which are JSSI, S, L and U-Type shown in Figure 3.1, 3 building heights which are 4, 10 and 20-story frame; 4 target ductility demands μ = 2, 4, 6 and 8; 3 target drift angles θ = 1/200, 1/150 and 1/125 rad; and 6 artificial and 4 past earthquake ground motions shown in Table 3.2.

In passive control design for MDOF system with EP damper, damper stiffness K_{di} and damper yield strength F_{dyi} at i-th story are determined by the method to satisfy the target of maximum story drift angle and maximum ductility demand, and assure uniformly distributed maximum story drift angle and maximum ductility factor over the building height under the design earthquake ground motion considered (Kasai and Ito, 2005, 2006). Yield story drift angle θ_y (= θ / μ) of MDOF system is the same among all story levels. In design and analysis, each story of MDOF system with damper is considered as mass and two shear springs which show EP damper with elasto-perfectly-plastic behavior and frame with linear behavior in a row to the mass (Figure 3.4).

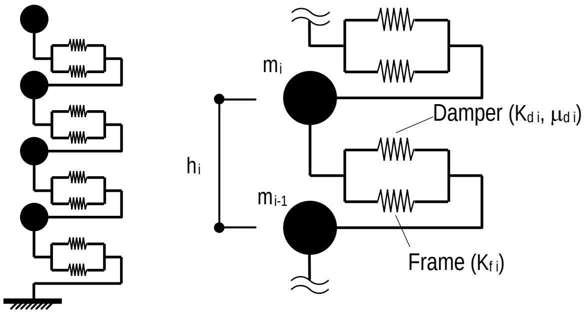

Figure 3.4 MDOF system with EP damper

3.3. Validation Study

Validation study for the proposed method is carried out using a wide range of MDOF models indicated in section 3.2 (1440 models in total), the accuracy of estimated cumulative plastic deformation factor η_i of damper at ***i***-th story is verified with time history analysis results.

In validation study for MDOF system with various post yield stiffness ratio p_i ($= K_{fi} / (K_{fi} + K_{di})$), cumulative plastic deformation factor obtained from analysis results at story level with higher p_i-value tends to increase strongly and exceed the estimation by Eqn. 2.4 considering complex effects of key factors such as p, μ, T_0 and t_d for SDOF system. Thus, by multiplying Eqn. 2.4 by revised factor (p_i / p) considered such effect by p_i distribution of MDOF system, the formula for prediction of cumulative deformation ductility factor η_i of damper at ***i***-th story is revised as follows.

$$\eta_i = \frac{1+\sqrt{p_i}}{3}\left[(1+\sqrt{p_i})(\mu_i-1)^2 + \frac{t_d}{T_0}\frac{0.3T_0^{1/3}(\mu_i-1)^{3/2}\exp(0.55T_0^{1/4}p_i)}{1-0.18(1-p_i)\ln(T_0)}\right]\frac{p_i}{p}, \quad p = \frac{1}{1+\sum_{i=1}^{N}K_{di}\Big/\sum_{i=1}^{N}K_{fi}} \quad (3.1a,b)$$

where p = post stiffness ratio of equivalent SDOF system to which is converted MDOF system.

We will estimate the η_i-value of damper based on target ductility demand μ, because μ_i obtained from analysis results becomes nearly equal to μ by utilizing above mentioned response control method (Kasai and Ito, 2005, 2006). The cumulative plastic deformation factor of damper obtained from analysis results (symbol) under 4 ground motions (El Centro NS, JMA Kobe NS, BCJ-L2 and Tohoku Univ. NS) and prediction (solid line) by Eqn. 3.1, in case of 4 types of 4, 10 and 20-story frame; $\theta = 1/150$ rad; $\mu = 4$, are shown in Figure 3.5a,b. The maximum ductility factor obtained from analysis results under 4 ground motions and post yield stiffness ratio of system p_i ($= K_{fi} / (K_{fi} + K_{di})$) are also shown in Figure 3.5c,d. As you can see Figure 3.5c, maximum ductility factor of analysis results fairly satisfy the design target due to inserting a sufficient amount of damper at each story regardless of frame stiffness distribution. In JSSI and S-Type MDOF system with almost uniform value of p_i over the building height, distributions of η_i-value obtained from analysis results tend to be also uniform over the building height. On the other hand, in L and U-Type MDOF system with various value of p_i over the building height, η_i-value obtained from analysis results tends to increase strongly at story level with higher p_i -value. Such tendencies are predicted accurately by proposed method (Eqn. 3.1) based on the behavior of SDOF system, regardless of variety of stiffness balance of damper to frame over the building height.

The η_i-value of damper estimated by the proposed method based on design target μ are plotted against the time history analysis results in Figure 3.6, where each data point corresponds to value at one story of one analysis case. Instead of calculating the median and standard deviation of η_i (prediction) / η_i (analysis), median a and standard deviation σ can equivalently be obtained by performing a one-parameter log-log linear least squares regression of η_i (prediction) on η_i (analysis). The regression model is expressed "ln(η_i (prediction)) = ln(a) +

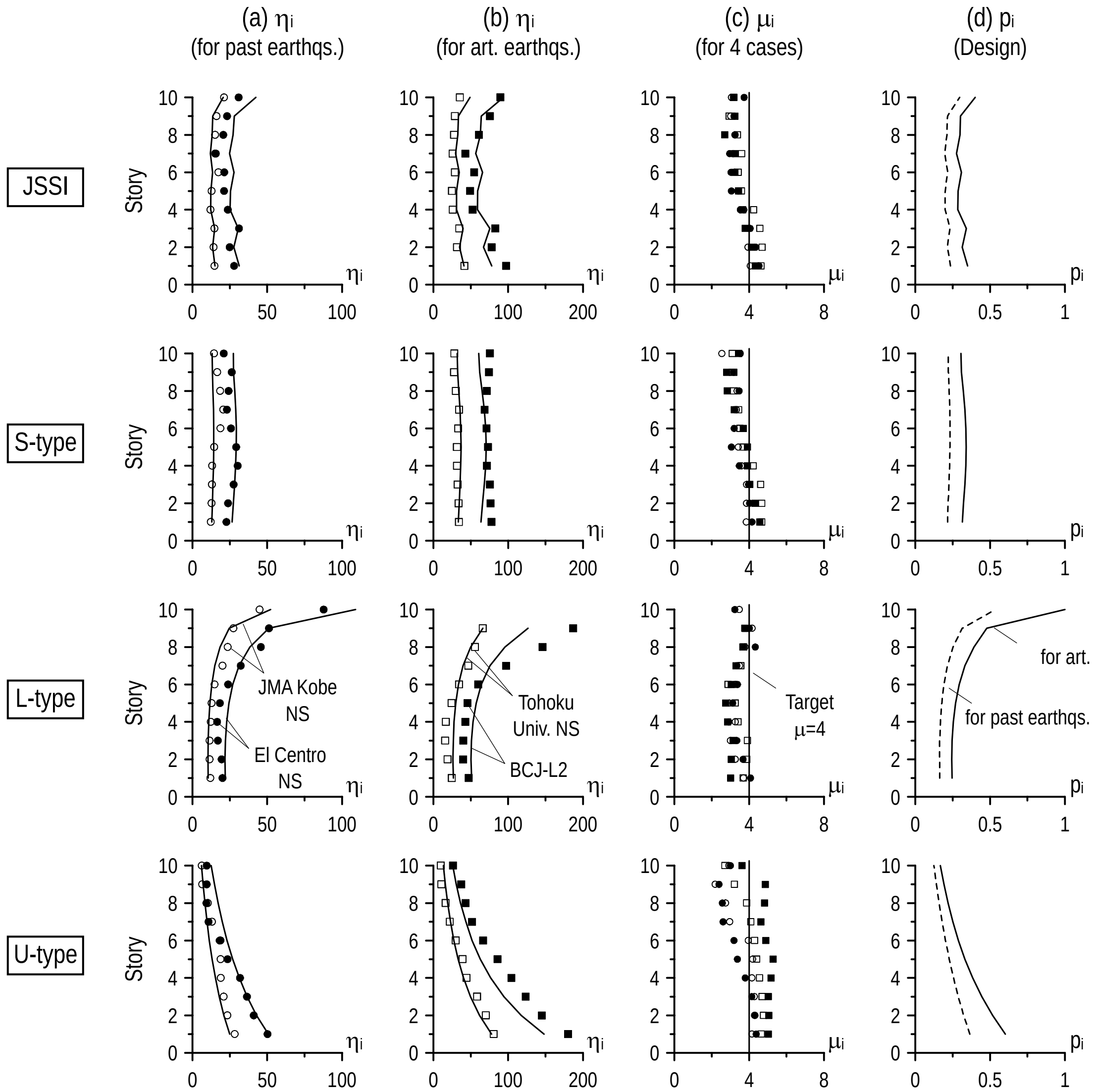

Figure 3.5 Comparison proposed method with analysis results
(10-story, $\theta = 1/150$ rad ($\theta_y = 1/600$ rad), $\mu = 4$, symbol : analysis, solid line : prediction (Eqn. 3.1))

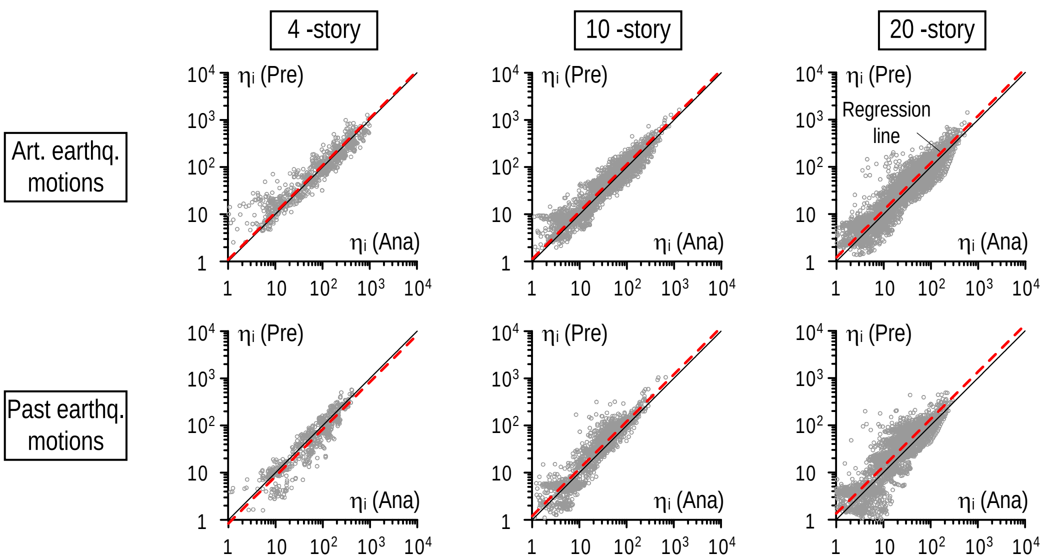

Figure 3.6 Comparison proposed method with analysis results of cumulative deformation ductility factor η

ln(η_i (analysis)) + ln(ε)", where a is incline of regression line and ε is the random error in η_i (prediction) given η_i (analysis) with median 1 and standard deviation σ. Median a and standard deviation σ for different story height and earthquake type are shown in Table 3.3. It can be seen that the proposed method gives good estimation in average, although we observe some scattering of its estimation. In order to give a reasonably conservative estimation for practice, η_i-value of damper estimated by Eqn. 3.1 should be scaled by a conservative factor 1.75 as the sum of a and σ for all data points. Statistically, this conservative factor would give more than 93% confidence for the η_i to be greater the exact value obtained from time history analysis.

Table 3.3 Accuracy of proposed method in prediction of cumulative deformation ductility factor η
(upper: median a, lower: standard deviation σ)

	4-story					10-story					20-story				
	Total	JSSI	S	L	U	Total	JSSI	S	L	U	Total	JSSI	S	L	U
Art. Earthq. Motions	1.089 (0.527)	1.010 (0.407)	0.955 (0.388)	1.174 (0.457)	1.294 (0.741)	1.141 (0.432)	1.191 (0.390)	1.119 (0.367)	1.288 (0.431)	0.990 (0.491)	1.200 (0.481)	1.241 (0.486)	1.210 (0.383)	1.430 (0.471)	0.971 (0.496)
Past Earthq. Motions	0.839 (0.527)	0.788 (0.435)	0.887 (0.430)	0.852 (0.468)	0.818 (0.725)	1.205 (0.480)	1.228 (0.457)	1.124 (0.395)	1.381 (0.580)	1.110 (0.443)	1.345 (0.721)	1.401 (0.694)	1.284 (0.595)	1.722 (0.875)	1.065 (0.610)

4. CONCLUSIONS

This study is aimed to develop the prediction method for cumulative plastic deformation of damper in multi-story elasto-plastically damped building. The proposed method is based on the behavior of SDOF system with EP damper subjected to earthquake ground motion, a rule to convert it to the prediction for MDOF model of multi-story building, with a consideration for distribution of stiffness balance of damper to frame, is also presented. The conclusions are as follows:

1. The prediction theory for cumulative plastic deformation of damper, by considering complex effects of stiffness parameter, maximum ductility factor, natural vibration period of structure and duration of earthquake ground motion gives good estimation in average, with some scattering of its estimation.

2. In MDOF system with various value of post yield stiffness ratio over the building height, cumulative plastic deformation factor at each story tends to depend strongly on the balance of post yield stiffness ratio over the building height. Cumulative plastic deformation factor at story level with higher post yield stiffness ratio extremely increases.

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