SEISMIC CAPACITY DIAGRAM FOR DAMAGE BASED DESIGN

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ABSTRACT :

In this paper, the seismic capacity based on *damage* concept is proposed for performance based design. The design approach is called *Seismic Damage-based Capacity Diagram.* This is presented as a graphical plot of strength capacity against the displacement of the structures, where as seismic damages of the system are shown in terms of damage indices. The seismic capacity diagram was computed by nonlinear static analysis (Cyclic Pushover Method). The well-known Park-Ang damage model was employed in the computation of damage index. Modified Takeda model was selected as the hysteretic behavior of structures. A 15 storey building was analyzed by pushover method. It was found that the damages in the lower floors were greater than those in the upper floors. This is mainly due to cumulative damage resulting from absorbed hysteretic energy in the cyclic load reversal. The application to performance based design was investigated in terms of demand–capacity diagrams. Finally, the performance point was evaluated on damage basis.

KEYWORDS: seismic capacity diagram, performance based design, pushover method, damage index, cumulative damage.

1. INTRODUCTION

In performance-based seismic design of buildings, capacity spectrum technique is an important tool to evaluate the performance point of the structure. Basically, there are two key elements in this method, namely seismic demand and capacity as proposed in ATC-40. The seismic demand is a representation of the earthquake ground motion, and it is presented in terms of forces and displacements imposed on structures by earthquakes. The seismic capacity represents the inelastic behavior of structure in terms of spectral acceleration and spectral displacement, which is known as capacity curve. The procedure to determine capacity curve relies on the use of nonlinear static seismic analysis (pushover method). The procedure of nonlinear static analysis has been improved from the original method as described in FEMA-440. The performance point is defined as the intersection point between demand and capacity where the ductility of structure is matched. This procedure is based on a basic assumption that displacement ductility is a damage criterion. However, it is known that displacement ductility is insensitive to cumulative damage resulting from cyclic loading. Currently, cumulative damage has been quantified in terms of damage indices by many researchers. The damage indices have been widely used to quantify the seismic damage. Furthermore, the application of damage indices in seismic design has been proposed, for examples, Tiwari and Gupta (2000) proposed a scaling model for damage-based strength reduction factor, from which the Park-Ang damage model (1985) was employed in the development of scaling model. Decanini et al. (2004) presented the response modification factors based on damage indices. Two different damage models were adopted, i.e., the well-known Park-Ang damage model and Krawinker and Zohrei damage model (1983). Cumulative damage has been incorporate to compute inelastic cyclic demand spectrum by Kunnath and Chai (2004). A low-cycle fatigue model was adopted to determine duration-dependent inelastic design spectra by Chai (2005). Recently, Panyakapo, P. (2006) proposed a constant-damage strength demand diagram to estimate the strength and displacement demands of structures for a target seismic damage. However, the application of damage index to the capacity spectrum technique has not been investigated.

In the pushover method, the building is subjected to a pattern of lateral force distribution which is monotonically increased to push the building laterally. These include single-mode load vector and multi-mode pushover procedures. The single-mode load vector as described in FEMA-440 consists of concentrated load, uniform load, triangular load, Code distribution load, first mode load, adaptive load, and SRSS load. For the multi-mode pushover method, the lateral loads are distributed correspondent to each mode shape (Chopra and Goel, 2002). However, seismic damage of structures resulting from these pushover procedures does not reflect cumulative damage because they are based on monotonic loading.

This paper presents seismic capacity of structure based on damage concept. Cyclic Pushover Analysis was adopted to quantify cumulative damage. The well-known Park-Ang damage model was employed in the computation of damage index. Modified Takeda model was selected as the hysteretic behavior of structures. A 15 storey building was analyzed by Cyclic Pushover method. The resulting capacity curve is called *Seismic Damage-based Capacity Diagram.* The application to the capacity spectrum technique for performance based seismic design is also presented in terms of demand–capacity diagrams.

2. BASIC CONCEPT

In this approach, the seismic demands are strength and displacement imposed on structure by earthquake, which are required to limit the seismic damage to a target value. This approach is based on *constant-damage* concept for performance-based design proposed by Panyakapo, P. (2006). The design approach is called *Constant-Damage Strength Demand Diagram.* This is presented as a graphical plot of strength against the displacement demand of the structures for a target seismic damage; whereas the natural periods of the systems are represented by the radical lines. For the seismic demand diagram, the strength and displacement demands of structures can be computed by these relations.

Strength demand of structures

$$S_a\left(DI_i\right) = \frac{\left(\dfrac{V_b}{W}\right)_{\mu=1}}{R_D} \tag{2.1}$$

Displacement demand of structures

$$S_d\left(DI_i\right) = \mu\frac{1}{R_D}\left(\frac{T}{2\pi}\right)^2\left(\frac{V_b}{W}\right)_{\mu=1} \tag{2.2}$$

where $S_a\left(DI_i\right)$ is the spectral acceleration for a target seismic damage, g

$S_d\left(DI_i\right)$ is the spectral displacement for a target seismic damage, cm.

$\left(\dfrac{V_b}{W}\right)_{\mu=1}$ is the base shear coefficient for elastic response system, g.

μ is the displacement ductility ratio of structural system.

R_D is strength reduction factor from elastic response to inelastic response for a target seismic damage.

T is the natural period of structural system, sec.

The seismic capacity is the relationship between the overall strength and displacement capacities of a structure under nonlinear static analysis. This is presented as a graphical plot of strength and displacement capacities of a structure, where as seismic damages of the system are shown on the trajectory in terms of damage indices. This is called *Seismic Damage-based Capacity Diagram*. The strength and displacement capacities can be computed from the conversion of pushover curve as follows:

$$S_{a,DI} = \frac{\left(V_b/W\right)_{envelop}}{\alpha_1} \tag{2.3}$$

$$S_{d,DI} = \frac{\Delta_{roof,envelop}}{PF_1 \times \phi_{1,roof}} \tag{2.4}$$

Where $S_{a,DI}$ is the spectral acceleration for each value of damage index, g

$S_{d,DI}$ is the spectral displacement for each value of damage index, cm.

$\left(V_b/W\right)_{envelop}$ is the envelop base shear coefficient for cyclic inelastic response, g.

α_1 is the modal mass coefficient for the first mode

$\Delta_{roof,envelop}$ is the roof displacement, cm.

PF_1 is Participation Factor for the first mode

$\phi_{1,roof}$ is the amplitude of the first mode at the roof level

3. NONLINEAR STATIC ANALYSIS (CYCLIC PUSHOVER METHOD)

The cyclic pushover method has been modified from the conventional pushover analysis to account for the effect of cumulative damage resulting from cyclic response. In this study, the loading procedure was adapted from a laboratory test displacement history. The procedure of cyclic pushover analysis is summarized as follows:

a) Compute the lateral force distribution corresponding to the first mode shape.

$$f_o = \lambda_i \Gamma_1 m \phi_1 A_1 \tag{3.1}$$

where f_o is the lateral force in the first mode,

λ_i is a variable factor which defines the direction of force,

i is the number of cycles for the specified displacement history
for i =1,3,5,….. , $\lambda_i = 1$, and for i = 2,4,6,….., $\lambda_i = -1$

Γ_1 is the Participation factor of the first mode

A_1 is the acceleration in the first mode $= \omega_1^2 D_1$

ω_1, D_1 is the angular frequency and displacement in the first mode

b) Specify the pushover path as a displacement control, where the relationship between displacement and number of cycles is shown in Table 1.

Table 1 Displacement history for each cycle

Number of cycles	1	3	2	2	2	2	Upper limit
Displacement	0.75μ	μ	1.5μ	2μ	3μ	4μ	6μ

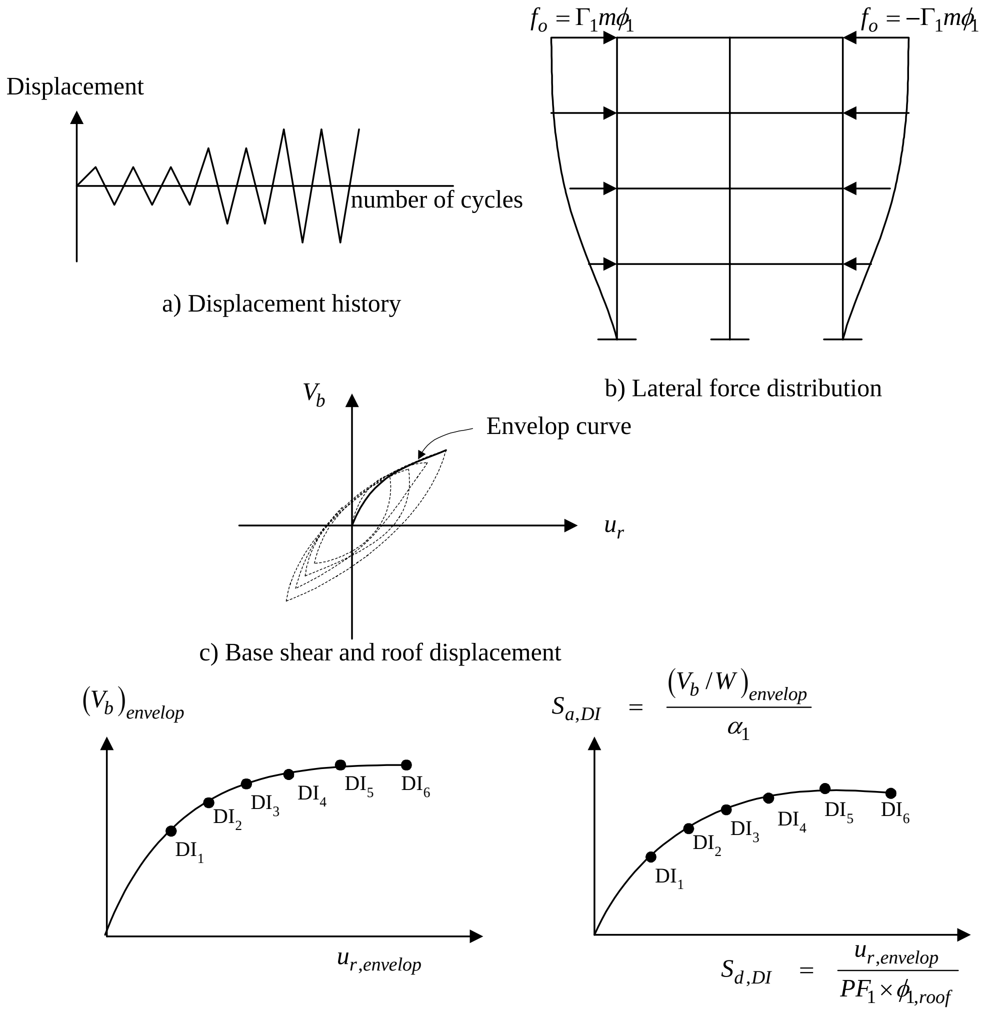
c) Perform nonlinear static analysis using the above specified force distribution and displacement history. The results are plotted for the relationship between base shear and top displacement.
d) Determine the envelop curve for the relationship between base shear and top displacement to obtain the Pushover Curve $(V_b - u_r)$.
e) Convert the pushover curve to Capacity Diagram by using Equation 2.3-2.4.
f) Compute the seismic damage of structure based on Park-Ang damage index (Pak and Ang, 1985). And plot the values of damage index along the capacity diagram.

The above procedure is also presented in Figure 1.

4. ANALYSIS OF 15-STOREY BUILDING

In this study, a 15-storey reinforced concrete building with symmetrical floor plan was employed in the nonlinear static analysis. The details of building can be summarized as follows: a) The floor plan is 28.90x47.00 meters with overall height 52.50 meters, b) the floor systems are flat plates with reinforced concrete and post-tensioned concrete, c) columns are 0.6x1.50 meters, d) compressive strength of concrete is 300 ksc, and the tensile strength of reinforcing steel is 4,000 ksc. The reinforced concrete structure was designed according to EIT (2000). Since this is an old building, it had not been designed for seismic loading. The slab-column frame was modeled as effective beam width model. The modified Takeda model was assumed as the hysteretic behavior of structure. The cyclic pushover analysis was performed by the computer program RUAUMOKO (Carr, 2006) to generate the pushover curve, and the capacity curve was then computed. The results of pushover curve and capacity curve are shown in Figures 2 and 3, respectively. In Figure 3, the capacity curve resulting from cyclic pushover method is compared with that of conventional pushover method.

The plastic hinges formation in the structure was analyzed at the end of cyclic pushover analysis, as shown in Figure 4a. The seismic damages of the beams were plotted against the storey levels for axes A-B, B-C, C-D. The total seismic damages of these beams were separated into damages caused by maximum deformation and cumulative damage, as shown in Figure 4b. It can be observed that cumulative damage has an important effect on the total seismic damage, especially in the lower floors between the floor levels 2-4. This is mainly due to the absorbed hysteretic energy in the cyclic load reversal.



a) Displacement history

b) Lateral force distribution

c) Base shear and roof displacement

d) Pushover curve

e) Capacity curve

Figure 1 Procedure for cyclic pushover method

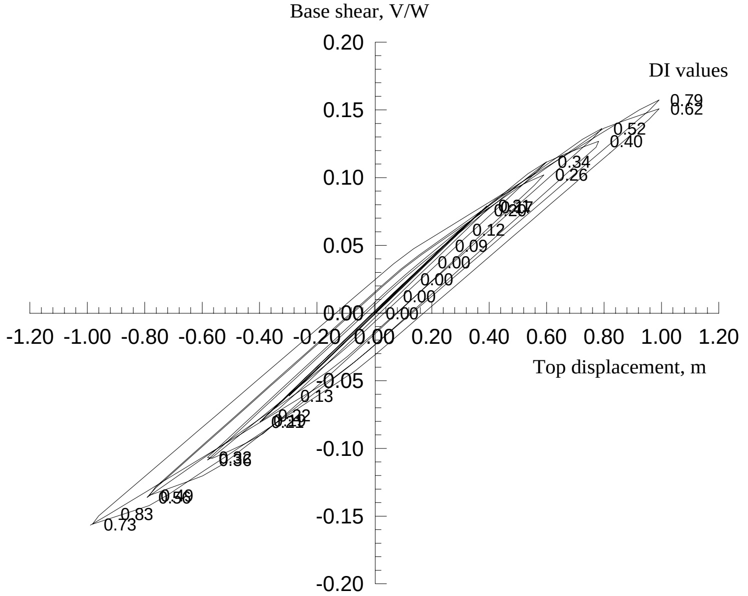


Figure 2 Pushover curve by cyclic pushover method

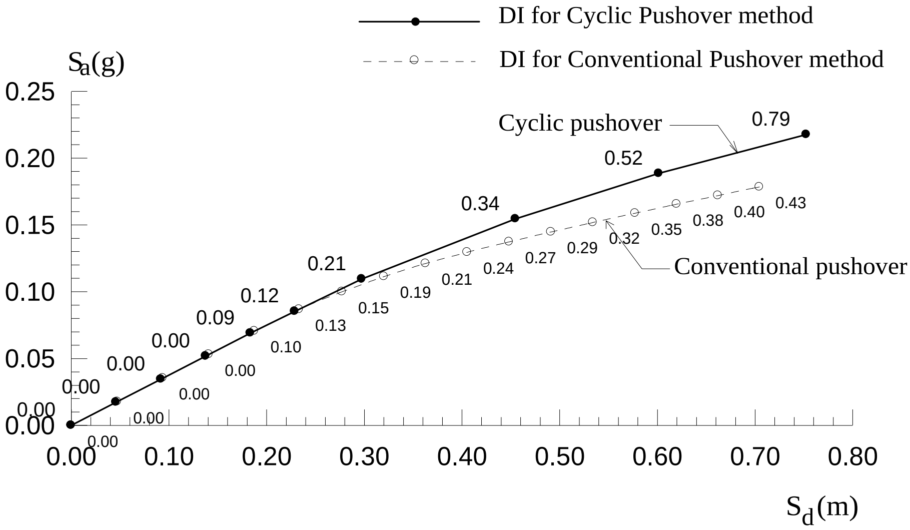
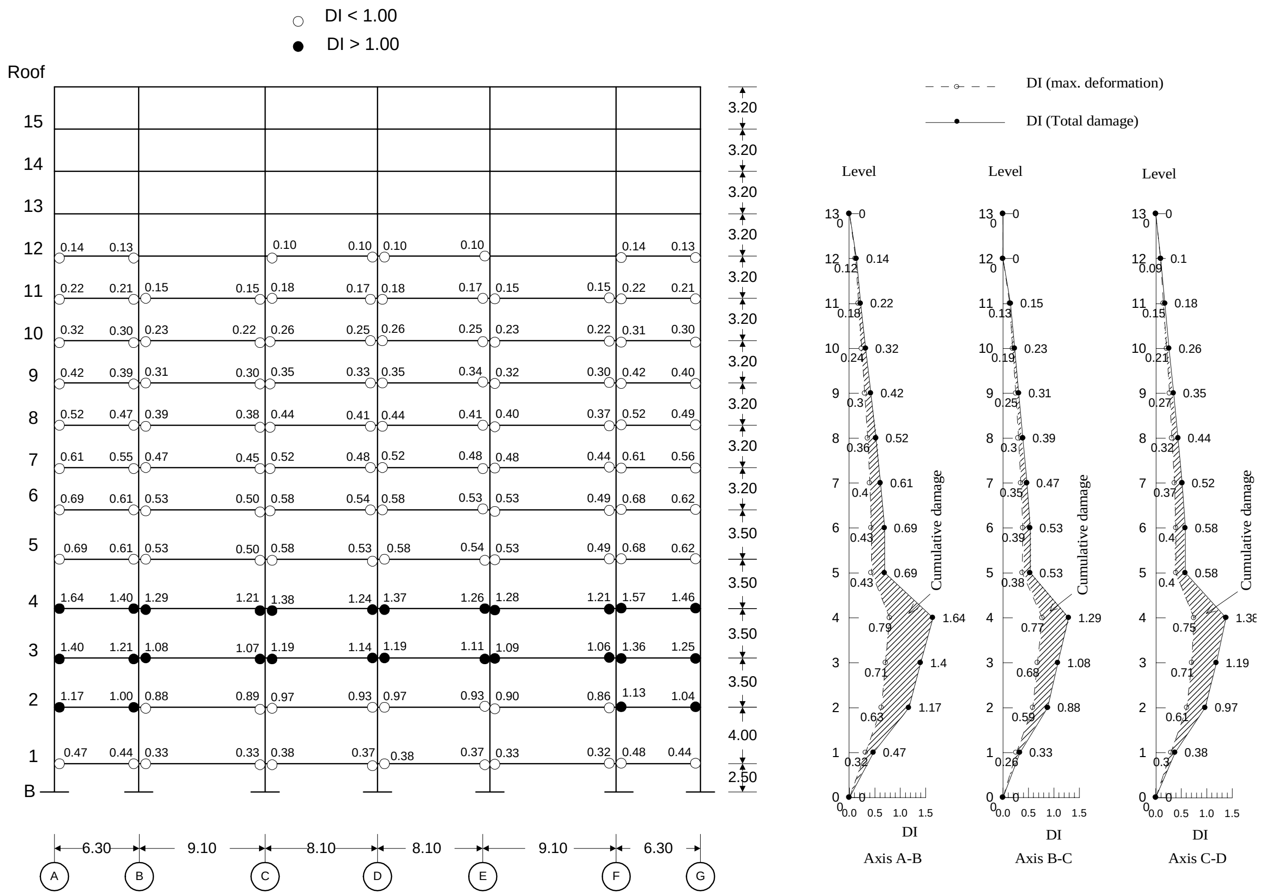


Figure 3 Seismic Damage-based Capacity Diagrams for cyclic pushover and conventional pushover method



(a) Plastic hinges formation (b) Seismic damage in the beams

Figure 4 Seismic damage and cumulative damage in the structure

The capacity curve was plotted into the demand diagram to obtain the seismic demand-capacity diagrams. In this study, the seismic demand diagram was taken from the previous study (Panyakapo, P. 2006), which was developed for buildings located on soft soil sites. The results are presented for target DI equal to 0.1-1.0, as shown in Figure 5. It can be observed that the intersection points between these two curves indicate the locus of performance point. However, there is only one suitable point, where the seismic damage of demand diagram matches with the seismic damage of capacity diagram. That is $DI_{demand} = DI_{capacity} = 0.11$. It was found that at this performance point, the spectral acceleration and spectral displacement are 0.08g and 0.21 meters, respectively.

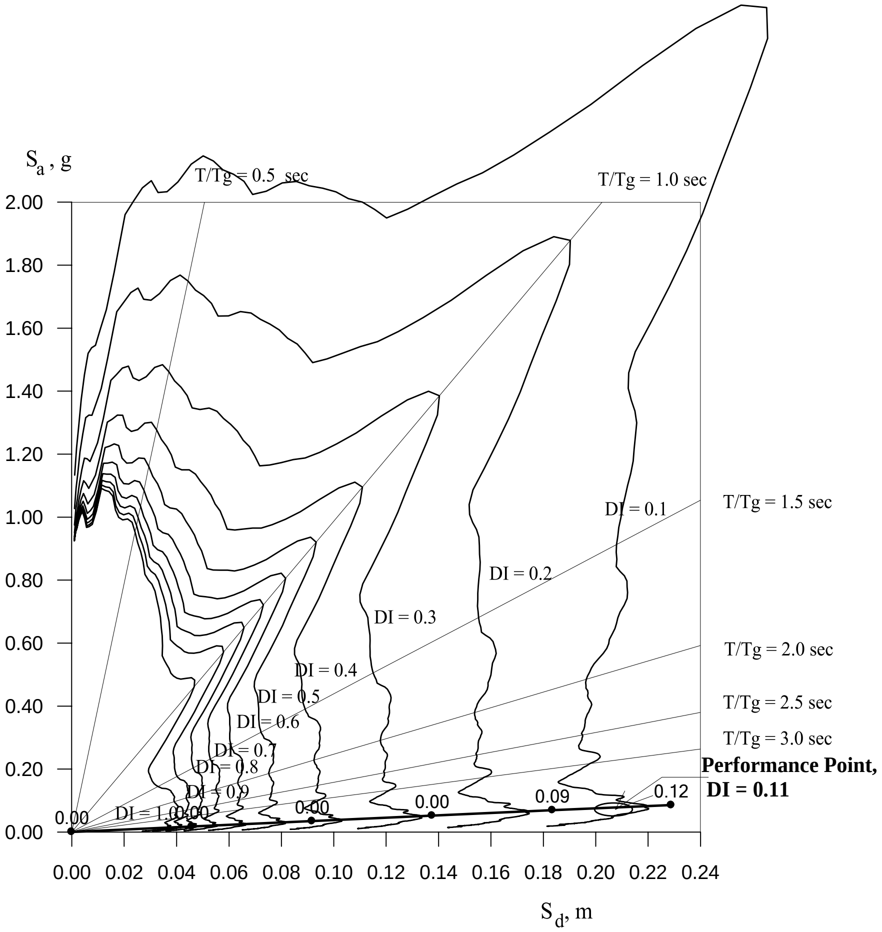


Figure 5 Seismic Demand-Capacity Diagrams for damage based design

5. CONCLUSIONS

Based on the above results, the following conclusions can be drawn:

a) Cumulative damage is an important factor for determining seismic damage. This effect cannot be accounted by conventional pushover method. The cyclic pushover method is an alternative approach to consider the effect of cumulative damage. Furthermore, this method can be applied for performance based seismic design.

b) The application of capacity diagram for damage based design was presented in terms of demand–capacity diagrams. A capacity curve which is called *Seismic Damage-based Capacity Diagram* was proposed. When this capacity diagram is combined with seismic demand diagram, the performance point can be evaluated on damage basis.

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