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THE USE OF DAMAGE FUNCTION IN PERFORMANCED-BASED SEISMIC DESIGN OF STRUCTURES

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SUMMARY

A design philosophy, based on the energy concept and yield point spectra method, is developed for the performance based seismic design. A physically based analytical model capable of describing the effects of pinching, stiffness degradation and strength degradation is used to construct the seismic design parameters and the seismic demand. Seismic design parameters, which were proposed to derive the seismic demand, will be constructed for different hysteretic loops by using 75 earthquake records. Incorporate with the developed Yield Point Spectra and the proposed equivalent ductility ratio the acceptable design region of the structures can be determined for considering both safety and serviceability in design and rehabilitation.

INTRODUCTION

Performance based seismic design procedures and codes have been recommended to substitute traditional design procedures and design codes. Differing from traditional design codes, the characteristics and the advantages of the performance-based designs are listed below.

1. Multi design performance levels
2. Damage related design Index

In order to perform it, the structural nonlinear behavior should be realized to control the structural behavior in different earthquake excitations. A large amount of studies have been discussed about the structural nonlinear behavior. In general, both the maximum structural displacement and the structural Damage Index have been recommended to serve as the design indices in the performance based seismic design. Methods used to determine the system maximum displacement have been discussed by several researchers (Miranda 2002, Kowalsky 2000 and Chopra 2001). The uses of the Damage Index in the performance based seismic design have also been discussed (Bertero 1996, 2002) based on the energy concept. Some parameters, such as the yield strength reduction factor and the displacement modification factor etc., have been proposed and constructed to derive the information of the structural nonlinear behavior. In this study, important seismic design parameters that can be used to control and realize the structural nonlinear behavior are selected and studied. In the past the relationship between the seismic design parameters and the structural hysteretic loops has not been discussed adaptively because the lack

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of the analytical hysteretic model, which can involve the stiffness, strength degradation effects and pinching effects. In this study, an analytical nonlinear SDOF model which can consider these effects is used to derive the seismic design parameters. The relationship of these parameters will be discussed and suggested to revise the seismic code. In this study the Yield Point Spectra Method is selected to determine the performance point of structures. By combining the seismic design parameters and the design philosophy based on the Yield Point Spectra Method, a complete performance based seismic design philosophy will be constructed. The objectives of this study are:

a. Construct the seismic design parameters, which can be used to construct the seismic demand for the inelastic SDOF system. The influence of different hysteretic loops on the seismic design parameters will be discussed.
b. Construct a design philosophy for performance-based seismic design based on energy concepts and yield point spectrum, which can be used easily, conveniently and quickly for structural design and rehabilitation.

SEISMIC DESIGN PARAMETERS

For performance based seismic design, it is important to control the structural behavior in the inelastic state during earthquake ground motions. In order to attain this goal, it is suggested to use seismic design parameters to realize and control the structural behavior in the inelastic state. These include:

1. Displacement Modification Factor,
2. Yield Strength Reduction Factor,
3. Seismic Energy Response Parameter,
4. Damage Index,
5. Equivalent Ductility Ratio,

These seismic design parameters can help us to construct the seismic demand spectra for the inelastic systems, and to realize and control the structural behavior in the inelastic state. A total of 75 strong ground motion data were collected from hard site condition in Taiwan to generate the above-mentioned seismic design parameters. The predominant period of each ground motion is identified which will be used as a normalized factor for period in developing the seismic demand spectra. Next, the nonlinear analytical SDOF model, which can represent the degradation and pinching effects while structures suffer strong ground motion, will be introduced.

Nonlinear Analytical SDOF Model

In this study, the nonlinear SDOF hysteretic model proposed by Mostaghel (1999) was used for analysis. This model can be implemented to predict the pinching and degrading hysteretic behavior of a structure. In this model, the nonlinear control parameter λ_p (ranges from 0 to 1) controls the level of pinching effects. If $\lambda_p = 1$ the model will be equal to the bilinear system which indicates no pinching effects. The nonlinear control parameters λ_k and λ_l control the velocity of stiffness and strength degradation. In summary, the nonlinear model used in this study has four nonlinear control parameters to consider the pinching effects and the degradation of a system:

1. Post-yielding stiffness ratio α ($|\alpha| \le 1$, and when $\alpha = 1$ indicates an elastic system),
2. Stiffness degradation control parameter λ_k ($\lambda_k \ge 0$, and when $\lambda_k = 0$ indicates no degradation),
3. Strength degradation control parameter λ_l ($\lambda_l \ge 0$, and when $\lambda_l = 0$ indicates no degradation),
4. Pinching control parameter λ_p ($0 \le \lambda_p \le 1$, and when $\lambda_p = 1$ indicates no pinching effect),

The strength degradation and stiffness degradation of the system are related to the system absorbed hysteretic energy:

$$\Phi_{k,i+1} = k_{i+1}/k = \left(1 + \lambda_k E_{H,i+1} / k u_y^{\,2}\right)^{-1} \tag{1a}$$

$$\Phi_{l,i+1} = u_{y,i+1}/u_y = \left(1 + \lambda_l E_{H,i+1} / k u_y^{\,2}\right)^{-1} \tag{1b}$$

where i : ith time step, Φ_k : Stiffness degrading level, Φ_l : Strength degrading level, k: Initial system stiffness, u_y: Initial system yield displacement. If the value of λ_k and λ_l are larger, the velocity of degradation is faster.

Combining these four nonlinear control parameters adaptively, the hysteretic loop for different kinds of nonlinear behavior of the realistic structures can be modeled. By comparing the results of the nonlinear analytical model and the experimental results (cyclic loading test of 1/2-scale model in NCREE Structural Lab.), both the hysteretic behavior of the flexure failure mode (BMR1 Model) and the infill wall-frame mode (W_F model) can be generated by using the nonlinear analytical model, as shown in **Figure 1a** and **Figure 1b**. Based on the proposed inelastic model the seismic demands can be studied in a more realistic way. In this study, the Bilinear model ($\alpha \neq 0$), the BMR1 model and the W_F model will be used to constructed the seismic design parameters. The nonlinear control parameters for different hysteretic model are shown in **Table 1**. Based on the proposed inelastic model the following three seismic demand factors are evaluated:

a. Displacement Modification Factor C: The definition of the Displacement Modification Factor is defined as the ratio between inelastic system maximum displacement for specific ductility level ($Sd_{inelastic}$) and elastic system maximum displacement ($Sd_{elastic}$). Through numerical study it is found that the value of the Displacement Modification Factor has highest value for the W_F model because of the severe stiffness and strength degradation of the system model.

b. Yield Strength Reduction Factor Ru: The Yield Strength Reduction Factor for different hysteretic models and system ductility is studied. It is found that the value of the Yield Strength Reduction Factor has highest value for Bilinear model because of the higher value of the post yielding stiffness ratio. This factor has lowest value for W_F model because of the severe stiffness and strength degradation of the system model.

c. Seismic Energy Response Parameter γ: Fajfar (1992) proposed using the parameter γ to consider the hysteretic energy absorbed by a system during earthquake ground motion excitations. The parameter γ is defined as:

$$\gamma = \frac{\sqrt{E_H / m}}{\omega Sd_{inelastic}} \tag{2}$$

where E_H: hysteretic energy absorbed by the system for a specific ductility level; m: system mass; ω: system natural frequency of vibration; $Sd_{inelastic}$: system maximum displacement for a specific ductility level. Researches indicate that the damage caused by earthquake excitation is related not only to a system maximum displacement but also to the cyclic load reversals resulting in low cycle fatigue. Low cycle fatigue occurs when a system absorbs large hysteretic energy during earthquake ground motion. To avoid low cycle fatigue the hysteretic energy absorbed by the structural system needs to be considered quantitatively during earthquake excitation, and the parameter γ can reflects the structural hysteretic energy quantitatively. ***Figure 2a*** and ***Figure 2b*** show the parameter γ for different hysteretic model and for system ductility equal to 2 and 6, respectively. The value of the parameter γ calculated by the Bilinear model has the highest value and calculated by W_F model has the lowest value. The relationship between the system ductility, period and the parameter γ is depend on the selected inelastic model. Fortunately the value of the parameter γ is not wide ranging. From the result of this analysis results (system ductility equal

to 1 to 6) the upper and lower limits of the parameter γ are shown in ***Table 2***. One can select a higher value of γ to make design conservative.

Damage Index

Damage Index has been proposed and used to identify the damage condition of the members and the structures. It was found that the damage of member and structure is related to not only on the maximum displacement of the members and the structures but also on the absorbed hysteretic energy. As described above the system absorbed hysteretic energy, E_H, can be calculated by using the predefined parameter γ:

$$E_H = m\gamma^2\omega^2 Sd_{inelastic}{}^2 = k\gamma^2\mu^2 u_y{}^2 \tag{3}$$

Combining this equation with the Damage Index proposed by Park and Ang (1985), DI_{pa}, the damage index can be rewritten as:

$$DI_{pa} = \frac{\mu}{\mu_{umon}} + b\frac{\gamma^2\mu^2}{\mu_{umon}} \tag{4}$$

The value of *b* depended on the structural nonlinear characteristics.
Different from Park & Ang damage model, Bozorgnia and Betero (2001) introduced two improved Damage Index equations as shown below

$$\begin{aligned} DI_{bb,1} &= [(1-\alpha_1)(\mu-\mu_e)/(\mu_{umon}-1)] + \alpha_1(E_H/E_{Humon}) \\ DI_{bb,2} &= [(1-\alpha_2)(\mu-\mu_e)/(\mu_{umon}-1)] + \alpha_2(E_H/E_{Humon})^{0.5} \end{aligned} \tag{5}$$

where $u_e = u_{elastic}/u_y$=maximum elastic portion of deformation / u_y and $u_e = 1$ is for inelastic behavior, and $u_e = \mu$ is for the response remains elastic, α_1 and α_2 are constant depended on the stability of hysteretic behavior (similar to the value b in Park-Ang damage model). E_{Humon} is the hysteretic energy capacity under monotonically increasing lateral deformation.

For the special case of the EPP systems the damage index can be expressed as:

$$\begin{aligned} DI_{bb,1} &= [(1-\alpha_1)(\mu-\mu_e)/(\mu_{umon}-1)] + \alpha_1(E_H/F_y u_y)/(\mu_{umon}-1) \\ &= [(1-\alpha_1)(\mu-\mu_e)/(\mu_{umon}-1)] + \alpha_1\gamma^2\mu^2/(\mu_{umon}-1) \\ DI_{bb,2} &= [(1-\alpha_2)(\mu-\mu_e)/(\mu_{umon}-1)] + \alpha_2[(E_H/F_y u_y)/(\mu_{umon}-1)]^{0.5} \\ &= [(1-\alpha_2)(\mu-\mu_e)/(\mu_{umon}-1)] + \alpha_2\gamma\mu/\sqrt{(\mu_{umon}-1)} \end{aligned} \tag{6}$$

Few characteristics of this improved Damage Index are listed below:

a. If the response remains elastic, both $DI_{bb,1}$ and $DI_{bb,2}$ will equal to zero.
b. Under monotonic lateral deformation if the maximum deformation capacity (d_{umon}) is reached, then both $DI_{bb,1}$ and $DI_{bb,2}$ will equal to one.
c. If $\alpha_1 = 0$ and $\alpha_2 = 0$ the Damage Index is assumed to be only related to the maximum plastic deformation.
d. If $\alpha_1 = 1$ and $\alpha_2 = 1$ the Damage Index is assumed to be only related to the hysteretic energy absorbed by the systems.

This Damage Index proposed by Bozorgnia and Bertero can calibrate some drawbacks of the Damage Index proposed by Park and Ang. In this model it is necessary to define the value of α_1 and α_2 for different hysteretic model. This kind of study is beyond our scope.

The Damage Index proposed by Bracci et al. (1993) is also introduced. The definition of the Damage Index proposed by Bracci et al. is given by

$$DI_b = D_1 + D_2 - D_1 D_2$$

$$D_1 = \frac{\phi_\alpha - M_\alpha / k_\alpha}{\varphi_u - M_u / k_u} \quad and \quad D_2 = \frac{\Delta M}{M_y} \tag{7}$$

where Φ_α = current level of curvature (displacement)

Φ_u = ultimate curvature (displacement) for monotonic loading

M_α = current level of moment (force)

M_u = moment (force) at ultimate monotonically deformation

k_α = unloading stiffness at current level

k_u = unloading stiffness at ultimate monotonically deformation

ΔM = strength loss during cyclic loading

The advantage of the Damage Index proposed by Bracci et al. is that it considered the characteristics of the system hysteretic loop such as the strength degrading and the stiffness degrading effects directly in the form of the Damage Index. By combining the analytical nonlinear model and the Damage Index proposed by Bracci et al., the Damage Index can be rewritten as below (assume the value of the post yield stiffness ratio equal to zero)

$$\begin{aligned} DI_b &= D_1 + D_2 - D_1 D_2 \\ D_1 &= \frac{\mu - (1/\Phi_k)}{\mu_{umon} - (1/\Phi_{k,umon})} = \frac{\mu - (1 + \lambda_k \gamma^2 \mu^2)}{\mu_{umon} - (1/\Phi_{k,umon})} \\ D_2 &= \frac{\Delta M}{M_y} = \frac{F_y (1 - \Phi_l)}{F_y} = \frac{\lambda_l \gamma^2 \mu^2}{1 + \lambda_l \gamma^2 \mu^2} \end{aligned} \tag{8}$$

where Φ_k : Stiffness degrading level

$\Phi_{k,umon}$: Stiffness degrading level for the ultimate monotonic loading

Φ_l : Strength degrading level

This Damage Index also can calibrate the drawbacks of the Damage Index proposed by Park and Ang. Such as for the case of the elastic response, the value of the DI_b will be equal or smaller than 0 (D_1= constant and D_2=0), and for the case of under monotonic lateral deformation if the maximum deformation capacity (d_{umon}) is reached the value of the DI_b will be equal to 1 (D_1=1 and D_2=0).

Based on the Damage Index DI_b proposed by Bracci et al., the Damage Index spectra by using the BMR1 model and the W_F model can be generated (the effects of the stiffness degradation was neglected, i.e. $\Phi_k = \Phi_{k,umon} = 1$), with different levels of strength degrading, for ultimate monotonically ductility equal to 6, as shown in ***Figures 3a*** and ***3b***. It is found that the Damage Index proposed by Bracci et al. is not sensitive to the normalized structural period and is sensitive to the system ductility. Besides, the value of the Damage Index is larger by using the W_F model than using the BMR1 model, because of the severe strength degrading in W_F model. It should be noted the value of the Damage Index will equal 1.0 when a system ductility is equal or larger than the ultimate ductility obtained from monotonic loading.

Equivalent Ductility

The concept of the Equivalent Ductility proposed by Fajfar (1992) can also be used to calculate the constraint of system ductility for seismic design. From the definition of the Damage Index and the Damage Index Spectra, it is found that the capacity of the system ductility can not reach the system ultimate monotonically ductility during the earthquake ground motions excitation. From this point of view

one can calculate the constraint of the design system ductility, which is called the design Equivalent Ductility, for a specific value of the system ultimate monotonic ductility by using the definition of the Damage Index during the earthquake ground motion. Based on this concept if the design system ductility is lower than the design Equivalent Ductility, the Damage Index of the structures during the earthquake ground motion excitation will not exceed the constraint of the previous defined Damage Index.

Before calculating the design Equivalent Ductility from the definition of Damage Index an important assumption must be made on parameter γ in advance. It is observed that the parameter γ is independent of the system ductility and the structural period. This assumption is rational because the value of the parameter γ is not wide ranging as shown in **Table 2**. If the value of the upper limit of the parameter γ is assumed to calculate the design Equivalent Ductility and is used to design, the lower value of the design Equivalent Ductility will be derived. A designer can use this equivalent ductility to make a conservative design. The design Equivalent Ductility can be derived using different damage index model and was shown below

a. Park & Ang Damage Model:

$$\mu_{eq,pa} = \frac{\sqrt{1 + 4DI_{pa} b\gamma^2 \mu_{umon}} - 1}{2b\gamma^2} \tag{9a}$$

b. Bozorgnia and Bertero Damage Model (a special case for EPP model):

$$\mu_{eq,bb1} = \frac{(\alpha_1 - 1) + \sqrt{(1-\alpha_1)^2 + 4\alpha_1\gamma^2\left[(1-\alpha_1)\mu_e + DI_{bb,1}(\mu_{umon} - 1)\right]}}{2\alpha_1\gamma^2}$$

$$\mu_{eq,bb2} = \frac{DI_{bb,2}(\mu_{umon} - 1) + (1-\alpha_2)\mu_e}{\left[1 + \alpha_2\left(\gamma\sqrt{\mu_{umon} - 1} - 1\right)\right]} \tag{9b}$$

c. Bracci er al. Damage Model:

$$\mu_{eq,b} = \frac{-1 + \sqrt{1 + 4\lambda_l\gamma^2(1 - DI_b)(\mu_{umon} - 1)\left[1 + DI_b(\mu_{umon} - 1)\right]}}{2(1 - DI_b)(\mu_{umon} - 1)\lambda_l\gamma^2} \tag{9c}$$

The Equivalent Ductility calculated from the definition of the Damage Index proposed by Bracci et al did not consider the effects of the stiffness degrading (set Φ_k and $\Phi_{k,umon}$ equal to 1). Based on the definition of the design Equivalent Ductility it is found that if the value of the system ultimate ductility from monotonic loading and the value of the parameter γ were pre-estimated, the value of the design Equivalent Ductility can be derived. The value of b, α_1, α_2 and λ_l are depend on the hysteretic loop of the system. Of course, for different hysteretic loops different values of the parameter γ, and different values of b, α_1, α_2 and λ_l need to be determined to calculate the design Equivalent Ductility.

By using the Damage Index proposed by Bracci et al the Equivalent Ductility using different hysteretic model, such as the BMR1 model and the W_F model which have a different level of the strength degrading, can also be obtained as shown in **Table 3** for service level (assume $DI_b = 0.4$) and **Table 4** for life safety level (assume $DI_b = 0.8$). The Equivalent Ductility for the BMR1 model and the W_F model can be plotted with respect to the parameter γ for different system ultimate monotonically ductility, as shown in ***Figure 4a*** on service level ($DI_b = 0.4$) and ***Figure 4b*** on the life safety level ($DI_b = 0.8$)**.** From Figure 4 it is found that for the same value of the parameter γ, the design Equivalent Ductility is smaller by using the W_F model than using the BMR1 model because in the W_F hysteretic model more severe strength degradation was observed. It is a rational result because if the structures absorbed the same value of hysteretic energy, the W_F model will have larger damage than the BMR1 model because of the loss of severe strength in the W_F model. From ***Figure 4a*** it is found that the value of the Equivalent Ductility

for W_F model in service level (DI_b = 0.4) is not sensitive to the value of the system ultimate ductility from monotonic loading. It means that no matter what the value of the system ultimate ductility is selected the wall frame structure will be damaged as shown in the figure and un-repairable when the system ductility exceeds a constant value during the earthquake ground motion excitation.

GENERATE ACCEPTABLE DESIGN REGION USING YIELD POINT SPECTRA

The Yield Points Spectra Method, proposed by Mark Aschheim (2000), can be used to design the system stiffness, structural period and design strength directly. This method can also be used to design multi performance objectives including the demand for service level and the life safety level. It is suggested to use the Yield Point Spectra Method in conjunction with the concept of equivalent ductility ratio to construct the performance based design procedure. Based on the developed inelastic yield strength demand spectra and inelastic yield displacement spectra ($uy_{inelastic} = Sd_{inelastic} / \mu$), respectively, the Yield Point Spectra can be constructed by plotting the yield strength coefficient demand spectra Cy with respect to the yield displacement demand spectra in ADRS format. For seismic design, the Yield Point Spectra can help us to construct the Acceptable Design Region and gives a reference to a designer on how to determine the design structural yield strength, the design structural period and the design system ductility for specific seismic constraints such as the constraints of the Damage Index and the constraint of the system maximum displacement to be used in the performance based seismic design.

To determine the Acceptable Design Region in the Yield Point Spectra it is necessary to specify some constraint values, such as the deformation constraint and/or damage level constraint. Three different types of acceptable design region are described as follows:

(a) Constraint on maximum displacement of structure As shown in ***Figure 5***, the combination of the Yield Point Spectra to the yield point of four different kinds of structure, and the structural response, including the system ductility and system maximum displacement during the earthquake ground motion excitations is demonstrated. From this figure it is found that system 1 ($T=T_1$) and system 2 ($T=T_2$) have the same value of the yield displacement but have different value of the system ductility and system maximum displacement $(u_{y,i} \cdot \mu_i, i = 1,2)$, and system 4 ($T=T_4$) has larger values of the yield displacement and its' system ductility is smaller than 1.0 which means the system 4 ($T=T_4$) will remain elastic during the earthquake ground motion.

(b) Constraint on design equivalent ductility For a specific constraint value of the Damage Index of the structures one can use the developed design Equivalent Ductility as mentioned before to constrain the system ductility, and usually the selected design system ductility must be lower than the design Equivalent Ductility. From the use of the Yield Point Spectra, as shown in ***Figure 6,*** it is known that the position of the yield point of the structures must be on the right hand side of the black line for $\mu = \mu_{eq}$, as shown in the figure of Acceptable Design Region.

(c) Combining constraints of Damage Index and maximum displacement As shown in ***Figure 7***, both Damage Index and maximum displacement are considered as constraints in the yield point spectrum. From this figure it is found that if the position of the yield point of the structure is located in the Acceptable Design Region then the system ductility ratio will not exceed the value of the Equivalent Ductility μ_{eq}. It means that the value of the Damage Index during the earthquake ground motion will not exceed the value of the constrained Damage Index, and the value of the maximum displacement will not exceed the value of the constrained S_d i.

(d) Combining constraints of two performance levels Suppose two performance objectives (consider both life safety and serviceability) were used in the design example, as shown in ***Table 5***. The Acceptable Design Region for both performance levels including the service level and the life safety level is shown in either ***Figure 8a*** or ***Figure 8b***. The value of the T_{ser}, the structural period for the

service level, is determined by the constraint value of the maximum displacement (Sd_{ser}) of the structures for the service level. The value of the $T_{saf,1}$ and $T_{saf,2}$, the structural period for the life safety level, is determined by the constraint values of the maximum displacement of the structures for the service level Sd_{saf} and the value of the Sd_{saf} / μ_{eq} , respectively. The main difference between these two figures is the relative value among T_{ser}, $T_{saf,1}$ and $T_{saf,2}$. For ***Figure 8a*** the value of the T_{ser} is smaller than the value of the$T_{saf,1}$ and $T_{saf,2}$. For ***Figure 8b*** the value of the T_{ser} is between the value of the $T_{saf,1}$ and $T_{saf,2}$. If the position of the yield point of the structures is located in the Acceptable Design Region as shown in these two figures the structures will satisfy the design performance objectives as shown in ***Table 5***.

SEISMIC DESIGN USING YIELD POINT SPECTRUM

Based on the above discussion on the Damage Index, the design Equivalent Ductility and the Yield Point Spectra, a design philosophy for the performance-based seismic design can be introduced. The design procedure is listed as follows:

1. Define design performance objectives quantitatively:
   Based on the initial estimation on the characteristics of the structure such as the material of the structures, the structural type and height defined, the design performance objectives must be determined quantitatively. It is suggested that at least two performance levels were selected to design a structure: the service level and the life safety level. Then determine the constraints of the inter-story drift index (IDI) and the Damage Index (DM) for both serviceability and life safety.
2. Transform MDOF system to SDOF system:
   Transform the constraints of the inter-story drift index (IDI) for MDOF to the constraints of the maximum displacement (S_d) for SDOF. The process of transformation will depend on the initial estimation on the characteristic of the structures.
3. Construct the seismic elastic spectra and the seismic demand spectra:
   The seismic elastic demand spectra will depend on the site conditions and the characteristics of the structures (such as the damping ratio of the structure) as discussed before. The Seismic Demand Parameters, including the parameter C, Ru, γ, are dependent on the characteristics of the structure (such as the nonlinear behavior and the system damping ratio of the structures) and the site condition.
4. Calculate the design Equivalent Ductility:
   The value of the design Equivalent Ductility will depend on the parameter γ, the constraint value of the Damage Index and the value of the ultimate ductility of monotonic loading which must be estimated in advance from the characteristics of the structures.
5. Use the Yield Point Spectra method to determine the Acceptable Design Region.
6. Determine design strength, period, system ductility of the structure:
   By using the Acceptable Design Region of the Yield Point Spectra, the design structural yield strength, the design structural period, and the design system ductility during the earthquake ground motion excitation can be determined. Check the position of the yield point of the structure in the Yield Point Spectra to find if the design result satisfy the design performance objectives.

SUMMARY AND CCONCLUSIONS

A design philosophy, based on the energy concept, has been developed for performance based seismic design in this study. By combining the use of the Yield Point Spectra and all of the seismic demands, including seismic strength demand, seismic displacement demand and seismic energy demand for inelastic SDOF systems, the Acceptable Design Region of the Yield Point Spectra can be derived which provides design information considering multi performance levels. Some significant conclusions of this study are summarized as follows:

1. Seismic Energy Response Parameter γ, which can reflect the amount of the hysteretic energy absorbed by the structures, can be used to calculate the Damage Index of the structures during the earthquake ground motion excitation and the Equivalent Ductility. The variation of the value of the parameter γ is not wide-ranging and it is convenient to estimate the value of the Damage Index of the structures during the earthquake ground motion excitations and the value of the Equivalent Ductility.
2. Advantages and Disadvantages of the Damage Index proposed by different researches are discussed. From the definition of the Damage Index the definition of the Equivalent Ductility can be derived. Using the concept of the Equivalent Ductility, the Damage Index of the structures can be limited by the constraint of the system ductility during the earthquake ground motion excitations.
3. Based on the energy concept, a design philosophy for performance based seismic design was proposed in this study. Seismic demands for different performance levels, including seismic strength demand, seismic displacement demand and seismic energy demand for inelastic SDOF systems, can be constructed and illustrated by the Yield Point Spectra. Using the Yield Point Spectra the Acceptable Design Region can be constructed and illustrated according to the constraint of the Damage Index and the maximum system displacement, and based on it a designer can select and derive the design structural strength, design structural period and design system ductility to make a design. For rehabilitation combining the Yield Point of the structure to the Yield Point Spectra can check the performance level of the structure. The design philosophy proposed in this study will not need the iteration steps because all the information about the seismic demands for inelastic SDOF systems can be shown and constructed in the Yield Point Spectra.

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Table 1: Nonlinear control parameters for different hysteretic model

	α	λ_k	λ_l	λ_p	ζ
Bilinear model	0.1	0.	0.	1.0	0.05
BMR1 model	0.	0.1	0.1	0.3	0.05
W_F model	0.	0.5	0.5	0.1	0.05

Table 2: Suggested value on the Parameter γ for different hysteretic model

	Upper limit of the parameter γ	Lower limit of the parameter γ
EPP model	1.1	0.6
Bilinear model	1.3	0.8
BMR1 model	1.0	0.6
W_F model	0.8	0.5

Table 3: Estimated equivalent ductility for BMR1 and W_F models (DI_b =0.4 for service level)

λ_l =0.1(BMR1 model), DI_b=0.4									
$\mu_{mon} \setminus \lambda$	0.6	0.7	0.8	0.9	1	1.1	1.2	1.3	1.4
6	2.3854	2.253	2.129	2.014	1.908	1.81	1.721	1.639	1.563
8	2.6988	2.507	2.335	2.181	2.044	1.922	1.813	1.714	1.625
10	2.9305	2.688	2.478	2.295	2.136	1.996	1.873	1.763	1.665
12	3.1067	2.823	2.583	2.378	2.201	2.049	1.915	1.797	1.693
$\lambda_l = 0.5$ (W_F model), DI_b=0.4									
$\mu_{mon} \setminus \lambda$	0.6	0.7	0.8	0.9	1	1.1	1.2	1.3	1.4
6	1.6064	1.451	1.322	1.213	1.12	1.039	0.97	0.908	0.854
8	1.6761	1.496	1.35	1.229	1.128	1.042	0.968	0.903	0.847
10	1.721	1.525	1.368	1.24	1.133	1.043	0.967	0.9	0.843
12	1.7523	1.544	1.38	1.247	1.137	1.044	0.966	0.898	0.84

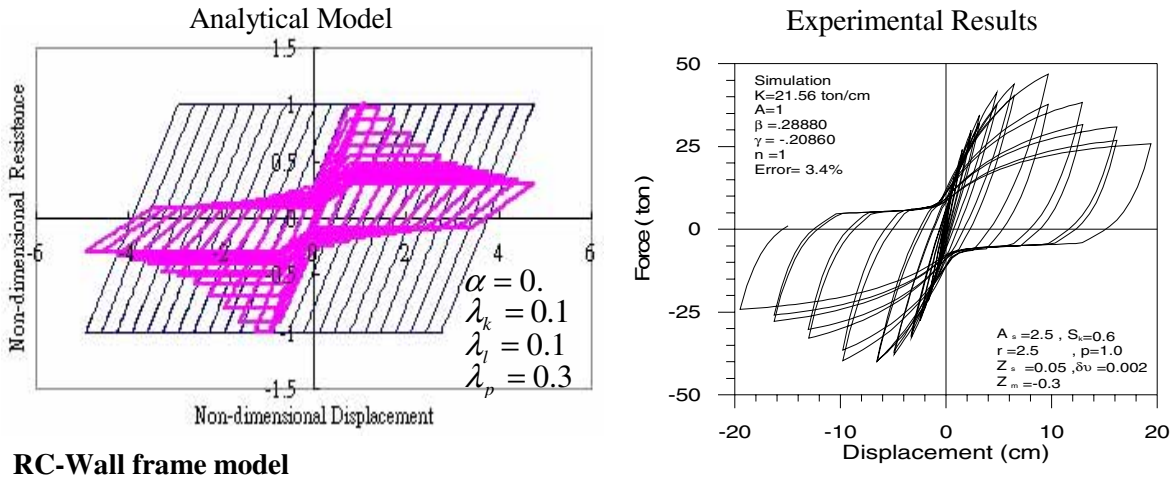
Table 4: Estimated equivalent ductility for BMR1 and W_F models (*DI_b* =0.8 for safety level)

$\lambda_l = 0.1$ (BMR1 model), DI_b=0.8									
μ_{mon}	0.6	0.7	0.8	0.9	1	1.1	1.2	1.3	1.4
6	4.326	4.154	3.98	3.82	3.66	3.51	3.37	3.23	3.107
8	5.224	4.932	4.66	4.4	4.168	3.95	3.76	3.58	3.41
10	5.925	5.516	5.15	4.82	4.521	4.26	4.02	3.8	3.608
12	6.477	5.965	5.52	5.12	4.778	4.47	4.2	3.96	3.747
$\lambda_l = 0.5$ (W_F model), DI_b=0.8									
μ_{mo}	0.6	0.7	0.8	0.9	1	1.1	1.2	1.3	1.4
6	3.18	2.916	2.69	2.49	2.317	2.16	2.03	1.91	1.805
8	3.505	3.165	2.88	2.64	2.438	2.26	2.11	1.98	1.859
10	3.719	3.325	3	2.74	2.514	2.32	2.16	2.02	1.891
12	3.87	3.436	3.09	2.8	2.565	2.36	2.19	2.04	1.913

Table 5: Conceptual value of damage index, system ductility and maximum displacement for service level and life safety level

	Damage Index	System Ductility	Maximum Displacement
Service Level	0	<1	Sd_{ser}
Life Safety Level	<0.6	$< \mu_{eq}$ (Calculated by Damage Index)	Sd_{saf}

(a) BMR1 Model



(b) RC-Wall frame model

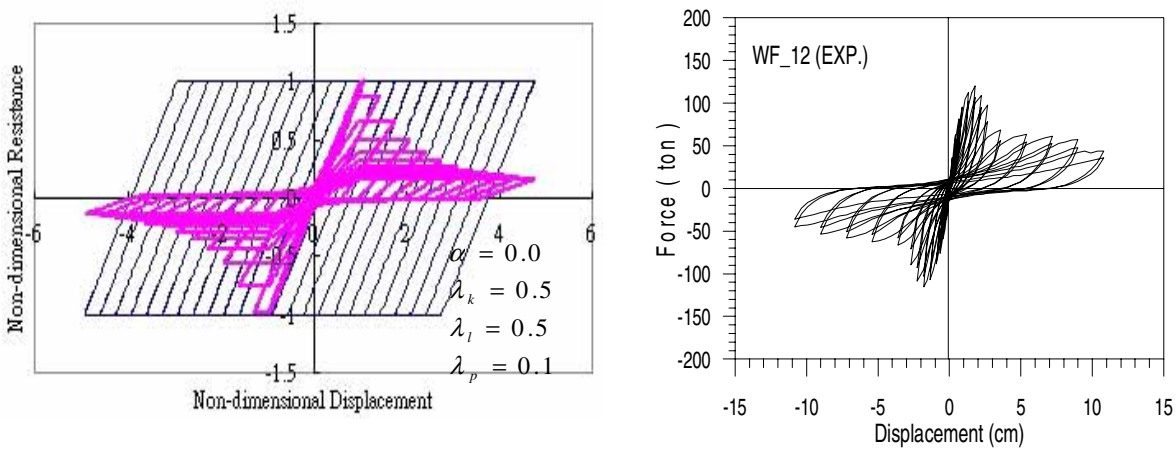


Figure 1: Comparison between analytical (left) and experimental (right) inelastic Hysteretic model: (a) flexure failure model,(b) Wall-frame model,

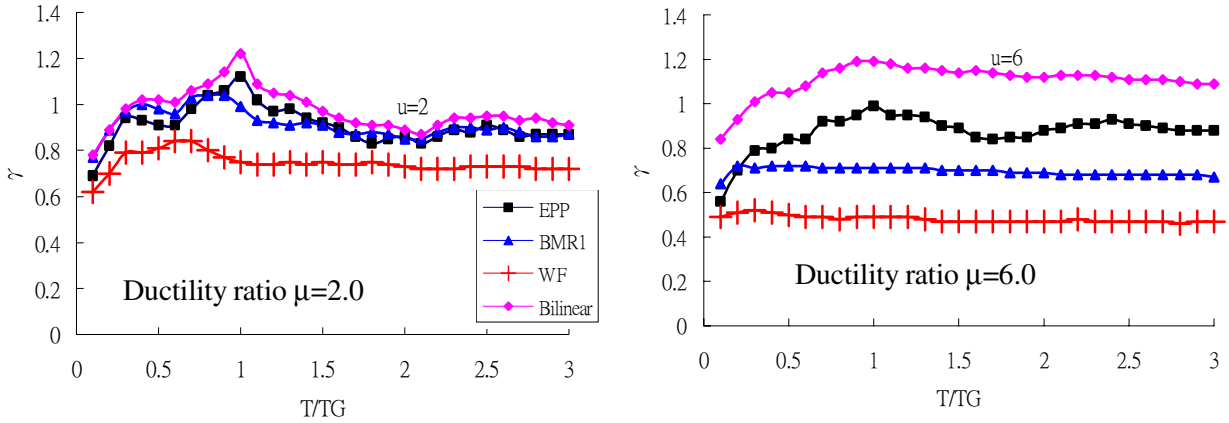


Figure 2: Comparison on γ-spectrum using different hysteretic models;
(a) for ductility ratio μ=2.0, (b) for ductility ratio μ=4.0.

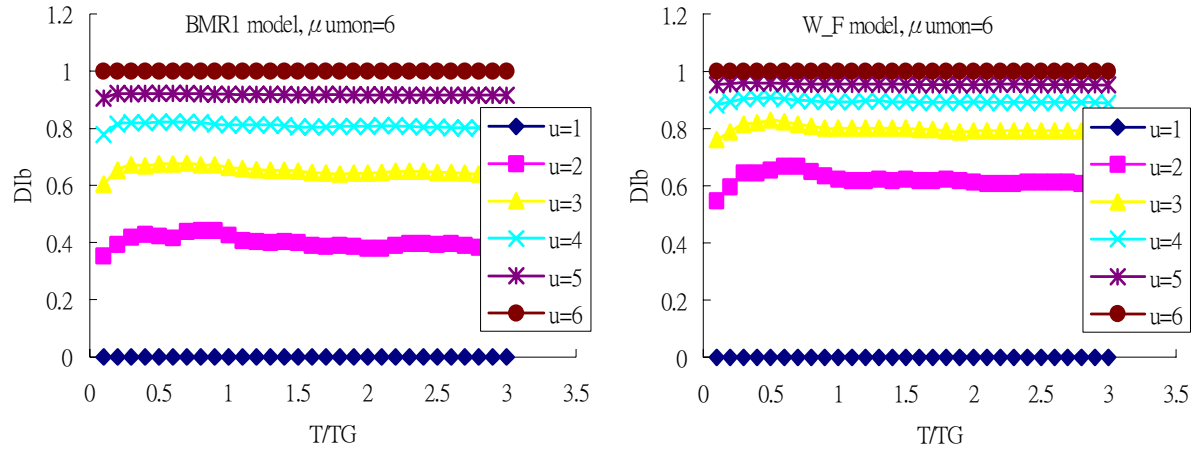


Figure 3: Damage Index Spectra DI_b (μ_{mom} =6): (a) for the BMR1 model (λ_l =0.1), and (b) for the W_F model (λ_l =0.5) with

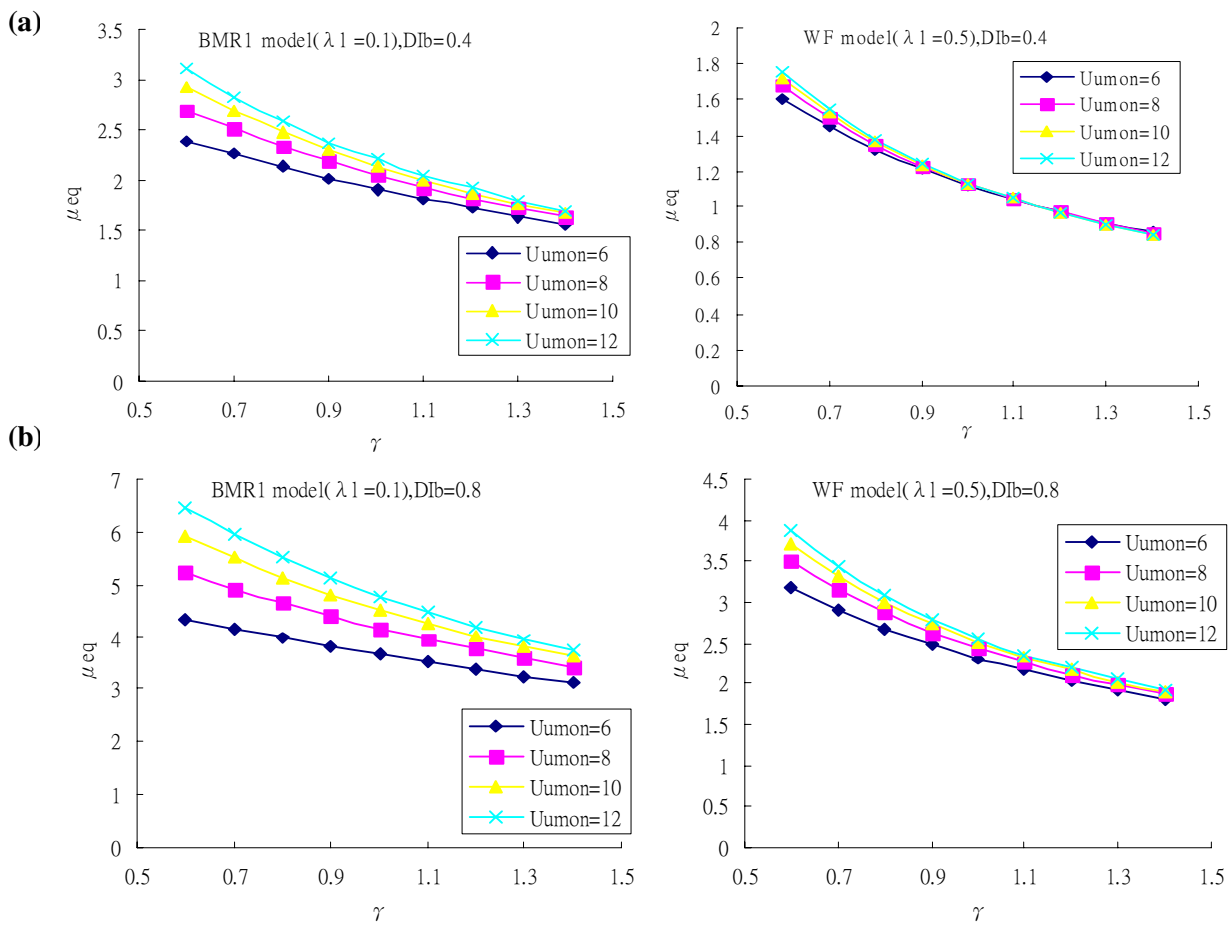


Figure 4: Plot of Equivalent Ductility with respect to γ-value for different ductility ratio of monotonic loading; (a) for case of DI_b=0.4, (b) for case of DI_b=0.8.

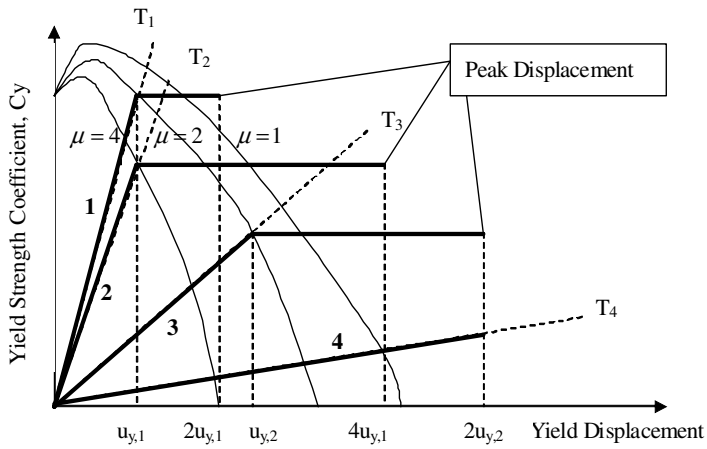


Figure 5: Plot of yield point spectrum and the system capacity curve (four different structural systems with period of T_1, T_2, T_3, and T_4).

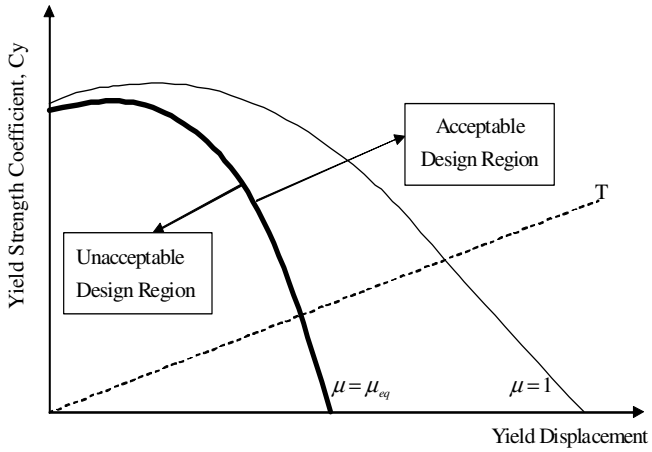


Figure 6: Identified acceptable design region using equivalent ductility as constraint in Yield Point Spectrum.

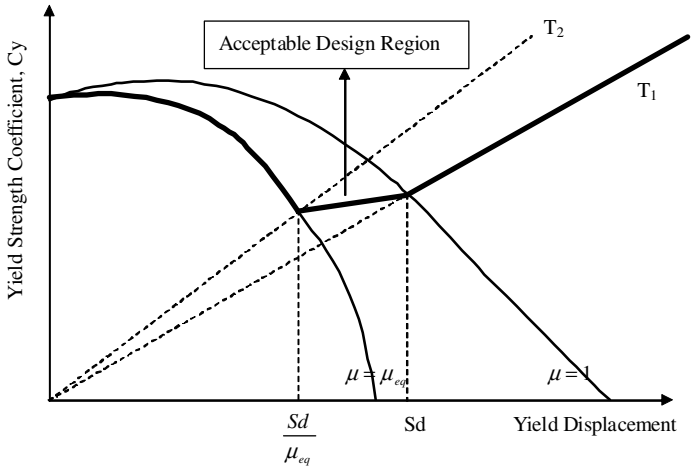


Figure 7: Identified acceptable design region using the constraint of the system equivalent ductility and the maximum displacement in Yield Point Spectrum.

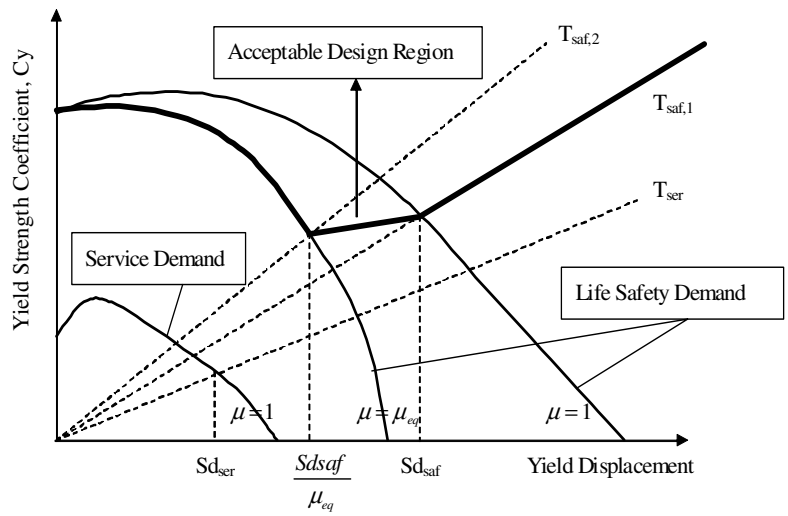


Figure 8a: Plot of acceptable design region in yield point spectrum considering both service level and life safety level ($T_{saf,1}$ is in between $T_{saf,2}$ and T_{ser}).

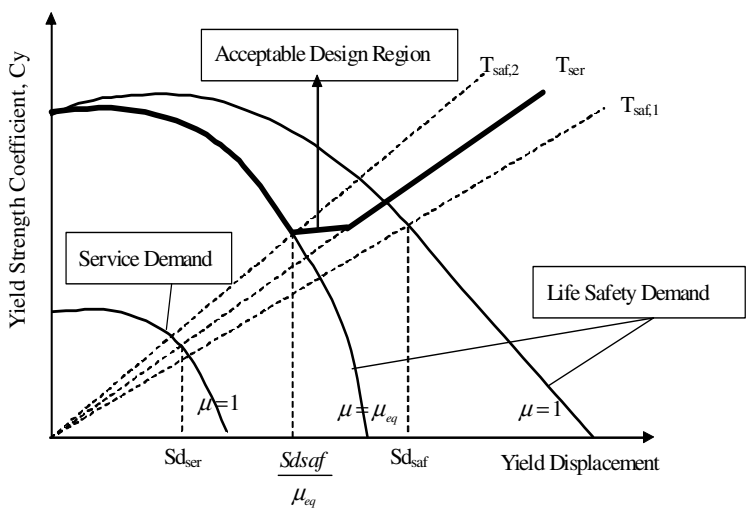


Figure 8b: Plot of acceptable design region in yield point spectrum considering both service level and life safety level (T_{ser} is in between $T_{saf,2}$ and $T_{saf,1}$).