THE NEED FOR IMPROVING THE RELIABILITY OF REDUCTION FACTORS AND DEFORMATIONS USED IN THE PRACTICE OF SEISMIC ANALYSIS AND DESIGN OF STRUCTURES.

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ABSTRACT

Based on the ductility of the structures, present wide world seismic code provisions allow to reduce elastic strength demands for a given structure system using constant reduction factors (R) and to reach maximum lateral non cyclic deformations limited to constant drift values for different types of structures. While both concepts are simple to use, this study demonstrates that they lead to unreliable designs. The main objective of this study is to find cyclic yield strength and deformation spectra of elastic perfectly plastic single degree of freedom (SDOF) structures subjected to several earthquake ground motions. The results of this investigation shows that: (1) R varies with the structure period (T), the characteristics of the strong motion, and the target cyclic (μ_c) or non cyclic (μ_{nc}) ductility ratio; (2) spectra based on μ_{nc} show sudden unexpected changes between two very close periods; (3) spectra obtained using μ_c are smoother than those based on μ_{nc}; and (4) the use of ductility ratios is not a reliable measure of damage due to nonlinear dynamic structural response. Damage arises not only due to the maximum lateral cyclic physical plastic deformation but it also results due to the enveloping physical ductility measured in the envelope of the complete hysteretic response, as well as due to the manner in which energy is dissipated. In addition, damage depends on the characteristics of the ground motion, not only on those of the severe expected earthquake but also on those of the subsequent aftershocks.

KEYWORDS

Strength reduction factor. Maximum non cyclic and cyclic lateral deformations. Cyclic and non cyclic ductility ratios. Physical ductility. Sudden non cyclic strength reduction. Damage. Drift.

INTRODUCTION

At present, the majority of earthquake resistant codes require the use of reduction factors (R) to reduce the earthquake elastic strength demand to a yielding strength design level. These factors are constant for each of the different type of structure systems and materials. For instance, for ductile unbraced concrete or steel moment resistant frames the recommended R factor specified by the ASCE seismic design provisions (ASCE 7-05) is eight, regardless of the period of the structure. The procedure for determining the reduced strength is very simple; just divide the elastic strength spectra ordinates by 8 to obtain the yielding strength spectra. According to Miranda and Bertero (1994), the values of R used by current codes are based on observations of structural performance during past earthquakes. According to the majority of codes performance based design relates the expected level of damage to the expected site acceleration and its probability of being exceeded, and to the expected maximum lateral non cyclic deformations. This study presents the cyclic characteristic of the dynamic response to ground motions, and the differences between cyclic and non cyclic strength and deformation demands are discussed. The u_{cpe} defined as the summation of all new plastic deformations neglecting the repeated ones, and the u_c defined as the maximum lateral cyclic deformation are better measures of damage than the drift based on the maximum non cyclic lateral deformation, $|u_m|$. In addition, the hysteretic energy, that it is not part of this study, should be considered along with u_c and u_{cpe} in different damage indices associated to each level of damage. Even more, μ_c or μ_{nc} are just numbers that are not associated to the yielding deformation therefore, are not measures of damage. In order to better appreciate the variation of R with the variation of T, and how the variation of R affects the design strength and deformations equal target values of μ_c and μ_{nc} are used. By doing so, it is possible to better understand the reasons why the cyclic yield strength demand, the u_c

and the u_{cpe}, are larger than the non cyclic yield strength demand, the $|u_m|$ and the non cyclic plastic deformation, u_{ncp}. The causes for the sudden decrease of the non cyclic strength spectral ordinates are studied.

CYCLIC AND NON CYCLIC RESPONSES

Figure 1 shows the force-deformation relationship of a beam-column subassemblage under a cyclic deformation that simulates the effect of an earthquake ground motion. Clearly, the response is cyclic and includes reversals of plastic deformations

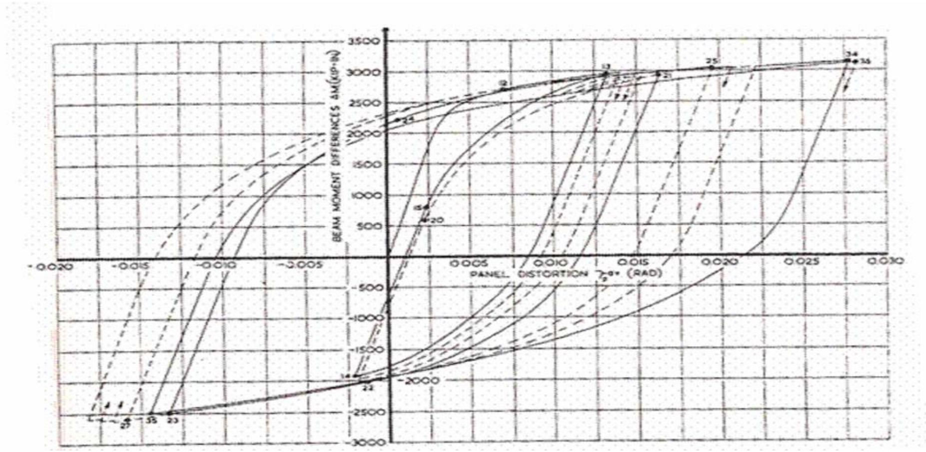


Figure 1. Force deformation relations for structural components in structural steel.
(Krawinkler, Popov & Bertero, 1971).

Figure 2 is an elastic perfectly plastic (EP) idealization of the response of the subassemblage shown in Figure 1. The relation between elastic and yielding strength and deformation (Figure 2) is:

$$R_{\mu nc} = F_0 / F_y = u_0 / u_y \qquad (1)$$

$R_{\mu nc}$ is a strength reduction value used to obtain inelastic response, (different from the code given values) and associated with the non cyclic ductility ratio; F_0 is the elastic strength demand and F_y is the yielding strength associated to $R_{\mu nc}$. The non cyclic ductility ratio is: $\mu_{nc} = |u_m| / u_y$ (2)

The one direction non cyclic physical ductility (Lara, Parodi, Centeno, Bertero, 2004) is a measure of potential damage, and according to the μ_{nc} concept is given as: $u_{ncp} = |u_m| - u_y$ (3)

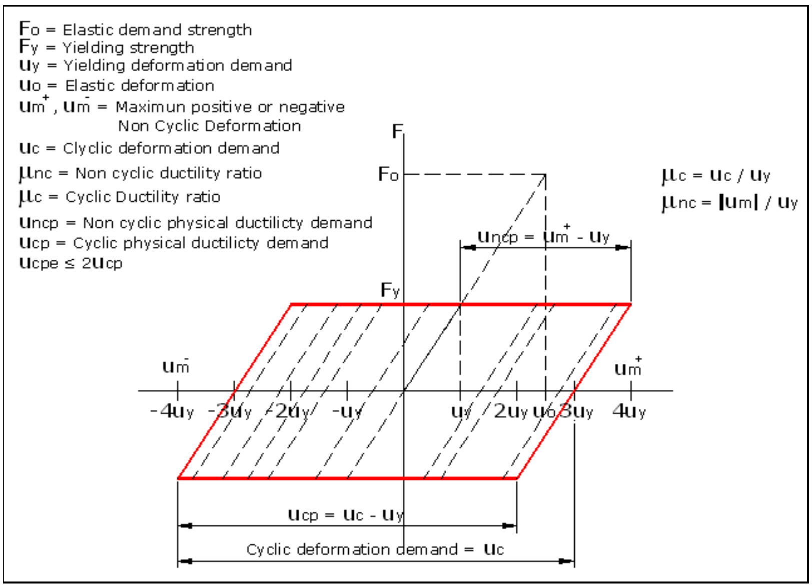


Figure 2. Elastic perfectly plastic force-deformation relationship.

From Figures 1 and 2 it can be seen that u_c is equal to $[(u_m^+ + u^-) - u_y]$ and it is measured from the envelope of the hysteretic responses. This is the contribution of the maximum lateral deformation to the damage. In addition, u_c is measured from the absolute maximum lateral deformation, u_m, to the deformation at the previous last zero force crossing of the envelope, (Mahin and Bertero, 1978). In this way, u_c accounts for the previous plastic deformations. In Figure 2 the strength reduction associated to the cyclic ductility ratio is:

$$R_{\mu c} = F_0/F_y = u_0/u_y \tag{4}$$

The cyclic ductility ratio, (Mahin and Bertero, 1978) is then given as: $\mu_c = u_c / u_y$ (5)

And the one direction cyclic physical ductility (Lara, Parodi, Centeno, Bertero, 2004) is given by:

$$u_{cp} = u_c - u_y \tag{6}$$

The enveloping cyclic physical ductility (Lara, Bertero, Ventura, Centeno, 2007) measured in the envelope of all hysteretic responses (potential damage) for Elastic Perfectly Plastic (EPP) structures satisfies the following relationship:

$$u_{cpe} \leq 2u_{cp} \tag{7}$$

The contribution to the total damage given by all new plastic excursions including those during reversals, but with exception of all repeated plastic deformations is u_{cpe}. Another contribution to the measure of damage is the energy absorbed (dissipated) during repeated cycles which is not analyzed here but has to be considered because it leads to low cycle fatigue.

CYCLIC AND NON CYCLIC STRENGTH DEMAND SPECTRA

Figure 3 shows the cyclic and non cyclic strength demand spectra for the SCT-1, CDAO and CDAF records of the 1985 Michoacán, Mexico, earthquake for $\mu_c = \mu_{nc} = 8$, and 5% damping (ξ). The abscissa of these plots represents the ratio between the period of the structure, T, and the dominant period of the prescribed ground motion, Tg. For most of the period ratios (for values of T/Tg between 0.25 and 2.0) , the spectral ordinates of the cyclic spectra are larger than or equal to the non cyclic spectra. . It is also observed that the cyclic spectra are smoother than the non cyclic ones and that the non cyclic spectra show sudden variations of their ordinates, and that these are rarely seen in the cyclic spectra. One of them is in the SCT1 record, between T/Tg = 0.75 and T/Tg = 0.83s.

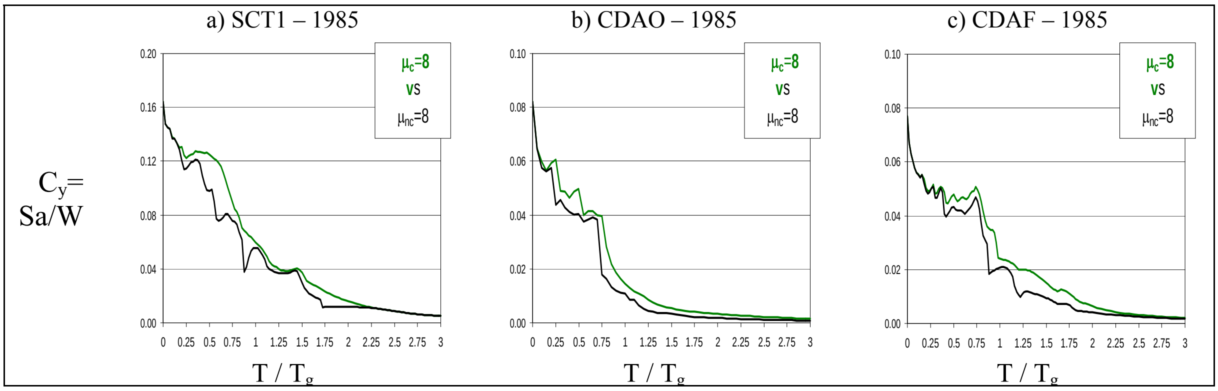


Figure 3. Cyclic and Non Cyclic Strength Demand Spectra for three records of the Michoacán, México 1985 earthquake (ξ = 5%).

Figure 4 shows the μ_c and μ_{nc} spectra (ξ = 5%) for the 1995 Takatori record of the 1995 Kobe, Japan, earthquake obtained 1.5 km from the epicenter, (Lara, Parodi, Centeno and Bertero, 2004). Again, the ordinates of the cyclic strength spectra are generally larger than the non cyclic spectra. The larger the value of μ_c and μ_{nc} the larger the region affected by the difference in spectral ordinates. The same observations indicated above can be made, particularly the sudden decreases in ordinates of the μ_{nc} spectra can be observed, for example, in the strength spectra between T = 1.0s and T = 1.05s for μ_{nc} = 8.

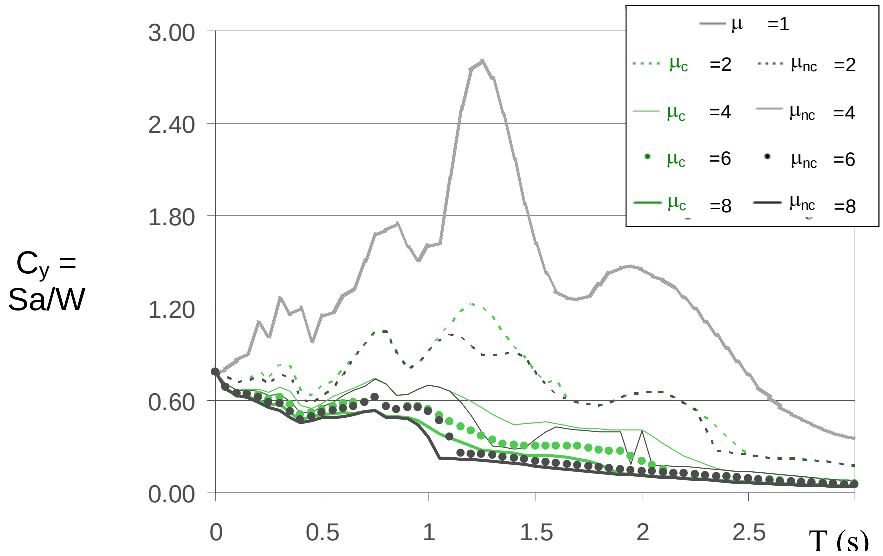


Figure 4. Cyclic and Non Cyclic Strength Demand Spectra for the 1995 Takatori record of the Kobe 95 earthquake.

Figure 5 shows the cyclic and non cyclic strength demand spectra for the Llolleo, Valparaíso and Llayllay records of the 1985 Valparaíso, Chile, earthquake and for the Caleta record of the 1985 Michoacán earthquake (ξ = 5%), (Lara, Bertero, Ventura and Centeno, 2007). The spectra are calculated for $\mu_c = \mu_{nc} = 6$. It can be observed that there are different ranges of periods where the cyclic spectra ordinates are larger than the non cyclic spectra. As before, all μ_{nc} spectra show sudden decreases of the ordinates, i.e. the Llolleo record between T = 0.25s and T = 0.26s for μ_{nc} = 6 while the μ_c spectra are smoother.

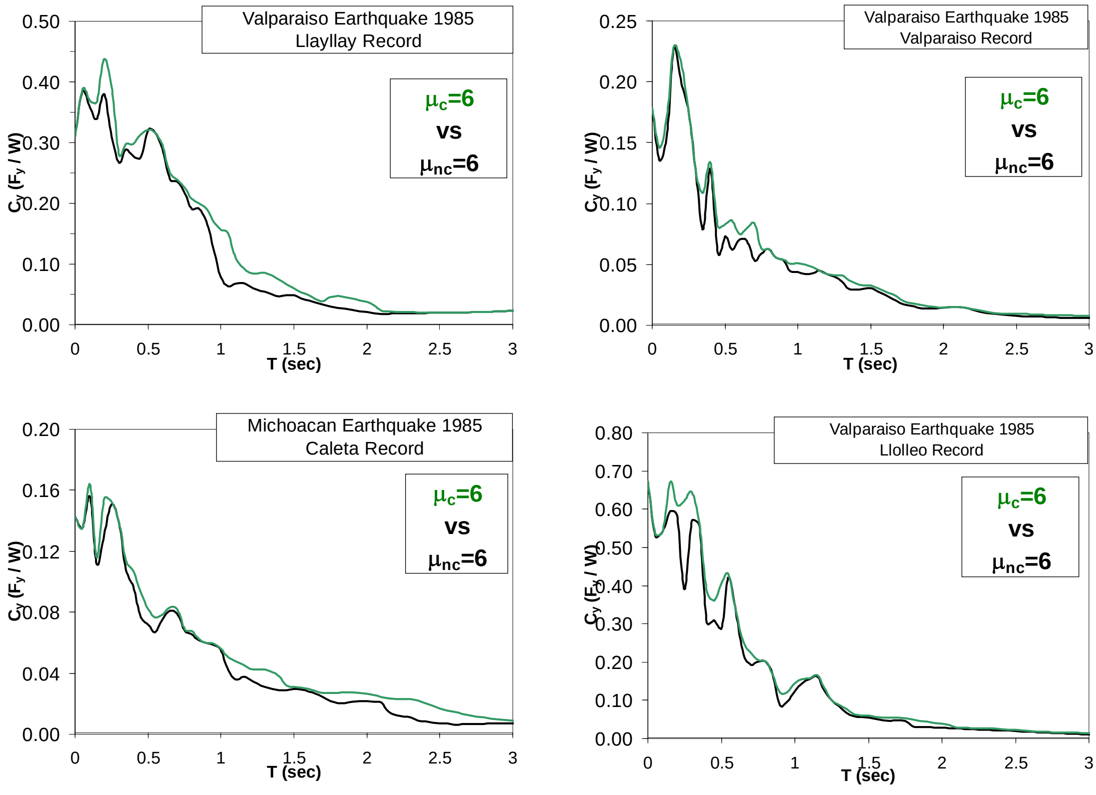
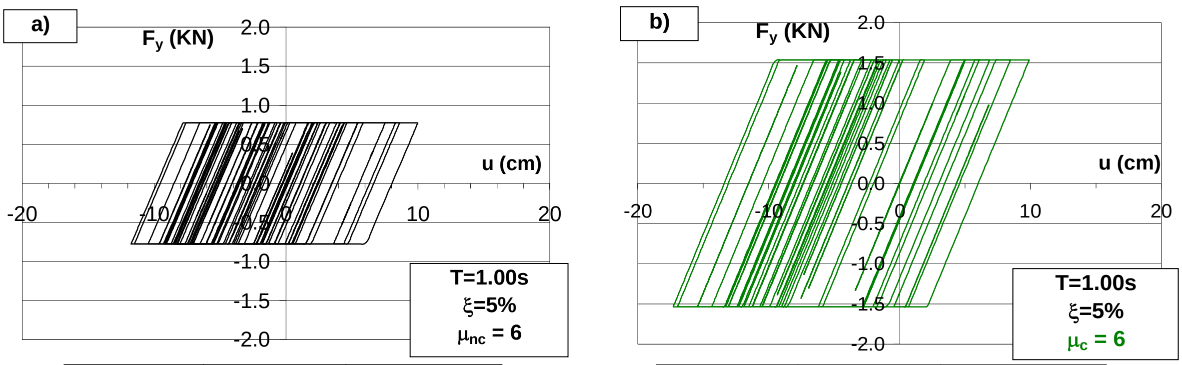


Figure 5. Cyclic and Non Cyclic Strength Demand Spectra for μ_c and μ_{nc} = 6. ξ = 5%

STRENGTH REDUCTION FACTORS

The hysteretic responses of a T = 1.0s structure under the Llayllay record for $\mu_{nc} = \mu_c = 6$ are shown in Figures 6a and 6b respectively. These figures clearly show how the hysteretic response is affected by the type of ductility ratio being used and the corresponding value of R. The elastic strength demand, F_0, is 7.53kN. The value of F_y that meets the target $\mu_{nc} = 6$ is 0.77kN therefore, $R_{\mu nc}$ is 9.75, while F_y for the target $\mu_c = 6$ is 1.53kN, thus, $R_{\mu c} = 4.9$. Choosing $\mu_{nc} = 6$ as the target ductility could be appealing because this selection leads to a more economical design. However, F_y = 0.77kN restricts the damage to u_{ncp} = 9.78cm. Due to the cyclic characteristic of the dynamic response, the summation of all the new plastic excursions, u_{cpe}, calculated for μ_c = 6 reaches 38.84cm. Clearly, F_y = 0.77kN will not be able to restrict the damage to the u_{cpe} demanded. It will be necessary to use F_y = 1.53kN in order to assure enough strength to keep the damage within the limit of u_{cpe} = 38.84cm, (Figures 6a and 6b).



u_0= 19.1 cm F_0= 7.53 KN	u_{cp} = 17.82 cm u_{ncp}= 9.78 cm	E_I = 184.4 KN cm E_D = 53.4 KN cm
u_y= 1.96 cm F_y= 0.77 KN	u_{pcum} =168.9 cm u_{ncpe} = 35.64 cm N = 73	$E_{H\mu nc}$= 131 KN cm

u_0= 19.10 cm F_0= 7.53 KN	u_{cp} = 19.42 cm u_{ncp}= 13.94 cm	E_I= 238.7 KNcm E_D= 94.4 KN cm
u_y= 3.89 cm F_y= 1.53 KN	u_{pcum}= 94.10 cm u_{cpe} = 38.84 cm N = 42	$E_{H\mu c}$= 144.3 KN cm

Figure 6. Hysteretic Responses for SDF´s with T=1.00s subjected to the Llayllay Record of the Valparaiso 1985 Earthquake, for μ_{nc} = 6 (Fig. 6a) and μ_c = 6 (Fig. 6b)

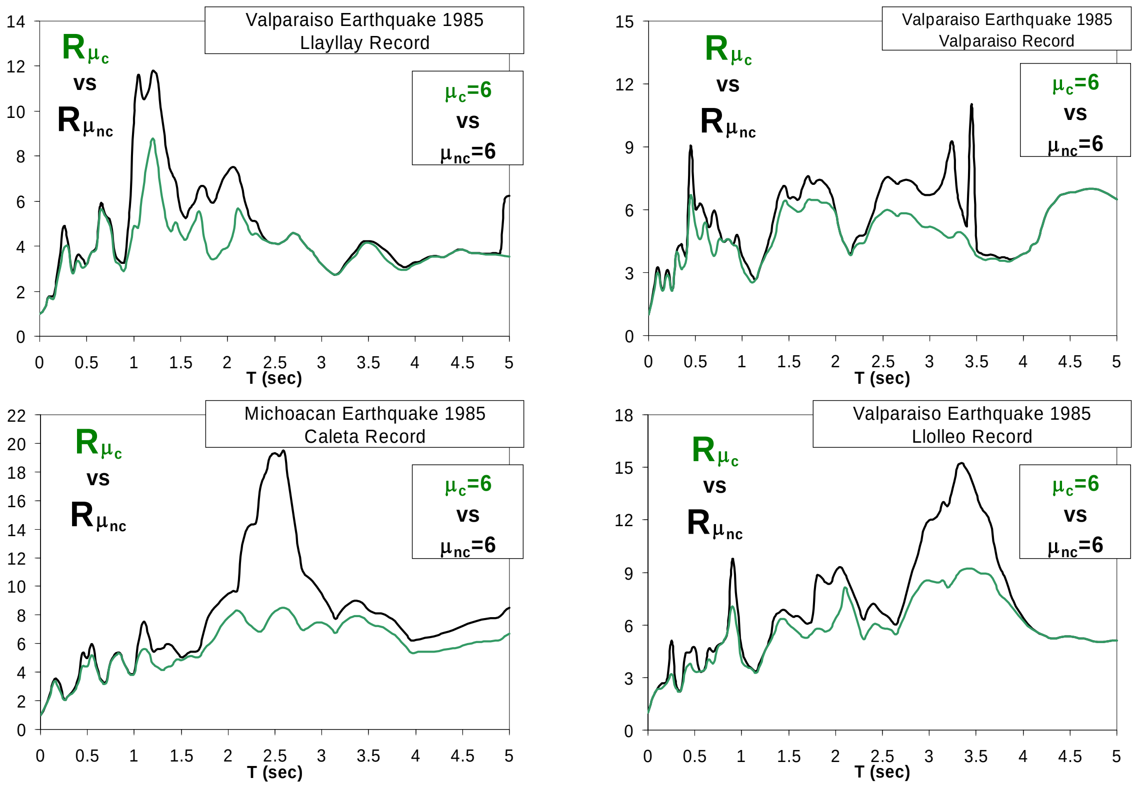


Figure 7. Cyclic and non cyclic strength reduction factor demand spectra for $\mu_{nc} = \mu_c = 6$ and $\xi = 5\%$

Figure 7 shows the strength reduction spectra calculated for $\mu_c = \mu_{nc} = 6$ for SDOF structures subjected to four subduction ground motions, (Lara, Bertero, Ventura and Centeno, 2007). For all records, differences between $R_{\mu c}$ and $R_{\mu nc}$ are very small for $T \leq 0.5$s and become more important for longer values of T up to about T 3.5s. The largest differences occur in different period ranges, i.e. for the Mexican Caleta record for T = 2.5 sec, $R_{\mu nc} = 19$ and $R_{\mu c}=8$. Notice that the ordinates vary with the excitation.

PHYSICAL DUCTILITY DEMAND SPECTRA

Plastic deformation or physical ductility is related to damage, so it can be argued that this is one of the parameters to be measured in order to control damage. As already established, u_{cpe} measures all the new plastic deformations during the response including those occurring during reversals, but without considering the repetitions of plastic deformations because it is assumed that their contribution to damage is minor. The u_{ncp} measures only the plastic deformation that is part of the maximum non cyclic lateral deformation, u_m, used to calculate the drift. In order to compare both measures of damage it is convenient to use the same reference parameter, like μ_{nc} and μ_c, which are fixed to a value of six in this study. Observing Figure 8 u_{cpe} demands are larger than u_{ncp} demands, meaning that the R associated to u_{cpe} is lower than the corresponding R associated to u_{ncp}.This means the strength to be supplied to a structure capable to limit the damage to u_{cpe} is larger than that to limit the damage to u_{ncp}. If the strength provided to the structure is the one that limits the damage only to u_{ncp} then the structural damage is likely to be more severe . It follows that that considering the u_{cpe} spectra for design should provide the adequate yield strength resistance. It also should be noted that μ_c or μ_{nc} are not, strictly speaking, measures of damage but are rather numbers that can be used to limit the lateral cyclic or non cyclic maximum deformations u_c or u_m respectively.

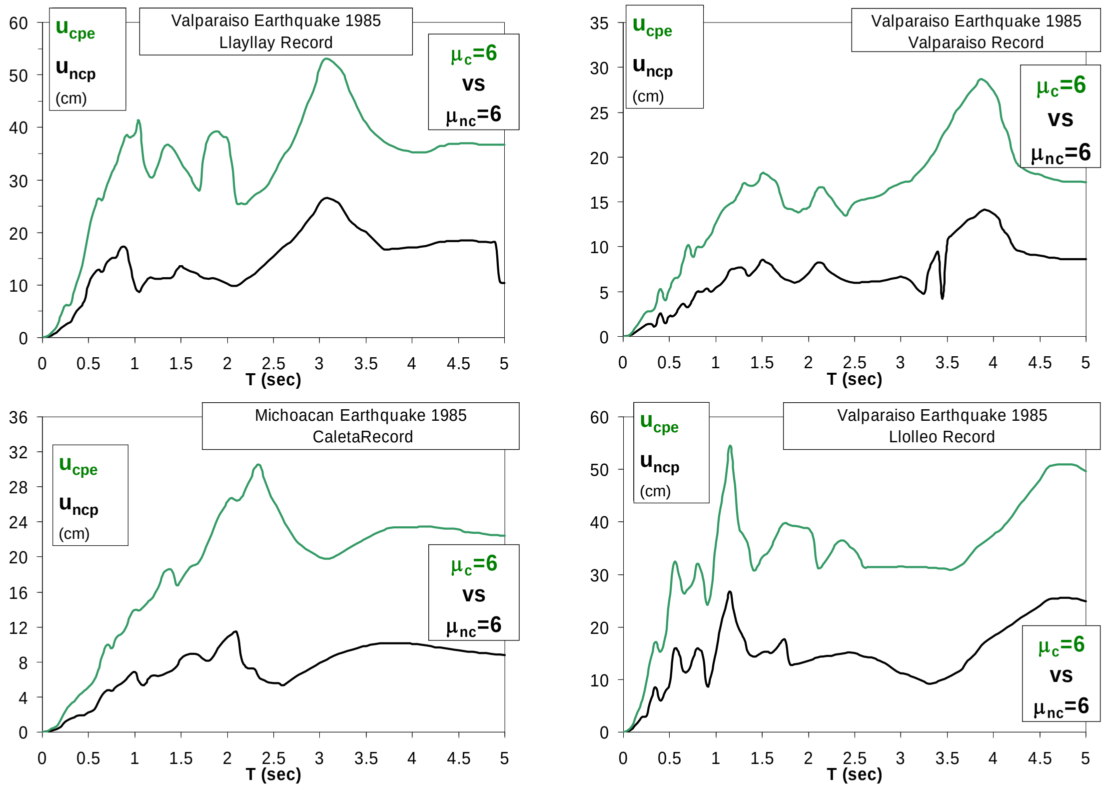


Figure 8. Cyclic Physical Ductility Demand Spectra and Non Cyclic Physical Ductility Demand Spectra for μ_{nc} and $\mu_c = 6$. $\xi = 5\%$.

SUDDEN VARIATIONS OF THE μ_{nc} SPECTRA

The inelastic μ_{nc} spectra generally show several sudden abrupt changes of their ordinates (Sasani, Bertero, Anderson, 1999) and it is of interest to determine the reason for these changes. Consider the inelastic response of two structures characterized by T = 1.0 and T = 1.05s and μ_{nc} = 8 (Figures 9 and 10) to the Takatori 1995 ground motion. For structures with close periods there is no apparent reason to have a large difference between their responses. However, Figures 9b, 10b, show the contrary. For T = 1.0s, u_m = + 71.33cm, and u_y = 8.92cm (Figure 9b) while for T = 1.05s, u_m = - 49.24cm, and u_y = 6.18cm (Figure 10b). Figures 11a and 11b show the respective time histories. In addition, from Figures 9b and 10b, for T = 1.0s, $R_{\mu nc}$ = 4.5 while for T = 1.05s, $R_{\mu nc}$ = 7.2 meaning that in just 0.05s increase in period there is a sudden decrease in strength of 60%.

Figure 12a shows that for T = 1.0s there are two values of $R_{\mu nc}$: 4.5 and 7.1 that would allow a dynamic response limited by the target μ_{nc} = 8. The lowest value, $R_{\mu nc}$ = 4.5, will provide the maximum yielding strength and therefore is chosen as the strength reduction. In effect, for this μ_{nc}, F_0 = 15.75kN and F_y = 3.5kN. Notice that $R_{\mu nc}$ = 4.5 is associated to negative values of u_m, while $R_{\mu nc}$ = 7.1 is related to positive values of u_m and that both deformations cross at $R_{\mu nc}$ = 7.5 and μ_{nc} = 9.0.

Figure 12b shows that to meet the target μ_{nc} = 8 for the T = 1.05s structure there are also two values of $R_{\mu nc}$: 7.2 and 7.5. The first is associated to positive values of u_m and the second to negative values of u_m. Again, the lowest $R_{\mu nc}$ = 7.2, is chosen as the strength reduction to obtain a response limited by μ_{nc} = 8 for this structure. Both deformations cross each other at $R_{\mu nc}$ = 7.0 and μ_{nc} = 6.8. The reason for these changes is the use of u_m that does not account for the previous plastic deformation. When cyclic deformations are used to calculate the response limited by target cyclic ductility ratios, the above mentioned incongruence does not occur. In Figure 12a there is a one to one relation between $R_{\mu c}$ and μ_c. For T = 1.0s and μ_c = 8, $R_{\mu c}$ = 3.75. Thus, for F_0 = 15.75kN, F_y = 4.21kN. In Figure 12b there is also a one to one relation between $R_{\mu c}$ and μ_c. For μ_c = 8, $R_{\mu c}$ = 4.2 thus F_0 = 15.93kN and F_y = 3.75kN. This means that for this small increase of T the difference in strength reductions is only 10%, which is compatible with the difference in the values of F_0.

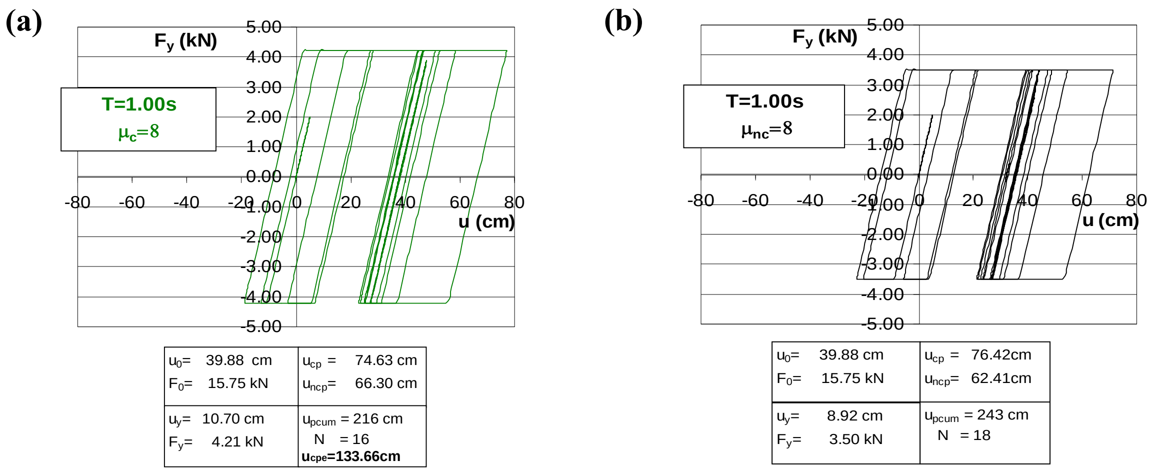
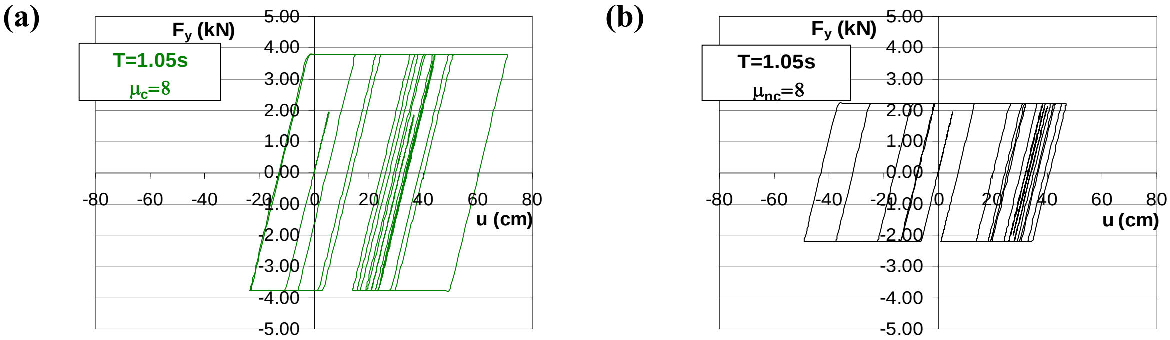


Figure 9. Hysteretic Response for SDFS with T=1.00s to the Takatori Record from Kobe 1995 Earthquake ; (a) μ_c =8; and (b) μ_{nc} =8



(a)

u_0= 44.49 cm F_0= 15.93 kN	u_{cp} = 73.37 cm u_{ncp}= 60.18 cm
u_y= 10.49 cm F_y= 3.75 kN	u_{pcum} = 236 cm N = 18 u_{cpe}=135.74cm

(b)

u_0= 44.49 cm F_0= 15.93 kN	u_{cp} = 76.42cm u_{ncp}= 43.06cm
u_y= 6.18 cm F_y= 2.21 kN	u_{pcum} = 325 cm N = 20

Figure 10. Hysteretic Response for SDFS with T=1.05s to The Takatori Record from Kobe 1995 Earthquake: (a) μ_c =8; and (b) μ_{nc} =8

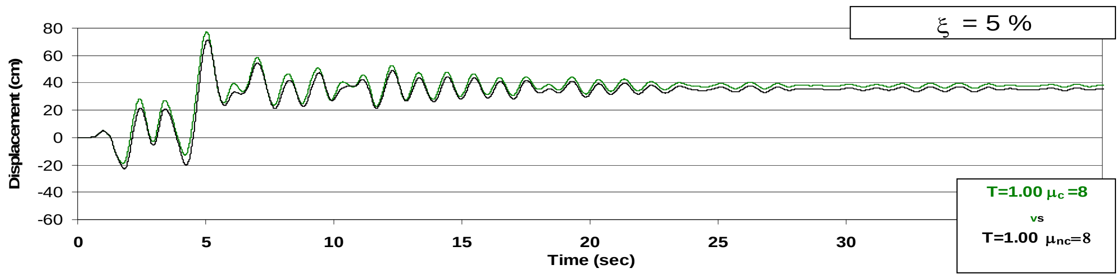


Figure 11a. Time History Response for SDFS with T=1.00s and $\mu_c = \mu_{nc}$ =8 to the Takatori Record from Kobe 1995 Earthquake

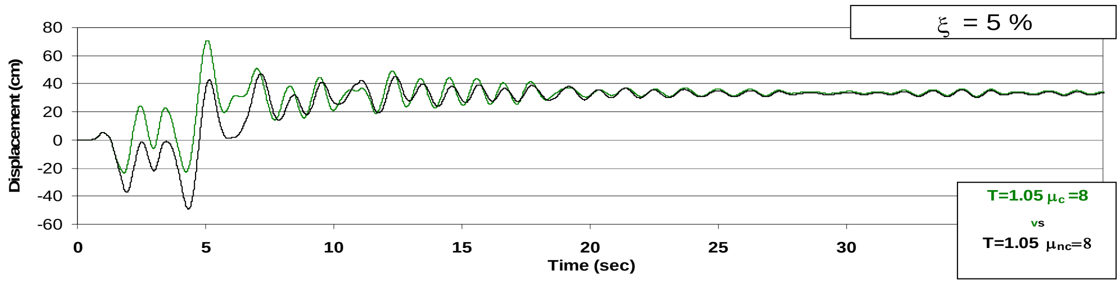
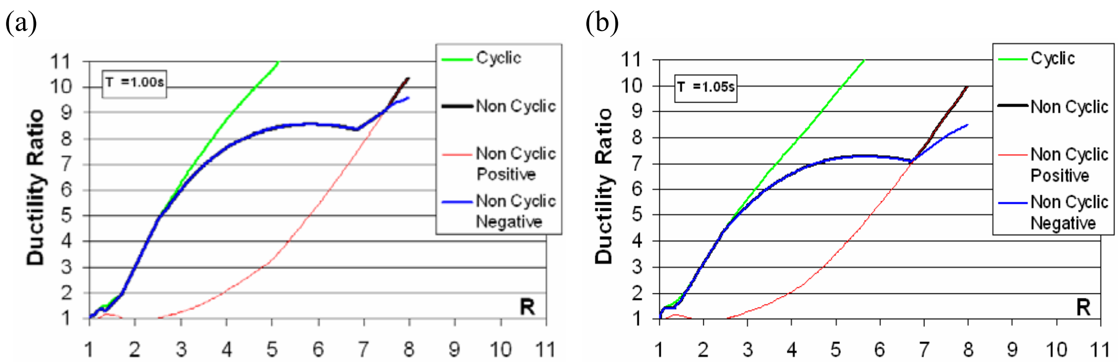


Figure 11b. Time History Response for SDFS with T=1.05s and $\mu_c = \mu_{nc}$ = 8 to the Takatori Record from Kobe 1995 Earthquake.



Figures 12a, 12b. Cyclic and non cyclic ductility ratio vs. strength reduction factors

CONCLUSIONS

Experimental evidence shows that the dynamic response of structures to earthquake ground motions is hysteretic and that the hysteretic loops contain reversals of plastic deformation. This study shows the close dependency between R, the period of the structure and the dynamic characteristic of the ground motion . To illustrate the sensitivity of results like cyclic and non cyclic strength and deformations and variations of the strength reduction factors, the inelastic responses have been investigated using equal values of μ_c and μ_{nc}. These values are not measures of damage because first, damage is due to plastic deformations thus it is necessary to measure physically the amount of plastic deformation in order to understand the magnitude of the damage. Second, the yielding deformation is not known thus μ_c and μ_{nc} do not give any idea about the quantity of plastic deformations during seismic response.

The cyclic deformation, u_c, measured in the inelastic time-history response or in the envelope of the hysteretic response is introduced and proposed as a more reliable measure of damage due to cyclic lateral deformation than the maximum non cyclic lateral deformation, $|u_m|$. In addition, the enveloping plastic deformation measured in the envelope of the hysteretic response, u_{cpe}, is proposed as an additional measure of damage, under the assumption that the new plastic excursions induce the largest amount of damage while the damage induced by repeated plastic deformations becomes negligible except for the possibility of leading to low cyclic fatigue type of failure.

Since u_c is always larger or equal to $|u_m|$, the strength required to control u_c will always be larger or equal to that required to control $|u_m|$. Consequently, $R_{\mu c}$ associated to u_c will always be lower or equal to $R_{\mu nc}$ associated to $|u_m|$ and the strength required to limit the damage to u_{cpe} will always be equal or larger to that required to control $|u_m|$.

This study showed that spectra calculated for μ_{nc} usually suffer sudden decreases of their ordinates, which are rarely seen in μ_c spectra. The decreases occur when the value of u_m^+ tends to be close to that of u_m^-, thus, in order to keep the fixed μ_{nc} for any period the response must change in such a way that the maximum lateral non cyclic deformation will change from positive to negative or vice versa. This happen just because the use of $|u_m|$ to calculate the previously selected target value of μ_{nc}. To keep the target μ_{nc} the response must accommodate deformations changing signs if necessary inducing false estimations not only about the real maximum plastic lateral deformation that is cyclic but also even with respect to the inelastic time history response (Figures 11a y 11b). Even more, the maximum lateral deformation to consider for design must be the cyclic u_c, which varies with the period and depends on the R chosen thus there will be only one lateral lateral deformation to calculate μ_c as seen in Figures 12a and 12b.

Since the maximum drift depends on $|u_m|$, as defined by current codes, the drift can not be considered as a measure of damage because as a fixed value for different types of structures it does not depend on the structure period. In addition, the maximum drift does not consider the damage that can be produced by the number of inelastic cycles of the energy that has to be absorbed (dissipated). Damage must be measured physically considering first, the value of u_c that measures the maximum lateral cyclic plastic deformation that can be compared with the monotonic lateral deformation. Second, the value of u_{cpe} that measures the total amount of all new plastic deformations including the reversals of plastic deformations that occur during earthquake response without including the repetitions of plastic deformation under the assumption that they do not cause any significant damage. The u_{cpe} can be compared to the plastic monotonic deformation. The assumption of using u_{cpe} could be less conservative than accounting for a fraction of the total plastic deformation as it is used in some other measures of damage, (Park, Ang, Wen, 1987; Bozorgnia, Bertero, 2002). Finally, the number of cycles and the plastic deformation of each cycle should be taken into account in a damage index equation as the hysteretic dissipated energy during the ground motion, normalized by the monotonic energy

In addition, damage should consider the cyclic characteristic of the inelastic response of not only the one due to the main expected shock but also due to the aftershocks, which could lead to failure due to low cyclic fatigue or incremental collapse. It must be recognized that in general large earthquakes are not single events; they are multi events.

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