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IMPORTANCE OF CYCLIC PHYSICAL DUCTILITY AND CYCLIC STRENGTH DEMAND SPECTRA IN ANALYSIS AND DESIGN OF EARTHQUAKE RESISTANT STRUCTURES UNDER SUBDUCTION GROUND MOTIONS

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ABSTRACT

Accelerograms of earthquake ground motions resulting from severe subduction earthquakes are usually characterized by long duration of strong motions. Experiments conducted worldwide on models of civil engineering facilities have shown that their response to such long duration of strong motion is hysteretic and includes several cycles with significant reversals of plastic deformation. Development of plastic deformation or physical ductility means potential damage, therefore the spectrum to be used for earthquake resistant design of structures should account for such observed cyclic inelastic dynamic response. Unfortunately in the past most of the publications on seismic design have based the design spectrum only on the maximum lateral deformation which is not a reliable parameter to account for the possible damage because it neglects the reversals of plastic deformation and on the ductility ratio (non cyclic) which is not a physical parameter to measure damage but just a target value to limit the maximum lateral response. In this study the envelope of the hysteretic response is used to demonstrate that the physical ductility limited by a cyclic ductility ratio is a more reliable measure of damage. Demand spectra for target values of cyclic and non cyclic ductility ratios are compared making emphasis on the difference between cyclic physical ductility and non cyclic physical ductility demand. The study demonstrated that demands calculated for target cyclic ductility ratios are more reliable than those obtained for target non cyclic ductility ratios for estimating the structural damage which is the result of development of physical ductility.

Introduction

The practice of earthquake resistant design is at present based on designing for a reduced strength of that required by elastic behavior using a constant reduction factor and, for controlling the demanded maximum lateral deformation accepting inelastic behavior that is considered is given by the conventional ductility ratio. This is called herein Non Cyclic Ductility Demand Ratio defined as the quotient between the maximum lateral deformation $|u_m|$ and the yielding deformation u_y of a structural system subjected to a ground motion. However, there have been studies where the rationality of this approach has been questioned demonstrating that reduction factors are not constant (Miranda and Bertero 1994) and that the cyclic deformation should be used to account for the hysteretic response (Mahin and Bertero 1978). Designing for earthquakes means reducing strength but controlling ductility because development of ductility physically means damage therefore, in order to use a more reliable measure of damage for design the physical ductility should be measured at least in the envelope of the hysteretic response considering the reversals of plastic deformation.

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Additionally, physical ductility should be limited by a Cyclic Ductility Demand Ratio since the Non Cyclic one does not consider the reversals of deformation observed in Fig. 1a which shows the hysteretic force-deformation relation of a laboratory tested structural component (Krawinkler, Bertero, and Popov 1971).

The effect of reversals of plastic deformation was studied by (Mahin and Bertero 1978) who discussed the Cyclic Ductility demand Ratio (CDR) concept which was defined as "the relation between the maximum cyclic deformation u_c measured on the envelope of all hysteretic responses and the yielding deformation u_y of a structural system subjected to a ground motion" (Fig. 1b).

Later, (Lara, Parodi, Centeno, and Bertero 2004) used this concept to introduce the concept of Cyclic Physical Ductility Demand and compared it with the Non Cyclic Physical Ductility Demand for 22 near source ground motions. They showed that the differences depend on the structure period, on the cyclic or non cyclic ductility ratio selected and on the ground motion. Similar conclusions were obtained for the Cyclic Strength Demand and Non Cyclic Strength Demand spectra.

The main objective of this study is to investigate the effects of cyclic physical ductility measured in the hysteretic responses of elastic perfectly plastic Single Degree of Freedom (SDOF) systems subjected to subduction ground motions.

Cyclic and Non Cyclic Ductility Ratios

Consider a SDOF system with period T and damping ratio ξ subjected to a ground motion and assume that the system is designed for a strength F_y lower than the elastic strength demand F_0. Assume also that the system under the dynamic excitation will respond with several cycles including reversals of plastic deformation as shown in Fig. 1a and that Fig. 1b is the idealized Elastic perfectly Plastic (EP) envelope of all hysteretic loops that could have developed during dynamic response.

Non Cyclic Ductility Demand Ratio

This is a parameter conventionally used to limit the structure lateral maximum inelastic deformation in such a way that local element deformations are limited to acceptable levels. It is defined as:

$$\mu_{nc} = |u_m| / u_y \qquad (1)$$

Where μ_{nc} is the conventional or non cyclic ductility demand ratio (NCDR) and u_m is the absolute value of the maximum lateral deformation measured on the envelope of all hysteretic cycles of the structure response. For the example of Fig. 1b, u_m = -5u_y. Since u_m does not consider the cyclic characteristic of the response of the structure it will be more properly called the maximum non cyclic lateral deformation.

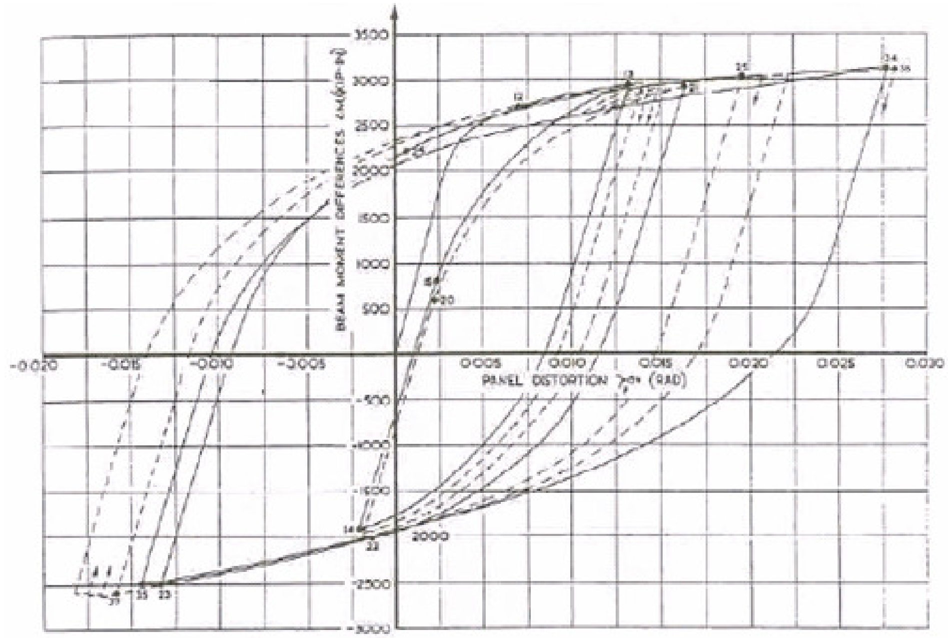


Figure 1a. Force deformation relations for structural components in structural steel (Krawinkler, Popov & Bertero, 1971).

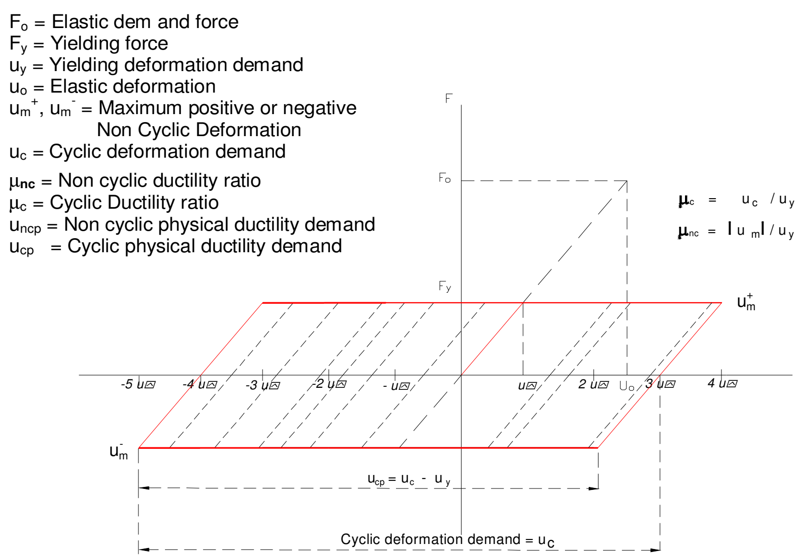


Figure 1b. Elastic perfectly plastic force deformation relationship

Cyclic Deformation and Cyclic Ductility Demand Ratio

It can be seen in Fig. 1b that the structure not only has suffered a positive plastic deformation but also a negative plastic deformation. The criteria of using only the maximum deformation $u_m^- = -5u_y$, neglects the fact that the structure already had entered into the plastic range when it yielded for the first time and deformed plastically until reaching $u_m^+ = 4u_y$. Therefore in order to have a better estimation of the total physical ductility this prior maximum deformation should be included to the maximum $u_m^- = -5u_y$ by means of a cyclic deformation u_c. This u_c is defined herein as the cyclic deformation measured on the envelope of the hysteretic time history response between a zero force crossing and the maximum deformation $|u_m|$ at the other extreme of the envelope. Knowing u_c the Cyclic Ductility demand Ratio (CDR) can be defined as:

$$\mu_c = u_c/u_y \tag{2}$$

This parameter will be used to limit the structure cyclic deformation to a value that will control local element deformations to acceptable levels and it is intended to present it as a substitute of the conventionally used NCDR.

Concept of Cyclic Physical Ductility Demand

Cyclic Physical Ductility demand (PD) has been defined by (Lara, Parodi, Centeno and Bertero 2004) as $u_{cp} = (u_c - u_y)$. Since u_{cp} is measured in the envelope of all hysteretic loops the total CPD for the model of Fig. 1b is $u_{cpt} = 2u_{cp}$. It is known that development of physical ductility in critical regions of the structure during a ground motion means developing of damage therefore, it is proposed that cyclic PD be considered as a measure of damage. As a way of comparison, (Lara, Parodi, Centeno and Bertero 2004) also defined the Non cyclic Physical Ductility demand as the difference $u_{ncp} = (|u_m| - u_y)$ measured in the same envelope but referred only to the conventional maximum non cyclic lateral deformation.

Cyclic Physical Ductility as a Measure of Damage

Consider a SDOF structure of unit mass, initial stiffness of 394.3 kN/m, elastic strength of 7.5 kN and damping ratio of 5% responding inelastic to a subduction type ground motion (Llayllay record of the 1985 Chilean earthquake).

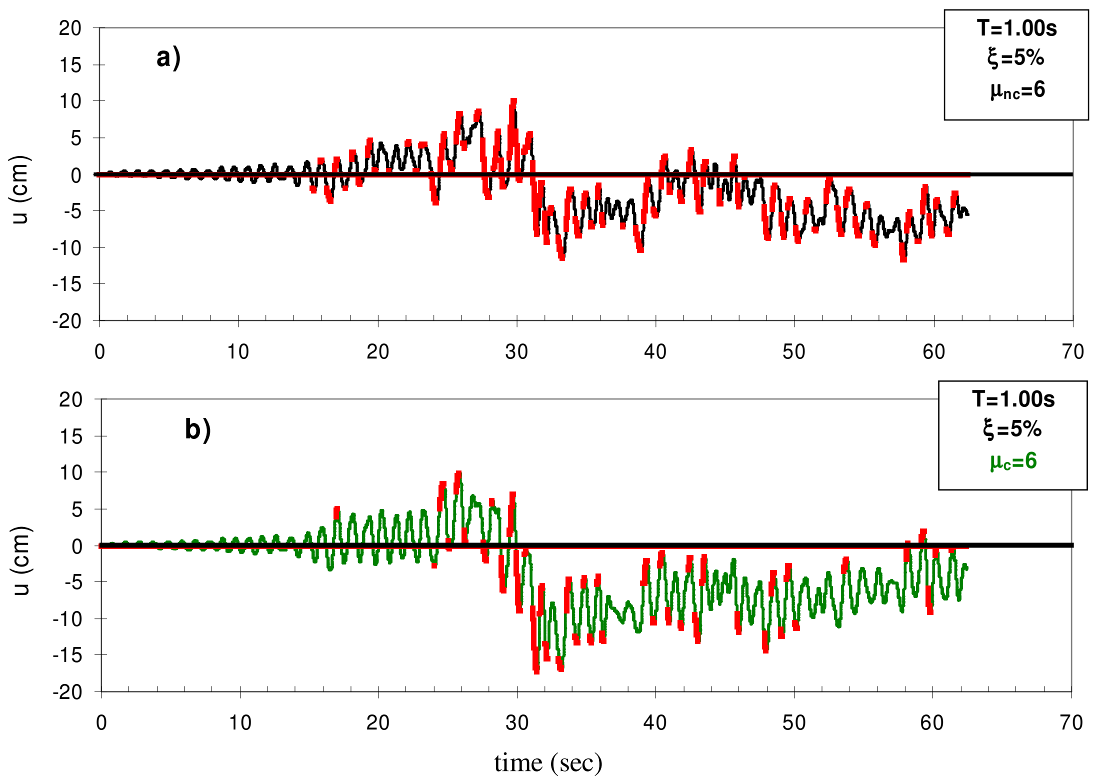
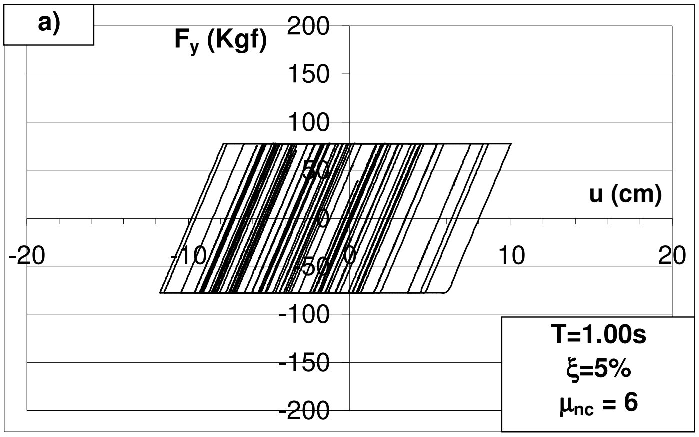
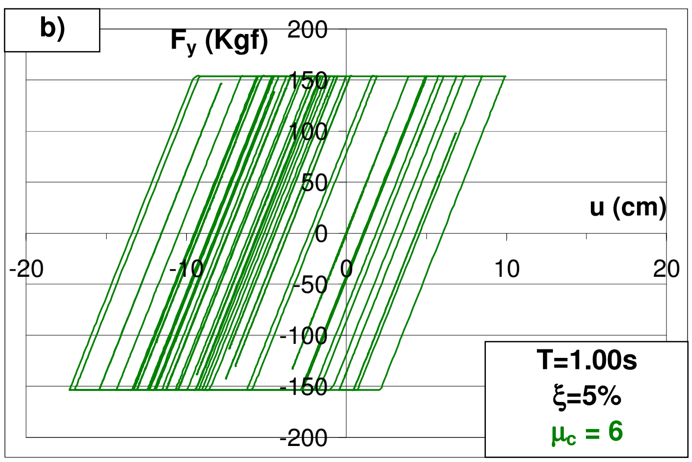


Figure 2. Time History Response for SDFS with T=1.00s Designed for a) Non Cyclic and b) Cyclic Ductility Ratio Llayllay Record from Valparaiso Earthquake 1985.



u_0= 19.1 cm F_0= 753.2 kg-f	u_{cp} = 17.82 cm u_{ncp}= 9.78 cm	E_I = 18440 kg-f cm E_D = 5340 kg-f cm
u_y= 1.96 cm F_y= 77.57 kg-f	u_{pcum} =168.9 cm u_{cpT} = 35.64 cm N = 73	$E_{H\mu nc}$= 13100 kg-f cm



u_0= 19.10 cm F_0= 753.2 kg-f	u_{cp} = 19.42 cm u_{ncp}= 13.94 cm	E_I= 23871 kg-f cm E_D= 9436 kg-f cm
u_y= 3.89 cm F_y= 153.42 kg-f	u_{pcum} = 94.10 cm u_{cpT} = 38.84 cm N = 42	$E_{H\mu c}$= 14435 kg-f cm

Figure 3. Hysteretic Response for SDFS with T=1.00s Designed for a)Non Cyclic and b) Cyclic Ductility Ratio Llayllay Record from Valparaiso Earthquake 1985.

Consider also a conventional design where the lateral deformations will be limited to a target non cyclic ductility demand ratio μ_{nc} = 6. Fig. 2a, where every yielding and plastic deformation has been colored, shows the time history response of this T = 1.0 sec structure. The maximum lateral deformation which is negative, occurs at time t = 58 sec, measures 11.74 cm and since the yielding deformation is 1.96 cm (Fig. 3a), μ_{nc} = 6 as expected. However, μ_{nc} is just a number and should not be considered as a measure of damage. Damage is ductility and the only ductility under the μ_{nc} concept is the non cyclic physical ductility. In this case u_{ncp}^- = 9.78 cm. But, it should be noted in Fig. 2a that besides the maximum negative there are several other deformations including another maximum in the positive direction that occurs before the negative at t = 30 sec, measures 10cm and has not been considered in the above calculations. It is clear then that damage can not be due only to the u_{ncp}^- = 9.78 cm but due also to the other plastic deformations in the response. If of all other plastic deformations at least the maximum positive in the envelope is considered the corresponding u_{ncp}^+ is

10.00 – 1.96 = 8.04 cm. Therefore, the total physical ductility demand which covers the total plastic deformation measured in the envelope of all hysteretic responses (Fig. 3a) is u_{cpt} = 35.64 cm which is 3.6 times 9.78 cm. Consequently it can be concluded that to consider only the maximum lateral deformation to have an estimate of the physical ductility causing damage misses a large amount of ductility to be measured in the envelope of all hysteretic loops.

Assume now that the designer considers to limit the cyclic deformation u_c of the same structure to a target cyclic ductility ratio μ_c = 6. In Fig. 4 at about 26 sec the structure reaches a maximum positive deformation of 9.37 cm. However, this maximum positive deformation is followed by 6 cycles of inelastic deformation including reversals of plastic deformation and after all those cycles a maximum negative deformation of 17.83 cm at about 31.4 sec is achieved (Fig 2b). Both maximum deformations are the extremes of the envelope of all the hysteretic responses shown in Fig 3b which also shows that the yielding deformation is 3.89 cm. According to above definitions the cyclic deformation is u_c = 23.31 cm and μ_c = 6 as expected. But μ_c is again another number and neither should be considered as a measure of damage but just as a target value to limit the cyclic deformation. Thus in this study it is proposed the use of cyclic physical ductility demand calculated using μ_c, as a measure of damage because it considers the plastic deformation beyond yielding including the reversal of plastic deformation measured in the envelope of all hysteretic responses (Figs. 3b). Then, $u_{cp} = u_c - u_y$ = 19.42 cm and u_{cpt} = 38.84 cm.

It is important to mention that when the μ_{nc} = 6 controls $|u_m|$ a value for u_{cpt} was calculated as twice the summation of u_{ncp}^+ and $|u_{ncp}^-|$. However, as it will be seen later the selection of μ_{nc} has another implication regarding the strength reduction factor. For this reason conceptually u_{cpt} must be obtained from a response where u_c and u_{cpt} are limited by μ_c.

The u_{cpt} has the advantage of giving the designer an estimation of the total cyclic physical ductility demand limited by μ_c and measured in the envelope of the hysteretic response. The u_c includes the elastic, the plastic and the maximum reversal of plastic deformation. Consequently u_c becomes a better estimation of deformation demand than just the maximum lateral or non cyclic maximum deformation demand $|u_m|$.

From the above example there are some other important issues to be considered like the reduced strength demand, the resulting strength reduction factor, the cumulative plastic deformations, the number of inelastic excursions and, the energy dissipated through inelastic behavior of this T = 1 sec structure for both non cyclic (Fig. 3a) and cyclic ductility ratio (Fig. 3b).

Designing for Cyclic Physical Ductility

Observing Fig. 3b the yielding strength demanded by the ground motion to meet the target μ_c = 6 is F_y = 1.53 kN and since the elastic strength demand is 7.53 kN, the cyclic strength reduction factor $R_{\mu c}$ for the T = 1.0 sec structure is 4.9. The yielding strength demand to meet the target μ_{nc} = 6 (Fig. 3a) is F_y = 0.77 kN then the corresponding non cyclic strength reduction factor $R_{\mu nc}$ is 9.75. The differences in both values of R are extremely large, i.e. $R_{\mu nc}$ is almost 100% larger than $R_{\mu c}$. That is, if μ_{nc} = 6 is used for design the required strength is almost half of that required if μ_c = 6 is decided to use for design. These results could be appealing for the designer since he/she could think is producing an economical design choosing μ_{nc} = 6. According to the μ_{nc} design concept, the strength F_y = 0.77 kN restricts the maximum lateral deformation $|u_m|$ to 11.74 cm (Fig. 3a). However, as above explained the dynamic response is cyclic and there is a deformation in the opposite side that completes the envelope of the hysteretic response reaching 10.00 cm giving a cyclic deformation u_c = 19.78 cm which the strength of 0.77 kN would not be able to maintain during the response. Regarding damage as above defined the strength F_y = 0.77 kN is able to keep u_{ncp} at a maximum of 9.80 cm (Fig. 3a) however, that strength will not be able to restrict u_{cpt} at 39.8 cm. Clearly with F_y = 0.77 kN the structure will be subjected to a considerable larger amount of damage. On the contrary, if the designer chooses μ_c = 6 for design, the yielding strength F_y = 1.53 kN will be able to keep the cyclic deformation u_c at a maximum value of 23.31 cm and u_{cpt} at a maximum value of 38.84 cm (Fig. 3b) for that ground motion. If the designer considers that these deformations are too large he/she can reduce μ_c and restrict u_c and u_{ncpt} to lower values.

Using μ_{nc} = 6 the number of inelastic excursions reaches 73, the cumulative plastic deformations is 168.9cm, the damping energy is 0.53 kN-m and the hysteretic energy dissipation demand is 1.31 kN-m while using μ_c = 6 the number of inelastic excursions is 42, the cumulative plastic deformations add 94.1 cm, the damping energy is 0.94 kN-m and the energy dissipation demand is 1.44 kN-m. Clearly using μ_{nc} the number of inelastic excursions is 74% larger, the cumulative plastic deformations are 80% larger and the dissipation of energy demanded is 8.5% lower than when using μ_c. The large number of inelastic excursions and the large cumulative plastic deformations using μ_{nc} indicate larger potential damage than using $\mu_{c.}$

Equation of Motion

The time history response of a nonlinear SDOF system subjected to EQGMs is given by the solution of the following equation of motion:

$$m\ddot{u} + c\mathring{u} + F_s = - m\ddot{u}_g\,(t) \tag{3}$$

Dividing by m and setting c = $2m\omega_n\xi$ gives:

$$\ddot{u} + 2\zeta\omega_n\mathring{u} + \frac{F_s}{m} = -\ddot{u}_g\,(t) \tag{4}$$

In equations 3 and 4, m is the mass, c is the damping coefficient, F_s is the elastic resistance which after been reduced by a reduction factor R becomes the restoring force F_y. The resistance function for this investigation is assumed to be EPP, ω_n is the natural frequency of the structure in the elastic range and also when the inelastic system vibrates within the elastic range and ζ is the fraction of the critical damping in the elastic and supposed to be the same in the inelastic range. The relative deformation response is u, $\ddot{u}_g(t)$ is the ground acceleration and $\mathring{u}$ is the relative velocity response. Equation 4 is solved for the deformation response, u, using the numerical method proposed by (Newmark 1959).

Strength Reduction Factor Demand Spectra

It is known that the area of all cycles of inelastic response shown in the hysteretic time history (Figs. 3a and 3b) equals the energy dissipated during dynamic response. The structure capacity to dissipate energy through inelastic hysteretic behavior induces a reduction in forces from the elastic level and since dissipation of energy varies for every period the reduction is not a constant. Codes however have expressed this reduction using constant reduction factors which according to (Miranda and Bertero 1994) are based on observations of structural performance during past earthquakes. The use of large reduction factors as recommended by the codes increases considerably the maximum lateral deformations (Lara and Bertero 2003). Reduction factors should account for damping, energy dissipation capacity and overstrength (Miranda and Bertero 1994) and also depend on the period.

However, the influence of the strength reduction factors is not only in the reduction of the elastic force demanded by the ground motion. They also influence on the control of maximum (cyclic or non cyclic lateral) deformations through the ductility ratios (μ_c or μ_{nc}) because during inelastic response as the yielding strength decreases due to an increase in the reduction factor, u_c or $|u_{max}|$ increase. Therefore it is necessary to estimate the strength required in a structure to limit the deformations. Fig. 4 shows the strength reduction factor spectra calculated for $\mu_c = \mu_{nc} = 6$ for SDOF structures subjected to four subduction ground motions. The results for other values of μ_{nc} and μ_c are not shown due to limitations on the number of pages.

For the Chilean records differences between $R_{\mu c}$ and $R_{\mu nc}$ are very small for T ≤ 0.5 sec and become more important for longer values of T. The largest differences occur in different period ranges. For Valparaiso between T = 2.5 and 3.5 sec, for Llayllay between T = 1.2 and 2.4 sec, and for Llolleo between T = 1.7 and 3.8 sec. For the Mexican Caleta record differences between $R_{\mu c}$ and $R_{\mu nc}$ begin at T = 1 sec being the largest between T = 2 and 3 sec. For instance, for T = 2.5 sec, $R_{\mu nc}$ = 19 and $R_{\mu c}$=8.

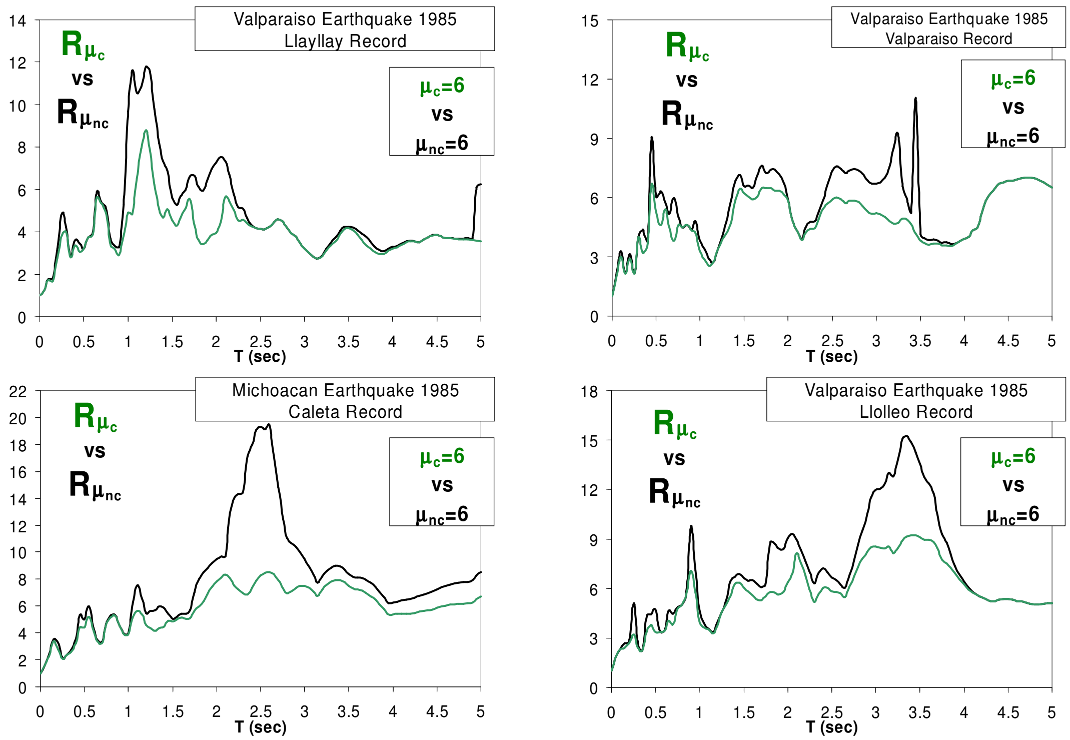


Figure 4. Cyclic and Non Cyclic Strength Reduction Factor Demand Spectra for μ_{nc} and $\mu_c = 6$. $\xi = 5\%$.

The reasons for these differences are first, due to the numerical procedure involved in the calculation of the ductility ratio. The first step in the numerical solution of the differential equation of motion for inelastic response is to reduce the elastic strength to F_y by means of a factor R´ larger than 1. The solution of equation 4 will provide a maximum lateral or a maximum cyclic deformation which divided by u_y will give values for μ_{nc} or for μ_c. Repeating this procedure there will be a value for μ_{nc} or μ_c for every R´. However these values of ductility ratio will be different from the pre determined target values therefore it becomes necessary to interpolate them with respect to R´. In this study the values of R´ introduced in equation 4 begin with 1.25 and vary every 0.25. The second reason is due to the measuring of the maximum deformation. When the maximum lateral deformation is measured in order to meet the pre determined target value of μ_{nc} there is a value of R´ associated to μ_{nc} and when the cyclic deformation is measured to meet the pre determined value of μ_c the associated value of R´ is different. The reasons are that the cyclic deformation is always larger or at least equal to the maximum lateral deformation and that the strength required to limit u_c is larger than that required to limit u_m. Therefore the value of R´ = $R_{\mu c}$ for μ_c will be lower or equal than the value of R´ = $R_{\mu nc}$ required to meet the target value of μ_{nc}.

It should be noted that observing Fig. 4 the strength reduction factor $R_{\mu nc}$ or $R_{\mu c}$ can not be a constant value as recommended by the codes. Consider the Llolleo spectrum (Fig. 4) and assume that a constant $R_{\mu nc} = R_{\mu c} = 6$ is chosen for design. Two structures with periods T = 2.6 and 4 sec are affected by this strength reduction factor although the differences in stiffness is 2.37. Noticing that the ordinates of both spectra for those periods are the same, for T = 2.6 sec and $\mu_{nc} = \mu_c = 6$, $|u_m| = 6u_y$ and $u_c = 6u_y$ while for T = 4 sec and $\mu_{nc} = \mu_c = 6$, $|u_m| = 14.2u_y$ and $u_c = 14.2u_y$ being $14.2u_y$ an undesirable value for maximum cyclic or non cyclic deformation. Clearly R´ varies with cyclic or non cyclic ductility ratios and with the period. Consequently, the appropriate definition of the reduction factor expressed by (Miranda and Bertero 1994) holds and is equal to:

$$R_\mu = F_y\,(\mu = 1)\,/\,F_y\,(\,\mu = \mu_i\,) \qquad (5)$$

Where R_μ = Reduction in elastic strength demand due to inelastic hysteretic behavior of the structure; F_y (μ = 1) is the elastic strength demand = F_0 in Fig. 1b; F_y ($\mu = \mu_i$) is the yielding strength required to keep μ_{nc} or μ_c at values lower or equal than the target non cyclic or cyclic ductility ratio respectively, previously selected.

Cyclic and Non Cyclic Strength Demand Spectra

Fig. 5 shows Cyclic Strength Demand Spectra (CSS) and Non Cyclic Strength Demand Spectra (NCSS) for the Valparaiso, Llayllay and Llolleo records of the 1985 Chilean earthquake as well as for the Caleta record of the 1985 Michoacan earthquake. The ordinates represent the seismic yielding coefficient C_y and the abscissas the structure periods T. It is not possible due to limitations of space to show the spectra for different values of μ_{nc} and μ_c.

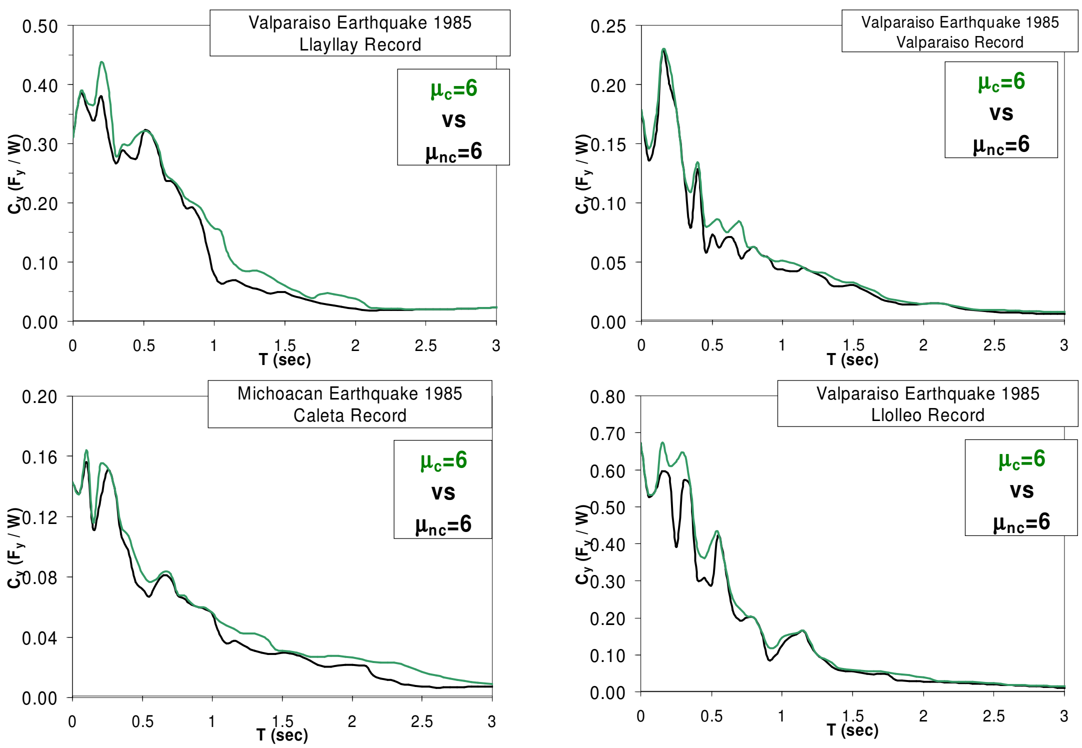


Figure 5. Cyclic Strength Demand Spectra (CSS) & Non Cyclic Strength Demand Spectra (NCSS) for μ_{nc} and $\mu_c = 6$. $\xi = 5\%$.

For all the cases the ordinates of $\mu_c = 6$ are larger than those of $\mu_{nc} = 6$ which agrees with the discussion about the strength reduction factor spectra. The μ_{nc} spectra present some sudden decreases of the ordinates not seen in the μ_c spectra . For instance, for Llayllay record and $\mu_{nc} = 6$ there are decreases in the ordinates which appear smoothly in the CSS. These decreases are due to the sudden increases of the strength reduction factor that occur when μ_{nc} is used (Fig. 4) because it does not measure the cyclic deformation. The maximum differences in ordinates for Llayllay occur at T = 1 sec for $\mu_{nc} = \mu_c = 6$ where C_y for $\mu_c = 6$ is about 0.16 while C_y for $\mu_{nc} = 6$ is about 0.09. This is because $R_{\mu nc}$ is larger than $R_{\mu c}$. For long period structures the difference in the ordinates becomes negligible because acceleration response in very flexible structures tends to zero. Note that for the Valparaiso record there are three structures affected by $C_y = 0.15$. Consider two of them with periods T = 0.06 and 0.3 sec which for $C_y = 0.15$ have the same ordinates for both spectra. The differences in stiffness is 5 thus for T = 0.06 sec and $\mu_{nc} = \mu_c = 6$, $|u_m| = 6u_y$ and $u_c = 6u_y$ while for T = 0.3 sec and $\mu_{nc} = \mu_c = 6$, $|u_m| = 30u_y$ and $u_c = 30u_y$ being $30u_y$ an extremely undesirable value for maximum cyclic or non cyclic deformation. Therefore, design should not be based on the results of strength spectra but on physical ductility.

Cyclic and Non Cyclic Physical Ductility Demand Spectra

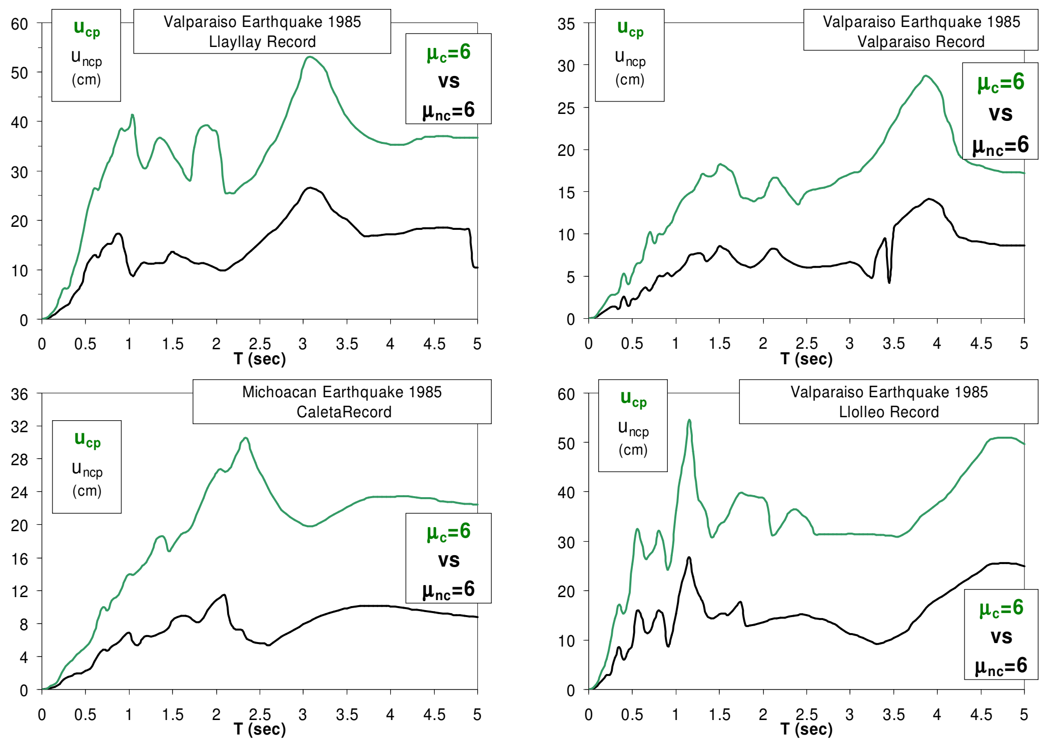


Figure 6. Cyclic Physical Ductility Demand Spectra (CPDS) & Non Cyclic Physical Ductility Demand Spectra (NCPDS) for μ_{nc} and $\mu_c = 6$. $\xi = 5\%$.

Fig. 6 shows the Cyclic and Non Cyclic Physical Ductility Demand Spectra for $\mu_c = \mu_{nc} = 6$ respectively for the same records as in Fig. 5. All the characteristics of the spectra shown are similar to the spectra calculated for other ductility ratios and not shown due to limitations of space. The physical cyclic and non cyclic physical ductility demands were already defined in this study. They represent physically the amount of plastic deformation demand measured on the envelope of the hysteretic responses for each period structure and also represent the potential damage because damage occurs when ductility is developed. For instance, for the Llayllay record when $\mu_{nc} = \mu_c = 6$, for T = 1 sec, u_{cp} is about 36 cm while u_{ncp} is about 10 cm. The difference is due to the measuring process of physical ductility (PD) which in the case of μ_{nc} the non cyclic PD is just $u_{ncp} = (|u_m| - u_y)$ while in the case of μ_c the total cyclic PD is $u_{cpt} = 2(u_c - u_y)$, i.e. the plastic deformation in the envelope of all the hysteretic loops. Therefore total u_{cpt} represents physically a better measure of the potential damage. Recalling Fig. 5 it was determined for the same record and structure that $C_y = 0.09$ for μ_{nc} and $C_y = 0.16$ for μ_c. This low strength $C_y = 0.09$ will be able to restrict only non cyclic PD to about 10 cm but it will not be sufficient to limit the cyclic PD that for this design amounts to about 36 cm. Instead, designing for $C_y = 0.16$ this strength will restrict the u_{cpt} to 39.84 cm demanded by the same record. Therefore the expected damage using μ_{nc} will be considerable larger than if μ_c is used. It should be noted that because the total PD in the envelope is measured for μ_c these spectra are smoother than those for μ_{nc}. The sudden changes in μ_{nc} spectral ordinates, like those at T = 3.4 sec in the Valparaiso record are due to instabilities in the numerical procedure and because μ_{nc} allows to measure PD, only as part of u_m neglecting cycle and reversals of deformations.

Conclusions

In this study cyclic total Physical Ductility (PD) u_{cpt} measured in the envelope of all hysteretic responses has been proposed as a more appropriate measure of damage. Cyclic deformation u_c measured in the same envelope is used to calculate cyclic ductility ratios μ_c which are proposed as substitute for conventional non cyclic ductility ratios μ_{nc} based on maximum non cyclic lateral deformation $|u_m|$, because $|u_m|$ neglects the cyclic deformations that occur during dynamic response.

Analytical and experimental studies have shown that providing ductility and toughness to a structure allows it to develop hysteretic inelastic behavior which reduces the strength required to maintain elastic behavior. It has been shown herein that these reductions depend on the period and on the ductility ratio and are not constant as indicated by Codes. Non cyclic strength reduction factors $R_{\mu nc}$ that control $|u_m|$ are larger than cyclic ones $R_{\mu c}$ that control u_c (for the same values of μ_{nc} and μ_c) because cyclic deformations and required strengths are larger than non cyclic ones. Therefore acceleration spectral ordinates for μ_{nc} are lower than those of μ_c leading the designer to use μ_{nc}. If μ_{nc} is used for design the resulting low strength will not be enough to restrain u_{cpt}. Therefore, design should be based on total cyclic PD limited by μ_c and then estimating the appropriate strength that will limit the total cyclic PD. The additional strength resulting for using μ_c protects the structure for the design earthquake as well as for aftershocks and future less severe ground motions. A structure designed for μ_{nc} not only will not be able to restrain the structure to the cyclic PD demand but if it survives a severe design earthquake it will remain weak and will not stand a possible aftershock. Consequently, estimations of cyclic strength and cyclic physical ductility demands become more reliable measures of inelastic behavior than just the non cyclic strength or the non cyclic physical ductility. In this study it has also been shown the large cumulative PD and the large number of plastic excursions in the response of structures designed using μ_{nc} with respect to those values when μ_c is used. These large values indicate larger potential damage. Cumulative PD is the total plastic deformation but it is not known the potential damage of each plastic excursion thus estimations of u_{cpt} demands become more reliable measures of inelastic behavior than just the non cyclic physical ductility. Also, estimations of cyclic deformations to calculate μ_c are an improvement with respect to estimations of non cyclic maximum lateral deformations to calculate μ_{nc} because these non cyclic deformations neglect the cyclic characteristic of dynamic response.

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