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ANALYSIS OF LOW CYCLE FATIGUE PHENOMENON AND ITS IMPACT ON SEISMIC BEHAVIOR AND STRUCTURAL DESIGN

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Abstract- A seismic design procedure that does not take into account the maximum and cumulative plastic deformation demands that a structure is likely to undergo during severe ground motion could lead to unsatisfactory performance. Current seismic design methodologies do not spot some variants relative to the seismic design into the strong motions. Particularly inattention explicitly the plastic deformation and probable significant reduction at lateral strength may cause irreparable results in the soft soils subject to the cycles of motions. There is total accordance about contrast to low cycle fatigue. Several recommendation were proposed on the quality of its influence at seismic design. For sense to performance seismic design issue the relative between damage measure and performance issues should be evaluated. Seismic design methodologies that account for low cycle fatigue can be formulated using simple damage models. The practical use of one such methodology requires the consideration of the severity of repeated loading through a normalized plastic energy parameter. Damage models that quantify the severity of repeated plastic cycling through plastic energy are simple tools that can be used for practical seismic design. The concept of constant cumulative ductility strength spectra, developed from one such model, is a useful tool for performance based seismic design and can be used to identify cases in which low cycle fatigue may become a design issue, and also can be used to estimate the design lateral strength of structures against cumulative plastic deformations.

Keywords: Low Cycle Fatigue, Damage Index, Plastic Energy, Strength Reduction Factor, Constant Cumulative Ductility Spectra.

I. INTRODUCTION

Current philosophy for seismic design of typical residential or commercial structures accepts the possibility that significant inelastic behavior will occur during severe seismic excitations. The mechanical characteristics of a structure deteriorate when deformations reach the range of inelastic behavior. Such deterioration can be important during long and severe ground motions, when several excursions into the inelastic range are expected.

A possible consequence of deterioration of the hysteretic behavior of a structure is failure of critical elements at deformation levels that are significantly smaller than its ultimate deformation capacity. In this paper, this failure mode will be termed 'low cycle fatigue'. Low cycle fatigue should be avoided, particularly for conditions that may result in repeated plastic cycling. The complexity of low cycle fatigue has resulted in significantly different opinions regarding how to account for it during seismic design. This paper discusses a set of simple tools recently developed for practical seismic design against low cycle fatigue. Although emphasis is placed on the design of reinforced concrete structures, the tools can be calibrated for other structural materials.

This article discusses the concept of cumulative ductility strength spectra, which represents a recently developed tool to improve seismic design of ductile structures subjected to long duration ground motions. A constant cumulative ductility spectrum provides, within a format that is similar to that of current seismic design codes, the lateral strength that is required by an earthquake-resistant structure to control, within acceptable levels, its cumulative plastic deformation demands. Expressions to establish strength reduction factors that allow the estimation of spectral ordinates of constant cumulative ductility spectra are provided.

II. LOW CYCLE FATIGUE

Experimental and field evidence indicate that the strength, stiffness and ultimate deformation capacity of reinforced concrete elements and structures deteriorate during excursions into the plastic range of behavior. Excessive hysteretic degradation may lead to an excessive accumulation of plastic deformation that may lead to failure at deformation levels that are significantly smaller than the ultimate deformation capacity of the structure under unidirectional loading.

This phenomenon, denoted herein as low cycle fatigue, has been repeatedly observed in laboratory tests. For example, Panagiotakis and Fardis (2001) recently observed that the deformation at failure of reinforced concrete elements subjected to typical load-histories applied in laboratory tests can be estimated as 60% of their ultimate deformation capacity [6]. Independently, Bertero (1997) recommended that the maximum ductility demand a structure undergoes during ground motion should be limited to 50% of its ultimate ductility [5].

The importance of plastic cycling on the deformation capacity of reinforced concrete structures has been known for some time. This effect caught the attention of several researchers during the 1970s when experimental studies were carried out on the cyclic response of reinforced concrete members and beam column sub-assemblages. It was observed that the hysteretic behavior of ductile beams showed a tendency for degradation due to the presence, among other things, of flexural cracking, bond deterioration and shear effects.

As a consequence, these beams tended to eventually exhibit non-ductile behavior and even fragile failure. Several researchers discussed the need to account for the effect of cycling on the performance of earthquake-resistant structures. Some of the options that were visualized involved proportioning the beams to control the level of shear stress. Detailing schemes were formulated to enable structural elements to undergo several cycles of plastic deformation with stable hysteretic behavior.

In the 1980s and 1990s, the engineering profession confronted the need to design structures with predictable performance. Performance-based seismic design became a fundamental concept for the formulation of seismic design methodologies. As a consequence, proposals for design against low cycle fatigue began focusing on deformation control rather than relying exclusively on detailing recommendations to ensure stable hysteretic behavior. A key issue during the development of design methodologies to control low cycle fatigue was the recognition that the lateral strength of a structure plays an instrumental role in controlling the seismic demands that eventually induce this type of failure.

Some researchers have suggested that there is no direct relation between strength and the level of seismic damage in structural elements, and that an increase in strength does not necessarily result in increased seismic safety. Within the context of design against low cycle fatigue, it is important to emphasize that lateral strength is not supplied to enhance the deformation capacity of a structure, but as a mean of controlling maximum and cumulative plastic deformation demands, and avoiding uncontrolled and excessive degradation of its structural properties.

III. TARGET DUCTILITY

Target ductility is defined as the maximum ductility $(\mu_{\max})$ the structure can reach during the design ground motion before the level of structural damage exceeds a preset threshold. Within the context of low cycle fatigue, this threshold corresponds to incipient failure or collapse.

In general, it has been agreed that as the severity of plastic cycling increases, $\mu_{\max}$ should decrease with respect to the ultimate ductility (μ_u) the structure is able to undergo under monotonically increasing lateral deformation (unidirectional loading).

How much smaller $\mu_{\max}$ should be with respect to μ_u (or how much bigger μ_u with respect to $\mu_{\max}$) depends on three variables: the value of the known ductility (either or μ_u), a ground motion parameter that quantifies the severity of plastic cycling, and a structural parameter that characterizes the cycling capacity of the structure.

Using the concept of target ductility, two approaches can be considered for the formulation of a performance-based design methodology that accounts for low cycle fatigue. The first of these approaches requires estimating $\mu_{\max}$ given that μ_u is known. That is, an approach requires the estimation of a threshold value for the maximum plastic response in the structure given that its ultimate deformation capacity is known. The steps involved in Approach A can be schematized as follows:

1) Define the type of detailing to be used in the structure.
2) Establish the value of the fundamental period of vibration (T) of the structure. The determination of T within the context of performance-based design has been discussed by Bertero (1992), and Priestley (2000) [5].
3) Establish values to characterize the ultimate and cumulative deformation capacities of the structure. Note that these values depend on the type of detailing to be used.
4) Establish $\mu_{\max}$ as a function of the severity of ground motion and of the ultimate and cumulative deformation capacities of the structure.
5) Establish the design base shear that will allow the structure to control its maximum plastic demand within the threshold defined by $\mu_{\max}$.

IV. PERFORMANCE BASED DESIGN USING DAMAGE INDEX

Iemura and Mikami showed the flowchart of seismic design based on performance evaluation in Figure 1. At first, performance objectives of structures against earthquake ground motion are defined, and structural limit which is shown in Design Specifications of Highway Bridges etc. is determined corresponding to the performance. In the meantime, the damage index of inelastic structures is employed as a measure of seismic performance objective [4].

Afterwards, the target value of damage index equivalent to the structural limit is provided. Then, the structural characteristic to satisfy the target value (Performance objectives) is calculated with numerical simulation of inelastic response of SDOF. The structural characteristic means the required yield strength and the required ductility factor in this study. Finally, by using the obtained structural characteristic, performance based design using the damage index can be performed concretely.

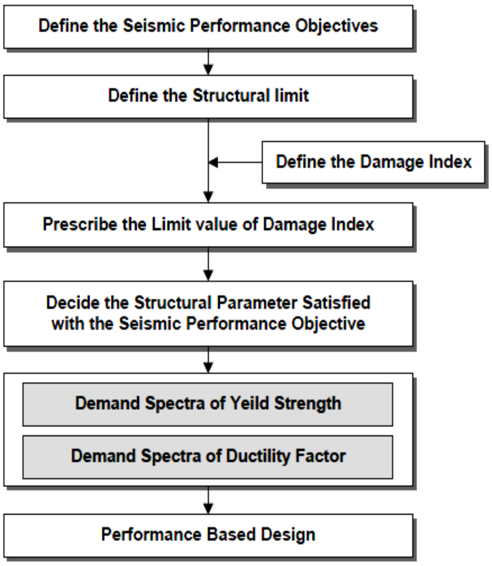


Figure 1. The flowchart of seismic design based on performance evaluation [4]

V. ENERGY AS DESIGN REPRESENTATION OF CUMULATIVE LOADING

Significantly different methods have been proposed to estimate the severity of plastic cycling, and various design methodologies that account for the effect of low cycle fatigue have been offered. An option that has been considered attractive, due to its simplicity, has been the characterization of cumulative loading through energy concepts. Housner (1956) offered one of the earliest discussions regarding the need to consider explicitly the effect of plastic cycling through energy concepts. Later, several attempts have been made to estimate the energy demands in simple systems, and to offer insights on how to use these demands for design purposes [5].

Design for low cycle fatigue was advanced with the formulation and calibration of damage indices, and the formalization of an energy balance equation for design purposes. Based on these concepts, several design methodologies that account for low cycle fatigue have been formulated.

Today there are still significantly different approaches towards the formulation of a design representation for the energy demands. Some researchers suggest that energy spectra could be formulated and used for design purposes. Other options include accounting for cumulative loading in the structure through indirect measures of the plastic energy, and deriving the plastic energy demands from other relevant seismic demands.

The total plastic energy dissipated by a structure during an earthquake ground motion is denoted herein as $E_{H\mu}$. The plastic energy demand can be interpreted physically by considering that it is equal to the total area under all the hysteresis loops the structure undergoes during a ground motion. In this sense, $E_{H\mu}$ provides a rough idea of the cumulative plastic deformations in the structure. Nevertheless, $E_{H\mu}$ by itself does not provide enough information to assess structural performance. Thus, it is convenient to take into account simultaneously $E_{H\mu}$, and strength and stiffness of a system, as follows:

$$NE_{H\mu} = \frac{E_{H\mu}}{F_y \delta_y} \tag{1}$$

where $NE_{H\mu}$ is the normalized plastic energy, F_y and δ_y (shown in Figure 2(a)) are the yield strength and yield displacement, respectively. For an elastic-perfectly-plastic system subjected to a single plastic excursion (Figure 2(b)):

$$E_{H\mu} = \delta_p F_y = \left(\delta_c - \delta_y\right) F_y = \left[\frac{\delta_c}{\delta_y} - 1\right] \delta_y F_y = \left(\mu_c - 1\right) \delta_y F_y \tag{2}$$

where δ_c is the cyclic displacement, δ_p is the plastic displacement associated with the plastic excursion, and μ_c, equal to δ_c / δ_y, is the cyclic ductility. The normalized plastic energy for the plastics excursion can be expressed as:

$$NE_{H\mu} = \frac{E_{H\mu}}{\delta_y F_y} = \frac{\delta_p F_y}{\delta_y F_y} = \frac{\delta_p}{\delta_y} = \mu_p = \mu_c - 1 \tag{3}$$

where, μ_p is the plastic ductility reached in the excursion. Note that for a single plastic excursion, $NE_{H\mu}$ is a direct measure of the plastic displacement.

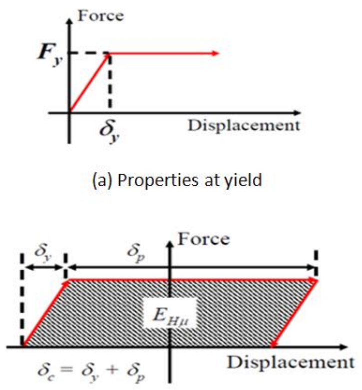
For an elastic-perfectly-plastic system subjected to multiple plastic excursions, $NE_{H\mu}$ is the sum of all plastic displacements reached in the different cycles normalized by δ_y, in such way that:

$$NE_{H\mu} = \frac{\sum_{i=1}^{N_{exc}} \delta_{pi}}{\delta_y} = \sum_{i=1}^{N_{exc}} \mu_{pi} \tag{4}$$

where, δ_{pi} and μ_{pi} are the plastic displacement and plastic ductility, respectively, associated with the ith excursion, and N_{exc} is the total number of plastic excursions during the ground motion. Note that $NE_{H\mu}$ is a direct measure of the cumulative plastic displacement demands. For a system with degrading hysteretic behavior, $NE_{H\mu}$ could be defined to include all plastic excursions for which the capacity does not degrade to a value less than a specified fraction of F_y (say 0.75). Such a definition allows for rational evaluation of structural damage in reinforced concrete structures through the use of $NE_{H\mu}$.

VI. SIMPLE DAMAGE MODELS TO PREDICT LOW CYCLE FATIGUE

Although using energy-derived parameters as a representation of repeated cumulative loading allows the formulation of relatively simple seismic design methodologies, this approach should be carefully assessed. The plastic energy dissipating capacity of a reinforced concrete structure does not depend exclusively on its mechanical characteristics, but also on the specifics of its loading history.



(a) Properties at yield

(b) Plastic excursion and cyclic demands

Figure 2. Definitions of strength and deformation quantities [4]

Particularly, the plastic energy dissipated by a large number of small amplitude cycles can significantly exceed that dissipated up to failure through the application of a few large amplitude cycles [3]. Three low cycle fatigue models are discussed next. Two of these models are well-known and have been used extensively to formulate seismic design methodologies that account for low cycle fatigue. The third model is a simple energy-based model introduced by Teran-Gilmore and Jirsa (2004) [1].

A. Park and Ang. Damage Index

Park and Ang. [1985] have formulated a damage index to estimate the level of damage in reinforced concrete elements and structures subjected to cyclic loading:

$$DMI_{PA} = \frac{\delta_{\max}}{\delta_u} + \beta \frac{NE_{H\mu}}{F_y \delta_u} \tag{5}$$

where $\mu_{\max}$ is the maximum ductility demand, μ_u is the ultimate ductility, and β is the structural parameter that characterizes the cycling or cumulative deformation capacity of the element or structure (i.e. the stability of its hysteretic behavior). In Equation (5), *DMI* denotes damage index; and the subscript 'PA', Park and Ang. The work done by several researchers suggest that β of 0.15 corresponds to systems that exhibit fairly stable hysteretic behavior; while values of β ranging from 0.2 to 0.4 should be used to assess damage in systems exhibiting Substantial strength and stiffness deterioration. Under the presence of repeated cyclic loading into the plastic range, 1.0 represents the threshold value at which low cycle fatigue is expected to occur [2].

B. Linear Cumulative Damage Theory

A damage index, that can take into account the change in energy dissipating capacity of a structure as a function of its displacement history, can be formulated from the linear cumulative damage theory(Miner's hypothesis). Miner's hypothesis considers that the damage induced by each plastic excursion is independent of the damage produced by any other excursion, in such way that there is a need for a clear convention to define and delimit each excursion. Powell and Allahabadi (1987) suggest that, for earthquake induced deformations, the Rain flow Counting Method is a good option to achieve this.

$$DMI_{MH} = \sum_{i=1}^{N_{inc}} \left(\frac{\delta_{pi}}{\delta_{ucp}} \right)^b = \sum_{i=1}^{N_{inc}} \left(\frac{\mu_{pi}}{\mu_{ucp}} \right)^b \tag{6}$$

where, N_{inc} is the total number of plastic excursions, δ_{ucp} is the ultimate cyclic plastic displacement, δ_{pi} is the plastic displacement associated to the *i*th excursion, and *b* is the structural parameter that characterizes the cumulative deformation capacity of the structure. Also, $\mu_{pi} = \delta_{pi} / \delta_y$ is the cyclic plastic ductility associated to the *i*th excursion; and $\mu_{ucp} = \delta_{ucp} / \delta_y$, the ultimate cyclic plastic ductility. In Equation (6), *DMI* denotes damage index; and the subscript 'MH', Miner's Hypothesis. DMI_{MH} is equal to one implies incipient failure due to low cycle fatigue. Typical values of b range from 1.6 to 1.8. It has been suggested that a b of 1.5 is a reasonably conservative value to be used for seismic design and damage analysis of reinforced concrete and steel ductile structures.

C. A Simple Model to Predict Low Cycle Fatigue

Teran-Gilmore and Jirsa (2004) have recently proposed a simple model to assess the occurrence of low cycle fatigue [1]. Basically, this model represents a simplification of the linear cumulative damage theory through the assumption of a fixed shape for the distribution of the plastic excursions that occur during the ground motion:

$$DMI_{MH}^{s} = (2 - b) \frac{NE_{H\mu}}{\mu_{ucp}} \tag{7}$$

where $NE_{H\mu}$ is the ground motion parameter that quantifies the severity of the plastic demands, μ_{ucp} is the ultimate cyclic plastic ductility, and *b* is the structural parameter that characterizes the cumulative deformation capacity. As before, *b* equal to 1.5 can be considered to be a reasonable conservative value to be used for seismic design of ductile structures. DMI_{MH}^{s} is equal to one implies incipient failure due to low cycle fatigue. As suggested by Figure 3, the analytical upper limit for the value of μ_{ucp} is given by $2(\mu_u - 1)$.

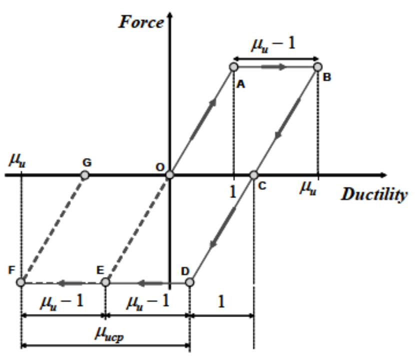


Figure 3. Upper bound values for the ultimate plastic cyclic ductility[1]

In reality, the physical upper limit of μ_{ucp} will be somewhat less than this, because a plastic excursion close to μ_u will damage significantly the capacity of a structure to accommodate plastic deformation in the opposite direction:

$$\mu_{ucp} = 2r(\mu_u - 1) \quad (8)$$

where r is a reduction factor (less than one). For incipient collapse $(DMI_{MH}^{s} = 1)$, Equation (7) can be reformulated in terms of μ_u as:

$$NE_{H\mu} = \frac{2r}{2-b}(\mu_u - 1) \quad (9)$$

According to Equation (7), the value of $NE_{H\mu}$ estimated from Equation (9) establishes the maximum plastic energy demand that a structure can accommodate before failure due to low cycle fatigue.

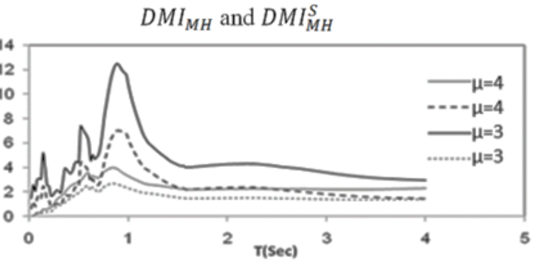
Figure 4(a) shows damage estimates derived from Equations (6) and (7) (b = 1.5 and $\mu_{ucp} = 7.5$) for 'Tabas'. The value of μ_{ucp} was established from Equation (8) by assuming μ_u equal to 6 and r equal to 0.75. The discontinuous lines correspond to Equation (6). Equation (7) yields, with respect to Equation (6), higher estimates of damage for $\mu_{\max}$ of 2, slightly higher estimates for $\mu_{\max}$ of 3, and slightly lower estimates for $\mu_{\max}$ of 4.

To explain the results summarized in Figure 6, it is necessary to consider that the energy dissipating capacity of a structure increases as the amplitude of its plastic excursions decreases. In the case of $\mu_{\max}$ is 3, the amplitude of the majority of the plastic excursions

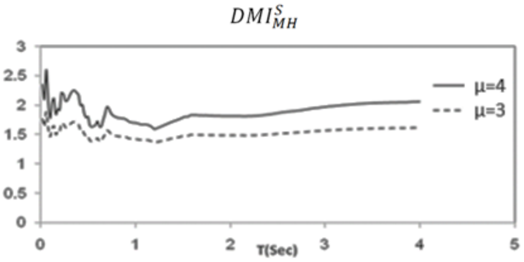
($\frac{\mu_{\max}}{\mu_u} = \frac{3}{6} = 0.5$) is small with respect to the ultimate deformation capacity.

While Equation (6) accounts for an increased energy dissipation capacity, Equation (7) does not, so that the latter yields higher estimates of damage. As the value of $\mu_{\max}$ increases, the mean amplitude of the plastic excursions increases with respect to the ultimate deformation capacity. Because the energy dissipating capacity of a system will tend to decrease under these circumstances, Equation (7) yields similar and even unsafe estimates of damage with respect to Equation (6) for $\mu_{\max}$ of 3 and 4. Figure 4(b) shows the mean ratio of the damage estimates obtained from Equations (6) and (7) $(DMI_{MH}^{N} = DMI_{MH}^{S} / DMI_{MH})$. The ratio shows a strong dependence on $\mu_{\max}$ and a weak variation with respect to T.

As the plastic energy demand increases on a given structure, its target ductility should decrease with respect to μ_u, in such way that an increase in the energy content of the ground motion requires the amplitude of the plastic excursions to be reduced relative to the ultimate deformation capacity.



(a) Mean estimate of damage



(b) Mean normalized of damage

Figure 4. Estimates of damage from Equation Tabas [7]

Considering the effect of the amplitude of the plastic excursions in the estimates of DMI_{MH}^{S} relative to those of DMI_{MH} (a decrease in this amplitude implies further conservatism in the estimates of DMI_{MH}^{S}), it can be said that Equation (7) yields unsafe assessment of low cycle fatigue when applied to motions with low energy content. As the energy content of the motion goes from low to moderate, the assessment of low cycle fatigue using DMI_{MH}^{S} goes from unsafe to adequate; and, as the energy content goes from moderate to high, this assessment ends up being slightly conservative. As a consequence, the use of DMI_{MH}^{S} to assess incipient failure due to low cycle fatigue yields adequate results for the design of structures subjected to ground motions with moderate and high energy content. In case of structures subjected to low energy demands, DMI_{MH}^{S} yields unsafe assessment of failure; and thus, needs to be complemented with other design criteria.

After extensive studies on the seismic performance of single-degree-of-freedom (SDOF) systems, it was observed that for motions having moderate to very high energy content, Equation (9) with r equal to 0.75 yields similar assessment of the occurrence of low cycle fatigue as Equations (5) and (6) (Teran-Gilmore and Jirsa, 2004). Based on this observation, Equation (9) can be rewritten for design purposes as:

$$NE_{H\mu} = \frac{1.5}{2-b}(\mu_u - 1) \quad (10)$$

In the case of ductile structures b = 1.5, in such way that:

$$NE_{H\mu} = 3(\mu_u - 1) \quad (11)$$

VII. STRENGTH REDUCTION FACTORS, TRADITIONAL CONCEPT

Within the context of current seismic design codes, the design lateral strength is obtained by reducing the design elastic strength spectra evaluated at T by an appropriate strength reduction factor. Because of the need to rationalize the use of strength reductions factors within performance-based design formats, significant research effort has been devoted in recent years to the formulation of transparent and reliable strength reduction factors. The strength reduction factor, R, is defined as:

$$R_\mu\left(\mu_{\max}, T\right) = \frac{S_a\left(1, T\right)}{S_a\left(\mu_{\max}, T\right)} \tag{12}$$

where $S_a\left(\mu, T\right)$ denotes spectral pseudo-acceleration evaluated at μ and T, μ equal to 1 implies elastic behavior, and $S_a\left(1, T\right)$ is the seismic coefficient corresponding to the minimum strength that would keep a structure with 5% critical damping in the elastic range. Equation (12) should be differentiated from strength reduction factors used in current seismic design codes. Normally, strength reduction factors used in practice implicitly consider that the actual lateral strength of a structure can be two to five times its design strength.

While Equation (12) only considers reduction in strength due to inelastic behavior, a practical strength reduction factor should account for reductions due to inelastic behavior and expected over-strength in the actual structure. The value of R strongly depends on μ and T, and is significantly influenced by the type of soil in which the design ground motion is generated. The following trends have been observed for the strength reduction factor corresponding to long duration motions with narrow frequency content:

1) R tends to one as T approaches zero.

2) R increases rapidly as the value of T is increased, until it peaks at a value considerably larger than μ at T close to T_g.

3) R is not particularly sensitive to the duration of ground motion or other important ground motion characteristics, such as intensity and epicenter distance.

4) The values of R corresponding to very soft soil can be affected significantly by a variation in the frequency content of the motion.

Particular importance to this article is the observation that for very soft soils, such as those located in the Tabas, R reaches values considerably larger than μ for T close to T_s. This is illustrated in Figure 5 by the continuous black lines, which correspond to values of R for μ equal to μ_u. As shown, under the assumption that the maximum ductility demand undergone by a SDOF system is equal to μ_u, R can reach values up to $2\mu_u$.

The values of R corresponding to constant 'cumulative' ductility strength spectra are defined as:

$$R_\mu\left(NE_{H\mu}, T\right) = \frac{S_a\left(\mu = 1, T\right)}{S_a\left(NE_{H\mu}, T\right)} \tag{13}$$

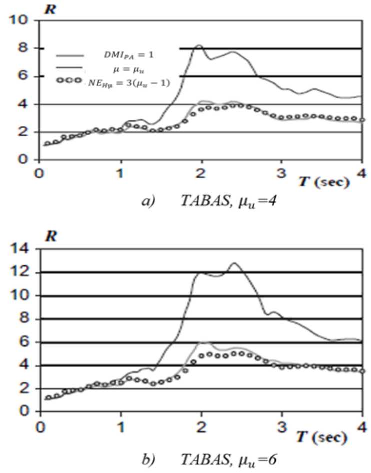


Figure 5. Strength reduction factors corresponding to Tabas, 5% critical damping

where, $S_a\left(NE_{H\mu}, T\right)$ denotes spectral pseudo acceleration corresponding to a 'cumulative' ductility strength spectrum evaluated at $NE_{H\mu}$ and T, and $S_a\left(\mu = 1, T\right)$ is the seismic coefficient corresponding to the minimum strength that would keep a structure with 5% critical damping in the elastic range.

As shown in Figure 5, the values of R derived for 'Tabas' from the 'cumulative' ductility criteria are very similar to those obtained from the Park and Ang. damage index, and considerably smaller than those corresponding to the criteria in which μ is assumed equal to μ_u. In fact, the values of R derived from the 'cumulative' ductility criteria never exceed value of μ_u, even for T close to T_s.

In the short and medium terms, performance-based seismic design that accounts for the effect of low cycle fatigue should consider the following:

1) In the case of very soft soils (long duration motions with narrow frequency content), the design lateral strength should comply with the following two conditions: $\mu_{\max} \le 0.7\mu_u$ and $NE_{H\mu} \le \frac{1.5}{2-b}\left(\mu_u - 1\right)$.

Consistent with this, the value of R used for design purposes should not exceed the value of μ_u. An option to establish transparently the values of R for practical seismic design is to incorporate the use of constant 'cumulative' ductility strength spectra to current codes. Within this context, 'cumulative' ductility strength spectra may complement or substitute the use of constant 'maximum' ductility strength spectra. In any case, it is important for current codes to allow for rational estimation of the maximum lateral displacement demand in the structure for the purpose of non-structural damage control and avoidance of structural instability.

2) In any other type of soil, seismic design should focus on controlling maximum ductility. Nevertheless, the minimum design lateral strength should be such that the maximum ductility demand in the structure is limited to $0.7\mu_u$. Perhaps and based on recommendations made by other researchers, a more stringent limit for $\mu_{\max}$, such as

$0.6\mu_u$, can be imposed. As suggested before, strength reduction factors currently used in practice implicitly consider reductions due to: a) Inelastic behavior; and b) Expected over-strength. The rational use of 'maximum' and 'cumulative' ductility strength spectra should be the basis for the rational and transparent formulation of strength reduction factors for practical performance-based seismic design [6].

VIII. CONCLUSIONS

Damage models that quantify the severity of cumulative loading through plastic energy are simple tools that can be used for practical seismic design. The concept of constant cumulative ductility strength spectra, developed from one such model, is a useful tool for performance-based seismic design.

Seismic design of ductile structures, located in firm soil, should focus on controlling their maximum ductility demand. Nevertheless, even for motions with low energy content, the maximum ductility demand should not be too close to μ_u.

The results obtained in this paper suggest that providing earthquake-resistant structures with enough lateral strength to control its maximum ductility demand within the threshold of $0.7\mu_u$ is enough to avoid incipient failure or collapse. Constant cumulative ductility strength spectra can be used to identify cases in which cumulative plastic demands may become a design issue, and provide quantitative means to estimate the design lateral strength required to avoid failure due to low cycle fatigue. In the case of long duration motions with narrow frequency content, strength requirements should be such that they control adequately the maximum and cumulative ductility demands in the structure according to: $\mu_{\max} \le 0.7\mu_u$ & $NE_{H\mu} \le \frac{1.5}{2-b}(\mu_u - 1)$, respectively.

In this case, the value of R used for design purposes should not exceed the value of μ_u. Studies are currently being carried out to define if constant 'cumulative' ductility strength spectra should complement or substitute the use of constant 'maximum' ductility strength spectra during seismic design of ductile structures located in the TABAS. As for structures that exhibit irregularities and exhibit rapidly deteriorating hysteretic behavior, the set of tools discussed herein become sensitive to the specifics of the local and global hysteretic behavior, and, thus, its application becomes less reliable.

While the tools discussed herein can be used to determine the strength and ultimate deformation requirements of ductile structures with stable hysteretic behavior, a more stringent application should be considered for structures with erratic seismic behavior. In this respect, the effects of upper modes and of stiffness and strength degradation in constant 'cumulative' ductility strength spectra should be assessed. Finally, it should be considered that some type of soils, other than those located in the Tabas, may exhibit high levels of energy content that may imply the need for using 'cumulative' ductility strength spectra.

NOMENCLATURES

b: structural parameter that characterizes the cumulative deformation capacity

J : The number of water units

DMI_{MH} : Miner's Hypothesis (linear cumulative damage theory)

DMI_S : Simplified damage model to assess the occurrence of low cycle fatigue

DMI_{PA} : Park and Ang. damage index

$E_{H\mu}$: Plastic energy demand

F_y : Strength at yield

N_{exc} : Total number of plastic excursions

$NE_{H\mu}$: Normalized plastic energy, cumulative ductility associated to a constant cumulative ductility strength spectra

r: reduction factor used to characterize the cyclic deformation capacity of a system

$SDOF$: single-degree-of-freedom

T: Fundamental period of vibration

T_s, T_g : Corner or dominant period of ground motion

β : Constant in Park and Ang. damage index that characterizes the cumulative deformation capacity of a reinforced concrete element or structure

δ_C : Cyclic displacement associated to a plastic excursion

δ_p, δ_{pi} : Plastic displacement associated to a plastic excursion, subscript indicates *i*th Excursion

δ_{ucp} : Ultimate cyclic plastic displacement capacity

δ_y : Displacement at yield

μ: maximum ductility demand associated to a constant maximum ductility strength spectra

μ_c : Cyclic ductility, δ_C / δ_y

$\mu_{\max}$: Maximum ductility demand

μ_p, μ_{pi} : Plastic ductility associated to a plastic excursion, δ_p / δ_y and δ_{pi} / δ_y, respectively (subscript indicates *i*th excursion)

μ_u : Ultimate ductility, δ_u / δ_y

μ_{ucp} : Ultimate cyclic plastic ductility, δ_{ucp} / δ_y

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