Evaluation of seismic damage of building structures designed by the constant ductility approach

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The characteristics of the seismic damage experienced by structures designed based on the constant ductility approach are investigated in this study. The constant ductility response spectra of 45 earthquake records are constructed by conducting an inelastic dynamic analysis on Single Degree of Freedom (SDF) models in the period range of 0.0 to 5.0 sec. The cyclic damage resulting from the seismic responses of the SDF models is evaluated using the equivalent number of displacement cycles having the maximum ductility amplitude (N_e). The correlations between N_e and the system period, the ductility factor and the frequency content of the ground motion are investigated. The results indicated that N_e is dependent on the ductility factor of the SDF system. The higher is the ductility factor, the greater is the equivalent number of displacement cycles at the maximum ductility amplitude. Also, this study presents guidelines to introduce the effect of cyclic damage into the design procedures of the current seismic codes.

في هذه الدراسة تم بحث سمات التلف الزلزالي المعرضة إليه المنشآت المصممة طبقا لطريقة الممطولية الثابتة. فقد تم إنشاء أطياف الممطولية الثابتة لعدد 45 سجل زلزالي و ذلك بالقيام بتحليل ديناميكي لا مرن علي نماذج ذات درجة حرية واحدة في مدى الزمن الدوري من صفر الى خمس ثواني. و قد تم تقييم التلف الدوري الناتج عن السلوك الزلزالي للنماذج ذات درجة الحرية الواحدة باستخدام عدد دورات الإزاحة المكافئة عند مدى الممطولية الأقصى N_e. و قد تم دراسة مدى الارتباط بين N_e و بين الزمن الدوري و معامل الممطولية و المحتوى الترددي للحركة الأرضية. و قد أوضحت النتائج أن N_e تعتمد علي معامل الممطولية. فكلما زاد معامل الممطولية زادت عدد دورات الإزاحة المكافئة عند مدى الممطولية الأقصى. كذلك عرضت هذه الدراسة بعض الإرشادات لإدخال تأثير التلف الدوري إلي طرق التصميم الخاصة بأكواد الزلازل.

Keywords: Dynamic analysis, Inelastic analysis, Seismic design, Response spectra, Damage indices.

1. Introduction

The equivalent static force approach is adopted in building codes for estimating the seismic design forces. This approach is dependent on the use of a constant ductility inelastic design spectrum to provide information on the peak pseudo acceleration response for any Single Degree Freedom (SDF) system having a specific period, damping ratio and a maximum ductility factor.

The constant ductility inelastic design spectrum can be constructed by conducting an inelastic dynamic analysis on SDF models if the acceleration record of the earthquake is known. Also, it can be constructed based on an elastic design spectrum and appropriate force reduction factors (R_μ). The force reduction factor accounts for the structural inelastic deformation and is mainly dependent on the maximum ductility factor of the system (μ).

This approach of calculating the seismic design forces based on the constant-ductility inelastic response spectrum is adopted in most international seismic design codes because of its relative simplicity. However, in this approach, the estimated design forces are independent of the level of seismic damage experienced by the system due to the repeated loading cycles. The calculated design forces are only dependent on the maximum displacement experienced by the system due to the seismic response.

The objective of the current study is to investigate the characteristics of the seismic damage experienced by structures designed based on the constant ductility approach. The study objective is achieved by constructing constant ductility inelastic response spectra of 45 different ground motion records and evaluating the damage experienced by the SDF systems of these spectra using the equivalent number of displacement cycles having the maximum ductility amplitude (N_e). The effects of the period, the displacement ductility factor of the structure and the frequency content of the earthquake on the characteristics of the experienced damage are evaluated. Also, this study presents guidelines to introduce the effect of cyclic damage into the design procedures of the current seismic codes.

2. Constant ductility inelastic response spectrum

The constant ductility inelastic response spectrum of a specified ground motion and a specified damping ratio is a plot of the peak pseudo acceleration response of an inelastic SDF system having a unit mass versus the natural period of the system. Each plot is drawn for SDF systems having a constant maximum ductility factor, and several of these plots for different maximum ductility factors are included to cover the required range of maximum ductility factors.

The constant ductility inelastic response spectrum can be constructed approximately from the elastic response spectrum by estimating appropriate values of the force reduction factor R_μ, which represents the ratio between the elastic and the inelastic spectrum ordinates for fixed values of elastic period and maximum ductility factors (Miranda and Bertero [1]). The construction of the constant ductility inelastic spectra could be developed also through an exact approach by conducting an inelastic dynamic analysis on SDF models if the acceleration record of the earthquake is known.

The selected earthquake records in this study are 45 strong motion earthquakes which have been presented by Naumoski et al. [2]. The earthquakes cover a wide range of ground motion durations and frequency contents. The records are divided into three equal groups based on the ratio of the peak ground acceleration PGA in (g) to the peak ground velocity PGV in (m/sec.), commonly referred to as (A/V) ratio. The (A/V) ratio can be considered as a simple qualitative measure of the frequency content of the ground motion (Naumoski et al. [2]). The group of high (A/V) represents high frequency content earthquakes and contains records having A/V>1.2, while the group of intermediate (A/V) represents intermediate frequency content earthquakes and contains records having 0.8<A/V<1.2. The group of low (A/V) represents low frequency content earthquakes and contains records having A/V<0.8.

Constant ductility inelastic response spectra of the selected ground motion records are constructed using a developed computer program SPECTRUM. The program depends on using the inelastic dynamic analysis of SDF models for constructing the inelastic response spectrum. The damping ratio considered in the analysis is 5.0 %. The maximum ductility factors considered are 2, 4 and 8. Figs. 1-a, 1-b and 1-c represent the response spectra of the three earthquake groups (high A/V ratio, intermediate A/V ratio and low A/V ratio, respectively), constructed using the mean plus one standard deviation (M+SD) of pseudo accelerations of all the records in each group. Fig. 1-d shows the response spectrum of the whole earthquake ensemble constructed using the M+SD of pseudo accelerations of all the records in the three groups. The M+SD values are used to provide high level of confidence that the pseudo acceleration plots presented in the figures will not be exceeded by the pseudo acceleration responses of the individual records.

3. Seismic damage

The data obtained from the constant ductility inelastic response spectrum is limited to the maximum demands of ductility and it does not provide any information about effective damage potential of the earthquake that is related to the repeated loading cycles. Under the effect of cyclic loading, structures are expected to experience cumulative damage. Every cycle in a loading history causes damage, and even though this damage may not cause noticeable deterioration in strength, it will affect the onset and the rate of deterioration of strength at a later time (Krawinkler, [3]). The cumulative damage will cause the structural elements to fail at lower level of displacement as compared to the displacement level that can be reached under monotonic loading. This means that, under the effect of cyclic loading, the structure performance should be characterized by both ductility and accumulated damage. Thus, for a realistic assessment of performance, all inelastic cycles and their cumulative effect on damage should be accounted for.

Several damage models have been proposed to quantify numerically the level of damage to structures due to an earthquake. Detailed information and evaluation of damage indices can be found in Krawinkler [3], Grigoriu [4], Kappos [5] and Williams et al. [6]. Indices may be evaluated locally for an element, by measuring local response parameters of the flexural plastic hinges, e.g., strain, curvature, rotation, and the dissipated energy. Global damage indices for the whole structure are calculated by summing of the local indices by a weighing procedure.

In the current study the damage model proposed by Park and Ang [7] is considered. This damage model has been selected for its simplicity as well as its ability to take adequate account of the damage caused by the repeated loading cycles. The Park and Ang damage index (D) can be written as:

$$D = D_\mu + D_e = \frac{\delta_m}{\delta_{um}} + \frac{\beta \int dE}{P_y \, \delta_{um}} . \qquad (1)$$

Eq. 1 defines damage as a linear combination of the maximum displacement δ_m normalized by the monotonic displacement capacity δ_{um} (the ultimate displacement under monotonic loading) and the absorbed hysteretic energy $\int dE$ normalized by product of the yield force P_y and the monotonic displacement capacity δ_{um}. The absorbed hysteretic energy term is scaled by an empirical factor β.

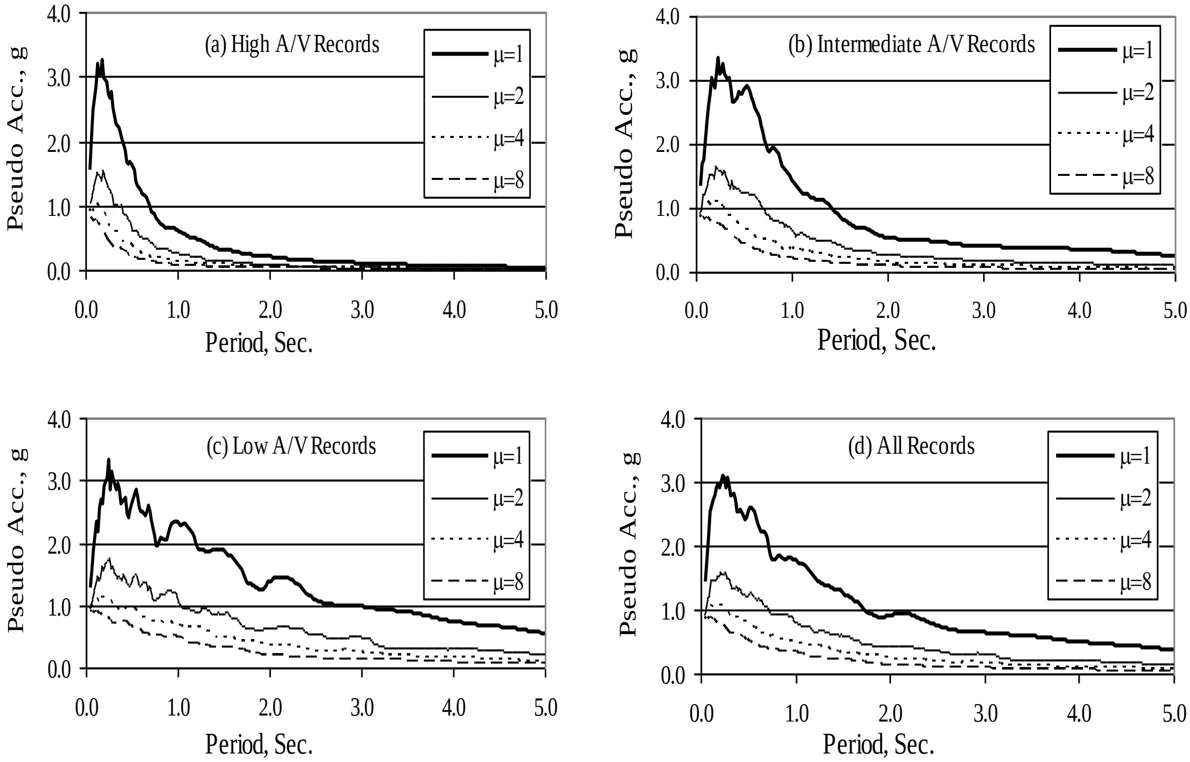

Fig. 1. Relationships between the period and the M+SD of pseudo accelerations.

The value of the empirical factor β can be estimated by calibrating the damage model using experimental work. The first term in eq. (1) (D_μ) is called the ductility-based damage index and represents damage contribution due to maximum displacement. The second term in eq. (1) (D_e) is the damage contribution due to the cyclic loading effects.

The drawback of the damage model presented in eq. (1) is in utilizing the total displacements without excluding the recoverable elastic part. This results in non-zero values of the damage index when the system acts elastically. This drawback can be eliminated by subtracting the recoverable yield displacement δ_y from the displacements δ_m and δ_{um} as suggested by Kunnath et al. [8]. In the current study, a modified version of the Park and Ang damage model is considered as follows:

$$D = D_\mu + D_e = \frac{\delta_m - \delta_y}{\delta_{um} - \delta_y} + \frac{\beta \int dE}{P_y(\delta_{um} - \delta_y)}. \qquad (2)$$

The absorbed hysteretic energy ($\int dE$) is estimated in terms of an equivalent number of complete inelastic displacement cycles (N_e) having ductility amplitude of δ_m. Assuming an elasto-plastic force-displacement relationship of the SDF model as shown in fig. 2, the relationship between ($\int dE$) and N_e can be estimated as follows:

$$\int dE = 4 N_e P_y(\delta_m - \delta_y). \qquad (3)$$

Substituting eq. (3 into eq. 2) yields:

$$D = \frac{\delta_m - \delta_y}{\delta_{um} - \delta_y} + \frac{4N_e\beta(\delta_m - \delta_y)}{\delta_{um} - \delta_y}$$
$$= \frac{(\mu_m - 1)}{(\mu_{um} - 1)}(1 + 4N_e\beta). \qquad (4)$$

Where, μ_m is the maximum ductility factor (the maximum displacement divided by the yield displacement), μ_{um} is the monotonic ductility capacity factor (the ultimate displacement under monotonic loading divided by the yield displacement) and N_e is the equivalent number of displacement cycles having ductility amplitude of μ_m.

Eq. (4) indicates that seismic damage is dependent on the maximum ductility factor μ_m as well as the equivalent number of displacement cycles N_e. This means that the description of any damage state should be based on determining both the levels of μ_m and N_e together. The damage index D is equal to 1.0, when reaching the maximum capacity of the structural response under the effect of earthquake loading. In this case, μ_m is equal to the cyclic ductility capacity factor μ_{uc} and eq. 4 can be rewritten as:

$$\mu_{uc} = \frac{(\mu_{um} - 1)}{(1 + 4N_e\beta)} + 1. \qquad (5)$$

Eq. (5) indicates that the cyclic ductility capacity factor (μ_{uc}) is dependant on the equivalent number of cycles at maximum capacity N_e. The greater is the number of inelastic cycles N_e, the higher is the absorbed hysteretic energy and the smaller is the cyclic ductility capacity μ_{uc}. The cyclic ductility capacity factor μ_{uc} approaches 1.0 when N_e approaches infinity and μ_{uc} approaches μ_{um} when N_e equals zero.

4. Seismic damage in building codes

Building codes generally specify certain level of the cyclic ductility capacity factor (μ_{uc}) for each structural system depending on the expected system performance under cyclic loading. For example, the level of μ_{uc} specified in building codes for brittle structures such as un-reinforced masonry is much lower than the level specified for ductile moment resisting frames. These levels of μ_{uc} are often determined based on experimental data of structural components subjected to histories of repeated inelastic loading cycles as well as field observation of the performance of existing structures during previous earthquakes. Usually, in building codes, there are no specifications to the design levels of the equivalent number of cycles at maximum capacity N_e associated with the specified levels of μ_{uc}.

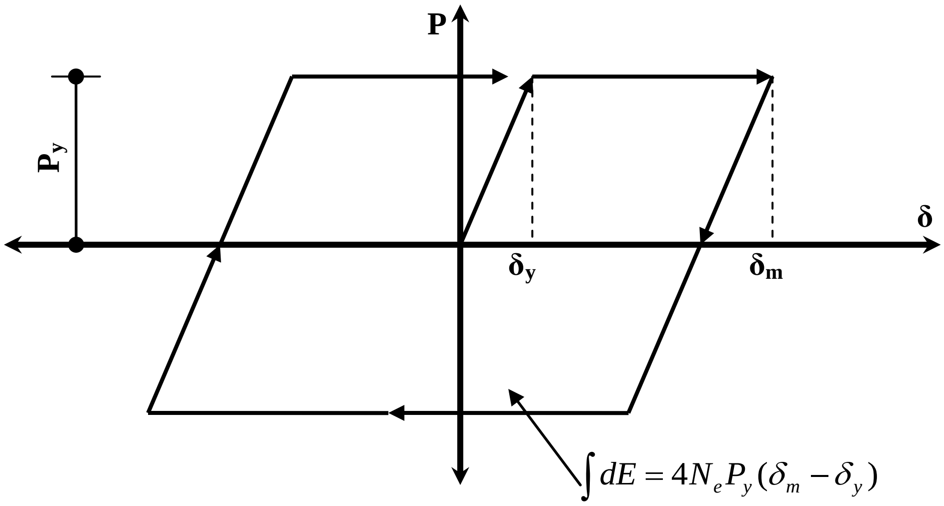

Fig. 2. Force-displacement relationship.

Moreover, no calculations are required to estimate the maximum demand level of N_e that is experienced by the designed structure when subjected to the design earthquake loading. The specified levels of μ_{uc} are used as target ductility levels of the designed structures regardless of the levels of cyclic damage which these structures are expected to experience. This trend in neglecting the effect of the repeated loading cycles in seismic design can be attributed to the approximate nature of the conventional seismic design procedures utilized in current building codes.

However, there is an exception to this trend in the New Zealand code (SANZ, 1992), where a level of N_e associated with the cyclic ductility capacities (μ_{uc}) is explicitly specified. In this edition of the New Zealand code, it is assumed that the structure should be capable of undergoing four cycles of lateral displacement at maximum ductility amplitude without a reduction in the load carrying capacity more than 20%. The 20% reduction in the load carrying capacity is considered to be equivalent to the failure state (D=1.0).

It should be noted that the "NZS 4203:1992" edition is now an obsolete standard as it has been replaced with the "NZS 1170.5:2004" standard. This newer standard does not explicitly state the same requirement of four cycles to maximum ductility amplitude. However, in the absence of specific guidance otherwise, most researchers are most likely still using the requirement of four cycles to a target displacement level without strength deterioration of more than 20% as the basis for assessing laboratory experiments of structural components.

Some may interpret the current approach of ignoring the calculations of the repeated loading cycles (N_e) by arguing that the structural components designed and detailed according to current code provisions have capacity levels of N_e (associated with μ_{uc}) greater than the demand levels of N_e that can be imposed by any earthquake. In other words, the structural components designed and detailed according to current code provisions can sustain the levels of μ_{uc} specified in the code even if they are associated with a history of repeated cycles that is more severe than any earthquake can cause.

Examining this interpretation requires conducting an analysis of seismic damage in order to present the demand levels of N_e experienced by the SDF models when subjected to the earthquake loadings. It also, requires estimating the levels of N_e associated with the cyclic ductility capacities (μ_{uc}) specified in building codes.

5. Analysis of seismic damage

Cyclic damage experienced by the SDF systems used in constructing the constant ductility response spectra is evaluated by estimating the levels of N_e for each earthquake record in the period range of 0.0 to 5.0 sec. This is achieved first, by calculating the absorbed hysteretic energy ($\int dE$) experienced during the earthquake response of the SDF system and second, by using eq. (3) to find the value of N_e that produces the same amount of hysteretic energy.

Figs. (3-a, 3.b and 3.c) represent the envelope (maximum) levels of N_e for each of the three earthquake groups. Fig. 3-d shows the envelope levels of N_e for all the records in the three earthquake groups. The results presented in fig. 3 indicate that the peak levels of N_e correspond to ductility factors of (2, 4 and 8) are (3.3, 4.7 and 6.1) for the high A/V records, (3.5, 4.4 and 5.4) for intermediate A/V records, (3.0, 4.2 and 5.1) for low A/V records and (3.5, 4.7 and 6.1) for all records.

Figs. (4-a, 4-b and 4-c) represent the M+SD levels of N_e for each of the three earthquake groups. Fig. (4-d shows the M+SD levels of N_e for all the records in the three earthquake groups. The results presented in Figs. 4 indicate that the peak levels of N_e correspond to ductility factors of (2, 4 and 8) are (1.6, 2.4 and 2.9) for the high A/V records, (1.8, 2.6 and 3.1) for intermediate A/V records, (1.7, 2.4 and 2.6) for low A/V records and (1.5, 2.1 and 2.5) for all records.

The results presented in figs. 3 and 4 indicate that N_e is dependent on the ductility factor of the SDF system. The higher is the ductility factor, the greater is the experienced number of displacement cycles at maximum ductility amplitude. Records having high and intermediate A/V ratios produce greater levels of N_e than the records having low A/V ratio. No clear correlation can be found between the period of the SDF system and the level of N_e.

The envelope levels of N_e presented in Fig. 3 provide 100% level of confidence that the level of N_e of an individual record is below the envelope value. However, it is not practical to use the envelope values of the seismic demands for design purposes due to economical reasons. The M+SD values are used to provide a reasonable level of confidence that the level of N_e of an individual record is less than the (M+SD) value. This level of confidence of the M+SD values is dependent on the distribution of the data.

The (M+SD) levels of N_e shown in fig. 4, are significantly lower than the level of N_e=4 which is considered in the New Zealand code. This may confirm the point of view discussed in the previous section that the structural components designed and detailed according to current code provisions can sustain the levels of μ_{uc} specified in the code even if they are associated with a history of repeated cycles that is more severe than any earthquake can cause.

However, there is still the fact that the designed structures will be subjected to variable levels of N_e depending on the structural properties and the characteristics of the ground motion. Therefore, there is still a need for the development of a rational approach to account for the effect of N_e in seismic codes as this would certainly allow some reduction in the seismic design forces and lead to more reliable and consistent seismic design procedures. The effect of N_e on the seismic design forces comes from the fact that the reduction factors (R_μ) are dependent on the cyclic ductility capacity factors (μ_{uc}) which are in turn dependent on (N_e) as indicated by eq. 5.

6. Accounting for the repeated loading cycles

Accounting for the repeated loading cycles in seismic design procedures adopted in seismic codes requires determining the following information:

1- The cyclic ductility capacity factors (μ_{uc}) as functions of the associated equivalent number of loading cycles at maximum ductility (N_e).

2- The demand levels of N_e imposed by the design ground motion record.

The relationships between μ_{uc} and N_e can be obtained using the damage model described by eq. (5). The value of the empirical factor β used in eq. (5) can be estimated by calibrating the damage model with results obtained from experimental work conducted on structural components.

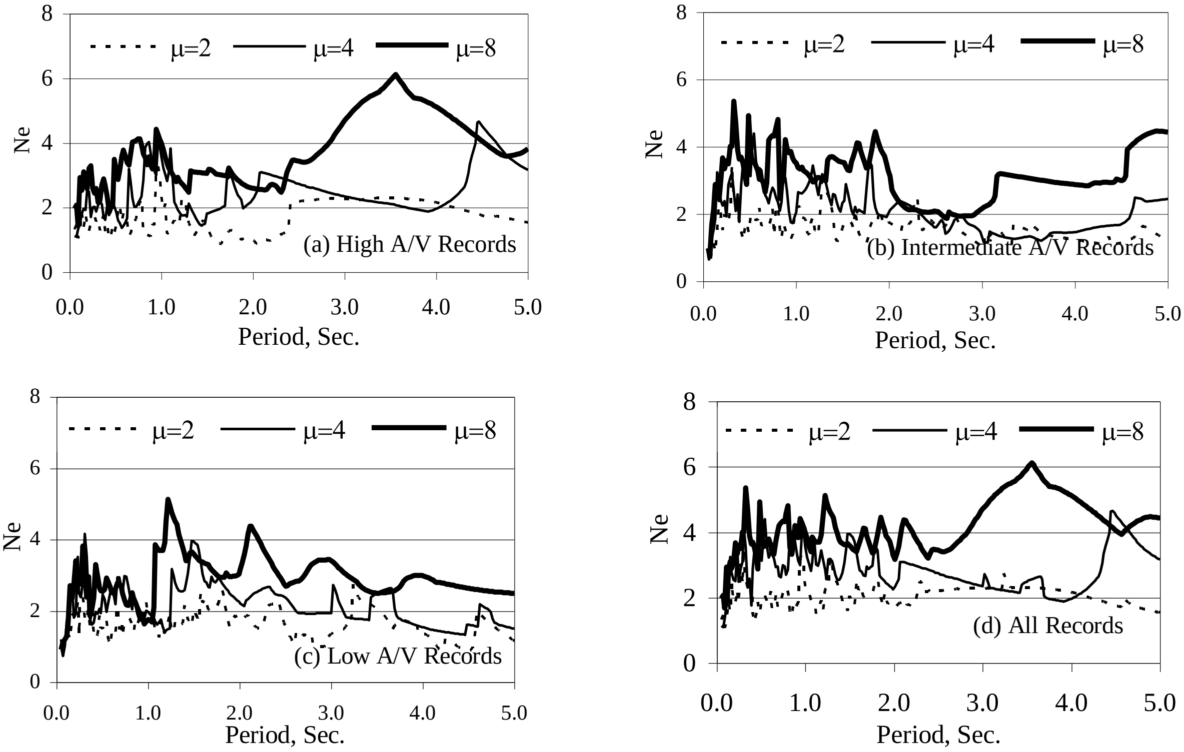

Fig. 3. Relationships between the period and the envelope levels of N_e.

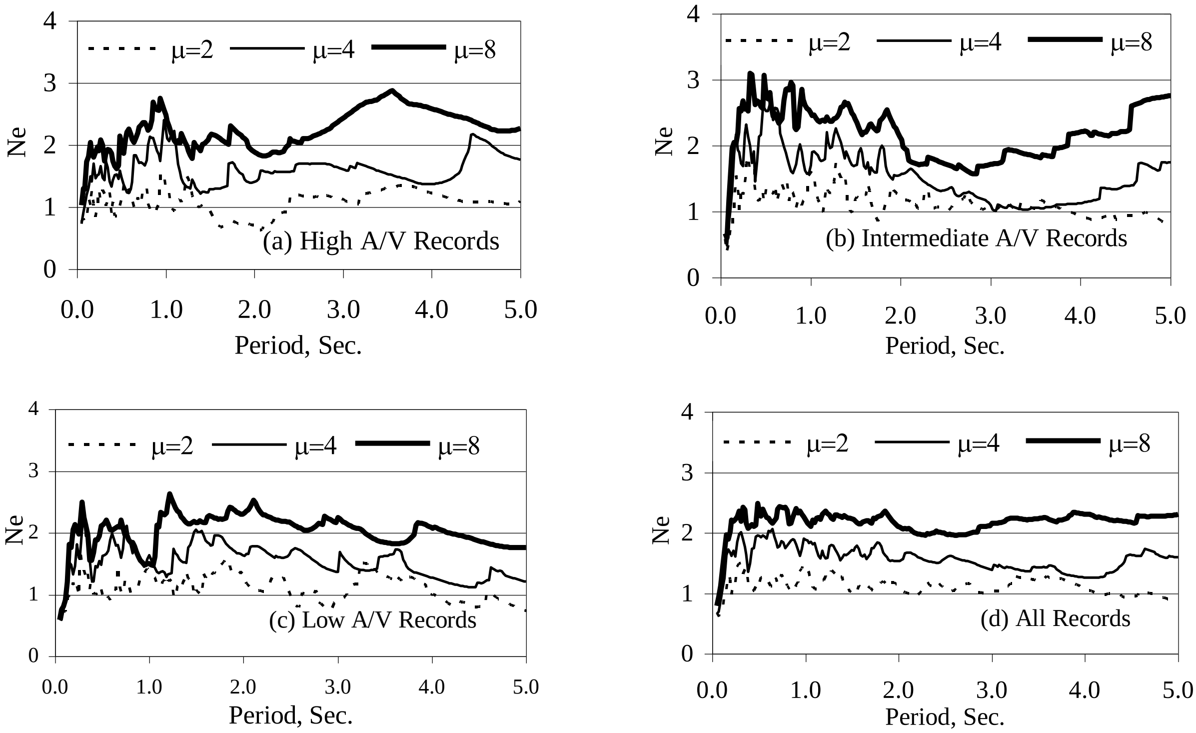

Fig. 4. Relationships between the period and the (M+SD) levels of N_e

The damage model of eq. (5) indicates that the greater is the number of inelastic cycles N_e, the smaller is the cyclic ductility capacity μ_{uc}. The cyclic ductility capacity factor μ_{uc} approaches 1.0 when N_e approaches infinity and μ_{uc} approaches μ_{um} when N_e equals zero.

The demand levels of N_e imposed by the design earthquake are obtained in the previous section. The results of the current study regarding the demand levels of N_e can be improved by increasing the considered number of ground motions. The results of the demand levels of N_e can be used to construct design charts to be provided in the seismic codes to enable the designer to determine the demand level of N_e which the structure is expected to experience under the effect of the design earthquake. The demand level of N_e can be calculated directly by conducting an inelastic dynamic analysis if the acceleration record of the earthquake is known.

It should be noted that the demand level of N_e is dependent on the ductility factor of the system as pointed out in the previous section. The higher is the ductility factor, the greater is the demand level of N_e imposed by the design ground motion record.

The force reduction factors (R_μ) are to be calculated explicitly as functions of the cyclic ductility capacity factors (μ_{uc}). In this case, the values of both μ_{uc} and R_μ will be dependent on the calculated level of N_e.

Conclusions

The results presented in this study indicate that the experienced number of displacement cycles at maximum ductility amplitude (N_e) is dependent on the ductility factor of the system. The higher is the ductility factor, the greater is the experienced number of displacement cycles at maximum ductility amplitude.

Records having high and intermediate A/V ratios produced greater levels of N_e than the records having low A/V ratio.

No clear correlation can be found between the period of the system and the level of N_e.

Accounting for the effect of N_e in current seismic codes requires introducing the cyclic ductility capacity factors as functions of the associated levels of the equivalent number of loading cycles at maximum ductility factors along with providing the demand levels of N_e imposed by the design ground motions.

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