13th World Conference on Earthquake Engineering
Vancouver, B.C., Canada
August 1-6, 2004
Paper No. 3205

ENERGY-BASED PERFORMANCE EVALUATION OF DETERIORATING STRUCTURES

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SUMMARY

The seismic performance of deteriorating structures is investigated by employing energy-based hysteresis and damage models. Low-cycle fatigue principle forms the basis of both models where damage is expressed as the reduction in the effective stiffness. The model parameters are calibrated by using the experimental data obtained from reinforced concrete specimens subjected to constant and variable amplitude displacement cycles. The results indicate that both displacement demands and damage in deteriorating structures increase significantly due to the degradation of stiffness and strength under strong ground motions from large magnitude earthquakes which cause a significant number of inelastic displacement cycles due to their long effective durations.

INTRODUCTION

Deterioration in the mechanical properties of concrete, masonry and steel structures are usually observed under repeated cyclic loading in the inelastic response range. Therefore such a behavior becomes critical when these types of structures are subjected to ground motions with specific characteristics. The first important characteristic is the presence of a long acceleration pulse, leading to a large peak ground velocity. Such a dominant pulse produces excessive displacement and inter-storey drift demands which in turn causes damage in structures.

The second important characteristic is the presence of a significant number of large amplitude acceleration cycles during the effective durations of ground motions. This is generally a result of the fault-rupture process during a large magnitude near-field event, when the fault rupture characteristics are directly reflected into the ground motion. Although the amplitudes of these cycles may be less than the dominant pulse, their compound effect is detrimental, especially on systems which degrade under repeated significant excitation cycles.

In this study, an energy-based low-cycle fatigue model is proposed for degrading systems. The model parameters are calibrated by using the experimental data obtained from reinforced concrete specimens. The displacement controlled loading histories are composed of either constant amplitude or variable amplitude cycles. Furthermore energy-based hysteresis and damage models are developed for Single

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Degree of Freedom (SDOF) systems. Damage is expressed in two parts. The first part is related to the maximum response displacement whereas the second part is related to low-cycle fatigue. The objective of this paper is to evaluate the comparative performance in deteriorating and non-deteriorating systems subjected to severe strong ground motions from large magnitude earthquakes.

DETERIORATION IN STRUCTURAL SYSTEMS

Structural systems can be classified into two groups according to the behavior they exhibit when they are subjected to cyclic loading in the inelastic response range: a) Non-deteriorating systems, b) Deteriorating systems. Non-deteriorating systems show no or very little strength degradation under cyclic loading. Systems with stiffness degradation are also included in this group. Such structures exhibit stable hysteresis loops with constant energy dissipation in each constant-amplitude cycle. However deteriorating systems, or systems with both stiffness and strength deterioration as defined in this study, cannot maintain stable cyclic energy dissipation under cyclic loading. Although they can maintain their initial strength at larger displacements, they exhibit reduced cyclic energy dissipation under constant amplitude cycles. Therefore cyclic energy dissipation capacity can be employed as a convenient measure in differentiating between non-deteriorating and deteriorating systems.

In this study, a two parameter low-cycle fatigue model is used to quantify the deterioration characteristics of structural systems. As shown in Figure 1, the relationship between the energy dissipation capacity per cycle (normalized with respect to the first cycle energy dissipation) and the number of constant amplitude cycles is defined in the form of an exponential function.

$$\overline{E}_{h,n} = \alpha + (1-\alpha)e^{\beta(1-n)} \tag{1}$$

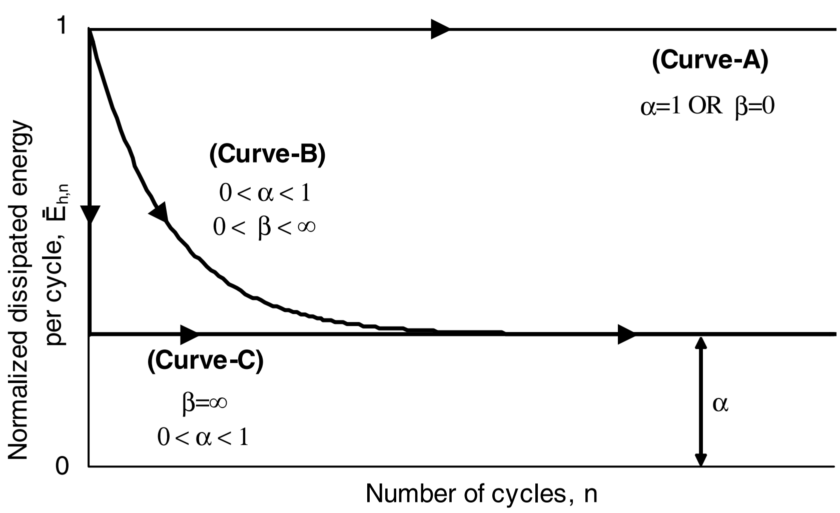

Figure 1. Energy-based fatigue model with two parameters (α, β)

Here, $\bar{E}_{h,n}$ is the normalized dissipated energy at cycle n, α and β are the two fatigue parameters. The first parameter α is related to the level of degradation at large values of n and the second parameter β is related to the rate of degradation. A system with α=0 loses all of its energy dissipation capacity as $n\rightarrow\infty$, whereas a system with α=1 never loses its energy dissipation capacity (Curve-A in Figure 1). An elastic-perfectly plastic system is an example of a non-deteriorating system with α=1. The second parameter β has a wider range between 0 and ∞, and it represents the rate of loss in cyclic energy dissipation capacity. In the limit, β=0 means no degradation whereas $\beta=\infty$ defines a system which loses all of its energy dissipation capacity after completing the first cycle (Curve-C in Figure 1). Curve-B in Figure 1 shows a typical system with realistic fatigue parameters having values between the upper and lower limits.

Experimental results obtained from different reinforced concrete specimens are employed in order to calibrate the low-cycle fatigue parameters and to relate them to the general behavior of structural systems under cyclic excitation. The experimental data used is listed in Table 1 with the characteristic properties of each specimen. The second, third and the fourth columns represent the name of the specimen, the researchers that conducted the experiments and the year of the research, respectively. The fifth column shows the pattern employed in the cyclic loading history: constant amplitude loading (CA) or variable amplitude loading (VA). The next five columns give information about the structural properties which may have influence on the response of the tested specimens: compressive strength of concrete (f_c), shear-to-span (a/d) ratio, axial load level (N/f_cA_g), longitudinal reinforcement ratio (ρ_l) and transverse reinforcement ratio (ρ_t). The next two columns contain the values of the low-cycle fatigue parameters α and β calibrated for each specimen in the list. For constant amplitude (CA) and variable amplitude (VA) cyclic test data, an inverse solution procedure is employed to estimate the model parameters. This is achieved by employing a least square estimation based on fitting the analytical and the experimental cumulative dissipated energy versus number of cycles relationship.

Table 1. Properties of reinforced concrete beam-column specimens subjected to cyclic loading

No	Name	Researchers	Year	LH	f_c (MPa)	a/d ratio	N/f_cA_g	ρ_l (%)	ρ_t (%)	α	β	Class
1	WS1	Wight and Sozen	1973	CA	33.5	2.87	0.115	2.4	1.5	0.85	0.20	ND
2	WS2	Wight and Sozen	1973	CA	33.5	2.87	0.115	2.4	1.5	0.90	0.30	ND
3	WS3	Wight and Sozen	1973	VA	26.1	2.87	0.147	2.4	0.5	0.45	1.80	MD
4	WS4	Wight and Sozen	1973	VA	33.6	2.87	0.071	2.4	0.3	0.60	1.20	MD
5	SO1	Saatcioglu and Ozcebe	1989	VA	37.3	2.86	0.131	3.2	2.0	0.95	0.30	ND
6	SO2	Saatcioglu and Ozcebe	1989	VA	37.3	2.86	0.126	3.2	2.0	0.95	0.40	ND
7	SO3	Saatcioglu and Ozcebe	1989	VA	34.8	2.86	0.141	3.2	1.7	0.60	0.40	MD
8	PJ1	Pujol	2002	CA	29.9	2.25	0.096	2.5	0.6	0.45	0.30	MD
9	ES1	Erberik and Sucuoglu	2002	CA	20.6	3.33	0	1.3	0.8	0.16	0.75	SD
10	ES2	Erberik and Sucuoglu	2002	CA	20.6	3.33	0	1.3	0.8	0.26	1.16	SD
11	ES3	Erberik and Sucuoglu	2002	CA	20.6	3.33	0	1.3	0.8	0.23	0.81	SD
12	ES4	Erberik and Sucuoglu	2002	VA	20.6	3.33	0	1.3	0.8	0.15	0.80	SD

In the last column of the table, the specimens are classified according to their estimated low cycle fatigue parameters. The abbreviation "ND" denotes theoretically a non-deteriorating, or in practice a slightly deteriorating system with α parameter closer to unity and β parameter closer to zero. Examples of this sort of behavior belong to test specimens WS1, WS2 (Wight [1]), SO1 and SO2 (Saatcioglu [2]). For these specimens, parameter α ranges between 0.85-0.95 and parameter β ranges between 0.2-0.4. The force-deformation (F-u) relationships for WS1 and SO1 are shown in Figure 2 for the sake of demonstration. These curves represent a desired behavior with stable loops and with little stiffness and strength degradation.

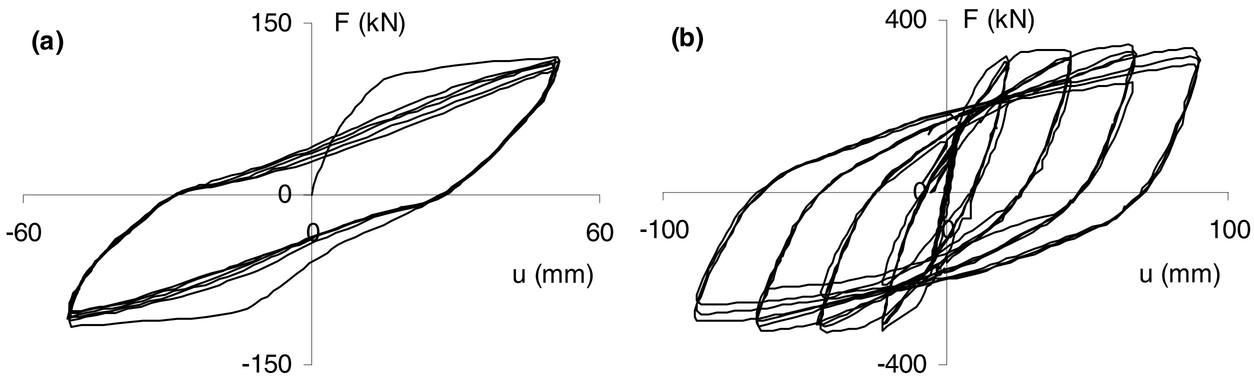

Figure 2. Force-deformation (F-u) relationships for specimens a) WS1 and b) SO1 which are classified as non-deteriorating systems (ND)

The abbreviation "MD" denotes moderate deterioration in structural members. Examples of this sort of behavior belong to test specimens WS3, WS4, SO3 and PJ1 (Pujol [3]) with parameter α ranging between 0.45-0.60 and parameter β ranging between 0.3-1.8. The observed behavior for "MD" type of structural members includes gradual degradation in strength with increasing cycle number and slight pinching; however the specimen can still dissipate a considerable amount of energy after a significant number of cycles. Such a behavior is presented in Figure 3 for the specimens WS4 and SO3.

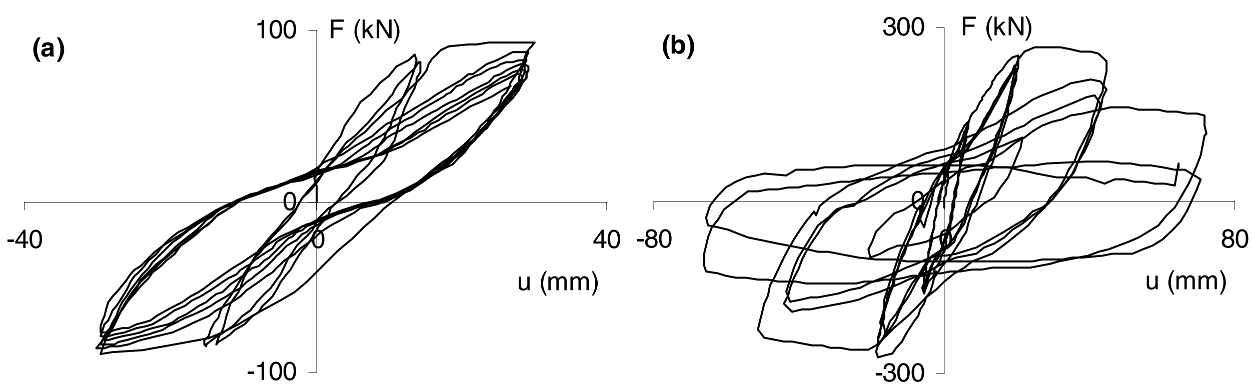

Figure 3. Force-deformation (F-u) relationships for specimens a) WS4 and b) SO3 which are classified as moderately deteriorating systems (MD)

The abbreviation "SD" denotes severe deterioration in structural members. Examples of this sort of behavior include test specimens ES1, ES2, ES3 and ES4 (Erberik [4]). The specimens used in this test program were intentionally designed to behave poorly under cyclic loading. Straight bars were used as longitudinal reinforcement, which caused excessive bar slip even in the early stages of displacement reversals. Such serious bar slip further caused excessive pinching in all specimens which reduced the energy dissipation capacity significantly. The strength deterioration is drastic which also causes significant reduction in energy dissipation capacity. The force-deformation curves given in Figure 4 for specimens ES3 and ES4 validate this behavior. For "SD" type of structural members in the table, parameter α ranges between 0.15-0.26 and parameter β ranges between 0.75-1.16. These four test specimens are only the selected ones from the test program given in this reference. The average values of α and β including all the tests in the program was 0.2 and 0.8, respectively.

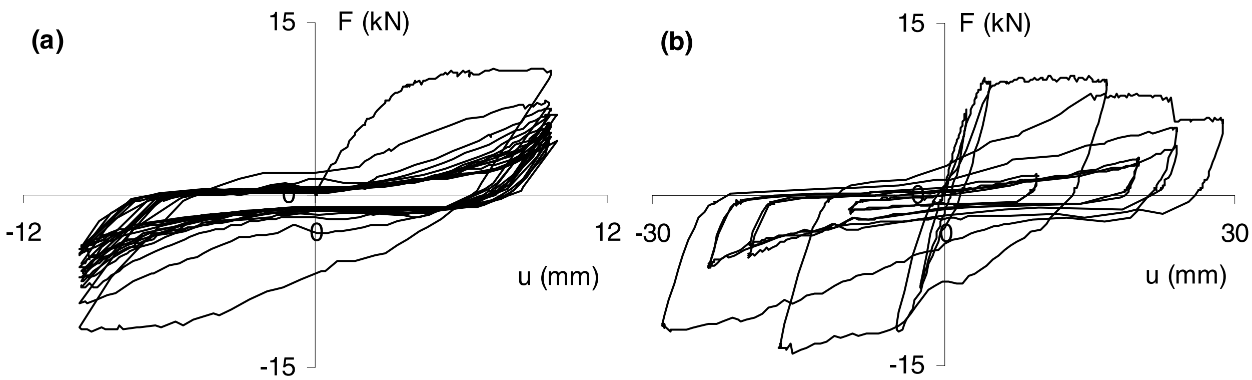

Figure 4. Force-deformation (F-u) relationships for specimens a) ES3 and b) ES4 which are classified as severely deteriorating systems (SD)

For the seismic performance evaluation of deteriorating structures, three different classes of structural systems are defined based on the aforementioned experimental database. These classes are defined as non-deteriorating (ND) system, moderately deteriorating (MD) system and severely deteriorating (SD) system and a different pair of low cycle fatigue parameters (α, β) is assigned to each class. For ND systems, although it is not very possible to observe a perfect hysteretic behavior with no strength degradation and no loss in energy dissipation capacity in practice, the theoretical values of α=1 and β=0 are assigned as the low cycle fatigue parameters. Considering the experimental results, the values of the parameters α and β for MD systems are taken as 0.5 and 1.0, respectively. Finally the low-cycle fatigue parameters for SD systems are taken as the average values obtained for the test conducted by Erberik [4] since the specimens used in this test program simulates severe degradation behavior quite well. Hence the selected values for α and β are 0.2 and 0.8, respectively.

Figure 5 presents the normalized dissipated energy per cycle ($\bar{E}_{h,n}$) versus cycle number (n) relationship for each specimen in Table 1, obtained by substituting α and β parameters into Equation 1. Three different levels of performance can be clearly distinguished from the grouping of the curves, each group corresponding to a class of structural system defined as ND, MD or SD. The group of curves at the top is an indication of superior structural performance whereas the ones at the bottom represent an inferior structural behavior. The group of curves in between has a wider band of data when compared to the other two sets of curves.

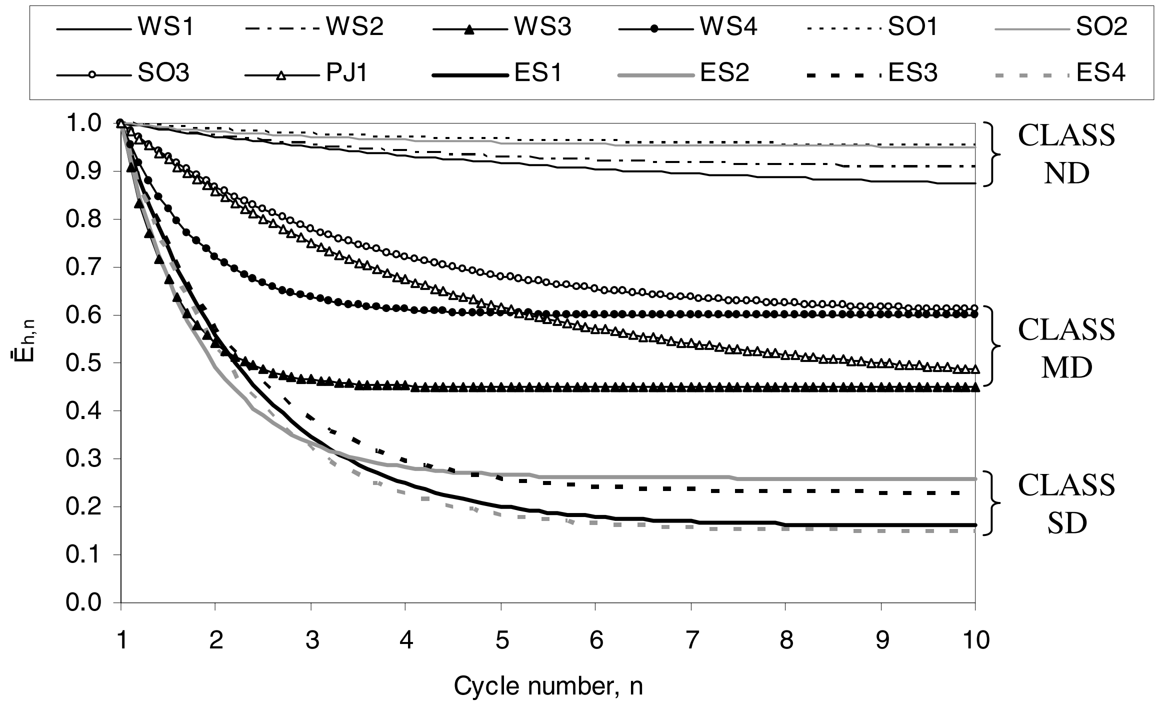

Figure 5. Normalized dissipated energy per cycle ($\bar{E}_{h,n}$) versus cycle number (n) relationship for each specimen in Table 1

ENERGY BASED HYSTERESIS MODEL

A simple piece-wise linear hysteresis model is developed for representing the force-deformation response of SDOF deteriorating systems. It operates on a bilinear skeleton curve and it is based primarily on the stiffness degrading model (Clough [5]), extended with an energy-based memory for simulating strength degradation. The energy-based fatigue model given in Equation 1 is employed for calculating the reduction in the energy dissipation capacity under repeated inelastic displacement cycles. Once the reduced energy dissipation capacity at an equivalent cycle number is predicted by the model, the force-displacement path is determined by reducing the strength capacity of the degrading system accordingly. Pinching is not considered explicitly in the generated force-deformation reloading paths, however loss of energy dissipation capacity due to pinching, or anchorage slip in reinforced concrete members, is the main feature of the model. A sketch of the model is given in Figure 6. The governing rules and details of the hysteresis model can be found in Sucuoglu [6].

Figure 7 and 8 demonstrate that the hysteresis model simulates the observed energy dissipation reasonably well for the test specimens under constant amplitude cyclic loading, although the parameter estimation is based on cumulative dissipated energy variation. The test specimens used for demonstration are ES3 and PJ1. In the figures, the comparison of the experimental and analytical force-displacement curves is given on the left and the comparison of the experimental and predicted normalized dissipated energy per cycle ($\bar{E}_{h,n}$) vs. cycle number relationship is given on the right. Full cycle definition is used here since constant amplitude loading history is symmetric. The same model can also predict energy dissipation characteristics under variable amplitude loading as shown in Figures 9 and 10. Cumulative dissipated energy per half-cycle (ΣE_h) vs. half-cycle number relationship for ES4 and WS4 are used for comparison since variable amplitude is not symmetric and amplitude of loading changes per half-cycle.

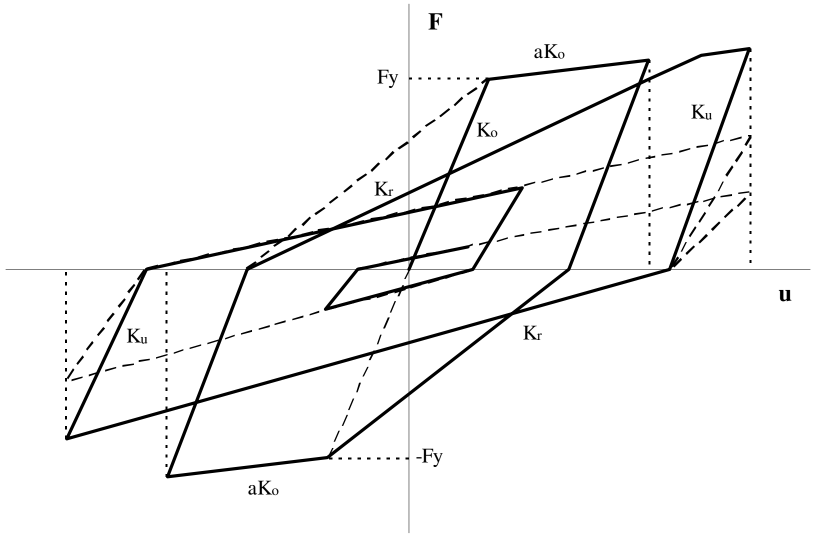

Figure 6. Sketch of the energy-based hysteresis model

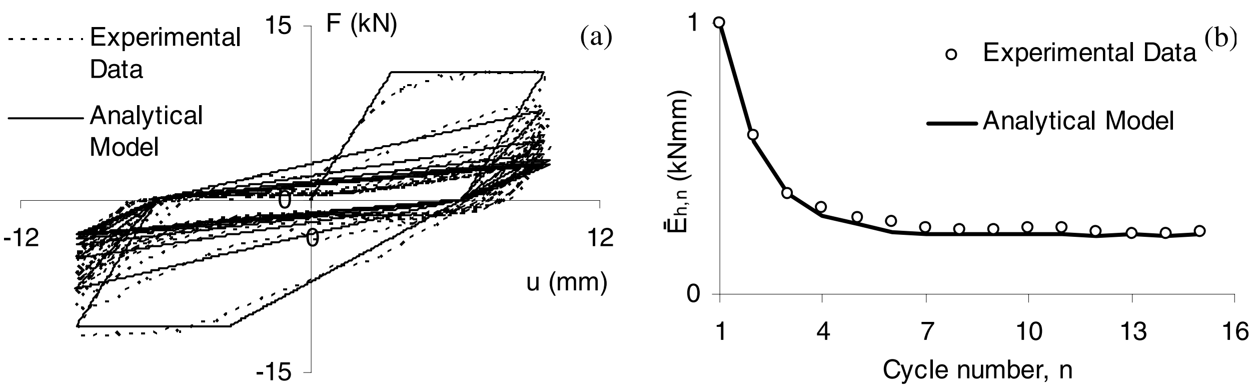

Figure 7. Comparison of experimental data and analytical model for ES3 in terms of a) force-deformation relationship, b) normalized dissipated energy per cycle–cycle number relationship

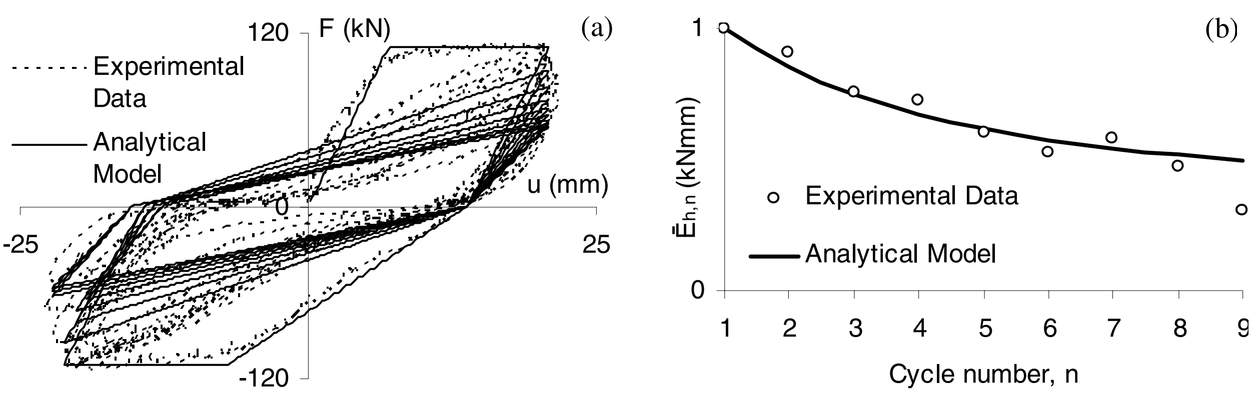

Figure 8. Comparison of experimental data and analytical model for PJ1 in terms of a) force-deformation relationship, b) normalized dissipated energy per cycle–cycle number relationship

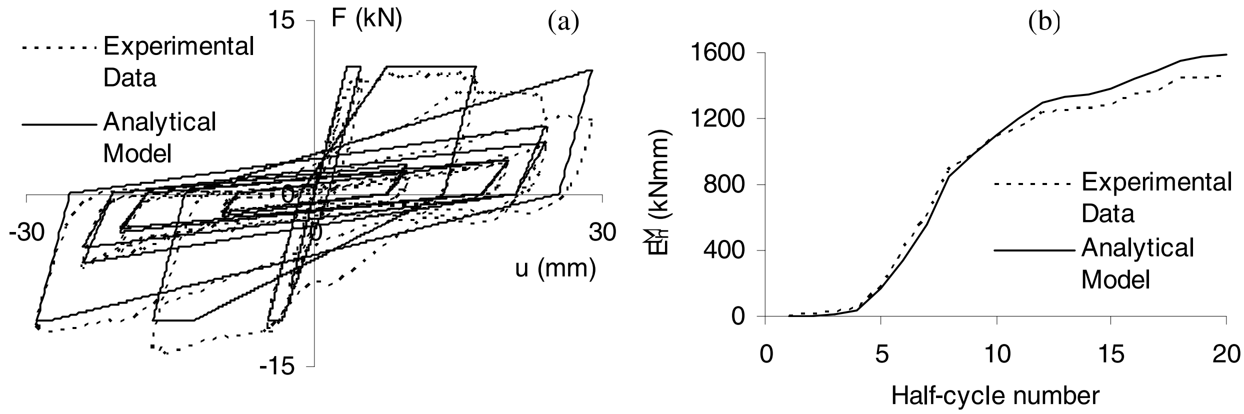

Figure 9. Comparison of experimental data and analytical model for ES4 in terms of a) force-deformation relationship, b) cumulative dissipated energy–half-cycle number relationship

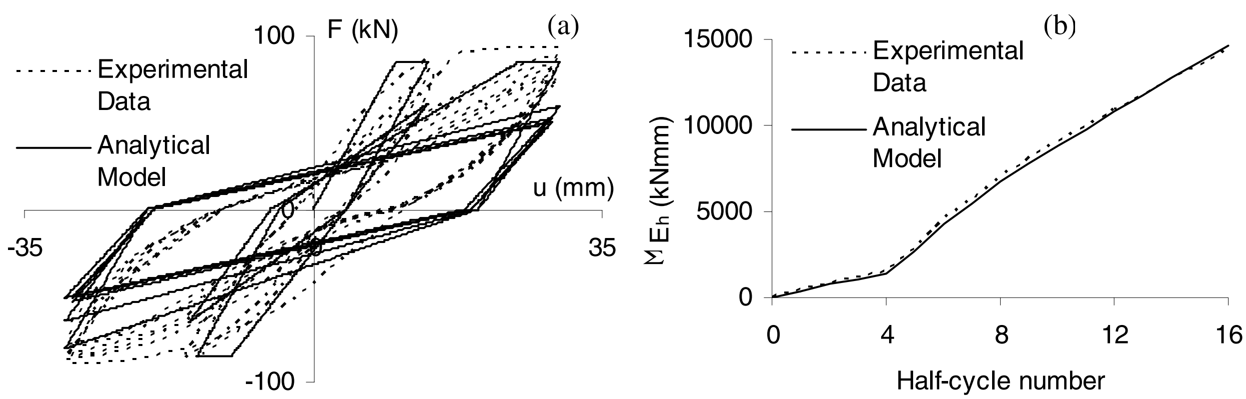

Figure 10. Comparison of experimental data and analytical model for WS4 in terms of a) force-deformation relationship, b) cumulative dissipated energy–half-cycle number relationship

ENERGY-BASED DAMAGE MODEL

Dissipated energy represents the complete response of a system throughout its entire response duration. Therefore deterioration of structural characteristics can be expressed in terms of the loss in energy dissipation capacity if appropriate physical links can be established.

A hybrid damage model is developed in this study for degrading systems which takes into account the combined effects of maximum displacement response and strength deterioration due to low-cycle fatigue, Displacement response and strength deterioration under seismic excitations are both expressed in terms of dissipated energy as explained in the previous section.

The damage model is adopted to a system which exhibit both stiffness and strength degradation, subjected to low-cycle fatigue cycles of constant displacement amplitude as illustrated in Figure 11 where the first and n^{th} cycles are shown. It is assumed that the energy dissipated during a variable displacement loading at any half-cycle, attaining a displacement amplitude u_m, is dissipated by low-cycle fatigue at a constant amplitude of um at n cycles. The projection of the intercept of the equivalent stiffness k_n with the initial yield level F_y on the displacement axis indicates that the same amount of damage would be experienced if the system was pushed to the displacement u_n. Accordingly, damage is expressed in two parts constituting u_n. One is due to the observed maximum displacement u_m, and the other is due to the additional displacement Δu_n arising from strength loss ΔF_n. Displacement component Δu_n is obtained by extending the effective stiffness (k_n) line of the n^{th} cycle until it reaches the horizontal initial capacity (F_y) axis. The value of Δu_n increases with the degradation of the system under constant amplitude displacement reversals. Both displacement components are transformed into damage measure through normalizing them with the plastic displacement capacity (ultimate displacement capacity minus the yield displacement) of the system. Analytical expression of the damage at the n^{th} cycle is given below.

$$D_n = \frac{u_m - u_y}{u_u - u_y} + \frac{\Delta u_n}{u_u - u_y} \quad (2)$$

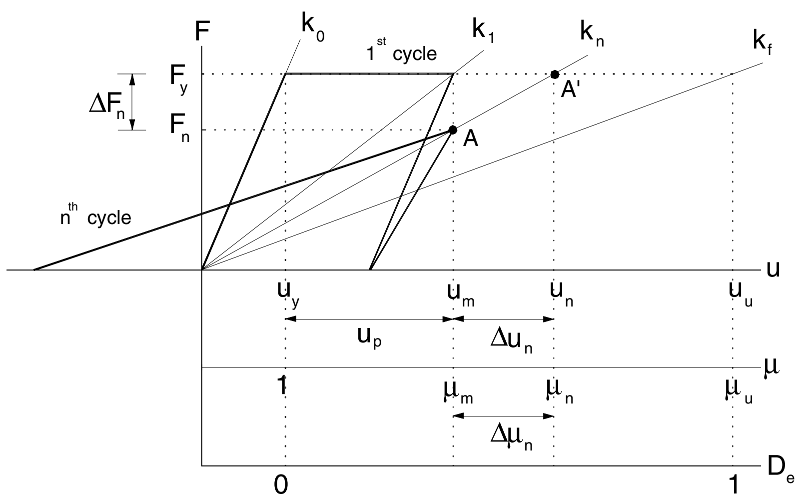

Figure 11. Geometric description of the damage model

DAMAGE ESTIMATION UNDER NEAR-FIELD GROUND MOTIONS

The energy-based hysteresis and damage models developed in this study are employed for estimating the seismic performance of inelastic SDOF systems under different strong motion excitations. This may provide an insight on the performance assessment of degrading systems during future earthquakes.

Three different ground motions are used for response analysis. These are the El Centro 1940 NS component (ELC), Yarimca NS component from the 17 August 1999 Kocaeli earthquake (YPT) and Duzce Meteorology Station NS component from the 12 November 1999 Duzce earthquake (DZC). The acceleration traces of the ground motions are shown in Figure 12. Peak ground accelerations are 340, 314 and 400 cm/s^2, and peak ground velocities are 35, 73 and 70 cm/s for ELC, YPT and DZC, respectively. All three ground motions were recorded in the near fields of their respective sources during strong earthquakes with magnitudes above 7.

Dynamic responses of degrading systems are calculated under the selected ground excitations. As mentioned before, three different sets of low-cycle fatigue parameters are considered. These are the values representing non-deteriorating (ND) systems (α=1, β=0), moderately deteriorating (MD) systems (α=0.5, β=1.0) and severely deteriorating (SD) systems (α=0.2, β=0.8), respectively.

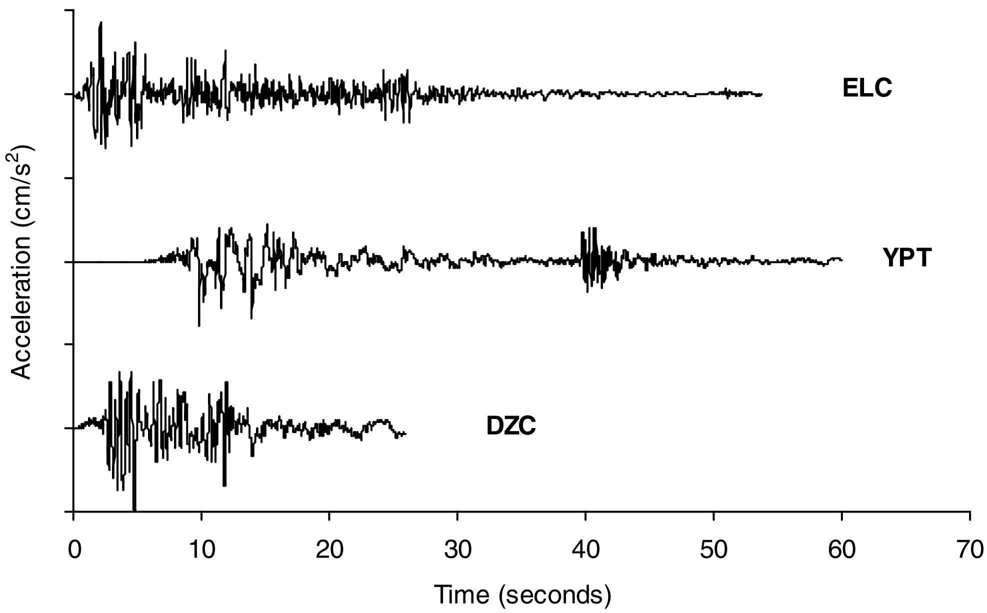

Figure 12. The ground motions used in inelastic response analysis: El Centro 1940 NS component (ELC), Yarimca NS component from the 17 August 1999 Kocaeli earthquake (YPT) and Duzce Meteorology Station NS component from the 12 November 1999 Duzce earthquake (DZC)

The displacement responses of degrading SDOF systems with 5% critical damping (ξ) and yield strength-to-weight ratio (η) of 0.2 are calculated using the ground motion records under concern. A sample of displacement response histories for the vibration period T equal to 0.5 second under the YPT record is shown in Figure 13. It is evident from this figure that both the maximum displacement response amplitude and the number of large-amplitude displacement cycles increase significantly with the level of deterioration under a strong ground excitation. The increase in the permanent displacement at the termination of excitation is also remarkable.

The spectral displacement responses of the elastic, ND, MD and SD systems under ELC, YPT and DZC are presented in Figure 14 in the form of inelastic to elastic spectral displacement ratios. Although the number of large amplitude displacement cycles cannot be compared from this figure, it is clearly observed that spectral displacements of deteriorating systems increase notably in the short and medium period ranges. Further the well accepted equal displacement rule, which is based on assuming equal elastic and inelastic spectral displacements in the moderate and long period ranges, does not hold for deteriorating systems in the moderate period range between 0.5 and 1.5 seconds. This range widens with the intensity of ground motion. Similar observations were also reported by Gupta and Kunnath [7], Gupta and Krawinkler [8] and Song and Pincheira [9].

Seismic damage accumulation with time for deteriorating systems induced above is calculated under the selected ground motions by using Equation (2) for SDOF systems up to T=2 second. Then the maximum damage obtained at the end of each seismic excitation is expressed in spectral form, presented in Figures 15, 16 and 17 for ELC, YPT and DZC records, respectively. In these figures, two components of the damage function D_n in Equation (2) are also shown separately. The first component is the damage resulting from the maximum response displacement or ductility, and the second component is the accumulated damage due to low-cycle fatigue. The second component only exists for the systems that exhibit strength deterioration (MD and SD), hence it is zero for the systems with no strength deterioration (ND).

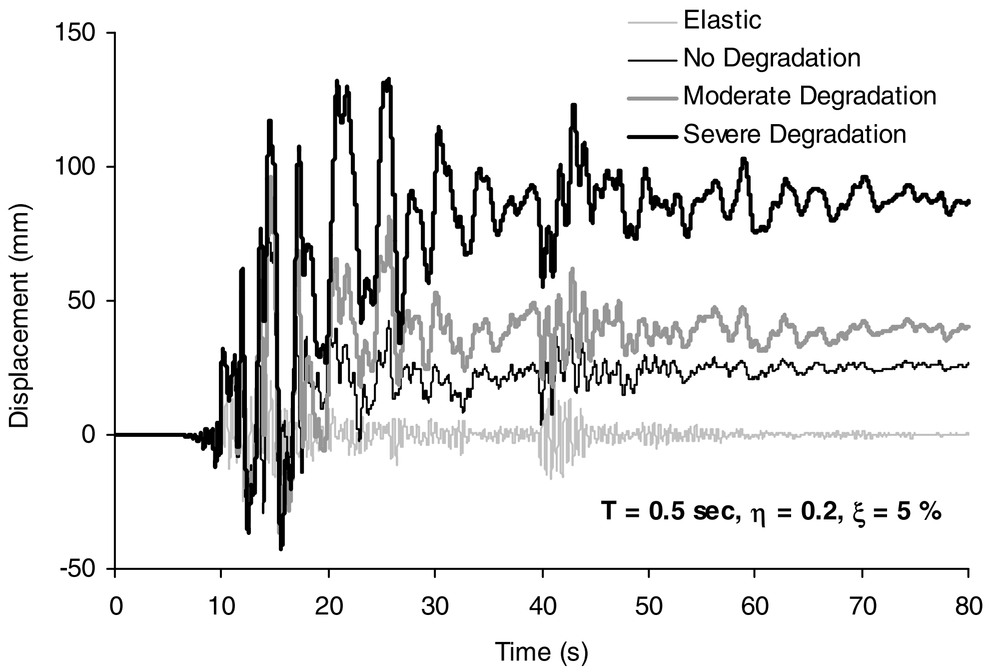

Figure 13. Displacement responses of elastic and inelastic deteriorating SDOF systems under the YPT ground motion record (T=0.5 second, ξ=5% and η=0.2)

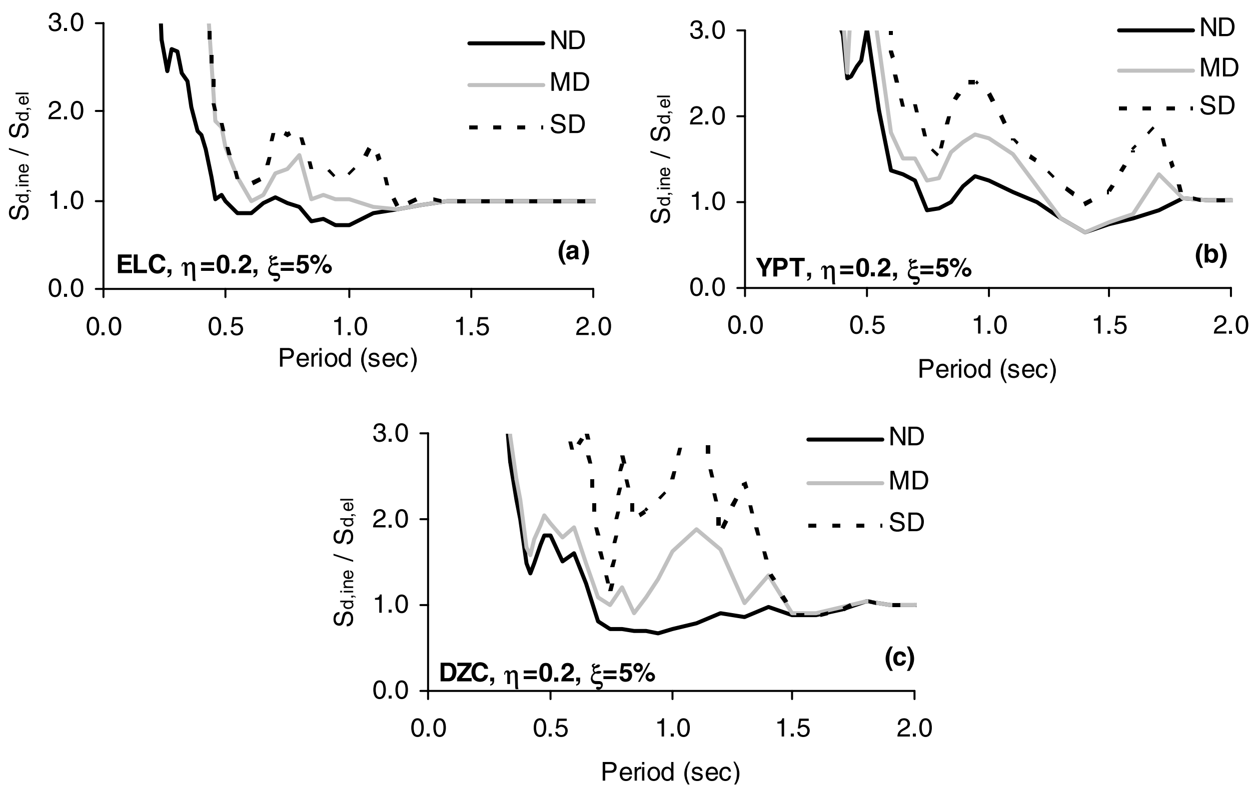

Figure 14. Inelastic to elastic displacement ratios for SDOF systems with η=0.2 subjected to a) ELC, b) YPT and c) DZC.

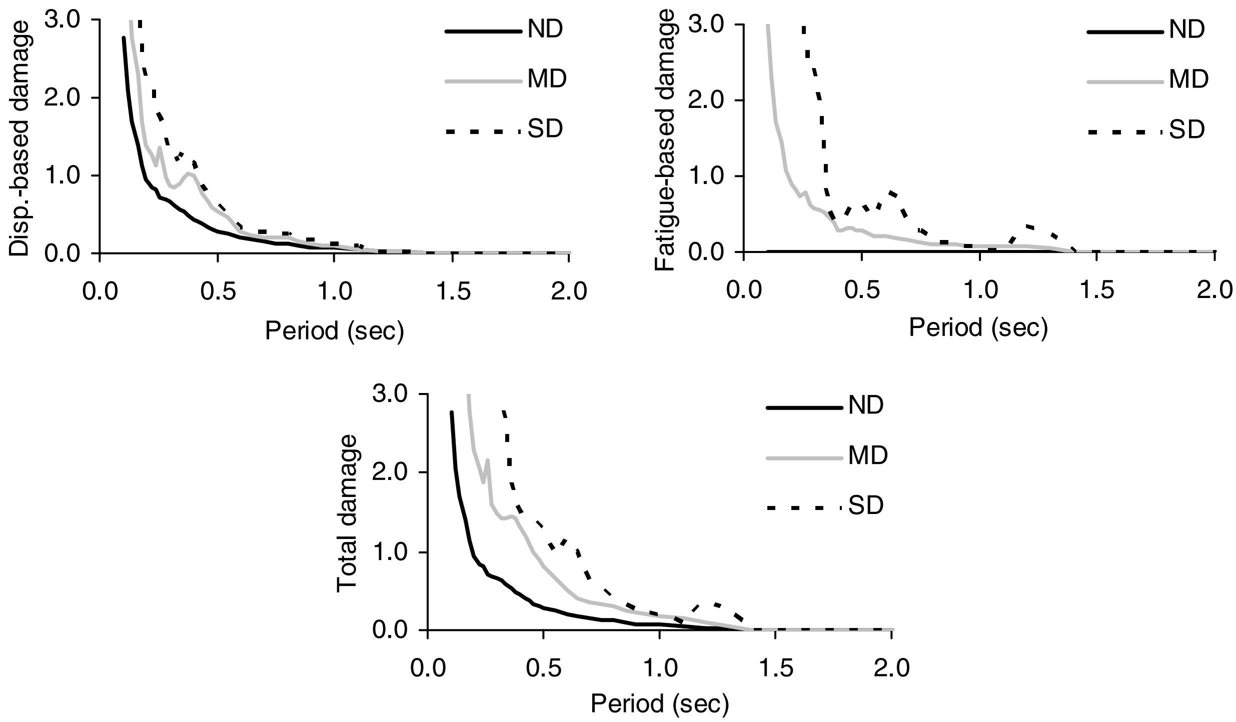

Figure 15. Spectral variation of total damage and its components under ELC for deteriorating systems with η=0.2 and ξ=5%

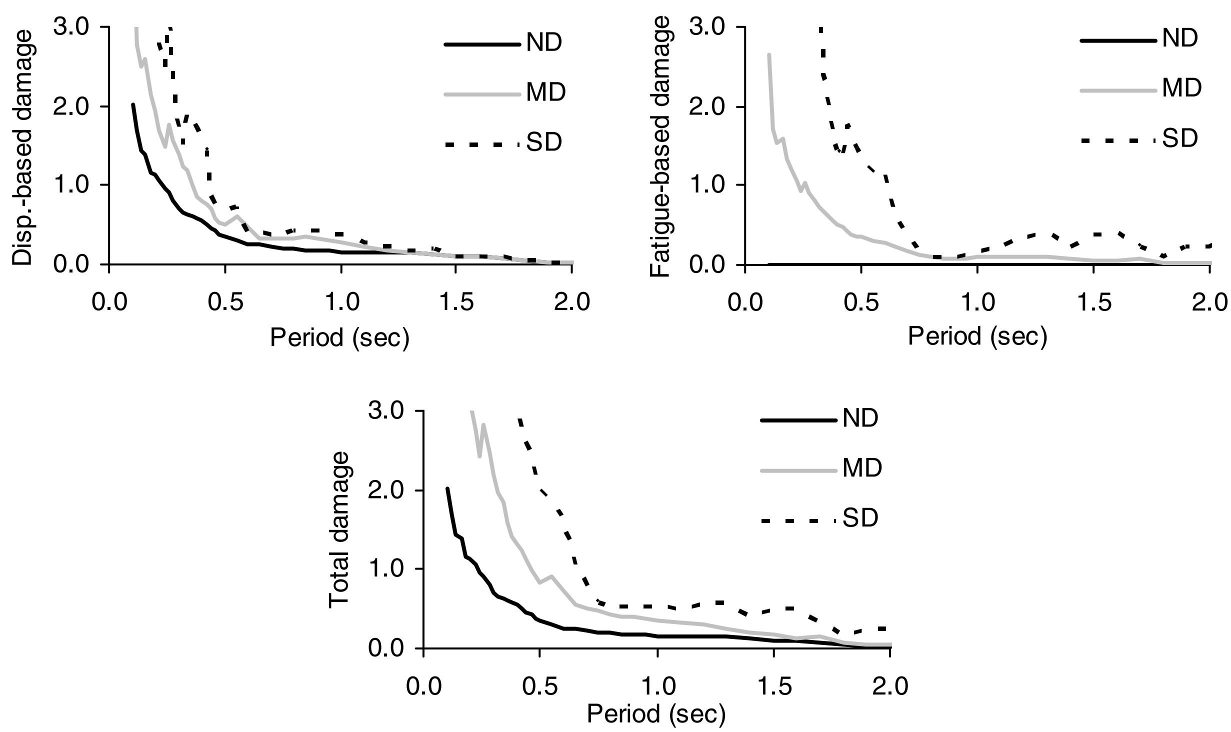

Figure 16. Spectral variation of total damage and its components under YPT for deteriorating systems with η=0.2 and ξ=5%

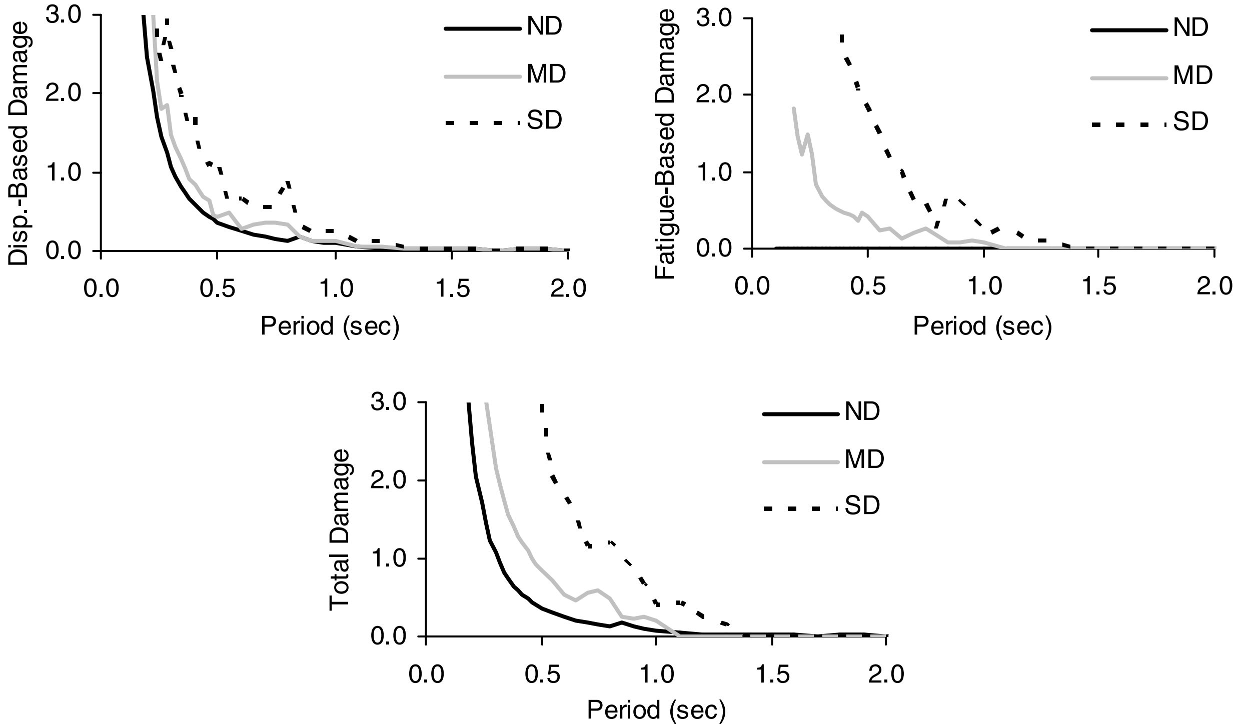

Figure 17. Spectral variation of total damage and its components under DZC for deteriorating systems with η=0.2 and ξ=5%

The figures reveal that the level of deterioration influences the fatigue based component of damage function much more than it influences the displacement based component. Although the displacement based component is affected from the level of deterioration only in the short period range, total damage is sensitive to deterioration over a wider range including both short and medium periods.

The ELC record may be considered weaker in intensity compared to the YPT and DZC records in view of the peak ground velocities. However its long duration has a significant influence on the fatigue based component of damage for deteriorating systems. Hence spectral distribution of damage for degrading systems under ELC is comparable to the damage distribution under the other two ground motions with higher peak ground velocity. Damage spectrum offers a broader definition for the intensity, or damage potential of ground motions since it contains the effect of the number of large-amplitude response cycles, or the effective response duration, which increases damage in deteriorating systems considerably.

Damage spectra for inelastic systems with constant strength ratio η are obtained as smooth curves, decaying inversely with the vibration period under the selected ground motion components as shown in Figures 15-17. In order to obtain a uniform spectral damage distribution over the entire period range, larger design strength ratios are assigned to shorter period systems in seismic design codes. Accordingly, damage spectra such as these shown in the above figures reflect the expected shape of the strength spectra for obtaining a uniform damage distribution. Therefore if strength deterioration under repeated displacement cycles is inherent under long duration seismic excitations, its effect on damage can only be compensated by a larger yield strength.

SUMMARY AND CONCLUSIONS

An energy-based hysteresis model is developed in this study for predicting the seismic response of deteriorating SDOF systems in terms of strength and energy dissipation capacity. Further, a damage model is proposed for measuring the seismic performance of degrading systems. Both models are verified by experimental results. Finally these models are employed for calculating the dynamic performance of degrading systems under strong ground motions. The following conclusions are obtained from the results of the presented study:

- The low cycle fatigue model with two parameters α and β formulated in terms of normalized dissipated energy gives reasonable estimates for calculating the losses in stiffness, strength and cyclic energy dissipation capacities of deteriorating systems.
- A hysteresis model that captures the variation of cyclic energy dissipation capacity predicts the response of degrading systems reasonably well.
- Spectral displacements of deteriorating systems increase significantly with the level of deterioration in the short and medium period ranges, significantly exceeding the elastic displacements.
- Permanent displacements at the end of ground excitations increase significantly with the level of deterioration
- Seismic performance of degrading systems reduce remarkably in the short and medium period ranges under long duration strong excitations which produce a number of significant response cycles. This reduction is mainly caused by the fatigue component of damage function and it has to be considered realistically in seismic performance evaluation of existing structures.

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