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A DETAILED EVALUATION ON DEGRADING BEHAVIOR OF STRUCTURAL SYSTEMS

Murat Altug Erberik[1] and Burak Kurtman[2]

ABSTRACT

Deterioration in mechanical properties of concrete, masonry and steel structures are usually observed under repeated cyclic loading in inelastic response range. Therefore such a behavior becomes critical when these structures are subjected to strong ground motions with specific characteristics. The objective of this study is to address the influence of degrading behavior on simple systems. The Structural Performance Database on the PEER web site, which contains the results of cyclic, lateral-load tests of reinforced concrete (RC) columns, is employed to quantify the degradation characteristics of simple systems by calibrating the selected degrading model parameters for unloading stiffness, strength and pinching. Obtained values of the parameters from cyclic test results are compared with the recommended values in literature. It is concluded that the combined effect of degradation parameters on seismic response of single degree of freedom (SDOF) models is evident, and the values of the degradation parameters that are employed in nonlinear seismic analysis should be selected carefully.

Introduction

Structures usually exhibit inelastic behavior under severe cyclic loading associated with strong ground motions. The load-deformation curve plotted under this inelastic action shows itself in the form of hysteresis loops. The hysteresis term refers to the memory nature of the inelastic system, meaning that the restoring force depends not only on the current deformation but also on the past deformations. Each hysteresis loop is a measure of the energy dissipated under cyclic loading as a result of internal friction within the structure and yielding of the structural members.

The performance-based design approach enables engineers to achieve more realistic and economical earthquake resistant design. The philosophy behind this approach is to determine the damage level of the structure. Hence information about the structural behavior and properties of hysteresis loops are very important. Under repeated cyclic loading, degradation in the mechanical properties of structural systems is usually observed in inelastic response range. Such deterioration should be taken into account, especially in seismic assessment of existing structures.

[1]Professor, Dept. of Civil Engineering, Middle East Technical University, Ankara 06531, Turkey
[2]Graduate Student, Dept. of Civil Engineering, Middle East Technical University, Ankara 06531, Turkey

Analytically, degradation of mechanical properties is reflected in load deformation relationship in three different forms: stiffness degradation, strength degradation and pinching. Samples from cyclic test results of reinforced concrete (RC) members that experienced aforementioned types of degradation are presented in Fig. 1. Numerous hysteresis models with stiffness and strength degradation, and pinching characteristics have been developed by different researchers (Takeda et al. 1970; Saiidi and Sozen 1979; Roufaiel and Meyer 1987; Kunnath et al. 1990; Stojadinovic and Thewalt 1996; Ibarra et al. 2005). The main objective of this research is to examine the degradation characteristics on seismic response of simple SDOF systems. For this purpose, Pacific Earthquake Engineering Research (PEER) Center Structural Performance Database is employed, which mainly includes quasi-static cyclic test results of rectangular and circular RC columns (Taylor and Stone 1993; Taylor et al. 1997). Selected degrading hysteresis model parameters are calibrated by using the test results and then compared with the recommended values in the literature, if any. In the last part of the study, effect of degradation parameters on the seismic behavior of single degree of freedom (SDOF) systems is investigated. This study is promising in the sense that it questions some of the commonly used degrading hysteresis model parameters and rules in the light of experimentally observed behavior and then examines the effect of experimentally calibrated parameters on the seismic response of degrading SDOF systems.

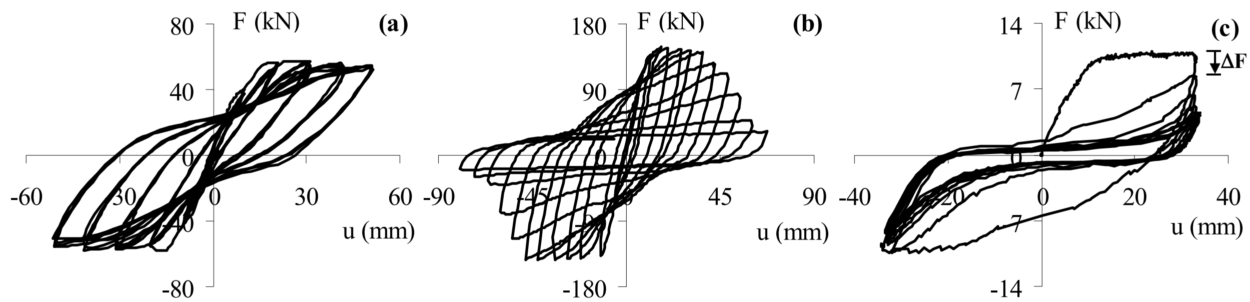

Figure 1. Samples of degradation modes observed in the columns under cyclic loading: a) stiffness degradation (Atalay & Penzien 1975); b) strength degradation (Takemura & Kawashima 1997); c) pinching (Erberik & Sucuoğlu 2004).

Experimental Database

In this study, 185 cyclic lateral load test results of rectangular RC columns with flexural failure from PEER Center Structural Performance Database (University of Washington 2002; Pacific Earthquake Engineering Research Center 2003) mode are considered. In addition, test results from Erberik and Sucuoğlu (2004) are included to the database, which add up to a total number of 196 tests. Detailed information regarding the properties of cyclic lateral load tests on rectangular RC column specimens can be found in tabular form elsewhere (Kurtman 2007).

Cyclic tests are classified in three groups in order to investigate the degradation characteristics of the selected RC specimens more specifically rather than considering the complete database with various material and geometrical parameters as well as different loading histories. The classification is conducted in terms of hysteretic energy dissipation characteristics of RC column specimens. Hysteretic energy dissipation as a numerical quantity is meaningless because of the differences in the yield strength, lateral stiffness, ductility, degradation characteristics and loading histories of the column specimens. The solution for this problem is to normalize the experimental dissipated energy values with respect to a reference value. Hence the ratio of experimental to theoretical cumulative dissipated energy, which can be considered as an "energy-based index", is employed as a non-dimensional measure for the classification of cyclic test results of RC columns in the database. Theoretical dissipated energy is calculated by using the well-known stiffness degrading model (Clough and Johnston 1966) in the literature. This simple and practical model represents stable hysteretic behavior of well detailed RC members, which makes it a good candidate to be used as a reference model. Hereafter, this model is called as "Clough model". The energy-based index, I_{EB}, is defined as the ratio of the cumulative experimental dissipated energy to the cumulative theoretical dissipated energy obtained from the Clough model and it is given as

$$I_{EB} = \frac{\sum_{i=1}^{N} E_{h,i(exp)}}{\sum_{i=1}^{N} E_{h,i(sd)}} \tag{1}$$

where N is the total number of half-cycles, $E_{h,i(exp)}$ is the experimental dissipated energy per half-cycle whereas $E_{h,i(sd)}$ is the theoretical dissipated energy per half-cycle. In calculations, force-based half-cycle definition (i.e. half-cycle bounded by two zero force points) is used.

Table 1 shows the classification of the cyclic test results in the database according to I_{EB}. The column specimens having an I_{EB} value of 0.85 or greater are assumed to be contained in "Group A", meaning that they are mostly well-designed specimens and can be modeled with an acceptable degree of accuracy with the Clough model. Generally, there are no or slight deterioration observed in Group A columns. The specimens which have I_{EB} values between 0.85 and 0.70 are contained in "Group B". In general, these specimens exhibit moderate degradation characteristics, especially strength and stiffness degradation but there are few tests that they exhibit also pinching behavior. The specimens that have I_{EB} values smaller than 0.7 are classified as "Group C". Most of the specimens in Group C have experienced severe degradation. Also pinching behavior is observed in approximately 30% of the specimens in this group.

Table 1. Classification of column specimens according to energy-based index (I_{EB})

Group	Range of values	Number	Percentage
A	$I_{EB} \geq 0.85$	41	20.9 %
B	$0.85 > I_{EB} \geq 0.70$	81	41.3 %
C	$I_{EB} < 0.70$	74	37.8 %
Total		196	100 %

Unloading Stiffness Degradation

The initial or elastic stiffness of an RC member deteriorates during the load cycles due to the cracking of concrete. This degradation is observed both in the unloading branch and the reloading branch of a hysteresis loop for an RC member. There are some well-known and widely used approaches for the unloading stiffness degradation in the literature. One of them is the "focus-based rule". The unloading branches aim at an imaginary and stationary point which is located at a distance of αF_y on the extension of the elastic branch on the opposite side. As a result, the unloading stiffness decreases with the increasing displacement ductility. Unloading stiffness can be calculated as

$$K_{un} = \frac{F + \alpha F_y}{u + \alpha\, u_y} \tag{2}$$

where (u,F) is the load reversal point, F_y is the yield force and α is the focus-based unloading stiffness degradation parameter (Fig.2). The focus-based rule has been used by the hysteresis model developed for the computer program IDARC (Park et al. 1987). Typical values recommended by IDARC for the focus-based stiffness degrading parameter α is as follows: For non-degrading behavior; α=200, for mild degrading behavior; α=15, for moderate degrading behavior; α=10 and for severe degrading behavior; α=4.

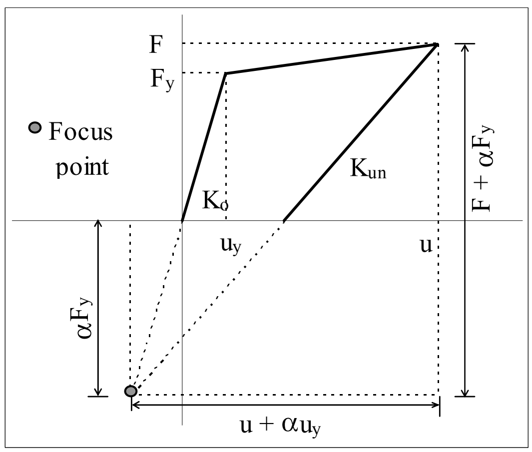

Figure 2. Simple sketch of focus-based unloading stiffness degradation rule.

20 cyclic tests are selected from each specimen group with experimental force-displacement relationships that have a linear type of unloading branch. After the selection of cyclic tests, the values of initial stiffness and unloading stiffness are calculated by fitting imaginary lines along the unloading branches of the experimental force displacement data, and the slopes of these lines are calculated from simple geometry. After the determination of values for the unloading stiffness parameters and the amount of deviation from initial stiffness for each unloading branch of the force-displacement relationship of the selected column specimen, statistical properties such as mean and standard deviation are computed. As a result, the obtained mean value of the unloading stiffness parameters can be considered as representative of that cyclic test, but also accounting for the variability in terms of standard deviation. The statistical results are presented in Table 2. Mean deviation from initial stiffness values in Table 2 indicates that there is a significant reduction in stiffness for all specimen groups. Hence assuming a non-degrading unloading stiffness branch in hysteresis modeling of RC members should be seriously questioned.

Table 2. Statistics for unloading stiffness degradation parameters

Parameter α	Group A		Group B		Group C	
	Mean	St. Dev.	Mean	St. Dev.	Mean	St. Dev.
Value	2.80	3.25	1.50	0.63	0.92	0.59
Deviation (%)	45.85	13.75	56.03	9.07	67.87	9.79

Strength Degradation

Strength degradation in RC structural members under cyclic loads is a great concern for engineers. In this study, cyclic strength degradation behavior of RC members during hysteretic response is investigated. Cyclic strength degradation is defined by FEMA 440 (Applied Technology Council 2005) as the lateral strength loss with increasing number of load cycles. Fig.1.c presents an example for experimental force-displacement relationship that demonstrates cyclic strength degradation.

Strength degradation is usually not uniform. In majority, experimental results show that in the first few cycles, strength degrades more rapidly and then it becomes nearly stabilized at a constant level for specimens with dominant flexural behavior (Taylor et al. 1997). The positive loading direction of the force-displacement relationship shown in Fig.1.c is such an example. A strength degradation rule is in terms of exponential formulation is suitable for modeling this behavior

$$\Delta F = A\ F_y\ (1 - e^{-B\,n\,\mu}) \tag{3}$$

where ΔF is the strength degradation per half-cycle, F_y is the yield strength, n is the half-cycle number at the same displacement amplitude and μ is the ductility ratio, in other words, the ratio of the maximum displacement of the half-cycle (u_m) to the yield displacement (u_y). In Eq.3, parameters "A" and "B" are for strength degradation. Parameter "A" is related with the degree of degradation and parameter "B" is related with the rate of degradation. In the limiting case of A=0.0, theoretically there exists no strength loss. However in the other limit when A=1.0, all strength capacity can be lost, depending on the rate of degradation, or in other words parameter "B". For the same value of parameter "A", larger the value of parameter "B", more rapid the strength degradation. Theoretically, parameter "B" can take values between zero and infinity, however the practical range of values is between 0.05-0.25.

The next step is to calibrate the strength degradation parameters by making use of the available test data. In this study, Gauss-Newton procedure is used to find the least squares estimates of the cyclic strength degradation parameters "A" and "B" for the nonlinear model given in Eq.3. This process is repeated for the selected column tests which have constant amplitude cyclic loading history. The results are presented in Table 3 in terms of statistical descriptors mean and standard deviation.

Table 3. Statistics for cyclic strength degradation parameters

Statistical parameters	**Slight-to-Moderate Degradation**		**Severe Degradation**	
	Parameter A	Parameter B	Parameter A	Parameter B
Mean	0.27	0.10	0.69	0.17
St. Deviation	0.09	0.04	0.19	0.07

Pinching

Pinching can be defined as narrowing of the hysteresis loops mainly due to the bond deterioration at the interface of reinforcing steel and concrete. In this study, the cyclic column tests in the database which exhibit pinching are used to calibrate and verify a well-known pinching rule, which was developed by Park et al. (1987). The pinching behavior is modeled with two different slopes for the reloading curve. First line of reloading aims at point B (see Fig.3) on the previous unloading branch which has a strength level of γF_y. When reloading reaches the displacement level of u_s which is the crack closure point (point C in Fig.3) reloading aims the initial target point (point A in Fig.3).

For the calibration of the pinching parameter γ, the dissipated energy values of experimental half-cycles are compared with the dissipated energy values of analytical half-cycles which are generated by considering the pinching rule. The experimental dissipated energy per half-cycle values are calculated from the available digitized force-displacement data. In addition, observed strength capacities at each half-cycle are recorded for the calculation of analytical dissipated energy values in order to isolate the effect of pinching behavior from the effects of strength and stiffness degradation behavior. The analytical half-cycles for the pinching rule are determined from the geometrical relations using the strength capacity of the actual half-cycle, maximum displacement value, initial elastic stiffness and the pinching parameter γ.

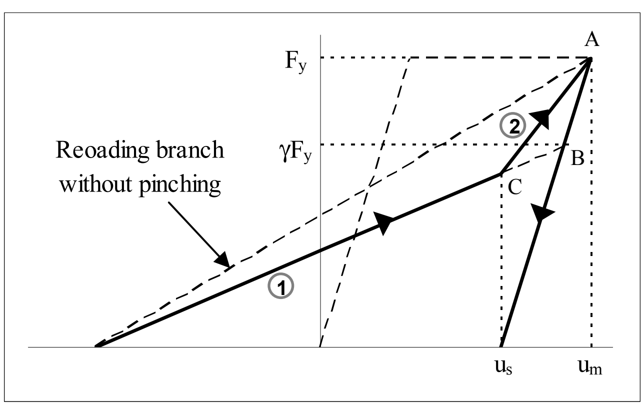

Figure 3. Simple sketch of pinching rule proposed by Park et al. (1987).

This procedure is then repeated for 397 pinched half-cycles extracted from the selected 25 cyclic column tests. The results are listed in Table 4. The values obtained for the cyclic tests in groups A and B have been combined together due to insufficient data. Hence the combined group is assumed to represent the specimens which exhibit slight-to-moderate degradation under cyclic loading.

Table 4 Statistics for the pinching parameter γ

Statistical Descriptors	Slight-to-moderate degradation		Severe degradation
	Group A	Group B	Group C
Number of data	1	8	16
Mean	0.76		0.56
St. Dev.	0.06		0.13

Effect of degradation parameters on the seismic response of SDOF systems

The seismic response of SDOF systems with various structural (in terms of period, strength ratio and damping) and degradation (in terms of unloading stiffness, strength and pinching parameters) characteristics have been obtained using a series of strong ground motion records from recent devastating earthquakes. However due to limited space, only a small fraction of the results are demonstrated in this section in order to give an idea about the effect of degradation parameters on seismic response of SDOF systems. For this purpose, only one ground motion record from 1999 Kocaeli, Turkey Earthquake is selected since the response values obtained from this record conforms with the general trend of response statistics obtained from the considered set of ground motion records. The trace was recorded at Yarimca Petkim Station (north south component), with a peak acceleration of 0.322g and a peak velocity of 79.6 cm/s.

Fig.4 presents the force-deformation relationships of SDOF systems with period T=0.5 seconds, strength ratio η=0.2 and damping ratio ξ=5% subjected to Yarimca NS record. The unloading stiffness degradation parameter values α=20, 4 and 0.5 represent slight, moderate and severe degradation levels, respectively. As observed, ductility ratios are not very different in cases of slight and moderate degradation, but increases in the case of severe degradation. In addition, unloading stiffness degradation causes the hysteresis loops to become narrower in terms of area and in turn, decreases energy dissipation capacity significantly as seen in Fig.4. Another observation is that the residual (offset) displacement values tend to decrease as the degradation in unloading stiffness increases.

Fig.5 presents the force-deformation relationships of SDOF systems with period T=0.5 seconds, strength ratio η=0.2 and damping ratio ξ=5% subjected to Yarimca NS record, in which only cyclic strength degradation is considered with values of parameters "A" and "B" (0.2, 0.05), (0.4, 0.1) and (0.6, 0.15) for the cases of slight, moderate and severe strength degradation, respectively. The plots show that deterioration in strength is accompanied by a slight increase in ductility demand. Furthermore, energy dissipation capacity decreases with increasing level of strength degradation although not as significant as in the case of unloading stiffness degradation.

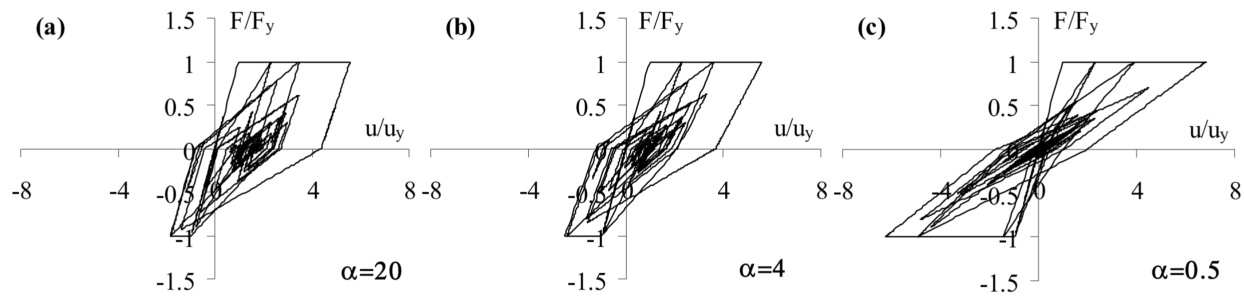

Figure 4. Force-displacement relationships of SDOF systems with unloading stiffness degradation (focus-based rule) subjected to NS component of Yarimca Petkim record (T=0.5s, η=0.2, ξ=5%).

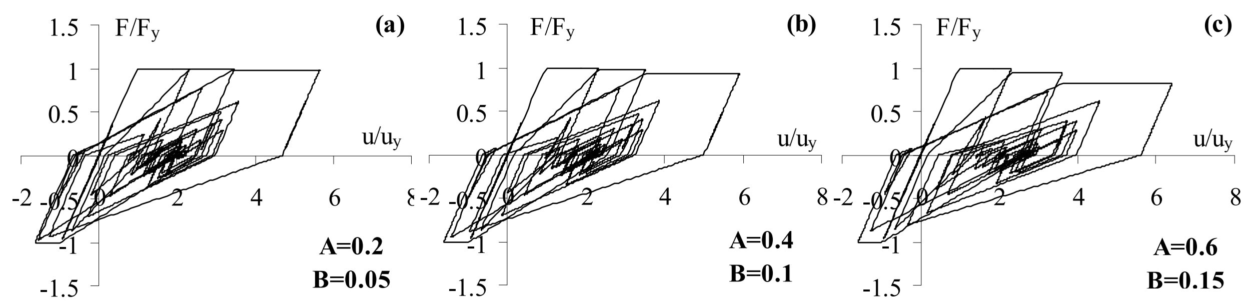

Figure 5. Force-displacement relationships of SDOF systems with strength degradation (exponential type) subjected to NS component of Yarimca Petkim record (T=0.5s, η=0.2, ξ=5%).

Fig.6 presents the force-deformation relationships of SDOF systems with period T=0.5 seconds, strength ratio η=0.2 and damping ratio ξ=5% subjected to Yarimca NS record, in which three values of parameter γ are considered: 0.75, 0.60 and 0.40, representing slight, moderate and severe levels of pinching. As it can be observed from Fig.6, ductility ratios are nearly the same for different levels of pinching. However the effect of pinching behavior on the shape of the hysteresis curve, and in turn, on the energy dissipation characteristics of simple systems can be significantly observed in the figures.

Finally, SDOF systems with combined unloading stiffness degradation, strength degradation and pinching characteristics are compared with non-degrading SDOF systems. Non-degrading model is selected as the Clough model. In severely degrading model, the parameters are taken as α=0.5, A=0.6, B=0.15 and γ=0.4. Fig.7 shows a typical comparison of force-deformation relationships of non-degrading systems and severely degrading systems subjected to Yarimca NS record. For both systems, the period is taken as T=0.5 seconds, strength ratio as η=0.2 and damping ratio as ξ=5%. It is observed that the ductility demand of severely degrading SDOF system is significantly larger than the ductility demand of non-degrading SDOF system. Furthermore, narrowing of cycles is observed, which is an indication of reduced energy dissipation capacity.

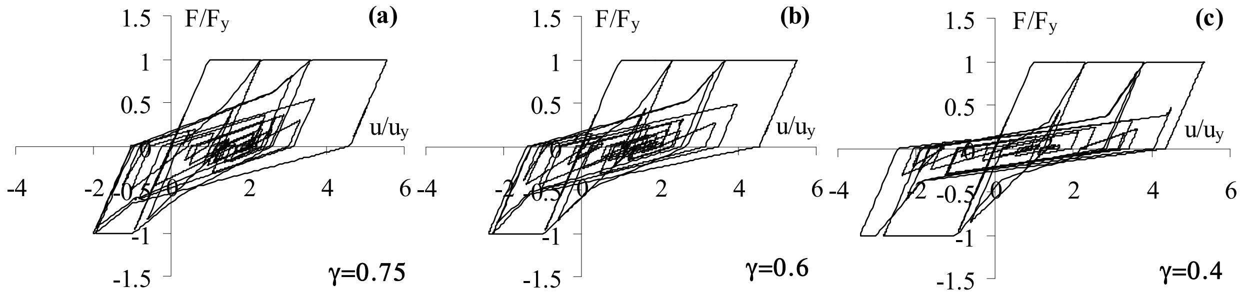

Figure 6. Force-displacement relationships of SDOF systems with pinching behavior (Park et al. rule) subjected to NS component of Yarimca Petkim record (T=0.5s, η=0.2, ξ=5%).

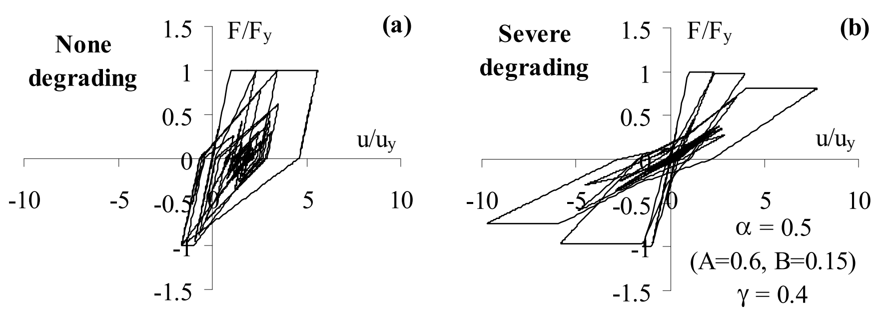

Figure 7. Force-displacement relationships of SDOF systems with none and severe-degradation subjected to NS component of Yarimca Petkim record (T=0.5s, η=0.2, ξ=5%).

Conclusions

Based on the limited experimental database, selected degrading model parameters and response history analyses with specific structural characteristics and ground motion records, the following conclusions can be stated:

- In general, a well detailed and designed RC member can exhibit a force-displacement relationship very close to the Clough (stiffness degrading) model, which is simple to implement and practical to use in structural analysis procedures.
- The experimental data reveals that unloading stiffness deviates significantly from the initial stiffness even in the case of slight-to-moderate degradation. Hence it is erroneous to assume a non-degrading unloading stiffness branch in modeling of structural members.
- When the values of the hysteresis model degradation parameters α and γ obtained after calibration are compared with the values in the literature, it is observed that the recommended values differ from the calculated values. Therefore, the recommended values for the aforementioned hysteresis model degradation parameters in the literature should be used with great attention in estimation of the actual cyclic behavior.
- Either detrimental or beneficial, unloading stiffness degradation seems to influence the residual displacement in SDOF systems under seismic action.
- When a single mode of degradation is considered, its effect on the dynamic response of

SDOF systems may not be so significant. However when all the degradation modes (unloading stiffness degradation, strength degradation and pinching) are combined in a structural system, the effect of degradation on response values (maximum displacement, residual displacement, hysteretic energy dissipation, etc.) becomes much more pronounced.

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