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SEISMIC RESPONSE OF DEGRADING SDOF SYSTEMS DUE TO NEAR-FIELD GROUND MOTIONS

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Abstract. *The effect of rupture directivity at near-fault sites is investigated. The study compares the ratio of maximum inelastic to maximum elastic displacement demand,* C_R*, for a wide range of SDOF systems subjected to fault-normal, near-field ground motions. Oscillators with both bilinear and quadrilinear backbones are considered. The quadrilinear oscillators include an elastic, a hardening and a negative stiffness branch that terminates at a horizontal plateau, and therefore this modelling is more suitable for simulating the real-world buildings, which degrade. A sensitivity analysis of the parameters that describe the SDOF systems is performed in order to study their effect on* C_R*. It is demonstrated how the seismic response varies with respect to the backbone parameters, the period and the seismic demand. The results show that the bilinear approximation, which is the common, underestimates the ductility demand compared to the quadrilinear case, regardless of the seismic intensity and the backbone parameters.*

1. INTRODUCTION

Near-fault ground motions with forward directivity are characterized by strong, coherent, long period pulses and permanent ground displacements. These properties differentiate the response of structures subjected to “non pulse like” ground motions. The special characteristics of near-field, forward directivity ground motions are directly correlated to the magnitude, the source type, the direction of rupture propagation relative to the site and also to the residual ground displacement resulting from the slip of the fault. The frequency content of near-field motions, which differentiates them from near-field non forward directivity and far-field ground motions, is not evident in every record in a zone approximately 20-60 km around the location of fault rupture. The impulsive character is present mainly in the strike-normal direction, generating the forward directivity effect (Somerville *et al.*1997, Baker, 2007). The effect of significant velocity pulses on the structural response was first highlighted by Bertero and Mahin (1978). Divergent views can be found in the literature, that either associate the directivity effects of near-fault ground motions to acceleration pulses (Makris and Black 2004, Sucuoglou *et al.* 1999) or to displacement pulses.

The conflicting opinions about the origin of directivity effects, which focus the influence of near-fault ground motions at different spectral regions and the elevated seismic demand they induce on structures, indicate the use of quadrilinear SDOF to simulate structural response far into the inelastic region. The deteriorating quadrilinear models can be used in order to obtain the response under high inelastic demand, where the system capacity is expected to degrade rather than steadily increase as in the case of bilinear systems. Furthermore, Ibarra *et al*. (2005) suggests that the backbone characteristics, and a parameter for cyclic deterioration may be sufficient to correspond to the structural response, regardless of the loading history.

The objective of this study is to investigate the effects of near-field ground motions on the inelastic behavior of single-degree-of-freedom (SDOF) systems with varying properties. Medians of the inelastic displacement ratio, C_R, of SDOF systems are shown for both bilinear and quadrilinear systems. The study emphasizes on the response of quadrilinear systems, since this is a more realistic description of the capacity of structures, while most contemporary literature refers to bilinear oscillators. The properties of a series of oscillators are varied, studying their effect on C_R, with respect to the ratio of the fundamental period over the pulse duration T_p.

2. INELASTIC DISPLACEMENT RATIO C_R

The inelastic displacement ratio, C, is defined as the maximum lateral inelastic displacement demand divided by the maximum elastic displacement demand, over the entire time history. Therefore, C is given by the expression (Chopra, 2007):

$$C = \frac{u_m}{u_y} = \frac{\mu}{R_y} \tag{1}$$

To compute C we adopt systems with given demand R_y, where R_y is the strength reduction factor equal to the ratio of acceleration demand S_a over the yield acceleration of the oscillator. The inelastic displacement ratio for given R_y, is denoted as C_R, being consistent with the notation in Miranda (2000). The assumption of given yield strength reduction factor R_y, has certain advantages over the constant-ductility case. Producing systems with selected yield strength reduction factor R_y, requires only linear and mainly invertible functions, since only one value of yield strength corresponds to a selected R_y value, while in order to calculate the C for systems with given ductility μ, requires an iterative procedure.

Current seismic design provisions for the computation of inelastic deformations are based on the inelastic design spectrum of Newmark and Hall (1982), which uses the R_y-μ-T_1, relationships of Veletsos and Newmark (1960). This equation has been the basis for several approaches to obtain approximate R_y-C_R-T relationships for near-field ground motions, as discussed in the following paragraph. According to the Newmark-Hall approach, C_R for far-fault ground motion record can be calculated as:

$$C_R(T_1) = \begin{cases} \infty & T_1 < T_a \\ (R_y^2+1)\big/2R_y & T_b < T_1 < T_{c*} \\ 1 & T_1 > T_c \end{cases} \tag{2}$$

where

$$T_{c*} = \frac{2R_y}{1+R_y^2} T_c \tag{3}$$

T_a, T_b, T_c, are spectral periods which vary according to the soil type.

The computation of C_R for structures located in the near-fault zone has been addressed for many years by the research community and various approximate relationships for C_R have been proposed, referring almost exclusively to bilinear systems. However, the different pulse periods of pulse-type motions, its significant influence on the spectral shape and the local amplifications it causes on C_R, indicates that it is preferable to normalize the fundamental period with the pulse period. Moreover this practice substantially decreases the record-to-record variability and eliminates the influence of the parameters that characterize the near-fault excitation. While Báez and Miranda (2000) suggest that PGV is the most influential parameter on C_R, according to Ruiz-Garcia (2011), neither PGV nor the distance to the source significantly affect C_R once T_1 is normalized with respect to the predominant period of the ground motion, T_p, where T_p is the period of vibration corresponding to the peak spectral velocity of a linear SDOF system having 5% damping ratio. Other studies, including Mavroeidis *et al.* (2004), discuss also the moderate influence of earthquake magnitude on structural response, focused on some distinct values of normalized periods (T_1/T_p<1). Finally, Chopra and Chintanapakdee (2004), support that when the periods are normalized with the spectral value T_c, the produced C_R values for near-field and far-fault ground motions are very close.

3. MODELLING OF THE OSCILLATORS

The SDOF oscillators are modeled either as bilinear having an elastic and a hardening branch, or with quadrilinear backbones having pinching hysteresis and including an elastic, a hardening, and a negative stiffness branch, terminating at a residual plateau (Fig.1). These systems are described by the post-yield hardening ratio a_h, corresponding to the strain-hardening stiffness, the negative slope of the post-capping stiffness a_c, the pre-capping ductility μ_c defining the beginning of the softening branch, and finally, the coefficient r representing the residual strength capacity, as a fraction of the yield strength. The parameters are varied one at a time, generating several plausible structural models, some of them being more brittle and other more ductile. Using an oscillator with properties a_h = 5%, μ_c = 1.2, a_c = -50%,

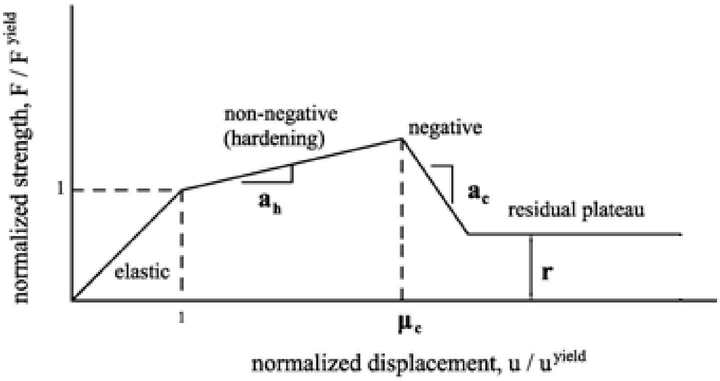

Figure 1: The force-displacement relationship of the oscillator in normalized coordinates (Vamvatsikos and Fragiadakis, 2006).

Table 1: The 33 near-fault records adopted.

Year	NGA	T_p	$D_{5\text{-}95}$	Event/ Station	Mag.	Mech.	R_{rup}
1971	77	1.6	7.1	San Fernando / Pacoima Dam (upper left abut)	6.61	R	1.8
1979	150	1.2	3.4	Coyote Lake / Gilroy Array #6	5.74	SS	3.1
1979	158	2.4	7.1	Imperial Valley-06 / Aeropuerto Mexicali	6.53	SS	0.3
1979	159	2.3	11.5	Imperial Valley-06 / Agrarias	6.53	SS	0.7
1979	170	4.5	14.9	Imperial Valley-06 / EC County Center FF	6.53	SS	7.3
1979	173	4.5	13.0	Imperial Valley-06 / El Centro Array #10	6.53	SS	6.2
1979	179	4.6	10.2	Imperial Valley-06 / El Centro Array #4	6.53	SS	7.0
1979	180	4	9.4	Imperial Valley-06 / El Centro Array #5	6.53	SS	4.0
1979	181	3.8	8.5	Imperial Valley-06/ El Centro Array #6	6.53	SS	1.4
1979	182	4.2	4.8	Imperial Valley-06/ El Centro Array #7	6.53	SS	0.6
1979	183	5.4	5.8	Imperial Valley-06 / El Centro Array #8	6.53	SS	3.9
1979	184	5.9	6.9	Imperial Valley-06 / El Centro Differential Array	6.53	SS	5.1
1979	185	4.8	11.8	Imperial Valley-06 / Holtville Post Office	6.53	SS	7.7
1980	292	3.1	16.6	Irpinia-Italy-01/ Sturno	6.90	N	10.8
1984	451	0.95	3.1	Morgan Hill / Coyote Lake Dam (SW Abut)	6.19	SS	0.5
1984	459	1.2	6.9	Morgan Hill / Gilroy Array #6	6.19	SS	9.9
1986	529	1.4	4.5	N. Palm Springs / North Palm Springs	6.06	RO	4.0
1987	615	0.79	8.1	Whittier Narrows-01 / Downey - Co Maint Bldg	5.99	RO	20.8
1987	721	2.4	18.8	Superstition Hills-02 / El Centro Imp. Co. Cent	6.54	SS	18.2
1987	723	2.3	10.5	Superstition Hills-02/ Parachute Test Site	6.54	SS	0.9
1989	738	2	6.0	Loma Prieta / Alameda Naval Air Stn Hanger	6.93	RO	71.0
1989	802	4.5	8.4	Loma Prieta/ Saratoga-Aloha Ave	6.93	RO	8.5
1992	821	2.7	6.9	Erzincan-Turkey/ Erzincan	6.69	SS	4.4
1992	828	3	16.2	Cape Mendocino/ Petrolia	7.01	R	8.2
1992	879	5.1	0.0	Landers/ Lucerne	7.28	SS	2.2
1994	1063	1.2	7.1	Northridge-01/ Rinaldi Receiving Sta	6.69	R	6.5
1994	1086	3.1	5.8	Northridge-01/Sylmar Olive View Med FF	6.69	R	5.3
1999	1176	4.5	15.4	Kocaeli-Turkey/ Yarimca	7.51	SS	4.8
1999	1182	2.6	25.8	Chi-Chi- Taiwan / CHY006	7.62	RO	9.8
1999	1202	1.4	28.1	Chi-Chi- Taiwan / CHY035	7.62	RO	12.7
1999	1503	5.7	28.0	Chi-Chi-Taiwan/ TCU065	7.62	RO	0.6
1999	1529	9.7	16.5	Chi-Chi-Taiwan/ TCU102	7.62	RO	1.5
1999	2457	3.2	8.6	Chi-Chi- Taiwan-03 / CHY024	6.20	R	19.6

T_p (sec): The period of the velocity pulse.
$D_{5\text{-}95}$ (sec): Significant duration of the records. The duration is defined as the time needed to build up between 5 and 95 percent of the total Arias Intensity.
R_{rup} (km): Closest distance to rupture plane.
R: Reverse.
SS: Strike-Slip.

N: Normal.
RO: Reverse-Oblique.

r= 5%, and a fixed damping ratio equal to 5%, we have formed a reference oscillator that is used as the basis for comparing all modified models.

4. EARTHQUAKE GROUND MOTIONS

A total of 33 ground motions have been used, recorded normal to the fault trace. The records and their properties are listed in Table 1. The classification of the records and their pulse period follows that of PEER NGA database [18]. In many records, the normal components show strong directivity effects (e.g. record #21, record #31), while the fault-parallel components are associated with weak directivity effects. In some cases, prominent directivity effects are evident in both components, as in Erzincan (record #23), where the pulse period is very close for both components.

5. PARAMETRIC INVESTIGATION

The influence of the type of the oscillator and its properties on the seismic demand are studied through plots of C_R versus the period of the systems.

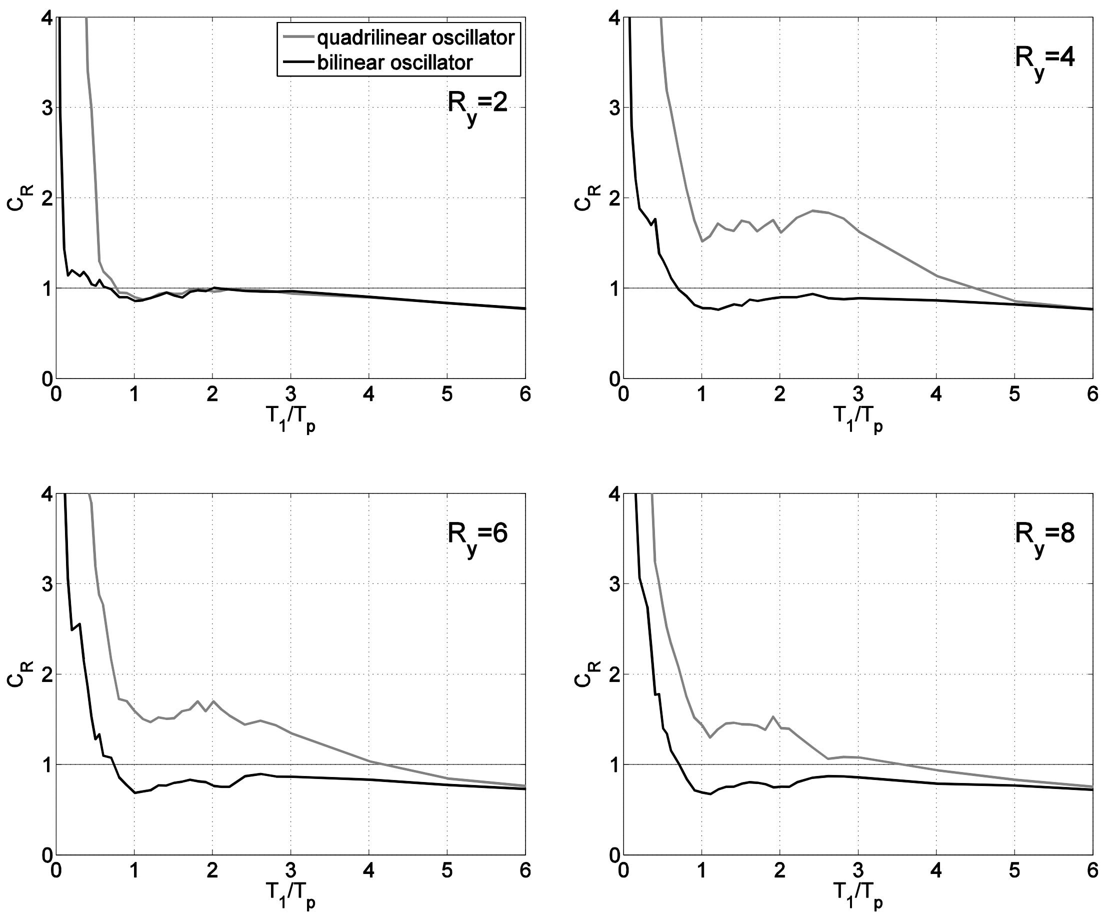

Figure 2: Median inelastic displacement ratios of quadrilinear oscillators and bilinear oscillators subjected to the normal component of pulse type records.

5.1 Influence of oscillator type

Current research on the effects of near-fault ground motions has concentrated on the investigation of bilinear systems, while there are very few studies on degrading systems, which is the case of most real world buildings. Figure 2, presents the median inelastic deformation ratio C_R of quadrilinear against bilinear systems. The oscillators are subjected only to the fault-normal component of ground motions that contain a velocity pulse. The post-stiffness ratio of the bilinear oscillator is set equal to 0.05,

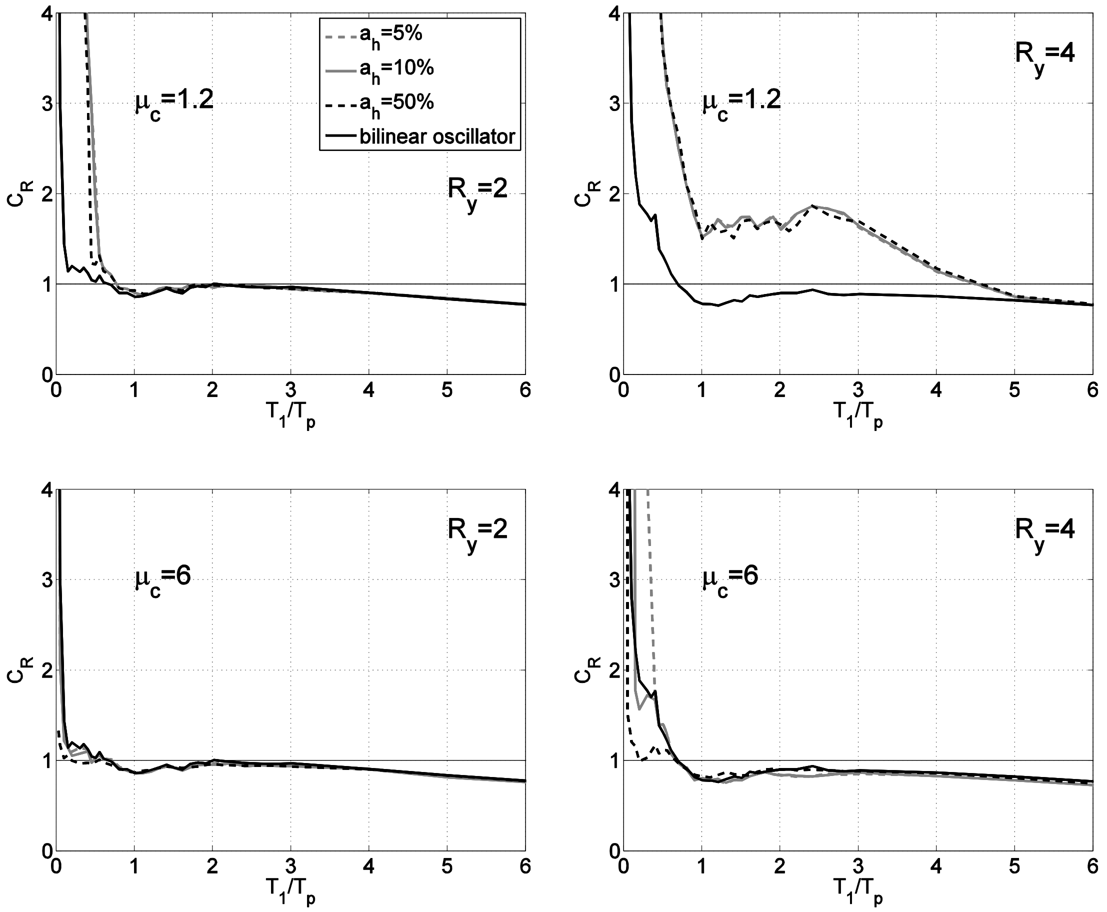

Figure 3: Influence of the slope of the hardening branch, a_h of the oscillators characterized by μ_c=1.2 and μ_c=6, on C_R.

while the quadrilinear system is the reference oscillator, described in section 2. The plots are obtained for four different intensity levels corresponding to R_y factor values equal to 2, 4, 6 and 8.

According to Fig. 2, the ductility developed by quadrilinear oscillators exceeds the levels of the corresponding bilinear for given C_R values. For R_y=2, the two curves converge for normalized periods larger than 0.85, having significant divergence only for small T_1/T_p values. For weaker systems, as R_y increases, the bilinear SDOF underestimates the C_R-demand over the entire period range. For every level of R_y, the two curves converge to C_R=1 as T_1/T_p increases, which takes place approximately at T_1/T_p=4, as opposed to T_1/T_p=0.8 for bilinear systems. From Fig. 2, it is evident that median C_R values are quite different when computed for bilinear and quadrilinear systems, indicating that using a bilinear model to estimate the inelastic response, is conservative when the structure has a degrading backbone.

5.2 Influence of oscillator's properties

As shown in Fig.1, the oscillator can be fully described by four parameters. The four parameters are the non-negative slope of the hardening branch, a_h, the normalized displacement μ_c, which defines the beginning of the negative stiffness segment, the slope of the negative stiffness branch, a_c, and the height of the residual plateau, r, equal to the ratio of the residual strength over the yield strength. These backbone properties (a_h, a_c, μ_c, r) are set according to the reference oscillator and are varied one at a time to study their effect on C_R.

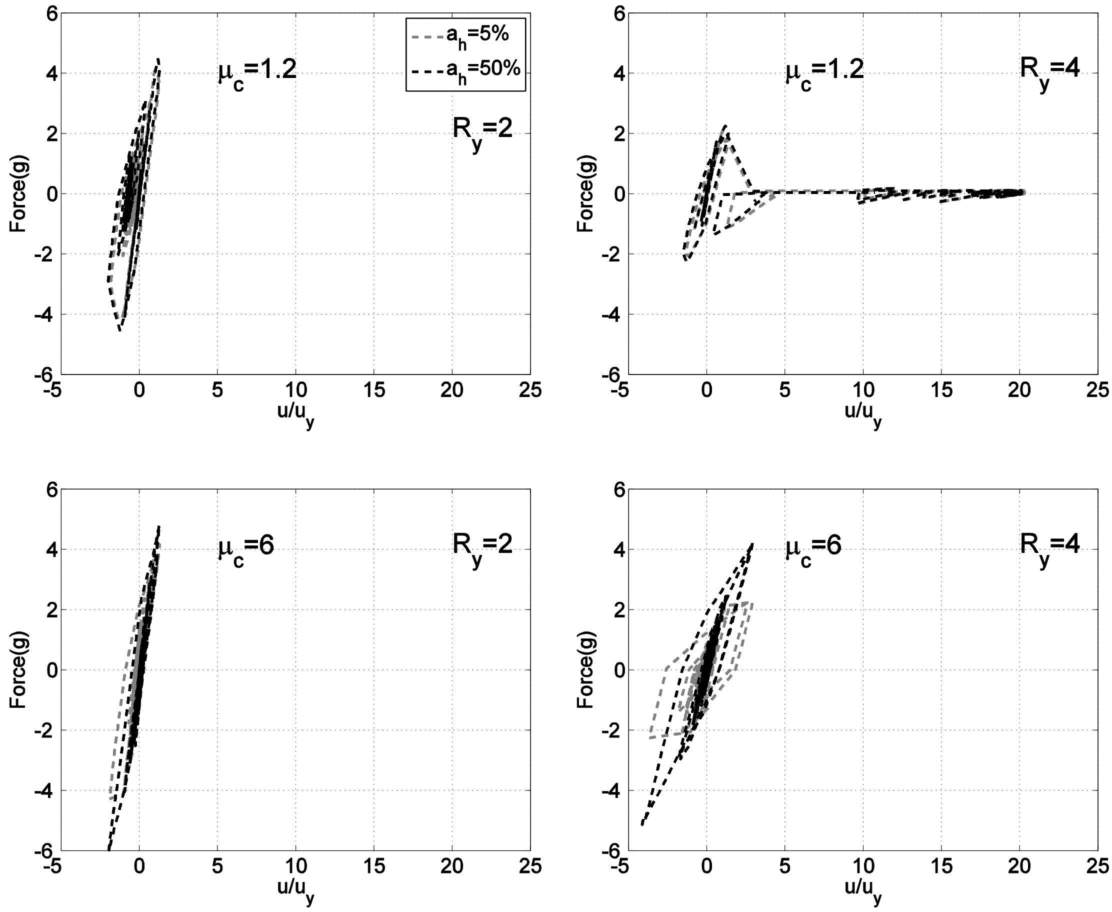

Figure 4: Hysteresis loops of quadrilinear oscillators characterized by μ_c=1.2 and μ_c=6 for the Chi-Chi Taiwan record and T_1/T_p=0.45.

Median inelastic displacement ratios for two quadrilinear oscillators characterized by μ_c=1.2 and μ_c=6 are presented in Fig. 3.The other backbone parameters are set according to the reference oscillator.

Compared to the oscillator having μ_c=1.2, the bilinear system (solid black line) underestimates the C_R compared to the quadrilinear oscillators, especially as R_y increases. Regardless of the R_y-demand, for T_1/T_p<1, the normal component of the near-field ground motions produce increased ductility demand compared to values beyond this limit. Considering nearly elastic systems (R_y=2), this threshold is slightly decreased to 0.85 and approaches the response observed for bilinear systems. In this region of small periods, the inelastic displacements are significantly higher than the elastic and increase exponentially for shorter periods. The increased C_R values at short periods, already apparent from the Newmark-Hall relationship (Eq.2), starts for T_1/T_p larger than that of the bilinear case. This segment is affected by the residual capacity of the system and will be shown more clearly when we will study the effect of the r parameter. For R_y>2, three regions can be identified. The first is, as in the case of systems with R_y=2, the ductility demand significantly exceeds R_y. In the second region, between T_1/T_p≈1÷2, C_R is stabilized around 1.5. For T_1/T_p>2, the values of C_R decrease linearly as T_1/T_p increases until a limiting value of T_1/T_p which depends on the level of R_y. This threshold also marks the beginning of the fourth, equal deformation region (R_y≈μ).

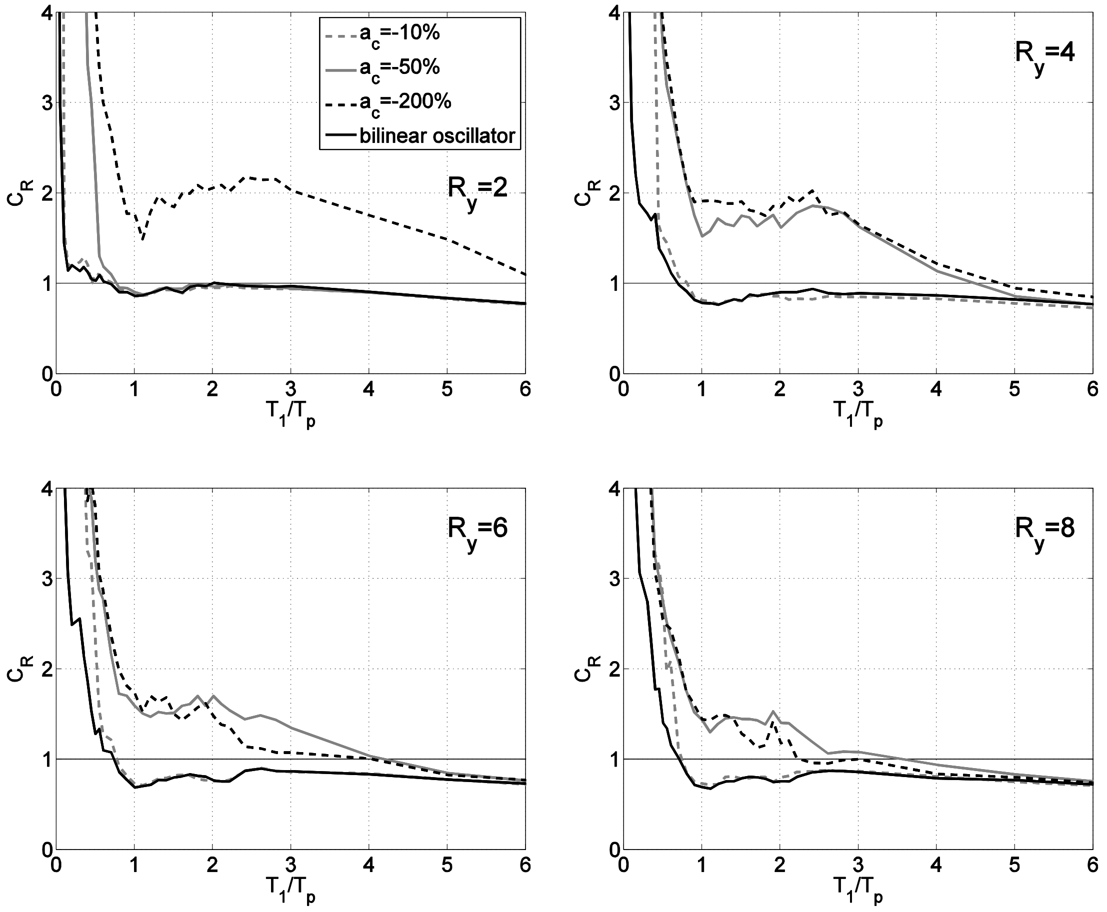

Figure 5: Influence of the negative slope, a_c of the negative stiffness segment on C_R.

On the other hand, if increasing μ_c of the reference oscillator from 1.2 to 6 the seismic response differentiates significantly and approaches that of the bilinear system. The effect of varying the slope a_h on C_R is increased mainly for fundamental periods less than 0.5.T_p and as the level of R_y increases. It can be noted that for a_h=50%, the produced C_R values are smaller than the values of the bilinear system.

Regarding the reference oscillator (μ_c=1.2), it can be observed that the sensitivity of C_R with respect to post-yield stiffness a_h, is rather small. The negligible differences when varying the slope a_h, are attributed to the hysteretic behavior of the system. To be more specific, the hysteresis loops of the reference oscillator and of the oscillator characterized by μ_c=6, for T_1/T_p equal to 0.45, subjected to the Chi-Chi Taiwan record (Table 1, #31), are shown in Fig.4, for R_y=2,4.

As can be seen from Fig.3, differences in the response of the reference oscillator are observed only for some T_1/T_p, values e.g., Fig.3, R_y=2 and T_1/T_p between 0.2 and 0.5. In that region as shown in Fig.4, the hysteresis is performed in the pre-fracturing range ($\mu<\mu_c$), forming large loops. The energy is absorbed in a narrow, with respect to the displacement, region around the origin of the axes, while the strength reaches its peak values. For larger ratio T_1/T_p the loops follow the same pattern of hysteresis for every level of R_y. For R_y>2 only a minor part of the hysteresis is performed in the initial range of the backbone, while the residual energy is absorbed through cycling beyond the negative drop. As R_y increases, the hysteresis of the backbone practically begins when the negative slope takes over, at a displacement over sixty times the corresponding yield displacement, while the level of strength is significantly reduced.

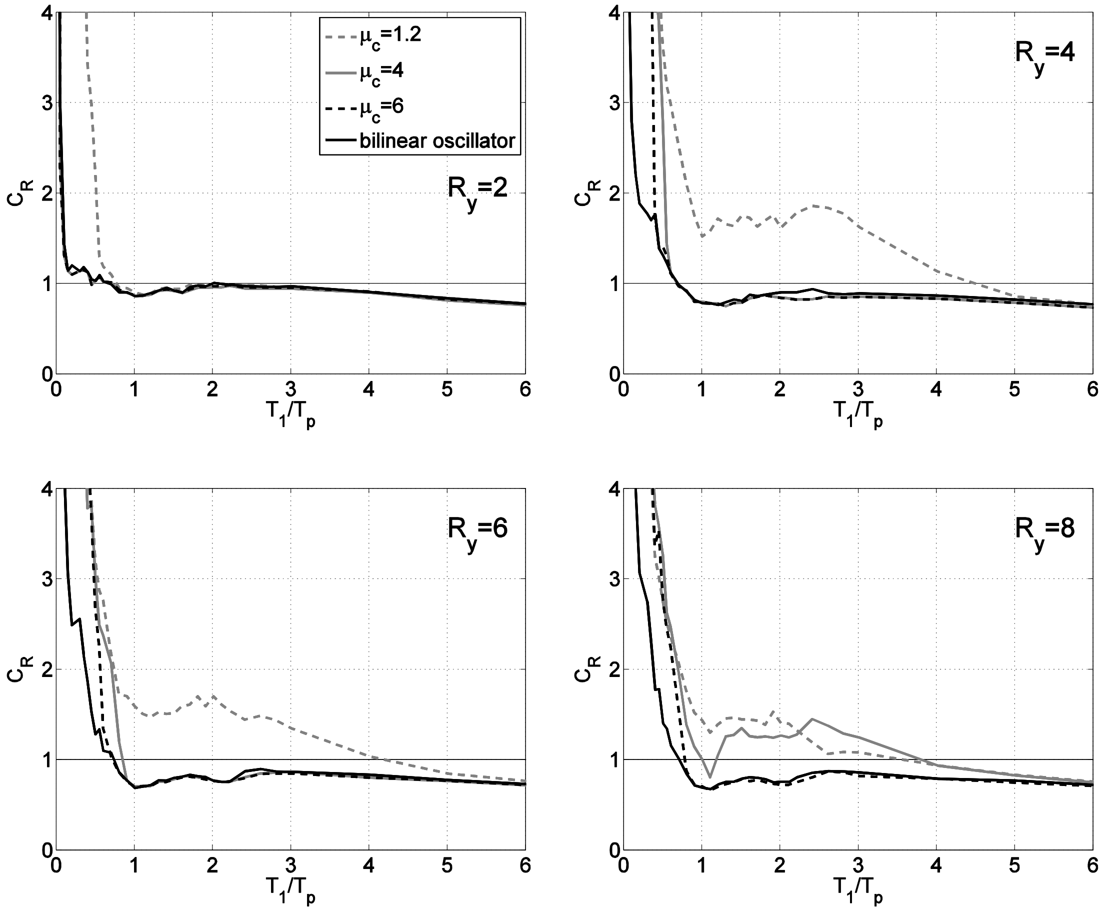

Figure 6: Influence of the normalized displacement, μ_c on the C_R

In the case of the oscillator characterized by μ_c=6, the variance in a_h shifts the hysteresis loops increasing the sensitivity of the response. For R_y=2, the response is not significantly influenced by the increase of μ_c and the hysteresis shape approaches that of the reference oscillator (μ_c=1.2). As R_y increases, the loops are formed again in the pre-fracturing region, while their shape is not affected. Respectively, the strength and displacement of the system under cyclic loading are not impressively varied with respect to the level of lateral strength, indicated by R_y. More pronounced variance in the shape of the loops can only be seen for large values of T_1/T_p and for highly ductile systems. Finally, it should be pointed out that with the exception of μ_c, neither the slope of the negative segment a_c nor the height of the residual plateau r, significantly affect the hysteretic behavior of systems with regard to variations of a_h.

Contrary to the rather insignificant effect of a_h on the seismic response of the reference oscillator, the variation of the negative stiffness slope a_c, has a more pronounced affect as shown in Fig. 5. For systems with R_y equal to 2, a_c=200% results to remarkably higher values of C_R compared to systems with smaller a_c values. Moreover, for a_c=200%, the spectral shape of C_R compared to other a_c values, is not affected by the increase in R_y. Inversely, a smaller slope value of 10% in the high-frequency and moderate-frequency region will give responses considerably smaller than those computed for oscillators having negative slope a_c=-50% or a_c=-200% and close to that of the bilinear system. This trend is amplified by the low value of the residual strength r and the relatively small value of μ_c of the reference system.

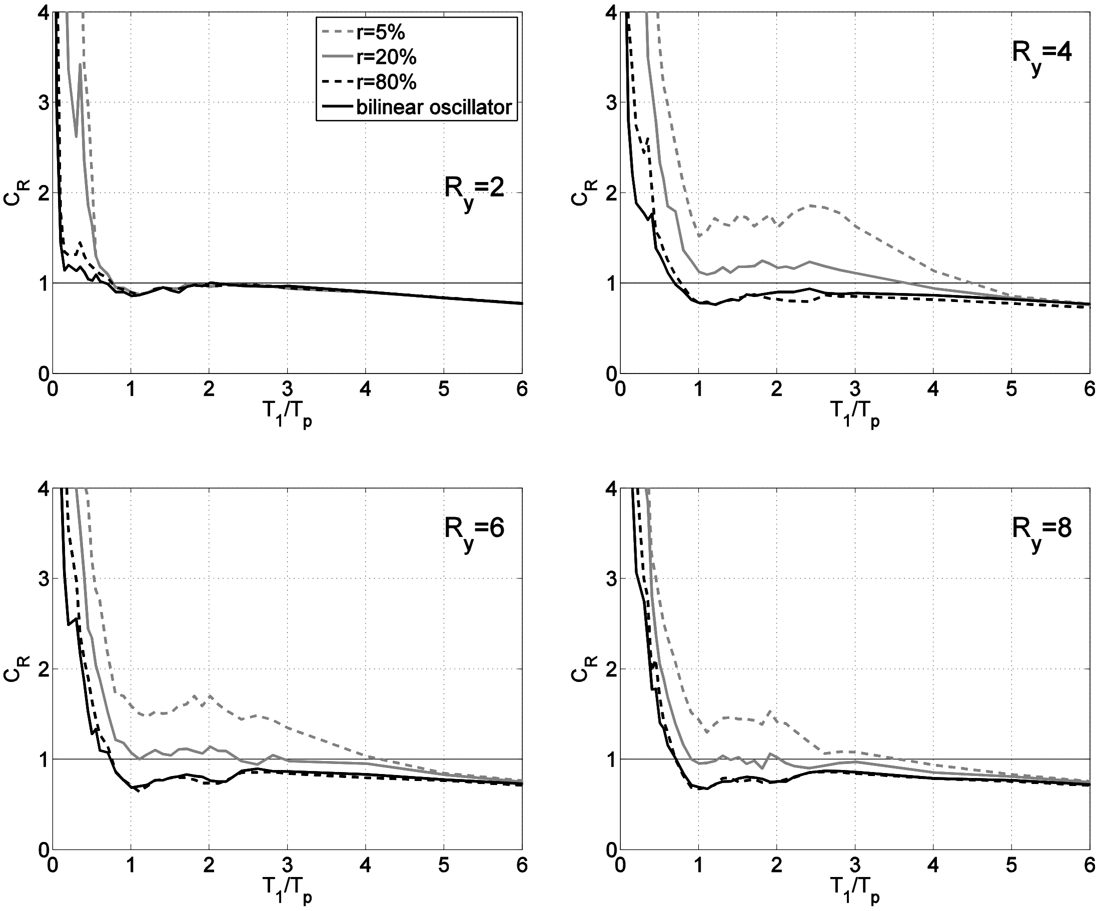

Figure 7**:** Influence of the height of the residual plateau, r, on the C_R.

It is remarked that increasing the value of μ_c is expected to affect mostly highly inelastic systems (R_y=8). Increasing the level of the residual strength (e.g., r=20%), will eliminate the sensitivity of the response to variations of a_c, thus reducing its importance. However, it can be proved that there is no divergence in the response of systems for a_c varying between 10% and 25%.

The response of quadrilinear oscillators with varying μ_c is very close to the response observed for varying a_c concerning the spectral shape of the curves and the T_1/T_p values, where the spectral shape differs (Fig. 6). For high and moderate R_y levels only oscillators with low μ_c (μ_c=1.2) have considerably divergent behavior. It should be pointed out that the influence of the normalized displacement on C_R is associated, as discussed before, to the properties of the reference oscillator. For residual strength r=20%, or larger, the effect of μ_c on C_R is smaller compared to the case of r=5%.

The sensitivity of seismic response to the r parameter is shown in Fig.7. The C_R curves corresponding to different values of r, have a similar degrading pattern, while, the peak values of C_R for T_1/T_p>1 and R_y=4, 6, 8 range around 1.5 and 2 and coincide with the formerly computed values. The trends observed in the previous plots are verified again. The different regions are clearly segregated, while the T_1/T_p thresholds coincide with the previously mentioned values. For R_y=2, the differences on C_R are clustered in the region of small periods (T_1/T_p<0.85). The response seems very sensitive to r, while as R_y increases causes larger divergences in C_R values, compared to all other parameters investigated. The deviation in the calculated values can be observed for every value of the r, not only for the outliers, and is obvious for a wide range of periods, regardless of R_y.

6 CONCLUSIONS

The median of inelastic displacement ratios, C_R, of bilinear and quadrilinear oscillators with varying backbone parameters when subjected to fault-normal, near-fault ground motions are investigated. The conclusions of this study are briefly summarized:

- The relationship between the peak deformation of the inelastic and the corresponding linear SDOF systems is considerably affected by the properties of the oscillator. Oscillators with quadrilinear backbones produce C_R values remarkably higher than those of bilinear oscillators.
- The properties of the backbone affect significantly the seismic behavior. The C_R ratios are sensitive to all four backbone parameters. Among the four parameters considered, the normalized height of the residual plateau r, seems to be the most influential for almost all periods values, regardless of the level of R_y-demand. However, the response is also sensitive to the combination of the four parameters, especially that of μ_c and r.
- For nearly elastic systems the differences on C_R are clustered in the region T_1/T_p<0.85, while after this threshold the equal deformation rule applies. For larger R_y values four regions can be identified, depending on the value of the T_1/T_p ratio. Initially increased ductility demand increases C_R for shorter periods. In the second region, T_1/T_p≈1÷2, C_R is stabilized around 1.5. For T_1/T_p>2, C_R decreases linearly as T_1/T_p increases, until a limiting value, beyond which the equal-displacement rule applies.

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