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INFLUENCE OF GROUND MOTION DURATION ON DEGRADING SDOF SYSTEMS

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SUMMARY

The influence of ground motion duration (GMD) in seismic response of structures is investigated using single degree of freedom (SDOF) systems with different constitutive laws to represent structures with different levels of degradation in strength and stiffness. Two different demand measures are considered to represent maximum and cumulative response. GMD influence is studying using two specific duration scenarios to consider short and long duration, each with 20 records. The study is divided in two parts, in the first part incremental dynamical analysis (IDA) is used to evaluate the influence of GMD in the seismic response of structures with different hysteretic behaviour for both demand measures used, and different levels of ground motion intensity. In the second part, fragility curves are obtained to evaluate the influence of GMD on structural failure probability of structures with different models of hysteretic behaviour.

1. INTRODUCTION

Due to the importance of GMD on seismic response of structures many efforts have been realized to understand GMD effects on seismic response of structures and the importance of this parameter in the evaluation of damage in structures [Fajfar, 1992; Manfredi, 2001; Terán-Gilmore, 2001; Malhotra, 2002; Bojorquez and Ruiz, 2004; Boomer *et al*, 2004; Chai, 2005; Iervolino *et al*, 2006]. Recent investigations are focus in understand the effect of this parameters on seismic response of structures considering different demands measures [Iervolino *et al*, 2006], but in this study degrading structures were not considered. A realistic hysteretic behaviour model is more efficient to represent correctly the response of structures, and it is clear that structures lose strength and stiffness when the response is beyond the elastic range. The aim of this work is evaluate the influence of GMD for hysteretic behaviour models with stiffness and strength degradation. Eleven hysteretic models are considering to represents different levels of degradation. Hysteretic models were obtained using a modified bilinear behavior by means of two different degradation functions, the first given by hysteretic energy and the second by maximum displacement. Four oscillation periods (from 0.1 to 4s) and two target ductility are used to represent structures with small, moderate, long and with very long periods, and to get ductility levels low and high.

Two sets of real ground motion records are selected to represent short and long duration scenarios. First, the structural response of the SDOF systems is evaluated for maximum and cumulative demands using IDA's curves [Vamvatsikos and Cornell, 2002]. Finally, fragility curves are developed to investigate the role of GMD in failure probability of structures with degradation in their mechanical properties.

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2. DEGRADATION FUNCTIONS AND SDOF SYSTEMS

Eleven different constitutive models obtained through a bilinear model behaviour that includes strength and stiffness degradation and obtained using two different degradation functions, hysteretic energy [Bojórquez and Rivera, 2005] and maximum displacements [Otani, 1981] (equation 1 and 2) are analyzed with respect to GMD. The first seven models were obtained using the hysteretic energy degradation function, while in the last four were used maximum displacement for mechanical properties degradation. For all the cases, a post-yielding stiffness equal to 3% of the initial stiffness was considered. The models are described in table 1 for both degradation functions, and a summary of all the cases used herein are represented in figure 1. The models without degradation and with strength degradation are representative of structural situations such as welded connections steel frames. The models with stiffness and with both degradations are included trying to describe the behaviour of reinforced concrete structures.

Table 1: Models used for the SDOF systems

Models (hysteretic energy)	β (strength)	B (stiffness)	Level of Degradation
M1	0	0	No degradation
M2	0.45	0	Small strength degradation
M3	0.90	0	Large strength degradation
M4	0	0.20	Small stiffness degradation
M5	0	0.40	Large stiffness degradation
M6	0.45	0.20	Both small degradation
M7	0.90	0.40	Both large degradation
Models (displacement)	**α (strength)**	**A (stiffness)**	**Level of Degradation**
M8	0.25	0	Small strength degradation
M9	0.50	0	Large strength degradation
M10	0	0.25	Small stiffness degradation
M11	0	0.50	Large stiffness degradation

$$V = V_o \left(\frac{10}{10 + \frac{E_H}{Fy_o\, \delta y_o}} \right)^{\beta} \tag{1}$$

In equation (1) V is the considered variable (strength or stiffness), V_o is the initial value of the considered variable (strength or stiffness), Fy_o and δy_o are the initials values of strength and yielding displacement of the structure, E_H is the dissipated hysteretic energy. Finally, β defines the velocity of the degradation and with this the level of degradation. Degradation function (1) need to be calibrated using realistic experimental test, but the goal of this study is evaluate the influence of different levels of degradation on seismic response of structures.

$$V = V_o \left(\frac{\delta y_o}{\delta_m} \right)^{\alpha} \tag{2}$$

In equation (2) δ_m is the maximum displacement of the structure, α defines the velocity of the degradation and with this the level of degradation, and the other parameters were defined in equation 1.

For each of these models four oscillations periods are used: 0.1, 0.6, 1.5 and 4 s. These periods are representative of different regions of the Eurocode design spectrum in order to investigate if conclusions hold in the entire spectral range. For each SDOF, yielding strength of the hysteretic loop is adjusted to get two target ductility levels. Yielding values are computed dividing the Eurocode elastic spectral strength, corresponding to the period of interest by a factor of 3 (DL3) and 6 (DL6) (damping is always 5% of critical). In total 88 SDOF systems are considered in the analyses. SDOF systems are summarized in Table 2.

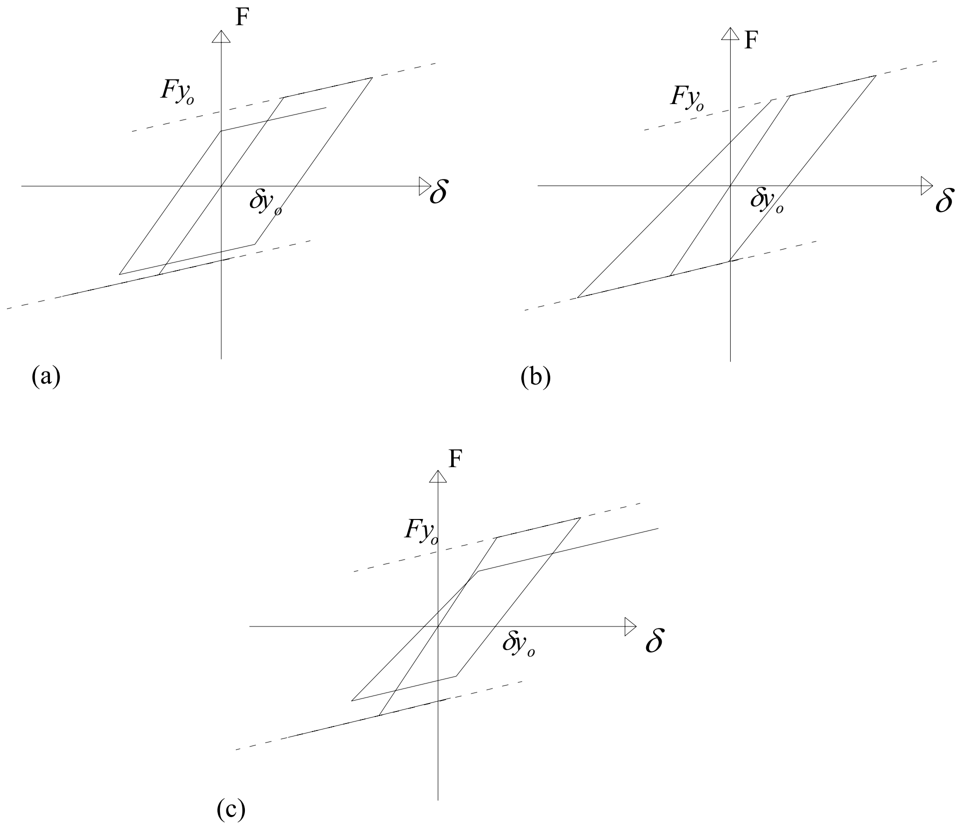


Figure 1: Models with (a) strength, (b) stiffness and (c) strength and stiffness degradation

Table 2: Investigated SDOF systems

Period (T)	Ductility (DL)	Models
0.1 s	3	M1, M2, M3, M4, M5, M6, M7, M8, M9, M10, M11
	6	
0.6 s	3	
	6	
1.5 s	3	
	6	
4 s	3	
	6	

3. DURATION-RELATED MEASURE AND SCENARIOS

3.1 Duration-related measure

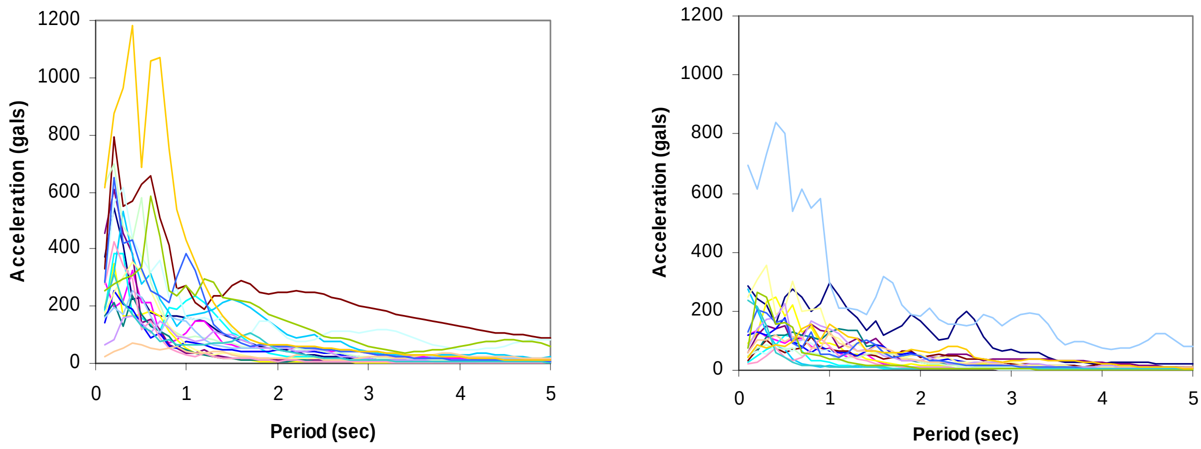
It has been observed how cyclic structural damage is related to energy released during ground shaking. There are available more than 30 definitions of seismic duration in the literature [Boomer *et al*, 2004] trying to measure such damage potential [Uang and Bertero, 1990; Malhotra, 2002; Kunnath and Chai, 2003]. The I_D factor (equation 3) by [Cosenza and Manfredi, 1997], has been proven to be a good predictor for computation of plastic cycle demand [Manfredi, 2001], for this reason I_D was used in this study to represent duration. Therefore duration scenarios are made of records sampled in narrow I_D bins, and influence of this factor on the nonlinear response is investigated.

$$I_D = \frac{\int_0^{t_E} a^2(t)\,dt}{PGA\ PGV} \tag{3}$$

In equation (3) $a(t)$ is the acceleration time-history, PGA and PGV represent the peak ground acceleration and velocity; t_E is the total duration of the seismic event.

3.2 Duration scenarios

The accelerograms for nonlinear time-history analysis are selected to represent specific duration scenarios. Herein, two bins of 20 records are defined to have specific median I_D ($I_D \approx 5$ ‘short duration’, $I_D \approx 22$ ‘long duration’). The accelerograms used here correspond to the same used in other investigation [Iervolino *et al*, 2006], but in this work only scenarios I_D5, I_D22 were necessary, more detail about the accelerograms are described in the study before mentioned. The records may be easily retrieved from the Pacific Earthquake Engineering Research Center database at http://peer.berkeley.edu/smcat/. Due to all accelerograms come from the same catalog, a uniform processing is assumed. Figure 2 shows the response spectra of earthquake records used in this study for scenarios I_D5 and I_D22.



(a) I_D5 **(b) I_D22**

Figure 2: Response spectra of earthquake records used for the analysis

4. DEMAND MEASURES

The two nonlinear demand measures selected to represent maximum and cumulative demand indexes are: displacement ductility (equation 4) ratio of the peak (δ_m) and yielding (δ_y) displacements and hysteretic ductility (equation 5), where the parameters were defined before. Further details about this indices and their ability to capture nonlinear behaviour may be found in [Cornell and Sewell, 1987; Krawinkler and Nassar, 1992; Cosenza *et al*, 1993; Fajfar and Vidic, 1994; Farrow and Kurama, 2003; Conte *et al*, 2003].

$$D_{kin} = \frac{\delta_m}{\delta y_o} \tag{4}$$

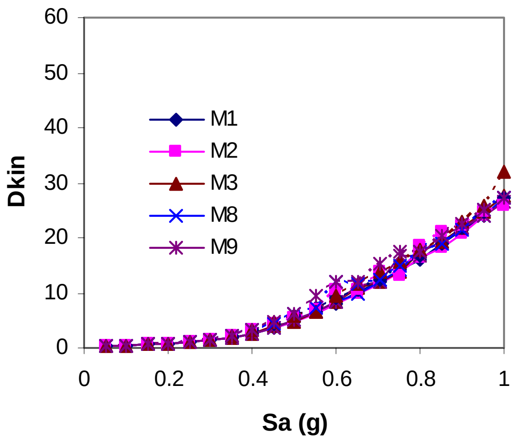
$$D_{hyst} = \frac{E_H}{Fy_o \, \delta y_o} + 1 \tag{5}$$

5. INFLUENCE OF “GMD” USING IDA CURVES

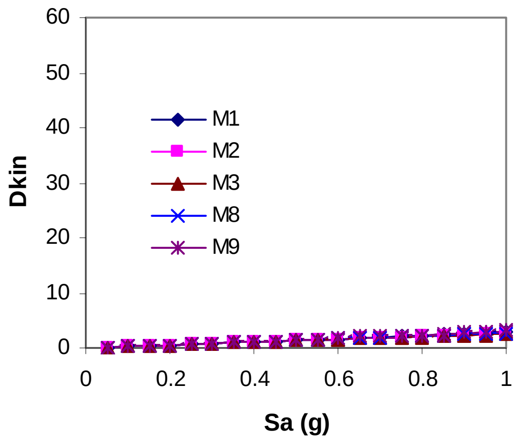
The Influence of GMD on seismic response of SDOF systems with degradation in their mechanical properties is evaluated using IDA’s curves. All the records are scaled to a common spectral acceleration (Sa) for the period of the structure, specific studies [Shome *et al*, 1998; Iervolino and Cornell, 2005] show the efficiency of this scaling criteria. After records are scaled, medians of demand measures are plotted versus Sa for each of the records sets used here. IDA curves for the two records sets representing different I_D are compared. If for larger I_D and the same Sa level the demand is larger, it is possible to conclude that duration matter for that particular demand measure. Otherwise, if the same demand occurs for two different record sets with different time duration of motion, duration is not an important parameter for that demand measure.

5.1 Influence of GMD for strength degradation systems

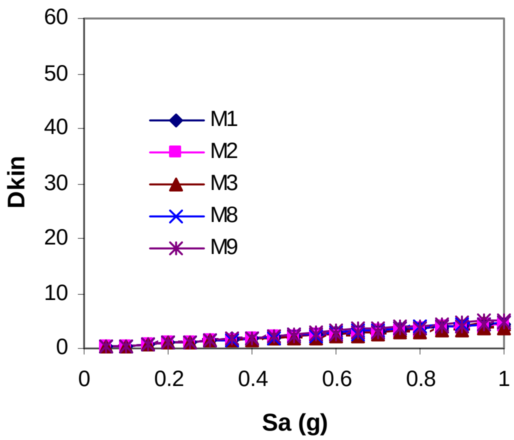
IDA's curves for the case of strength degradation systems for D_{kin} demand is showed on figure 3 for the case of systems with DL3, and for the models M1, M2, M3, M8 and M9 that were obtained using both degradation function (hysteretic energy and maximum demands). In this case are showed the medians of the response for different levels of intensity. Continues lines corresponding to results of the set records with I_D5 while discontinues lines correspond to I_D22. In the case of structures with period of 0.1, 0.6 and 1.5 second, D_{kin} demand for both sets of records used herein is very similar independent of the strength degradation level. This lead to conclude that is possible to ignore the effect of duration in the case of system with period small to long and with strength degradation due to hysteretic energy or maximum displacement. For structures with very long periods, D_{kin} is larger when the structure is subjected to set with I_D5, this corresponds to records set with short duration, there is not a clear explaination about it, and more investigation is required. In the figure 3 is observed very similar response for different models of behaviour and similar I_D sets. For all before, IDA curves suggests that the hysteretic behaviour used is not an important parameter to evaluate the effect of GMD in maximum demands for these cases. For structures with very long periods the influence of higher modes is an important parameter and need to be considered but this is out of this investigation.



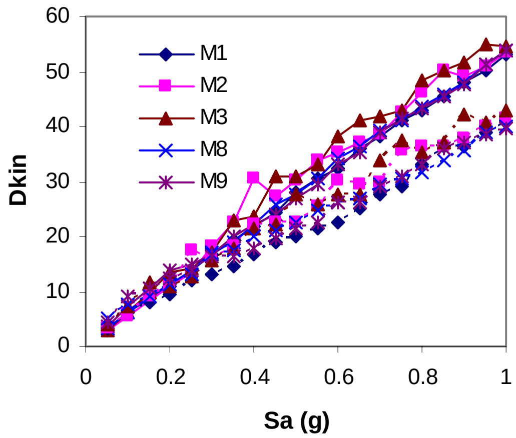
(a) T=0.1s



(b) T=0.6s



(c) T=1.5s



(d) T=4.0s

Figure 3: IDA curves for D_{kin} demand all periods with DL3 using models M1, M2, M3, M8 and M9 (—— I_D5, -----I_D22).

The influence of GMD on D_{hyst} demand is illustrated in figure 4 for a structure with period 0.6, DL6 and using an energy degradation function, but the same conclusions are valid for other periods, ductility levels and models of behaviour. In this figure is observed how GMD loses importance in D_{hyst} demand with an increasing in the level of strength degradation, because with an increasing in the degradation the ratio of D_{hyst} between the responses using I_D22 and I_D5 is small. However, there is a very dependency of cumulative demands due to GMD especially for structures without degradation. For this, GMD play an important role in the case of cumulative demands and need to be considered to represent correctly the response of structures subjected to earthquake ground motions.

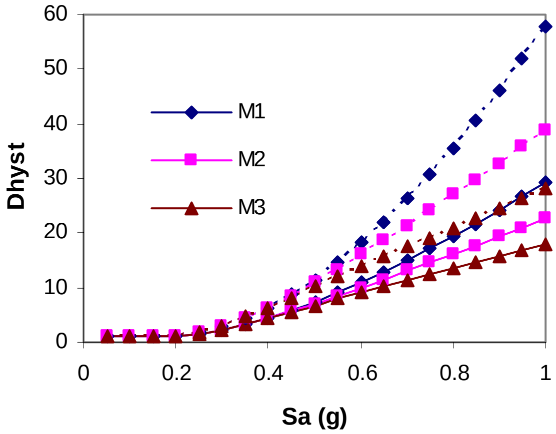


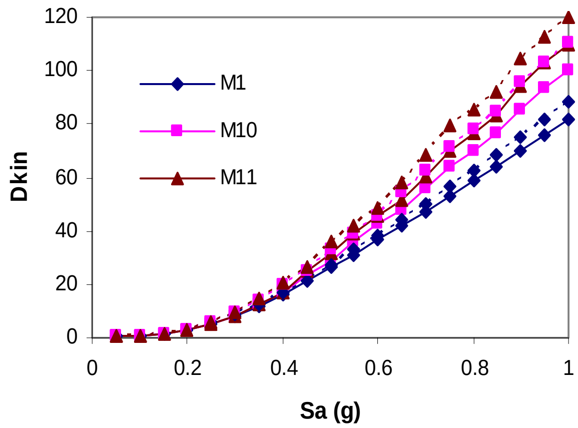
Figure 4: IDA curves for D_{hyst} demand T=0.6s, DL6 using models M1, M2 and M3 (—— I_D5, -----I_D22).

5.2 Influence of GMD for stiffness degradation systems

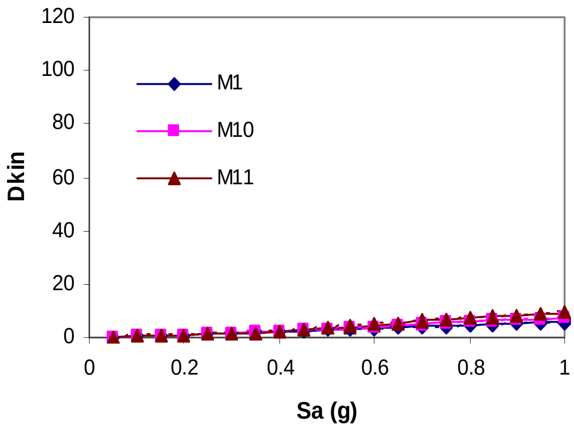
The importance of stiffness degradation in D_{kin} demand is observed in figure 5 for structures with DL6, models M1, M10 and M11 and all the periods. In the case of small periods, depending on the level of degradation, GMD gain importance especially for structures with large degradation, while the same that in the case of strength degradation is observed for structures with moderate, long and very long periods. For structures with small periods the influence of GMD and level of degradation is clear because the response (D_{kin}) increase with an increasing of duration of the earthquake, and the different is more important for models with large degradation of the system. For the case of periods 0.6 and 1.5, IDA curves suggest that duration and hysteretic loop not get influence in seismic response. There is not an effect of GMD, because for different I_D sets and the same behaviour model, is obtained a very similar response (D_{kin}) for all the intensity levels used here, this is valid for all the cases. Is interesting to observe as both duration and degradation level "lost" importance with an increasing in the period, and this is valid for structures with strength and stiffness degradation. The same results as in the case of D_{hyst} for strength degradation systems were obtained for the model with stiffness and with both stiffness and strength degradation. A lot of results were obtained but due to the lack of space just specific results were illustrated, but these are representative of all the study.

6. FRAGILITY CURVES

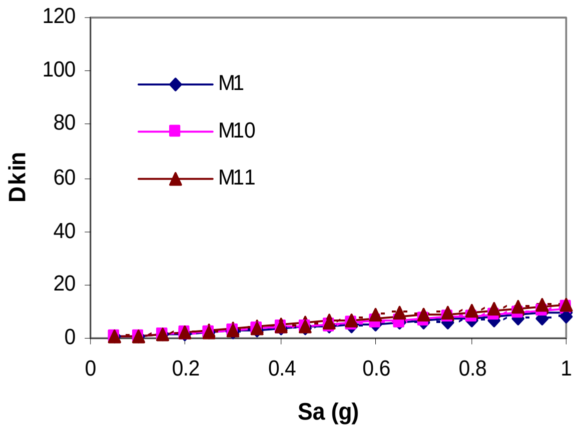
The Influence of GMD was evaluate before in terms of median demands by IDA curves, but in those cases the dispersion was not taking into account and with this the impact of duration on the structural failure probability (SFP) of structures. To evaluate impact of GMD in the SFP of structures with different hysteretic behaviour, fragility curves are obtained considering a deterministic ductility capacity of 3 (DC3). As in the case of IDA curves, in the next figures continue lines represent curves obtained for I_D5 and discontinues for I_D22. It is assumed a lognormal distribution on IDA curves around the median to obtain fragility curves. Fragility curves for the case of D_{hyst} are not reported due to the lack of space but the conclusions are valid for both demands measures used herein. For the sake of brevity and the lack of space only selected results are given with details.



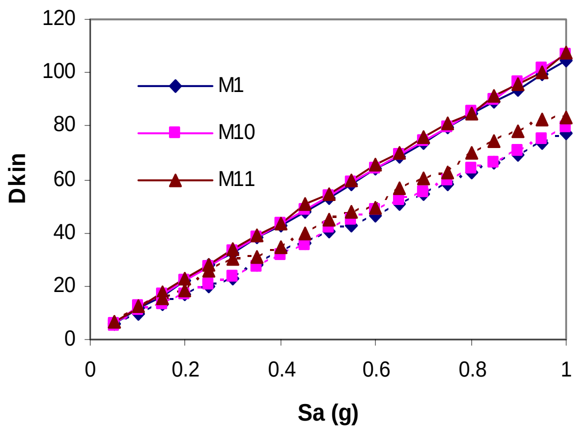
(a) T=0.1s



(b) T=0.6s



(c) T=1.5s



(d) T=4.0s

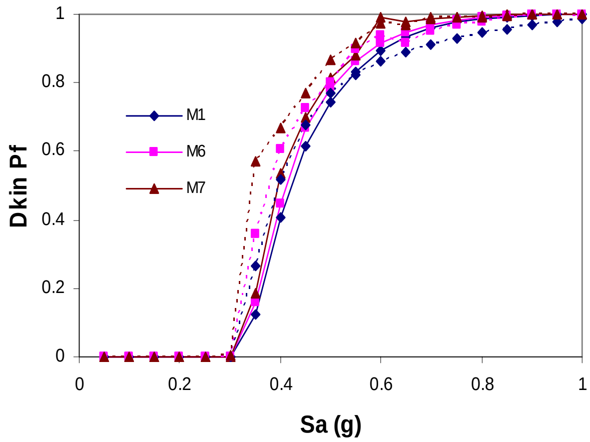
Figure 5: IDA curves for D_{kin} demand all periods with DL6 using models M1, M10 and M11

6.1 Impact of GMD on the SFP of structures with different levels of degradation

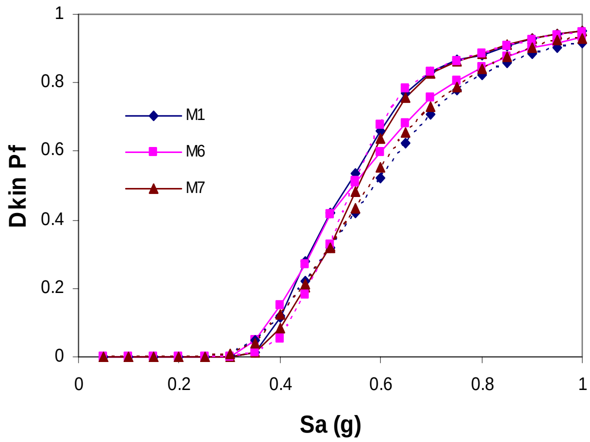
To evaluate the impact of ground motion duration on the SFP of structures with degradation in their mechanical properties, fragility curves in terms of D_{kin} are obtained for SDOF systems with all the periods used here, DL3, DC3 and for models M1, M6 and M7 that correspond to structures with different levels of degradation in strength and stiffness. Fragility curves for the case of I_D5 and I_D22 are illustrated in figure 6. For the case of small periods, fragility curves suggest a very dependency of model used in the probability of failure, the larger differences are between the model M7 (that corresponds to the model with large degradation in strength and stiffness) for I_D5 and I_D22, this suggest that there is a very importance on the level of degradation for this kind of structures. For structures with moderate, long, and very long periods, the level of degradation loses importance, in fact in some cases for structures with large degradation, the SFP is small for the case of records with large duration. The fragility curves confirm the results given by IDA curves, in the case of structures with moderate and long periods, the influence of GMD in the seismic response of structures (based in maximum demands) with different models of behaviour is despicable. For the case of structures with small and very long periods more investigation is necessary.

7. CONCLUSIONS

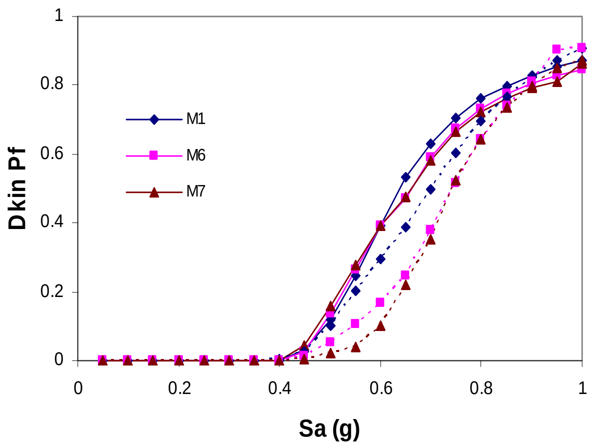
The importance of GMD for structures with degrading hysteretic models was studied using IDA and fragility curves. This work showed not only the role of duration for structures with different hysteretic behaviour also the importance of the period of the structures. IDA curves suggest that the effect of GMD is not important for maximum demands, for structures with degradation in strength and stiffness and with periods moderate to long. Fragility curves confirm the same results given by IDA's, and with all the analysis realized the importance conclusion is that in the case of structures with moderate and long periods the influence of GMD is insignificant not matter the constitutive law used to represent the structures for the case of maximum demands. In conclusion a simplified model as bilinear hysteretic model can represents correctly the maximum demands in structures with moderate to long period and the effect of GMD can be ignorant for maximum demands and this kind of structures. For short periods the results need more investigation and maybe this is related to the large variability of the response at high frequencies. In structures with very long periods the higher modes of vibration need to be considered. For the cases of cumulative demands the role of GMD and hysteretic behaviour is very important and is necessary take into account these parameters with the aim to propose new methodologies that take into account the cumulative damage in structures.



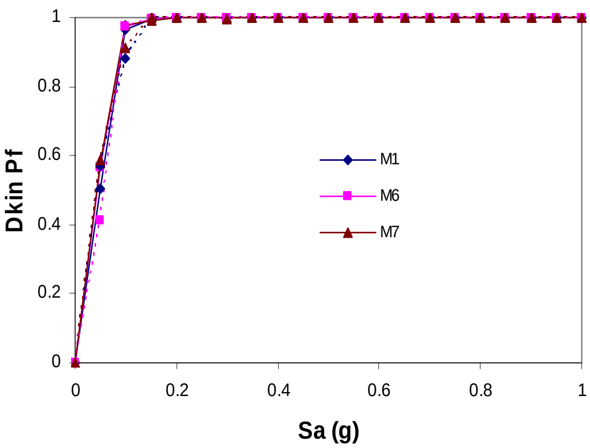
(a) T=0.1s



(b) T=0.6s



(c) T=1.5s



(d) T=4.0s

Figure 6: Fragility curves for DL3, DC3, models M1, M6 and M7 and D_{kin} demands

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