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INFLUENCE OF ADDED VISCOUS DAMPERS ON THE PROBABILISTIC SEISMIC PERFORMANCE EVALUATION OF RC FRAMES

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This paper deals with the parameters which influence the probability of reaching the near collapse limit state of RC frame structures equipped with nonlinear fluid viscous dampers. The study can be divided into two steps. The first aims to assess how the median and the dispersion of seismic demand can vary in the RC frame structures with and without dampers, considering a wide set of ground motions. The second step evaluates the expression in closed form, given by 2000 SAC/FEMA method, to assess the annual probability of failure of RC structures. This probability has been estimated considering a wide set of ground motions and different methods to approximate the hazard curve. The evaluations have been made on the basis of the results of a large number of nonlinear dynamic analyses; in particular, 180 nonlinear dynamic analyses have been made for the case studies with and without dampers. In conclusion, it has been noticed that the probabilistic assessment depends on the number of records considered and that the simplified formula provided by the 2000 SAC-FEMA method is strongly sensitive to the variation of the hazard curve and the dispersion.

Keywords: Nonlinear fluid viscous dampers, Nonlinear dynamic analyses, Probabilistic method, Median, Dispersion, SAC/FEMA method.

1 INTRODUCTION

Motivated by the recent seismic events, there has been an increase of concern towards seismic assessment and retrofit of existing buildings (Landi *et al*. 2014a). One of the innovative techniques of seismic retrofit is the insertion of the nonlinear fluid viscous dampers, which have the characteristic of having a lower velocity exponent than the unity. Their advantages are the reduction of damper forces at high velocities, the supply of higher dampers forces at low speed and the dissipation of a larger amount of energy than the other dampers. Since the assessment of seismic response is considerably complex for the presence of a large number of uncertainties, it is better to adopt a probabilistic approach. For this reason, in this paper, it has been followed a probabilistic approach, in particular the 2000 SAC/FEMA method (Cornell *et al*. 2002). This approach provides a closed form expression to evaluate the annual probability of exceeding a specified performance level for a given structure. The variability of terms inside the closed form expression and their influence on the definition of the probability of exceeding a specified performance level, have been analyzed here, considering the near collapse limit state, a wide set of ground motions and different methods to approximate the hazard curve. The study has been performed without applying scaling factors to the earthquake records, but considering different records for increasing values of seismic intensity. The considered case study is a RC frame, characterized by three bays and six floors (3B6F), designed to resist only gravity loads; nonlinear fluid viscous dampers have been inserted for the seismic retrofit. The seismic demand parameters here considered are the maximum displacement at the top of the structure and the maximum interstorey drift. Nine return periods have been chosen to identify nine values of seismic intensity and twenty ground motions have been selected for each of them. The analyses have been performed considering two different models for the plastic hinges behavior: the first model with post peak strength deterioration, the second model without it. In the first case the results have been obtained only for the records which converged for both structures (170 and 104 for the structure with and without dampers respectively), in the second case the results have been obtained for all the records considered, that is 180 for both structures.

2 PROBABILISTIC APPROACH

Among the probabilistic approaches there is the 2000 SAC/FEMA method, that provides a closed form expression to evaluate the seismic risk of a structure (Cornell *et al*. 2002). It is represented by P_{PL}, the annual probability of exceeding a specified performance level (e.g., the annual probability of collapse or the annual probability of exceeding the life safety level). Three approximations of the probabilistic representation of ground motion intensity, displacement demand and displacement capacity have been proposed in order to obtain a closed form expression of P_{PL}. The first assumes that the site hazard curve can be approximated in the region around P_{PLSa} (in the region of hazard levels close to the limit state probability P_{PL}) by the following relation:

$$H(s_a) = P[S_a \geq s_a] = k_o s_a^{-k} \tag{1}$$

where $H(s_a)$ is the annual probability of exceeding s_a, S_a is the spectral acceleration at the fundamental period (assumed as intensity measure), k and k_0 are constants depending on the interpolation of the hazard function in a log-log plot in the region of interest. The second approximation assumes that the median drift demand $\hat{D}$ can be represented, in the region around P_{PLSa}, by the following relation:

$$\hat{D} = a(S_a)^b \tag{2}$$

where a and b are constants depending on the interpolation of the results in terms of seismic demand. Lastly, the third approximation assumes that the drift demand D is lognormally distributed about the median with the standard deviation of the natural logarithm, $\beta_{D|Sa}$; this definition will be considered as dispersion. Also the drift capacity C is assumed to be lognormally distributed with dispersion β_C. With the previous approximations it is possible to derive the following expression:

$$P_{PL} = H\left(s_a^{\hat{C}}\right)\exp\left[\frac{1}{2}\frac{k^2}{b^2}\left(\beta_{D|S_a}^2 + \beta_C^2\right)\right] \tag{3}$$

where $s_a^{\hat{C}}$ is the spectral acceleration associated to the attainment of the capacity.

3 THE CONSIDERED CASE STUDY

The considered case study is a RC frame characterized by three bays and six floors (3B6F). This frame has been designed to resist gravity loads only. Nonlinear fluid viscous dampers have been inserted so that the structure can sustain a higher level of seismic action. With regard to the mechanical properties of dampers, the exponent of velocity is α = 0.5, the supplemental damping provided by the dampers is equal to 24.5% and the damping coefficient is equal to 556 kN $(s/m)^{0.5}$(Landi *et al*. 2014b). They have been inserted equal in every central bay and on each floor. The beams are 30 cm wide and 60 cm deep in all floors. On the ground floor the columns at the edges have a square cross section with a 40 cm side length, while the central ones with a 45 cm side length; on the first floor both columns have square cross section 40×40 cm; on the third floor 35×35 cm and on the last three floors 30×30 cm. The geometry of the structure has been illustrated in Figure 1. A concrete with a cylinder strength equal to 28 MPa and a steel with a yield strength equal to 450 MPa have been assumed in this study. The structure is assumed to be located in Santa Sofia (FC), Italy. The PGA for the LS limit state is 0.29 g (soil type C).

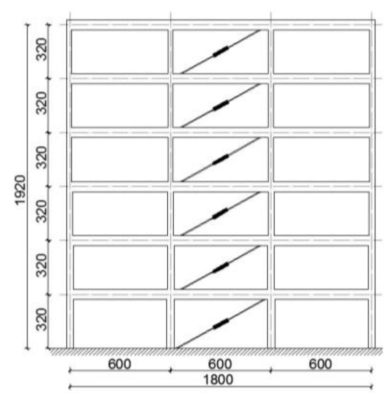


Figure 1. Geometrical characteristics of the considered RC frame (dimensions in cm).

Table 1. The three cases in which the performed analyses have been grouped.

Case 1	Bilinear moment-rotation curve with post peak strength deterioration	
	Structure with dampers	Structure without dampers
	170 records	104 records
Case 2	Bilinear moment-rotation curve with post peak strength deterioration	
	Structure with dampers	Structure without dampers
	104 records	104 records
Case 3	Trilinear moment-rotation curve without post peak strength deterioration	
	Structure with dampers	Structure without dampers
	180 records	180 records

The assessment has been performed on the basis of the results of a series of nonlinear dynamic analyses, performed using a concentrated plasticity model implemented in a FE computer program (Sap2000). A moment-rotation curve has been assigned to the plastic hinges, located at the ends of each element. The moment-rotation curve has been identified by assigning the yielding and ultimate bending moments and the corresponding chord rotations, which have been calculated with the empirical relations given in the Commentary to the National code. The obtained results are grouped in three cases, as shown in Table 1. In the first case the post peak strength deterioration is considered in the moment rotation curve and the probabilistic assessment is based on 170 and 104 records for the structure with and without dampers, respectively. In the second case the same plastic hinge model of the first case is adopted, but the probabilistic assessment is based on the same number of records for both structures, i.e. 104. In the third case a trilinear moment rotation curve without post peak strength deterioration is assumed and the probabilistic assessment is based on 180 records for both structures.

4 RESULTS AND COMMENTS

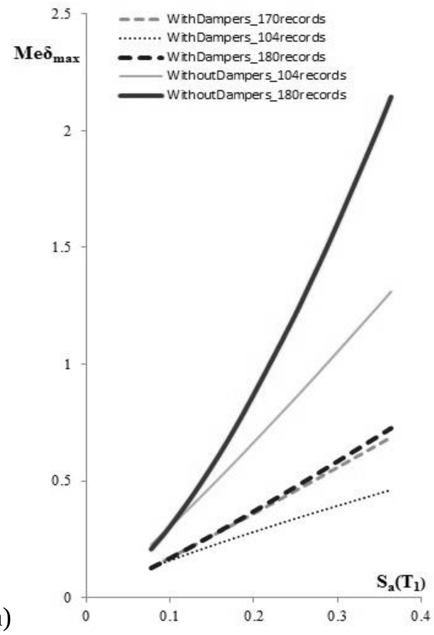
Two seismic demand parameters have been considered (D_{roof}, displacement at the roof; δ_{max}, maximum interstorey drift) and for each of them the median and the dispersion have been determined.

Table 2. Probabilistic parameters for δ_{max}, cases 1, 2, and 3.

Case 1		Case 2		Case 3	
Structure with dampers 170 records	Structure without dampers 104 records	Structure with dampers 104 records	Structure without dampers 104 records	Structure with dampers 180 records	Structure without dampers 180 records
$Me\delta_{max} = 2.041 \cdot S_a^{1.0768}$	$Me\delta_{max} = 4.122 \cdot S_a^{1.1327}$	$Me\delta_{max} = 1.059 \cdot S_a^{0.8221}$	$Me\delta_{max} = 4.122 \cdot S_a^{1.1327}$	$Me\delta_{max} = 2.272 \cdot S_a^{1.1285}$	$Me\delta_{max} = 9086 \cdot S_a^{1.5088}$
β_{regr}=0.3359 +0.4341S_a	β_{regr}=0.4016 +-0.2375S_a	β_{regr}=0.3254 +0.257S_a	β_{regr}=0.4016 +-0.2375S_a	β_{regr}=0.2975 +0.7001S_a	β_{regr}=0.2906 +1.1428S_a
β_{cost} = 0.4595	β_{cost} = 0.5629	β_{cost} = 0.4224	β_{cost} = 0.5629	β_{cost} = 0.4803	β_{cost} = 0.6389

As for the dispersion, two different dispersion formulations have been considered. The first considers a variable dispersion with the seismic intensity, obtained with a regression analysis (β_{regr}). The second formulation, indicated by the notation β_{cost}, considers a constant dispersion with seismic intensity. This is obtained performing a regression analysis of lnD on lnS_a on the totality of the results. Table 2 shows the results obtained from the probabilistic assessment in the three cases only for the δ_{max}. For the sake of brevity the results relative to D_{roof}, which are characterized by the same trends as those relative to δ_{max}, are not shown. Figure 2 illustrates in particular the trend of the median and dispersion β_{regr} obtained for the three cases described in Table 1. It can be noticed that if we consider a greater number of records for both the structures, a trend in line with the expectations is obtained: the dispersion β_{regr} always increases for both the structures when seismic intensity increases and the dispersion of the structure without dampers is greater than that of the structure with dampers. Table 3 compares the results in terms of collapse probability obtained for case 3 in two different situations: considering an interpolation of the hazard curve of the first order and of the second order (Vamvatsikos 2013). Moreover, the results in Table 3 are obtained considering two different intervals of H in the hazard curve: a) interval defined by all considered 9 values of H; b) restricted interval defined by 5 values.

(a)



(b)

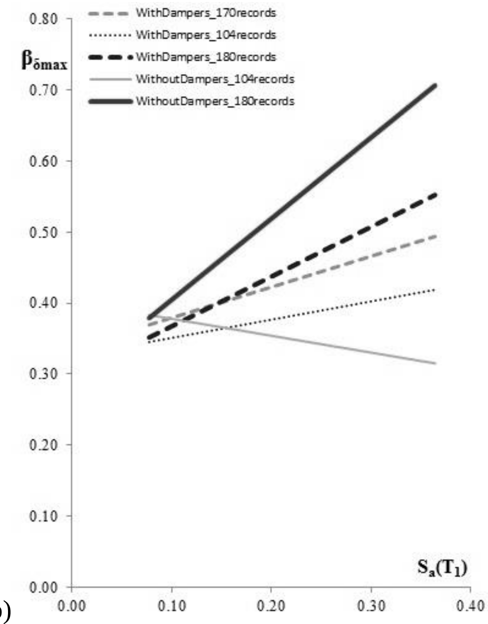


Figure 2. Comparison of cases 1, 2, and 3: (a) $Me\delta_{max}$-$S_a(T_1)$; (b) $\beta\delta_{max}$-$S_a(T_1)$.

Table 3. Influence of the approximation of the hazard curve on the failure probability (collapse defined by attainment of δ_{max}): a) 9 points in the hazard curve; b) 5 points.

$\delta_{max,u}$=2.5375%, Case 3 **With Dampers** $S_{a,1}^{NC}$=1.1027, a=2.27, b=1.1285, β_c=0.275				
	a) I order	a) II order	b) I order	b) II order
$H(S_{a,1}^{NC})$	$2.3\cdot10^{-5}$	$1.46\cdot10^{-6}$	$4.7\cdot10^{-6}$	$1.20\cdot10^{-7}$
		β_{regr} =1.0695		
$P_{F,NC}$	$1.0\cdot10^{-3}$	$9.7\cdot10^{-4}$	$1.1\cdot10^{-2}$	$4.2\cdot10^{-4}$
		β_{cost} =0.4803		
$P_{F,NC}$	$5.9\cdot10^{-5}$	$2.6\cdot10^{-5}$	$3.33\cdot10^{-5}$	$1.98\cdot10^{-5}$

Table 3 (Continued).

Without dampers $S_{a,1}^{NC}=0.4067$, $a=9.86$, $b=1.1509$, $\beta_c=0.275$				
	a) I order	a) II order	b) I order	b) II order
$H(S_{a,1}^{NC})$	$3.8\cdot10^{-4}$	$2.7\cdot10^{-4}$	$2.6\cdot10^{-4}$	$2.3\cdot10^{-4}$
		$\beta_{regr}=0.7554$		
$P_{F,NC}$	$1.2\cdot10^{-3}$	$2.7\cdot10^{-3}$	$2.6\cdot10^{-3}$	$1.3\cdot10^{-3}$
		$\beta_{cost}=0.6389$		
$P_{F,NC}$	$8.9\cdot10^{-4}$	$1.9\cdot10^{-3}$	$1.5\cdot10^{-3}$	$1.2\cdot10^{-3}$

5 CONCLUSIONS

In conclusion we can note that the results of probabilistic assessment depend on the number of records considered: reliable trends have been obtained only for 180 records for both structures; the median values of demand parameters for the structure without dampers are greater than with dampers regardless of the number of considered records. With regard to β_{regr} it is possible to note that: it increases with seismic intensity; it depends on the number of records; the expected trend (greater dispersion for the structure without damper) has been determined only for a high number of results (180 records). With regard to β_{cost}, we can note that: the expected trend has been obtained also for few results; it increases with the number of seismic events for both structures with and without dampers. Finally, it is possible to observe that the expression of the annual probability of failure proposed by 2000 SAC/FEMA method is strongly sensitive to modifications of the hazard curve and dispersion; for the hazard curves determined with the interpolation of the first order, only considering β_{cost} has given $P_{F,NC}$ values always in line with the expectations. Otherwise, for the hazard curves determined with the interpolation of the second order, a lower influence of the dispersion has been observed and the expected trend has been derived with both dispersions β_{regr} and β_{cost}.

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