SIMPLIFIED METHOD OF FRAGILITY ANALYSIS OF STRUCTURES WITH NON-TRADITIONAL SEISMIC PROTECTION

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SUMMARY

The paper presents simplified method for fragility analysis of passive seismically protected structures. Application of this method to frame structures retrofitted by two types of friction devices is demonstrated. Seismic intensity parameter represented by the mean value of the pseudovelocity response spectrum in a specified periods band is derived and made use of. Employment of this parameter gives the possibility to apply linear regression of the response parameters of the considered non-linear systems on this seismic intensity. This regression analysis and the concept of “mean seismic excitation” form the basis of the proposed simplified method for fragility estimation. The effect of the randomness of the friction forces is estimated by Monte Carlo simulations assuming friction force is normally distributed. The fragility analysis on the normalized seismic intensity is performed to compare the fragility (or probability of failure) of the considered structures. The results of the fragility analysis give possibility to identify the key risk contributors for the considered structures. On this basis recommendations for improvement of their seismic response are given.

INTRODUCTION

Traditional aseismic design relies on relatively high strength or structural ductility. An alternative approach, based on innovative methods for nontraditional seismic protection of structures, aiming at avoiding or minimizing inelastic deformations in the main members of structures, has been developed extensively in the last decades. The variety of design concepts, most of which are directed towards aseismic protection of important buildings and structures, naturally requires to study their seismic safety.

The paper presents simplified method for fragility analysis of passive seismically protected structures. Application of this method to frame structures retrofitted by two types of friction devices is demonstrated.

STRUCTURAL MODEL

The study is performed for the case of a four story braced frame (Figure 1) designed after a moment resisting steel frame. In each story steel friction devices with prestressed bolts in slotted holes are introduced. The restriction of the maximum relative displacement a_0 of the sliding surfaces is assumed to be set by introduction of ‘bearing’ unprestressed bolts in slotted holes with a smaller size in parallel of the prestressed bolts in slotted holes [Dimova, 1998]. The bracings are assumed to act both in tension and compression and are hinged to the connecting plate.

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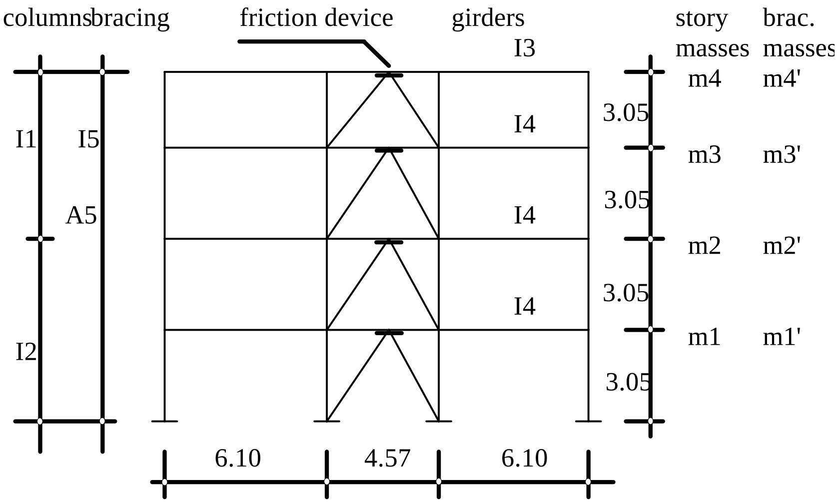

Figure 1: Four story frame (dimensions in meters)

The structure has the following dimensions: story masses $m_1 = m_2 = m_3 = 41610$ kg, $m_4 = 40820$ kg; second moments of area $I_1 = 7117.5\ cm^4$, $I_2 = 8740.8\ cm^4$, $I_3 = 12486\ cm^4$, $I_4 = 15567\ cm^4$, $I_5 = 1210\ cm^4$;cross-section $A_5 = 32\ cm^2$; bracing masses $m'_1 = m'_2 = m'_3 = m'_4 = 93.7$ kg.

Friction forces are modeled by use of the velocity method and the magnitude of the friction coefficient μ during the sliding phase decreases with the growth of the relative velocity of the sliding surfaces (see Fig. 2). The value of $\varepsilon = 0.001$ m/s is chosen to enable an adequate description of sticking phase in accordance with [Dimova *et al*., 1995]. Numerical simulations are performed by accepting tg$\alpha = 0.05$ s/m, as proved by [Zinoviev, 1952] for steel - steel surfaces (denotations of ε and α are given on Fig. 2) and $\mu_{max} = 0.15$. A "correctness" condition is introduced in order to avoid the relative velocity difference high frequency oscillations and connected with them disaccuracies of the numerical solution.

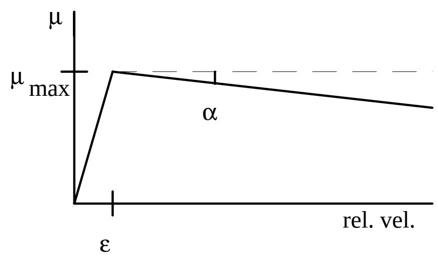

Figure 2: Modelling of friction coefficient

Maximum friction force magnitude Ffr_{max} is considered to be 200 kN in all four friction devices. The action of restrictors is modeled by uniaxial link finite element with high stiffness ($k_l = 2\ 10^9$ kN/m), thus practically allowing no relative displacement of the sliding surfaces. In the numerical simulations the value of $a_0 = 0.005$ m is considered to permit the development of energy dissipation through friction. Also, such value of a_0 gave good results in the study of the effectiveness of the system with joint connections [Dimova and Tzenov, 1990].

Further, in the comparative study of the seismic response variability and fragility, the following abbreviations are introduced:

FBS (flexible basic system) - initial 'bare' frame with fundamental period of 1.0 s;

RBS (rigid basic system) - frame with fixed bracing, with fundamental period of 0.31 s.

FRS (friction system) - braced frame with friction devices without restrictors;

FRSR (friction system and restrictors) - braced frame with friction devices and restrictors.

SIMPLIFIED FRAGILITY ANALYSIS

Theoretical background

The present study is based on a method for estimation of reliability for elasto-plastically behaving structures under strong earthquake motions, using reliability index, as first proposed by [Kanda, 1985] and developed by [Hirata *et al.,* 1993] for base-isolated structures. Safety margin *Sf(e)* concerning some seismic response parameter for a given seismic intensity *e* is defined as the ratio of its seismic capacity *R* to the calculated for *e* value of the seismic response parameter *S(e), i.e.*

$$Sf(e) = R / S(e) \tag{1}$$

and under the assumption that *R* and *S* are log-normally distributed the fragility in function of the seismic intensity parameter *e* is

$$Pf(e) = \phi\left(\frac{lnSm(e) - lnRm}{\sqrt{\beta r^2 + \beta s^2}}\right) \tag{2}$$

where:

ϕ is the cumulative function of standard normal distribution;

Sm(e) and *Rm* are the median values of the seismic response *S(e)* and seismic capacity *R*, respectively;

βr and βs are the lognormal standard deviations of *R* and *S(e)*, respectively.

Thus having the regression equation of the seismic response *S(e)* on the chosen seismic intensity parameter *e* (see section 3.3) one can express the seismic fragility of the structural members by use of eq. (2). It gives the possibility to consider the randomness inherent in the structural response to seismic excitations (accounted by βs) and the randomness in structural capacity (accounted by βr). The effect of modelling uncertainty herewith is not taken into consideration. When needed, it could be expressed in the manner, for example as a preset confidence interval [Hirata *et al.,* 1993].

Seismic response parameters for fragility estimation

The seismic response parameters have to be chosen on the clear definition of what constitutes failure for each of the safety related components of the considered structure. On the basis of the aseismic design requirements and the experience of nonlinear analysis of steel frame structures, the following seismic response parameters are considered in each *i-th* story for fragility estimation:

(i) story drifts *Di*;

(ii) maximum moment *Mi* in the columns which have uniform cross-section;

(iii) axial force *Ni* in the bracings of FRSR. Axial force in the bracings of the FRS is not considered to be a critical parameter, because it remains almost constant during the sliding of the friction device (the contribution of the inertial force due to the bracings mass is negligible).

Fragility of restricting devices (bearing bolts) is not considered, because they are assumed to be designed for a shear force which exceeds the force which causes the buckling of bracings. Since the fragility analysis in this paper is directed to the potentiality of the considered structures to withstand seismic excitations without damage of the main frame members, the considered seismic capacities correspond to the elastic limit or to the Codes requirements for story drifts (1/250 of the story height according to the provisions of the Bulgarian Codes for design of buildings and structures in seismic regions).

Selection of seismic intensity parameter

In the present study following ground motion parameters are considered as seismic intensity parameters: peak ground acceleration *Ap*, peak ground velocity *Vp*, spectral pceudovelocity *Sv* and spectral acceleration *Sa* with damping *h* 5% of critical. Since the considered MDOF non-linear systems (FRSR and FRS) exhibit first periods of free vibrations which depend on the amplitude of vibration and vary between 0.31 s (the fundamental period of RBS) and 1.0 s (the fundamental period of FBS), the average values *Svm* and *Sam* in the periods band of 0.31 to 1.0 s of *Sv* and *Sa*, respectively, are considered as seismic intensity parameters of FRSR and FRS. The seismic intensity parameters for FBS and RBS are the *Sv* and *Sa* values corresponding to their fundamental periods.

Twenty observed earthquake records with *Ap* ranging between 1.05 and 11.48 m/s^2 are used to investigate the correlation between the response of the considered systems and above mentioned seismic intensity parameters, as described in detail in [Dimova and Hirata, 1999]. Linear regression analysis is performed for the seismic response parameters of the considered structures on these seismic intensity parameters. As a measure of the goodness of the linear fit the coefficient of determination Rd^2 is used [Size, 1987].

The response characteristics of both linear systems, RBS and FBS, correlate much better with corresponding values of the seismic intensity parameter *Sv* (and respectively with *Sa*) exhibiting a mean value of the coefficient of determination for all the response parameters $Rdm^2 > 0.95$, than with the seismic excitation characteristics *Ap* and *Vp* ($Rdm^2 < 0.77$). The response characteristics of FRSR exhibit slightly bigger coefficients of determination on the mean value of spectral acceleration *Sam* ($Rdm^2 = 0.86$), than on the mean value of spectral pseudovelocity *Svm* ($Rdm^2 = 0.83$). On the contrary, the responses of FRS correlate better with *Svm* ($Rdm^2 = 0.88$) , than with *Sam* ($Rdm^2 = 0.81$). The choice of *Sv* as seismic intensity parameter for fragility analysis of linear systems such as RBS and FBS and *Svm* as a seismic intensity parameter for fragility analysis of nonlinear systems such as FRSR and FRS is supported also by the following reasons:

(i) *Sv* is a basis of the Housner's spectrum intensity *SI* defined as the area under the spectrum curve between periods of 0.1 and 2.5 s. The seismic intensity parameter *Svm* could be considered as a kind of *SI* calculated for the period band ΔTi (from 0.31 s to 1.0 s in the considered case) and normalized to ΔTi . In this way *Svm* relates *SI* and also gives information for the shape of *Sv* in the considered period band ΔTi;

(ii) for zero damping oscillator the Fourier amplitude spectrum (FAS) of the accelerogram is the upper limit of *Sv*. Since FAS may be interpreted as a measure of the total energy in the end of the earthquake within the undamped oscillator, thus *Sv* and *Svm* also reflect this quantity for small values of damping.

(iii) FAS, divided by 2π, is the ground acceleration amplitude intensity at a given circular frequency of ϖ per unit of ϖ. This way *Sv* and *Svm* for small values of damping directly relate the ground acceleration amplitude characteristics, too.

Concept of 'mean seismic excitation'

Fragility of considered structures is estimated for seismic loading specified by a response spectrum. In this study for demonstration purposes is considered the response spectrum of Bulgarian Codes for second category of soils as shown in Figure 3. From this spectrum twenty artificial accelerograms are generated and made use of for the response analyses. The mean values of the accepted seismic intensity parameters of these artificial accelerograms are as follows: $\overline{S}v(T = 0.31s, h = 5\ \%) = 0.3194$ m/s; $\overline{S}v(T = 1.0\ s, h = 5\ \%) = 0.4596$ m/s; $\overline{S}vm\ (T = 0.31 \sim 1.0\ s, h = 5\ \%) = 0.4285$ m/s. Seismic responses of FRSR, FRS, RBS and FBS for the generated accelerograms are calculated and the coefficients of variation (c.o.v.) are obtained.

The response of the considered structural systems (FRSR, FRS, RBS and FBS) is calculated for 11 different seismic intensities, ranging between 1 and 4 times the initial intensity of generated accelerograms. In order to reduce the number of calculations of structural response, assumption for 'mean seismic excitation' is made. More precisely, it is assumed that the seismic excitation which causes responses closest to the mean values in the original seismic intensity, will cause mean responses in all the other considered intensities and the c.o.v. will not change (see Figure 4). Under this assumption the regression lines of the response of the linear systems FBS and RBS on seismic intensity could be easily calculated (two points are needed to obtain the straight lines parameters) and only the response of FRSR and FRS should be calculated to all the considered levels of seismic intensity for only one accelerogram.

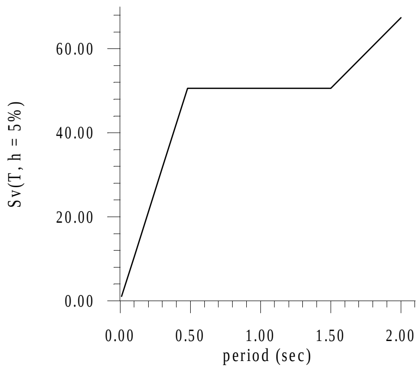

Figure 3: Target response spectrum

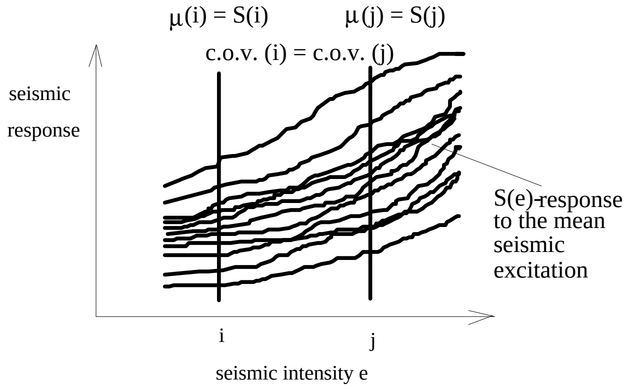

Figure 4: Concept of 'mean seismic excitation'

The above proposed concept of 'mean seismic excitation' and linear regression of the response of FRSR and FRS on *Svm* is proved by setting some value of *Svm* higher than the initial one, for example *Svm* = 1.0 m/s. Using the linear regression equations the predicted response is found. The generated twenty artificial accelerograms are scaled to *Svm* = 1.0 m/s and the mean responses are obtained from the 20 calculated responses of FRSR and FRS, respectively. The calculated and the predicted mean values are compared in Table 1. The results obtained show very good agreement except for the prediction for the fourth story response of FRS, where the friction device starts to act for intensities of *Svm* = 0.8 and higher, so the regression line is derived for different quantities of response in the considered intensities band and exhibit comparatively low coefficient of determination. These results could be improved by a more appropriate choice of the range of seismic intensities in which the regression analysis will be performed. For example, if the regression lines for the fourth story drift and moment of the FRS are obtained for seismic intensity *Svm* > 0.8 m/s, the predicted values become *D4* = 0.78531 cm and *M4* = 47.985 kN.m and the respective errors are +23.60% and +39.17% thus reducing the prediction error more than 2.6 times.

Table 1: Comparison of calculated and predicted mean values of the response of FRSR and FRS

parameter	story	FRSR			FRS		
		calculated	predicted	error (%)	calculated	predicted	error (%)
Di (cm)	1	1.42807	1.45770	+2.07	2.16978	2.54370	+17.23
	2	1.41961	1.43512	+1.09	2.57492	2.96720	+15.23
	3	1.30324	1.28624	-1.30	2.06348	2.2936	+11.15
	4	1.20415	1.08246	-10.11	0.63537	1.12451	+76.98
Mi (kN.m)	1	140.788	143.746	+2.10	212.171	246.883	+16.36
	2	93.827	96.032	+2.35	181.617	204.210	+12.44
	3	81.369	77.859	-4.31	134.047	141.482	+5.54
	4	77.229	65.865	-14.71	34.478	70.668	104.97
Ni (kN)	1	981.138	1012.540	+3.2			
	2	972.200	988.586	+1.68			
	3	849.177	861.216	+1.42			
	4	744.422	654.116	-12.13			

When using the mean seismic excitation concept the regression analysis of seismic response parameters on seismic intensity is performed for one accelerogram. The used seismic intensity parameters $\overline{S}v$ and $\overline{S}vm$ for only one accelerogram are linearly proportional to its peak acceleration *Ap*. In this case the fragility calculated on $\overline{S}v$ and $\overline{S}vm$ coincides with the fragility on the normalized seismic intensity *Sn* calculated on *Ap*, as shown in Figure 5 for the fragility of the first story bracing of FRSR (*N1*) and second story drift of FRS (*D2*), respectively. Fragility is shown in terms of normalized seismic intensity *Sn* (seismic intensity *Svm* and *Ap* normalized to the initial mean seismic intensity $\overline{S}vm$ = 0.4285 m/s and mean $\overline{A}p$ = 4.242 m/s^2, respectively). Herewith arises the question what is the meaning of introduction of the proposed seismic intensity parameters $\overline{S}v$ and $\overline{S}vm$. To answer this question fragility of the above considered seismic response parameters *N1* and *D2* are calculated for twenty recorded accelerograms with different spectral content and intensity used in sect. 3.3. Linear regression on *Svm* and *Ap* is performed. It is assumed that the coefficients of variation of the response parameters coincide with those for generated accelerograms. The comparison of the fragilities on the normalized intensity conclusively shows that the fragility calculated for the specified target response spectrum gives an estimate of the fragility for the recorded accelerograms with different spectral content, when the latter is calculated on *Svm* (see Figure 5a,b).

a) b)

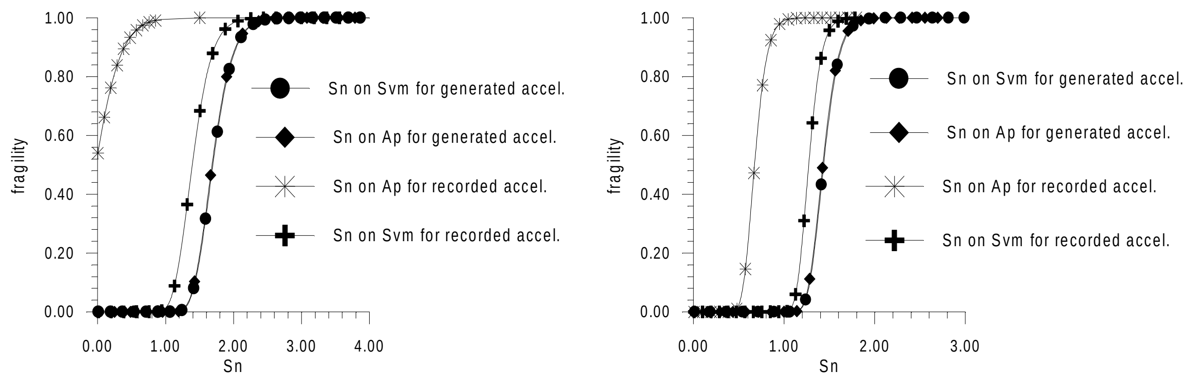

Figure 5: Fragilities of FRSR and FRS on different seismic intensity parameters:

a) fragilities of N1 of FRSR ; b) fragilities of D2 of FRS.

Variability of response due to randomness of friction forces

Randomness of friction forces in friction devices may result from the randomness of material properties connected mainly to the surface finish and randomness of the normal force due to aging effects in the prestressed joints or inexact setting. The maximum friction force is assumed normally distributed around its mean and set by random numbers with coefficient of variation of 0.2. Monte Carlo simulation of sample size 100 of the response of each of the systems with friction devices is performed for the 'mean' seismic excitation represented by accelerogram No 16. The obtained c.o.v. of the response parameters show no considerable scatter of the results in the first two stories (c.o.v. < 0.1)

For the FRS the highest c.o.v. are obtained in the third floor for the story drifts (0.52) and moments in columns (0.60). The analysis of the response of the considered structure have shown the scatter of the third story drift of FRS is considerable for $Ffr_{max} \leq 160$ kN since the friction device of FRS in the fourth story does not work for $Ffr_{max} \geq 120$ kN and the third floor slab displacements are confined by the sticking in the fourth story. The story drift in the third story decreases gradually with the growth of Ffr_{max} and for $Ffr_{max} \geq 160$ kN exhibits no considerable scatter.

The c.o.v. of all the considered parameters of the FRSR are smaller than those of the FRS except the c.o.v. of the story drift (0.69) and moment in the fourth story (0.68). The restrictors in the third story act for $Ffr_{max} \leq 160$ kN. In the fourth story the restrictors act only for the lowest value of Ffr_{max} and the friction device slides for $Ffr_{max} \leq 160$ kN. Thus the scatter of the fourth story drift for $Ffr_{max} \leq 160$ kN is caused by the confinement of the third floor slab by the action of the restrictors in the third story. These high c.o.v. of the story drifts and related to them moments in the upper stories of the FRS and FRSR naturally call for optimization of the design values of Ffr_{max} in the height of the structure. This is needed to provide a 'regularity' of the system response, i.e. simultaneous work of the restrictors and/or friction devices in all the stories.

FRAGILITY ESTIMATION

In the fragility estimation the coefficient of variation of the seismic capacities δr is set 0.15 according to the Japanese Standard for limit state design of steel structures. The lognormal standard deviation βs of each response parameter is calculated as a square root of the sum of squares of the lognormal standard deviation of the response due to randomness of the seismic excitation and lognormal standard deviation of the response due to variation of friction forces. The results are shown in Figure 6a for FRS and in Figure 6b for FRSR, respectively. Fragility is shown in terms of normalized seismic intensity *Sn* (seismic intensity normalized to the initial mean seismic intensity $\overline{S}v_m$ = 0.4285 m/s).

The key risk contributors for FRS (Figure 6a) are the first story drift and the second story drift. Different from the case of FRS, the vulnerable seismic response parameters of FRSR (Figure 6b) are the axial force in the first story bracings and the axial force in the second story bracings for $Pf > 0.2$. For $Pf < 0.2$ the key risk contributors of FRSR become the story drifts in the fourth and third stories. This result is a consequence of the high values of the lognormal standard deviations βs (up to 0.72) for the third and fourth story drifts. They are obtained by the combination of the relatively high c.o.v. due to the randomness of both, seismic excitation and friction forces. Thus the consideration of the randomness of the friction forces puts forward new key risk contributors in the range of the relatively small fragilities due to the big scatter of the seismic response parameters which normally do not contribute the vulnerability of the structure. The above identification of the key risk contributors gives the possibility to clarify the ways of improving the structural seismic response. For both, FRS and FRSR it would be optimization of the value of maximum friction force in the different stories thus providing simultaneous action of the restrictors and/or friction devices in all the stories for a given seismic intensity

a) b)

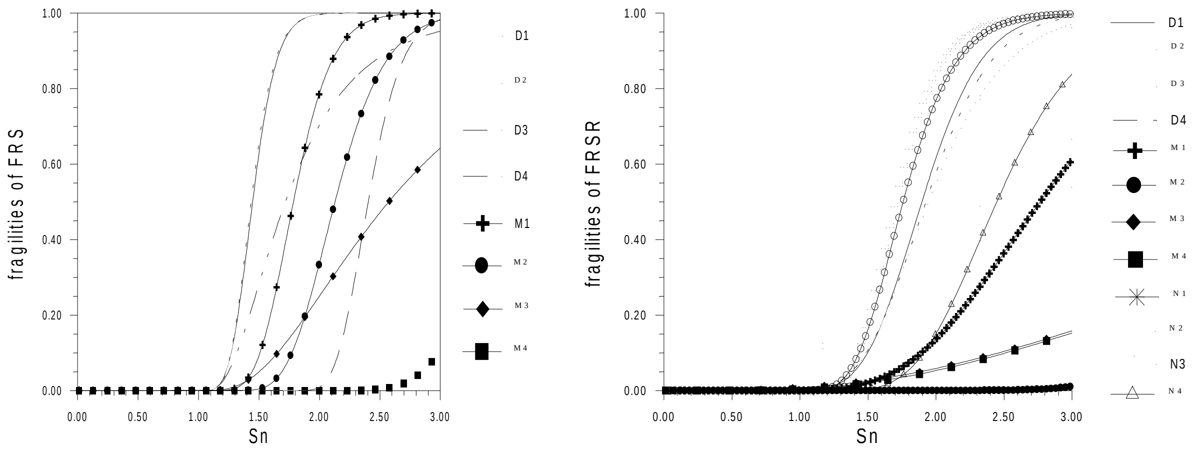

Figure 6: Fragilities on normalized seismic intensity

a)FRS; b) FRSR

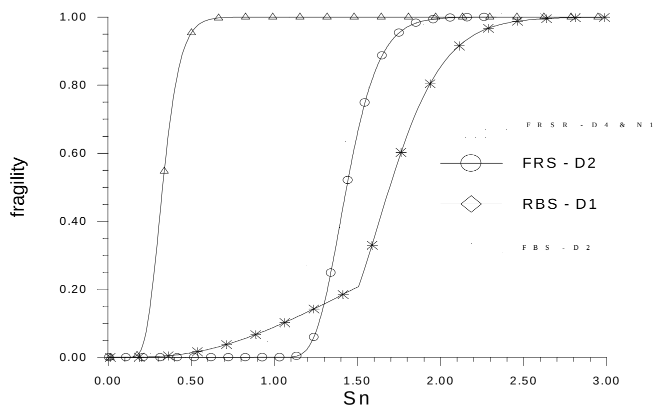

Figure 7: Envelope fragilities

The plot in Figure 7 represents the "envelope" fragilities of two considered systems with friction devices (FRSR and FRS), initial 'bare' frame (FBS) and this frame with rigidly connected bracings (RBS). The fragilities of FBS and RBS are normalized to their initial seismic intensity - $\overline{S}v(T$ = 1.0 s, h = 5 %) = 0.4596 m/s for FBS and $\overline{S}v(T$ = 0.31s, h = 5 %) = 0.3194 m/s for RBS. The most compromised system is FBS, which will be damaged with *Pf* close to 1.0 for seismic intensity equal to 0.6 of the initial one. All the considered braced frames will withstand the input motion with the original intensity with *Pf* less than 0.09 , but the two systems with friction devices and especially FRSR show higher seismic safety than RBS. When the initial "bare " frame is retrofitted by rigidly connected bracings the effect is lower, than in case of connecting the bracings by friction devices (till *Pf* = 0.78) and especially by friction devices and restrictors. RBS will be damaged with *Pf* = 0.5 for *Sn* = 1.346. For this value of the normalized intensity FRS exhibits *Pf* = 0.260 and FRSR - *Pf* = 0.17. These results conclusively show that the installation of restrictors of the relative displacements of the sliding surfaces of friction devices contributes substantially to the seismic safety of the structure.

CONCLUSIONS

1. The simplified method of fragility estimation, based on the concept of "mean seismic excitation" and linear regression of the seismic response parameters on the proposed seismic intensity parameter, defined as the mean value of the pseudovelocity spectrum in a specified periods band, allows to reduce considerably the number of simulations and gives possibility to concentrate the computational efforts in obtaining more exact 'mean seismic excitation' and coefficients of variation of the structural response parameters.

2. The consideration of the randomness of the friction forces puts forward new key risk contributors in the range of the relatively small fragilities due to the big scatter of the seismic response parameters which normally do not contribute the vulnerability of the structure - story drifts and related to them moments in the upper stories which exhibit high coefficients of variation. This result naturally calls for optimization of the design values of the maximum friction force in the height of the structure to provide simultaneous action of the restrictors and/or friction devices in all the stories for a given seismic intensity.

3. The comparative fragility analysis, based on the normalized seismic intensity, shows that when the initial "bare" frame is retrofitted by rigidly connected bracings, the effect will be much lower, than the case of connecting the bracings by friction devices and especially by friction devices with restrictors.

4. The seismic response of systems using friction devices could be substantially improved by implementing restrictors for the relative displacements of the sliding surfaces. The system using friction devices with restrictors exhibits higher seismic safety, than the system with friction devices and could be proposed for further development and application.

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