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Probabilistic analysis of structures equipped with FVDs accounting for their brittle failure

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Abstract

Anti-seismic devices should be designed with proper safety margins against their failure. Seismic standards generally prescribe safety factors (reliability factors) in order to reach a target safety level. In the case of Fluid Viscous Dampers (FVDs), these factors are applied to the stroke and velocity, and their values are not homogenous among seismic codes. This paper investigates the influence of the values of the safety factors for FVDs on the reliability of the devices and of the structural systems equipped with them. An advanced FVD model is employed to account for the impact forces arising when the dampers reach the end-stroke and the brittle failure due to the attainment of the maximum force capacity. The effect of damper failure on the seismic risk of the structural system is investigated by performing multiple-stripe analysis and monitoring different global and local demand parameters. A parametric study has been carried out, considering a case study consisting of a low-rise steel building, coupled with a dissipative system with linear and nonlinear properties and studying the consequences of different values of safety factors for stroke and forces.

Keywords: fluid viscous dampers, energy dissipation systems, seismic response, seismic risk assessment, passive protection systems, reliability factors.

1 Introduction

Fluid viscous dampers (FVDs) are devices widely used for seismic passive protection of both new and existing structures, with the aim of reducing displacements and drift demands. Several approaches are to date available for designing both size and location of viscous dampers within a building frame or in external configurations, based on direct procedures [1-5] or optimization methods [6,7]. These design approaches generally control the seismic performance of buildings under the design seismic intensity level. However, the reliability under extreme earthquake events may be characterized by low robustness and inadequate safety levels due to dampers that usually exhibit a brittle collapse behaviour, which may lead to the collapse of the whole structural system. Consequently, the choice of adequate safety factors for the design of dampers is very important for gaining a satisfactory performance under strong actions and for controlling the probability of failure.

In order to investigate this aspect, a model which is able to describe the brittle failure of FVDs is proposed and used in the present paper to evaluate the probability of collapse of structures equipped with such devices. More in detail, the proposed model assumes that the collapse of the damper is due to the attainment of its force capacity, caused by the over-velocity experienced by the damper or to the achievement of the end-stroke. Successively, the seismic risk of a 3-storey steel building equipped with FVDs, already considered as benchmark structure in previous studies [8], is evaluated by means of a probabilistic approach. The probabilistic response of the building is assessed by performing Multi Stripe Analysis (MSA) at different intensity measure (IM) levels. Results are given in terms of demand hazard curves for the main global and local engineering demand parameters (EDPs) of interest, which are the maximum interstorey drift (IDR) and the maximum absolute acceleration (A), the maximum absolute force (F_{di}) and the maximum stroke (Δ_{di}) of the dampers among the storeys. Both linear and nonlinear devices have been considered and their capacity (stroke and strength) has been designed according to a seismic action having a Mean Annual Frequency (MAF) of exceeding equal to $2{\cdot}10^{-3}$ and by assuming five combinations of amplification factors relevant to damper stroke and strength, in accordance with the main international codes [9-11]. The case without dampers and the one in which the damper failure is disregarded are also considered for comparison purposes.

2 Methods

The model proposed and used in this paper is depicted in Figure 1. It is composed of three elements: a dashpot, describing the dissipative behaviour; a hook and gap element, set in parallel to the dissipative device, which simulate the impact due to either excessive shortening ($-\Delta_{d,max}$) or elongation ($+\Delta_{d,max}$); and a third element, set in series with the others, simulating the failure due to the attainment of the force capacity. In this paper, the strength capacity is assumed to be the same in traction and in compression and the failure occurs when the modulus of damper force attains the limit value $F_{d,max}$. The damper model discussed above is implemented in OpenSees [12] using two-node link elements simulating each of the three components and various material properties to describe the different behaviours; further details can be found in [13]. The case study considered is a 3-storey benchmark steel building, consisting of perimeter moment-resisting frames and internal gravity frames with shear connections (Figure 2a). The period of the first vibration mode of the building is T_1 =1 s and the seismic hazard of the site in terms of spectral pseudo-acceleration $S_a(T_1)$ is reported in Figure 2b.

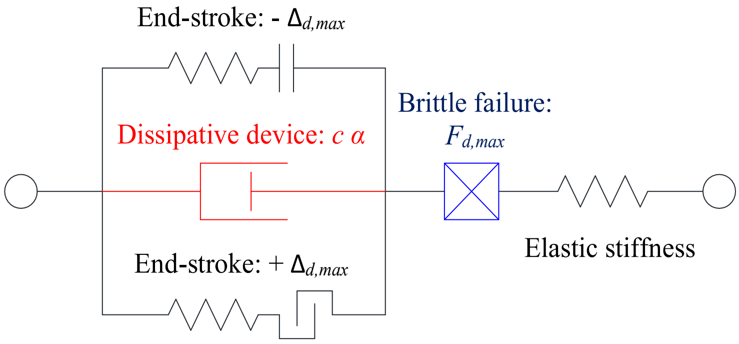
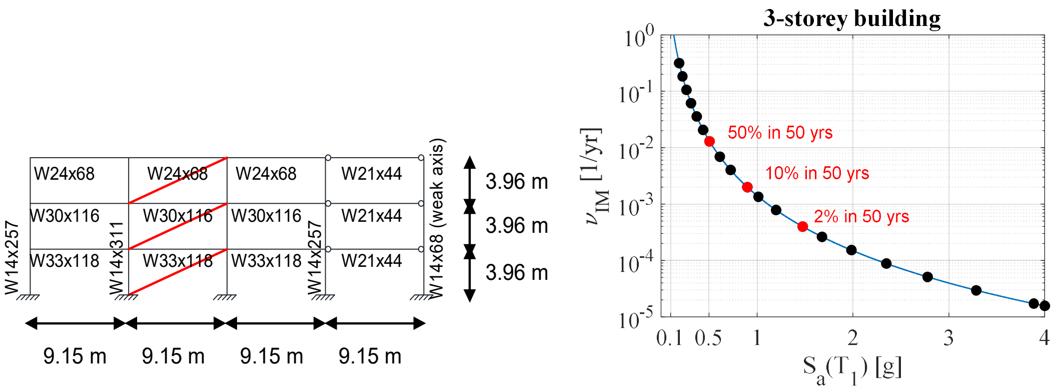


Figure 1. Dissipative device model encompassing the failure mechanisms.



(a) (b)

Figure 2. The 3-storey building (a) and the IM hazard curve (b)

The design of the FVDs is carried out to enhance the building performance under a seismic scenario with a 10% probability of exceedance in 50 years (ULS scenario according to Eurocode 8). To this aim, a target value ξ_{add} = 30% has been chosen for supplemental damping. Dampers are designed by assuming the same viscous constant for all the storeys; further details regarding the design process can be found in [13]. Table 1 reports the FVDs constitutive parameters.

α	Floor 1, c_1 [kNs$^\alpha$/m$^\alpha$]	Floor 2, c_2 [kNs$^\alpha$/m$^\alpha$]	Floor 3, c_3 [kNs$^\alpha$/m$^\alpha$]
1	13,780	11,914	7428
0.6	7477	6465	4031
0.3	4669	4037	2517

Table 1. Constitutive parameters of the FVDs.

Table 2 shows, instead, the values of mean displacement $\Delta_{d,j}$, force $F_{d,j}$ and velocity v_j demand of the dampers, evaluated at the design condition. A probabilistic framework based on a conditional probabilistic approach is used to build the demand hazard curves, expressing the MAF (v_{EDP}) of exceedance of the monitored EDPs. The probabilistic procedure, described in detail in [13], has been applied by considering different amplification factors relevant to velocity (γ_v) and stroke (γ_Δ). Values ranging from 1 to 3 have been considered in order to show the influence of this design choice on the overall system reliability. Moreover, two more limit cases are considered: "No Failure" that is the case where no dampers' failures are permitted, and "Bare Model", which represents the frame without FVDs.

α	Floor 1 $\Delta_{d,1}$ [mm]	Floor 2 $\Delta_{d,2}$ [mm]	Floor 3 $\Delta_{d,3}$ [mm]	Floor 1 $F_{d,1}$ [kN]	Floor 2 $F_{d,2}$ [kN]	Floor 3 $F_{d,3}$ [kN]	Floor 1 v_1 [m/s]	Floor 2 v_2 [m/s]	Floor 3 v_3 [m/s]
1	35.4	44.5	37.1	3109	3336	1956	0.23	0.28	0.26
0.6	32.4	41.7	35.6	3090	3050	1824	0.23	0.29	0.27
0.3	29.6	39.7	35.7	3044	2796	1712	0.24	0.29	0.28

Table 2. Damper design parameters.

3 Results

The demand hazard curves of the global EDPs, inter-storey drift and absolute floor acceleration among the storeys (IDR and A), are illustrated in Figure 3; whereas the local EDPs, concerning the damper response in terms of force and stroke (F_{di} and Δ_{di}), are illustrated in Figure 4. For all the cases with dampers and amplification factors larger than 1.0, the rate of exceeding of the target drift performance (IDR=0.012) is around 0.0021 yr^{-1}, which is the hazard level of the design action. Only in the case where no amplification is considered ($\gamma_v = \gamma_\Delta = 1$, blue curve), the rate of exceeding of the target drift performance (IDR=0.012) is notably higher than the expected one, due to the failures experienced by the dampers at intensity levels lower than the design one. Once damper rupture is attained, the building response in terms of IDR approaches the bare frame response quite perfectly (black dashed line), while the absolute accelerations (A) become even higher due to end-strokes impacts experienced by the dampers, before their failures.

With reference to the response achieved at a MAF of 2x10^{-4}, generally considered as a satisfactory target for the MAF of collapse [13], it can be seen that only amplification factor larger than 2 ensure nearly the same response of the "No Failure" case, which means the absence of brittle failure of the dampers up to that desired MAF. These results are confirmed by the demand hazard curves of the EDPs related to the dampers reported in Figure 4, where it can be seen that all the curves follow the trend of dampers with unlimited capacity (red curves) until the collapse is attained; then the curves show a sudden vertical drop in terms of force (Figure 4a) and stroke (Figure 4b). Also in this the drop occurs at a MAF lower than the target one only if amplification factors larger than 2 are applied in the design for their dimensioning. Finally, Figure 5 shows the IDR demand hazard curves for the cases with nonlinear dampers (α=0.6 and α=0.3). The trends are similar to those observed with linear dampers, but the curves have a lower slope, i.e. the system show, for a given demand value, higher exceedance annual rates.

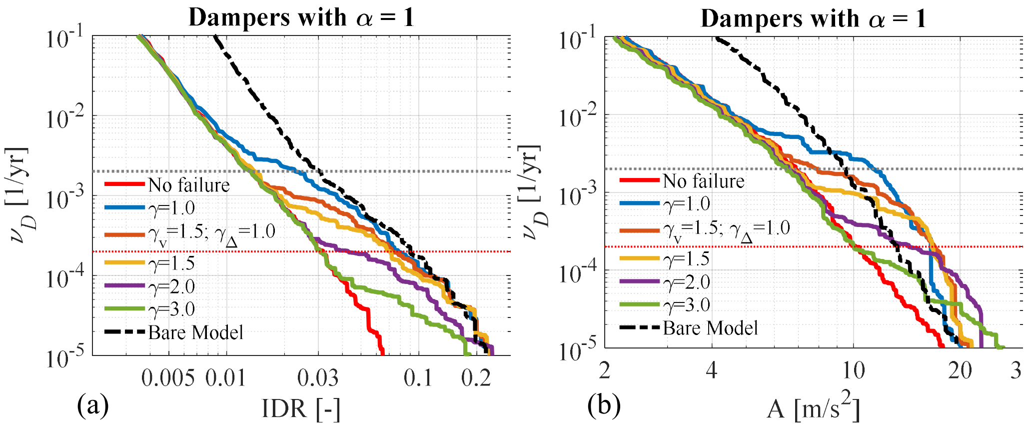


Figure 3. Demand hazard curves of (a) IDR and (b) A for different damper amplification factors.

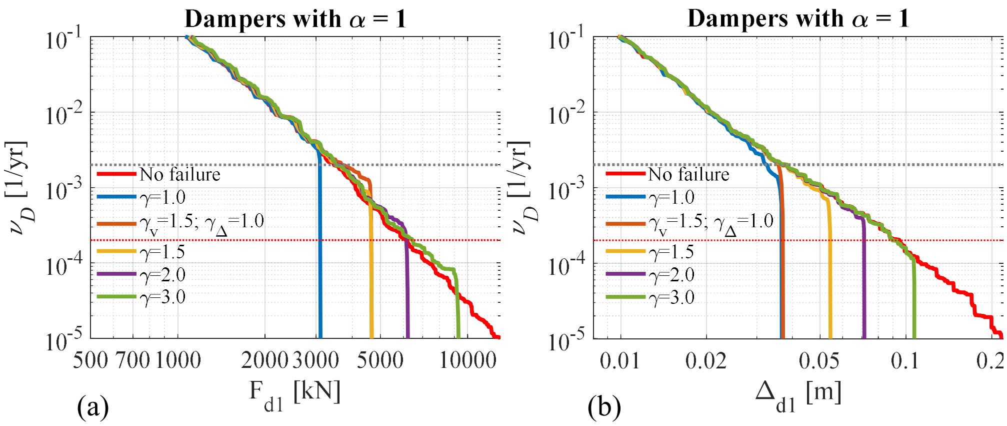


Figure 4. Demand hazard curves of the main local EDPs for different damper amplification factors.

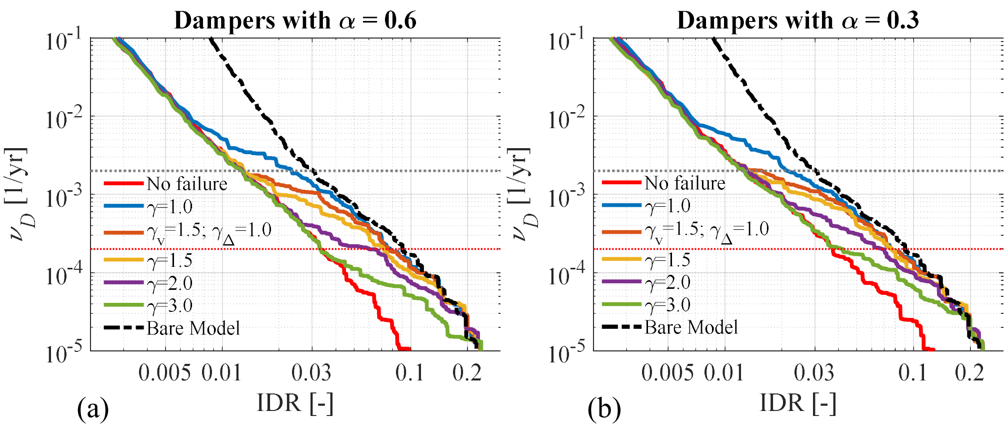


Figure 5. Demand hazard curves of the IDR parameter for nonlinear dampers: (a) α=0.6; (b) α=0.3.

4 Conclusions and Contributions

Seismic Standards generally prescribe that that the FVDs must be designed based on values of the response parameters (i.e., stroke and velocity) evaluated at the design condition and amplified by safety factors (reliability factors), in order to reach a target level of safety. However, the values of these reliability factors are not homogenous among the various Codes and the level of safety attainable through their use has not been sufficiently investigated. In the present paper a parametric investigation is carried out to explore the influence of these safety factors on the seismic risk of structural systems equipped with linear and nonlinear FVDs. The brittle failure of dampers, occurring when their internal force attains the device strength, has been considered in the probabilistic analyses. Based on the outcomes of the present study, the following conclusions can be drawn:

- The likelihood of the damper failure as well as the "rapidity" of the response transition from damped to bare (or partially damped) structural system are governed by the magnitude of the two amplification factors (γ_Δ,γ_v) adopted for damper stroke and velocity.
- If no amplification is provided ($\gamma_v = \gamma_\Delta = 1.0$), the dampers probability of failure is higher than the design hazard level (assumed equal to 0.0021 yr-1 in this work), thus, dampers experience failure at intensity levels lower than the design one.
- The use of amplification factors higher than 1.0 allows attaining lower failure probabilities, and this beneficial effect is more significant for larger γ factors.
- Only the largest amplification factors ($\gamma_v = \gamma_\Delta = 3.0$) ensure that the brittle failure of the device and thus the collapse of the building occur at a MAF lower than the target one, assumed equal to 2×10^{-4}.
- Nonlinear dampers exhibit higher failure probabilities (about two times for the case α=0.3) than the linear ones, thus the safety coefficient should depend on the degree of nonlinearity of the adopted dampers.

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