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COMPARISON OF DIFFERENT METHODS FOR VISCOUS DAMPER PLACEMENT IN EXISTING FRAME BUILDINGS

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The main purpose of this research is to investigate the effects of different vertical distributions of the properties of nonlinear fluid-viscous dampers for the retrofit of existing multi-story reinforced concrete frames. In particular, the different distributions are defined on the basis of the same value of the supplemental damping ratio. Since the viscous dampers are used for the retrofit of existing buildings, they are dimensioned assuming that the structure can exceed the elastic limit, with the only condition to satisfy the prefixed performance limit. In the design phase the different vertical distributions of damper properties are compared in terms of the total sum of the damping coefficients. The effectiveness of the different distributions is then examined by performing time-history analysis of several case studies considering a nonlinear behavior both for the viscous dampers and for the structural members. The results of the nonlinear dynamic analyses are examined in terms of inter-story drifts and dampers forces. The considered case studies are five RC frames characterized by different number of stories (3, 6 and 9 stories) and also by different properties in terms of regularity in elevation. In this way it is also possible to investigate the effect of the vertical distribution of the damper properties for regular and irregular frames.

Keywords: Damper distribution, Nonlinear viscous damper, Seismic retrofit, Design procedure, Nonlinear dynamic analyses.

1 INTRODUCTION

The importance of seismic assessment and rehabilitation of existing buildings is even more evident for structural engineers. In these cases an innovative technique as the dissipation of energy by added damping devices may be very promising in improving the seismic performance. The introduction of supplemental dampers allows to limit the energy to be dissipated by the structural elements and to obtain a reduction of their damage. In rehabilitation interventions, the use of fluid-viscous dampers offers some advantages (Diotallevi *et al.* 2012, Landi *et al.* 2013 and 2014) as their behavior is independent from the frequency and their dissipative capacity is very high. Moreover the addition of dampers only does not require in general significant interventions on the elements of the existing structure. Although the placement of dampers is a critical design concern, the building codes and guidelines in general do not prescribe a particular method for the optimization of the distribution of the damper properties. A large variety of damper placement methods have been proposed and may be identified by two primary categories (Hwang *et al.* 2013). The first one is based on simple design formulas for calculating the added damping ratio (Palermo *et al.* 2013). However, adopting these design expressions, a limited number of methods have been provided on how to distribute the total required damping coefficients to each story. In the second category many studies have proposed effective methods for an optimal distribution of damper properties (Takewaki 2009) but they seems to be complex for practical applications.

It is therefore the attempt of this study to investigate the effect of some distribution methods, along with a recently proposed method based on distributing dampers only to "Efficient Story" (Hwang *et al.* 2013). The investigation regards both the output of the design in terms of total damping coefficients and the evaluation of the structural performance. The latter is studied through nonlinear dynamic analyses considering a nonlinear behavior both for the viscous dampers and for the structural members.

2 DESIGN OF THE DAMPING SYSTEM

In the design phase the determination of the seismic demand in presence of supplemental damping is performed according to a procedure proposed in literature and here described (Ramirez *et al.* 2000). This procedure is based on the comparison between capacity and demand spectrum in the acceleration-displacement graphical representation. The capacity spectrum is derived from a nonlinear static analysis, while the demand spectrum is obtained by reducing the elastic response spectrum corresponding to the considered limit state. In particular, the demand spectrum is determined as the damped response spectrum associated to the global effective damping ratio of the building. This damping ratio can be derived as the sum of three terms (Ramirez *et al.* 2000): the inherent damping ratio, the supplemental damping ratio provided by the dampers and the hysteretic damping ratio, related to the nonlinear behaviour of the structure. The last term is present only if the structure exceeds the elastic limit. In the case of nonlinear structural behaviour (elastic-perfectly plastic) and nonlinear fluid-viscous damper the effective damping ratio is given by Eq. (1):

$$\xi_{eff} = \xi_i + \xi_{ve}\left(\mu\right)^{1-\frac{\alpha}{2}} + \frac{2q_H}{\pi}\left(1-\frac{1}{\mu}\right) \tag{1}$$

where ξ_i is the inherent damping, ξ_{ve} is the supplemental damping for a linear structural response, α is the exponent of the velocity of the dampers, μ is the ductility demand and q_H is a quality factor that depends on the type of hysteresis loop. From Eq. (1) it is evident that the effective damping depends on the displacement or ductility demand. Therefore, given the supplemental damping ratio under elastic structural response, the determination of the displacement demand requires to perform iterations, since the reduced demand spectrum depends on the effective damping, which in turns is related to the displacement or ductility demand. The assumed supplemental damping ratio is able to satisfy the design objective if the displacement demand is lower than the limit corresponding to the required performance level.

Once the required supplemental damping for the retrofit is calculated, the subsequent step is the dimensioning of the single devices in order to obtain the desired supplemental damping. At this point it could be necessary to make an assumption about the distribution of the damping properties along the height. According to the considered design framework, it is possible to use the expression of the supplemental damping ratio ξ_{ve1} of the first mode provided by Ramirez *et al.* (2000). If the damping coefficients are assumed proportional to a story quantity γ_j, from the expression of the supplemental damping of the first mode it is possible to obtain:

$$C_{NLj} = \frac{\gamma_j}{\sum_{j=1}^{N_D} \gamma_j} \sum_{j=1}^{N_D} C_{NLj} = \frac{\gamma_j \cdot \xi_{ve1} 8\pi^3 \sum_{i=1}^{N} m_i \phi_{i1}^2}{\sum_{j=1}^{N_D} (2\pi)^{\alpha_j} \cdot T_1^{2-\alpha_j} \lambda_j \cdot \gamma_j f_j^{1+\alpha_j} D_{roof}^{\alpha_j - 1} \phi_{rj1}^{1+\alpha_j}} \tag{2}$$

where C_{NLj} are the damping coefficients, N_D and N are respectively the number of devices and degrees of freedom, f_j is the amplification factor related to the geometrical arrangement of the damper, T_1 is the elastic period of the first mode of vibration, ϕ_{rj1} is the difference between the modal ordinates associated with the degrees of freedom to which is connected the damper, D_{roof} is the amplitude of the roof displacement, ϕ_{i1} and m_i are, respectively, the modal ordinate and the mass of the degree of freedom i. For a fixed supplemental damping ratio ξ_{ve1}, it exists an infinite number of selections of the dampers properties. This study compares different distributions methods of the damping coefficients C_{NLj}, defining for all the dampers an exponent of velocity α=0.5.

The considered distributions proportional to story quantities are: mass proportional distribution (MPD), story stiffness proportional distribution in case of shear type schematisation (STPD), story shear proportional distribution on the basis of the first mode lateral forces (SSPD), inter-story drift proportional distribution on the basis of the first mode deformations (IDPD), and two energetic methods proposed in literature (Hwang *et al.* 2013). These methods are based on the story shear strain energy proportional distribution, one distributing dampers to all stories (SEPD) and one distributing dampers only to the "Efficient Stories" defined as those stories with shear strain energy larger than the average story shear strain energy (SEESPD).

3 CASE STUDIES

In order to compare different distribution methods applied to a variety of buildings, five RC frames are considered (Fig. 1). These example frames include three vertically regular plane frames with 3, 6 and 9 stories (called 3F, 6F and 9F, respectively) and two vertically irregular plane frames. One of the irregular frames is a 6-story frame with soft story (6FIR), the other is a 6-story frame with a setback at the third story (6FIM). These structures are assumed to be located in a zone that has been subjected to a modification of the seismic classification of the territory. Added nonlinear viscous dampers are designed considering two values of the supplemental damping ratio so to provide two different structural performances: ξ_{ve1}=10% and ξ_{ve1}=20%.

Nonlinear static analyses are performed to investigate the nonlinear behaviour of the structures by applying modal load pattern. The seismic demand is defined by the design elastic spectrum provided by the Italian code for the life safety limit state (SLV) and for a site with peak ground acceleration equal to 0.26 g and soil type C. The material non linearity is modelled through plastic hinges at the ends of the structural members. The iterative procedure described in section 2 allows to assess the seismic response without dampers (ξ_{ve1}=0%) and with dampers (ξ_{ve1}=10% and ξ_{ve1}=20%).

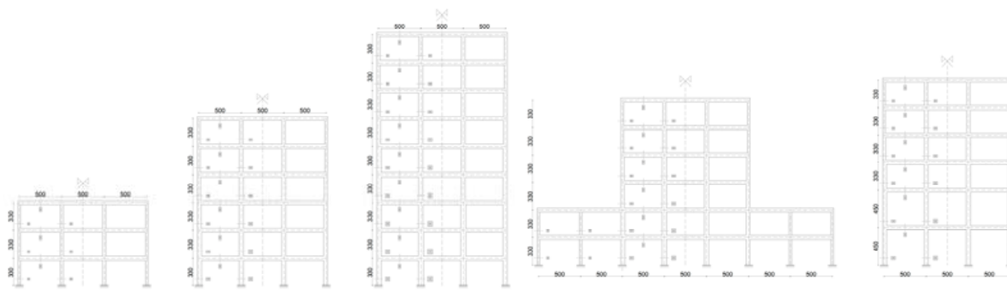

Figure 1. The case studies (regular frames 3F, 6F, 9F and irregular frames 6FIM and 6FIR).

Once the seismic demand is known for each value of supplemental damping, it is possible to design the dampers according to the different placement methods. The results of the design are compared on the basis of the total sum of damping coefficients. To compare the results of all the case studies, a synthetic comprehensive comparison is shown in Figure 2 in terms of damper coefficients. The values are shown in percentage considering for each frame as 100% the quantity calculated with the UD distribution. The comparison in terms of damper coefficients allows the understanding of which of the considered distribution methods are efficient. It is observed that MPD, STPD, SSPD, IDPD do not gain relevant advantages, resulting sometimes disadvantageous (see the irregular frame 6FIM). Among these methods slightly better results are obtained with SSPD and IDPD. The energetic methods provide a better performance, achieving at least a 20% of benefit for all frames. Among these methods, the SEESPD provides the lower values in terms of total sum of damping coefficients.

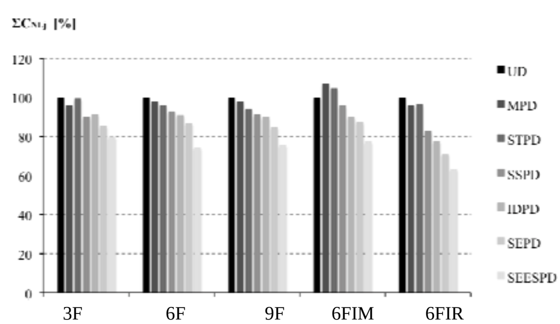

Figure 2. Comparison of the total sum of damping coefficients (ξ_{ve1}=20%).

4 NONLINEAR TIME HISTORY RESULTS

The frames, equipped with the different distributions of the damping coefficients, are then subjected to a set of seven real accelerograms selected in order to be compatible with the Italian building code spectrum used in the design phase. Several nonlinear dynamic analyses are performed considering both nonlinear dampers and nonlinear structural behaviour. The results of the analyses in terms of inter-story drifts and damper forces are then compared in order to evaluate the effectiveness of the different distributions.

Figure 3 illustrates a comparison between the average profiles of interstory drifts for the frame 6F equipped with the different distribution methods and for the two performance levels related to the two adopted supplemental damping levels. From this figure it is observed that the inter-story drifts profiles are quite similar for the structures with the different distributions of dampers. This is reasonable, as observed in literature (Hwang *et al.* 2013), since the added damping ratio for the first mode provided by the different methods is the same. However, it is important to note that the SEESPD method does not guarantee the displacement control in those story where the dampers are not installed, producing displacements sometimes larger than those of the bare frame. In fact, even if the SEESPD method can produce a more uniform distribution of drifts, this effect is particularly evident for the irregular frame with setback where there is a concentration of drift demand in the stories without dampers.

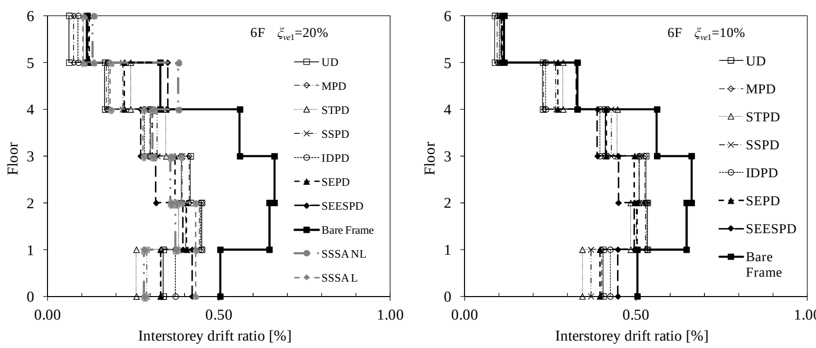

Figure 3. Interstory drifts for frames 6F (ξ_{ve1}=20% left; ξ_{ve1}=10% right).

Another significant design parameter for the dampers, that is related also to the cost, is the maximum damper force. Also this parameter is evaluated through the time-history analyses. To compare the results of all the case studies, a synthetic comprehensive comparison is shown in Figure 4 in terms of dampers forces. The values are shown in percentage considering as 100% those relative to the UD distribution. In Fig. 4 it is shown the same type of comparison of Fig. 2 but referred to the total sum of the maximum damper forces and to the two levels of added damping ratio. It is possible to notice that the methods MPD, STPD, SSPD, IDPD have not determined large advantages. They have provided a benefit less than the 5% for almost all cases, with better results for the IDPD, in particular for the frame 6FIR. The SEESPD method has given the lowest values of the damper forces, leading to an advantage variable in almost all cases from 15 to 25%, more significant for the irregular structures. The SEPD method has determined general improvements, even if the advantage has not been always so significant, as for the regular frames and ξ_{ve1}=20%.

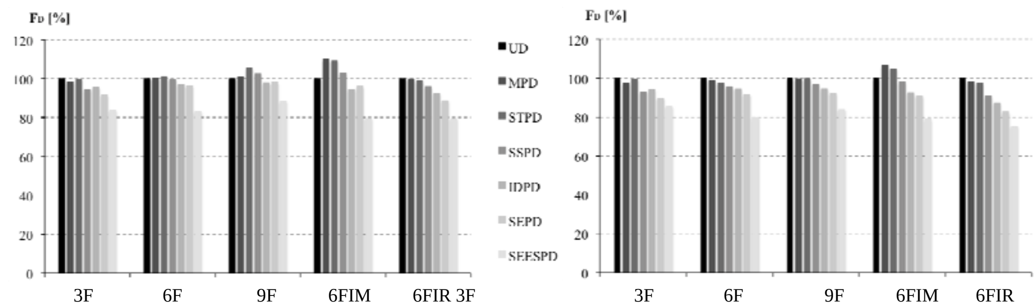

Figure 4. Total sum of maximum damper forces (ξ_{ve1}=20% left; ξ_{ve1}=10% right).

5 CONCLUSIONS

In the design phase the energetic methods SEPD and SEESPD have provided the best advantages in terms of total sum of the damping coefficients of the dampers. In general the results of nonlinear time-history analyses have shown that the profiles of the interstory drifts are quite similar for the structures equipped with the different distributions of dampers, with not significant variations of the maximum drifts. The results have highlighted also that the application of the SEESPD requires particular attention with regard to the control of the response in the stories without dampers. Considering the reduction of total damper force in relation to the UD distribution, the other simple non energetic methods have not provided large advantages, even if better results have been derived with IDPD. The best reduction of damper forces has been obtained with the method SEESPD, which has provided values similar to the more complex repetitive algorithm. The results of this research have shown that the energetic method could be a good choice for the practical design of viscous dampers.

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