INFLUENCE OF VERTICAL DISTRIBUTION OF DAMPER PROPERTIES FOR SEISMIC UPGRADING OF REGULAR AND IRREGULAR RC FRAMES

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ABSTRACT

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-storey 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 behaviour both for the viscous dampers and for the structural members. The results of the nonlinear dynamic analyses are examined in terms of interstorey drifts and dampers forces. The considered case studies are five RC frames characterized by different number of storeys (3, 6 and 9 storeys) 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.

INTRODUCTION

The importance of seismic assessment and rehabilitation of existing buildings is even more evident for structural engineers (BSSC, 1997). This is due to the large number of inadequate existing structures in earthquake regions. The need to assess and retrofit existing structures becomes particularly stringent for public and strategic buildings, which have to maintain their functionality for stronger earthquakes than ordinary buildings. The retrofit objective of satisfying the seismic requirements of new structures is often economically prohibitive and very difficult to reach, especially for strategic buildings. 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 (Constantinou et al., 1998; Christopoulos and Filiatrault 2006). In the rehabilitation interventions the use of fluid-viscous dampers offers some advantages (Diotallevi et al., 2012; Landi et al., 2013) as their behaviour is independent from the frequency and their dissipative density is very high. Moreover the only addition of dampers does not require in general significant interventions on the elements of the existing structure.

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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 (BSSC, 2003; 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 storey of the building. In this way there is an infinite number of selections for the damping coefficients along the height of the building corresponding to a prefixed supplemental damping ratio (Whittle et al., 2012; Hwang et al., 2013). In the second category, there have been many studies concerning the optimal damper placement and the optimal distribution of damper properties, including methods based on the principles of active control theory (Gluck et al., 1996) or methods based on gradient search (Takewaki, 1997 and 1999; Singh and Moreschi, 2002; Levy and Lavan, 2006). In addition to the above design methodologies, a sequential search algorithm (SSA) (Zhang and Soong, 1992) and a simplified sequential search algorithm (SSSA) (Lopez Garcia, 2001; Lopez Garcia and Soong, 2002) have been proposed for determining the damper location and damper coefficient distribution with the purpose to obtain the minimum interstorey velocities. Takewaki (2009) presented a more comprehensive list of contributions to the field of damper placement and concluded that despite the large quantity of information, structural engineers lack tools necessary for placing dampers optimally in a structure.

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

BACKGROUND

In the design phase the determination of 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 while the capacity spectrum is determined by associating pushover curve to the equivalent SDOF structure, making a bilinearization and converting it from base shear-roof displacement relationship to spectral acceleration-spectral displacement relationship.

The demand spectrum is determined by applying to the elastic response spectrum a damping reduction factor, which is a function of the effective damping ratio (Ramirez et al., 2000; BSSC, 2003). The effective 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):

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

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 ξ_h is the hysteretic damping provided by the nonlinear response of the structural members evaluated as proposed by Ramirez et al. (2000):

$$\xi_h = \frac{2q_H}{\pi}\left(1 - \frac{1}{\mu}\right) \tag{2}$$

where q_H is a quality factor that depends on the type of hysteresis loop. From Eq.(1) and (2) 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 iterative procedure can start assuming a certain value of displacement demand. The spectrum is then reduced according to ξ_{eff}, and the intersection with the capacity curve can be derived (Fig.1). This value has to correspond to the one initially supposed, otherwise another iteration should be performed by changing the value of the assumed displacement demand. The iterations are repeated until the difference between two subsequent values of displacement demand is negligible.

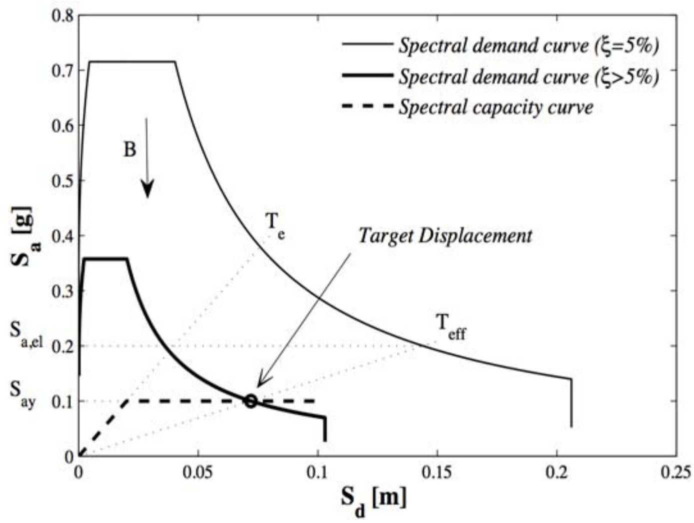

Figure 1. ADRS format: spectral capacity and spectral demand curves

The assumed supplemental damping ratio is able to satisfy the design objective if the displacement demand is lower than the displacement limit corresponding to the required performance level. In this procedure the supplemental damping ratio is fixed a priori and the identification of the value required to obtain a given performance needs to iterate the determination of the displacement demand. To overcome this difficulty some of the authors proposed in another research work (Diotallevi et al., 2013) an original and direct procedure aimed at determining the minimum supplemental damping ratio to be provided for obtaining a given performance, and in particular the rehabilitation of the existing structure for a given seismic action.

In the design phase, 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 following Eq.(3), expression of the supplemental damping ratio for the first mode provided by nonlinear fluid-viscous dampers (Ramirez et al., 2000):

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

where C_{NLj} are the damping coefficients, N_D and N are respectively the number of devices and of 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, $ø_{rj1}$ 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, $ø_{i1}$ 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 the velocity of the dampers α=0.5 and a diagonal geometric configuration f_j=cosθ_j, where θ_j is the angle between the diagonal-brace damper and the storey.

DISTRIBUTION METHODS OF THE DAMPING COEFFCIENTS

For the design simplicity and convenience, practical engineers often assume a uniform distribution (UD) of the damping coefficients, with the same damper coefficient at each storey $C_{NLj}= C_{NL}$=const., determined from Eq.(3):

$$C_{NL} = \xi_{ve1} \frac{8\pi^3 \sum_{i=1}^{N} m_i \phi_{i1}^2}{\sum_{j=1}^{N_D} (2\pi)^{\alpha_j} \cdot T_1^{2-\alpha_j} \cdot \lambda_j f_j^{1+\alpha_j} D_{roof}^{\alpha_j-1} \phi_{rj1}^{1+\alpha_j}} \tag{4}$$

Other distribution methods of the damping coefficients can be assumed, for example proportional to a storey quantity γ_j:

$$C_{NLj} = p \cdot \gamma_j \tag{5}$$

where p is a proportionality constant. The total damping coefficient of the structure is equal to the sum of all the damping coefficients:

$$\sum_{j=1}^{N_D} C_{NLj} = p \cdot \sum_{j=1}^{N_D} \gamma_j \tag{6}$$

Substituting Eq.(6) into Eq.(5), one can obtain the relationship between the damping coefficient at each storey and the total damping coefficient of the building:

$$C_{NLj} = \frac{\gamma_j}{\sum_{j=1}^{N_D} \gamma_j} \sum_{j=1}^{N_D} C_{NLj} \tag{7}$$

Substituting Eq.(7) into Eq.(3), we get:

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

The sum of the damper coefficients corresponding to the desired added damping ratio ξ_{ve1} can then be calculated using:

$$\sum_{j=1}^{N_D} C_{NLj} = \xi_{ve1} \frac{8\pi^3 \sum_{i=1}^{N} m_i \phi_{i1}^2}{\sum_{j=1}^{N_D} (2\pi)^{\alpha_j} \cdot T_1^{2-\alpha_j} \lambda_j \cdot \gamma_j f_j^{1+\alpha_j} D_{roof}^{\alpha_j - 1} \phi_{rj1}^{1+\alpha_j}} \sum_{j=1}^{N_D} \gamma_j \tag{9}$$

Employing Eq.(7) and Eq.(9), the formula for distributing the damping coefficient to each storey is equal to:

$$C_{NLj} = \frac{\gamma_j \cdot \xi_{ve1} 8\pi^3 \sum_{i=1}^{N} m_i \phi_{i1}^2}{\sum_{j=1}^{N_D} (2\pi)^{\alpha_j} \cdot T_1^{2-\alpha_j} \lambda_j \cdot \gamma_j f_j^{1+\alpha_j} D_{roof}^{\alpha_j - 1} \phi_{rj1}^{1+\alpha_j}} \tag{10}$$

The distributions proportional to storey quantities considered in this study are: mass proportional distribution (MPD), storey stiffness proportional distribution in case of shear type schematisation (STPD), storey shear proportional distribution on the basis of a modal analysis (SSPD), interstorey drift proportional distribution on the basis of a modal analysis (IDPD), and two energetic methods proposed in literature (Hwang et al., 2013), based on the storey shear strain energy proportional distribution, one distributing dampers in all storey (SEPD) and one distributing dampers only to the "Efficient Storeys" defined as those storeys with shear strain energy larger than the average storey shear strain energy (SEESPD).

CASES OF STUDY

In order to compare different distribution methods applied to a variety of buildings, five RC frames are considered (Fig. 2 and 3). These examples frames include three vertically regular planar frame with different number of storeys (3, 6 and 9 storeys) and two vertically irregular planar frames including a 6-storey planar frame with soft storey and a 6-storey planar frame with a setback at the third storey.

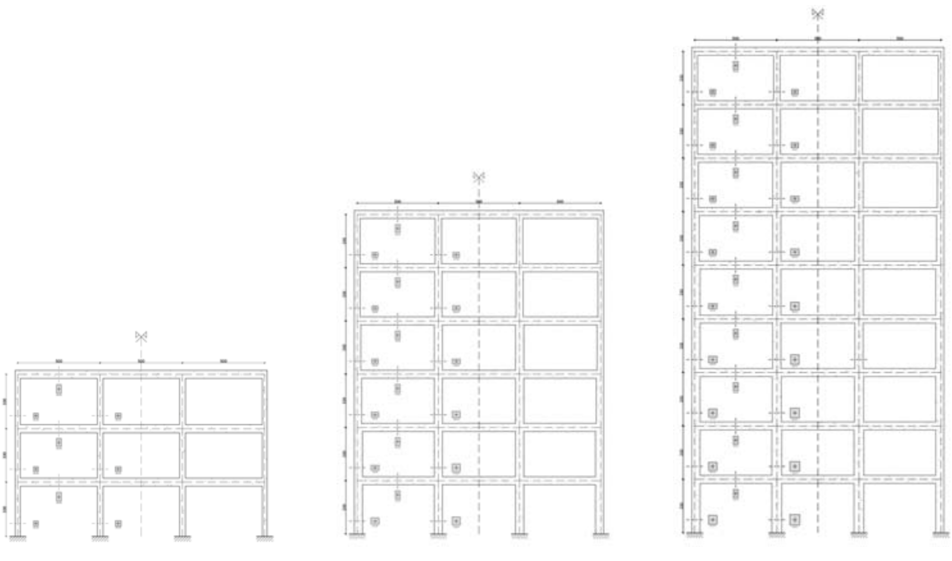

Figure 2. 3, 6 and 9-storey vertically regular RC frames. (3F-6F-9F)

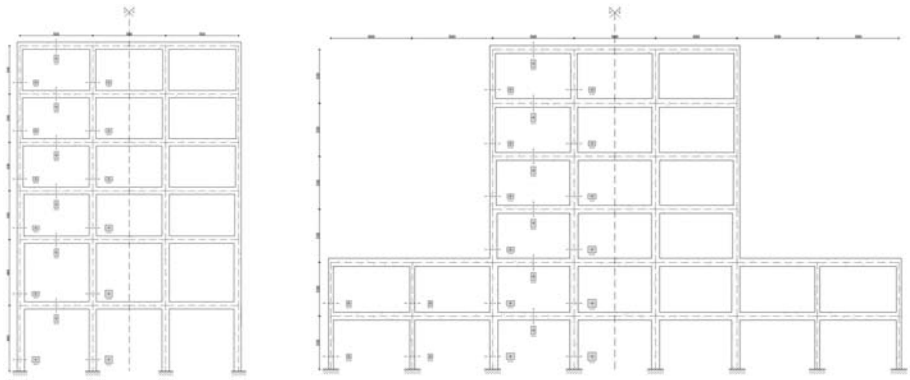

Figure 3. 6-storey vertically irregular RC frames: soft storey (6FIR) (left), setback (6FIM) (right)

The characteristic material strengths are equal to 25 MPa for the concrete and 450 MPa for the steel. All the frames (except the irregular frames in the first two storeys) are characterized by an influence area large 6 metres in the orthogonal direction, 6 metres long bays and interstorey heights of 3.3 meters. These structures are designed for only vertical loads and are assumed to be located in a zone that is now classified as seismic due 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%.

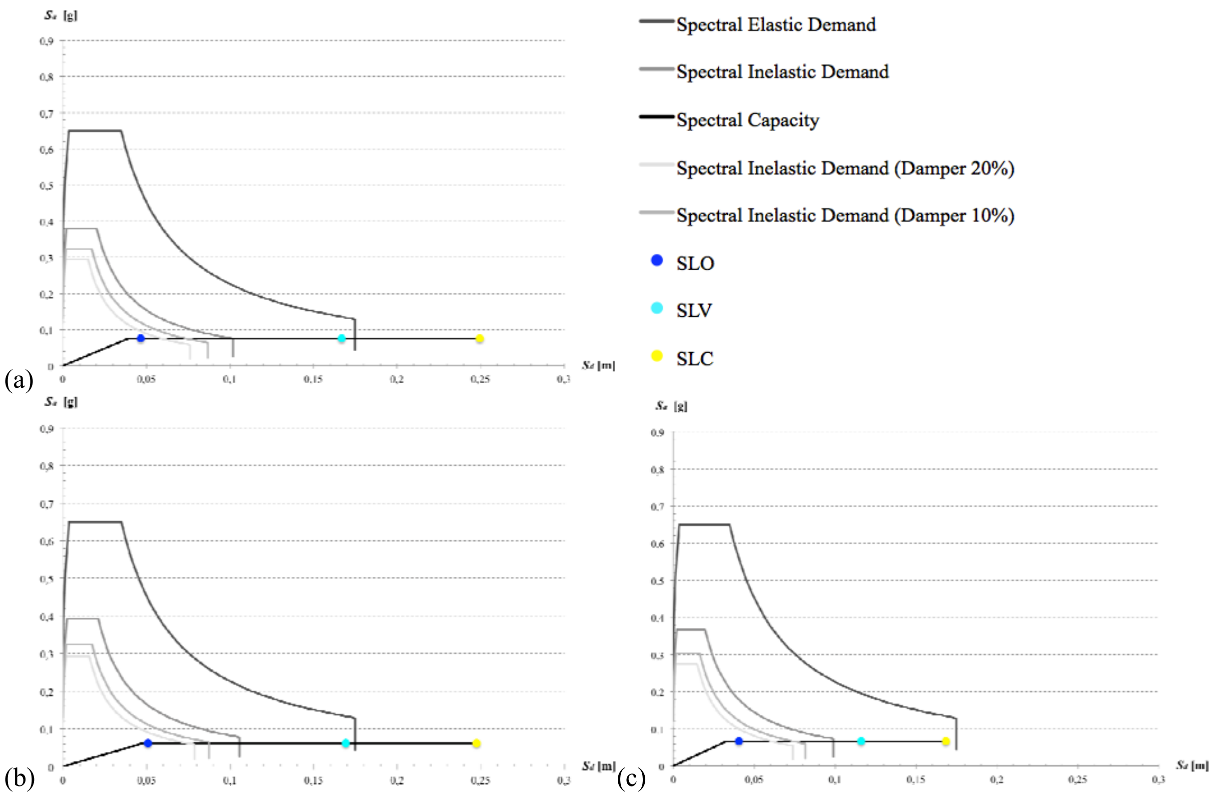

Figure 4. Assessment of the seismic demand with nonlinear static procedure for the frames 6F (a), 6FIR (b) and 6FIM (c)

Nonlinear static analyses are performed to investigate the nonlinear behaviour of the structures by applying modal distributed seismic actions to each floor. The seismic demand is defined by the design elastic spectrum provided by the Italian code (Min.LL.PP., 2008) 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 which are introduced at the ends of the structural members (CSI, 2009); the empirical relations provided by the Italian code (Min.LL.PP., 2008) and similar to those proposed by Panagiotakos and Fardis (2001) are used to define the limit values of chord rotations. The iterative procedure allows to assess the seismic response with and without the dampers in a graphical way, in the ADRS (Acceleration-Displacement Response Spectrum) format. Without dampers, the supplemental damping ξ_{ve1} is equal to 0; with dampers it is equal to the two considered values ξ_{ve1}=10% and ξ_{ve1}=20%, thus obtaining two different values of seismic demand. In Fig.4 the determination of the seismic demand for the 6-storey regular and irregular frames is shown.

In this phase it is possible to dimension the dampers according to the different methods. The results of the design are compared on the basis of the total sum of damping coefficients obtained with the different distribution methods. In Tables 1, 2 and 3 it is shown the comparison between the damping coefficients obtained with such distribution methods for a supplemental damping ξ_{ve1}=20% and for the 6-storey regular and irregular frames. The damping coefficients determined according to the seven methods are different along the heights of the structure. In the last line of the Tables it is shown the percentage differences, considering the total sum of the damping coefficients determined with the uniform distribution (UD) as reference method.

The percentage differences are substantially independent from the supplemental damping introduced with the dampers. The results obtained with a supplemental damping of 10% are similar to those of Tables 1-3. Except for the frame 6FIM with setback and for the distributions MPD and STPD, all methods produce an advantage than the UD, but this advantage is significant mainly for the energetic distribution methods (SEPD and SEESPD). Moreover the advantage is more evident for the frame 6FIR with soft storey. In general it is maximized by the method that distribute dampers only to the Efficient Storeys. This method, in fact, allows to achieve a benefit variable between 22% and 37% in terms of total sum of damping coefficients in comparison with UD distribution.

Table 1. Damper coefficients for the 6-storey vertically regular frame 6F

Floor	C_{NLj} [kN(s/m)^{0,5}]						
	UD	MPD	STPD	SSPD	IDPD	SEPD	SEESPD
6	866	659	381	248	435	121	0
5	866	866	478	620	769	535	0
4	866	871	674	786	942	831	1035
3	866	879	919	966	1011	1098	1366
2	866	891	1189	1076	967	1169	1456
1	866	902	1338	1119	590	742	0
Total	5195	5069	4979	4814	4715	4496	3857
ΔUD [%]	-	-2,4	-4,2	-7,3	-9,2	-13,5	-25,8

Table 2. Damper coefficients for the 6-storey vertically irregular frame with soft storey 6FIR

Floor	C_{NLj} [kN(s/m)^{0,5}]						
	UD	MPD	STPD	SSPD	IDPD	SEPD	SEESPD
6	964	716	629	228	297	65	0
5	964	941	789	509	517	253	0
4	964	946	1113	757	650	474	0
3	964	955	1395	964	678	714	789
2	964	983	774	1124	1389	1503	1660
1	964	1011	871	1191	945	1084	1197
Total	5783	5553	5571	4774	4475	4094	3646
ΔUD [%]	-	-4,0	-3,7	-17,4	-22,6	-29,2	-37,0

Table 3. Damper coefficients for the 6-storey vertically irregular frame with setback 6FIM

Floor	C_{NLj} [kN(s/m)^{0,5}]						
	UD	MPD	STPD	SSPD	IDPD	SEPD	SEESPD
6	973	594	433	300	552	167	0
5	973	781	543	658	973	647	0
4	973	785	766	953	1166	1123	1404
3	973	792	1045	1171	1131	1339	1674
2	973	1544	1569	1306	865	1142	1427
1	973	1751	1738	1199	570	690	0
Total	5838	6247	6094	5587	5257	5108	4505
ΔUD [%]	-	7,0	4,4	-4,3	-10,0	-12,5	-22,8

NONLINEAR TIME HISTORY RESULTS

The frames, equipped with the different distributions of the damping coefficient, are then subjected to a set of 7 real accelerograms, selected through the software REXEL (Iervolino et al., 2010) in order to be spectrum-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 interstorey drifts and damper forces are then compared in order to evaluate the effectiveness of the different distributions in reducing the seismic response.

Fig.5 to Fig.7 illustrate a comparison between the average profiles of interstorey drifts for the structures equipped with the different distribution methods and for the two performance levels related to the two adopted supplemental damping levels. These figures in particular show the results for the 6-storey regular and irregular frames. From these figures it is observed that the interstorey 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 storey where the dampers are not installed, producing displacements sometimes larger than those of the bare frame. In fact, even if it can result in a more constant distribution of the drifts, this effect is particularly evident for the irregular frame with setback where there is a concentration of drift demand in the storeys without dampers.

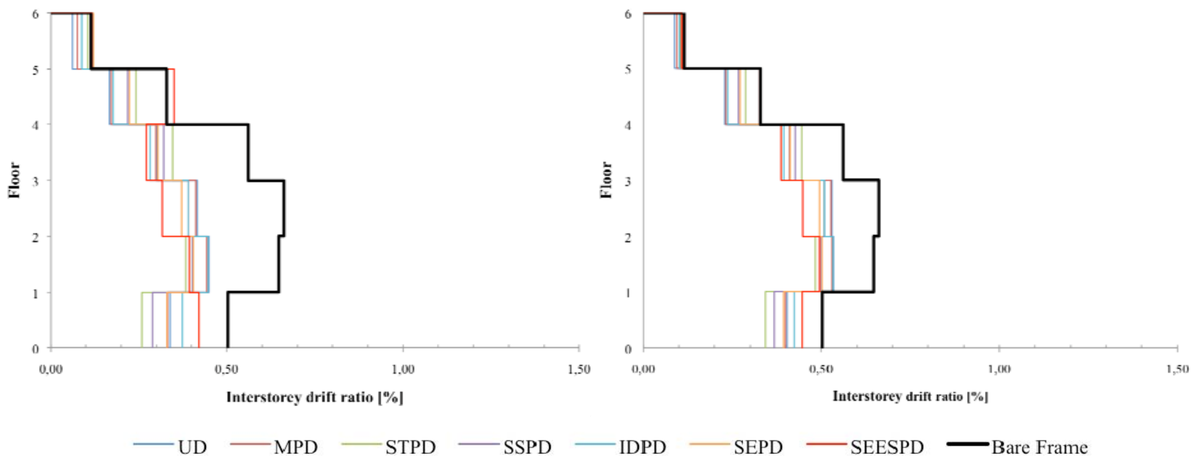

Figure 5. Comparison of interstorey drifts for frame 6F (ξ_{ve1}=20% left; ξ_{ve1}=10% right)

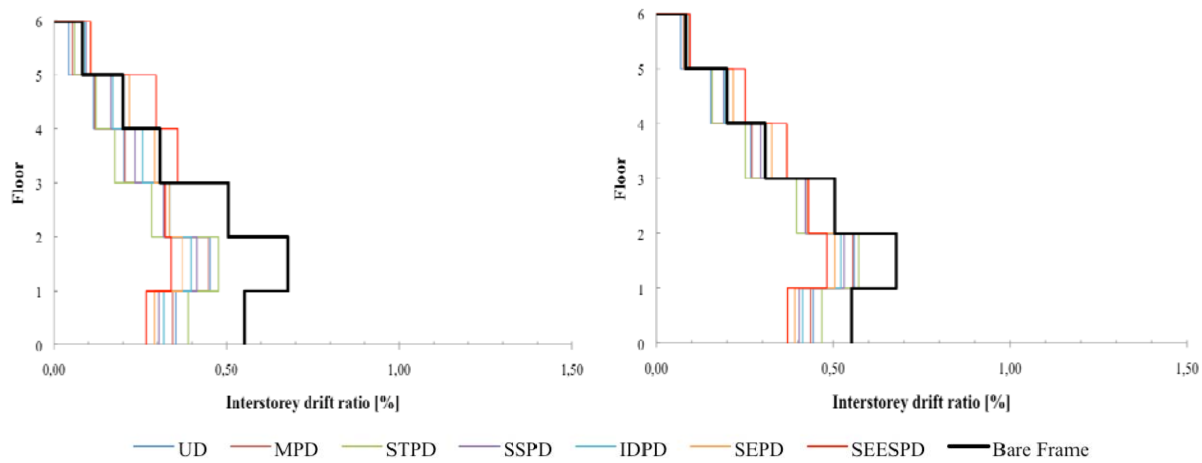

Figure 6. Comparison of interstorey drifts for frame 6FIR (ξ_{ve1}=20% left; ξ_{ve1}=10% right)

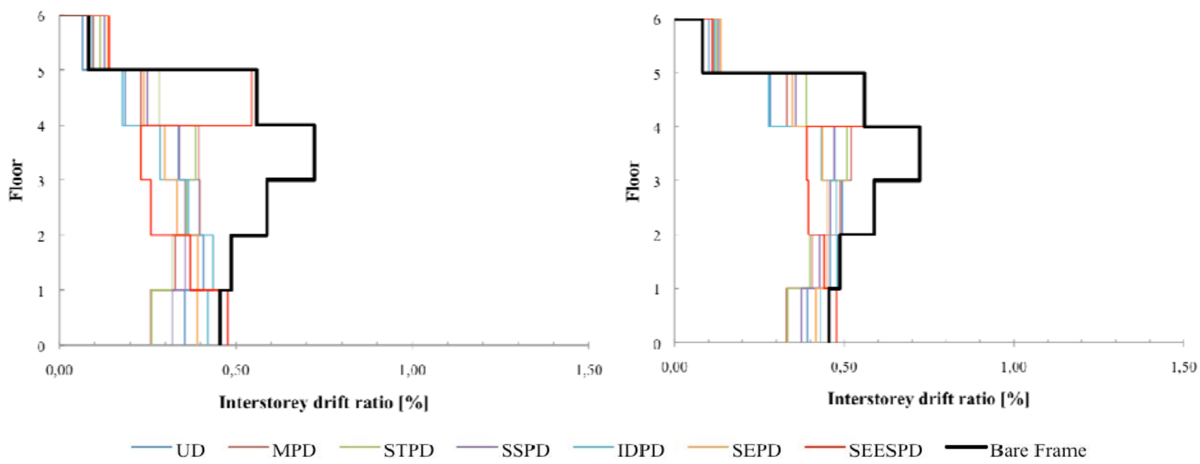

Figure 7. Comparison of interstorey drifts for frame 6FIM (ξ_{ve1}=20% left; ξ_{ve1}=10% right)

Another significant design parameter for the dampers, that is related also to the cost, is the maximum damper force. Also this parameter is then evaluated trough the time-history analyses. In Table 6 to Table 10 it is reported the maximum damper force at the different storeys for the different distribution methods. These tables in particular show the results for the 6-storey regular and irregular frames. In the last line of the Tables it is shown the percentage differences in comparison with the total sum of the damper forces determined with the uniform distribution (UD). Among the various methods, the SEESPD provides the lower values in terms of maximum damper force, in coherence with the similar tendency observed for the total sum of the damper coefficients.

To compare the results of all the case studies, a synthetic comprehensive comparison is shown in Fig.8 in terms of damper coefficients and in Fig.9 in terms of dampers forces. 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 (Fig.8) allows to understand which of the considered distribution methods is 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.

Table 4. Comparison of maximum dampers forces for frame 6F (ξ_{ve1}=20% above; ξ_{ve1}=10% below)

Floor	F_D [kN]						
	UD	MPD	STPD	SSPD	IDPD	SEPD	SEESPD
6	199	206	280	245	143	175	0
5	227	233	292	270	253	295	372
4	224	226	229	241	257	270	316
3	206	206	167	189	221	201	257
2	170	171	111	139	159	128	0
1	110	94	70	45	70	25	0
Total	1135	1136	1148	1130	1102	1094	945
ΔUD [%]	-	0,1	1,2	-0,4	-2,8	-3,6	-16,7

Floor	F_D [kN]						
	UD	MPD	STPD	SSPD	IDPD	SEPD	SEESPD
6	104	108	154	131	73	92	0
5	115	118	154	141	129	153	195
4	117	118	122	128	136	145	178
3	116	116	91	105	125	112	142
2	108	109	64	83	100	73	0
1	85	67	43	28	47	14	0
Total	644	636	628	616	609	590	515
ΔUD [%]	-	-1,2	-2,5	-4,4	-5,4	-8,4	-20,0

Table 5. Comparison of maximum dampers forces for frame 6FIR (ξ_{ve1}=20% above; ξ_{ve1}=10% below)

Floor	F_D [kN]						
	UD	MPD	STPD	SSPD	IDPD	SEPD	SEESPD
6	237	247	222	278	231	261	289
5	274	279	224	307	374	395	423
4	206	205	283	207	150	159	180
3	175	172	190	150	137	107	0
2	143	142	119	96	101	60	0
1	86	76	69	36	46	13	0
Total	1122	1120	1108	1074	1038	995	892
ΔUD [%]	-	-0,1	-1,2	-4,2	-7,4	-11,3	-20,4

Floor	F_D [kN]						
	UD	MPD	STPD	SSPD	IDPD	SEPD	SEESPD
6	124	130	114	150	123	141	159
5	142	145	115	164	200	214	234
4	112	112	158	113	80	85	94
3	103	102	117	85	75	57	0
2	93	93	77	56	58	31	0
1	71	56	50	21	28	7	0
Total	646	636	630	588	565	535	488
ΔUD [%]	-	-1,6	-2,5	-9,1	-12,7	-17,3	-24,6

Table 6. Comparison of maximum dampers forces for frame 6FIM (ξ_{ve1}=20% above; ξ_{ve1}=10% below)

Floor	F_D [kN]						
	UD	MPD	STPD	SSPD	IDPD	SEPD	SEESPD
6	249	423	427	308	153	186	0
5	265	385	392	345	245	317	406
4	276	222	279	314	316	353	375
3	269	222	215	258	307	293	343
2	218	189	141	168	218	169	0
1	135	109	88	62	94	37	0
Total	1413	1552	1542	1456	1334	1355	1125
ΔUD [%]	-	9,8	9,2	3,0	-5,6	-4,1	-20,4

Floor	F_D [kN]						
	UD	MPD	STPD	SSPD	IDPD	SEPD	SEESPD
6	133	231	231	164	80	97	0
5	142	213	218	188	129	169	216
4	142	115	149	167	164	189	229
3	152	123	119	146	178	168	200
2	140	117	84	100	141	99	0
1	109	74	56	39	66	22	0
Total	818	872	857	804	758	745	646
ΔUD [%]	-	6,6	4,8	-1,8	-7,3	-8,9	-21,1

In Fig. 9 it is shown the same type of comparison of Fig.8 but referred to the total sum of the maximum dampers forces and relative to the two levels of added damping ratio. The MPD, STPD, SSPD, IDPD distributions do not achieve significant advantages; in fact they provide a benefit less than the 5% on the average of all frames. The SEESPD method achieves the lowest values of the dampers forces, leading to an advantage from 15 to 20%. It should be noticed that SEESPD method does not guarantee the displacement control in the storeys without dampers especially in the vertically irregular structures, leaving the drifts in those storeys without dampers uncontrolled. The SEPD method therefore could be a valid alternative, even if the advantage is not always so significant, as for regular frames and high added damping.

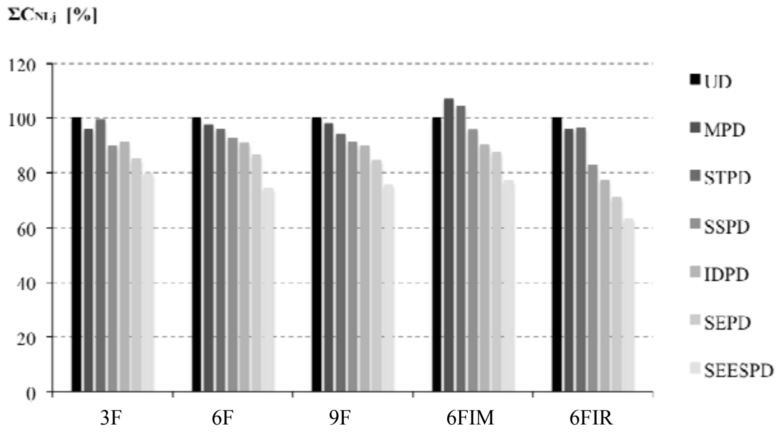

Figure 8. Comparison of the total sum of the damper coefficients (ξ_{ve1}=20%)

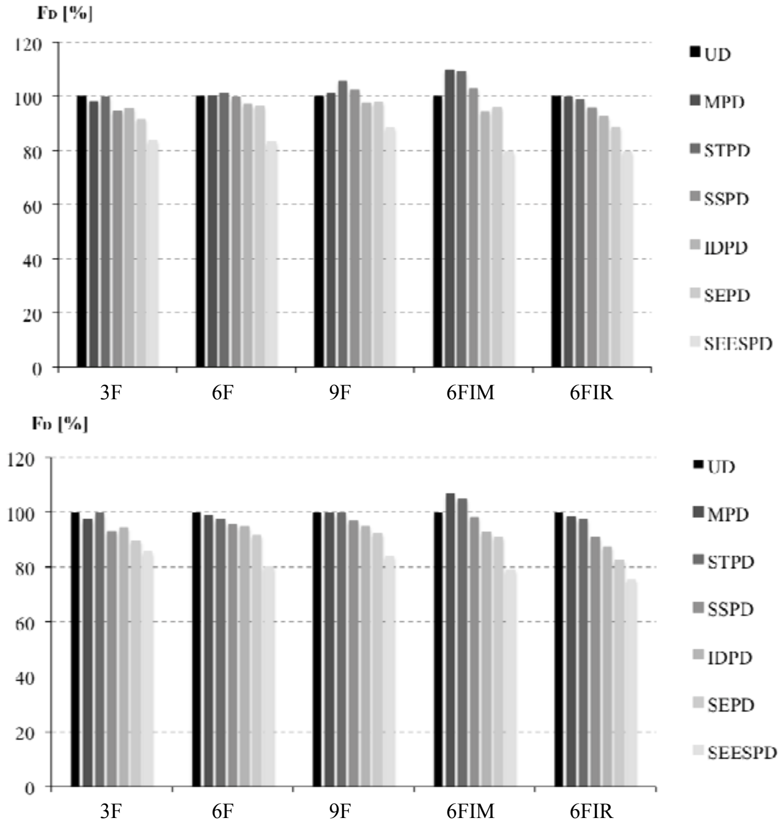

Figure 9. Comparison of the total sum of the maximum dampers forces (ξ_{ve1}=20% above; ξ_{ve1}=10% below)

CONCLUSIONS

Different distribution methods of the damping coefficient have been investigated for the retrofit of five RC frames characterized by different number of storeys and different properties in terms of vertical regularity, considering nonlinear behaviour both for the structures and for the viscous dampers and two levels of supplemental damping ratio. 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. Considering both the total sum of dampers forces and the structural response (in terms of interstorey drifts), a good compromise between dimensioning and control of performance has been obtained with the method SEPD. The most important benefit has been noticed for the vertically irregular frames while for the vertically regular frames the advantage has been not particularly evident, especially for high levels of supplemental damping. Considering these results, the uniform distribution method (UD) could remain a simple, practical and quite effective distribution method for inserting nonlinear viscous dampers in regular structures.

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