Direct Determination of the Required Supplemental Damping for the Seismic Rehabilitation of Existing Buildings

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SUMMARY:
This paper describes a simplified procedure to calculate the supplemental damping ratio that must be provided in order to rehabilitate existing buildings with viscous dampers. The proposed method is based on the construction of constant design acceleration curves. These curves allow to estimate the required effective damping as a function of the effective period, associated to the secant stiffness at maximum displacement. Combining these curves with constant ductility curves, which provide a correlation between the effective damping and the supplemental damping for given available ductility and damper typology, it is possible to determine the required supplemental damping and to design the damping system. The proposed method has then been verified through nonlinear dynamic analyses considering a set of RC plane frames. Finally it has been applied to a case study regarding an existing building located in Italy and designed without considering the earthquake action.

Keywords: Supplemental Damping; Seismic Rehabilitation; Viscous Dampers

1. INTRODUCTION

In recent years the retrofit of existing buildings in order to sustain the seismic actions has become one of the most relevant problems in seismic design. Recent earthquake events have highlighted that a relevant part of buildings in Italy is inadequate to withstand seismic actions. The consequences are heavy losses in economic terms and, most of all, in human lives. This aspect is related also to the subsequent modifications of the national seismic classification. Until 2003 the design for seismic actions was required only in a limited percentage of the national territory. Therefore it was possible to execute design projects considering only the gravity loads. The development of the seismic classification of the Italian territory has shown, instead, the possibility of earthquake shaking also in regions not considered under seismic risk before. As a consequence a large number of buildings have required rehabilitation interventions in order to withstand the effects of seismic actions. Nevertheless, there are still many existing structures not completely able to satisfy the seismic requirements provided by the current code. It is evident the great relevance of this issue for structural engineering, particularly in relation to strategic (Diotallevi et al., 2008) and historical structures. An even more widespread methodology to obtain the seismic rehabilitation is the use of passive dissipation systems. Their basic role is to absorb a portion of the seismic input energy and consequently to reduce the seismic effects on structural and non-structural elements (Soong and Dargush, 1997; Constantinou et al., 1998; Christopoulos and Filiatrault, 2006). These systems allow to maintain unchanged the geometric dimensions of the original structure and to limit the rehabilitation intervention to their incorporation. Anyway the determination of the supplemental damping that must be provided by these devices still presents some difficulties. Many reports (Ramirez et al., 2001), guidelines and international provisions (BSSC, 1997; BSSC, 2003) deal with the problem of the calculation of the supplemental damping ratio provided by the dampers. In this work we refer in particular to the report MCEER (Ramirez et al., 2001). It proposes a methodology based on the comparison between the spectral capacity curve of the structure, obtained through a nonlinear static analysis, and the design demand curve, obtained by reducing the elastic response spectrum through a factor which accounts for ductility effects and added dampers. However, in this procedure the supplemental damping is defined a priori, as the value is fixed before the execution of the seismic analysis. This way of applying the procedure simplifies the design, but it does not give any information about the real need of supplemental damping. In particular the calibration of this value requires to perform iterations. This work proposes, instead, a direct procedure to determine the minimum supplemental damping ratio to be provided by the dampers for the rehabilitation of the structure for a given seismic action. The purpose is the calculation of the required supplemental damping ratio by knowing the capacity of the buildings in terms of lateral strength and ductility. The procedure proposed in this work is based on the definition of constant design acceleration curves, which can be obtained from the response spectrum, and constant ductility curves, which can be defined in relation to the typology of the dampers used for the rehabilitation. This new method has been initially studied and applied with reference to RC frames characterized by three and six storeys. Subsequently the methodology has been verified through comparisons with nonlinear dynamic analyses of the considered frames. Finally it has been applied to a case study regarding an existing building located in Italy and designed without considering the earthquake action.

2. DETERMIANTION OF THE SIMPLIFIED PROCEDURE

The effective damping of a generic structure equipped with a passive dissipation system may be defined as follows:

$$\xi_{eff} = \xi_i + \xi_h + \xi_v \tag{2.1}$$

where ξ_i is the inherent damping ratio, ξ_h is the contribution due to the hysteretic behaviour of the structural members and ξ_v is the supplemental damping ratio provided by the dampers. The second contribution is not null only if the structural members exceed the elastic limit. The effective damping ξ_{eff} indicates the capability of the structure to dissipate the seismic input energy. Consequently, it is a term that indicates the possible reduction of the design acceleration due to the total dissipation. In the report MCEER the effect of dissipation is considered by associating a damping reduction factor B to each value of the effective damping. This factor can be used to reduce the spectral accelerations relative to the elastic response spectrum. The reduced spectral accelerations are the design values that have to be used for the seismic evaluation of the structures. If the reduced response spectrum is represented in the spectral acceleration-spectral displacement plane, it is possible to obtain the demand spectrum. This step is obtained using:

$$S_d = \frac{T^2}{4\pi^2} S_a \tag{2.2}$$

where S_d is the spectral displacement, S_a is the spectral acceleration and T is the vibration period. Following the method proposed in the report MCEER, in order to verify if the effective damping is enough to rehabilitate the building, the demand spectrum has to be compared with the capacity spectrum of the structure. This spectrum is derived from the base shear-roof displacement curve, called also pushover curve, which can be obtained from a nonlinear static analysis of the structure. The transformation of the pushover curve into the capacity spectrum can be given by the following relations:

$$S_a = V_b / M_1 \ ; \qquad S_d = D_{roof} / \phi_{roof1} \Gamma_1 \tag{2.3}$$

where V_b is the base shear, D_{roof} is the roof displacement and ϕ_{roof1} is the modal deformation at the roof relative to the first mode. ϕ_{roof1}= 1 if the mode shape is normalized in order to have unit component at the roof. Γ_1 and M_1 are respectively the participation factor and the effective modal mass of the fundamental mode. For a plane structure they are expressed as follows:

$$\Gamma_1 = \sum_{i=1}^{N} m_i \phi_{i1} / \sum_{i=1}^{N} m_i \phi_{i1}^2 \; ; \qquad M_1 = \Gamma_1 \left(\sum_{i=1}^{N} m_i \phi_{i1} \right) \tag{2.4}$$

where m_i is the mass of the i^{th} storey, ϕ_{i1} is the corresponding modal deformation and N is the number of masses. The curve obtained using Eqn. 2.3 and 2.4 is then idealized with a bilinear diagram in which the post-elastic branch is delimited by the yield and ultimate points. If the design demand curve intersects the spectral capacity curve just calculated, the assumed supplemental damping is enough to rehabilitate the structure. On the contrary, if the displacement demand exceeds the capacity, it is necessary to improve the damping ratio provided by the dampers.

Independently from the method used to idealize the spectral capacity curve, it is evident the iterative nature of the method described, as the value of the supplemental damping is assumed before the execution of the procedure. Conversely, it is possible to define an alternative methodology that allows to determine the minimum required value of the supplemental damping to rehabilitate the structure, starting from the characteristics of the building. To explain such method we refer to a generic structure with a spectral capacity curve represented by an elastic-perfectly plastic behaviour. As far as the structure is concerned, once the pushover analysis is carried out, it is possible to know the maximum acceleration bearable by the structure (S_{ay}), the maximum spectral displacement (S_{dm}, limit value for the considered limit state) and the available ductility. Therefore, from Eqn. 2.1, assuming the displacement demand equal to the corresponding capacity, only the effective damping and the supplemental damping remain unknown and have to be determined to obtain the rehabilitation. These quantities are calculated by associating an equivalent elastic system to the structure. Its period is defined considering the line connecting the origin with the point identified by the maximum spectral displacement S_{dm} and by the maximum acceleration S_{ay} (Fig. 2.1).

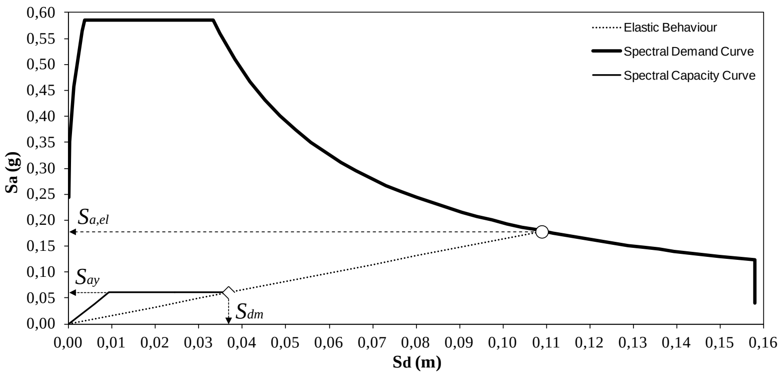


Figure 2.1 Equivalent elastic behavior

A secant period T_{eff} is then associated to the equivalent system:

$$T_{eff} = 2\pi \sqrt{S_{dm} / S_{ay}} \tag{2.5}$$

where the terms are known from the spectral capacity curve. Considering now this equivalent single-degree of freedom system, it is possible to evaluate the elastic acceleration demand $S_{a,el}$ (Fig. 2.1) from the elastic response spectrum (associated to ξ= 5%), which in the S_a-S_d plane is represented by the original demand curve. Referring to an elastic behaviour, indeed, the spectral accelerations are not reduced taking into account the dissipation effects caused by ductility. As a consequence, the elastic acceleration demand $S_{a,el}$ can be obtained from the period calculated with Eqn. 2.5 and extending the straight line referred to T_{eff} until the elastic spectrum. With the purpose to bear this acceleration it is necessary to provide a specific value of supplemental damping through a dissipation system. The real structure, in fact, is able to sustain a lower acceleration. The entity of this supplemental damping has to allow the passage from the elastic acceleration demand to the maximum bearable acceleration. This means that a value of the damping reduction factor B_{req} has to be determined in order that the reduced demand curve passes through the limit point of the capacity spectrum. This value, as far as the previous considerations are concerned, is given by the ratio between the two spectral accelerations, the elastic and the maximum one:

$$B_{req} = S_{a,el} / S_{ay} \tag{2.6}$$

Once this factor is calculated, the value ξ_{eff} associated to B_{req} can be obtained using correlation tables between B and the damping ratio (Ramirez et al., 2001). The determination of the minimum supplemental damping provided by the dampers requires to consider also the real behaviour of the structure, and in particular to evaluate the dissipation due to the hysteresis of the structural members:

$$\xi_h = \frac{2q_h}{\pi}\left(1 - \frac{1}{\mu}\right) \tag{2.7}$$

where μ is the ductility demand, assumed equal to the ductility capacity, and q_h is a factor equal to the ratio of the actual area of the hysteresis loop to that of an elastic-plastic system. This factor is equal to 1 for elastic-plastic behaviour and less than 1 for loops with degradation (Ramirez et al., 2001). The required supplemental damping can then be derived using Eqn. 2.1, Eqn. 2.7 and the obtained value of ξ_{eff}:

$$\xi_v = \xi_{eff} - \left(\xi_i - \frac{2q_h}{\pi}\left(1 - \frac{1}{\mu}\right)\right) \tag{2.8}$$

It is useful to underline that the supplemental damping ξ_v has been derived without considering the typology of dampers to be inserted into the building. Obviously the real contribution has to be evaluated in relation to the type of devices and to the damping value under elastic or inelastic response of the structure.

The application of the described procedure could be easier by making reference to a graphical representation. In particular it is possible to define constant design acceleration curves which allow to obtain directly the effective damping for the retrofit. These curves are constructed starting from the elastic response spectrum that associates a value of spectral acceleration to every period. From this spectrum and for a fixed value of the maximum bearable acceleration S_{ay} it is possible to calculate, for every period, the ratio between the elastic spectral acceleration and the fixed one. In this way every value of the secant period is associated to a value of the damping factor B and, consequently, to a value of the effective damping necessary to pass from the elastic spectral acceleration to the maximum one. Considering that:

$$B = B(\xi_{eff}) \qquad S_{a,el} = S_{a,el}(T_{eff}) \tag{2.9}$$

and fixing a value of S_{ay}, it is possible to build a curve that gives a value of ξ_{eff} in ordinate as a function of T_{eff}. ξ_{eff} is, in fact, an inverse function of B, which in turn is given by the ratio between $S_{a,el}$ and S_{ay}:

$$\xi_{eff} = B^{-1}(S_{a,el}(T_{eff}) / S_{ay}) \tag{2.10}$$

The constant design acceleration curves are then created by repeating this procedure for different values of the fixed acceleration S_{ay}. With these curves it is possible to determine immediately the value of ξ_{eff} as a function of T_{eff}, calculated from Eqn. 2.5, and of S_{ay}, derived from the pushover analysis. By drawing the vertical straight line associated to the secant period, the curve related to the maximum acceleration S_{ay} is intercepted in a point that, in ordinate, gives the value of the required effective damping (Fig. 2.2). These curves can be obtained at the variation of the type of soil and of the expected seismic intensity. Note that for low values of the maximum sustainable acceleration it is possible to find no values of the effective damping, since values larger than 100% would be necessary. On the contrary, considering high values of S_{ay}, ξ_{eff} could be lower than 5% and so not represented. These curves do not give any information about the supplemental damping ratio ξ_v that is necessary to implement in the structure in order to have an effective damping ξ_{eff} equal to the one indicated on the graph. This result is obtained through the construction of constant ductility curves (Fig. 2.3).

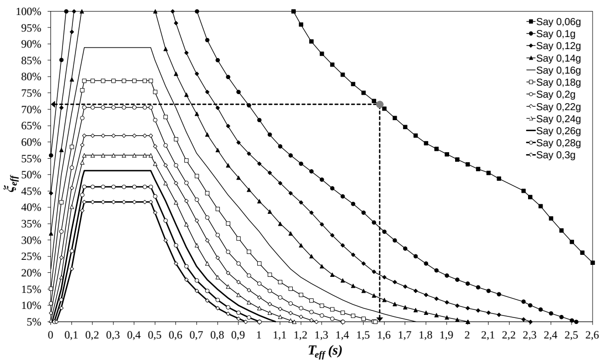


Figure 2.2 Constant design acceleration curves

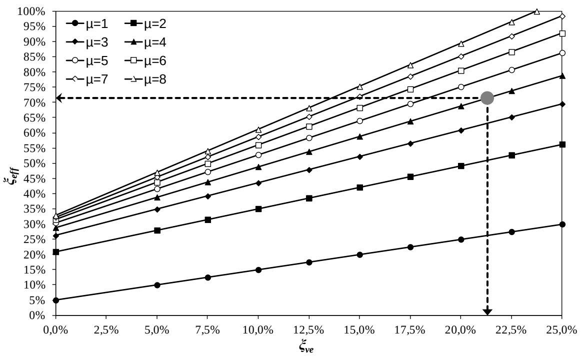


Figure 2.3 Constant ductility curves

According to Eqn. 2.1, it is possible to write:

$$\xi_{eff} = \xi_{eff}(\xi_v, \mu) \tag{2.11}$$

By fixing a value of the inherent damping of structures (usually 5% of the critical one) and considering a constant ductility contribution ξ_h, associated to an assigned value of μ, the effective damping changes when ξ_v varies. Consequently, considering different values of the ductility, different curves associating the required supplemental damping with ξ_{eff} are constructed. At this point, if the structure has a nonlinear behaviour, it is necessary to explicit ξ_v as a function of the supplemental damping of the same structure with linear behaviour and of the ductility demand. Considering a nonlinear structure with linear fluid-viscous dampers, such relation is given by:

$$\xi_v = \xi_{ve} \cdot \sqrt{\mu} \tag{2.12}$$

where ξ_{ve} is the supplemental damping for the structure with linear behaviour. Using Eqn. 2.12, Eqn. 2.1 becomes:

$$\xi_{eff} = \xi_i + \xi_h + \xi_{ve}\sqrt{\mu} = \xi_i + \frac{2q_h}{\pi}\left(1-\frac{1}{\mu}\right) + \xi_{ve}\sqrt{\mu} \tag{2.13}$$

By inverting Eqn. 2.13 the following relation is derived:

$$\xi_{ve} = \left[\xi_{eff} - \left(\xi_i + \frac{2q_h}{\pi}\left(1-\frac{1}{\mu}\right)\right)\right] \Big/ \sqrt{\mu} \tag{2.14}$$

The constant ductility curves for linear fluid-viscous dampers are illustrated in Fig. 2.3.

Afterward, with the effective damping value obtained through the constant design acceleration curves, it is possible to enter in the constant ductility curves graph and read the minimum value of the required supplemental damping ξ_{ve} at the intersection with the curve related to the available ductility of the structure. Note that the maximum value of the supplemental damping has been taken equal to 25%, because the current Italian code (D.M. 14/01/2008) sets a limit to this value through a coefficient η (corresponding to the opposite of B) defined as:

$$\eta = \sqrt{10/(5+\xi)} \geq 0,55 \tag{2.15}$$

This restriction can sometimes bring no results. It may occur that the straight line related to ξ_{eff} does not intercept the constant ductility curve associated to the available ductility of the structure. In this case, the supplemental damping that must be provided by the dampers results larger than the one allowed and, consequently, it is not applicable. However, in this situation, it is possible to estimate the improvement of the bearable acceleration of the structure, generated by the application of the maximum allowed supplemental damping. Considering ξ_{ve} equal to 25%, it is possible to calculate the maximum effective damping $\xi_{eff,max}$ related to the available ductility of the structure (Eqn. 2.13). As far as this value is concerned, the structure is not able to sustain the acceleration $S_{a,el}$ obtained for T_{eff} (for this period it would be necessary ξ_{eff}), but a lower value $\overline{S}_{a,el}$, associated to a response spectrum relative to a lower seismic intensity. The value $\overline{S}_{a,el}$ is calculated as follows:

$$\overline{S}_{a,el} = S_{ay} \cdot B(\xi_{eff,\max}) \tag{2.16}$$

To determine this new value, it should be considered that the ratio between $S_{a,el}$ and the new maximum acceleration $\overline{S}_{a,el}$ is related to the difference between the required effective damping ξ_{eff} and the maximum one $\xi_{eff,max}$. It follows that:

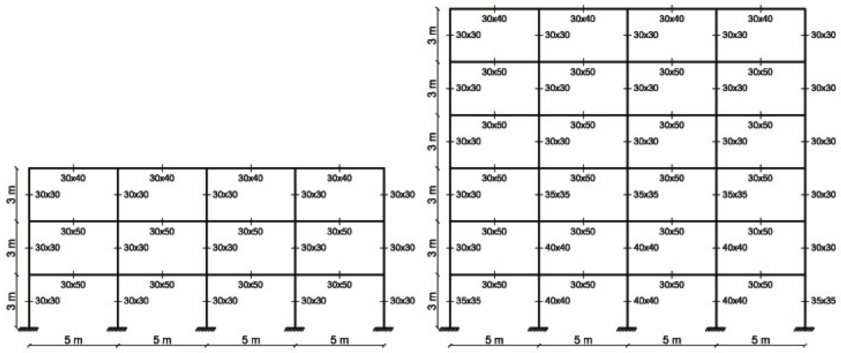
$$\Delta\xi = (\xi_{eff} - \xi_{eff,\max}) = B^{-1}(S_{a,el} / \overline{S}_{a,el}) \tag{2.17}$$

As a consequence, going back to the constant design acceleration curves, a point can be fixed on the vertical straight line related to T_{eff}, at the intersection with the horizontal straight line associated to $\Delta\xi$. Through this point passes a curve related to the new maximum sustainable acceleration $\overline{S}_{a,el}$ of the structure, provided by the maximum supplemental damping. This value is a definite percentage of the required design acceleration $S_{a,el}$ and it expresses also the percentage of the design seismic action that the structure is able to absorb through the dampers.

3. APPLICATION OF THE METHOD ON SIMPLE PLANE FRAMES

The proposed procedure has then been applied and verified considering two reinforced concrete plane frames characterized by three and six storeys (Fig. 3.1). These frames have been designed considering only gravity loads. The length of all bays is equal to 5 m and the floor height is equal to 3 m. The dimensions of the beams at the top are: width equal to 30 cm and depth equal to 40 cm. The dimensions of the beams at the other floors are: width equal to 30 cm and depth equal to 50 cm. The columns have been designed considering a square cross-section with a dimension variable from 30 cm at the top to 40 cm at the base. A concrete with a cylinder strength equal to 28 MPa and a steel with a yield strength equal to 450 MPa have been assumed.

The analysis of the nonlinear behaviour of the structures has been performed by using a finite element computer program (SAP2000). In particular the plastic hinges, located at the ends of each element, have been characterized with a bilinear moment-rotation curve defined by assigning the yield and the ultimate bending moments and the corresponding chord rotations (Fig. 3.2). The rotations $\theta_{u,}$ related to the collapse limit state (CP), as the ones related to the other limit states (damage limitation, DL, and life safety, LS), have been calculated using empirical expressions provided by the national code and inspired to the ones proposed by Panagiotakos and Fardis (2001).



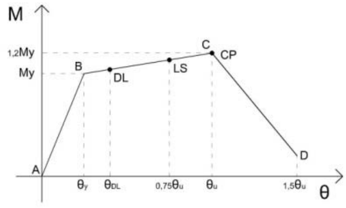


Figure 3.1 Three and six storey frames **Figure 3.2** *M-θ* curve

The capacity curve of each frame has been obtained by performing a pushover analysis with a modal pattern of lateral loads. These loads have been calculated considering a seismic weight equal to 1000 KN for the lower storeys and equal to 600 KN for the top storeys. The collapse point has been determined at the achievement of the ultimate rotation in the first plastic hinge. Starting from the pushover base shear-top displacement curves, it has been possible to determine the idealized elastic-perfectly plastic diagrams. Following the Italian code, the idealized diagram is characterized by an elastic branch which passes through the point of the pushover curve associated to 60% of the maximum base shear and by a plastic branch such that the area under the idealized curve is equal to the one under the pushover curve. The determination of the idealized diagrams has allowed to identify the three parameters μ, S_{ay} and S_{dm} that are necessary to calculate the minimum supplemental damping. For the six-storey frame, referring to the collapse limit state, the following values have been obtained: μ = 3,58, S_{ay} = 0,038 g and S_{dm} = 6,02 cm. From these values an effective period T_{eff} equal to 2,51 s has been calculated. The constant design acceleration curves have been constructed considering a response spectrum associated to a peak ground acceleration (PGA) equal to 0,244g. On these curves, a value of ξ_{eff} equal about to 60% has been obtained by drawing the vertical straight line associated to T_{eff}, and by intersecting this line with the curve related to S_{ay}. Then, from the constant ductility curves, a value of ξ_{ve} equal about to 17,4% has been determined by assuming to insert linear fluid-viscous dampers (Fig. 3.3). The same procedure with the same response spectrum has also been applied for the three-storey frame, for which a required supplemental damping ξ_{ve} equal approximately to 22% has been derived.

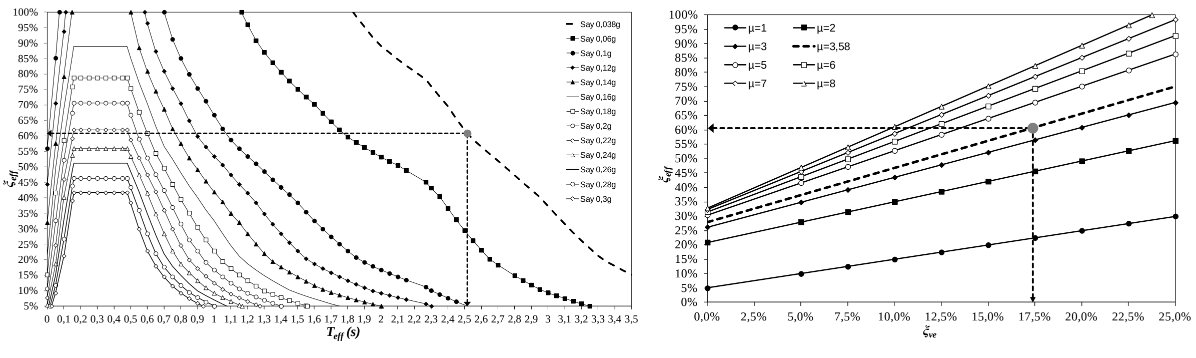


Figure 3.3 Constant design acceleration curves and constant ductility curves for the six-storey frame

By knowing the values of the supplemental damping it has been possible to dimension the damping system, characterized by linear viscous dampers inserted between each storey. Assuming identical devices, the following relation has been used (Ramirez et al., 2001):

$$\xi_{ve} = \left(\frac{T_1}{4\pi}\right)\frac{\sum_{j=1}^{N_D} C_j f_j^2 \phi_{rj}^2}{\sum_{i=1}^{N} m_i \phi_{i1}^2} = C\left(\frac{T_1}{4\pi}\right)\frac{\sum_{j=1}^{N_D} f_j^2 \phi_{rj}^2}{\sum_{i=1}^{N} m_i \phi_{i1}^2} \qquad (3.1)$$

where C is the damping coefficient, T_1 is the period of the fundamental mode, f_j is a coefficient that accounts for the geometric configuration of the damper j, ϕ_{rj} is the relative modal displacement between the storeys where the device j is inserted and N_D is the number of dampers. The value of C has been obtained from the solution of Eqn. 3.1.

The results of the design procedure have then been verified through a series of nonlinear dynamic analyses performed using five recorded ground motions (Tab. 3.1). These records have been scaled in order that their elastic spectral acceleration at the fundamental period of the structures corresponds to the one of the code elastic spectrum used in the design of the damping system.

Table 3.1 Selected ground motions for the nonlinear dynamic analyses

Event	**Station**	**Component**	**PGA (g)**
Chile (1985)	El Almendral	N90W	0,284
Imperial Valley (1940)	El Centro	S00E	0,348
Northridge (1994)	Newhall	090	0,583
Montenegro (1979)	Petrovac	NS	0,438
Kern County (1952)	Taft	111	0,178

The results obtained from the nonlinear dynamic analyses of the frames with dampers have been compared with those of the frames without dampers. The comparison shows that the values of displacements are considerably reduced in the configuration with dampers. Furthermore the average value of the maximum displacements obtained with each accelerogram is close to the one calculated through the pushover analysis and the design procedure (Fig. 3.4, Fig. 3.5). Moreover the design procedure has provided a conservative estimate of the average of the maximum displacements from nonlinear dynamic analyses. In addition, a direct comparison of the configuration of the plastic hinges has showed that in the frames with dampers no plastic hinge have attained the ultimate rotation and the collapse condition (Fig. 3.6). This comparison has been performed in the instant in which the structure achieved the maximum displacement. This result, obtained in all the time-history analyses, underlines again the effectiveness of the supplemental damping calculated with the proposed method.

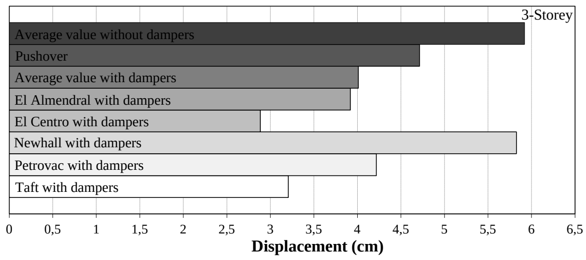


Figure 3.4 Maximum displacements of 3-storey frame

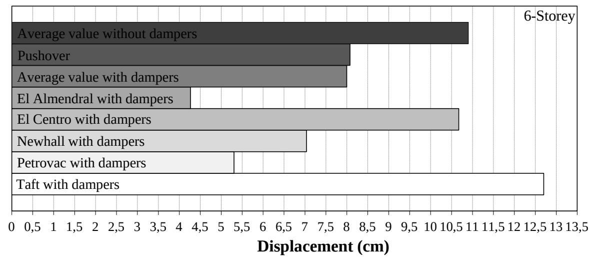


Figure 3.5 Maximum displacements of 6-storey frame

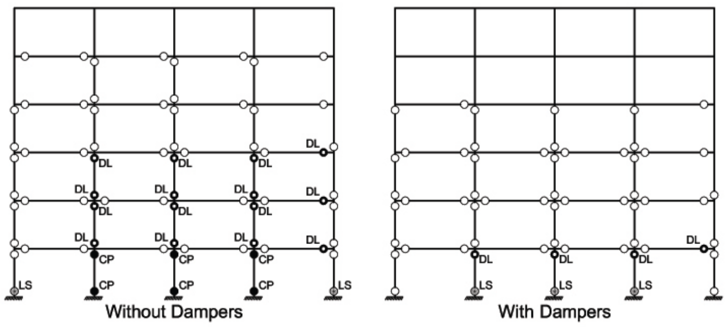


Figure 3.6 Configuration of the plastic hinges and indication of the reached limit state (damage limitation, DL, life safety, LS, and collapse prevention, CP)

4. APPLICATION OF THE METHOD TO AN EXISTING BUILDING

The proposed method has been applied for studying the possible rehabilitation of an hotel building located in Italy. This building is characterized by a spatial reinforced concrete frame structure of six storeys above ground. A first assessment, performed with a modal dynamic analysis, has shown that the resistance capacities are in the order of 20-30% of those required to sustain the seismic intensity provided by the code. Then, a pushover analysis of the structure has been carried out adopting the same modelling criteria illustrated for the simple plane frames (Fig. 4.1), and in particular considering the modal pattern of lateral loads. The nonlinear static analysis, performed for both the main directions of the structure, has allowed to determine the capacity curves and their bilinear idealization. So it has been possible to obtain the three required values to determine the minimum supplemental damping: for *x* direction, μ = 1,81, S_{ay} = 0,069 g and S_{dm} = 5,54 cm; for *y* direction, μ = 1,45, S_{ay} = 0,06g and S_{dm} = 5,25 cm. At this point the effective damping has been calculated using the constant design acceleration curves constructed for a response spectrum related to the code seismic intensity. The obtained values, associated to the effective periods in the two directions, are the followings: about 85% in *x* direction and 95% in *y* direction. Considering linear fluid-viscous dampers, the constant ductility curves fail to provide solutions for these values of effective damping. This means that the curves associating the effective damping with the supplemental damping do not intersect the obtained values of ξ_{eff}. This result shows that considering also the maximum damping allowed by the code it is not possible to rehabilitate the structure with the contribution of the dampers only. The rehabilitation could be achieved considering a contribution of the dampers larger than the limit of 25 % (at least 48% in *x* direction, 67% in *y* direction). Nevertheless, it has been possible to evaluate the improvement of the maximum bearable acceleration that could be obtained using the maximum allowed damping. Considering ξ_{ve} equal to 25%, from Eqn. 2.13 it has been possible to calculate $\xi_{eff,max}$ in *x* direction (53%) and in *y* direction (45%) and consequently $\Delta\xi$ in both directions. Following the procedure previously explained, it has been obtained $\overline{S}_{a,el}$ = 0,14g in *x* direction and $\overline{S}_{a,el}$ = 0,105g in *y* direction (Fig. 4.2). These two values are equal to 63% (*x*) and 47% (*y*) of the required values.

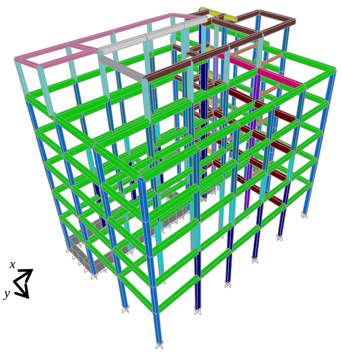


Figure 4.1 Model of the building

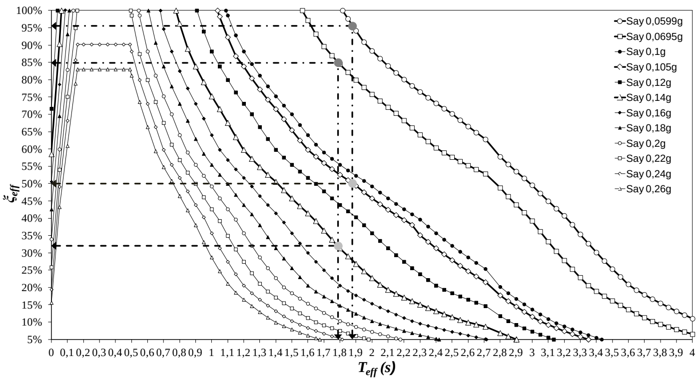


Figure 4.2 Improvement of the maximum bearable acceleration

With the purpose to obtain the complete rehabilitation of the building, four additional reinforced concrete shear walls have been considered on the external frames (Fig. 4.3). These walls have considerably improved the stiffness of the structure in both directions and have allowed to obtain capacity curves characterized by larger values of base shear than the ones of the original buildings. Since the only insertion of shear walls has not been able to provide the complete rehabilitation, a damping system has been considered together with the additional walls. Using again the proposed method and considering new values of maximum acceleration, limit displacement and ductility, a value of ξ_{eff} equal to 40% has been derived for both directions. With these values it has been possible to determine the intersections with the constant ductility curves and then the values of the minimum supplemental damping: 10,5% in *x* direction and 13% in *y* direction (Fig. 4.4). To take caution against the collapse condition, the dampers have been dimensioned considering ξ_{ve} equal to 15%.

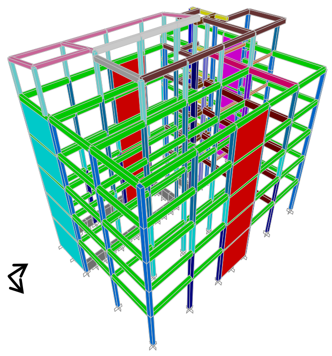


Figure 4.3 Model with shear walls

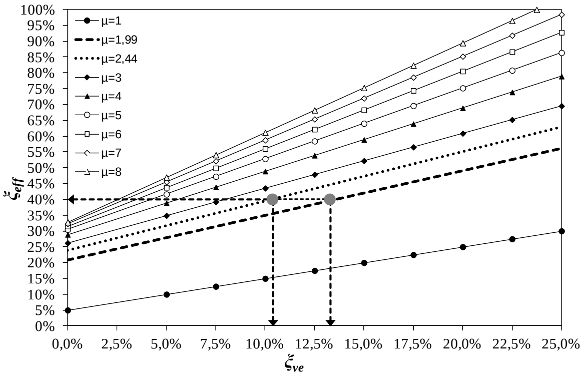


Figure 4.4 Calculation of ξ_{ve} using constant ductility curves

5. CONCLUSIONS

The proposed calculation method has proven to be a useful tool for the direct determination of the minimum required supplemental damping for the rehabilitation of existing structures. The application of the method could be analytical or graphical. The latter is based on the construction of constant design acceleration curves and of constant ductility curves, and provides the required supplemental damping in a fast and simple way, drawing horizontal and vertical straight lines on the graphs. These curves are of general validity and can be used for every existing building, depending on the considered response spectrum. It is also possible to calculate different required damping ratios, in relation to the variation of the seismic intensity and to the type of dampers used. The proposed method has been verified through nonlinear dynamic analyses considering a set of RC plane frames. A good asgreement has been found between the results of the analyses and of the design procedure. Finally the method has been applied to a case study regarding an existing building located in Italy and designed without considering the earthquake action. This application has shown that for buildings with low resistance capacities it is possible to define, in the design phase, the maximum degree of improvement which can be obtained with the dampers, considering the code limitations regarding the supplemental damping.

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