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A procedure for the direct determination of the required supplemental damping for the seismic retrofit with viscous dampers

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ABSTRACT

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 has been developed according to both analytical and graphical approaches. The graphical formulation is based on the construction of constant design acceleration or constant design displacement 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.

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. The recent seismic events, as L'Aquila or Emilia earthquakes in Italy, have highlighted that a relevant part of buildings is inadequate to withstand the 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 seismic classification of the territory. The development of the seismic classification of the Italian territory has shown, for example, the possibility of earthquake shaking also in regions where it was possible to design considering only the gravity loads. 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 and historical structures.

A widespread methodology to obtain the seismic rehabilitation is the use of passive dissipation systems [1–8]. 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 [9–12]. These systems allow to maintain unchanged the geometric dimensions of the original structure and to limit the rehabilitation intervention to their addition. Several researchers studied the seismic response and the design criteria of structures equipped with dampers [13–23]. In particular various contributions have been dedicated to determine algorithms and procedures for the individuation of the optimal damper configurations [24–33]. Anyway the determination of the supplemental damping that must be provided by these devices still presents some difficulties. Many reports [34], guidelines and international provisions [35–37] 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 published by MCEER [34]. 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 and simple procedure to determine the minimum required supplemental damping

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necessary for the retrofit of an existing structure to achieve a desired performance [38,39]. This method could be very useful in the design of retrofit interventions with viscous dampers. It allows to simplify the calculation and to avoid iterative procedures. The starting point is the knowledge of the capacity of the buildings in terms of lateral strength and ductility. The procedure proposed in this work has been developed according to both analytical and graphical approaches which are valid for all types of buildings. It is also proposed a particular procedure to determine the maximum improvement of the seismic behaviour that can be achieved with viscous dampers according to code limitations for the supplemental damping. The proposed method has then been applied to a set of RC plane frames and verified through comparisons with nonlinear dynamic analyses. Finally it has been also used for studying the retrofit of a real building in order to verify the applicability for more complex structures.

2. The proposed procedure

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

$$\xi_{eff} = \xi_i + \xi_h + \xi_v \tag{1}$$

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 mentioned 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:

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

where S_d is the spectral displacement, S_a is the spectral acceleration and T is the fundamental 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:

$$S_a = \frac{V_b}{M_1} \tag{3}$$

$$S_d = \frac{D_{roof}}{\phi_{roof1} \Gamma_1} \tag{4}$$

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. $\phi_{roof1} = 1$ 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:

$$\Gamma_1 = \frac{\sum_{i=1}^{N} m_i \phi_{i1}}{\sum_{i=1}^{N} m_i \phi_{i1}^2} \tag{5}$$

$$M_1 = \Gamma_1 \left(\sum_{i=1}^{N} m_i \phi_{i1} \right) \tag{6}$$

where m_i is the mass of the ith storey, ϕ_{i1} is the corresponding modal deformation and N is the number of masses. The curve obtained using Eqs. (3)–(6) 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 obtain directly the minimum required value of the supplemental damping to rehabilitate the structure, starting from the characteristics of the building.

2.1. Analytical formulation

To explain this 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}), which is also the yield acceleration, the maximum spectral displacement (S_{dm}, limit value for the considered limit state) and the available ductility. Therefore, from Eq. (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. 1). A secant period T_{eff} is then associated to the equivalent system:

$$T_{eff} = 2\pi \sqrt{\frac{S_{dm}}{S_{ay}}} \tag{7}$$

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. 1) from the elastic response spectrum (associated to $\xi = 5\%$), 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 Eq. (7):

$$S_{a,el} = S_{a,el}(T_{eff}) \tag{8}$$

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 value, as far as the previous considerations are concerned, is related to a reduction factor B_{req} that is given by the ratio between the elastic spectral accelerations and the maximum one:

$$B_{req} = \frac{S_{a,el}}{S_{ay}} \tag{9}$$