Engineering Structures 100 (2015) 79–93

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Effectiveness of different distributions of viscous damping coefficients for the seismic retrofit of regular and irregular RC frames

Luca Landi *, Filippo Conti, Pier Paolo Diotallevi

Department DICAM, University of Bologna, Bologna, Italy

ARTICLE INFO

Article history:
Received 2 August 2014
Revised 13 April 2015
Accepted 21 May 2015
Available online 12 June 2015

Keywords:
Damping distribution
Seismic retrofit
Existing buildings
Viscous dampers
Design procedure
Nonlinear dynamic analyses

ABSTRACT

The main purpose of this research has been to investigate the effectiveness of different vertical distributions of the damping coefficients of nonlinear viscous dampers for the seismic retrofit of existing multi-storey reinforced concrete frames. In particular, different simple distributions were compared with other procedures proposed in literature, including two energy methods and a repetitive simplified sequential search algorithm. The effectiveness of the different distributions was then examined by performing time-history analyses and considering a nonlinear behaviour for both the viscous dampers and the structural members. The structures being considered are five RC frames with a different number of storeys and both regular and irregular configurations in elevation. The results of the nonlinear dynamic analyses were examined in terms of maximum and residual interstorey drifts, peak floor accelerations and maximum damper forces. The energy methods, in particular, provided good results in terms of reduction in cost, efficiency of the distribution and simplicity of application, compared to other effective, but more complex methods.

1. Introduction

The importance of seismic assessment and rehabilitation of existing buildings is increasingly evident for structural engineers. There are still many existing structures that are not able to satisfy the current seismic code requirements. The retrofit objective of satisfying the seismic requirements for new structures is often economically prohibitive and extremely difficult to achieve, especially for strategic buildings, where the seismic performance must be higher than for ordinary buildings. In these cases, the employment of an innovative technique, such as dissipating energy by adding damping devices, may be very promising in terms of improving seismic performance [1–12]. By introducing supplemental dampers, it is possible to reduce the energy dissipated through the structural elements, and to restrict damage to them [13–16]. Looking at the possible rehabilitation interventions, fluid-viscous dampers offer several advantages [1], since their behaviour is independent of frequency and their energy dissipation capacity is very high. Moreover, the fact that only dampers need to be added means, in general, that no significant intervention is required to the existing structure.

Several researchers have studied the seismic response and the design criteria of structures equipped with dampers [17–33]. Although their placement is a critical design issue, building regulations and guidelines, in general, do not prescribe a particular method to optimize the distribution of damper properties [34,35]. A large number of different damper placement methods have been proposed, and these can be classified into two primary categories [36]. The first is based on simple design formulae for calculating the added damping ratio [31,35]. However, only a limited number of methods have been provided to show how the total required damping coefficient can be distributed to each storey of the building when adopting these design expressions. This is the case despite the fact that there is an infinite number of possibilities in selecting the distribution of the damping coefficients along the height of the building corresponding to a prefixed supplemental damping ratio [36,37]. In terms of the second category, many studies have been concerned with the optimal damper placement and the optimal distribution of damper properties, including methods based on the principles of active control theory [18] or methods based on gradient search [38–42]. In addition to the above design methodologies, a sequential search algorithm (SSA) [43–45] and a simplified sequential search algorithm (SSSA) have both been proposed as methods for determining damper location and damper coefficient distribution, with the purpose of achieving minimum interstorey velocity. Takewaki [46] presented a more comprehensive list of contributions to the field of damper placement and concluded that, despite the large amount of information, structural

* Corresponding author. Tel.: +39 051 2093245; fax: +39 051 2093236.
E-mail address: l.landi@unibo.it (L. Landi).

http://dx.doi.org/10.1016/j.engstruct.2015.05.031
0141-0296/

engineers lack the tools necessary to achieve the optimal placement of dampers within a structure.

The purpose of this study is, therefore, to investigate the effect of several distribution methods belonging mainly to the first category, and using the design approach for viscous dampers proposed by Ramirez et al. [20]. Among the distribution methods being examined is also a recently proposed method based on the concept of "Efficient Storey" [36]. The different distribution methods were applied to a set of RC frames with a different number of storeys. In order to study the correlation between the distribution methods and structural regularity, the structures considered differed in terms of their regularity in elevation. Moreover, in this research, structural behaviour was considered as nonlinear and, in order to study the influence of the inelastic excursion, the structures were retrofitted, with different levels of supplemental damping being considered. The investigation involved both the output of the design, in terms of the total damping coefficient, and the seismic response of the structure and damping system, in terms of maximum and residual interstorey drifts, peak floor accelerations and maximum damper forces. The seismic response was studied through nonlinear time-history analyses, assuming a nonlinear behaviour for both the viscous dampers and the structural members.

2. Background: determination of seismic demand with supplemental damping

During the design phase, seismic demand in the presence of supplemental damping was determined according to a procedure proposed in literature and described here [20]. This procedure is based on the comparison between capacity spectrum and demand spectrum in an acceleration-displacement graph. 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. More specifically, the demand spectrum is determined as the damped response spectrum associated to the effective global damping ratio of the building. This damping ratio accounts for both the contribution of dissipative devices and the hysteretic behaviour of the structural elements. The intersection between the capacity curve and the demand spectrum gives the performance point and the actual displacement demand. The curve of base shear V_b versus roof displacement D_{roof} obtained from the pushover analysis is transformed into the capacity spectrum by applying the following relationships (Fig. 1):

$$S_a = \frac{V_b}{M_1} \tag{1}$$

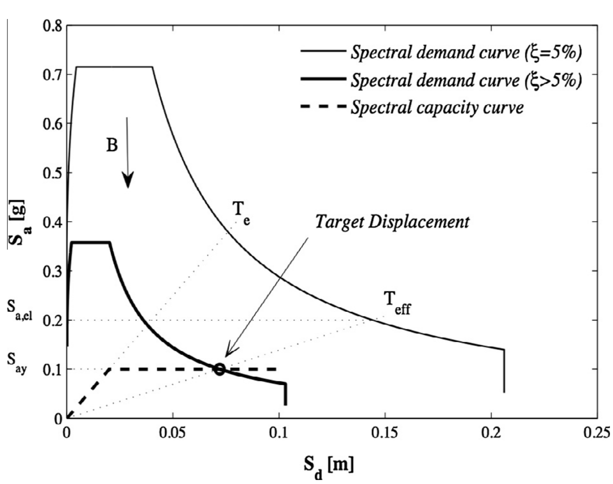

Fig. 1. ADRS format: spectral capacity and spectral demand curves.

$$S_d = \frac{D_{roof}}{\phi_{roof1}\Gamma_1} \tag{2}$$

where ϕ_{roof1} is the modal deformation at the roof relative to the first mode. $\phi_{roof1} = 1$ if the mode shape is normalized to have unity component at the roof. Γ_1 and M_1 are the participation factor and the effective modal mass of the fundamental mode, respectively. The application of the procedure requires a bilinear idealization of the capacity spectrum, in order to obtain the elastic stiffness, yielding point and post-elastic stiffness of the equivalent SDOF structure.

The demand spectrum is determined by applying a damping reduction factor to the elastic response spectrum. This factor is a function of the effective damping ratio [20,35] and its values, as proposed in recent research works [21,23], are included in FEMA 450 [35]. The effective damping ratio can be derived as the sum of three terms: the inherent damping ratio, the supplemental damping ratio provided by the dampers, and the hysteretic damping ratio associated to the nonlinear behaviour of the structure. The latter is present only if the structure exceeds the elastic limit.

In the case of nonlinear structural behaviour, the supplemental damping ratio can be determined by replacing the fundamental elastic period T_e with the effective period T_{eff}, calculated by considering the secant stiffness of the structure at the displacement demand that depends on the seismic action. If the bilinear idealization of the capacity curve has a negligible post-elastic stiffness or it is an elastic-perfectly plastic diagram, the effective period may be obtained as follows:

$$T_{eff} = T_e\sqrt{\mu} \tag{3}$$

where μ is the ductility demand. At the intersection of the capacity spectrum with the demand spectrum, the damping reduction factor B of the spectral ordinates can be expressed by the following equation:

$$B = B(\xi_{eff}) = \frac{S_{a,el}(T_{eff})}{S_{ay}} \tag{4}$$

where $S_{a,el}$ is the elastic demand in terms of acceleration and S_{ay} is the yield acceleration of the structure. The effective damping ratio can be derived from the analysis of each contribution:

$$\xi_{eff} = \xi_i + \xi_{ve}(\mu)^{1-\frac{\alpha}{2}} + \xi_h \tag{5}$$

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, and ξ_h is the hysteretic damping. This contribution can be evaluated as proposed by Ramirez et al. [20]:

$$\xi_h = \frac{2q_h}{\pi}\left(1 - \frac{1}{\mu}\right) \tag{6}$$

where q_H is a factor equal to the ratio of the actual area of hysteresis loop to that of the assumed perfect bilinear oscillator. This factor is, therefore, related to the quality of the structural system in terms of its dissipative capacity. Several indications for defining q_H can be found in literature [20].

From Eqs. (5) and (6), it is evident that the effective damping depends on the displacement, or ductility demand. Therefore, given the supplemental damping ratio under elastic structural response, a series of iterations must be carried out to determine the displacement demand, since the reduced demand spectrum depends upon the effective damping, which, in turn, is related to the displacement, or ductility demand. The iterative procedure starts by assuming a certain value of displacement demand. The spectrum is then reduced according to ξ_{eff}, and the intersection with the capacity curve can thus be derived (Fig. 1). This value has to correspond to the value initially presumed, otherwise another iteration is required, and this is performed by changing the value of the assumed displacement demand. The iterations