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Maximum damping forces for structures with viscous dampers under near-source earthquakes

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ABSTRACT

This paper examines the inelastic response behaviour of structures with supplemental viscous dampers under near-source pulse-like ground motions. It is well known that the design of dampers requires the effective evaluation of maximum seismic velocities or maximum damping forces. In order to avoid complicated methods, such as the dynamic inelastic analysis, this study proposes a simple and effective evaluating method for these maximum values using the inelastic velocity ratio. This ratio is a modification factor which allows the evaluation of the maximum inelastic velocity or damping force from their corresponding elastic counterparts. The paper focuses on structures. Extensive parametric studies are conducted to examine the influence of characteristics of structure (period of vibration, post-elastic stiffness, force reduction factor), of supplemental damping (equivalent viscous damping ratio) and of ground motion (type of earthquake fault) on the maximum seismic velocities and damping forces.

1. Introduction

In order to decrease the maximum seismic response of buildings, bridges and other civil structures, a variety of passive energy dissipation devices have been implemented on them for over forty years [1–3]. Various experimental and analytical studies about structures with supplemental damping have been presented in the past, such as studies of Refs [4–10], amongst others. More specifically, Constantinou and Tadjbakhsh [4] examined the optimum design of a first story damping system. Makris and Constantinou [5] investigated the fractional-derivative Maxwell model for viscous dampers and Nishimura [6] studied on the performance evaluation of damping devices installed in a building structure. Additionally, Symans et al. [7] reviewed the energy dissipation systems for seismic applications and Lavan and Dargush [8] investigated a multi-objective evolutionary seismic design with passive energy dissipation systems. Konstantinidis et al. [9] examined experimentally the the force-output of fluid dampers by in situ monitoring and Nishimura [10] investigated the performance of a building structure with nonlinear dampers under Tohoku earthquake. Furthermore, a large variety of damper placement methods have been published in the pertinent literature. One can mention here the pioneering work of Takewaki [11] as well as the contributions of Lopez-Garcia [12], Singh and Moreschi [13], Uetani et al. [14] and Lavan and Levy [15,16]. Furthermore, Trombetti and Silvestri [17] found that a mass-proportional distribution is very efficient, but can be impractical to implement. Aydin et al. [18] found that the optimal configurations and locations of dampers can be achieved using transfer functions. Cimellaro [19] investigated the simultaneous stiffness-damping optimization problem with respect to structural acceleration, displacement and base shear. Silvestri and Trombetti [20] proposed that viscous dampers of each floor of a structure should be connected to a fixed point and this system is far superior to those offered by damper placements which see dampers placed between adjacent storeys (as in the traditional setup). Hwang et al. [21] compared the distribution methods for viscous damping coefficients to buildings. Recently Adachi et al. [22] proposed a practical method for optimum design of nonlinear oil dampers with relief mechanism installed in multi-story framed building structures while Adachi et al. [23] showed that maximum interstory velocities plays a critical role in super high-rise buildings.

Generally, the use of passive energy dissipation devices leads to reduced displacement structural response; however, nonlinear time history analysis is also required for the majority of passively damped civil structures since their earthquake vibration induces inelastic deformations in one or more structural elements [24,25]. The maximum seismic velocity is essential for the design of supplemental viscous dampers and generally for the assessment of performance based seismic design of inelastic structures with these systems [26]. Practically, the design velocity of a building

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storey (hence of the dampers) is based on design/elastic velocity spectra proposed by codes [27]. More specifically, according to the provisions of FEMA-450 [27] for supplementary dampers (Chapter 15), the '*design earthquake story velocity*' is allowed to be evaluated by the '*design earthquake story displacement*', using the elastic pseudo-velocity spectrum. In this case, the actual velocity is considered to be equal to the elastic counterpart, assuming an '*equal velocity rule*', similar to the well-known '*equal displacement rule*' which correlates the maximum elastic with the maximum inelastic displacement. Hatzigeorgiou and Papagiannopoulos [28] recently examined the relation between the maximum seismic velocity of inelastic structures in comparison with the maximum seismic velocity of elastic structures. Thus, taking into account that the elastic velocity spectra lead to different velocities in comparison with the actual ones as well as many structures with supplementary dampers can behave inelastically, it is evident that the elastic velocity spectra cannot be used in these cases. Therefore, the '*equal velocity rule*' seems to be an unreliable assumption, which can leads to overstated energy dissipation with fictitious seismic performance level and overdesigned dampers. The nonlinear time history analysis leads to reliable estimation of actual velocities reducing the aforementioned shortcoming. Nevertheless, this approach appears to be complicated for the everyday engineering practice due to the increased computational effort. For this reason, Hatzigeorgiou and Papagiannopoulos [28] proposed an alternative method, which is based on the inelastic velocity ratio (*IVR*). The *IVR* can be defined as the ratio of the maximum inelastic to maximum elastic velocity of a structural system, where its knowledge allows the computation of maximum inelastic velocity directly from the corresponding elastic one. This approach is quite similar to the estimation procedure and philosophy of 'inelastic displacement ratio', i.e., the ratio of the maximum inelastic to maximum elastic displacement for SDOF systems [29–32].

It should be noted that in many cases of seismic design, structures may lead to damage or failure in case of near-field ground motions, which are not taken into account when using code-based seismic design provisions constructed on the basis of ordinary far-field ground motions [33]. Thus, near-field ground motions have been identified as imposing extreme demands on structures to an extent not predicted by typical measures such as response spectra [34]. Therefore, it should be recognized that further research is needed for the evaluation of behaviour and structural performance of structures with supplemental damping under near-field earthquakes, mainly due to pulse-like character of these ground motions [35,36].

This paper extends the work [28], which has been focused on far-field ground motions, investigating the maximum seismic velocities of elastic and inelastic structures with supplemental fluid (oil) viscous dampers under near-source pulse-like ground motions. Furthermore, this work examines two additional key parameters that have not been examined in the pertinent literature, i.e., the influences of post-elastic stiffness of structures under consideration and of type of earthquake fault on the *IVR*. Extensive parametric studies are conducted to obtain the empirical expressions for the *IVR*, in terms of the period of vibration, the effective viscous damping ratio, the force reduction factor and the type of earthquake fault. Finally, one characteristic numerical example is presented in order to illustrate the proposed method and demonstrate its accuracy.

2. Maximum seismic velocities of elastic and inelastic systems

This section examines the inelastic behaviour of single-degree-of freedom (SDOF) systems with viscous damping under near-source pulse-like ground motions. The analysis is concentrated on the evaluation of maximum seismic velocities. Firstly, an elastic–perfectly plastic response is assumed to model their structural behaviour, which is shown in Fig. 1a, while the more general bilinear elastoplastic model (Fig. 1b) is also investigated to take into account the influence of post-elastic stiffness on the maximum seismic velocities.

The equation of motion of these systems is given by [37]

$$m\ddot{u} + c\dot{u} + k^{T}u = -ma_{g} \quad (1)$$

where m is the mass, u the relative displacement, c the effective viscous damping coefficient, k^T the tangent stiffness, a_g the acceleration of the ground motion and upper dots stand for time derivatives. The maximum force response of a linear elastic system can be denoted by f_{el}, while the yield strength of a nonlinear elastoplastic system can be denoted by f_y. Thus, the force reduction R factor can be defined as the ratio of maximum elastic to the maximum inelastic force, i.e., $R = f_{el}/f_y$. For a defined the yield displacement u_y, the yield force f_y can be expressed in terms of the yield displacement and the elastic stiffness k_{el} as $f_y = k_{el} \cdot u_y$.

Strain hardening or softening takes place after yielding initiates. For a defined inelastic (tangent) stiffness, i.e. the slope $k_{in} = H \cdot k_{el}$ of the second branch of the skeleton force–displacement relationship (see Fig. 1b), where H the post-yield stiffness ratio. An elastic–perfectly plastic response assumes that $H = 0$. Although its simplicity these models are effective to simulate the behaviour of highly ductile systems including buckling restrained braced frames and eccentric braced frames [38]. Furthermore, elastic–perfectly plastic SDOF systems have been successfully applied to describe the seismic response of multi-degree-of-freedom (MDOF) conventional systems [39,40]. For example, Uang and Bertero [41] adopted such a model to simulate the seismic behaviour of a 3-D multi-degree-of-freedom (MDOF) dual system with two exterior ductile moment-resisting frames and one interior concentrically K-braced frame in the excitation direction that had been experimentally tested. They found that for steel dual systems of medium rise buildings it is possible to estimate with sufficient accuracy the input energy for a multi-storey building structure from the absolute input energy spectra for a SDOF system and the fundamental period of the multi-storey structure. Furthermore, this model has also been applied for MDOF passively damped structures [42,43], since the dynamic peak response of MDOF structures with dampers can be predicted effectively by their equivalent SDOF systems [44].

In order to investigate the maximum seismic velocities of elastic and inelastic systems, the inelastic velocity ratio (*IVR*) is defined as the ratio of the maximum inelastic to maximum elastic velocity of a single-degree-of freedom (*SDOF*) system. Thus,

$$IVR = \frac{\dot{u}_{max,in}}{\dot{u}_{max,el}} \quad (2)$$

Fig. 2 shows the velocity time histories for an elastic–perfectly plastic SDOF system with supplemental viscous dampers examining both the elastic and inelastic response.

This system has elastic stiffness k_{el} = 2000 kN/m, mass m = 50.66 kN s^2/m and effective (inherent + supplemental) damping c = 127.3 kN s/m. The corresponding period of vibration is T = 1.0 s, the effective viscous damping ratio is ξ = 20% and a force reduction factor R = 2.5 is assumed for the case of inelastic behaviour. This system has been subjected to the following four near-source pulse-like strong ground motions:

- Coalinga earthquake (07/22/83, USGS Station 1651 – Transmitter Hill, Dir. 270) – (#415 of PEER Strong Ground Motion Database [45]).
- North Palm Springs earthquake (07/08/86, USGS Station 5070, North Palm Springs, Dir. 210) – (#529 of PEER Strong Ground Motion Database [45]).