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Stochastic seismic response of building with super-elastic damper

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ABSTRACT

Hysteretic yield dampers are widely employed for seismic vibration control of buildings. An improved version of such damper has been proposed recently by exploiting the superelastic force–deformation characteristics of the Shape-Memory-Alloy (SMA). Although a number of studies have illustrated the performance of such damper, precise estimate of the optimal parameters and performances, along with the comparison with the conventional yield damper is lacking. Presently, the optimal parameters for the superelastic damper are proposed by conducting systematic design optimization, in which, the stochastic response serves as the objective function, evaluated through non-linear random vibration analysis. These optimal parameters can be employed to establish an initial design for the SMA-damper. Further, a comparison among the optimal responses is also presented in order to assess the improvement that can be achieved by the superelastic damper over the yield damper. The consistency of the improvements is also checked by considering the anticipated variation in the system parameters as well as seismic loading condition. In spite of the improved performance of super-elastic damper, the available variant of SMA(s) is quite expensive to limit their applicability. However, recently developed ferrous SMA are expected to offer even superior performance along with improved cost effectiveness, that can be studied through a life cycle cost analysis in future work.

1. Introduction

A number of metallic yield dampers have been proposed in the past [1–8] as efficient energy dissipating devices for seismic vibration control of structures. Their usages are well acclaimed among the earthquake resistant design community for reduction of structural response and resulting damage under strong ground motion. The idea of metallic yield damper to absorb large portion of the input seismic energy was first introduced by Kelly [1] and Skinner et al. [2]. Since then a number of different types of energy-absorption devices have been proposed, such as X-shaped yield damper by Whittaker et al. [3] and triangular shaped plate damper by Tsai et al. [4]. A metallic damper based on lead extrusion was developed by Robinson and Greenbank [5] and Monti and Robinson [6]. The pure aluminum shear panels as dissipative device in the moment resisting frame has been proposed by Matteies et al. [7]. A detailed account of such devices can be obtained from Soong and

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Dargush [8]. The cyclic force–deformation hysteresis loop of the metallic yield damper is large enough to effectively dissipate the input energy of vibration.

Recently, the potential of smart materials are explored for making such device for controlling the seismic vibration of structure. One such class of smart material is the Shape-Memory-Alloy (SMA). The SMA can recover their original shape after experiencing large strain as much as 8% either by heating or unloading. The first one is referred as the Shape-Memory-effect, whereas, the latter is known as super-elasticity. Whereas the Shape Memory effect founds applications in several other areas for smart sensing and actuation, the property of super-elasticity is very appealing in view of vibration control of structure. Moreover, the SMA offers large ductility, excellent corrosion and fatigue resistance, which make it an attractive choice for outdoor application.

The usage of SMA as a material in damping device was initiated by Graesser and Cozzarelli [9] and Thomas et al. [10]. The effectiveness of SMA wire as an effective energy dissipation device was experimentally demonstrated by Dolce and Cardone [11]. Yan and Nie [12] has presented the usage of the super-elastic SMA as a damper by illustrating its superior energy dissipative capability, larger bearing strength and significantly reduced residual displacement. It was demonstrated that the dissipative capability of SMA is irrespective of the exciting frequencies those are typically encountered in earthquake. Similar study was also conducted by DesRoches [13] to conclude that the equivalent viscous damping of super-elastic SMA wire is less than 7% and higher cyclic strain may lead to degradation of the damping and re-centering property. The super-elastic damper was employed to supplement isolation system for highway bridge by Wilde et al. [14]. A shake table test was conducted by Dolce et al. [15] to study the usefulness of SMA in damping device. Casciati et al. [16] proposed a SMA passive device to substantially limit the peak bearing displacement under strong earthquake. An excellent review of the versatile usage of SMA in seismic vibration control is provided by Ozbulut et al. [17]. Adachi et al. [18] developed a SMA based damping device which can absorb seismic energy and reduce the seismic force by its pseudo yield effect. The effectiveness of the super-elastic damper was also demonstrated on a building model by Han and coworkers [19]. In view of the dependence of the super-elastic hysteresis on chemical composition, ambient temperature and strain rate, a sensitivity based study of the response with respect to these parameters has been conducted by Andrawes and DesRoches [20]. Another class of SMA, made of Cu–Al–Be alloy shows improved performance under temperature variation and also appears to be cost effective [17]. The application of Cu–Al–Be SMA in damping has been presented by Zhang et al. [21]. Recently, the attenuation of seismic response of structure using SMA damper has been demonstrated by Parulekar et al [22]. In their study, the performance of super-elastic SMA damper is also compared with the conventional metallic yield damper in order to present a detail account of their comparative performance. Details of typical super-elastic damper configuration are also provided in this study.

Studies on damper assisted building are generally based on nonlinear dynamic analysis under recorded ground motion. However, a few studies [23–25] on yield damper considered the stochastic nature of response when subjected to random earthquake. This is evaluated through random vibration analysis. The ground motion model employed therein represents ensemble characteristics of a suite of motions, rather than a single deterministic time history. Such analysis is also important in view of the probabilistic safety assessment [24]. It is generally observed that certain choice of parameters (optimal) ensure minimum response of the building. Further, the choice of optimal parameters is strongly dependent on the characteristics of ground motion.

In view of the large variability among the recorded ground motions, it is cumbersome to precisely postulate such optimal parameters for a damper based on a single deterministic dynamic analysis. In fact, the earlier studies [4,20] proposed the optimal value based on the parametric variation of response in an ad hoc manner without actually conducting a proper design optimization. Further, the scatter among the responses and the optimal parameters from one motion to another become significant. On contrary, the stochastic analysis based on specified power spectral density of excitation offers a convenient way. A specific power spectral density for seismic excitation can effectively represent a suite of ground motions with desired spectral characteristics that can be easily corroborated with target design spectrum. Thus, the stochastic response under commonly adopted power spectral density can be used as the objective function for response minimization. This is referred as stochastic structural optimization (SSO) and the optimal parameters, so obtained, can be used to establish an initial design.

Although the SSO has been attempted on yield damper [23,25], the same is not the case for the SMA based super-elastic damper. Therefore, in this study, the SSO is employed in search for optimal parameters for such damper to augment the initial design procedure. The evaluation of stochastic response to be used as objective function in optimization is based on nonlinear random vibration analysis. This is based on statistical linearization of the cyclic nonlinear force–deformation behavior of the super-elastic damper. A widely employed stochastic model of earthquake is employed to efficiently represent the wide variation in the dominant frequency content as observed in recorded motions.

Furthermore, the optimal performance of the SMA damper is also compared with the optimal performance of the yield dampers in order to provide an estimate of the improved performance that has been lacked in the previous studies. The improvements are also assessed to be robust by conducting parametric studies considering the anticipated variations in the system parameters as well as scenarios of the earthquake loading.