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Short communication

Smart hybrid isolation of a case study highway bridge exploiting seismic early warning information

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ABSTRACT

An innovative technique for seismic retrofit of a case study highway bridge is presented herein. It is done by means of the friction pendulum isolators (FPS) combined with smart magnetorheological dampers (MR), the latter calibrated through the use of a Seismic Early Warning System (SEWS). Hybrid systems, widely investigated by researchers in last years, generally represent a suitable solution in case of base-isolated bridges. As a matter of facts, the introduction of an isolation system allows to reduce shear and bending moment in piers, but may increase decks' relative displacements. A possible effective strategy for limiting this undesired effect may be the adoption of a dissipative system. Herein the passive smart use of MR devices is proposed. The MR dampers are smart in the sense that their mechanical properties can be tuned almost in real time, once before the earthquake strikes the site. A properly designed control algorithm modifies dampers' characteristics according to the intensity of the seismic event is going to occur, as forecasted by the SEWS. This retrofit strategy makes the structure someway adaptive, leading to a significant enhancement of the seismic performance against earthquakes even very different one each other. The case study is an existing reinforced concrete highway bridge built in the 70's, located in the city of Naples, southern Italy.

1. Introduction

After catastrophic earthquakes occurred in last decades, research in the field of seismic engineering has achieved a great improvement. Nowadays many seismic design methods are available in order to realize a new structure and/or retrofit an existing one. It is possible to distinguish two main different designing approaches. The first is the capacity design that favors energy dissipation by means of a global ductile behavior of a given structure, even through significant cyclic damage to structural elements. Innovative structural control systems may be employed as alternative, based on the installation of supplemental devices, typically aiming at reducing seismic demand to the main, hosting structure [1–3]. Different control strategies can be grouped into three main categories: passive, active or semi-active. While passive control systems are activated by the structural deformation induced by the earthquake, other types of seismic control need an external source of energy. In particular, in the case of active control, the enhancement of the structural performance is obtained by means of external forces, whose intensity varies during the earthquake aiming at reducing the structural demand. A large amount of energy is needed in such cases to make the actuators work. Semi-active (SA) control systems are based on the use of variable devices, i.e. devices whose mechanical characteristics (typically stiffness and/or dissipating capacity) can be changed in real time during the excitation. The decision about the instantaneous calibration of such devices is taken through a control algorithm, according to the instantaneous characteristics of earthquake demand or structural response. This control system also require a source of energy, however much smaller than that needed for active systems. In order to detect the earthquake input (feed-forward approach) or the structural response (feed-back approach), and to modify the device's properties, a framework of sensors and a computer are required as well, as for active systems. This makes active and SA control systems quite more expensive than passive ones. Among the main advantages of SA control devices there is the fact that, with respect to a passive system, they can be adapted according to the characteristics of the incoming

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seismic event, so optimizing the structural response. Moreover, if a plausible black-out occurred during the earthquake, while an active system would fail because of the lack of energy, a SA system would work as a passive one, thus ensuring anyway a form of control.

In some cases, the introduction of a control systems may improve the structural response from a point of view, while causing a worsening of other performance criteria. For instance, in the case of base-isolated structures, the installation of a flexible base system provides an elongation of the vibration period and thus a reduction of base moment and shear. On the other hand, it generates an increasing of displacements, with consequent possible pounding problems for adjacent structures. In order to reduce the incidence of such disadvantages, different control devices can be installed to work together in a so-called hybrid control system. Dissipative devices are generally adopted for the aforementioned case of base-isolated structures [4]. A pioneering study about hybrid isolation through the use of variable dampers was proposed by Makris et al. [5]. The effectiveness of the SA control of base-isolated structures was tested in several experiments. In Madden et al. [6], the ability of an adaptive seismic isolation system to protect structures subjected to earthquake ground motions was investigated. Experimental studies have been conducted on hybrid base isolation systems composed by rubber bearings and magnetorheological dampers (MR) [7,8]: researchers' efforts on hybrid isolation systems realized using MR dampers have been focused on the development of new control algorithms for reducing the response of base-isolated structures [9–11]. In Ali et al. [11], two control algorithms were developed to monitor the voltage input to an MR damper so that the desirable performance of the structural system could be achieved.

Recent innovative studies have shown the possible use of SA control strategy in combination with a Seismic Early Warning System (SEWS). A SEWS can reveal in advance information about the intensity of an incoming seismic event: P-waves, faster than the destructive S-waves, are the first detected by the SEWS, so giving the possibility of predicting, on the basis of their characteristics, the main features of the latter. The first applications of the SEWSs were addressed to give the alarm and let immediate rescue operations. Today research is pushing in order to get important technical information about seismic events, like PGA (peak ground acceleration) or PGV (peak ground velocity), from a SEWS: these data can be used in order to adjust in real time mechanical properties of a SA protection system installed on a given structure. This kind of combination has been firstly explored by Kanda et al. [12], then by Pnevmatikos et al. [13] and by De Iuliis et al. [14], introducing the idea of modifying structural properties on the basis of an incoming earthquake's intensity measure, forecasted by a SEWS available at the site.

In last ten years, authors have continuously worked in the perspective of developing an integrated seismic protection system where smart MR devices are calibrated on the basis of the incoming earthquake's entity, given by a SEWS [15–18]. In MR devices the energy dissipation is provided by the passage of a MR fluid in an openings' system. The fluid's viscosity, then its dissipative capacities, can be differently modified by means of the intensity of a certain current passing throughout the fluid. The main work of authors has been to study a possible control algorithm providing the voltage needed to feed MR devices, as a function of the earthquake's intensity predicted by the SEWS in terms of PGA or spectral acceleration at the natural period of the structure. In particular the adjustment of the device is supposed to happen only ones, that is just before the seismic event strikes. Such calibration is kept constant for the whole duration of the earthquake. MR device's mechanical properties can be modified in milliseconds through the application of small electric currents [19,20]: this makes them particularly suitable to be adopted as smart passive devices. It has been shown that the time required by a properly located seismic network to detect accelerations in correspondence of the fault area and to estimate the PGA at the structure's site is around 10–13 s [21]. As a consequence of this, the effectiveness of the proposed integrated system can be considered reliable in all cases where the sensor network of the SEWS is closer to the epicenter than the infrastructure to protect by 10 km or more.

The combination of smart passive devices with the SEWS prediction allows to gain an important simplification of the SA framework, since the on-line continuous acquisition and processing of the structural response is not needed: no additional sensors are required. Nevertheless, the use of such a type of smart control system remains still quite more complex than other (passive) control systems. Its use is justifiable if the structural enhancement is achievable not only in terms of mean response against a set of seismic records (as seismic codes typically strictly require), but for any possible seismic input expected in the area of interest. This purpose can be potentially attained by the SEWS-MR integrated framework herein proposed. This approach is summarized in the following, through the description of the main components involved:

1. variable dissipative devices installed at the structure to be controlled;
2. a SEWS network working in the area where the structure to be protected is located;
3. a control algorithm that allows to optimally calibrate MR devices on the basis of the forecasted characteristics of the incoming earthquake.

The control strategy - herein applied to a real existing case study structure - represents an evolution of the strategies presented by Maddaloni et al. [22–24] to protect existing bridges. In these works a particular benchmark bridge was considered in order to develop applicative examples [25–27].

In [22] two different control algorithms were proposed, providing the voltage u_c respectively as a function of the PGA estimate forecasted by the SEWS or of the spectral acceleration $S_a(T_1)$, evaluated at the fundamental period of vibration of the bridge on the 5% damped elastic response spectrum.

The earthquake's intensity forecasted by the SEWS was supposed to be quite accurate, but some uncertainties are unavoidable. As a consequence of this, an enhanced version of the proposed control algorithm was investigated in [23], considering the PGA value as the only seismic information made available by the SEWS. A wider number of natural earthquake records was adopted, covering a large range of magnitude, PGA values, frequency content, distances to fault and soil types, and so investigating the capability of the control strategy to adapt to quite different seismic inputs. Analyzing the structural response for different values of voltage u_c feeding MR devices, it was possible to calibrate the control algorithm aiming at providing the larger response's reduction with respect to the uncontrolled bridge. In particular, after a trial and error procedure, an hyperbolic tangent function $u_c[S_a(T_1)]$ yield the best results in terms of attenuation of structural response. The sensitivity of the proposed control algorithm to uncertainties in the estimate of PGA was also investigated in a previous work [23], where an high robustness of the control system was pointed out.

In [24] further enhancements of the control strategy have been pursued, leading to the definition of two different "regional" control algorithms, respectively for Italy and California. The idea of addressing the control algorithm to a specific area comes from the observation that different characteristics of seismic events can significantly influence its definition. Once a regional control