STRUCTURAL CONTROL STRATEGIES FOR SEISMIC EARLY WARNING SYSTEMS

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ABSTRACT:

A seismic early warning system (SEWS) is a set of actions that can be taken from the moment when a seismic event is triggered, with a significant reliability, to the moment the quake strikes in a given location. The leading (pre-information) time can be estimated in the range of few seconds to dozens of seconds. Current research activities on SEWS include the anticipate estimate of the peak ground acceleration (PGA) and/or of the response spectrum of the incoming earthquake.
Possible interactions between SEWS and structural control are related to the exploitation of the anticipate estimation of the PGA in the framework of semi-active control strategies, in particular using magnetorheological (MR) dampers. The latter are time-varying properties devices able to achieve a wide range of physical behaviors using low-power electrical currents. Changing the current in the damper causes a very fast modification of the mechanical properties of the MR fluids, due to the particular magnetic field applied. The main idea of this work is to change the MR damper behaviour according to the forecasted intensity of an upcoming earthquake provided by the SEWS, in order to obtain the optimal seismic response of the hosting structure. A reinforced concrete bridge is considered herein as a case-study. Three different control strategies are designed and compared, each one being based on the use of the following devices respectively: rubber isolator, viscous damper, semi-active magnetorheological (MR) damper, the latter working with a SEWS in the way described above. The effectiveness of each considered control technique is discussed with reference to several different seismic input.

KEYWORDS: Early warning, structural control, magnetorheological device, non linear analysis

1. INTRODUCTION

Generally speaking, a seismic early warning system (SEWS) is a system that can be used to prevent devastating damages, by the knowledge, ahead of time, of some earthquake parameters. These measures, for prevention or emergency, can be used for different purposes, e.g. evacuation of buildings, shut-down of critical systems (nuclear and chemical reactors), stop of high-speed trains. The leading time (pre-information) can be currently estimated in the range of few seconds to dozens of seconds.
An interesting interaction between SEWS and structural control is related to the possibility of exploiting the anticipate estimation of the peak ground acceleration (PGA) in the framework of semi-active structural control. A reinforced concrete bridge is considered herein, being characterized by all equal piers. It has been modeled with SAP 2000 computer program (CSI, 2008) and analyzed considering two different consolidated strategies of passive seismic control: base isolation through rubber devices, energy dissipation through non-linear viscous dampers. Both strategies need to be designed according to a pre-fixed intensity of the seismic action expected. A third control strategy is designed on the idea of using SEWS and semi-active techniques in combination. A magnetorheological (MR) device is designed for this purpose, allowing to adapt its mechanical properties according to the intensity of incoming earthquake provided by the SEWS. The device, calibrated just before the upcoming earthquake arrival, remains unaltered during the subsequent seismic excitation.
A set of 17 European far field records are used for non-linear dynamic analyses of the structure enhanced by each of the three strategies described above. By analyzing the results in terms of relationship among the predicted PGA and some parameters of the structural response, the effectiveness of MR dampers is compared with that of the other two, nowadays consolidated, passive control techniques.

2. SEWS AND STRUCTURAL CONTROL: A POSSIBLE APPLICATION

In the following, for a reinforced concrete bridge (Figure 1), three different devices for isolation and/or energy dissipation have been considered: isolator, viscous damper and semi-active magnetorheological device. In particular, a deck free to move via rolling bearings from a side and constrained to the pier by the additional device in the other one, is considered. The bridge is characterized by a repetitive deck and pier configuration, so that a simply model made up of a 2 degrees of freedom (DoFs) system has been considered (Figure 1).

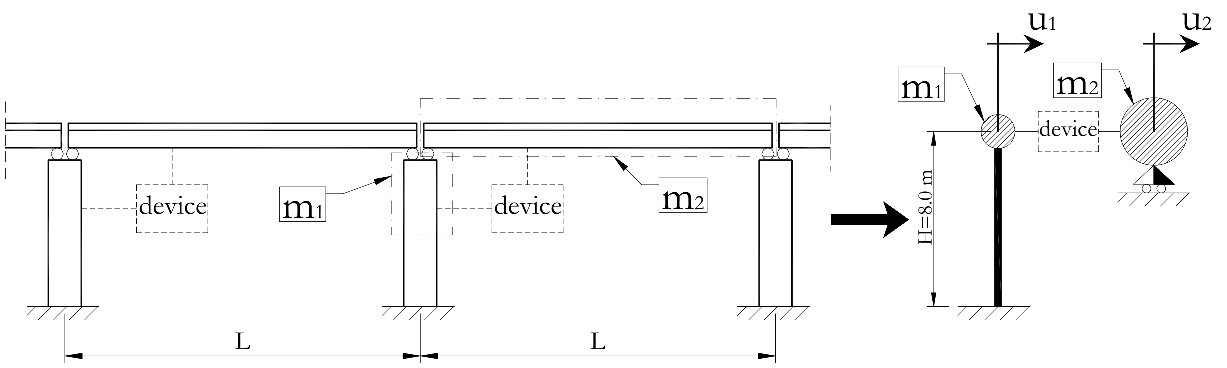

Figure 1 Reinforced concrete bridge (longitudinal view) and equivalent 2 DoFs model

Seismic masses of m_1=104 tons for the pier and m_2=1020 tons for the deck have been assumed. A set of 17 accelerograms (European far field earthquakes with epicentral distance ≥ 10 Km), downloaded by the European Strong Motion Database (ESD, 2007), are used for non linear dynamic analyses (Table 1). Average device relative displacement Δ_{ave} and bending moment M_{ave} at the bottom of the pier are used for the design and verification of the bridge enhanced by each of the above seismic protection strategies. The threshold capacity values for Δ_{ave} and M_{ave} are assumed to be 0.05 m and 6.0 MNm respectively.

Table 1 Record details

N.	Code Name	Earthquake Name	Country Name	Date	Mw	PGA [m/s^2]	Epicentral Distance (km)
1	000181ya	Tabas	Iran	16/09/1978	7.3	0.853	68
2	000612ya	Umbria Marche	Italy	26/09/1997	6.0	0.948	38
3	000289xa	Campano Lucano	Italy	23/11/1980	6.9	1.058	48
4	001229ya	Izmit	Turkey	17/08/1999	7.6	1.174	73
5	001928ya	Patras	Greece	14/07/1993	5.6	1.879	10
6	000361xa	Umbria	Italy	29/04/1984	5.6	2.045	19
7	001313xa	Ano Liosia	Greece	07/09/1999	6	2.601	16
8	007157ya	Firuzabad	Iran	20/06/1994	5.9	2.728	22
9	000623ya	Umbria Marche (aftershock)	Italy	06/10/1997	5.5	3.027	11
10	001715xa	Ano Liosia	Greece	07/09/1999	6.0	3.2	14
11	000856xa	Umbria Marche (aftershock)	Italy	03/04/1998	5.1	3.801	10
12	000139ya	Friuli (aftershock)	Italy	15/09/1976	6.0	4.136	25
13	000594ya	Umbria Marche	Italy	26/09/1997	6.0	4.538	11
14	004673ya	South Iceland	Iceland	17/06/2000	6.5	4.677	15
15	000623xa	Umbria Marche (aftershock)	Italy	06/10/1997	5.5	5.124	11
16	000594xa	Umbria Marche	Italy	26/09/1997	6.0	5.138	11
17	000593xa	Umbria Marche	Italy	26/09/1997	5.7	5.278	13

2.1 Base isolation of the bridge

The base isolation through high damping rubber bearing devices (HDRB) is the first strategy of passive seismic control considered for the comparison. The HDRB is made up of alternating layers of steel laminates and

hot-vulcanized rubber. These devices are characterized by their low horizontal stiffness guaranteeing the increase of the fundamental period of vibration of the structure, and thus the de-coupling of the horizontal movement of the structure from the ground motion.
A model based on the hysteretic behavior proposed by Wen (1976) and recommended for base-isolation analysis by Nagarajaiah et al. (1991), an equivalent stiffness of 2000 kN/m and a damping ratio equal to 10 % have been considered for the non linear analyses.
The device chosen herein allows to fulfill the verification criteria, leading to a value of the average moment equal to M_{ave}=5.7 MNm and a contended average displacement.

2.2 Non-linear viscous dampers design

Viscous dampers are essentially made up of a cylinder filled with silicone fluid and a piston free to move in both directions, creating two chambers.
The fluid viscous dampers considered herein are characterized by a non–linear constitutive force–velocity law $F_{vis}=c\cdot\mathring{u}^{\alpha}$ with c damping constant, $\mathring{u}$ relative velocity at the devices ends, α assumed equal to 0.15.
In order to determine the optimal value for c, several non-linear dynamic analyses have been performed. A plot of the average values of the maximum device displacement (Δ_{ave}) and maximum bending moment at the bottom of the pier (M_{ave}) obtained for each time-history as functions of the damping constant is shown in Figure 2.
A c value equal to 250 kN/(m/s)$^{\alpha}$ turns out to be the optimal choice, allowing to fulfill the verification criteria (Δ_{ave}=0.048 m $\leq$ 0.05 m; M_{ave}=5.1 MNm $\leq$ 6.0 MNm), and also leading to the lowest value of the average bending moment.

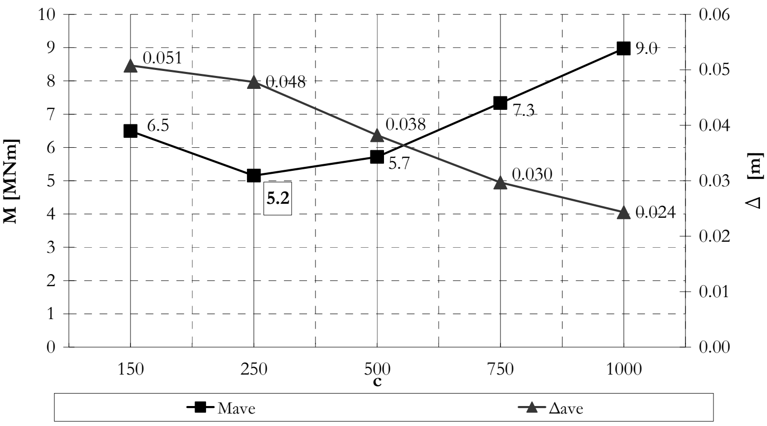

Figure 2 Evaluation of the optimal damping constant value

2.3 Magnetorheological dampers for the semi-active control of the bridge

This third control strategy is designed according to the idea of using SEWS and semi-active control techniques in combination. A magnetorheological (MR) device is designed for this purpose, allowing to adapt its mechanical properties according to the intensity of an incoming earthquake provided by the SEWS. The device properties, calibrated just before the earthquake described, remain unaltered during the seismic excitation.
An estimate of the intensity of an incoming ground motion, expressed in terms of peak ground acceleration (PGA), is assumed to be provided by an installed SEWS tens of seconds before the quake strikes. The deck is connected to the pier through the magnetorheological (MR) devices having the possibility to change their behavior according to a fixed intensity of the feeding current.
The simplest model for the MR devices, derived by the Bingham model of MR fluids (Carlson and Jolly, 2000), combination of a viscous and a friction damper taken in parallel, is assumed. Therefore the force F_d in the damper can be expressed as follows:

$$F_d = C_d(i)\cdot\dot{u} + F_{dy}(i)\cdot\mathrm{sgn}(\dot{u}) \tag{2.1}$$

where $\mathring{u}$ is the relative velocity between the damper's ends, C_d the viscous damping constant, F_{dy} the variable plastic threshold controlled by the applied magnetic field which, in turn, depends on the current i in the coils inside the MR damper. Varying the current from zero to a maximum value (i_{max}), a wide range of plastic threshold values can be achieved, starting from a minimum value, essentially due to the friction force of the gaskets, up to a maximum value due to the magnetic saturation. The $C_d(i)$ and $F_{dy}(i)$ expressions are assumed as in the Eqn. 2.2 depending on a single parameter (χ), whose value has to be chosen in the design stage.

$$c_d(i)=\chi\left(0.36+1.15\frac{i}{i_{\max}}\right)\ ;\ F_{dy}(i)=\chi\left(0.10+1.28\frac{i}{i_{\max}}\right) \tag{2.2}$$

The selection of the best value of χ has been done performing non-linear dynamic analyses of the bridge (using the above set of 17 accelerograms) each time fixing a different value for χ and an average value for the current intensity ($i=0.5\ i_{max}$). A plot of the average values of the maximum displacement device (Δ_{ave}) and bending moment (M_{ave}) at the bottom of the pier, obtained for each non linear analysis versus the test values for χ is shown in Figure 3.

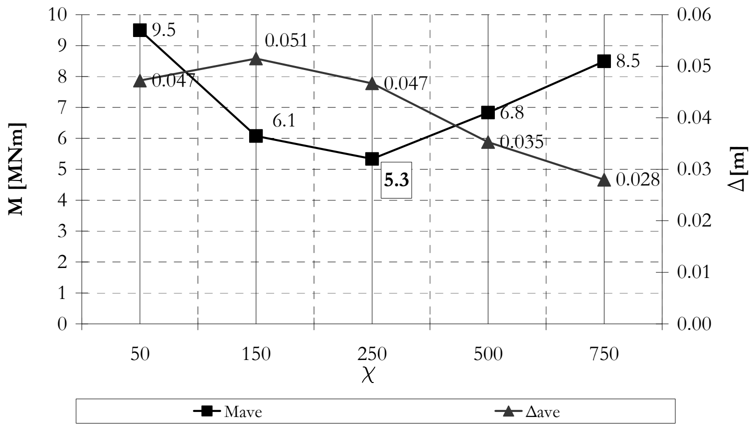

Figure 3 Evaluation of the constant factor (χ) best value

The value 250 results to be the best one for χ, allowing to fulfill the verification criteria (Δ_{ave}=0.047 m ≤ 0.05 m; M_{ave}=5.3 MNm ≤ 6.0 MNm), also leading to the lowest value of the average moment.
Once selected the best MR device for the case under exam, 7 non linear analyses have been performed for each accelerogram, each time changing the current intensity (i=0, 0.5, 1.0, 1.5, 2.0, 2.5, 3.0 A, respectively). The results for two of the seventeen analyses done are reported in Figure 4 (max displacement device and max bending moment versus current level): it is clear how the maximum relative displacement of the device and the maximum bending moment change with the current intensity *i*.

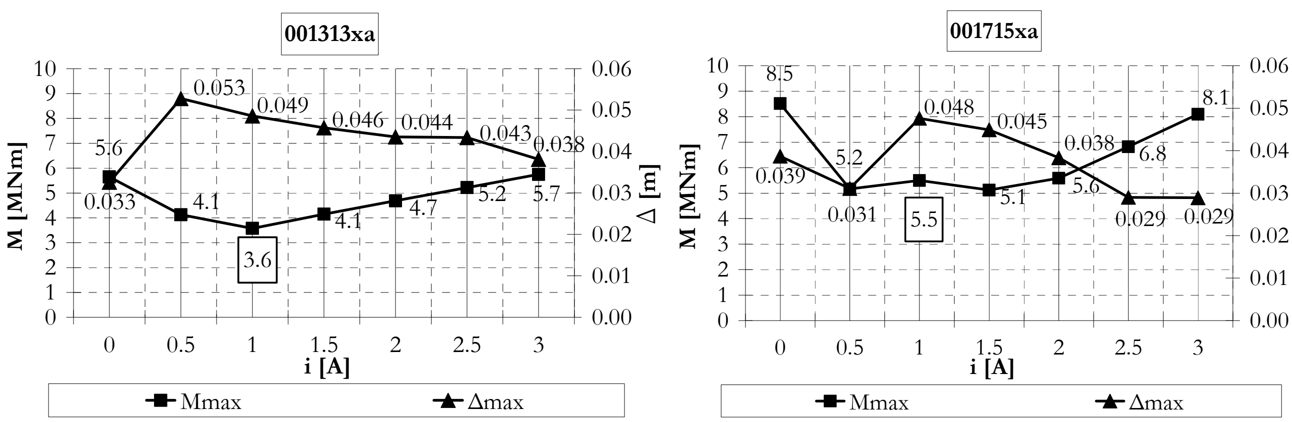

Figure 4 Evaluation of the current intensity (i) best value

The best value of the current intensity for each accelerogram is determined as the one providing the minimum bending moment (e.g. see the boxed values in the two diagrams in Figure 4). Operating a linear regression of these data, the simple relationship i=0.40 PGA, has been obtained (Figure 5). This expression can be used to establish, given a PGA value predicted by the SEWS, which intensity of current is better to supply to the MR damper in order to achieve an optimal reduction of the seismic response.

The non-linear analyses of the MR controlled bridge have been performed again adopting for each accelerogram the current value obtained by the above defined relationship *i*=*i*(PGA) and the PGA values, showed in Table 1 and supposed to be provided by the SEWS ahead of time. The results of such are discussed in the following paragraph.

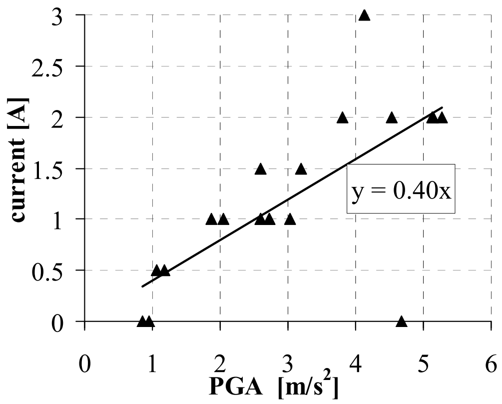

Figure 5 Relationship between PGA and the optimal intensity of current

3. COMPARISON OF THE RESULTS

Figure 6 reports the results, in terms of maximum bending moment at the bottom of the pier, obtained for each accelerogram, considering all the three previously designed control techniques.

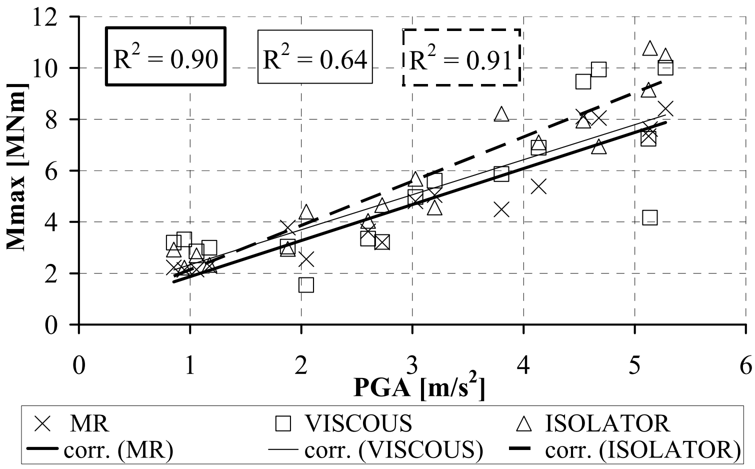

Figure 6 Comparison among the three different possibilities of seismic retrofit

A linear regression has been done with reference to the results corresponding to the same seismic protection strategy, leading to the squared value of the correlation coefficients shown in Figure 6. It is evident the good correlation of results for MR and isolator devices, which means that as the PGA increases, the value of the seismic response (i.e. maximum bending moment at the bottom of the pier) proportionally increases.
This result allows to assume that the PGA is a good parameter to consider when control strategy is based on the use of semi-active techniques in combination with SEWS.
In other words, the knowledge of the PGA provided by the SEWS represent a good way to determine (through a mathematical relationship) the mechanical properties of the MR device and to optimize the seismic response for different intensities of the earthquakes.
Furthermore, the use of the MR device in the structural control provides the lowest values of the standard deviation (SD) and the average (μ) both for bending moment and displacement device (Table 2).

Table 2 Standard deviation and average values of the response parameter for the different devices used

	SD_{moment} (MNm)	**μ_{moment} (MNm)**	**SD_{Δ} (m)**	**μ_{Δ} (m)**
MR	2.3	4.8	0.041	0.048
VISCOUS	2.7	5.2	0.043	0.048
ISOLATOR	2.9	5.7	0.055	0.055

4. CONCLUSIONS

An innovative approach to the concept of seismic early warning system (SEWS) is obtained considering an exploitation for structural control. In short, a SEWS is a system that can provide the knowledge of some parameters, ahead of time, of the seismic event that is occurring. The leading time can be currently estimated in the range of few seconds to dozens of seconds. Possible interactions between SEWS and structural control are related to the possibility of exploiting the anticipate estimation of the peak ground acceleration (PGA) in the framework of semi-active structural control.
In the paper, non linear analyses for a reinforced concrete bridge have been performed. The bridge, characterized by all equal piers, has been modelled by SAP 2000 computer program and analyzed considering different possibilities of seismic retrofit as base isolation and energy dissipation. Both strategies need a design approach based on a preliminary assumption about the intensity of the seismic action expected. A different strategy, developed in the present work, considers the addition of a variable-damping, magnetorheological device (semi-active control). The properties of the damper, in this case, do not need to be fixed at the design stage, but could be varied according to the intensity of incoming earthquake provided by the SEWS with the aim of ensuring the optimal structural response.
A set of 17 European far field records are used for non linear dynamic analyses of the bridge. The results in terms of relationship among the estimated PGA values and some structural response parameters have been provided. This result allows to assume that the PGA is a good parameter to consider when control strategy is based on the use of semi-active techniques in combination with SEWS. The knowledge of the PGA provided by the SEWS represents a good way to assign through a mathematical relationship, the mechanical properties of a semi-active MR device and to optimize the seismic response for different intensity of the earthquakes. Furthermore, among the three different control strategies, the use of MR device, allows to obtain the lowest values of the standard deviation and average of the response parameters.
In conclusion, this first attempt to exploit seismic early warning systems for structural control using MR devices appear to be a promising technique, to be further enhanced in the future.

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