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REGIONAL-BASED CONTROL ALGORITHMS USING EARLY WARNING INFORMATION FOR SEISMIC PROTECTION OF A HIGHWAY BRIDGE

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Abstract. *The possible exploitation of a seismic early warning system (SEWS) in the framework of semi-active (SA) structural control using magnetorheological (MR) dampers has been investigated by authors in the last years. The main idea consists in changing the MR damper behaviour according to the forecasted intensity (expressed in terms of peak ground acceleration, PGA) of an incoming earthquake provided by the SEWS to obtain the higher seismic demand reduction for the hosting structure. In other words, a "smart passive" use of MR dampers driven by a SEWS information has been promoted.*

The present paper focuses on the control algorithm needed to select the optimal voltage u_c *to set the variable devices according to the PGA estimate. The authors found that the different characteristics of earthquakes that occur in different sites, as frequency content, duration and magnitude, could play a significant role in the definition of the best control algorithm. For this reason, these aspects are considered by generating regional-based control algorithms. Different* u_c*(PGA) logics have been built for three selected worldwide regions (Japan, California and Italy) on the basis of the results of several dynamic simulations performed using natural earthquakes recorded in each of these area.*

The effectiveness of the proposed control algorithms has been checked with reference to a case-study: a prestressed concrete highway bridge.

1 INTRODUCTION

In the last decade the research for unconventional strategies for the seismic protection of structures has recorded remarkable progress. Most of the innovative approaches proposed aim to modify the dynamic response of the structures to reduce the vibrations induced by the earthquake [1]. In this field, the semi-active (SA) control is considered as the emerging technology for seismic protection [2].

In the same time, "geophysics science" has made important progress in the development of a system, usually called Seismic Early Warning System (SEWS), capable to predict, few seconds before, the arrival of an earthquake [3]. Generally speaking SEWS can be used to prevent devastating damages, by the knowledge, ahead of time, of some earthquake parameters. These measures 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. Actually applications of SEWS are growing worldwide: first in Japan [4], more recently in California [5] and Italy [6].

The authors, in their recent studies, have tested an innovative technology capable to exploit a SEWS in the framework of semi-active control system [7, 8, 9] by the use of magnetorheological (MR) dampers. As known, the latter are able to achieve a wide range of physical behaviours using low-power electrical currents [10]. Authors are investigating a possible "smart passive" use of MR dampers with the aim of joining positive aspects of both semi-active (e.g. adaptability to seismic demand) and passive strategies (ease of implementation and use) and of overcoming the operational limits of the former (e.g. related to possible and unpredictable malfunctions of the control chain [11] and delays [12]). The strategy is proposed to effectively control a highway bridge proposed as a benchmark structural control problem by Agrawal et al. [13], Nagarajaiah et al. [14] and Tan et al. [15]. In order to set the optimal behaviour for MR dampers, appropriate algorithms have been evaluated.

Two alternative control algorithms (strategies) have been proposed in 2011 [7] to calibrate MR dampers (i.e. to select the optimal value of feeding voltage u_c). The first one is based on the estimate of the Peak Ground Acceleration (PGA) of the incoming earthquake, the second one (resulted to be more effective) on the forecasted elastic spectral acceleration (S_a) at the fundamental period of the structure (T_1). In that pioneering paper on the subject both strategies allowed a strong reduction of the structural response, even compared with the three control techniques considered in the benchmark paper. However, a fast forecast of the PGA at a given site starting from an estimate of typical intensity measures, like for instance the magnitude, seems to be quite a mature subject [5] compared to a reliable estimate of more sophisticated quantities like the frequency content and/or the spectral accelerations. Furthermore, the effect itself of these quantities on systems response is still largely debated [16].

In Maddaloni et al. [9] the Peak Ground Acceleration (PGA) value is considered as the unique seismic parameter available by the SEWS and a relationship u_c(PGA) is assumed to set the MR dampers. Several analyses have been performed to demonstrate the effectiveness of the innovative idea proposed.

In this paper, with the purpose to further increase the performance achieved, a regional-based control algorithms, i.e. different relationships u_c(PGA) for each one of three world regions selected (Italy, California and Japan) are presented. In this way the different characteristics of earthquakes that occur in different sites, as frequency content, duration and magnitude, can be considered.

The proposed strategy is investigated by several numerical simulations, considering a total of forty-five strong real earthquakes, fifteen for each region.

2 THE BENCHMARCK HIGHWAY BRIDGE

A brief description about technical characteristics of the benchmark bridge [13, 14, 15] is herein presented.

Located in Orange Country of Southern California, the bridge consists of a two-span continuous cast-in situ pre-stressed concrete. The total length of each span is 58.5 m long, while the long pre-stressed support beam is 31.4 m. This central support is linked to two columns 6.9 m high. The mass of the deck is about 3200 tons while the total mass of the bridge is 4200 tons (Fig. 1). The abutments are skewed at 33°, so the bridge can be considered irregular in plan. In this case, to evaluate the seismic behavior of the structure, nonlinear analysis is recommended and simpler methods could be conduct as false results [17].

The bridge deck is isolated using four non-seismic elastomeric pads at each abutment, while eight fluid dampers are installed between the end abutments and deck in order to reduce seismic response. However in evaluation model, lead rubber bearings are used to replace eight traditional non seismic elastomeric pads (Fig. 2). This configuration represents the uncontrolled structure used as comparison to establish the effectiveness of the control systems proposed. The first mode of the structure is torsional with a natural period T_1=0.813 s.

Figure 1. Two views of the benchmark highway bridge

In the benchmark paper three sample control strategies (passive, semi-active and active) including devices, control algorithms and sensors are designed and presented for comparison. The passive strategy is based on 16 nonlinear viscous dampers, placed between the deck and the abutments. The active strategy is based on 16 hydraulic actuators, placed as before. The semi-active strategy is based on 16 MR dampers modeled according to the Bouc–Wen hysteretic model.

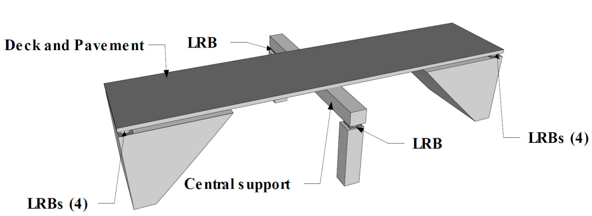

Figure 2. Uncontrolled configuration of the benchmark highway bridge

3 SEISMIC RECORDS FOR NONLINEAR ANALYSIS

As already cited, the present paper focuses on the control algorithm needed to select the optimal voltage u_c to set the variable devices according to the PGA estimate. The authors found that different characteristics of earthquakes occurring in several sites, as frequency content, duration and magnitude, could play a significant role in the definition of the best control algorithm. For this reason, three different worldwide regions are selected.

The considered regions are Italy, California and Japan. A total of forty-five strong real earthquakes, (fifteen for each region) all recorded on soil type B according the Eurocode 8 classification [18] are assumed as input for nonlinear analysis of the benchmark bridge. For the excitation of the longitudinal (EW) and transverse (NS) directions of the bridge, both components are simultaneously used. The main characteristics of the earthquake ground motions are shown in Table 1, 2 and 3 for Italy, California and Japan regions respectively.

The seismic inputs have been downloaded from the Italian Acceleration Archive (ITACA) [19], the Pacific Earthquake Engineering Research Center (PEER) [20] and the National Research Institute for Earth Science and Disaster Prevention (NIED) [21].

For the evaluation of the seismic performance of the bridge all the earthquakes have been used at the full intensity. As visible, the fifty-five accelerograms, even if are all referred to the same soil type B, cover a wide range of magnitudes (from 4.70 to 7.30 at magnitude moment scale) and PGA (from 0.101 g to 2.080 g).

N.	Earthquake name	Date [dd-mm-yy]	M_w	PGA NS [g]	PGA EW [g]	Epicentral distance [km]
1	Ancona-Rocca	21-06-72	6.2	0.179	0.084	22.87
2	Aquila-V.Aterno	06-04-09	6.3	0.353	0.330	5.65
3	Aquila-V.Aterno	06-04-09	6.3	0.443	0.402	9.63
4	Aquila	06-04-09	6.3	0.657	0.545	8.87
5	Brienza	23-11-80	6.9	0.217	0.178	42.21
6	Conza-Piana	01-12-80	5.5	0.166	0.201	9.54
7	Forgaria	15-09-76	5.9	0.349	0.332	16.83
8	Forgaria	11-09-76	5.6	0.129	0.234	26.21
9	Forgaria Cornino	16-09-76	5.3	0.242	0.201	6.67
10	Gemona	11-09-76	5.1	0.190	0.155	9.39
11	Gemona	15-09-76	5.9	0.252	0.255	14.67
12	Gran Sasso	07-04-09	5.6	0.251	0.281	16.81
13	Irpinia	23-11-80	6.5	0.218	0.178	42.21
14	Mazara del Vallo	07-06-81	4.9	0.193	0.134	9.76
15	Valpassiria	17-07-01	4.8	0.170	0.062	18.66

Table 1. Proprieties of the fifteen selected Italian ground motions

N.	Earthquake name	Date [dd-mm-yy]	M_w	PGA NS [g]	PGA EW [g]	Epicentral distance [km]
1	Baja California	07-02-87	5.5	1.388	0.669	8.69
2	Cape Mendocino	25-04-92	7.0	0.228	0.183	36.28
3	Imperial Valley	15-10-79	6.5	0.195	0.109	59.54
4	Northen Calif.	07-06-75	5.2	0.179	0.115	30.54
5	Northridge	20-03-94	5.3	0.157	0.125	9.00
6	Northridge	17-01-94	6.7	0.178	0.162	19.19
7	Oroville	08-08-75	4.7	0.189	0.095	10.07
8	Oroville	08-08-75	4.7	0.209	0.140	8.60
9	Palm Springs	08-07-86	6.1	0.139	0.106	27.70
10	San Fernando	09-04-71	6.6	0.268	0.364	25.36
11	Sierramadre	28-06-91	5.6	0.113	0.091	19.95
12	Upland	28-02-90	5.6	0.233	0.223	12.19
13	Victoria	09-06-80	6.3	0.621	0.587	33.73
14	Whittier	04-10-87	5.3	0.188	0.156	6.59
15	Whittier	04-10-87	5.3	0.264	0.199	13.04

Table 2. Proprieties of the fifteen selected Californian ground motions

N.	Earthquake name	Date [dd-mm-yy]	M_w	PGA NS [g]	PGA EW [g]	Epicentral distance [km]
1	Fujieda	01-08-11	6.2	0.518	0.342	39.0
2	Inukai	19-10-96	6.4	1.423	1.683	144.0
3	Iwase	07-12-12	7.3	0.221	1.575	394.0
4	Kamitakara	27-02-11	5.5	0.666	0.800	12.0
5	Kasumigaura	12-10-12	5.0	0.101	0.095	33.0
6	Katsura	14-03-10	6.5	1.282	1.193	97.0
7	Motegi	07-12-12	7.3	1.348	1.625	384.0
8	Noheji	07-12-12	7.3	0.146	0.142	432.0
9	Oguti	25-03-07	6.9	0.388	0.417	106.0
10	Shirakawa	07-12-12	7.3	1.957	1.592	362.0
11	Takane	25-03-07	6.9	1.123	1.640	149.0
12	Tamayama	07-12-12	7.3	1.498	1.550	332.0
13	Taneichi	07-12-12	7.3	1.345	1.623	360.0
14	Uodu	25-03-07	6.9	1.424	1.409	79.0
15	Yatsuo	25-03-07	6.9	2.080	1.114	81.0

Table 3. Proprieties of the fifteen selected Japanese ground motions

4 COMPARISON PARAMETERS: EVALUATION CRITERIA

In the benchmark papers [13, 14, 15] sixteen evaluation criteria named J_i are suggested in order to evaluate the effectiveness of the different control strategies proposed by different authors in the worldwide competition. The criteria measure the reduction in peak response quantities of the benchmark highway bridge, evaluated by normalizing the response quantities by the corresponding ones for the uncontrolled reference bridge. Each criterion is organized so that a value less than 1 indicates a better performance of controlled systems compared to the reference uncontrolled one.

In this paper, only criteria J_1 and J_2 are considered as they are considered the most significant for the present case of an highway bridge. Applying multicriteria procedures to synthesize the whole set of indexes, even if possible [22], is beyond the scope of the present work. At the base of the piers, J_1 measures the peak base shear force in the controlled structure normalized by the corresponding base shear in the uncontrolled structure and J_2 measures the peak overturning moment in the controlled structure normalized by the corresponding moment in the uncontrolled structure.

5 CONTROL ALGORITHMS FOR SEMI-ACTIVE STRATEGY

The combination of semi-active control with seismic early warning system is introduced herein as additional control strategy of the bridge. It represents an enhanced version of the one proposed in Maddaloni et al. [9]. In this previous work, the use of MR dampers as smart passive devices is suggested to effectively control the bridge under the action of the 16 earthquakes that cover a wide variety of magnitudes, distances to fault and soil types. The mechanical behaviour of such devices is adjusted once, shortly before the incoming earthquake, according to the PGA provided by a SEWS. The results demonstrate that the control algorithm, i.e. the relationship u_c(PGA), results to be more effective in a largest number of cases.

With the purpose to further increase the performance achieved, in this paper is presented a regional-based control algorithms, i.e. a different relationship u_c(PGA) for each one of three world regions selected (Italy, California and Japan).

The way to use SEWS information to calibrate the MR devices, is hereinafter reported:

1) Modal analysis of the structure is preliminarily performed in order to know the fundamental period of vibration T_1 of the hosting structures;
2) Once the SEWS provide the expected PGA of an incoming earthquake, the elastic damped response spectrum according to the Eurocode 8 [18] rules is defined;
3) The spectral acceleration $S_a(T_1)$ evaluated at the fundamental period of the bridge is finally exploited to set the voltage u_c in the MR dampers according to a given control algorithm $u_c[S_a(\text{PGA})]$ (Fig. 3).

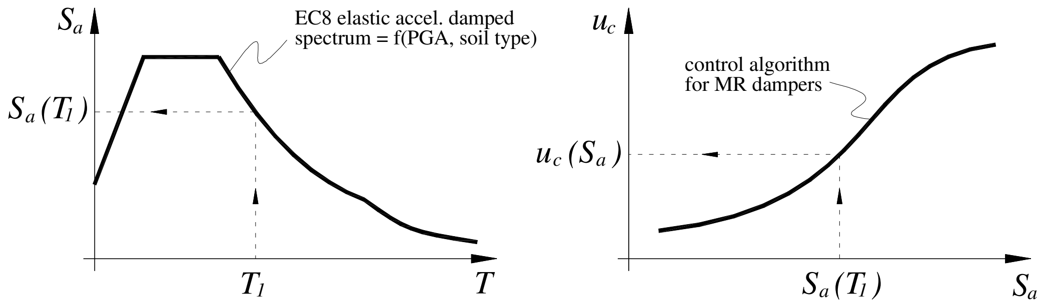

Figure 3. Procedure to calibrate MR dampers according to the expected PGA of the incoming earthquake

For each region, to find the best control algorithm $u_c[S_a(PGA)]$, several nonlinear analyses have been performed, each time feeding the MR devices with a different voltage value, starting from 0 V to 10 V and using a step of 0.01 V. Then for each analysis computed as above descript, the following steps are made:

a) The value of the performance indexes J_i (with i=1, 2) have been recorded;

b) For each index and each earthquake, a diagram showing the correlation between the index J_i and the value of command voltage u_c has been created;

c) For each of these cases, the optimal value of voltage $u_{c,opt,i}$ (i.e. the one leads the minimum value $J_{i,min}$ of J_i) has been found; then an interval of voltage values $\Delta u_{c,opt,i}$ around $u_{c,opt,i}$ has been defined including all the u_c values corresponding to J_i less than $1.3J_{i,min}$ (i.e. assuming a tolerance of 30% in terms of structural performance) and also more than 1 (Fig. 4).

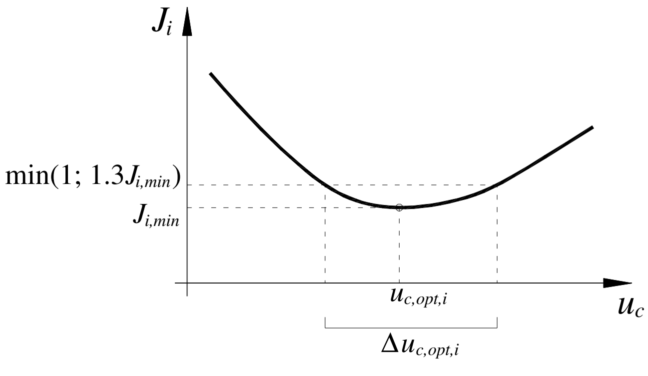

Figure 4. Definition of the optimal interval $\Delta u_{c,opt,i}$ of voltage for MR devices

For the same earthquake, the intervals $\Delta u_{c,opt,1}$ and $\Delta u_{c,opt,2}$ often result to be quite similar. For this reason and for brevity, herein only the interval $\Delta u_{c,opt,1}$ (i.e. related to the index J_1, proportional to the peak base shear force) is shown in Figs. 5, 6 and 7 as vertical gray lines. The lines having as abscissa the value $S_a(T_1)$ corresponding to one of the considered earthquakes, and as ordinates the interval $\Delta u_{c,opt,1}$. The black points represent the "best" values (namely $u_{c,opt,1}$) of the interval. The "x" are representative of the nonlinear analyses results when, for all the values of voltage u_c used to set the MR devices (from 0 V to 10 V), J_1 is larger than one (the x are located at minimum J_1 value).

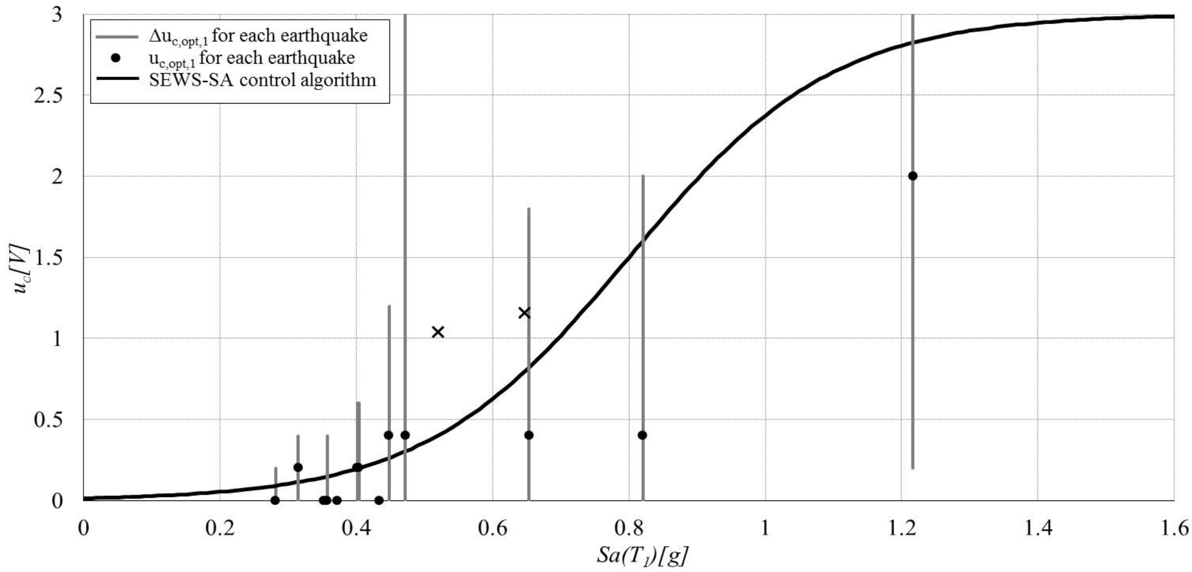

Figure 5. Values of $u_{c,opt,1}$ and of $\Delta u_{c,opt,1}$. Adopted control algorithm for Italian earthquakes.

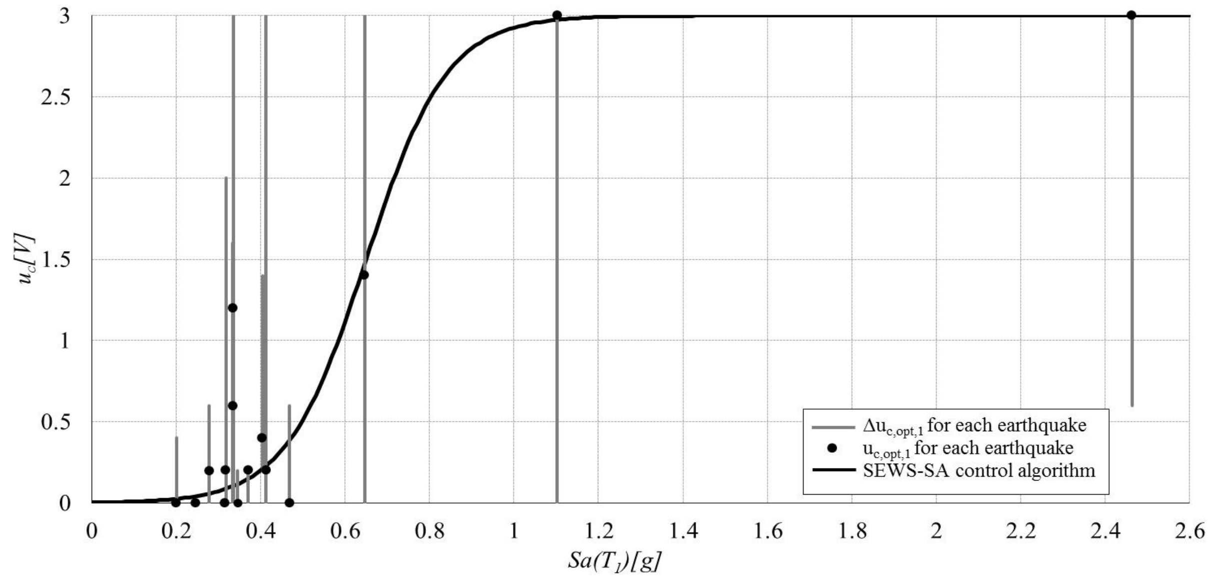

Figure 6. Values of $u_{c,opt,1}$ and of $\Delta u_{c,opt,1}$. Adopted control algorithm for Californian earthquakes.

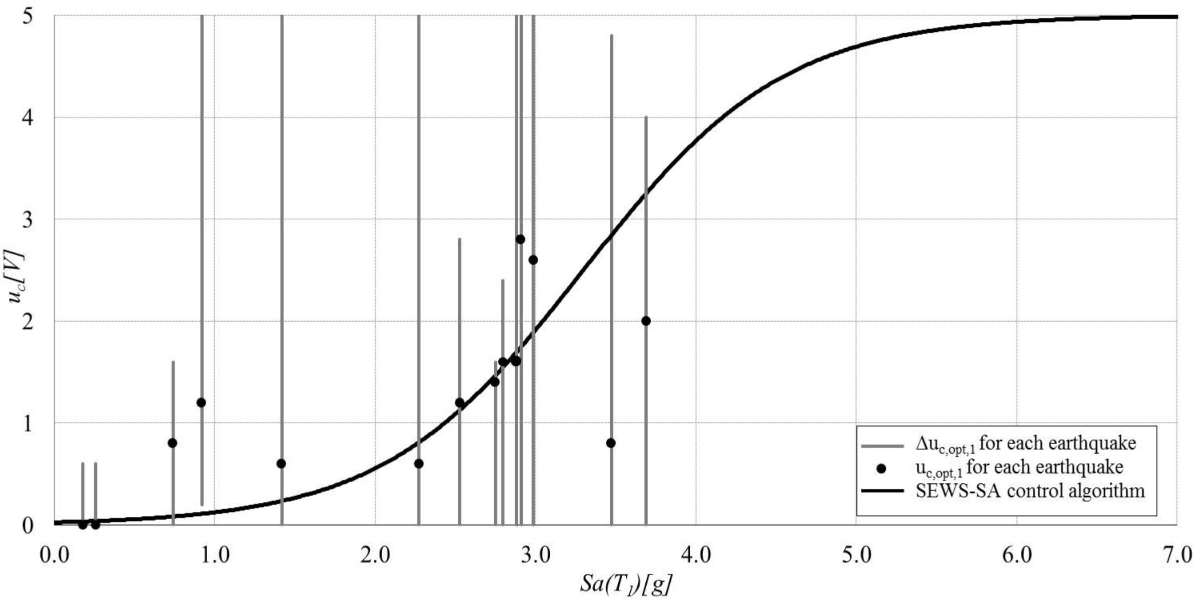

Figure 7. Values of $u_{c,opt,1}$ and of $\Delta u_{c,opt,1}$. Adopted control algorithm for Japanese earthquakes.

Starting from these results, three different control laws $u_c[S_a(T_1)]$ able to give, for each value of $S_a(T_1)$, a voltage intensity u_c as close as possible to the optimal value $u_{c,opt,1}$ or almost within the interval $\Delta u_{c,opt,1}$, have been founded (black line in Figs 5, 6 and 7).
The relationship is:

$$u_c\left[S_a(T_1)\right]=\left[1+tanh\left(\frac{S_a(T_1)-\alpha}{\beta}\right)\right]\cdot\frac{u_{c,max}}{2} \tag{1}$$

where α and β are two parameters (expressed in g, as the spectral acceleration S_a) governing the shape of the function, while $u_{c,max}$ represents the maximum voltage value.

The assumed values are:

- α =0.80, β =0.30, $u_{c,max}$=3 V for Italian region;
- α =0.65, β =0.19, $u_{c,max}$=3 V for Californian region;
- α =3.30, β =1.25, $u_{c,max}$=5 V for Japanese region.

As visible from the values of the assumed parameters, three completely different control algorithms have been funded. In the following, the proposed control strategy will be simply referred to as SEWS-SA.

Tables 4, 5 and 6 show the value of the bridge response parameters J_1 and J_2 obtained setting the MR devices by the three regional algorithms proposed. It is worth reminding that values of J_i greater than 1 correspond to performances of the controlled system worse that the uncontrolled ones.

The results are compared with that obtained using control strategies proposed in the benchmark and named passive, semi-active and active. Bold numbers indicate, for each earthquake, the best among the four strategies compared.

These results demonstrate the effectiveness of the proposed strategy for earthquakes with different characteristics as magnitudes and PGA. In particular, the SEWS-SA technique turned out to give results in many cases better than the one corresponding to the other strategies, in the remaining cases to comparable or slightly worse performances.

	J_1				J_2			
Earth.	*SEWS-SA*	*Passive*	*Semi-Active*	*Active*	*SEWS-SA*	*Passive*	*Semi-Active*	*Active*
#1	0.92	1.28	1.10	**0.88**	0.91	1.25	1.08	**0.86**
#2	**0.89**	0.94	0.81	0.89	0.73	**0.55**	0.81	0.89
#3	**0.72**	1.12	0.86	0.86	**0.49**	0.60	0.79	0.86
#4	**0.74**	0.81	0.81	0.83	**0.42**	0.63	0.81	0.83
#5	**0.87**	1.12	0.93	0.87	0.87	0.70	**0.70**	0.77
#6	**0.95**	1.31	1.08	0.97	0.92	1.03	0.85	**0.77**
#7	1.18	2.17	1.38	**1.14**	0.93	1.56	0.99	**0.83**
#8	1.09	2.05	1.20	**1.01**	0.99	1.31	0.79	**0.77**
#9	0.81	2.05	0.80	**0.74**	0.81	1.10	0.81	**0.75**
#10	1.16	1.09	1.03	**1.02**	1.13	1.17	1.00	**1.00**
#11	0.84	1.21	**0.77**	0.79	0.83	0.87	**0.77**	0.78
#12	1.05	0.88	1.08	**0.93**	0.93	0.95	0.95	**0.82**
#13	0.87	1.08	0.93	**0.87**	0.87	0.70	**0.70**	0.77
#14	**0.98**	1.12	1.00	0.98	**0.98**	1.25	1.00	0.98
#15	0.98	1.26	0.98	**0.92**	0.98	1.18	0.98	**0.92**

Table 4. Comparison of the four control strategies in terms of J_1 and J_2 for 15 Italian earthquakes

	J_1				J_2			
Earth.	SEWS-SA	Passive	Semi-Active	Active	SEWS-SA	Passive	Semi-Active	Active
#1	**0.72**	0.72	0.88	0.91	**0.69**	0.71	0.87	0.91
#2	0.81	0.91	**0.68**	0.76	0.81	0.93	**0.70**	0.75
#3	0.90	1.38	1.00	**0.89**	**0.89**	1.38	1.00	0.90
#4	0.88	0.95	**0.83**	0.90	0.88	0.96	**0.84**	0.90
#5	0.93	1.02	**0.83**	0.87	0.93	1.01	**0.83**	0.87
#6	**0.94**	1.13	0.96	1.03	1.05	**0.74**	0.87	0.90
#7	0.89	0.99	**0.87**	0.97	**0.92**	0.99	0.85	0.93
#8	1.00	1.13	1.15	**0.98**	1.00	1.15	1.20	**0.98**
#9	1.00	1.34	1.21	**0.84**	1.00	1.34	1.22	**0.84**
#10	0.80	0.77	**0.75**	0.76	0.75	**0.52**	0.70	0.74
#11	0.84	1.12	0.87	**0.82**	0.71	**0.55**	0.62	0.70
#12	0.81	0.87	0.76	**0.74**	0.80	0.85	0.75	**0.73**
#13	**0.81**	0.70	0.90	0.92	0.78	**0.68**	0.86	0.89
#14	0.89	0.96	0.87	**0.76**	0.89	0.96	0.87	**0.76**
#15	0.86	1.10	0.88	**0.78**	0.95	1.13	0.87	**0.90**

Table 5. Comparison of the four control strategies in terms of J_1 and J_2 for 15 Californian earthquakes

	J_1				J_2			
Earth.	SEWS-SA	Passive	Semi-Active	Active	SEWS-SA	Passive	Semi-Active	Active
#1	**0.77**	1.00	0.99	1.02	**0.64**	1.00	0.99	1.21
#2	**0.06**	1.00	1.00	1.00	**0.13**	1.00	1.00	1.00
#3	**0.90**	1.37	1.07	1.00	**0.90**	1.37	1.07	1.01
#4	**0.02**	1.00	1.00	1.02	**0.02**	1.00	1.04	1.00
#5	**0.72**	0.93	0.69	0.67	**0.72**	0.94	0.70	0.67
#6	**0.04**	1.00	1.00	1.00	**0.05**	0.99	1.00	1.00
#7	**0.04**	1.00	0.99	1.00	**0.05**	1.00	0.99	1.01
#8	**0.76**	0.93	0.76	0.71	**0.80**	0.93	0.75	0.72
#9	**0.94**	1.12	0.89	0.77	**0.95**	1.12	0.90	0.77
#10	**0.03**	1.00	0.99	1.01	**0.04**	1.00	1.00	1.01
#11	**0.06**	1.00	0.98	1.00	**0.09**	1.00	1.00	1.00
#12	**0.95**	1.00	0.96	0.95	**0.95**	1.00	0.96	0.95
#13	**0.85**	0.90	0.85	0.71	**0.85**	0.90	0.85	0.72
#14	**0.08**	0.99	0.99	1.00	**0.11**	0.99	1.00	1.00
#15	**0.97**	1.03	0.94	0.87	**0.81**	0.86	0.78	0.77

Table 6. Comparison of the four control strategies in terms of J_1 and J_2 for 15 Japanese earthquakes

Histograms in Figs. 8, 9 and 10 represent the SEWS-SA strategy in comparison with passive system. The latter is the more common and simple system present nowadays in the market and a victory against it, has been researched to validate the effectiveness of the strategy proposed.

The blue blocks indicate the number of times that SEWS-SA strategy reaches for J_1 and J_2 a value lower than the passive strategy. The gray-lines blocks indicate the number of times that the passive strategy reaches for J_1 and J_2 a value lower than the SEWS-SA strategy. For both technologies, the pointed block represents the number of times that is overpassed the limit equal to 1.00. As visible the proposed strategy, considering a combination of the semi-active control with seismic early warning system, results to be more effective in a largest number of cases.

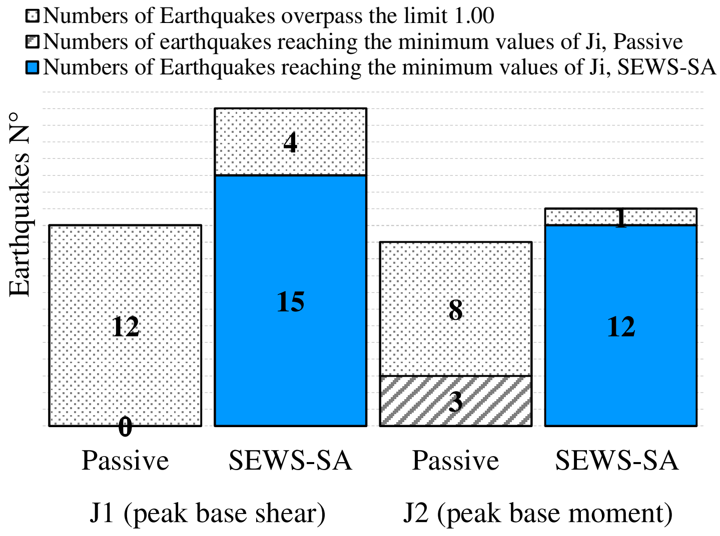

Figure 8. Comparison between Passive and SEWS-SA strategies in terms of J_1 and J_2 , Italy.

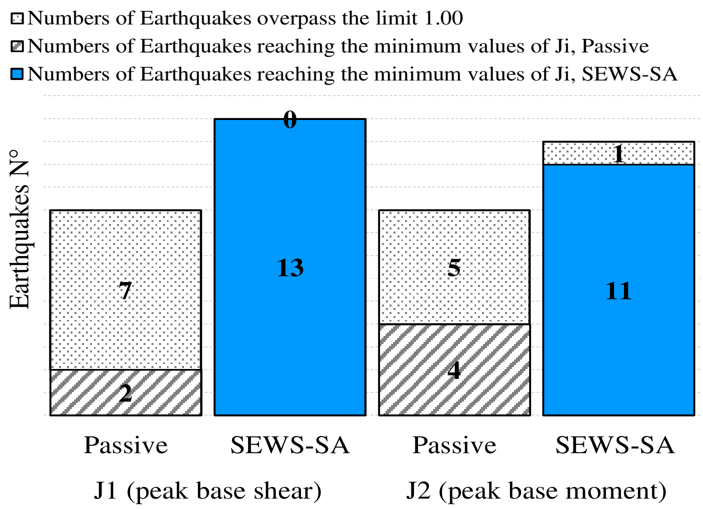

Figure 9. Comparison between Passive and SEWS-SA strategies in terms of J_1 and J_2 , California.

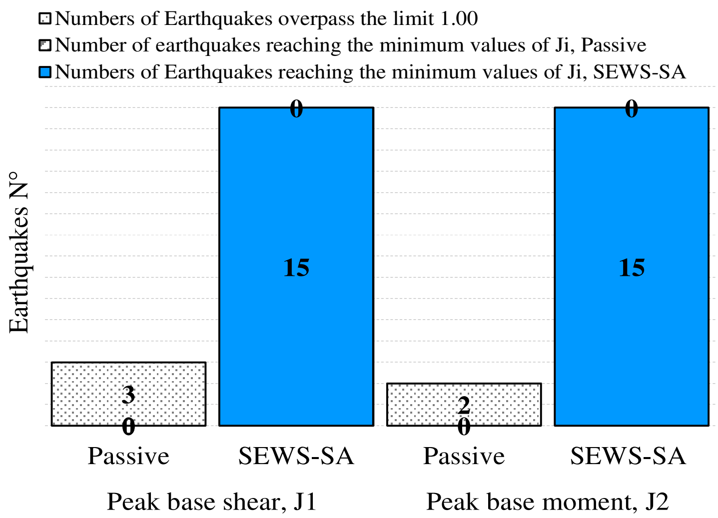

Figure 10. Comparison between Passive and SEWS-SA strategies in terms of J_1 and J_2 , Japan.

6 CONCLUSIONS

The present paper describes a methodology for exploiting earthquake information derived by a seismic early warning system (SEWS) in the framework of semi-active control strategies by using magnetorheological (MR) dampers. It represents an enhanced version of the one proposed in Maddaloni et al. [7, 9]. The main idea consists in changing the behaviour of MR dampers installed on the hosting structure, according to an anticipate estimate, provided by the SEWS, of the PGA of an incoming earthquake. The PGA value is adopted to build the elastic acceleration spectrum according to the Eurocode 8 rules [18]. Then, the spectral acceleration evaluated at the fundamental period of the structure is used to set the optimal voltage in the MR devices. The paper describes the application of this innovative and integrated protection technique to a case-study highway bridge located in Southern California. In this paper, is presented a regional-based control algorithms, i.e. a different relationship u_c(PGA) for each one of three world regions selected (Italy, California and Japan). The proposed strategy is investigated by several numerical simulations, considering a total of forty-five strong real earthquakes, fifteen for each region.

The results demonstrate that the effectiveness of the proposed idea enhances when an appropriate regional algorithm, i.e. a different relationship u_c(PGA) for each world regions selected (Italy, California and Japan), is considered. The SEWS-SA technique turned out to give results sometimes better and sometimes comparable to other consolidated strategies as a fraction of the cost. Only in few cases the numerical analyses yielded slightly worse performances.

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