COMPDYN 2013
4th ECCOMAS Thematic Conference on
Computational Methods in Structural Dynamics and Earthquake Engineering
M. Papadrakakis, V. Papadopoulos, V. Plevris (eds.)
Kos Island, Greece, 12–14 June 2013

EFFECTIVENESS AND ROBUSTNESS OF A SEMI-ACTIVE CONTROL STRATEGY BASED ON SEISMIC EARLY WARNING INFORMATION

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Keywords: Seismic early warning, semi-active control, earthquake forecasting, smart materials, dissipative devices.

Abstract. *A smart passive control strategy is herein investigated to protect seismically excited structures. It is based on the use of seismic early warning information to optimally calibrate variable dampers for an higher reduction of the structural response. In particular, the adoption of magnetorheological dampers calibrated according to the forecasted value of the seismic peak ground acceleration is proposed. Such variation of the devices' behavior is supposed to be commanded once few seconds before the earthquake actually arrives to strike the site and to be kept constant for the whole duration of the excitation.*

The effectiveness of such control technique is demonstrated with reference to a case-study structure consisting in a highway bridge located in Southern California. Several nonlinear time-history analyses using seismic registrations of natural events very different each other for magnitude, peak ground acceleration, and soil types have been performed. The results in terms of reduction in seismic demand are further compared with those other control techniques from literature, applied to the same structure, lead to.

The final part of the paper is dedicated to evaluate if and how possible errors related to the peak ground acceleration estimate may affect the efficacy of the proposed strategy in reducing structural response.

The control technique resulted to be promising for the ease of implementation for structures already served by a seismic early warning network, effectiveness, even compared with active control systems, and robustness.

1 INTRODUCTION

In the last decades, installation and use of seismic early warning systems (SEWS) to help communities in being more resilient regard earthquakes attacks are growing worldwide. Starting from the Japanese experience [1], this technology has been applied in Mexico [2], in Taiwan [3], and, more recently, also in Romania [4], Turkey [5], and Italy [6]. Many kinds of application of such innovative systems can be developed, all being based on a particular exploitation of early information to take decisions for protecting people and objects against severe earthquakes.

Recent studies [7-10] showed that a quite accurate estimate of the incoming earthquake intensity is nowadays possible in terms of ground motion peak indexes, i.e. the peak ground acceleration (PGA) and velocity (PGV). Such early information can be exploited to smartly control earthquake induced vibrations by optimally calibrating special, adjustable devices installed in the structure to be protected. Kanda et al. [11] firstly explored this kind application, proposing a structural control algorithm based on the estimate of the spectral characteristics of the arriving event. In the last decade authors of this paper made efforts to contribute to the development of such integrated seismic protection system [12-16], considering it really promising, especially for structures located in seismic zones already served by an early warning network. They promoted the passive smart use of variable dissipating devices. According to this idea, mechanical properties of adjustable dampers are set just before the arrive of a seismic event at the site, as a function of the estimate of an intensity measure of the incoming earthquake, as provided by a SEWS serving the area where the structure is located. This adjustment is supposed to happen only once, keeping unaltered the devices’ behaviour for the whole duration of the seismic excitation. Energy dampers based on magnetorheological (MR) fluids are considered. They may reliably change their dissipative capacity by order of magnitudes through low intensity currents fed into the devices, with reaction times comfortably bounded to 10 milliseconds, including trigger and set up times [17-19]. Therefore they are suitable to adopt in control systems exploiting SEWS, even at sites where the early warning leading time is extremely short (less than 1 second).

This idea is herein applied to a case-study consisting in a two-span continuous pre-stressed concrete highway bridge located in California, USA (details about this structure can be found in [20]. Each span is 58.5 m long. Abutments are present at the ends of the bridge, whereas the central support is provided by a 31.4 m long pre-stressed beam which rests on two columns approximately 6.9 m high. The width of the deck is 12.95 m. The total mass of the bridge is about 4200 tons; the mass of the deck is about 3200 tons (Fig. 1).

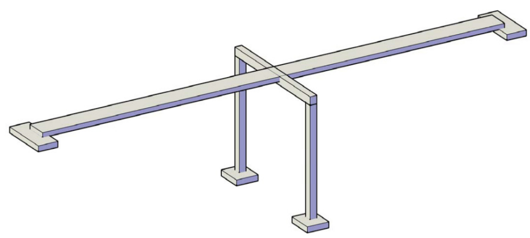

Figure 1: Schematic representation of the bridge.

The reference structure (hereafter referred to as “uncontrolled”) corresponds to a non linear numerical model of the bridge including an isolation system made up of four lead rubber bearings (LRBs) at each deck-end and two LRBs at central support. At this regard note that the bridge, for its configuration, 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 at false results [21].

The first six vibration periods results to 0.813 s (torsional shaped mode), 0.781 s (torsional/vertical), 0.645 s (vertical), 0.592 s (transverse), 0.565 s (vertical), 0.307 s (transverse). In the benchmark paper [20, 22, 23] three seismic upgrade alternatives are considered (passive, active, and semi-active, respectively) by introducing 16 devices between the deck and the abutments (nonlinear viscous dampers, hydraulic actuators, and magnetorheological – MR – dampers for the three control strategies, respectively). The performance of these techniques measured in terms of response reduction they lead to are herein compared with that of the proposed control strategy.

2 SMART PASSIVE VIBRATION CONTROL USING A SEWS

The use of MR dampers as smart passive devices is suggested herein to effectively control the case-study bridge under earthquake actions. The mechanical behaviour of such devices is considered to be adjusted once, shortly before the incoming earthquake, according to a forecasted intensity measure of the latter provided by a SEWS available at the site. Regarding the way to use SEWS information to calibrate the semi-active (SA) devices, the following procedure is proposed: (i) Modal analysis of the structure and foundation soil investigations are performed; (ii) once the SEWS provides an estimate of the PGA of an incoming earthquake, the elastic damped response spectrum according to the Eurocode 8 rules has to be defined; (iii) the spectral acceleration $S_a(T_1)$ is evaluated at the fundamental period of the bridge; (iv) this value is exploited to set the voltage u_c to be given to MR dampers within a given interval $0\sim u_{c,max}$ (herein $u_{c,max}$ is assumed to be 10 V), according to a control algorithm $u_c(S_a)$ so as to obtain the higher reduction of the structural response during the seismic excitation.

It is worth noting that the effectiveness of the proposed strategy is strongly dependent on the ability of the control algorithm to drive MR dampers to be the optimal “passive” devices for the expected seismic action. A possible way to calibrate such control logic is presented in the following with reference to the case-study assumed. This procedure is based on the results of several nonlinear time-history analyses performed under natural accelerograms very different each other, testing a wide variety of configurations (i.e. values of feeding voltage) for the MR dampers, and measuring the achieved response reduction via the adoption of specific performance indexes.

2.1 Case-study structure: definition of the control algorithm to drive MR dampers

A total of sixteen natural earthquakes (Table 1) have been considered to calibrate the control logic needed to control the MR dampers’ behavior for the case-study bridge as a function of the information (expected PGA) given by the SEWS about the incoming seismic event. The last six earthquakes as listed in Table 1 are those proposed in the benchmark paper [20, 22, 23]. The ten additional events have been chosen to cover a wider range of moment magnitudes (5.75 to 7.62), PGA values (0.151 to 1.157 g) and soil types (A to C, according to the Eurocode 8 [24] definition).

The effectiveness of the control strategies proposed for the bridge is herein measured through three performance indexes named J_i (i=1, 2, 3). They refer to the ratio of the values different response parameters assume in the controlled and in the uncontrolled conditions respectively (so that smaller values of J_i correspond to an higher reduction of the structural response). These indexes refer to the peak shear force at the base of the piers, the peak overturning moment in the same sections, and the peak mid-span displacement for the deck respectively. Authors acknowledge that many other criteria could be adopted to compare alternative upgrade strategies for the bridge [20, 22, 23]. Nevertheless the adoption of multi-criteria decision procedure [25], mandatory to make a summary judgment when an high number of criteria is involved, is beyond the scope of this work.

N.	Earthquake	Country	Year	M_w	PGA EW / NS [g]	Soil type
1	Coyote Lake	California	1979	5.75	0.434 / 0.316	B
2	Friuli	Italy	1976	6.50	0.351 / 0.315	B
3	Northwest	China	1997	6.10	0.300 / 0.274	C
4	Irpinia	Italy	1980	6.90	0.358 / 0.251	B
5	Corinth	Greece	1981	6.60	0.240 / 0.296	C
6	San Salvador	El Salvador	1986	5.80	0.406 / 0.612	C
7	San Fernando	California	1971	6.61	0.324 / 0.268	B
8	Duzce	Turkey	1999	7.14	0.728 / 0.822	C
9	Taiwan	Taiwan	1986	7.30	0.242 / 0.160	C
10	Trinidad	Colorado	1980	7.20	0.156 / 0.151	A
11	Kobe	Japan	1995	6.90	0.503 / 0.509	C
12	Northridge	California	1994	6.69	0.472 / 0.838	B
13	Chi-Chi	Taiwan	1999	7.62	0.417 / 1.157	B
14	El Centro	California	1940	6.91	0.313 / 0.215	C
15	Izmit	Turkey	1999	7.60	0.728 / 0.822	B
16	North Palm S.	California	1986	6.10	0.612 / 0.492	C

Table 1: Main properties of the earthquakes assumed for the analyses.

Several nonlinear analyses of the bridge have been made, under each of the 16 selected earthquakes, each time feeding the MR devices with a different voltage value, keeping it constant for the overall duration of the motion. In particular, command voltage values u_c from 0 to 10 V with a step size of 25 mV have been assumed, for a total of 6416 analyses. For each of these, the following operations have been done:

a) the values of the performance indexes J_i (with i=1, 2, 3) have been recorded as measures of the structural response under a given earthquake and for a certain calibration of the variable control devices;

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

c) for each of these cases, the optimal value of voltage $u_{c,opt,i}$ (i.e. the one leads to the minimum value $J_{i,min}$ of J_i) has been found; then an interval of suggested voltage values $\Delta_{uc,opt,i}$ around $u_{c,opt,i}$ has been defined including all the u_c values corresponding to values of J_i less than $1.3J_{i,min}$ (i.e. assuming a tolerance of 30% in terms of structural performance) and also less than 1 (Fig. 2).

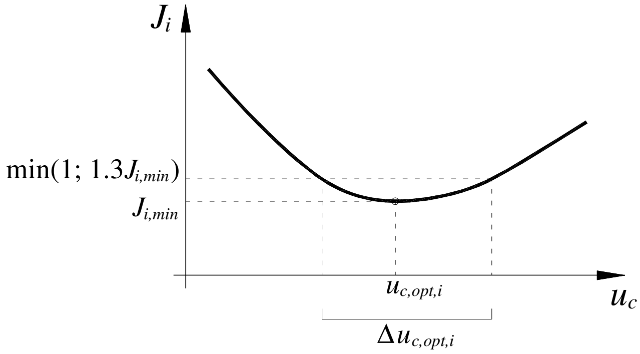

Figure 2: Definition of the optimal interval $\Delta_{uc,opt,i}$ of voltage for MR devices according to the i-th criterion.

Intervals $\Delta_{uc,opt,1}$, $\Delta_{uc,opt,2}$ and $\Delta_{uc,opt,3}$ in most cases resulted to be quite similar each other, obviously referred to the same seismic event. For the sake of brevity only intervals $\Delta_{uc,opt,2}$ (i.e. related to the index J_2, proportional to the peak base moment demand) are shown herein. Fig. 3 reports 16 vertical gray lines, each one having as abscissa the value $S_a(T_1)$ corresponding to one of the considered earthquakes, and as ordinates the interval $\Delta_{uc,opt,2}$ in which the command voltage for MR dampers should be chosen for a higher reduction of the structural response (measured by J_2) under the action of that seismic event. The black points represent the "best" value (namely $u_{c,opt,2}$) of the interval. In the paper, for each earthquake, the PGA value refers to the EW component (preliminarily chosen as the most significant for the present case).

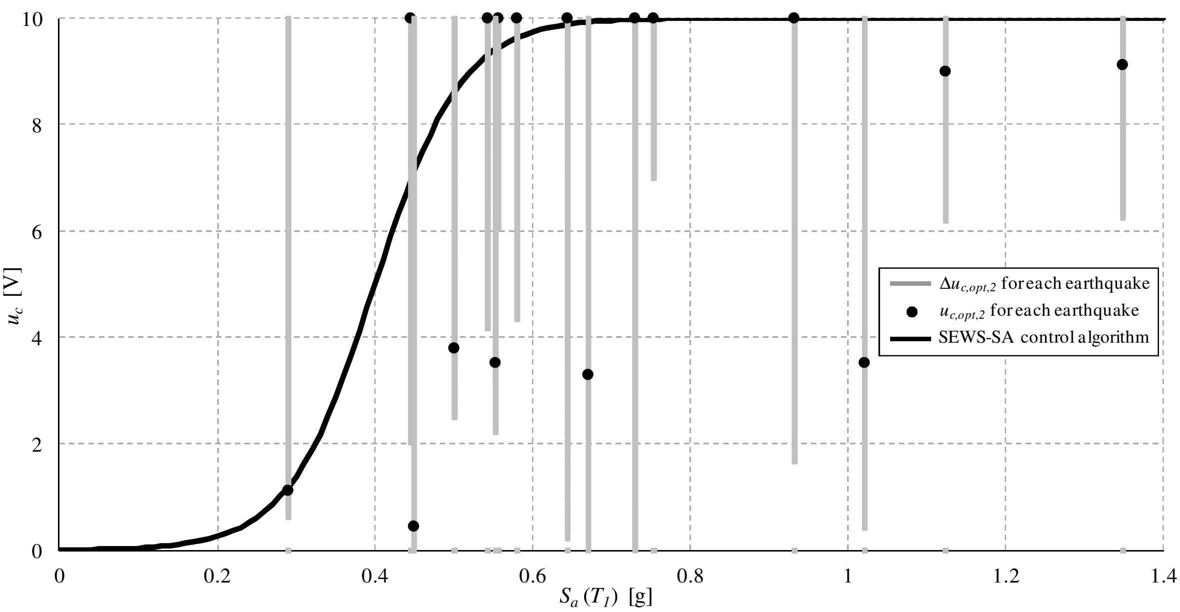

Figure 3: Values of $u_{c,opt,2}$ and of $\Delta_{uc,opt,2}$. Adopted control algorithm.

Starting from these results, a continuous control law $u_c[S_a(T_1)]$ able to give, for each value of $S_a(T_1)$, a voltage intensity u_c within the corresponding interval $\Delta_{uc,opt,2}$, as close as possible to the optimal value $u_{c,opt,2}$, has been investigated. The following relationship resulted to be a viable candidate, giving values of u_c tending to 0 V for small values of S_a, values tending to $u_{c,max}$=10 V for higher values of spectral acceleration:

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

where α and β are two parameters (to be expressed in g – gravitational acceleration – as the spectral acceleration S_a) governing the shape of this monotonically increasing function. Values of α and β within the intervals 0.00~2.00 g and 0.01~0.50 g (with a step of 0.01 g) make the shape of the curve have a physical sense. The optimal value for α (0.40) and β (0.11) has been individuated among those allow the curve representing Eq. (1) to cross all the sixteen gray lines in Fig 3 as the one corresponding to the higher reduction of the structural response measured by J_1, J_2 and J_3. The resulting algorithm is herein proposed to semi-actively control the bridge by exploiting seismic early warning information (in the following this strategy will be referred to as SEWS-SA). It is graphically represented in Fig. 3 with a black line.

2.2 Effectiveness of the proposed control strategy

Table 2 shows the value of response parameters J_1, J_2 and J_3 the proposed strategy and the benchmark ones leaded to with reference to the 16 seismic inputs. Bold numbers indicate, for each earthquake, the best performance among those due to the different strategies. The same data are represented for an easier comparison in graphical form in Figs. 4 and 5.

These results demonstrate the effectiveness of the proposed strategy for earthquakes with different characteristics as magnitudes, PGA and soil types. In particular, the SEWS-SA technique turned out to give results in many cases better than the ones corresponding to the other strategies, in the remaining cases to comparable or slightly worse performances. Pie charts in Fig. 5 report the number of times (out of 16) each technique outperforms all others in terms of J_1, J_2 and J_3 separately. Information synthesized in this figure allow to conclude that the proposed strategy results to be more effective in a largest number of cases (34 out of 48 considering J_1, J_2 and J_3 together). This conclusion is furthermore emphasized by Table 3 that reports the mean values of J_1, J_2 and J_3 each control technique leads to with reference to the set of 16 seismic inputs. It shows how the proposed strategy on average gives a reduction of the peak base shear very close to the one corresponding to the other compared techniques, leading instead to significantly better results in terms of base moment and mid-span displacement.

Earthquake	J_1				J_2				J_3			
	SEWS-SA	Passive	Semi-Active	Active	SEWS-SA	Passive	Semi-Active	Active	SEWS-SA	Passive	Semi-Active	Active
1	**0.83**	0.83	0.93	0.94	**0.81**	0.82	0.93	0.94	0.74	**0.73**	0.81	0.82
2	0.81	**0.67**	0.74	0.73	**0.47**	0.58	0.72	0.73	**0.3**	0.59	0.74	0.72
3	**0.50**	0.61	0.82	0.84	**0.24**	0.53	0.72	0.74	**0.22**	0.60	0.79	0.80
4	0.87	**0.75**	0.86	0.95	**0.44**	0.62	0.87	0.96	**0.29**	0.61	0.88	0.97
5	0.92	**0.83**	0.83	0.86	**0.51**	0.62	0.82	0.85	**0.32**	0.62	0.83	0.85
6	**0.53**	0.77	0.94	0.93	**0.55**	0.81	0.98	0.98	**0.41**	0.61	0.75	0.75
7	0.87	0.77	**0.75**	0.76	**0.47**	0.52	0.70	0.74	**0.31**	0.55	0.75	0.76
8	0.96	**0.79**	0.91	0.92	**0.57**	0.89	0.98	0.99	**0.35**	0.59	0.73	0.76
9	0.92	0.98	0.96	**0.90**	**0.67**	0.70	0.69	0.80	**0.45**	0.53	0.67	0.78
10	0.90	0.94	0.76	**0.70**	**0.53**	0.55	0.65	0.70	0.51	**0.41**	0.66	0.70
11	1.06	0.86	0.81	**0.79**	**0.53**	0.54	0.69	0.71	**0.57**	0.62	0.69	0.71
12	**0.68**	0.78	0.9	0.91	**0.93**	0.96	0.98	0.98	**0.54**	0.70	0.86	0.88
13	**0.68**	0.76	0.85	0.88	**0.93**	0.97	0.98	0.98	**0.54**	0.71	0.78	0.81
14	0.68	**0.64**	0.80	0.79	**0.37**	0.57	0.72	0.76	**0.29**	0.65	0.79	0.78
15	0.97	**0.78**	0.91	0.93	**0.57**	0.88	0.98	0.99	**0.35**	0.59	0.73	0.76
16	1.67	1.26	**0.98**	0.98	0.86	**0.65**	0.78	0.78	**0.57**	0.64	0.82	0.83

Table 2: Comparison of the response reduction given by the four control strategies for the sixteen earthquakes considered

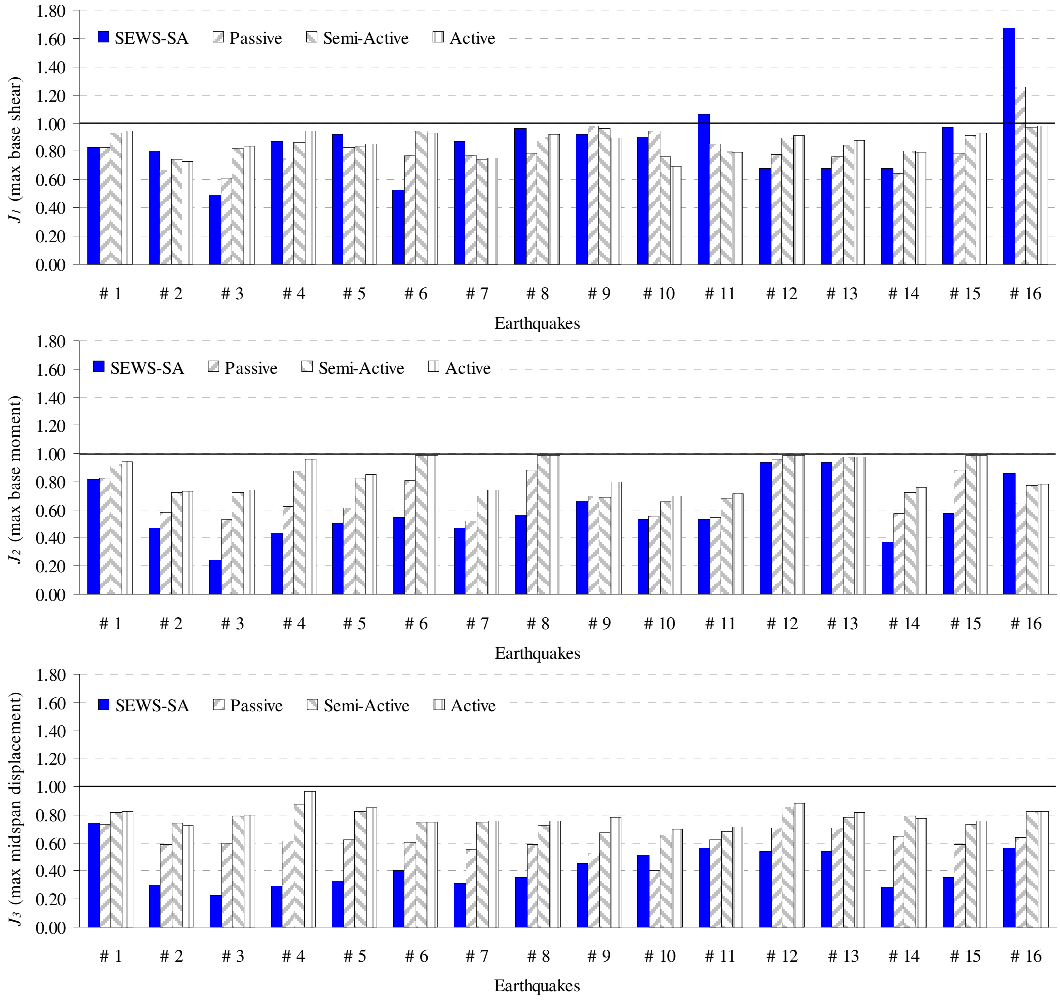

Figure 4: Comparison of the four control strategies in terms of J_1, J_2 and J_3, for each of the 16 earthquakes.

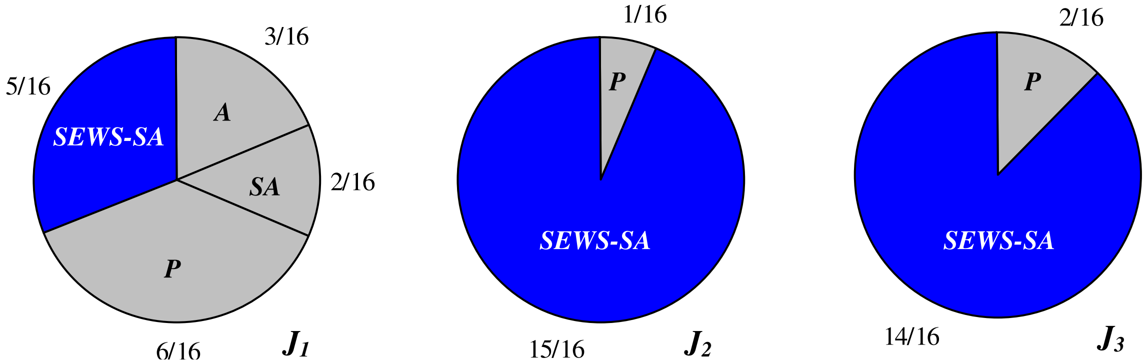

Figure 5: Number of times, out of the 16 cases, each strategy outperforms all others in terms of J_1, J_2 and J_3. "SEWS-SA": proposed strategy, "A": active, "SA": semi-active, "P": passive.

	SEWS--SA	Passive	Semi-Active	Active
mean J_1	0.87	0.81	0.86	0.86
mean J_2	0.59	0.70	0.83	0.85
mean J_3	0.42	0.61	0.77	0.79

Table 3: Mean values of performance indexes for the overall comparison of the four alternative control strategies

2.3 Robustness of the proposed control strategy. Role of SEWS uncertainties.

The sensitivity of the proposed SEWS-SA control algorithm (Eq. 1) to uncertainties in the estimate of PGA is analyzed as follows. The MR devices are calibrated as already explained in the previous sections but using a range of physical PGA values from a minimum of 0 g to a maximum of 2 g, considering that the PGA value estimated by SEWS (PGA_{SEWS}) can be even very different from the actual value (PGA_{ACTUAL}) due to a wrong estimation analysis.

As the PGA_{SEWS} value changes, MR are calibrated in a different manner according to the proposed control algorithm so as to modify the structural response even if the exciting earthquake (i.e. the real one) is the same. In this case, each of the performance indexes J_i can be intended as a function of the random variable PGA_{SEWS}. Fig. 6 shows the domain of values of J_1 for any given earthquake record when the algorithm driving the MR dampers is fed by a value of PGA_{SEWS} variable in the range 0~2 g, independently from the actual PGA value of that event. The circles indicate the values of index J_1 obtained from nonlinear analyses performed correctly setting the devices according to the proper estimate PGA_{ACTUAL}. For some earthquakes, J_1 appears to be very low sensitive to the value of PGA predicted (short lines). In other cases, its variation becomes more significant (longer lines). It is worth noting that in most cases the range of J_1 values due to the incorrect prediction of the PGA by the SEWS corresponds to a worst performance, but only in a very limited number of cases leads to values higher than 1. Finally, for each earthquake J_1 values corresponding to MR dampers turned off are also indicated in the same figure with a square, simulating black-out conditions. A fail-safe behavior of the proposed strategy can be easily drawn from the figure.

Similar results have been obtained with reference to J_2 and J_3 indexes, herein not reported for brevity.

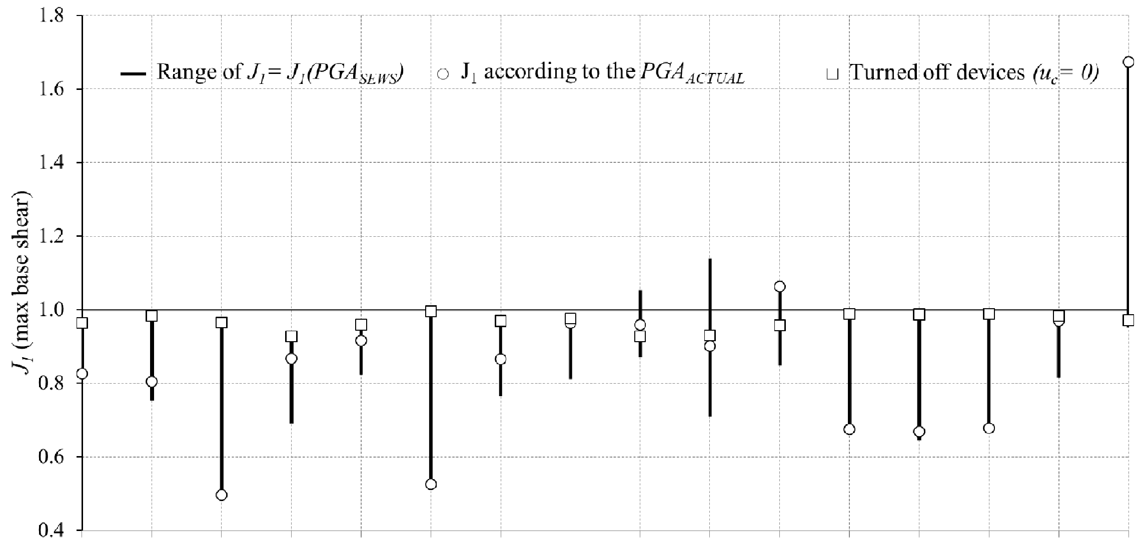

Figure 6. Seismic response of the bridge in terms of J_1 for PGA values given within 0~2g

To further assess the robustness of the proposed control strategy, the joint probability distribution of J_i (for i=1, 2, 3) has been evaluated starting from a given probability distribution for PGA. The latter has been assumed to be lognormal with a mean value equal to PGA_{ACTUAL} and coefficient of variation (CoV) equal to 0.45 (Fig. 7 shows the plot of the probability density function - PDF), according to the indications by Iervolino et al. [26].

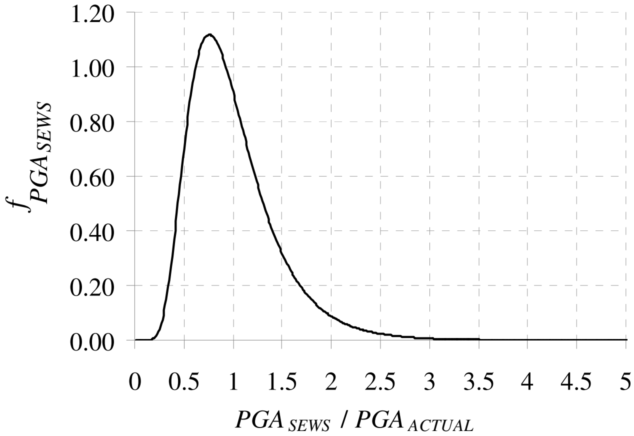

Figure 7. Lognormal PDF of PGA_{SEWS} with mean PGA_{ACTUAL} and CoV 0.45

For each earthquake and each performance index J_i the following steps have been performed: (i) the finite interval of PGA_{SEWS} values 0.01~2.00 g have been considered; this is sub-divided using a step size of 0.01 g; (ii) for each discrete value of PGA_{SEWS}, the probability mass value has been evaluated starting from the knowledge of the continuous PDF said above; in other words the transformation of the PDF into the PMF (probability mass function) of PGA_{SEWS} has been performed; (iii) for each discrete value of PGA_{SEWS}, the corresponding J_i value has been obtained; (iv) since the transformation J_i=J_i(PGA_{SEWS}) resulted to be not a one-to-one mapping, for a given j_i value of J_i let $PGA_{SEWS,k}$ (k=1, 2, …, m) represent the roots of the equation $J_i(PGA_{SEWS})=j_i$; then the probability of the event $J_i=j_i$ is obtained by adding the probability of PGA_{SEWS} at all the roots:

$$p_{Ji}(j_i) = \sum_{k=1}^{m} p_{PGA_{SEWS}}\left(PGA_{SEWS,k}\right) \tag{2}$$

This analysis has been performed with reference to J_1, J_2 and J_3, leading to similar results in terms of PMF shape and values. Outcomes for J_1 are shown in Fig. 8. The J_1 value corresponding to PGA_{ACTUAL} is individuated, within the range of values (i.e. vertical black lines), by a small white circle, as in Figure 10. Horizontal gray lines are the probability histograms of J_1. The following comments can be drawn:

- the $J_1(PGA_{ACTUAL})$ value resulted to be the most likely for the large majority of cases (15 out of 16 earthquakes), with a mass probability value ranging from 48% to 97% depending on the considered seismic action (earthquake #10 is the exception; for this, probability values resulted to be slightly scattered around the 10% value for each possible J_1 outcome);
- probability values for J_1 different from $J_1(PGA_{ACTUAL})$ generally are strongly reduced compared to the latter.

These results allow to confirm that unavoidable errors in the PGA estimates provided by the SEWS do not propagate to the seismic response. Conversely, the proposed strategy turns out to be able to damp these errors, resulting in a robust seismic behaviour of the protected structure.

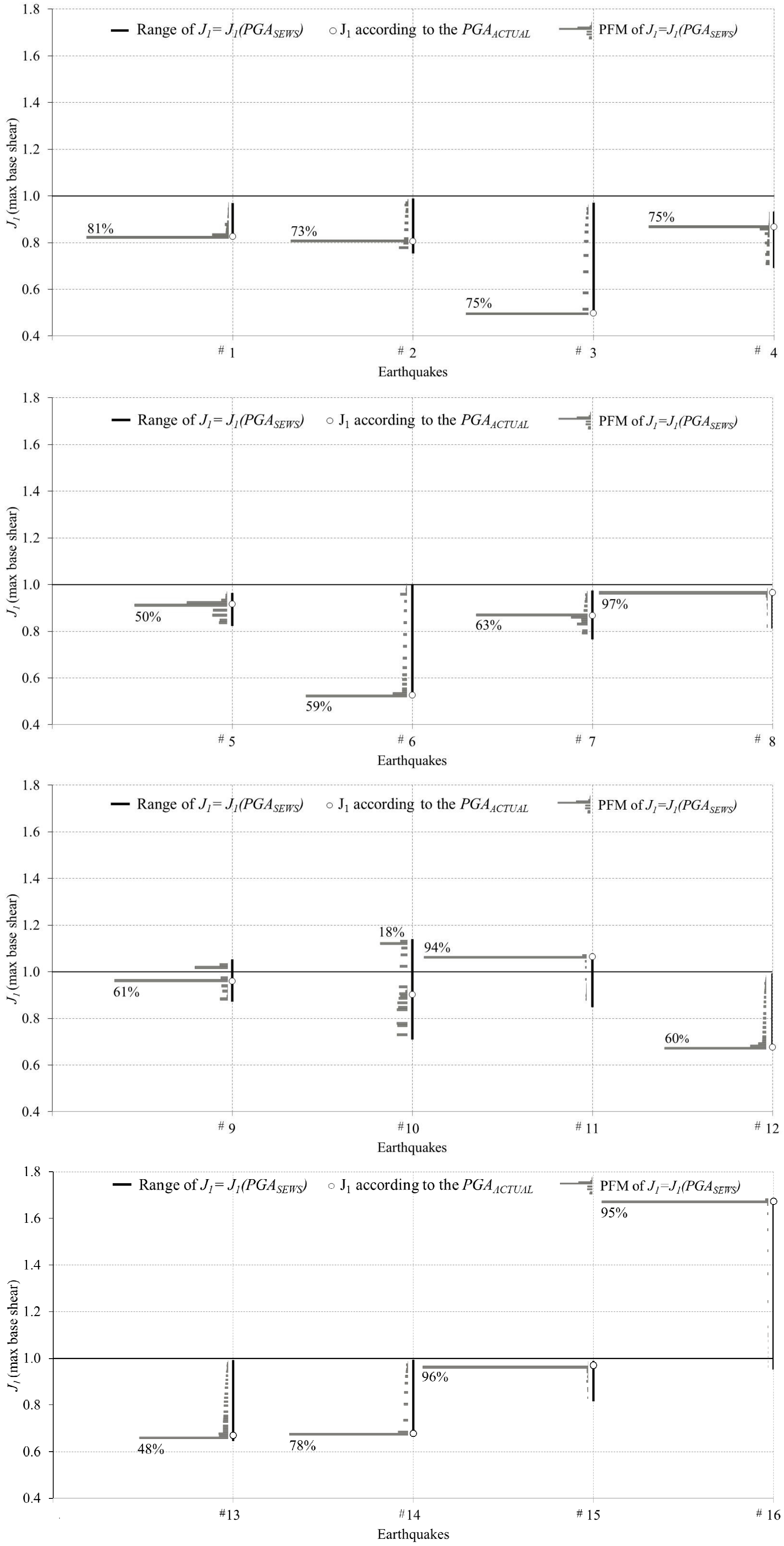

Figure 8. PMF of $J_1(PGA_{SEWS})$

3 CONCLUSIONS

A possible 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 has been herein proposed. This system has a relatively simple, yet effective, objective. Starting from an existing SEWS, in addition to its standard feature of emitting a warning message, authors proposes to exploit the system so as to utilize it to optimize the structural response of a structure, without any additional sensor and by the adoption of passive, but smart (adjustable) damping devices.

The present paper describes the application of this innovative and integrated protection technique to a case-study highway bridge located in Southern California. The seismic response of the benchmark bridge is investigated by nonlinear time-history analyses under 16 real earthquake ground excitations covering a wide variety of magnitudes, PGA and soil types.

The research on seismic early warning is recently going in the direction so to make a SEWS capable to quickly give reliable estimate of many features of the incoming earthquake. Herein the prediction of the PGA value is assumed to be available. A fast forecast of the PGA at a given site starting from an estimate of typical intensity measures, like for instance the magnitude, actually seems to be quite a mature subject [7-10] 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 [27].

Several trials and simulations have been performed to define the control algorithm, i.e. relationship useful to determine the optimal amount of voltage to be given to the dampers according to the spectral acceleration evaluated at the fundamental period of the structure, in turn defined starting from the forecasted PGA value.

The results demonstrate the effectiveness of the proposed strategy for earthquakes very different each other. In particular, the SEWS-SA technique turned out to give results sometimes better and sometimes comparable to other consolidated strategies at a fraction of the cost. Only in few cases the numerical analyses yielded slightly worse performances.

Possible errors on estimation of PGA provided by SEWS and their influence on the effectiveness of the proposed control system have been also discussed. The results obtained confirm that unavoidable errors in the PGA estimates provided by the SEWS do not propagate to the seismic response of the controlled structure. Conversely, the proposed strategy turns out to damp these errors, resulting in a robust seismic behaviour of the protected structure.

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