Use of Seismic Early Warning Information to Calibrate Variable Dampers for Structural Control of a Highway Bridge: Evaluation of the System Robustness

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SUMMARY
The seismic events occurred in recent years have highlighted the extreme vulnerability of a large part of existing constructed facilities and the need to adopt innovative solutions to improve their seismic performances. With this purpose, the possible exploitation of a seismic early warning system (SEWS) in the framework of semi-active (SA) structural control based on magnetorheological (MR) dampers is herein investigated. The main idea consists in changing the MR damper behavior according to an anticipate estimate, provided by the SEWS, of the peak ground acceleration (PGA) for an incoming earthquake. The adjustment is supposed to happen only once, just before the quake strikes. The application to a case-study problem (i.e. a highway bridge located in southern California) is shown, also allowing to assess the robustness of the proposed protection technique. Possible errors on estimation of PGA provided by SEWS and the way they affect the effectiveness of the control strategy are discussed.

Keywords: seismic early warning system, magnetorheological damper, semi-active structural control, system robustness.

1. INTRODUCTION

Seismic early warning systems (SEWS) can be used to prevent devastating damages, by the knowledge, ahead of time, of the event that is occurring. The original front-detection early warning scheme was made up of seismic stations surrounding a specific site at a given distance. At the occurrence of an earthquake, the stations are assumed able to detect the seismic waves and to release an alarm to the site management. The higher speed of electromagnetic signals compared to the seismic waves leaves a tight margin – lead time – which can be used to stop or to put in a safe mode a plant.
Recent studies on SEWS have shown that the analysis of the first seismic waves (P-waves) can lead to a quite accurate estimate of different intensity measures for the incoming earthquake, like peak ground acceleration (PGA) (Iervolino et al. 2008) and peak ground velocities (PGV) (Zollo et al. 2009). The possibility of exploiting the anticipate estimate of these measures to enhance the performance of a structural control system was firstly envisioned by Kanda et al. (1994). Occhiuzzi et al. (2006) proposed a simplified approach to combine the possibilities of SEWS with the flexibility of smart devices, added to a structure and able to quickly change their dynamic properties.
The present paper describes how this concept can be conveniently exploited to protect a highway bridge in areas where a SEWS is available (Occhiuzzi et al. 2008a, 2008b; Maddaloni et al. 2011). In particular, the possible exploitation of a SEWS in the framework of semi-active (SA) structural control by using magnetorheological (MR) dampers is investigated. Such a control system is based on a complex and emerging technology for seismic protection of civil structures, able to interact in real time with the structure during an earthquake. The main idea of this work consists in changing the MR damper behavior according to an anticipate estimate, provided by the SEWS, of the PGA of an incoming earthquake. In this case, the SA structural control framework becomes quite simple and it is based on the possibility to change only once the mechanical properties of passive, but smart, additional damping devices shortly before the arrival of the seismic event at the site.

The application of this protection technique to a case-study problem is presented. The reference structure is the one of the "highway bridge benchmark framework" proposed by Agrawal et al. (2009) to directly compare the amount of seismic protection corresponding to different control strategies.

2. THE BENCHMARK BRIDGE

The highway bridge is located in Orange County of Southern California. A brief description of the bridge and of its model are herein presented, whereas a detailed description can be found in (Agrawal et al. 2009). The superstructure of the bridge consists of a two-span continuous cast-in-situ pre-stressed concrete. Each span is 58.5 m long, spanning a four-lane highway, with two skewed abutments. 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. 2.1).

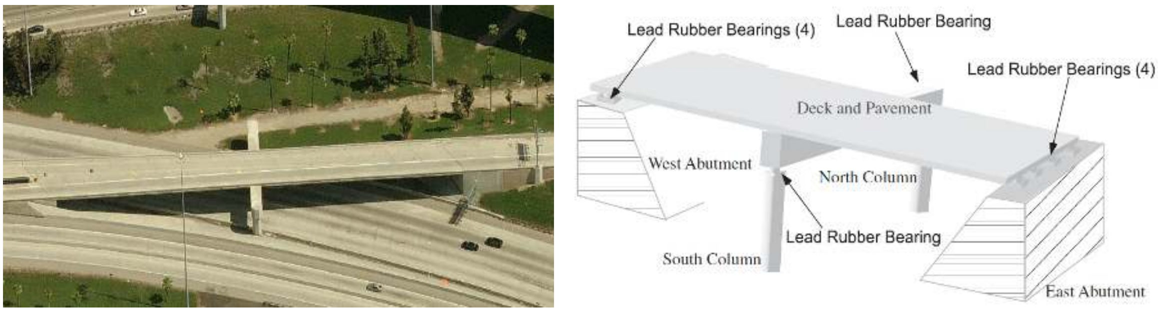

Figure 2.1. The benchmark highway bridge

The uncontrolled structure, used as a basis of comparison to quantify the effectiveness of various control systems, corresponds to a 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.
The dynamic characterization of the bridge in the linear range is as follows. The first mode of uncontrolled bridge is torsional with a natural period of T_1=0.813 s. The second mode is torsional coupled with vertical (period T_2=0.781 s). The third and fourth modes are vertical and transverse, respectively with periods T_3=0.645 s and T_4=0.592 s; the fifth and sixth modes are vertical and transverse with periods respectively equal to T_5=0.565 s and T_6=0.307 s (Fig. 2.2).

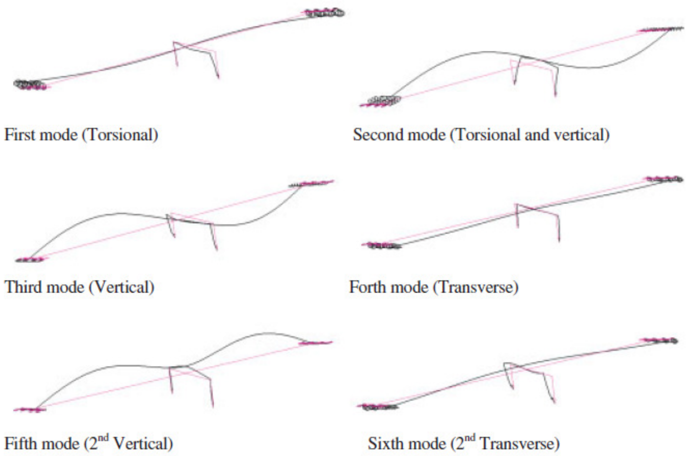

Figure 2.2. The first six modal shapes of the bridge

In the benchmark paper (Agrawal et al. 2009), the bridge is supposed to be upgraded to reduce the seismic response. Three types of sample control strategies, namely passive, active and semi-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, working according to the H_2/LQG control algorithm. The semi-active strategy is based on 16 MR dampers modeled according to the Bouc–Wen hysteretic model.
Six real earthquake ground excitations are proposed to perform nonlinear time-history analyses. To better analyse the seismic response of the benchmark bridge such number has been significantly increased herein: seismic behaviour of the structure is investigated by nonlinear time-history analyses and by adopting twenty-eight strong real earthquake ground excitations (Table 2.1). The earthquake accelerograms are downloaded from the Pacific Earthquake Engineering Research Center (PEER) and from the Italian Acceleration Archive (ITACA). As visible, the 28 accelerograms cover a wide variety of magnitudes, PGA, epicentral distance and soil types. For the excitation of the longitudinal (EW) and transverse (NS) directions of the bridge, both components are simultaneously used.

Table 2.1. The twenty-eight selected earthquake ground motions

N.	Earthquake name	Country name	Date y-m-d	Mw	PGA EW (g)	PGA NS (g)	Ground type	Epicentral distance (km)
1	Tohoku	Japan	2011-03-11	9.00	1.095	0.780	B	92
2	Coyote Lake	California	1979-08-06	5.75	0.434	0.316	B	26
3	Coalinga	California	1983-05-02	6.36	0.592	0.551	C	16
4	Cape Mendocino	California	1992-04-25	7.01	0.662	0.590	B	36
5	Aquila	Italy	2009-04-06	6.30	0.442	0.402	B	13
6	Erzican	Turkey	1992-03-13	6.69	0.515	0.496	C	17
7	Friuli	Italy	1976-05-06	6.50	0.351	0.315	B	20
8	Northwest	China	1997-04-11	6.10	0.300	0.274	C	84
9	Chalfant Valley	California	1986-07-20	5.77	0.285	0.207	C	18
10	Gazli	Uzbekistan	1976-05-17	6.80	0.608	0.718	B	16
11	Irpinia	Italy	1980-11-23	6.90	0.358	0.251	B	37
12	Izmir	Turkey	1977-12-16	5.30	0.410	0.146	B	43
13	Corinth	Greece	1981-02-24	6.60	0.240	0.296	C	21
14	Tabas	Iran	1978-09-16	7.35	0.836	0.852	B	89
15	San Salvador	El Salvador	1986-10-10	5.80	0.406	0.612	C	13
16	Loma Prieta	California	1989-10-18	6.93	0.481	0.526	B	27
17	Manjil	Iran	1990-06-20	7.37	0.515	0.496	B	40
18	San Fernando	California	1971-02-09	6.61	0.324	0.268	B	26
19	Umbria-Marche	Italy	1997-09-26	6.00	0.118	0.112	C	40
20	Duzce	Turkey	1999-11-12	7.14	0.728	0.822	C	41
21	Taiwan	Taiwan	1986-11-14	7.30	0.242	0.160	C	72
22	Trinidad	Colorado	1980-11-08	7.20	0.156	0.151	A	77
23	Kobe	Japan	1995-01-16	6.90	0.503	0.509	C	38
24	Northridge	California	1994-01-17	6.69	0.472	0.838	B	13
25	Chi-Chi	Taiwan	1999-09-20	7.62	0.417	1.157	B	18
26	El Centro	California	1940-05-18	6.91	0.313	0.215	C	47
27	Izmit	Turkey	1999-08-17	7.60	0.728	0.822	B	91
28	North Palm S.	California	1986-07-08	6.10	0.612	0.492	C	84

With the purpose of evaluating the effectiveness of different control strategies, in the benchmark paper sixteen evaluation criteria named J_i are assumed. 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 bridge.
In this paper, only criteria J_1, J_2 and J_3 are considered. J_1 measures the peak base shear force in the controlled structure normalized by the corresponding base shear in the uncontrolled structure, J_2 measures the peak overturning moment in the controlled structure normalized by the corresponding moment in the uncontrolled structure, J_3 measures the peak displacement at the midspan of the controlled structure normalized by the corresponding midspan displacement of the uncontrolled structure.

3. SEMI-ACTIVE STRUCTURAL CONTROL STRATEGY BASED ON A SEWS

An additional control strategy is introduced and compared to the three considered in the benchmark paper. The adopted systems are designed according to the idea of combining SEWS and SA control techniques by using MR dampers. The latter are time-varying properties devices able to achieve a wide range of physical behaviours using low-power electrical currents. The main idea of this work consists in changing the MR damper behaviour according to the forecasted intensity of an incoming earthquake provided by the SEWS, in order to obtain the optimal seismic response of the hosting structure.

In detail, the PGA estimate provided by a SEWS and the soil type information allow to built the elastic 5% damped response spectra, according to the Eurocode 8 rules (CEN, 2003). Subsequently, the spectral acceleration $S_a(T_1)$ evaluated at the fundamental period T_1 of bridge, is exploited to set voltage in the 16 MR devices according to an appropriate algorithm, i.e. voltage-spectral acceleration correlations. The MR devices herein adopted can be fed by voltages u_c ranging from 0 to $u_{c,max}$ = 10 V, corresponding to current ranging from 0 to 5 A. The adjustment is supposed to happen only once, just before the quake strikes. In this case, the SA structural control framework becomes relatively simple, if compared to classical semi-active control systems. Several non linear analysis of the response of the bridge at different currents feeding the MR dampers have shown a non linear correlation between the PGA of the incoming earthquake and the maximum response reduction. Therefore, the following relationship is a viable candidate to control the SA dampers:

$$u_c = \left[1 + \tanh\left(\frac{S_a(T_1) - \alpha}{\beta}\right)\right] \cdot \frac{u_{c,max}}{2} \tag{3.1}$$

Parameters α and β are adopted to give a desired shape to the hyperbolic tangent function of Eq. 3.1. In the following, two different choices are proposed: the first one mainly addressed to reduce as much as possible the number of J_i values (each one corresponding to one of the 28 earthquakes) greater than 1, the second one essentially addressed to give very strong response reduction (small values of J_i), even if for a lower number of seismic inputs.

The first objective was targeted by chosing the set of parameters as α = 1.27 and β = 0.22, referred to as SEWS-SA(A) and graphically shown in Fig 3.1 (green line), whereas the second objective was found to be correspondent to α = 0.50 and β = 0.10 - SEWS-SA(B) – red line.

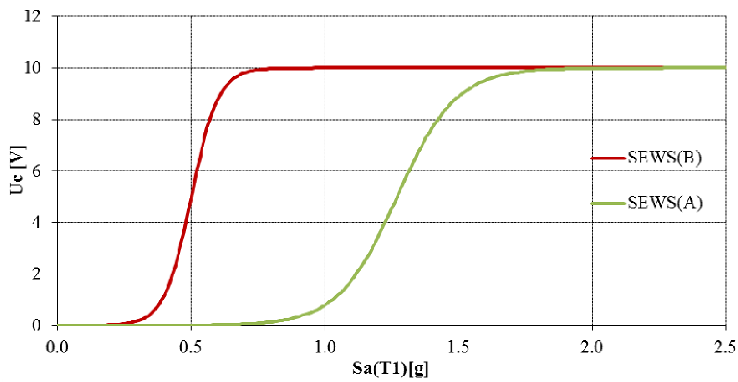

Figure 3.1. Voltage-spectral acceleration correlation for the proposed control algorithm strategies

The results of the SEWS-SA(A) strategy in terms of J_1, J_2 and J_3 are shown in the form of histograms in Fig. 3.2, whereas in Table 3.1 the same results are reported in a synthetic form. In the table, for the criteria J_1, J_2 and J_3 the maximum, the minimum and the average value for the 28 nonlinear analyses performed and the number of times that J_i overpass the limit of 1 are indicated. These results demonstrate the effectiveness of the proposed strategy for earthquakes with different characteristics as magnitudes, distances to fault and soil types. In particular, Table 3.1 clearly shows that the number of times for which J_i result greater than 1 is very low. Considering the SEWS-SA(A) strategy, a better overall performance of the controlled system compared to the reference bridge is guaranteed for a wide typology of earthquakes.

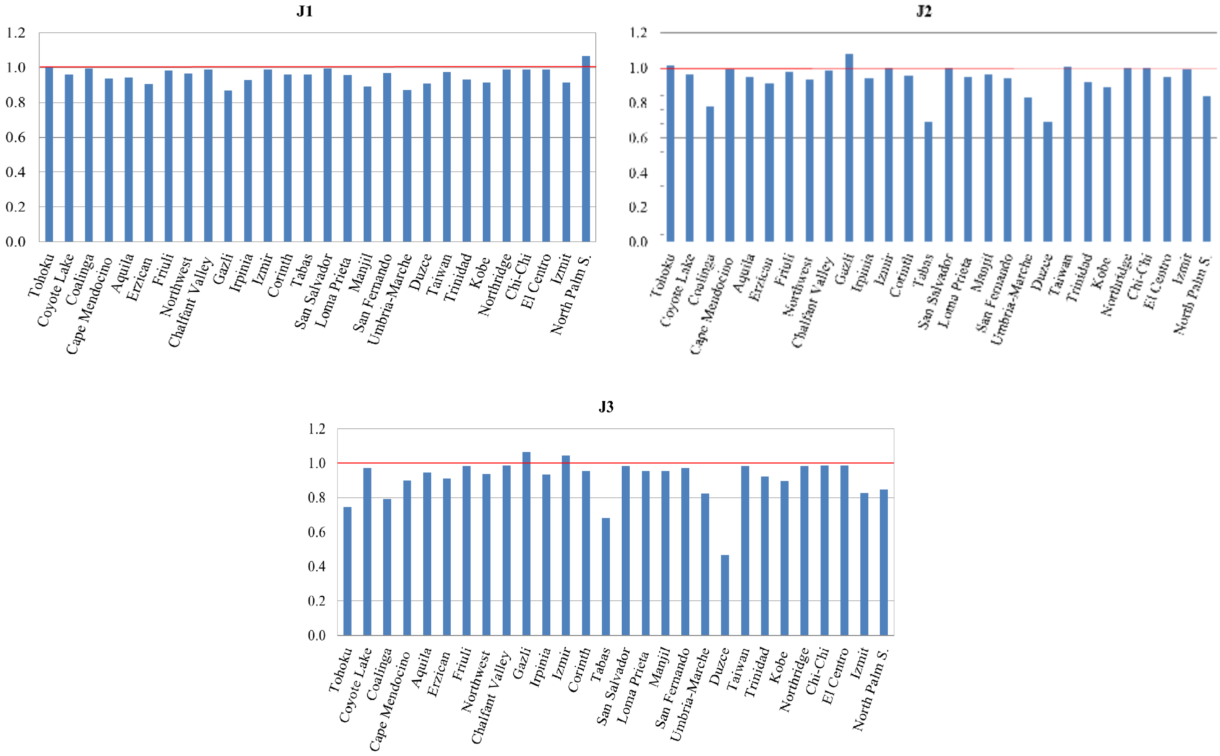

Figure 3.2. J_1, J_2, J_3 criteria results for the SEWS-SA(A) strategy

Table 3.1. Summary table results for SEWS-SA(A) strategy

	$\mathbf{J_1}$	$\mathbf{J_2}$	$\mathbf{J_3}$
Max J_i	1.07	1.08	1.06
Min J_i	0.87	0.69	0.47
Average	0.96	0.93	0.91
No. $J_i > 1$	2	3	2

Table 3.2 summarizes the results corresponding to the second strategy – SEWS-SA(B). These results demonstrate that the maximum values of the J_i criteria are incremented but also that in many cases the minimum and the average values of the indexes are typically decreased. The number of times that J_i overpass 1 is also incremented.

Table 3.2. Summary table results for SEWS-SA(B) strategy

	$\mathbf{J_1}$	$\mathbf{J_2}$	$\mathbf{J_3}$
Max J_i	1.67	1.41	1.42
Min J_i	0.50	0.26	0.28
Average	0.97	0.69	0.54
No. $J_i > 1$	8	3	1

In conclusion, the two proposed control strategies are capable of reducing the response of the benchmark highway bridge for a wide variety of earthquake records and according the target assumed. A comparison with other control techniques (passive, semi-active and active), proposed in the benchmark problem, is also investigated. The response quantities J_1, J_2 and J_3 are shown and compared in Table 3.3 for all twenty-eight earthquakes. Bold numbers indicate, for each earthquake, the best among the five strategies.

Table 3.3. Comparison among passive, semi-active, active, SEWS-SA(A) and SEWS-SA(B) strategies for each of the 28 natural earthquakes.

Response quantity	Control strategy	Tohoku	C. Lake	Coalinga	C. Mend.	Aquila	Erzican	Friuli
Peak base shear, J_1	Passive	0.83	0.83	1.05	**0.68**	1.12	**0.78**	**0.67**
	Semi-active	0.76	0.93	0.94	0.81	0.86	0.87	0.74
	Active	**0.66**	0.94	**0.92**	0.81	**0.86**	0.90	0.73
	SEWS-SA (A)	1.00	0.96	1.00	0.94	0.95	0.91	0.98
	SEWS-SA (B)	1.01	**0.83**	1.12	0.79	1.51	0.81	0.81
Peak base moment, J_2	Passive	0.83	0.82	**0.59**	0.68	**0.60**	0.66	0.58
	Semi-active	0.77	0.93	0.78	0.89	0.79	0.87	0.72
	Active	**0.68**	0.94	0.80	0.88	0.86	0.91	0.73
	SEWS-SA (A)	1.01	0.96	0.78	0.99	0.94	0.91	0.98
	SEWS-SA (B)	1.01	**0.81**	0.62	**0.47**	0.81	**0.44**	**0.47**
Peak mid-span displacement, J_3	Passive	**0.64**	**0.73**	0.60	0.60	0.55	0.66	0.59
	Semi-active	0.82	0.81	0.79	0.77	0.79	0.87	0.74
	Active	0.89	0.82	0.79	0.76	0.84	0.90	0.72
	SEWS-SA (A)	0.75	0.97	0.79	0.90	0.95	0.91	0.98
	SEWS-SA (B)	0.75	0.74	**0.41**	**0.28**	**0.51**	**0.32**	**0.41**

Response quantity	Control strategy	Northwest	C. Valley	Gazli	Irpinia	Izmir	Corinth	Tabas
Peak base shear, J_1	Passive	0.61	1.42	0.82	**0.75**	1.16	**0.83**	0.88
	Semi-active	0.82	1.16	0.81	0.86	1.01	0.83	**0.79**
	Active	0.84	**0.93**	**0.79**	0.95	**0.91**	0.86	0.81
	SEWS-SA (A)	0.97	0.99	0.87	0.93	0.99	0.96	0.96
	SEWS-SA (B)	**0.50**	1.61	0.91	0.87	1.40	0.91	1.00
Peak base moment, J_2	Passive	0.53	0.90	0.91	0.62	1.17	0.62	0.66
	Semi-active	0.72	0.84	1.02	0.87	1.01	0.82	0.85
	Active	0.74	**0.84**	1.00	0.96	**0.91**	0.85	0.84
	SEWS-SA (A)	0.93	0.98	1.08	0.94	1.00	0.95	0.69
	SEWS-SA (B)	**0.26**	1.02	**0.66**	**0.44**	1.41	**0.59**	**0.56**
Peak mid-span displacement, J_3	Passive	0.60	0.71	0.90	0.61	1.19	0.62	0.60
	Semi-active	0.79	0.84	1.01	0.88	1.06	0.83	0.76
	Active	0.80	0.84	1.00	0.97	**0.95**	0.85	0.75
	SEWS-SA (A)	0.94	0.99	1.06	0.93	1.05	0.95	0.68
	SEWS-SA (B)	**0.28**	**0.62**	**0.64**	**0.30**	1.42	**0.59**	**0.50**

Response quantity	Control strategy	S. Salv.	L. Prieta	Manjil	S.Fern.	U.-Marche	Duzce	Taiwan
Peak base shear, J_1	Passive	0.77	0.78	0.97	0.77	**0.85**	**0.79**	0.98
	Semi-active	0.94	**0.72**	0.90	**0.75**	0.87	0.91	0.96
	Active	0.93	0.73	0.98	0.76	0.89	0.92	**0.90**
	SEWS-SA (A)	1.00	0.96	**0.89**	0.97	0.87	0.91	0.98
	SEWS-SA (B)	**0.53**	1.00	1.30	0.86	0.87	0.96	0.92
Peak base moment, J_2	Passive	0.81	0.62	**0.70**	0.52	**0.38**	0.89	0.70
	Semi-active	0.98	0.74	0.95	0.70	0.60	0.98	**0.69**
	Active	0.98	0.76	1.03	0.74	0.72	0.99	0.80
	SEWS-SA (A)	1.00	0.95	0.96	0.94	0.83	0.69	1.01
	SEWS-SA (B)	**0.55**	**0.57**	0.70	**0.47**	0.81	**0.57**	0.99
Peak mid-span displacement, J_3	Passive	0.61	0.61	0.69	0.55	**0.29**	0.59	**0.53**
	Semi-active	0.75	0.72	0.93	0.75	0.59	0.73	0.67
	Active	0.75	0.72	1.01	0.76	0.72	0.76	0.78
	SEWS-SA (A)	0.98	0.95	0.95	0.97	0.82	0.47	0.99
	SEWS-SA (B)	**0.41**	**0.41**	**0.44**	**0.36**	0.80	**0.35**	0.79

Response quantity	Control strategy	Trinidad	Kobe	Northr.	Chi-Chi	El Cen.	Izmit	N. P. S.
Peak base shear, J_1	Passive	0.94	0.86	0.78	0.76	**0.64**	**0.78**	1.26
	Semi-active	0.76	0.81	0.90	0.85	0.80	0.91	**0.98**
	Active	**0.70**	**0.79**	0.91	0.88	0.79	0.93	0.98
	SEWS-SA (A)	0.93	0.91	0.99	0.99	0.99	0.91	1.07
	SEWS-SA (B)	0.89	1.06	**0.68**	**0.69**	0.68	0.97	1.67
Peak base moment, J_2	Passive	**0.55**	0.54	0.96	0.97	0.57	0.88	**0.65**
	Semi-active	0.65	0.69	0.98	0.98	0.72	0.98	0.78
	Active	0.70	0.71	0.98	0.98	0.76	0.99	0.78
	SEWS-SA (A)	0.92	0.89	1.00	0.99	0.95	0.99	0.83
	SEWS-SA (B)	0.87	**0.53**	**0.93**	**0.93**	**0.37**	**0.57**	0.86
Peak mid-span displacement, J_3	Passive	**0.41**	0.62	0.70	0.71	0.65	0.59	0.64
	Semi-active	0.66	0.69	0.86	0.78	0.79	0.73	0.82
	Active	0.70	0.71	0.88	0.81	0.78	0.76	0.83
	SEWS-SA (A)	0.92	0.89	0.99	0.99	0.99	0.83	0.85
	SEWS-SA (B)	0.87	**0.57**	**0.54**	**0.55**	**0.31**	**0.35**	**0.57**

The two proposed strategies lead to good results in comparison with those of other control systems. In particular, for the SEWS-SA(A) strategy, all the peak quantities assume values lower or (in few cases) slightly higher than one. Instead, for the SEWS-SA(B) strategy, the peak quantities assume, in some cases, values greater than one, but J_1, J_2 and J_3 criteria assume the minimum value among all strategies five times, eight-teen times and twenty-two times, respectively (Fig. 3.3) on a total of twenty-eight nonlinear performed analyses. The results clearly indicate that the shape of the hyperbolic function of the control algorithm has a sharp influence on the overall control effectiveness: strategy SEWS-SA(A) leads to a relatively mild response reduction, which is almost independent from the seismic event, whereas strategy SEWS-SA(B) trades off a better response reduction on some earthquakes with a worse behaviour in other cases.

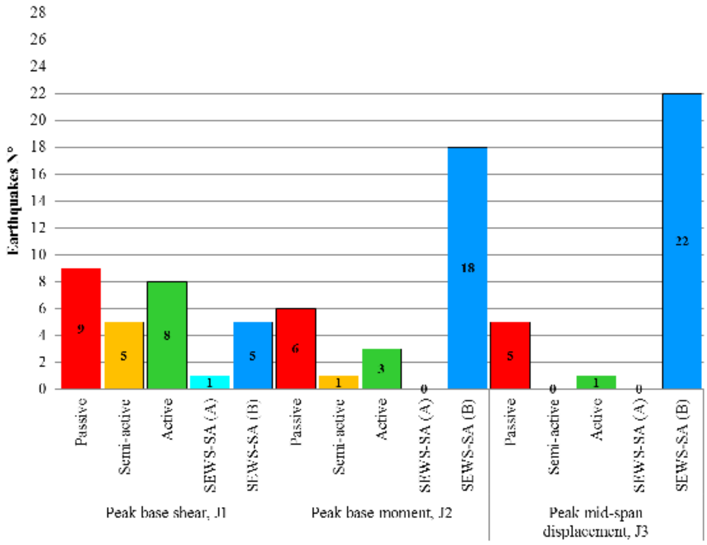

Figure 3.3. Number of times that the strategies allow to obtain the minimum peak value on 28 earthquakes

Furthermore, it is worth to note that the amount of response reduction is better or almost comparable to that obtained with more complex and expensive semi-active and active systems.

4. UNCERTAINTY IN EARLY WARNING PREDICTIONS

In numerical simulations, the MR dampers have been adjusted considering that the intensity measures estimates by the SEWS are accurate. At the current step of the research, this is not a guaranteed assumption. In Iervolino et al. (2007) and Iervolino (2010), important considerations are reported on this topic. It is shown that uncertainty on ground motion parameters stabilizes when at least 18 stations of the SEWS have been triggered. In this instant a lognormally distributed PGA with a coefficient of variation (CoV, i.e. the ratio of standard deviation to the mean) equal to 0.45 could be assumed with an acceptable approximation and according to the indications by Sabetta and Pugliese (1996). For this reason, the values of PGA, obtained from a lognormal distributions built considering a CoV equal to 0.45 and a mean value equal to the PGA reported in Table 2.1, are considered as input to set the voltage in the MR devices according the SEWS-SA(A) and SEWS-SA(B) control strategies.

Seismic events correponding to the lognormal distribution of PGA built for each earthquake, have been utilized as input of the the nonlinear analyses of the bridge in order to calculate the corresponding distributions of indexes J_1, J_2 and J_3. The CoV related to the so obtained three distributions have been compared (Figs. 4.1, 4.2) to the corresponding value (0.45) related to the input.

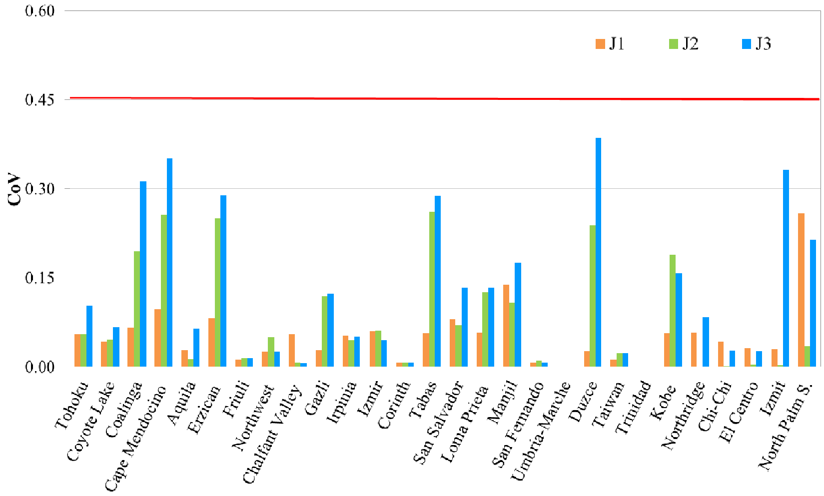

Figure 4.1. CoV of J_1, J_2 and J_3 values according to the SEWS-SA(A) strategy

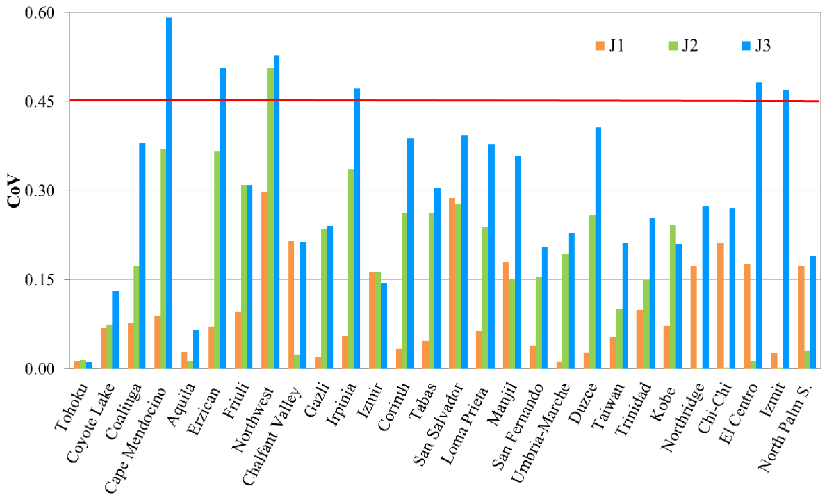

Figure 4.2. CoV of J_1, J_2 and J_3 values according to the SEWS-SA(B) strategy

For the SEWS-SA(A) strategy the results obtained 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 damp these errors, resulting in a robust seismic behaviour of the protected structure. As expected, for the SEWS-SA(B) strategy in some cases the values of the CoV is larger than 0.45.

5. CONCLUSIONS

The present paper describes a methodology for exploiting earthquake information derived by a seismic early warning system in the framework of semi-active control strategies by using MR dampers. The main idea consists in changing the MR dampers' behavior according to an anticipate estimate, provided by the SEWS, of the PGA of an incoming earthquake. The PGA value is adopted to define the code elastic acceleration spectrum. Then the spectral acceleration evaluated at the fundamental period of the structure to be controlled is used to set the optimal voltage in the MR devices.
The adjustment is commanded only once, just before the quake strikes. In this case, the SA structural control framework becomes quite simple, based on the possibility of change mechanical properties of passive, but smart, additional damping devices shortly before the arrival of the seismic event at the site

where the structure is located.
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 28 real earthquake ground excitations covering a wide variety of magnitudes, distances to fault and soil types. With the purpose of evaluating the effectiveness of different control strategies, three criteria J_1 (peak base shear force), J_2 (peak overturning moment) and J_3 (peak displacement at the midspan) have been considered.
Several trials and simulations allowed to define two different control algorithms, i.e. relationships useful to define the optimal amount of voltage to be given to the dampers according to the spectral acceleration evaluatedat the fundamental period of the structure, in turn defined starting from the forecasted PGA value. Each of these two logics is calibrated to achieve different targets in terms of response reduction under the whole set of considered seismic inputs.
The two proposed strategies, named SEWS-SA(A) and SEWS-SA(B), lead to good results in comparison with more consolidated as well as innovative control strategies. In particular, for the SEWS-SA(A) strategy, all the assumed performance indexes assume values lower or, only in few cases, slightly higher than one. Instead, for the SEWS-SA(B) strategy, they assume in some cases values greater than one, but also the minimum value among the ones corresponding to all the other strategies, respectively: five times, eight-teen times and twenty-two times on a total of twenty-eight non linear performed analyses.
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.

ACKNOWLEDGEMENT
This research has been partially funded by the Italian Department of Civil Protection in the frame of the national project ReLUIS 2009-2012 - Theme 3.

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