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A Case Study on Performance of Isolated Bridges under Near-Fault Ground Motion

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***Abstract*—**This paper presents a numerical investigation on the seismic performance of a benchmark bridge with different optimal isolation systems under near fault ground motion. Usually, very large displacements make seismic isolation an unfeasible solution due to boundary conditions, especially in case of existing bridges or high risk seismic regions. Hence, near-fault ground motions are most likely to affect either structures with long natural period range like isolated structures or structures sensitive to velocity content such as viscously damped structures. The work is aimed at analyzing the seismic performance of a three-span continuous bridge designed with different isolation systems having different levels of damping. The case study was analyzed in different configurations including: (a) simply supported, (b) isolated with lead rubber bearings (LRBs), (c) isolated with rubber isolators and 10% classical damping (HDLRBs), and (d) isolated with rubber isolators and 70% supplemental damping ratio. Case (d) represents an alternative control strategy that combines the effect of seismic isolation with additional supplemental damping trying to take advantages from both solutions. The bridge is modeled in SAP2000 and solved by time history direct-integration analyses under a set of six recorded near-fault ground motions. In addition to this, a set of analysis under Italian code provided seismic action is also conducted, in order to evaluate the effectiveness of the suggested optimal control strategies under far field seismic action. Results of the analysis demonstrated that an isolated bridge equipped with HDLRBs and a total equivalent damping ratio of 70% represents a very effective design solution for both mitigation of displacement demand at the isolation level and base shear reduction in the piers also in case of near fault ground motion.

***Keywords*—**Isolated bridges, optimal design, near-fault motion, supplemental damping.

I. Introduction

SEISMIC isolation of bridges, in case of design of new bridges as well as retrofit of existing ones, has been widely accepted and practiced in earthquake prone areas [1] and has advanced now to a mature technology since recent earthquakes have given some insight into the actual performance of seismically protected bridges [2].

Performance of isolated bridges under near-fault ground motions still represents an important issue to be tackled. Different studies show devastating effects of near-fault earthquakes on isolated bridges, due to both characteristics of displacement pulse which is commonly long-period and large at peak, and secondly, the high velocity of the pulse, in the order of magnitude of 1 m/s. This topic became a matter of concern especially after 1994 Northridge Earthquake where isolated structures constructed in vicinity of San Andreas Fault were subjected to long-period displacement pulses with high velocity contents, duration of which matched the isolated period of the structure and caused excessive displacement responses [3]-[6].

As a result, the isolation technology under near-fault motions was firstly criticized [7], but by virtue of its benefit it then became an appealing subject in literature, and many studies proposed different ways to curtail its proven poor performance such as employing Shape Memory Alloys [8], using Magneto Rheological Dampers [9], or optimizing Lead Rubber Bearings (LRBs) [10].

Reference [11] examined the efficiency of various dissipative mechanisms to protect structures from pulse-type and near-source ground motion. The study considered one or two degree(s) of freedom systems and concluded that a combination of relatively low friction and viscous force is attractive since base displacements are substantially reduced without appreciably increasing base shears and superstructure accelerations. They found that, at low isolation period range (T_i<2 s), additional viscous damping reduces displacements and base shear in the most effective way, while friction dissipation alone becomes effective in reducing displacement at large isolation periods, but the resulting base shear is the largest. At the high range isolation period (T_i>2s), viscous dissipation results in large displacements that are substantially reduced when some friction dissipation is introduced. Friction dissipation eliminates amplification due to resonance for isolation periods larger than 2 s.

The present paper presents a numerical investigation on a real bridge under near fault ground motion, which is assumed to be designed with elastomeric isolators and different levels of damping.

The case study is analyzed in configurations of simply supported not isolated bridge with 5% damping (SSB case), isolated bridge with 10% damping produced by HDLRB isolation system (IB case), and isolated bridge with 70% viscous damping ratio (IDB case). An additional configuration with optimal LRB is considered, as presented by the authors of the referred work [10]. In order to demonstrate the competitiveness of IDB case, a set of far fault ground motion as provided by Italian seismic code, was also considered.

Time history analysis are run to provide an accurate estimation of the structural response on a three DOFs model,

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properly accounting for input frequency content on the overall response.

II. High-Damping Seismic Isolation Systems

Reference [12] implemented a frequency domain procedure for damping optimization of viscoelastic isolators on regular bridges. They introduced a dimensionless optimum viscous damping parameter (ν_i) as a function of piers to isolation system relative stiffness ($\kappa = k_c/k_i$), and demonstrated that increasing the damping level of the isolation system is not favorable to any extent. There exists an optimum level of damping that minimizes the structural response in terms of deck displacement. With respect to optimum, higher damping values would be responsible of worse performance condition with larger deck displacements, and above all, increasing base shear.

For a regular bridge with n equal piers and isolators, the authors considered a simple model with a deck of total mass m and linear springs with stiffnesses $k_c = n \times k_{c,j}$ and $k_i = n \times k_{i,j}$ representing the total lateral stiffness of the piers (i.e. bridge lateral stiffness in non-isolated case) and the isolation system, respectively. The total damping of the isolation system and supplemental dampers is lumped in a dashpot with damping coefficient $c = n \times c_j$. Assuming that the target isolation period is fixed, the damping properties strongly affect the system response.

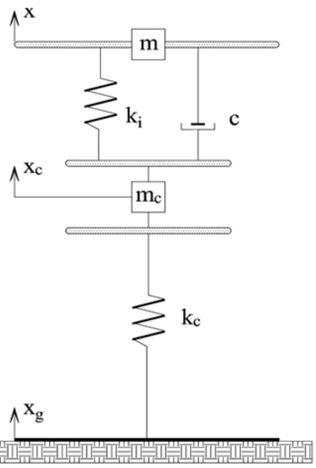


Fig. 1 Simplified model of isolated bridge

The authors found out a closed form expression of the optimum damping ratio $\nu_i = \frac{c}{2m\,\omega_i}$ ($\omega_i = \sqrt{k_i/m}$) as a function of the relative piers to isolators stiffness. Practically, optimum damping ratio arises to 70% in all cases where $k_c/k_i > 2{,}5$. This value of damping was also numerically validated, and it was found out that it provided both minimum deck displacement and almost minimum base shear.

The simple bridge model of Fig. 1 may represent a simplified model of real continuous bridges, where $k_c = n \times k_{c,j}$ and $k_i = n \times k_{i,j}$ represent the total lateral stiffness of the piers (i.e. bridge lateral stiffness in non-isolated case) and the isolation system, respectively, being m the deck mass. In this way, the outcome of the referred work can be assumed to be valid in most real cases, especially where isolation is more effective ($k_c/k_i \gg 1$).

Starting from this outcome, in the present paper, a value of 70% damping is assumed to be beneficial in a seismic isolation system for a benchmark bridge under near fault ground motion. This control system is finally compared with different isolation systems in terms of effectiveness of performance also under far fault motion.

III. Case Study

The case study is an equally three-span continuous concrete bridge, totally 90 m long with two similar piers of 8 m height having cross section area of 4.09 m^2 and moment of inertia of 0.64 m^4. Both abutments are assumed to be fixed. Details are given in Table I, while Fig. 2 shows a schematic drawing of the bridge in SSB configuration.

This bridge was first mentioned in the work of [13] to study the response of Friction Pendulum Bearings (FPS) and was then referred in the study of Jangid [10] where the target was to find the optimum parameters of an LRB system. In particular, the aim of Jangid was to find the optimal ratio of stiffness to hysteretic damping for a near-fault motion.

TABLE I
Properties of Bridge in SSB Configuration

Horizontal Stiffness	155025	kN/m
Weight of the Super Structure	7623.5	kN
Total Seismic Weight	8008.7	kN
Piers' mass to total mass percentage	4.8	%
Horizontal Natural Period	0.46	sec

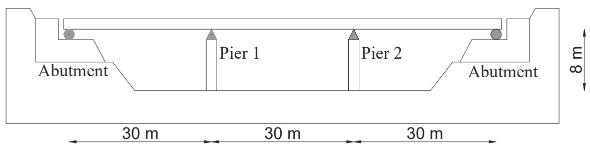


Fig. 2 Schematic view of the bridge in fixed deck configuration

Isolation systems are designed in order to achieve a fixed target period adopting on market available rubber materials. Stability items are also checked, i.e. rollout displacement and vertical buckling load. With the aim to control the commonly large displacements of the isolated deck, different levels of equivalent damping are supposed to be introduced properly designed not to increase transmitted force to substructure.

An HDLRB isolation system is designed with 10% damping for IB configuration. An additional 60% damping is also assumed to be provided by supplemental dampers for IDB configuration. A certain value of response displacement is assumed for preliminary design of the elastomeric bearings which is 0.4 m for 10% damped system (IB) and half of that for 70% damped system (IDB), whose details are provided in Tables II and III, respectively. These values have been checked for convergence with time history results. To meet stability criteria, maximum shear strain in the isolator was limited to 100%.

TABLE II
DETAILS OF ELASTOMERIC BEARINGS IB

Target Horizontal Period of the Isolated Bridge	2.5	sec
Damping Ratio	10%	-
Number of Bearings	8	-
Design displacement	0.4	m
Diameter of the Rubber	0.9	m
Horizontal Stiffness of each Bearing	642	kN/m
Total Isolators Horizontal Stiffness	5134	kN/m

TABLE III
DETAILS OF ELASTOMERIC BEARINGS IDB

Target Horizontal Period of the Isolated Bridge	2.5	sec
Damping Ratio Produced by Isolation system	10%	-
Damping Ratio Produced by Additional Damping system	60%	-
Number of Bearings	8	-
Design displacement	0.2	m
Diameter of the Rubber	0.64	m
Number of Rubber Layers in each Bearing	16	-
Horizontal Stiffness of each Bearing	642	kN/m
Total Isolators Horizontal Stiffness	5134	kN/m

Reference [10] investigated the same bridge to find out the optimum value of core yield strength of LRBs, estimated in the range 15-20% of the weight of the deck, with an equivalent period of the isolated bridge in the range 2.5-3s. For the sake of comparison, in this study, an LRB configuration with a total yield strength of 17.5% of deck mass and an equivalent period of 2.5 s at 0.35 m is also considered.

A. Near Fault Ground Motion Selection

A set of six recorded near-fault ground motions provided in [10] is also used in this section (Table IV). Fig. 3 graphically shows the input motion spectra combined through SRSS approach.

TABLE IV
INPUT GROUND MOTION

Waveform ID	Earthquake Name & Station	Mw	Fault Mechanism	PGA [g]
180	Imperial Valley-Array #5	6.53	strike slip	0.36
182	Imperial Valley-Array #7	6.53	strike slip	0.45
879	Landers-Lucerne	7.28	strike slip	0.71
1044	Northridge-Newhall	6.69	Reverse	0.7
1063	Northridge-Rinaldi	6.69	Reverse	0.87
1084	Northridge-Sylmar	6.69	Reverse	0.72

B. Analysis Results

Peak response values are obtained for IB, IDB, and LRB configurations and normalized to corresponding values of SSB as depicted in Fig. 4.

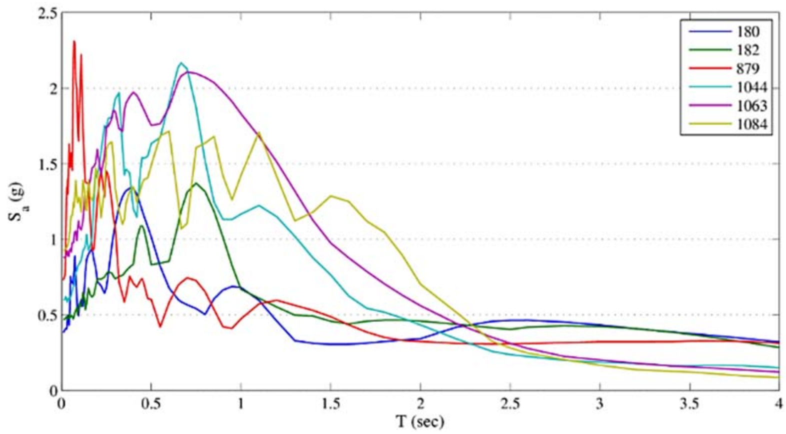


Fig. 3 Input ground motion response spectra

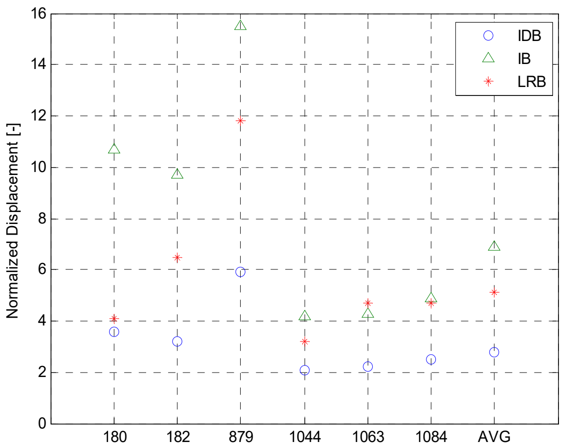
Displacement response in Fig. 4 (a) shows high sensitivity of the isolated mock-up to near-fault motion with respect to not-isolated one. Absolute displacements give insight to this matter: under near-fault motion 180, maximum response is 0.06 m for SSB, while it rises to 0.62 m for IB, a very large displacement hard to be accommodated. Under the same motion, IDB and LRB displacement responses are recorded 0.21 m and 0.24 m, respectively, which suggests a steep decrease. Peak displacement response in average is 0.07 m for SSB, 0.46 m for IB, 0.34 m for LRB, and 0.19 m for IDB. Note that values of peak response displacements recorded through time-history direct time-integration method match those assumed in the preliminary design of the bearings. Both base shear and acceleration response reduce in the range 75 to 85% in isolated configurations with respect to SSB.

The minimum base shear correlated with optimum LRB system proposed by Jangid is 5% higher than IDB. The notable difference is in terms of response displacement of the deck that is almost 50 % reduced with IDB. In addition to this, it must be said that a hysteresis type system like LRB or FPS could be tuned for optimum strength and/or stiffness parameters under near fault motion, but this could compromise the performance of the system under far field or even low magnitude earthquakes. Higher strength and equivalent stiffness may be required by near fault motions to reduce maximum displacement and/or maximum base shear: for this tuning the system may experience limited yielding when input properties are different from near fault, thus providing a non-isolated behavior.

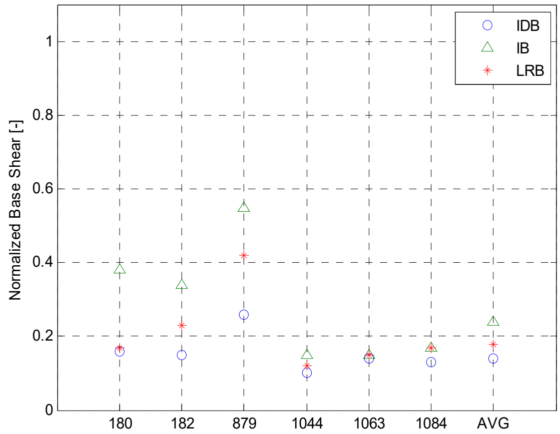
C. Performance Check under Code Provided Seismic Action

In order to compare the performance of the different examined solutions, a further analysis case is proposed considering a different location of the bridge according to seismic action provided by the Italian building code NTC [14].

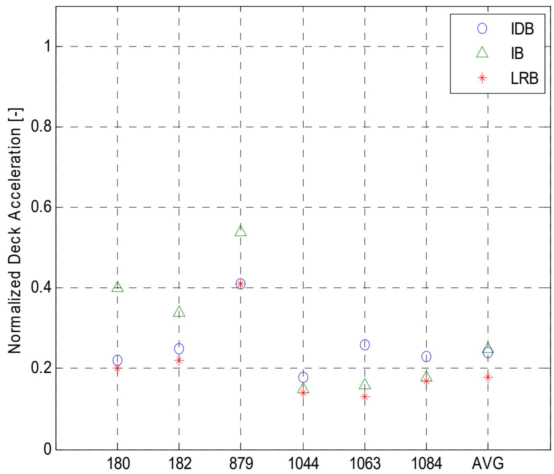
The design spectra (Fig. 5) with 5% of critical damping have been defined for the near collapse limit state SLC of the bridge (assumed with functional class III) located in Grottaminarda, Italy (15.03° longitude, 41.06° latitude) on soil type B (360 $\leq V_{s,30} \leq$800 m/s) with a nominal life of 50 years, corresponding to a return period of 1462 years. A set of seven unscaled spectra matching accelerograms (Fig. 5, Table V) was found in the European ground motion database using Rexel v3.4 beta [15]. The average spectrum has 10% lower and 30% upper tolerance in the period range 0.15-2 s.



(a) displacement



(b) base shear



(c) acceleration

Fig. 4 Normalized maximum values

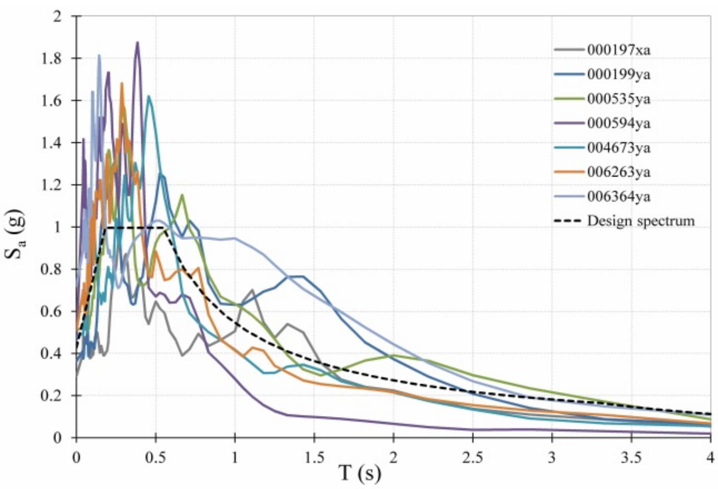


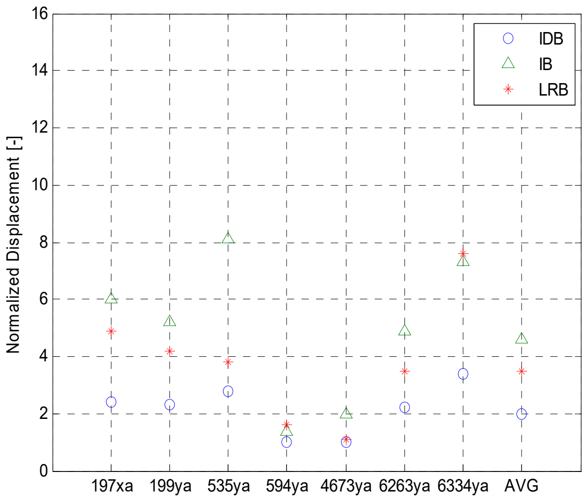
Fig. 5 Acceleration design spectra (z=5%) and selected ground motion

TABLE V
INPUT GROUND MOTION ACCORDING TO NTC

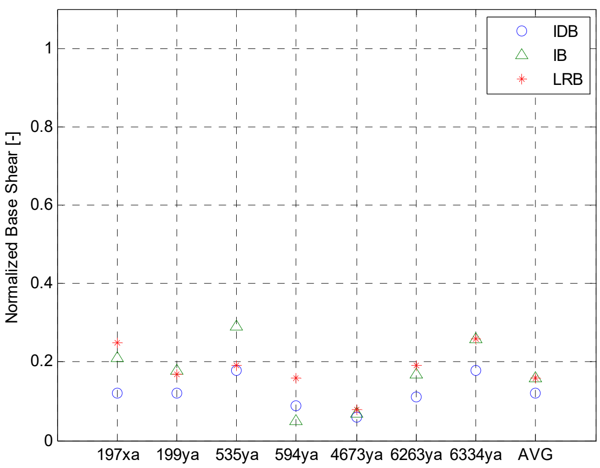
Waveform ID	Station ID	Earthquake Name	M_w	Epicentral Distance [km]	PGA [m/s^2]	PGV [m/s]
4673	ST2482	South Iceland	6.5	15	4.68	0.48
535	ST205	Erzincan	6.6	13	5.03	1.02
6263	ST2484	South Iceland	6.5	7	6.14	0.50
199	ST67	Montenegro	6.9	16	3.68	0.52
197	ST63	Montenegro	6.9	24	2.88	0.47
6334	ST2488	South Iceland (as)	6.4	11	7.07	0.97
594	ST60	Umbria Marche	6	11	5.14	0.32
mean:			6.54	13.86	4.94	0.61

Greater sensitivity of isolated structures to near-fault ground motions can be clearly understood by comparing the spectra of Fig. 3 at flexible range period around 1-3 s with those given in Fig. 5.

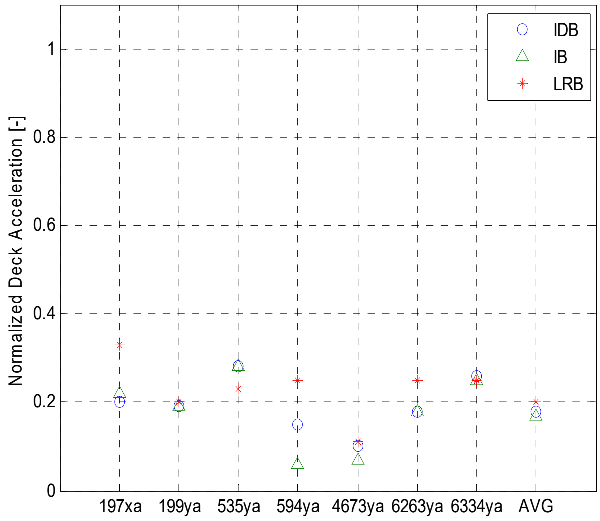
Time history analysis was run for IB, IDB, and LRB configurations, then was normalized to the corresponding values of SSB as depicted in Fig. 6.



(a) displacement



(b) base shear



(c) acceleration

Fig. 6 Normalized maximum values

As in the previous case, IDB proved to be the most advantageous configuration especially in terms of displacements with a maximum of 0.10 m in comparison with 0.24 m (IB) and 0.18 m (LRB) of alternative solutions. Base shear also lightly reduces with respect to IB and LRB, while accelerations mostly peak at the same value.

IV. CONCLUSION

Bridge isolation technology has been continuously growing in the last decades due to satisfactory behavior of isolated structures under real earthquakes and severe code requirements for mission critical structures.

A part from this, in high seismic prone areas or near fault seismicity regions, spectral displacements at isolated periods may result very hard to accommodate. In this perspective, providing supplemental damping to isolation systems may play a key role in attempt to mitigate maximum displacements.

Nowadays typical damping ratios amount to 10-15% for HDLRBs and may peak around 30% for LRBs. Higher values of damping like those suggested in the present paper could be obtained combining large viscous dampers with isolation devices.

Reference [12] in a previous study demonstrated that for a regular simply supported bridge isolated by means of elastomeric isolators, an optimal damping ratio could be defined to minimize the deck maximum displacement without increasing base shear, resulting in most practical cases equal to 70%.

Starting from this outcome, the authors investigated the effects of different isolation systems and equivalent damping ratios on a benchmark bridge under near fault ground motions.

Several configurations were examined including fixed deck to pier condition (SSB), isolated by HDLRBs with 10% damping (IB), isolated by HDLRBs with 70% optimal damping (IDB), and isolated with LRBs (LRB). This LRB system had been already suggested as optimally tuned in order to improve bridge performance under near fault ground motion.

Time history analysis was run under real earthquakes by numerical solving equation of motion in SAP2000. Results demonstrated competitiveness of HDLRBs in both reducing isolation displacements and providing minor benefits in terms of base shear.

Comparing IDB versus IB and LRB, not only displacements considerably reduce in the average of 50%, but also base shear drop remains practically unchanged. This effect on base shear is explained accounting that even if additional damping increases the damping force component, at the same time, it further reduces pier displacements resulting in smaller elastic force.

Thanks to repeatability of effective performance under both far field and near fault ground motions, the suggested control system provides both robustness and reliability in terms of effectiveness of seismic response.

References

[1] A. Martelli, and M. Forni, (2010), "Seismic Isolation and Protection Systems. The Journal of the Anti-Seismic Systems International Society, 1(1)

[2] F. Naeim, "Design of Seismic Isolated Structures: From Theory to Practice", Earthquake Spectra, 16(3), 709–710, 2000.

[3] W.I. Liao, C.H. Loh, and B.H. Lee, "Comparison of dynamic response of isolated and non-isolated continuous girder bridges subjected to near-fault ground motions", Engineering Structures, 26 (14), 2173-2183, 2004.

[4] R. S. Jangid, and J.M. Kelly, "Base isolation for near-fault motions", Earthquake Engineering and Structural Dynamics, 30 (5), 691-707, 2001.

[5] J. Shen, M.H. Tsai, K.C. Chang, and G.C. Lee, "Performance of a seismically isolated bridge under near-fault earthquake ground motions", Journal of Structural Engineering, 130 (6), 861-868, 2004.

[6] M. H. Jònsson, B. Bessason, and E. Haflidason, "Earthquake response of a base-isolated bridge subjected to strong near-fault ground motion", Soil Dynamics and Earthquake Engineering, 30 (6), 447-455, 2010.

[7] J. F. Hall, T. H. Heaton, M. W. Halling, and D.J. Wald, "Near-source ground motion and its effect on flexible buildings", Earthquake Spectra, 11(4), 569–605, 1995.

[8] O. E. Ozbulut, and S. Hurlebaus, "Optimal design of superelastic-friction base isolators for seismic protection of highway bridges against near-field earthquakes", Earthquake Engineering and Structural Dynamics, 40, 273-291, 2010.

[9] S.S. Sahasrabudhe, and S. Nagarajaiah, "Semi-active control of sliding isolated bridges using MR dampers: an experimental and numerical study", Earthquake Engineering and Structural Dynamics, 34(8), 965-983, 2005.

[10] R.S. Jangid, "Optimum lead-rubber isolation bearings for near-fault motions", Engineering Structures, 29 (10), 2503-2513, 2007.

[11] N. Makris, and S.P. Chang, "Effect of viscous, viscoplastic and friction damping on the response of seismic isolated structures", Earthquake Engineering and Structural Dynamics, 29, 85-107, 2000.

[12] D. Losanno, M. Spizzuoco, and G. Serino, "Optimal design of the seismic protection system for isolated bridges", Eartquakes and Structures, 6, 969–999, 2014.

[13] Y. P. Wang, L. L. Chung, and W. H. Liao, "Seismic response analysis of bridges isolated with friction pendulum bearings", Earthquake Engineering and Structural Dynamics, 27 (10), 1069-1093, 1998.

[14] NTC, "Nuove norme tecniche per le costruzioni", DM 14 gennaio 2008, Gazzetta Ufficiale n. 29 del 4 febbraio 2008 – Supplemento Ordinario n. 30, Italy, 2008.

[15] I. Iervolino, C. Galasso, and E. Cosenza, "REXEL: computer aided record selection for code–based seismic structural analysis", Bulletin of Earthquake Engineering, 8 (2), 399-362, 2010.