Improvement of the Dynamic Response of a Concrete Bridge using Special Bearings and Passive Control Devices

Al.G. Ercuşi
S.C. I.P.T.A.N.A. S.A., Department of Structures Computation, Romania

D.I. Creţu, I.R.Răcănel & T.Labiş Creţu
Technical University of Civil Engineering of Bucharest, Romania

SUMMARY:
In order to build safer bridge structures, in the design stage, the external loads acting during service life are to be considered. The earthquake action is probably the one which can have the most severe effects on the structures, mainly because of its high level of uncertainty concerning it's time and position of occurrence, intensity and duration. For this purpose, in the last decade, many steps were made worldwide for the improvement of the provisions regarding the consideration of the earthquake action.
In the past years the design concept to build safer bridge structures to resist against the seismic action led to rigid structural elements, having big dimensions of the piers cross sections and foundations. The developments of new calculation and experimental methods have introduced new concepts in the design of structures as the base isolation. These procedures were applied at the beginning for buildings, but at the present time, they are also used for bridges by using special bearing devices placed between the substructure and superstructure elements.
In this paper, a new designed bridge near Ploieşti city is analyzed. This new bridge is placed on the regional road DJ102 and overpasses the national road DN1B. For this bridge a special solution was chosen, the superstructure sustaining a roundabout intersection having eight accesses, four for entering and other four for exits. The bridge is placed in a region with a high level of the seismic hazard (k_s=0.28g). In order to reduce the level of the effective strength on the piers cross section but also foundations dimensions, special bearing devices were used combined with viscous dampers. Using artificially generated accelerograms and nonlinear time-history analyses, the response of the bridge on the seismic action is investigated and a comparison between the results on non-isolated and isolated structure is made.

Keywords: design, seismic action, effective stresses, seismic hazard, viscous damper

1. INTRODUCTION

The seismic action creates, because of its incertitude, a bottleneck in the process of designing economically affordable and aesthetically pleasing bridge structures, as it affects the bridge substructures demanding bulkier sections with consequently increased stiffness, which has implications in the overall performance of the structure by increasing its frequency, response accelerations, and post seismic interventions. Fortunately, by applying the principles of base isolation such constrains can be eliminated, as the seismic action no longer activates the inertial mass of the superstructure. Such effects can be obtained by using passive control devices placed between the super- and substructure, in the form of High Damping Rubber Bearings or Lead Rubber Bearings.
The study presented in this paper shows the benefits of using devices to control and improve the dynamic response of a concrete bridge subjected to seismic action. Achieving an optimum arrangement between the level of displacements and internal forces induced in the structure reflect a favourable effect on both structural safety and costs.

2. DESCRIPTION OF THE ANALYZED STRUCTURE

The bridge analysed in this paper will be erected at the intersection of on the national road DN1B and regional road DJ102 in the proximity of Ploiesti city and has the purpose of ensuring their continuity as well as the possibility of changing the driving direction without the need of electrified traffic signals achieving a continuous traffic flow. The roundabout solution, presented in Fig. 2, was chosen over the cloverleaf solution because of the continuity of the bicycle lanes that emerged from the regional road DJ102, that otherwise would have been between two automobile lanes, creating safety issues for the cyclists.

The superstructure is a continuous girder, built from C40/50 cast in place concrete and has 46 spans. 24 spans for the access ramps parallel to DN1B have 16 m length and 22 spans for the roundabout and the access ramps parallel to DJ102 have 24 m length, as shown in Fig. 1 and Fig. 3. The expansion joints are presented in Fig. 2. The boxed cross sections, presented in Fig. 4, have a constant construction height of 1.5 m and a number of interior girders that varies from 1 to 3 depending on the width of the deck and an overall thickness of 35-40cm. A cross girder, 30 cm thick, is situated at each bearing line to lead to an optimal transverse load distribution coming from the two lanes on the roundabout and 1 lane on the access ramps.

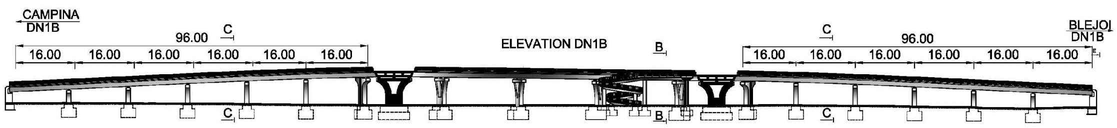

Figure 1. Elevation DN1B

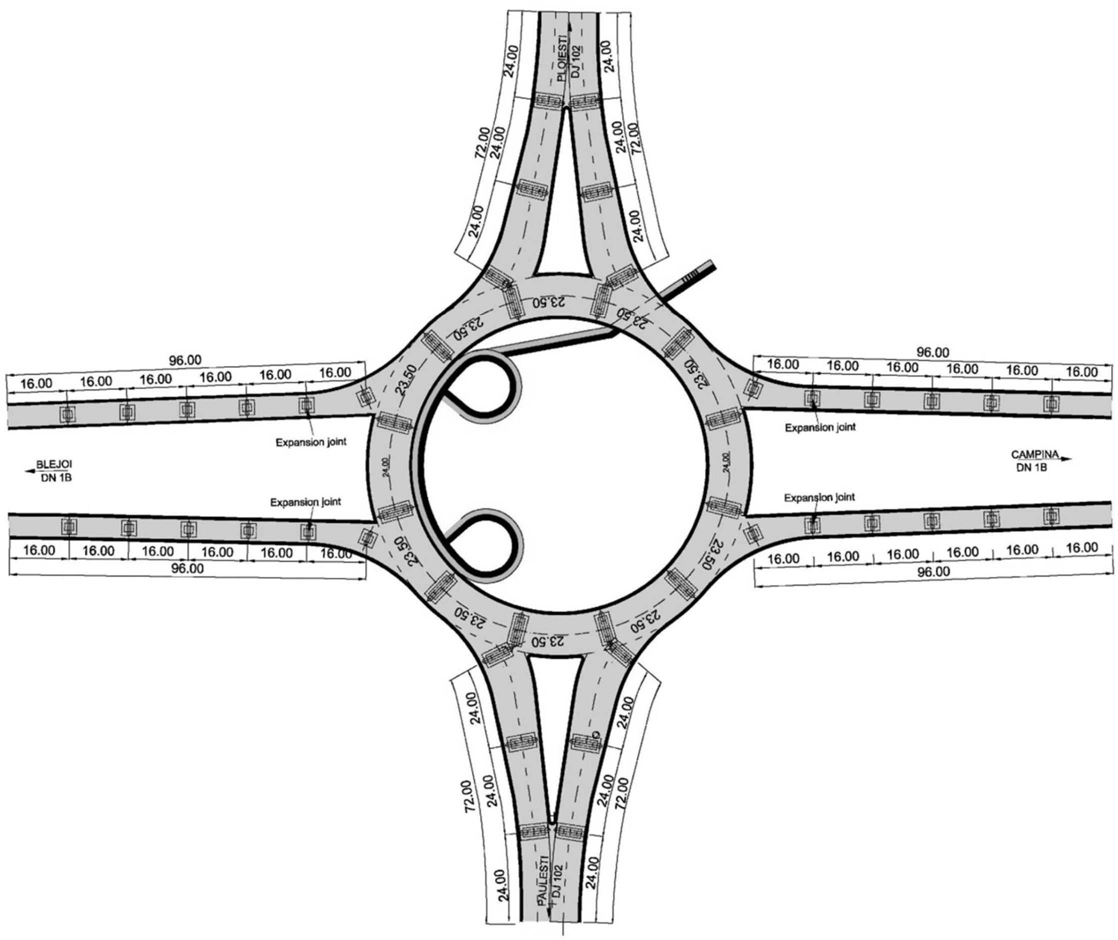

Figure 2. General layout of the roundabout and access ramps

The substructure consists of 6 abutments and 46 piers, with heights ranging from 3.7 m to 7.6 m, supported by shallow rectangular foundations 3.5 m deep. The piers that are associated to the access ramps of DN1B have a rectangular cross section with a thickness of 1.2 m and variable width that starts with 2.5 m at the bottom of the pier and varies along the height of the pier to match the bottom width of the girder which is 4 m. The piers associated to the roundabout and the ramps of DJ102 are 1.2 m thick and 4.5m wide, the width varies along the height of the pier to match the bottom width of the box girder, which is 9.5 m. As the piers on the roundabout and on DJ102 acted heavy, an opening 3.2 m high with a variable width was created along the height of the pier, as can be seen in Fig. 1 and Fig. 3.

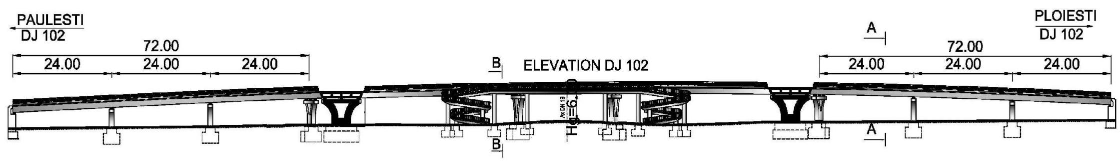

Figure 3. Elevation DJ102

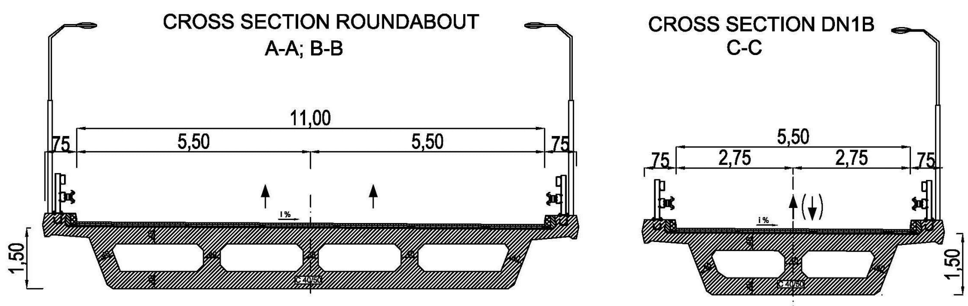

Figure 4. Cross section trough the bridge superstructure

The superstructure is connected to the substructure through high damping rubber bearings situated on the DN1B ramps, with two bearings on the bearing line, and lead rubber bearings situated on the roundabout and DJ102 ramps with 3 bearings on the bearing line.

3. DISCRETE MODELS USED IN ANALYSES

Bridge responses were obtained on several three dimensional simple finite element models, the difference between them being the characteristics of the bearings and the dampers. A 3D view of one of the models is presented in Fig. 5.

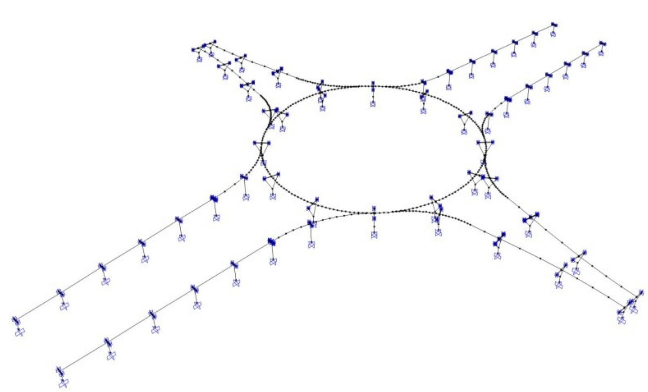

Figure 5. 3D view of the finite element model

The concrete box girder was modelled using straight frame finite elements with two joints. In order to respect the position of the cross sections neutral axis with respect to the piers supporting saddles and bearings, rigid link elements where used in horizontal and vertical direction, as can be seen in Fig. 6. The bearing devices where modelled with link elements with linear or non-linear behaviour, for example the standard elastomeric bearings have linear elastic properties and the LRB's (Lead Rubber Bearings) and HDRB's (High Damping Rubber Bearings) have a nonlinear behaviour according to the bilinear response curve in the ALGA S.P.A. (2008) catalogue.
In order to keep the displacements of the superstructure to a minimum, to add additional damping and to return the superstructure to its previous position after a seismically event, viscous dampers where added to the piers where expansion joints are situated.

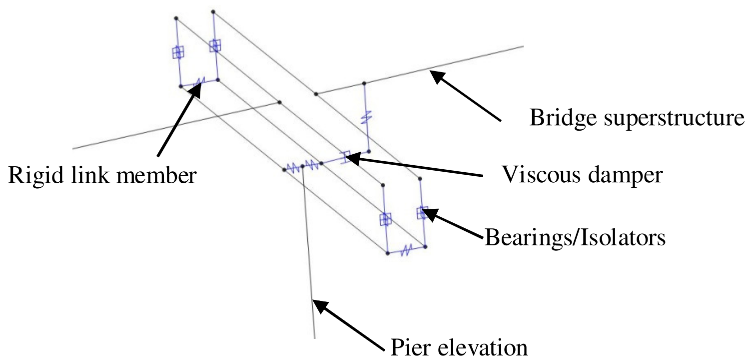

Figure 6. The connection between the super- and substructure

Because the substructure rests on shallow foundations, all six degrees of freedom of the joints connected to the ground where blocked trough restraints.
All finite elements and their characteristics have been modelled using CSI (2010) software.

4. PERFORMED ANALYSES AND RESULTS

In order to calibrate the models for the dynamic response, linear eigenvector analyses followed by response spectrum and linear time-history analyses were performed on the model with standard elastomeric bearings. The resulted maximum values for the internal forces on the piers as well as the nodal displacements at superstructure level were compared. The used design response spectrum according to P100 (2006) and SR EN 1998-2 (2006) describe the seismic input for the bridge location characterized by a corner period T_c=1.00 s, a horizontal design absolute acceleration a_{max}=7.55 m/s^2, considering a behavior factor q=1 because of the shallow foundations. The fundamental period of the structure is 1.761 s, according to the response spectrum an absolute acceleration of 4.8 m/s^2 and a relative response displacement of 0.34 m are associated to this value of structural vibration. Table 1 shows the variation of the internal forces at the base of the most stressed piers, but also the displacements at the superstructure level, at those particular locations. The most stressed piers tend to be those where the expansion joints are located, because there are two bearing lines which transfer the inertial mass of the superstructure to the substructure.

Table 1. Bending moment, shear forces and displacements from the seismic load only

1	A	B	C	D
2	Analysis type	Bending moments M, [kNm]	Shear forces, [kN]	Displacements, [m]
3	Response spectrum	15857	2167	0.365
4		18294	3120	0.357
5	Linear time-history	20052	2741	0.375
6		21681	3697	0.388
7	Differences [%]	+21	+21	+2.000
8		+15.6	+15.6	+7.900

The values presented in Table 1 show that the level of stress in the piers is high, leading to very large foundations and high reinforcement percentage values, as well as the displacements which tend to overpass the limits of usual expansion joints which are in the range of 0.20-0.25 m. This means that the magnitude of the displacements needs to be reduced as well as the values of internal forces. The issue of large displacements at the superstructure level can be addressed through the use of viscous dampers which are linked to the super- and substructure, as shown in Fig. 6. According to Naeim and Kelly (1999), Soong and Dargush (1997) a viscous damper with linear relation between the damping force F and speed v, can achieve at small speeds small damping forces, the equation for a linear damper is presented in Eqn. 1, where F is the damper force, c the damping constant and v is the speed.

$$F = c \cdot v \tag{1}$$

Because of this issue dampers with nonlinear behavior are usually used in practice, Eqn. 2 shows the mathematical expression of this behavior, where the exponent α takes values from 0.2-1, and *sign(·)* is the sign function, for high speed values, the damper acts slower, and doesn't damage the structure.

$$F = c \cdot v^{\alpha} sign(v) \tag{2}$$

By adding the viscous damper, the modal behaviour of the structure has not changed very much being 1.65 s, which means that the value of the absolute response accelerations is similar to previous adjustment of the structure. The changes can be observed in Table 2. Because of the added damping the internal forces and the displacement drop very much, bringing the displacement at values which are within the limits of usual expansion joint devices. Although the internal forces have dropped very much, their values would force unacceptable dimensions of the foundations and reinforcement in the piers.

Table 2. Bending moment, shear forces and displacements from the seismic load only

1	A	B	C	D
2	Analysis type	Bending moments M, [kNm]	Shear forces, [kN]	Displacements, [m]
3	Linear time-history	20052	2741	0.375
4		21681	3697	0.388
5	Nonlinear time-history	14618	2010	0.092
6		14321	2430	0.137
7	Differences [%]	-27	-26.7	-75.5
8		-33.9	-34.3	-64.7

In the attempt to reduce the internal forces in the substructure, the principles of base isolation are used by modelling special bearing devices with low stiffness and high damping capacity, which disconnect the superstructure from the substructure in case of a seismic event. This concept would imply high displacement values and thus forcing the use of viscous dampers, in consequence the viscous dampers from the previous model will be used in the present model too. On the ramps that emerge from DN1B HDRB's will be used, on the roundabout and the ramps from DJ102 LRB's will be used. The reasoning for such an arrangement lies in the fact that the roundabout is much heavier than DN1B ramps, as it sustains two lanes which means that bearings with a much higher vertical load capacity are needed, which come with a higher surface and a bigger stiffness which would transmit more force to the infrastructure. Another advantage that the LRB's have is the higher damping, compared to the HDRB's. The major disadvantage of the LRB is the economical aspect, as they have a complicated manufacturing process and tend to get pricier.

The LRB's and the HDRB's are placed at the top of all piers of the bridge. Both isolation systems were modelled into the structural analysis program using nonlinear "link" elements. The force-displacement relationship is described using a bilinear curve, presented in Fig. 7, for the LRB device while the HDRB has linear force-displacement behaviour as presented in Naeim and Kelly (1999).

Fig. 7 shows F_{max} and D_{max} as the maximum force and displacement of the isolator, F_y and D_y being yielding force and the yielding displacement, K_1 is the initial stiffness, K_2 the post yielding stiffness an K_{eff} is the effective stiffness. Starting from the fundamental period of the structure, which sets the structure outside the amplification domain of the response spectrum, the properties of the isolators can be established using Eqn. 3 and Eqn. 4, Chopra (2007) and Zekioglu et al. (2009).

In the equations below, T is the fundamental period of the structure, m the modal mass, K_{eff} the effective stiffness of the isolator, K_{piers} the bending stiffness of the piers and K_{str} is the overall stiffness.

$$T = 2\pi \sqrt{\frac{m}{K_{str}}} \tag{3}$$

$$K_{eff} = \frac{1}{n} \frac{K_{piers} \cdot K_{str}}{K_{piers} - K_{str}} \tag{4}$$

of the bridge structure. The isolator is chosen based on the values calculated for K_{eff}, in this situation the ALGA S.P.A. (2008) catalogue was used and the LRN D700 B750 Z550 LRB isolator and HDH D350 B400 Z300 HDRB isolator where selected. The LRB's properties are ξ=4% and G=0.9 MPa. The effective damping β_{eff} for this type of isolator is 30% and the maximum displacement is 140 mm. In this case, K_1 is the lead core and K_2 is the elastomer contribution respectively. The HDRB's properties are ξ=16% and G=1.4 MPa.

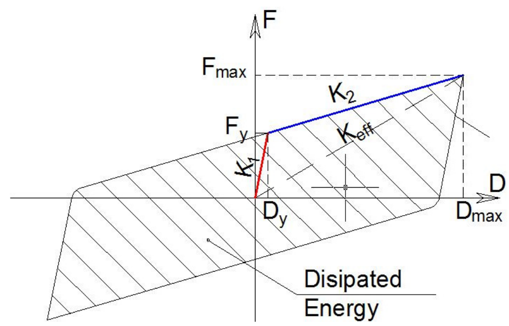

Figure 7. force displacement relationship of the isolators

Fig.8 and Fig. 9 show the hysteresis curves of the LRB and damper under the load of a generated accelerogram, this pier is situated at an expansion joint on a DN1B ramp.

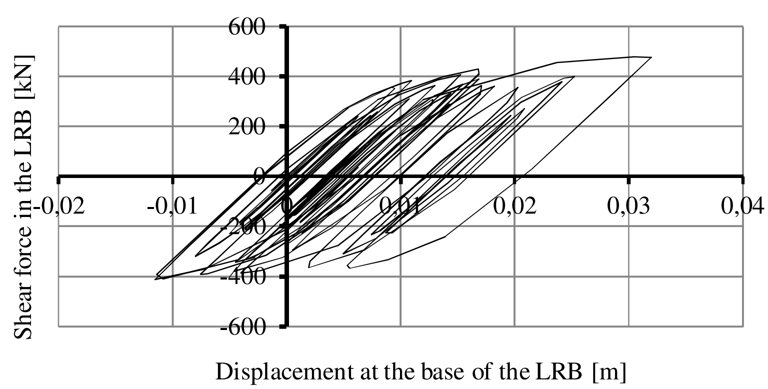

Figure 8. Hysteresis curve of the LRB

Table 3. Internal forces and displacements of the most stressed piers

1	A	B	C	D
2	Analysis type	Bending moments M, [kNm]	Shear forces, [kN]	Displacements, [m]
3	Nonlinear time	8196.7	1035.3	0.24
4	history	5752.5	888.5	0.23

The values of the internal forces have decreased considerably, as can be seen from Table 3, allowing the shallow foundations to be designed. Displacement values have not decreased that much but they are within acceptable limits.

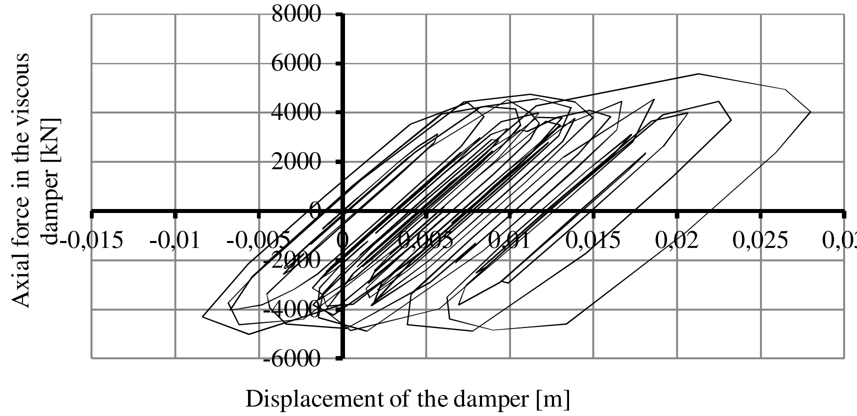

Figure 9. Hysteresis curve of the viscous damper

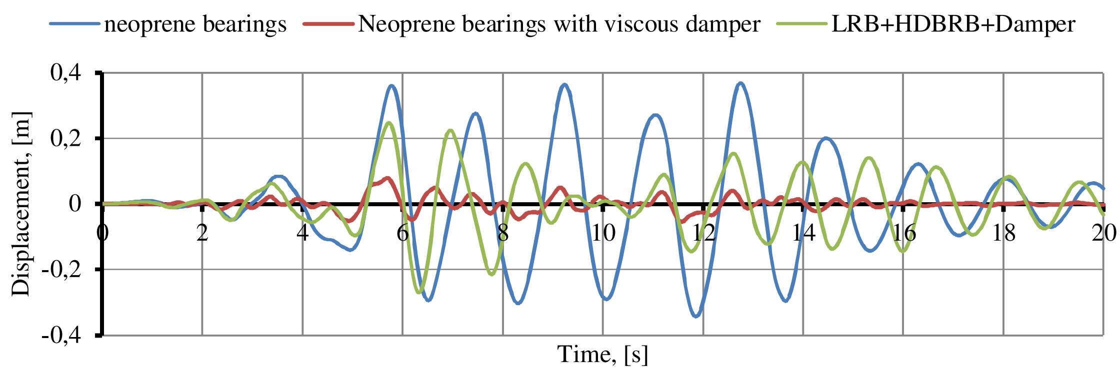

Figure 10. Time histories of the horizontal displacements of the superstructure

5. CONCLUSIONS

This paper investigates the behavior of a concrete roundabout bridge with access ramps, under seismic load with standard neoprene bearings but also with special isolation devices. Several finite element models were built for this purpose, using linear response spectrum, linear and nonlinear time-history analyses. The ground motion was simulated using a design response spectrum according to the Romanian norm P100 (2006) and SR EN 1998-2 (2006) for the location of the bridge, but also 3 artificially generated accelerograms based on the above mentioned response spectrum. All analyses were carried out on the structure with standard elastomeric bearings, but also on the model equipped with dampers and isolation devices. Because the fundamental period of the structure is outside the amplification domain, the main goal of the study is to reduce the superstructures displacements. The issue of internal forces is also very important because the beneficiary asked for shallow foundations.

The structure with standard elastomeric bearings exhibits large displacements at the superstructure level (0.375 m), as shown in Table 1 and very large internal forces making the design process impossible. Through the introduction of the viscous dampers the displacement reduced itself by 75% and also the stress level in the piers decreased, but still maintains at unacceptable values. The use of HDRB on the DN1B ramps and LRB devices on the DJ102 ramps and roundabout, while keeping the viscous dampers, the stress level in the piers decreased to an acceptable level.

REFERENCES

ALGA S.P.A. (2008). Algasism. High Damping Rubber Bearings. Lead Rubber Bearings

Chopra, A.K. (2007). Dynamics of Structures. Theory and Applications to Earthquake Engineering, Pearson Prentice Hall International.

CSI. (2010). CSI Analysis Reference Manual for SAP2000, Etabs and Safe, Berkeley, California, USA.

Naeim, F. and Kelly, J.M. (1999). Design of Seismic Isolated structures: from theory to practice, John Wiley&Sons, Inc., N.Y.

P100-2006. (2006). Romanian Seismic Design Code-Part I: Design Provision for Buildings

Soong, T.T and Dargush, G.F. (1997). Passive Energy Dissipation Systems in Structural Engineering, John Willey&Sons

SR-EN 1998-2. (2006). Design of structures for earthquake resistance. Part 2: Bridges

Zekioglu, A., Darama, H. and Erkus, B. (2009). Performance-Based seismic design of a large seismically isolated structure: Istanbul Sabiha Gökçen International Airport Terminal Building. *SEAOC 2009 Convention Proceedings* ,409-427.