Pseudo-Dynamic test of an old R.C. highway bridge with plain steel bars - part II: Investigation on the effectiveness of Yielding-based and FPS isolators

L. Di Sarno[1], R. De Risi[2], F.Paolacci[3], A.Marioni[4], M. Sartori[4], F.Taucer[5], P.Pegon[5]

[1]*University of Sannio, Benevento, Italy*
[2]*University of Naples Federico II, Naples, Italy*
[3]*University Roma Tre, Rome, Italy*
[4]*Alga Spa, Milan, Italy*
[5]*Joint Research Center, Ispra, Italy*

ABSTRACT

The “Retro” project funded by the European commission within the Series-project aims at studying numerically and experimentally the seismic behaviour of an old existing reinforced concrete bridge with portal frame piers and the effectiveness of different isolation systems. An experimental test campaign is performed at ELSA Laboratory of JRC (Ispra, Italy). Two piers (scale 1:2.5) in non-isolated and isolated configuration are tested using the PsD technique with sub-structuring. The work is subdivided in two parts: the present paper is devoted to the analysis of the “isolated” configuration whereas a companion paper illustrates the results of the “as-built” case. Friction pendulum systems (FPSs) were utilized as isolation devices for the bridge continuous deck. They have been currently designed and characterized using a Direct Displacement design approach. The effectiveness of the isolated bridge has been validated through dynamic non-linear analyses both on refined and simplified numerical models of the bridge. A comprehensive numerical investigation and the results of the on-going PsD experimental activities have shown the high effectiveness of both the isolation systems in reducing the damage level of the piers, especially limiting slippage of reinforcements due to the presence of plain steel bars and the shear damage in the transverse beams, already noticed in the “as-built” configuration of the viaduct.

1. INTRODUCTION

The present papers focuses on the seismic response analyses of the Rio Torto bridge, which is a typical reinforced concrete (RC) existing bridge built in the 1960s and located on the A1 highway between Firenze and Bologna, in the North of Italy (see also Figure 1). The bridge is not compliant with the modern seismic codes, as further discussed in the companion paper (Paolacci et al., 2013), which also includes a full description of the bridge geometry and material properties. The sample structure is located in a region with moderate seismic hazard level as also shown in Figure 1. Passive control retrofitting measures were used for the RC bridge to augment the seismic structural performance. The multispan decks was transformed into a continuous beam, then seismic isolators were used to enhance the dynamic response of the RC deck.

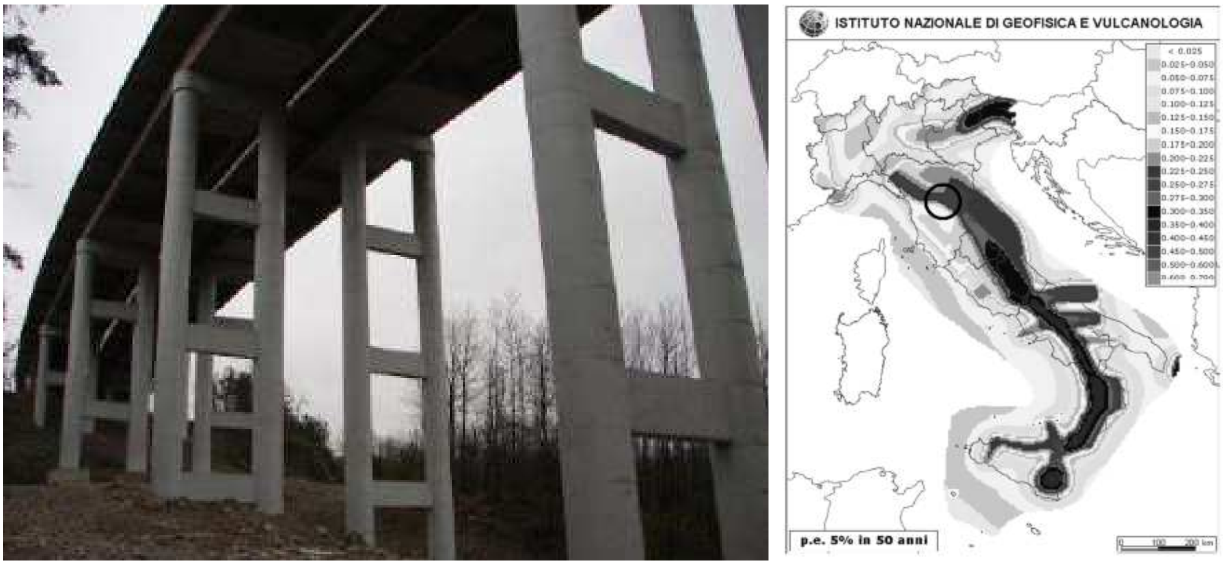

Figure 1 – Perspective of the Rio-Torto bridge (left) and national seismic hazard map (right).

The isolation system adopted herein includes the friction pendulum system (FPS) (e.g. Zayas *et al.*, 1990; Mokha *et al.*, 1991, among many others). The design of the FPS devices has been carried out with a displacement-based procedure focusing on two objectives: (a) keep the piers in the (quasi-) elastic range of response and (b) minimize the displacement demand on the expansion joints located at the abutments.

2. FRICTION PENDULUM SYSTEMS

Three basic types of friction pendulum (FP) devices are generally used for new and existing constructions: (i) isolators with one spherical sliding surface, that may be at the top or at the bottom of the device, connected to a spherical hinge; (ii) isolators with two main spherical surfaces and an interposed point rocker articulation that allows relative rotations (e.g. Fenz and Constantinou, 2006); (iii) devices with two perpendicular cylindrical surfaces and two perpendicular cylindrical articulations allowing the relative rotations (Marin, 2006). The selection of the type of FP device to use in a specific project device depends on the structure to be retrofitted. The type of FP depends remarkably on the allowable displacement of the structural system. Such displacements generally control the design of the isolators. The FPs with two-spherical surfaces is often used to minimize the plan dimensions of the isolator and to limit the vertical load eccentricity caused by the horizontal displacement. The third type is used when a different behaviour is required in two perpendicular directions. The first type of device is the most commonly adopted due to its simplicity; such devices was adopted herein to seismically isolate the Rio Torto bridge, which is characterized by relatively low displacements and the similar response along the lateral and transverse directions. The basic elements of the single-surface FP are: the upper anchor plate (1), the sliding surface (2), the sliding material interface (3), the rotation element (4), the rotation sliding surface (5) and the lower anchor plate (6). From a mechanical standpoint, the FP devices are characterized by a bilinear force-displacement relationship:

$$V_{FPS} = \mu_f \cdot N + \frac{N}{R} \cdot \Delta_{iso} \tag{1}$$

where μf is the friction coefficient, N is the normal force, R is the device curvature radius and Δiso is the sliding displacement in the isolator. Figure 2 provides a typical hysteretic behaviour obtained during dynamic tests on a FP with a single sliding surface:

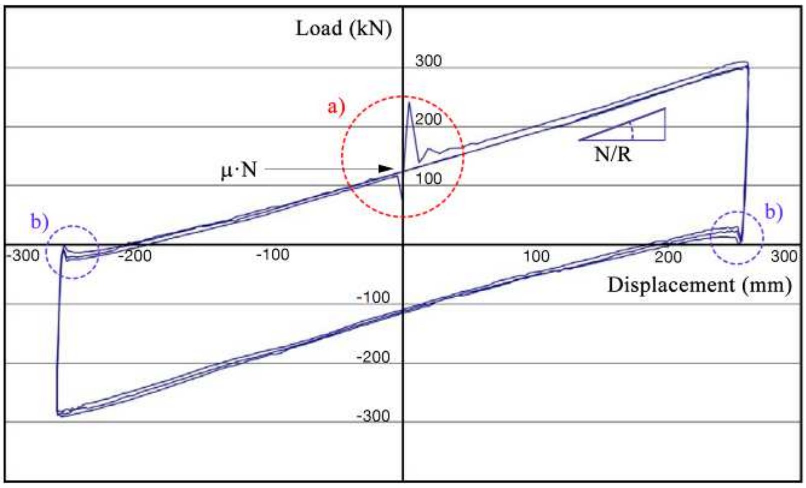

Figure 2 - Hysteretic behaviour obtained during dynamic tests on single concave surface sliding pendulum.

The variation of the friction coefficient relative to the breakaway of the motion (a) and change in sign of velocity (b) is also displayed in Figure 2.
The FP isolation system has been designed according to a displacement-based design method which is presented in detail in Della Corte *et al*. (2011). The method is based on the direct displacement based procedure proposed by Priestley *et al*. (2007). A few modifications have been proposed to the general method and specific design tools have been developed for the case of isolation by means of FPS. It is worth mentioning that the adopted methodology for the specific case study is focused on the design of FP systems, but it can be easily extended to other systems exhibiting a bilinear hysteretic behaviour. The radius of the FP used for the seismic retrofitting of the Rio Torto is equal to 3 m and the friction coefficient is equal to 4%. It is also used an height of articulated slider of 9 cm and a initial yield displacement of 0.5 mm. Nonlinear response history analyses for the base isolated sample Rio Torto bridge were carried out by using the 20th and 29th May Emilia (Italy) earthquakes.

3. NUMERICAL MODELLING

A comprehensive 3D Opensees (McKenna *et al*., 2004) model was developed to simulate accurately the seismic response of the Rio Torto bridge. The numerical model is similar to FE system used for the non-isolated case (Paolacci *et al*., 2013): joints and elements labeling, modeling of the piers (considering all the non linear sources, as the shear behavior and the fix-end rotation), deck represented as elastic beam, piers fixed to the base and uniform transverse supported assumption. Two differences were, however, included for the base isolated system: the Gerber-saddle was removed (i.e. a continuous beam was obtained) and isolation devices between the piers and the deck were introduced, as seismic retrofitting scheme. The use of base isolators for the bridge deck increased the number of vertical coordinates of the deck joints.
A simplified novel procedure was developed for the design of the base isolators used for the bridge deck. Two assumptions were employed in such design procedure, namely the system is partially isolated (i.e. the bridge with isolation devices at piers and pinned supports at abutments) and nonlinear (bilinear) devices were utilized as isolators. The non-linear response curve of the isolator is bilinear; the curve has an initial rigid branch and the lateral stiffness drops when the shear action in the device exceeds the force threshold (i.e. the friction strength in the case of friction pendulum system (FP) or the yield strength in the case of elasto-plastic isolators (EP)).
The FP devices used to seismically isolate the bridge deck of the Rio Torto were modelled in the computer program Opensees. The command used to simulate numerically the response of the FP is "singleFPBearing" element object (Schellenberg 2010), which is defined by two nodes. The i-Node represents the concave sliding surface and the j-Node represents the articulated slider. The element can have zero length or the appropriate bearing height. The bearing has unidirectional (2D) or coupled

(3D) friction properties (with post-yield stiffening due to the concave sliding surface) for the shear deformations, and force-deformation behaviors defined by UniaxialMaterials in the remaining two (2D) or four (3D) directions. To capture the uplift behavior of the bearing, the user-specified UniaxialMaterial in the axial direction is modified for no-tension behavior. By default P-Delta moments are entirely transferred to the concave sliding surface (i-Node). It is important to note that rotations of the concave sliding surface (rotations at the i-Node) affect the shear behavior of the bearing. To avoid the introduction of artificial viscous damping in the isolation system (sometimes referred to as "damping leakage in the isolation system"), the bearing element does not contribute to the Rayleigh damping. If the element has non-zero length, as in this case, the local x-axis is determined from the nodal geometry unless the optional x-axis vector is specified in which case the nodal geometry is ignored and the user-defined orientation is utilized.
The mechanical properties used to define singleFPBearing in Opensees are the type of friction material, the curvature radius and the height of the device. The Coulomb approach was used for the simulation of the devices for the Rio Torto bridge; thus kinetic friction is independent of the sliding velocity, in compliance with Coulomb's law. The latter assumption is compliant with the PSd test procedure.

4. EARTHQUAKE RESPONSE ANALYSES

The Mirandola records (MRN station) of the 20 and 29 May Emilia (Italy) earthquakes were employed to perform the earthquake response analysis of the sample bridge. The deck and piers maximum transversal displacement are displayed in Figure 3, in red and blue respectively. The maximum transverse displacement is about 18cm; the latter does is found at the 6th pier. The maximum lateral displacement of the piers is about 14 cm (Pier no.7). The deformed shape of the deck exhibits the maxima at mid-span, as expected. The maximum relative displacements occur for the deck between Piers 4 and 9.

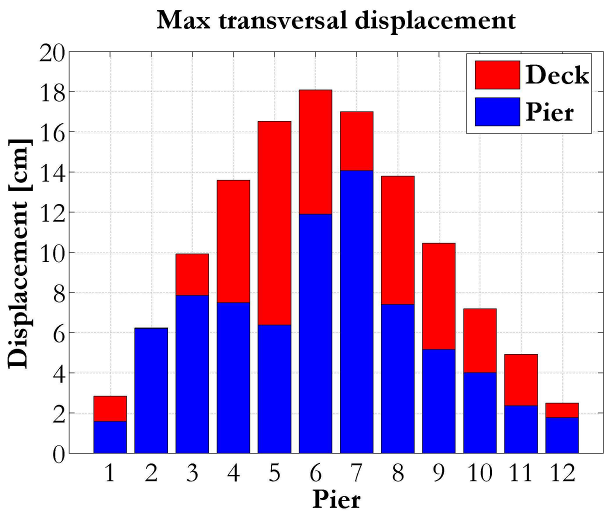

Figure 3 - Deck and piers maximum transversal displacement.

The difference between the displacements of the piers and the bridge deck is due to the devices activation. Figure 4 shows the hysteretic behaviour of the FP devices when the base isolated bridge is loaded by the sample strong motions.

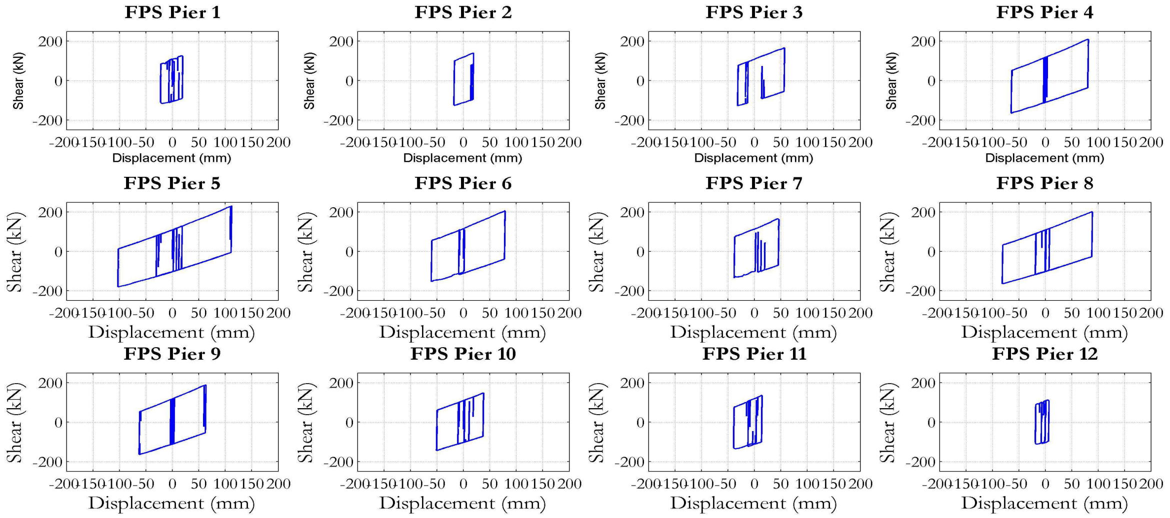

Figure 4 - Hysteretic behavior of the devices during the strong motion.

The devices are activated for a sliding shear of about 100 kN, as expected from a simplified analysis (i.e. $V=\mu\cdot N\approx 0.04\cdot 2500=100$ kN). It is also found that the highest energy dissipations for the devices installed on the top of piers between piers no.4 and 9 confirm the maximum relative displacements shown in Figure 3. Additionally, the activation of the device causes the limitation of the transmitted shear from the deck to the piers; the latter behave elastically, thus inhibiting the onset of structural and non-structural earthquake-induced damage. Figures 5 and 6 illustrate the maximum base shear in the piers and the maximum storey drift for each piers, respectively.

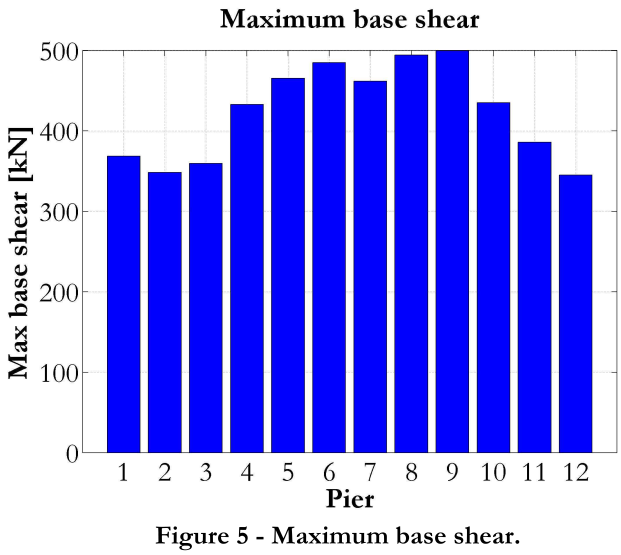

Figure 5 - Maximum base shear.

It was found by De Risi et al. (2011) that the first yielding of the bridge system is obtained for a base shear of about 500 kN. It is worth noting that Figure 12 proves that all the maximum base shear are lower than the latter yielding value, hence the occurrence of the inelasticity is prevented.

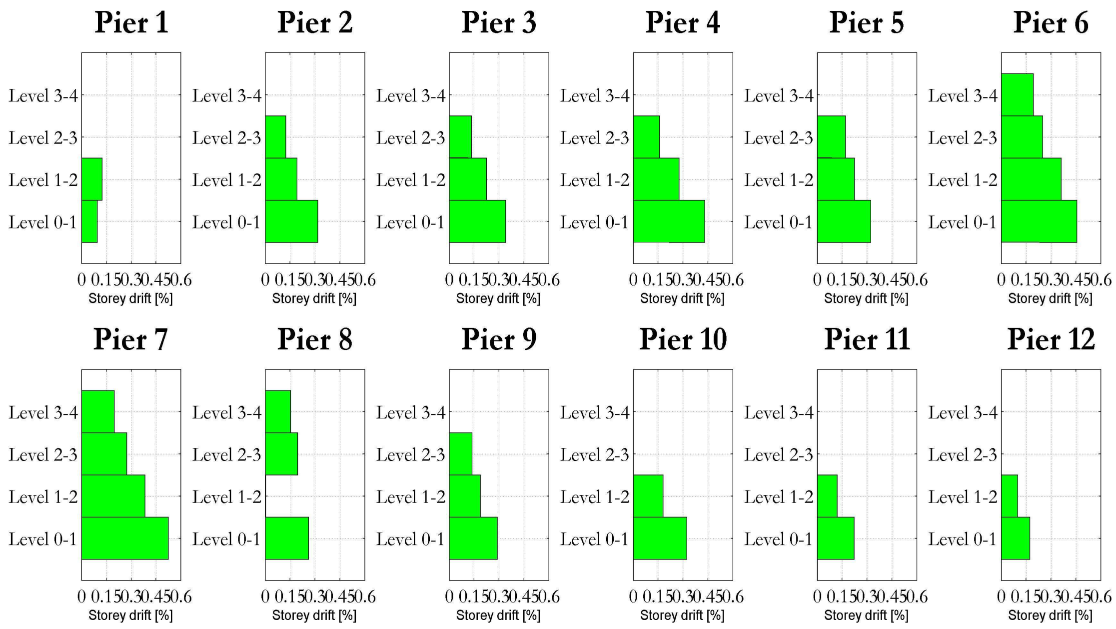

Figure 6 - Maximum inter-storey drift.

The drift corresponding to the shear failure of transverse beam or to the failure of beam-column joints, is about 1%. All the values depicted in Figure 6 are lower or equal to 0.5%, thus the damage is avoided. Figure 7 provides the hysteretic behavior of the single piers of the Rio Torto bridge. It found that the behavior of the piers 9 and 11 is nearly linear.

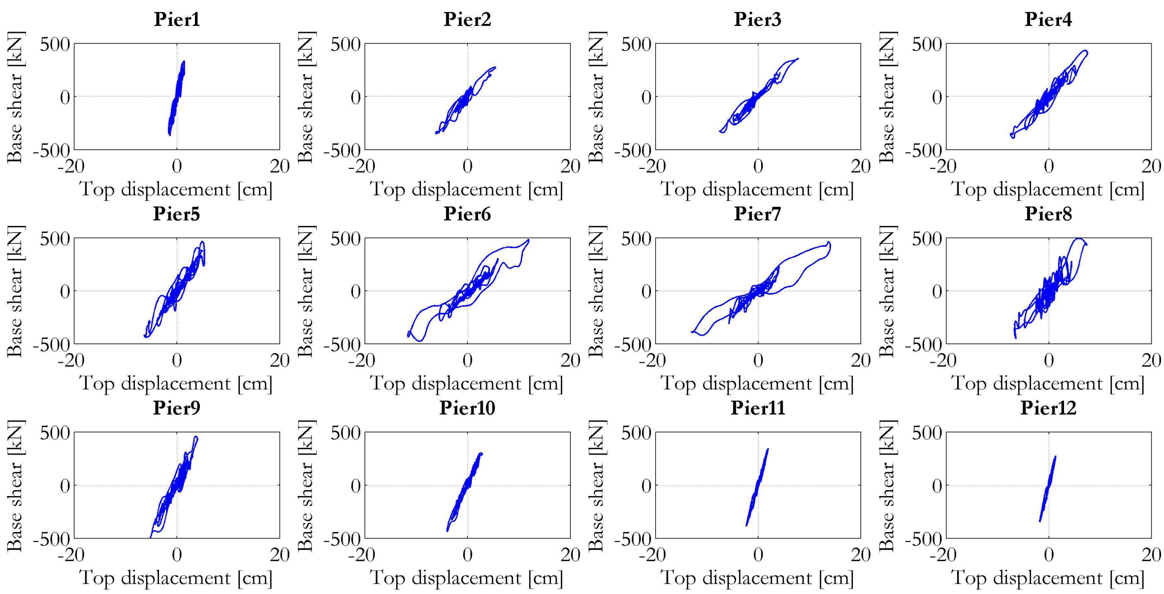

Figure 7 - Hysteretic behavior of the piers.

The insignificant irregular response that can be observed in the behavior of the pier 9 is caused primarily by the shear behavior of the transverse beams, that is slightly activate, as shown in Figure 8.

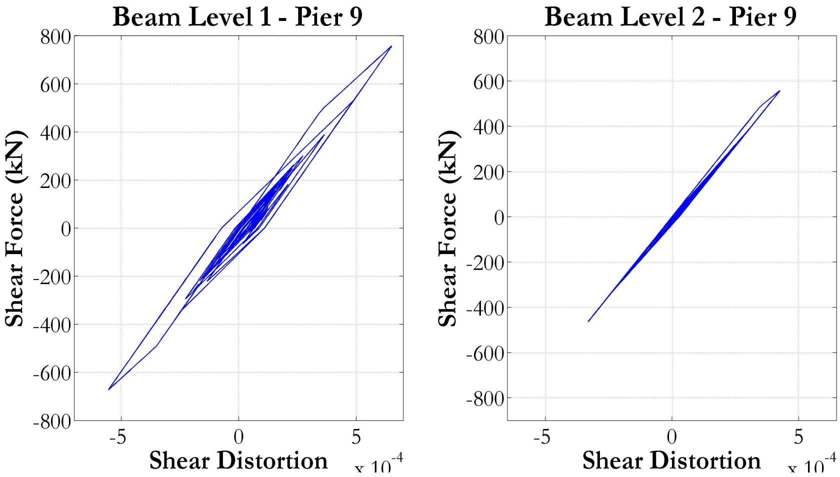

Figure 8 - Hysteretic behavior of the transverse beam.

Similar results were computed also for the 29th May Emilia earthquake, North-South component. The deck and pier maximum transversal displacements are summarized in Figure 9. The variations between the two depicted displacements are due to the devices activation. The hysteretic response is displayed pictorially in Figure 10.

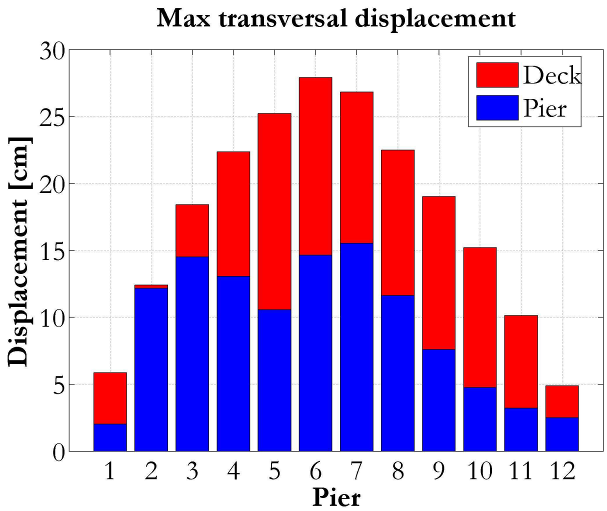

Figure 9 - Deck and piers maximum transversal displacement.

The devices are activated for a first sliding shear of about 100 kN, as expected from a simplified analysis (i.e. V=μ·N≈0.04·2500=100 kN). It is worth to note that the activation of the device causes the limitation of the transmitted shear from the deck to the piers, which remain elastic.

7. Conclusions

The present paper has illustrated preliminary results on the earthquake response analysis of a typical reinforced concrete existing bridge which is not code-compliant. The bridge structure is the sample structure that will be tested within the EU-funded SERIES project (7th European Framework Program). The research project aims at studying the seismic vulnerability assessment of existing RC bridges; retofitting measures, such as base isolation systems are also employed to augment the seismic structural performance. The outcomes of the nonlinear dynamic analyses carried out on the base isolated bridge when loaded by the 20th and 29th May Emilia (Italy) earthquakes show that the seismic performance of the sample structures will comply with the code requirement, thus preventing large earthquake-induced losses in the event of a major ground motions.

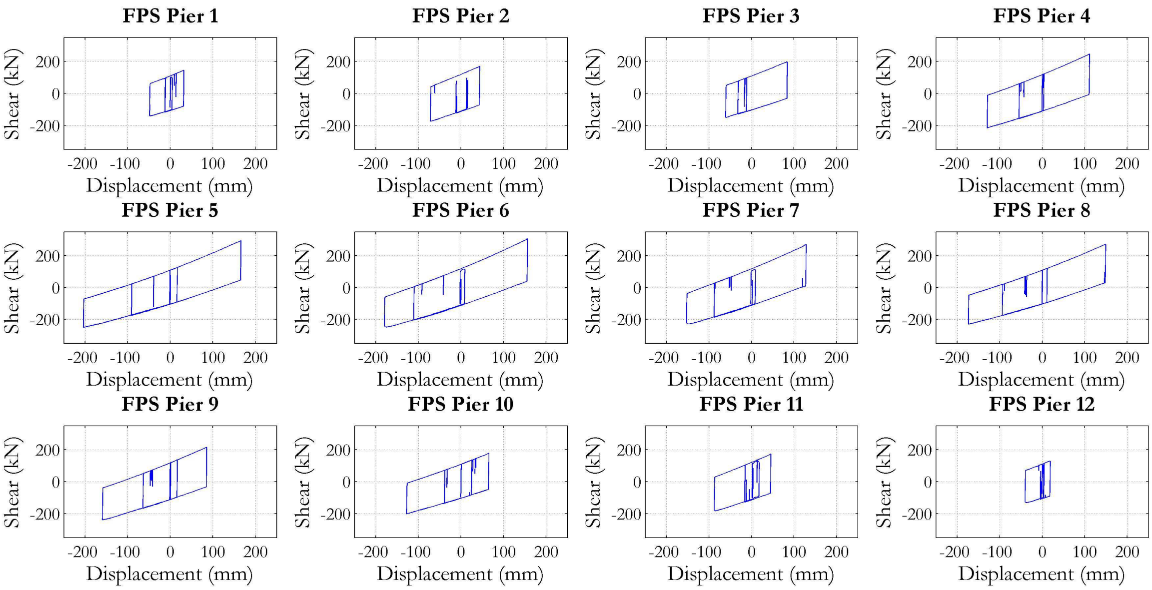

Figure 10 - Hysteretic behavior of the devices during the strong motion.

ACKNOWLEDGEMENTS

The financial support from the SERIES (Seismic Engineering Research Infrastructures for European Synergies) Project, funded within the 7th Framework Programme of the European Commission, is greatly appreciated. Any opinions, findings and conclusions or recommendations expressed in this paper are those of the authors and do not necessarily reflect those of SERIES.

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