Pseudo-dynamic test of an old R.C. highway bridge with plain steel bars - part I: Assessment of the "as-built" configuration

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ABSTRACT: The Retro TA project funded by the European commission within the Series-project aims at studying the seismic behaviour of existing reinforced concrete (RC) bridges and the effectiveness of innovative retrofitting systems. The research activity focuses on old bridges, designed chiefly for gravity loads. Towards this aim, the seismic vulnerability of an old Italian viaduct with portal frame piers (Rio Torto Viaduct) is evaluated and an isolation system is designed using both yielding-based and slide spherical bearings. Some results of predictive numerical analyses, both for "as-built" and "isolated" configuration are illustrated and discussed. The work is subdivided in two parts: the present paper is devoted to the analysis of the "as-built" configuration. The structure is assessed through dynamic analyses. To do so, the Italian guidelines for the seismic assessment of existing bridges, proposed within the Reluis research program (2005-2008), are employed. Progressive damage using natural records is estimated and failure modes of the system components are accurately analyzed. The assessed systems is found sub-standard; it is thus deemed necessary to utilize an adequate retrofitting system such as seismic isolation.

1. INTRODUCTION

The seismic vulnerability assessment of existing and new lifeline systems, especially transportation systems, is becoming of paramount importance in resilient social communities. The Italian transportation systems were mainly built in the late 60s and early 70s and were designed primarily for gravity loads. As results most of the bridges do not employ seismic details and hence their structural performance are generally inadequate under earthquake ground motions. Recently, a comprehensive research program funded by Italian Reluis consortium was initiated to formulate pre-normative European guidelines for the assessment of existing bridges (Pinto and Mancini, 2009). This research program was motivated by the urgent needs to assess the seismic vulnerability and retrofit existing bridge structures. The implementation of

comprehensive guidelines for the seismic assessment and retrofit of existing bridges requires the thorough understating of complex local and global response mechanisms. A full scale testing program was initiated within the European project “RETRO”, a research program of the Seismic Engineering Research Infrastructures for European Synergies (SERIES), financially supported by the Seventh Framework Programme of the European Commission (Taucer, 2011). The experimental test program aims at studying the seismic behaviour of an old reinforced concrete viaduct with frame piers and at investigating the effectiveness of innovative retrofitting systems. The results of predictive numerical analyses, both for “as-built” and “isolated” configuration are discussed herein. The work is subdivided in two parts: the present paper is devoted to the analysis of the “as-built” configuration whereas the second one shows the results of the isolated case. The seismic vulnerability of the structure is assessed using non-linear time-history analyses according to the Reluis guidelines (Reluis 2009). Towards this end, a three-dimensional model of the bridge has been implemented in Opensees (McKenna, et al , 2007).
The results show that the bridge can be considered sub-standard, especially with respect to brittle mechanisms, as shear failure of the transverse beams.

2. Bridge description

The Rio-Torto Viaduct is an old RC bridge located in Emilia-Romagna region as a connection link between Florance and Bologna with a total length of 421.1m (Fig. 1). It consists of a thirteen-span deck with two independent roadways, supported by 12 couples of portal frame piers (Fig. 1, 2), each composed of two solid or hollow circular columns of variable diameter (120-160 cm), connected at the top by a cap-beam and, at various heights, by one or more transverse beams of rectangular section.
The height of the piers varies between 13.8m, near the abutments, to 41 m, at the center of the bridge. The deck consists of two Π reinforced concrete beams 2.75m high, which are interrupted by some Gerber saddles placed at the second, seventh and twelfth bay respectively (Figure 1). The deck is connected to the piers by two steel bars inserted in the concrete, whereas, at the abutments it is simple rested.
The linear distributed weight of the deck is approximately 170kN/m for each road-way (see Table 1) . Each pier is loaded with a vertical load varying between 5600kN and 5300kN, while the length of the bays varies between 33 and 29 m. In Figure 3 the geometry of the deck is shown.

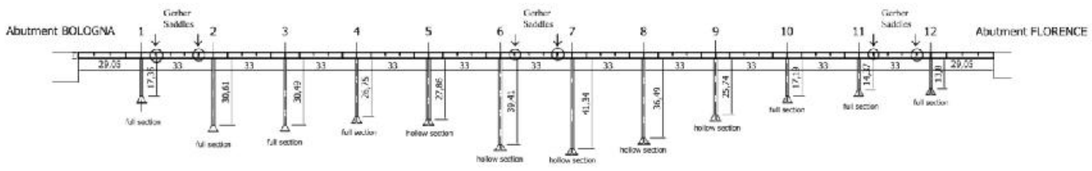


Figure 1. Longitudinal view of the viaduct Rio-Torto

Figure 2. Frontal view of the bridge

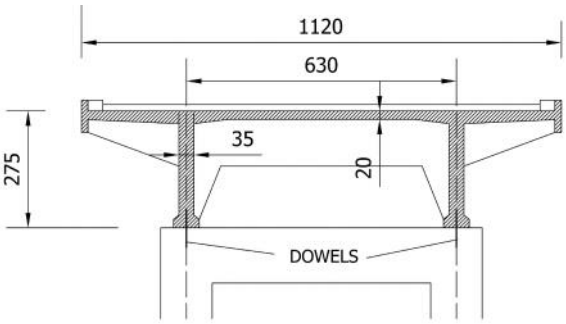
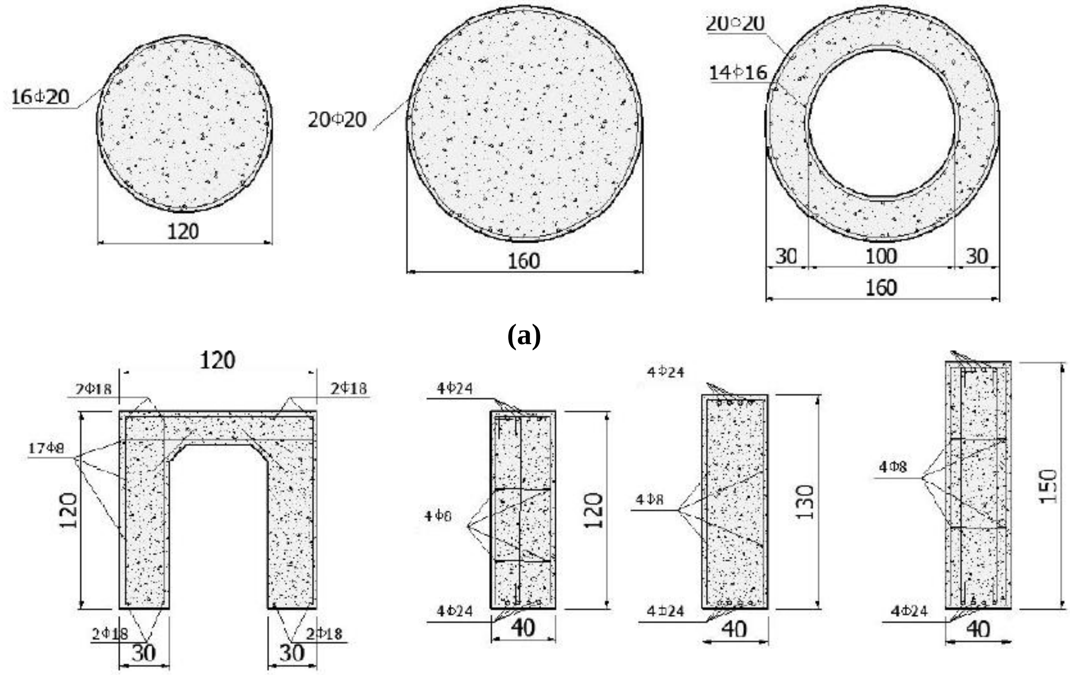


Figure 3. Transverse section of the deck

The columns have two types of cross-sections: a solid circular one with diameter of 120 cm and an hollow section with external and internal diameters equal to 160 cm and 100 cm respectively. Some details of the longitudinal steel bars in these two sections are illustrated in Fig. 4, where the reinforcement layout of the pier 9 and 11 is shown. The solid sections is longitudinally reinforced with 16ϕ20 mm, while the hollow sections contain 16ϕ20 mm and 14ϕ16.
The transverse beams have different rectangular sections: 40×120 cm,40×130 cm and 40×150 cm. Their longitudinal reinforcement is realized with ϕ24 and ϕ20 steel bars. The transversal reinforcement is realized with stirrups ϕ8 with spacing of 20 cm and inclined bars (45°). The Cap-beam of all the piers presents an inverted U-shaped section. All bridge piers have plain steel bars; the modelling of the non-linear local behaviour (e.g. bond-slip, bar buckling, etc.) is thus of paramount importance for the reliable structural assessment.
The data relative to the mechanical properties of materials of constructions were scarce. The class of concrete is known; it corresponds to an average unconfined cylindrical strength fc=26MPa. This value is compliant with the results that can be found in the literature for typical public structures built in Italy during the 60's (e.g. Verderame et al. 2001, among others). For the mechanical characteristic of old plain steel bars few studies are available in literature (Verderame et al 2001) . The steel grade used for the sample structure was the AQ42 with a mean strength f_y=350 MPa. The soil conditions is widely described in (Yenidogan et al 2013) to which the reader can make reference for more details.

Rio Torto viaduct is considered as a critical structure with class of IV and nominal life of 100 years according to the seismic design code of Italy (NTC-08). The most recent Emilia earthquake that struck the region also supported the idea of assessing the seismic resistance of Rio Torto bridge in case of major to moderate earthquakes. Particular emphasis to Emilia earthquake is considered by using the recordings of the seismic event as input signals in PsD tests of RETRO project.



(b)

Figure 4. Full scale Cross-sections of columns (a) Transverse and Cap-beams (b)

3. Development of a refined model of the viaduct

In the present paragraph the numerical model of one of the two roadways of the viaduct is outlined. The bridge was modelled by using the non-linear code OpenSEES. The finite element scheme is illustrated in Fig. 5.

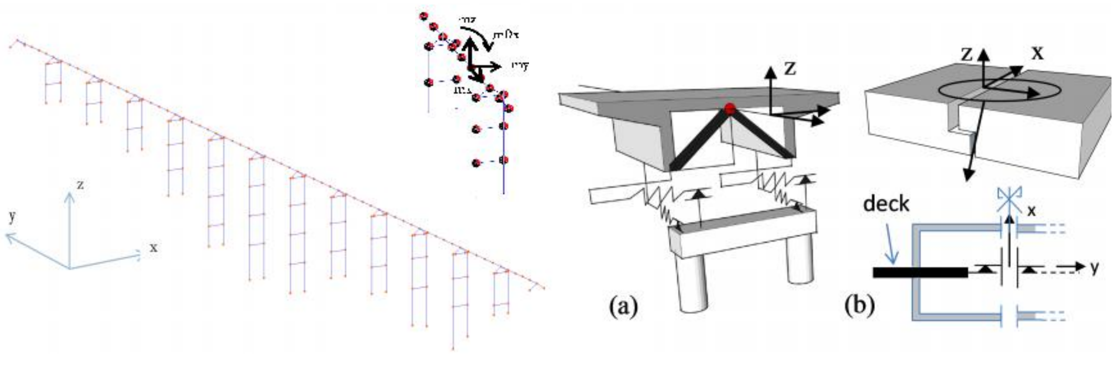


Figure 5. The OpenSEES model of one road-way of the Rio-Torto viaduct, (a) Pier-deck connection model (b) Gerber Saddle model

For the structural elements of the piers nonlinear fiber beam elements with flexibility formulation have been used. The section of each element is subdivided into fibers, assigning to each material the constitutive law.

An important aspect to consider is the bond-slip effect in proximity to the bottom and top of the columns. This phenomenon is due to the difference between the deformation of the bars and concrete which yields a typical crack pattern. In literature, the bond-slip problem and its contribution to the lateral flexibility of structures for horizontal forces have been widely investigated. It is worth pointing out that this effect may be pronounced for plain bars due to the low bond between concrete and steel. Following the approach proposed in (Zhao and Shritaran 2007), one way to account for the bond-slip effect consists of concentrating the rotation due to the slippage of the bars in a section. This model, already implemented in OpenSEES, is here adopetd to simulate this phenomenon. More details can be found in (Paolacci and Giannini 2012).

In order to calibrate the numerical model of the pier, a shear behavior of the transverse beam must be implemented. It is well known that shear response plays an important role especially for existing structures that do not meet seismic engineering design criteria. In the literature, several studies concerning the shear behavior of reinforced concrete beams or walls and their interaction with flexural response are reported and compared with experimental results, (Ceresa et al 2007, D'Ambrisi and Filippou 1999, Hidalgo et al 2002, Leet et al 2005).

Considering these formulations in the literature and the relatively scarce information about experimental results for shear behavior in the presence of plain longitudinal bars a phenomenological shear-strain hysteretic relationship for shear behavior of the transverse beam has been here assumed. It consists of a tri-linear envelope curve with stiffness and strength degradation with pinching response which is always observable in the reinforced concrete elements subjected to shear forces. The model is similar to the one proposed by D'Ambrisi and Filippou (1999) and Lee et al. (2005) except for both the influence of axial force on the shear relationship, here neglected, and the use of a tri-linear backbone curve.

For the behavior of concrete the Kent-Scott-Park model has been adopted. Moreover, the contribution of the tensile strength was neglected. According to the results in the literature, especially from experimental tests, the contribution of concrete tensile strength in modeling structures with plain steel bars and poor seismic details may be neglected (Marefat et al. 2009).

The rebars were modeled with the Menegotto-Pinto relationship. A yield stress equal to 350 MPa is assumed, along with a modulus of elasticity equal to 205000 MPa and a hardening parameter equal to 0.025.

To assign the mass along the deck, each span of the bridge was subdivided into 5 parts (with length ranging from 5.81 to 6.60 m).Consequently, the translational mass has been defined on these pieces along the longitudinal, transversal and vertical directions (m_x, m_y and m_z), while the rotational mass has been defined only around longitudinal direction (global y-axis).

The supports of the piers has been considered fully fixed in all directions while the abutments at both the sides of the bridge were assumed as simply resting in the longitudinal direction (global y) but restrained in the x and z directions. The Gerber saddles have been modelled using rigid elements with gap in the longitudinal direction and rigid rotational gap elements around the vertical direction. In addition, the relative displacements along x-direction were considered restrained, thus including the possibility to transfer shear in the transversal direction (Figure 9b). Because the pier-deck connection has been realized using two steel bars (dowels) of diameters 34 mm for each column (Fig. 5), they have been modeled using elasto-plastic elements with shear strength and elastic stiffness of the pairs of steel bars. Moreover, the vertical relative displacements are considered restrained, whereas all the rotation components are permitted.

In order to correctly simulate the behaviour of the deck, it has been modelled using elastic elements placed at the center of gravity of the deck, connected to each pier using a couple of inclined rigid beams (Fig. 5). If the considered return period is not specified in (NTC-08), required parameters of the generic return period are computed by two consecutive return periods in the seismic design code where the generic one falls between.

4. Discussion of the results

The first six eigenvalues and the corresponding participating masses of the viaduct are reported in Table 1. The mode shapes are displayed in Fig. 6. The first mode is along the longitudinal direction with a period of about 3.2 sec. The 2nd mode, as well as the 6th mode, are in the transversal direction, which involve piers from 7 to 11, with almost 50% of the entire mass involved in the vibration.

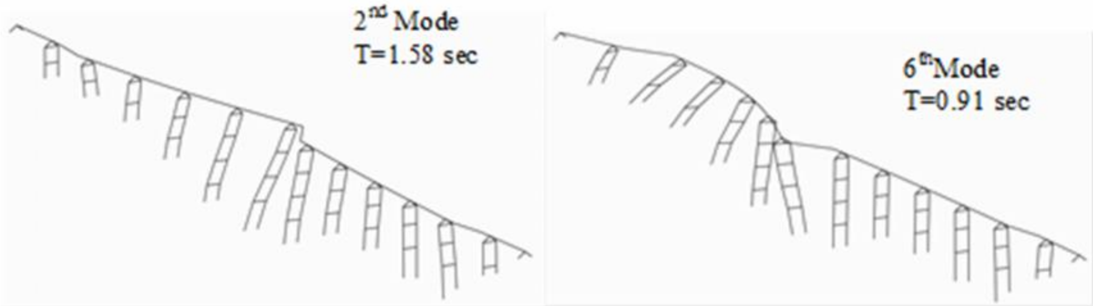


Figure 6. The main vibration modes of the bridge

Current practice and tendency for record selection stand in need to de-aggregate the uniform hazard spectrum (or spectra) at the first mode period of the structure (T_1), determine the modal magnitude (M) and site-to-source distance (r) pair, and select recorded ground motions corresponding to the modal [M, r] pair and local site conditions. In order to achieve the minimum manipulation on the selected input motions only real earthquake records with linear scaling procedures were considered (Yenidogan et al 2013).

The remaining mass participates to the vibration modes 3 and 4, which involve pier from 2 to 6. This particular behaviour is due to the effect of the Gerber Saddles that induce independent vibrations of the four parts in which the viaduct is subdivided.

Table 1. Vibration periods and Modal Participating Mass.

Mode	T(sec)	MPS (x)	MPS (y)
1	3.23	0.00	92.41
2	1.58	27.35	0.00
3	1.45	2.94	0.00
4	1.40	24.89	0.00
5	0.94	7.14	0.00
6	0.81	22.51	0.00

The distributed mass of the piers has a very limited influence on the seismic response of the viaduct. The maximum difference in terms of period and Modal Participating Mass is about 4%.

Moreover, the modes in which the local vibration of the piers and then its distributed mass is involved are very stiff modes. This proof again that the mass of the piers can be neglected in calculating the seismic response of the viaduct. It is also important to underline that the influence of the rotational mass of the deck on the seismic response of the viaduct is very limited. It is true that piers during the lateral displacement rotate, but the excited mass involved in this movement is very limited. So, the variation of the axial forces in the pier's columns is very limited too and its variation is due only to the horizontal force applied at the top of the piers. Moreover, the elastic torsional modes of the deck are negligible and therefore their contribution can be neglected.

Two limit states are considered for the seismic performance assessment of the "as built" Rio-Torto viaduct: Slight Damage (SD) and Ultimate Limit State (ULS), respectively. Given the geographical position of the bridge and the recent earthquake swarms occurred in the region (especially the earthquake records of the 20th and 29th May 2012), it was assumed to use the seismic records of the 2012 Emilia (Italy) earthquakes. The Mirandola records (MRN station) were utilized because of their seismological characteristics, i.e. PGAs and duration of the accelerograms. The record of May 29th East-West was used for the SD and the North-South component was used to assess the seismic performance at the ULS. The record history and the relevant response spectra for ULS are shown in Fig. 7 and 8.

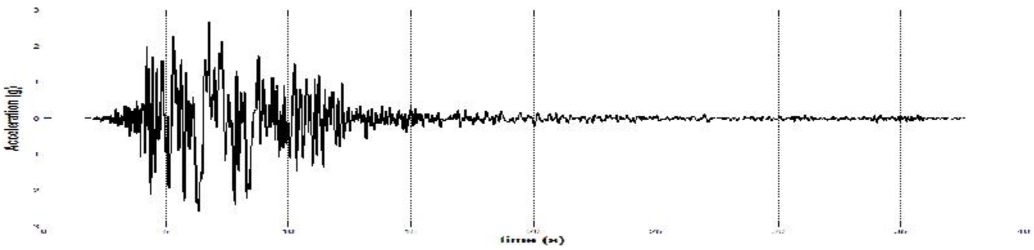


Figure 7. Record of the Emilia earthquake on May 29th (North-South component)

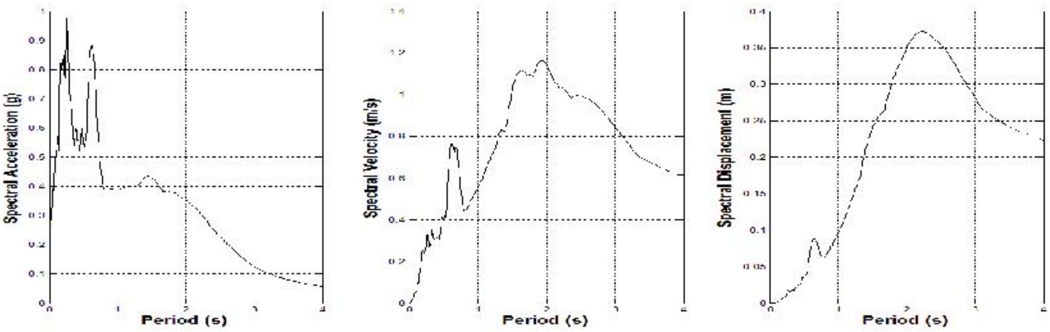


Figure 8. Response spectra of the record of the 29th May 2012 (East-West Component): acceleration (left), velocity (middle) and displacement (right) spectra

For the sake of brevity, in what follows only the result for ULS will be presented. They have been obtained mainly in terms of maximum lateral displacement of piers, maximum base shear of piers, cyclic response of each pier, maximum shear in the transverse beam and maximum slip at bottom section of columns.

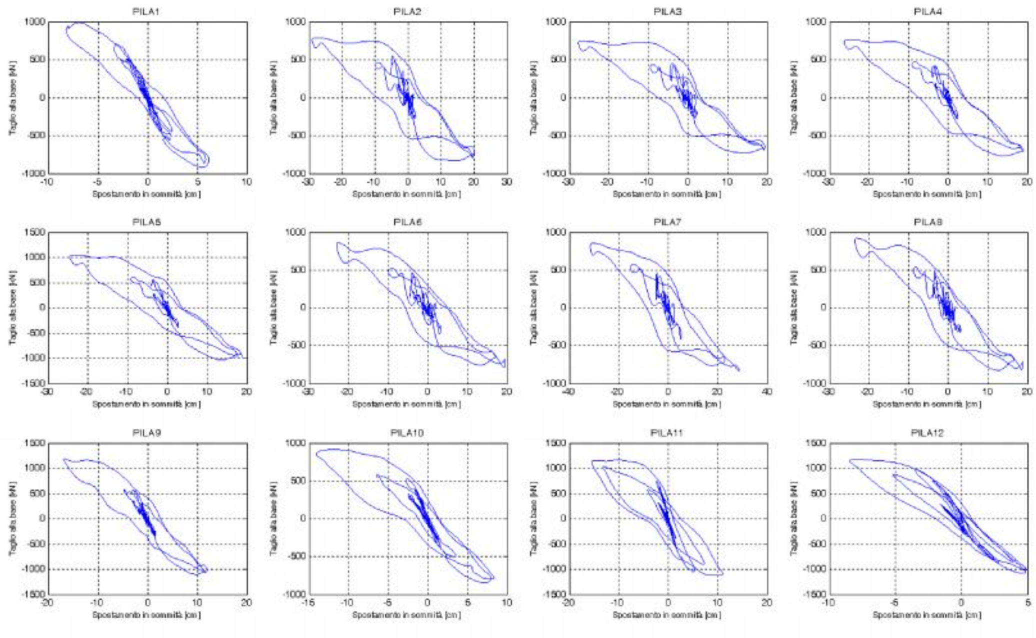


Figure 9. Force-deflection cycles of each pier

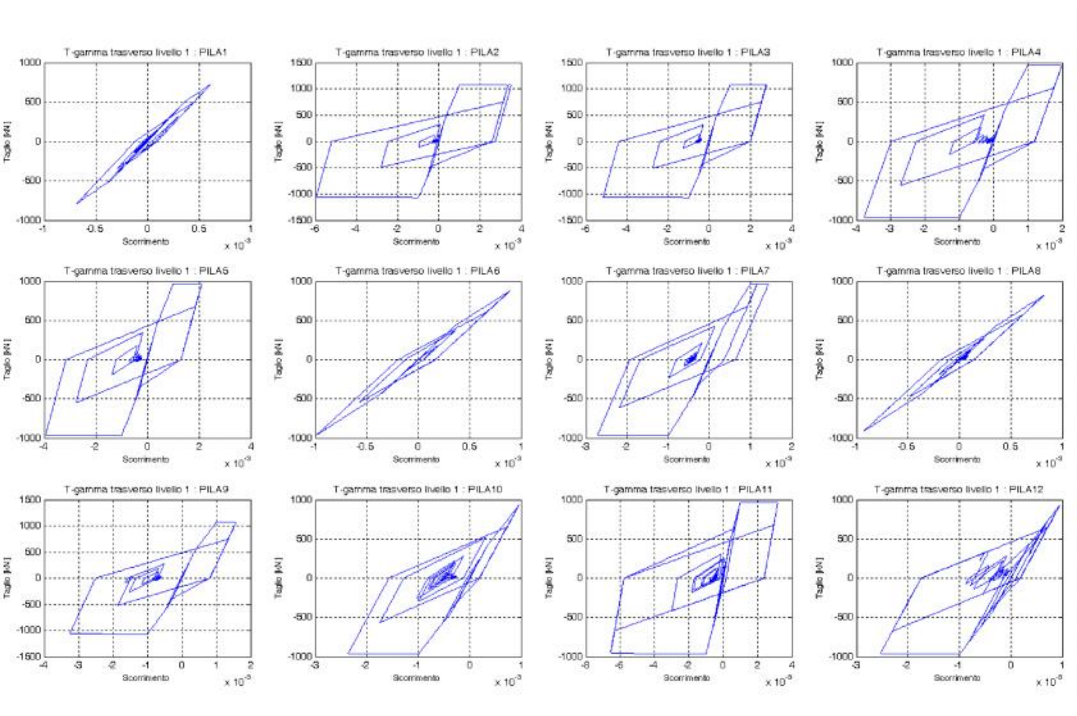


Figure 10. Shear force-deformation cycles of transverse beams at first floor for each pier

The maximum absolute displacement obtained (~ 32 cm) is, as expected, in the taller pier (#7), whereas pier #9 and #11 present a maximum displacement of 17 cm and 15 cm, respectively. The maximum base shear is about 1200 kN both for pier #9 and #11. The analysis of the cyclic response (Fig. 9) shows the high plastic deformations to which pier #9 and # 11 are subjected. A pronounced pinching effect is also present in the cyclic response of pier #11. This is due to the effect of shear and bond. The expected level of cracks width at the column base due to the bar slippage is of the order of 1.5 – 2 mm. In any case, the slippage is not enough to avoid flexural damage in the columns as shown by Moment-Curvature cycles; in fact the maximum ductility is about 3.

The level of shear damage in the transverse beam is also high as confirmed by the hysteretic behavior shown in Fig. 10, where the shear force-deformation cycles of the transverse beam at first floor of each pier are illustrated. The maximum shear deformation is 3×10^{-3} and 6×10^{-3} for pier #9 and #11 respectively, which correspond to an extensive shear cracking pattern as already shown in (Paolacci and Giannini 2012). In fact, for pier #12 has been demonstrated that 1% of drift corresponds to the shear failure of the transverse beam. Because the level of drift reached during the analysis is about 1% for pier #11 and 0.8 % for pier #9, and extensive shear damage is expected, at least at 1st and 2nd level of the piers.

The plastic flexural deformation of the transverse beam, not shown here for brevity, appears not very high (ductility 3-4) with a limited number of cycles. Therefore a limited flexural damage level is expected.

7.Conclusions

The main issues regarding the numerical simulation of the seismic response of the Rio-Torto viaduct for the PsD test campaign have been presented. In this paper the “as built” configuration has been considered. A refined non-linear model for the non-isolated case, developed in OpenSEES, has been presented and discussed. It includes, beyond the non-linear flexural deformation of the members, the non-linear shear deformation of the transverse beams and the strain-penetration effect typical of RC structures with plain steel bars.

The model has been calibrated based on a previous experimental campaign carried out at University Roma Tre for one of the piers (#12). The results of numerical simulations of the seismic response of the non-isolated bridge for Ultimate Limit State condition have been analyzed and discussed. This corresponds to the shear failure of the transverse beam and a high crack opening at the columns base. At this purpose a natural accelerogram recorded during the Emilia earthquake event of 29th May 2011 has been used.

A detailed local and global response of the viaduct has been provided, including force-deflection, moment-curvature and shear force-deformation relationship of all members fo each pier. The results have shown a high non-linear deformations of columns and beams with a clear involvement of tranverse beam in plastic shear deformation and a high crack-opening at colum bottoms.

This results will be a useful tool to compare the response of the viaduct during the PsD test with the simulated response and check for differences.

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