Available online at www.sciencedirect.com

ScienceDirect

Procedia Structural Integrity 62 (2024) 685–692

Structural Integrity
Procedia

www.elsevier.com/locate/procedia

II Fabre Conference – Existing bridges, viaducts and tunnels: research, innovation and applications (FABRE24)

A simplified procedure for the seismic retrofit of bridges by seismic isolation: Part 2 - predimensioning of the isolation system

Carlo Pettorruso[a]*, Virginio Quaglini[a]

[a]*Politecnico di Milano, Department of Architecture, Built environment and Construction engineering, Milan, Italy*

Abstract

This study presents a simplified procedure for the seismic retrofit of bridges by means of isolation system (IS), applicable to bridges with an isostatic or continuous deck layout, supported by conventional bearings that can be replaced by seismic isolators. The procedure consists of two steps: (1) the assessment of suitability of the bridges for seismic isolation; (2) the preliminary design of the isolation system. The first part of the procedure is presented in a companion paper. This contribution presents the second step of the procedure. A nonlinear static analysis of the existing bridge is performed, and its capacity curve is determined. This curve is then transformed into that of the equivalent SDOF system. Combining the information of the nonlinear static analysis and the bridge characteristics in the ADRS plane, the minimum characteristics of the isolation system to achieve a preset performance point are derived. Two scenarios are considered: in the first one it is sufficient to shift the period of the deck; in the second one, in addition to period shifting, it is necessary to introduce damping to control the displacement of the deck. Once the minimum characteristics of the isolators have been defined, the type and model can be identified through a search into databases of commercial devices. The application of the procedure to a case-study bridge and the validation of the method are finally shown.

Keywords: seismic retrofit; seismic isolation; isostatic spans; continuous spans; preliminary design

---

* Corresponding author. Tel.: +390223995108.
E-mail address: carlo.pettorruso@polimi.it

10.1016/j.prostr.2024.09.095

1. Introduction

The perception of the risk associated to the seismic vulnerability of road infrastructures, and in particular of bridge structures, is of recent acquisition in Italy. This is possibly caused by the fact that in the last major events that hit the country the road infrastructures did not suffer significant distress, in spite that the Italian infrastructural asset dates back mainly to a period between the '50s and '70s of the last century and was designed without consideration of the seismic action.

A way to enhance the seismic performance of existing bridges consists on mitigate the effects of earthquake by means of seismic isolation, and several authors have proposed simplified procedures for the retrofit of bridges by replacing their bearings with isolation devices (Dolce 2007, Cardone et al. 2008, Furinghetti 2022), while others studies, such as (Kun et al 2019), (Cardone 2010) have developed similar methods for buildings, but applicable to bridges as well. In line with previous research, also in the present study a procedure is proposed for designing the replacement of existing bridge bearings with isolation devices. The procedure, which is applicable to both simply supported and continuous deck bridges, consists of two steps. In the first one, the effectiveness of seismic isolation for the considered structure is checked; this part is presented in a companion paper (A simplified procedure for the seismic retrofit of bridges by seismic isolation: Part 1 - assessment of suitability). The second step, presented in this paper, concerns the preliminary design of the isolation system.

2. Fast procedure for the preliminary design of the seismic isolation retrofit: pre-sizing of the isolation system

The fast procedure was developed with the objective of evaluating the suitability of retrofit by replacing existing bridge bearings with isolation devices. For the proposed intervention to be effective and in accordance with current regulations and design provisions (Italian Building Code, IBC, 2018 and Eurocode 8, 2004, EC8), the behavior of the substructures must remain elastic during the earthquake.

First, a nonlinear static analysis is performed on the existing structure (Figure 1), to evaluate the resources and the critical mechanisms, and the relevant capacity curve is obtained. Among the various available procedures, the Pushover Analysis (Chopra et al 2002, 2004) in the case uncoupled modes, and the Multimodal Pushover Analysis (Paraskeva et al 2006, 2009) in the case of coupled modes, appear as the most suitable to capture the global behaviors of the bridge structures, or more generally of structures characterized by a very wide distribution of stiffnesses.

From the capacity curve of the bridge, the equivalent bilinear curve is obtained in accordance with §7.3.4.2 of IBC (2018) and the Commentary (2019).

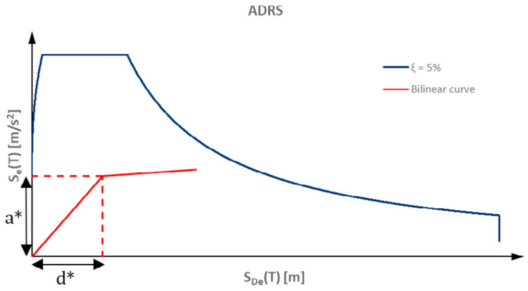

Figure 1. Equivalent bilinear capacity curve and demand spectrum

Given the equivalent bilinear curve, the point where the first and second branches meet, P*(a*, d*), is identified. This point is representative of the critical mechanism of the structure:

- in the case where the behavior is mainly ductile, P* is the point where the bilinear curve has a steep change in slope (Figure 1).
- in case of brittle behavior, P* is given by the discontinuity in the capacity curve.

The maximum displacement that can be allowed is the sum of two contributions:

$$d_p = d^* + d_s \tag{1}$$

where d* is the maximum displacement for the elastic capacity of the pier, defined above, and d_s is the maximum deck displacement allowed by the joints. This information provides the resource in terms of relative displacement between decks at the ultimate limit state (ULS). Based on this requirement, a performance point is defined in the ADRS plane, with coordinates:

$$P\ (a^*,\ d_p) \tag{2}$$

with a* being the maximum acceleration for the elastic capacity of the pier (achievement of either the first yielding moment or the shear resistance). The equivalent bilinear curve is reported in the ADRS plane and compared to the demand spectrum. Depending on the position of the performance point, two scenarios may occur.

Scenario A is characterized by the performance point beyond the demand curve; in this case the structure does not need additional damping and therefore the damping of the isolation system ξ_{is} can be neglected (Figure 2). .

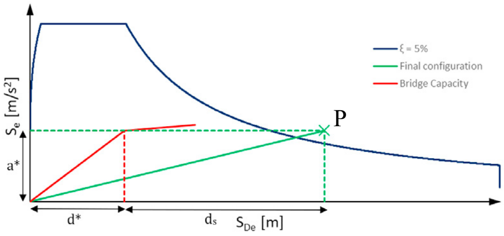

Figure 2. Scenario A: performance point beyond the demand curve

The equivalent two-degree-of-freedom system comprising the bridge and the isolation system can be represented as an in series-system made of two springs, with stiffnesses corresponding to the stiffness of the piers K and of the isolation system $k_{is,th}$.

The equivalent stiffness is given by the following formula:

$$K_{eq} = \frac{K\,k_{is,th}}{K + k_{is,th}} \tag{3}$$

the equivalent stiffness, K_{eq}, is determined from the slope of the line of the final configuration; the stiffness of the pier, K, is the slope of the first branch of the equivalent bilinear capacity curve. The only unknown is k_{is}, which is eventually determined as:

$$k_{is} = \frac{K\,K_{eq}}{K - K_{eq}} \tag{4}$$

Scenario B is characterized by the performance point behind the demand curve; in this case additional damping is needed in order to match the performance point with the demand, and this damping is introduced through the isolation system, ξ_{is}.

The stiffness of the isolation system, $k_{is,th}$, is defined like in Scenario A. In order to calculate $\xi_{is,}$, a desired performance point P'(a', d') is defined as the point where the straight line representing the period of the isolated structure crosses the demand spectrum (Figure 3). The isolation system is then designed so that the performance point, P, coincides with P'.

Imposing:

$$d_p = d'\,\eta \tag{5}$$

With:

$$d' = S_D\,(T_P,\ \xi_{5\%});\ d_p = S_D\,(T_P,\ \xi_{5\%}+\xi_{is,});\ \eta = \sqrt{\frac{10}{5+5+\xi_{is}}} \tag{6}$$

then

$$d_p = d' \sqrt{\frac{10}{5+5+\xi_{is}}} \tag{7}$$

From this equation it is possible to derive the design damping coefficient of the isolation system, $\xi_{is,th}$, which is:

$$\xi_{is,th} = \frac{10\, d'^2}{d^2} - 10 \tag{8}$$

Then it is possible to define the new design spectrum (depicted in green in Figure 3), which is damped by $\xi_{is,th}$ plus 5%.

At the end of the procedure, in both scenarios, the design characteristics of the isolation system are defined.

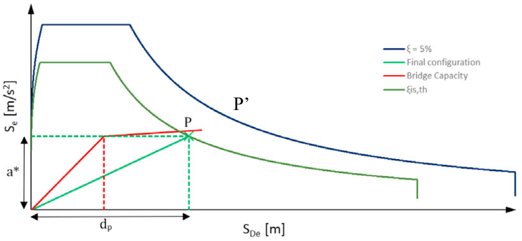

Figure.3. Scenario B: new spectrum

3. Case study

The proposed procedure is applied to a case study bridge (illustrated in Figure 4) and nonlinear dynamic analyses are performed to validate the method. The bridge is characterized by two 10 m high piers, having a circular cross section with 2 m diameter. The spans have three V-shaped beams, 35 m long. The piers have a longitudinal reinforcement arranged circumferentially consisting of 24φ26 bars for the 5m high pier and 32φ30 bars for the 10m high pier. The transverse reinforcement consists of φ16 stirrups spaced with 15 cm pitch. Geometrical details of beams and piers are reported in Figure 5.

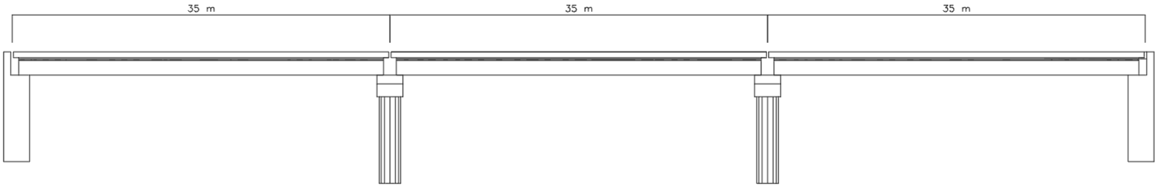

Figure 4. Bridge layout

The seismic scenario is defined according to IBC, assuming a design life V_N = 50 years and use class IV (cu = 2.0) (IBC, § 2.4.3), resulting in a reference period $V_R = V_N$ cu = 100 years for the structure (IBC, § 3.2.1). Only the Life Safety Limit State is examined, corresponding to a return period of 949 years (IBC, § 3.2.1) and an horizontal acceleration with a probability of exceedance equal to 10% in 50 years.

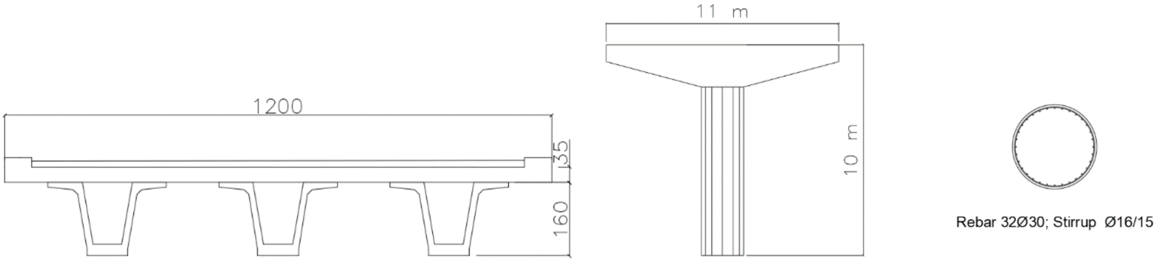

Figure 5. V-shape deck section on the left, and pier and reinforcement on the right

The municipality of Sirmione [PGA=0,241g, soil category B and topographic class T1] located in Lombardia in the province of Brescia was chosen to define the seismic scenario.

A set of seven bidirectional ground motions consistent with the target spectrum according to IBC were selected to validate the outcomes of the fast procedure; ground motion search was performed in the European Strong-motion Database (Ambraseys et al. 2002) using the REXEL v3.4 beta software (Iervolino et al. 2010). Relevant information on the ground motion data set is reported in Table 1, and the scaled horizontal spectra at 5% damping. Additional information is available in (Pettorruso and Quaglini 2023).

Table.1 Selected accelerograms

Earthquake Name	**Waveform ID**	**Earthquake ID**	**Mw**	**PGA_X [m/s^2]**	**PGA_Y [m/s^2]**	**SF_x**	**SF_y**
Campano Lucano	292	146	7	0,5878	0,5876	4,0921	4,0934
Friuli (aftershock)	147	65	6	1,3841	2,3189	1,7377	1,0372
Spitak	439	213	7	1,7932	1,7958	1,3413	1,3394
Tabas	182	87	7	3,316	3,7789	0,7253	0,6365
Montenegro	198	93	7	1,7743	2,1985	1,3556	1,0940
Umbria Marche	594	286	6	5,1383	4,5383	0,4681	0,5300
Campano Lucano	290	146	7	2,1206	3,1662	1,1342	0,7597

The numerical model was implemented in SAP2000 v23.1.0 software. The geometry (Figure 6) replicates the one described in the previous section. The piers were rigidly fixed to the ground and the abutments are one hinged and the other longitudinally free to move. The deck is modelled by means of elastic elements on which the permanent non-structural load and the variable loads are applied. The connection between the deck and the piers are modelled through rigid links, either fixed or unidirectionally moving, in accordance with the static layout of the bridge.

Concrete type C25/30 and steel quality Fe44k were assumed, and the material nonlinearities were modelled through concentrated plasticity: the piers were elastic elements, with a bidirectional plastic hinge (parametric P-M2-M3) at the basis in order to account for inelastic concrete deformation. Brittle behavior is considered through the inclusion of hinges with rigid brittle behavior in the two main shear directions.

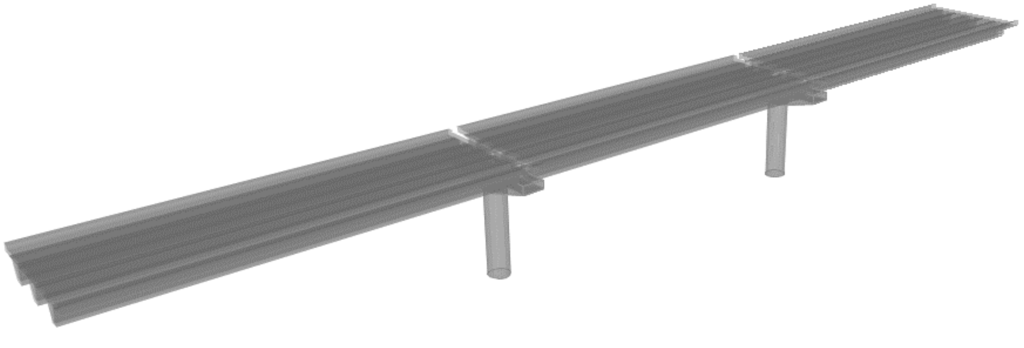

Figure 6. Numerical model

4. Result

4.1. Application of the proposed procedure

The first step in the design procedure is to perform the nonlinear static analysis and to define the elastic limit of the bridge; the response in the two main directions is different and the relevant bilinear curves are represented in Figure 7.

The capacity curves show a ductile collapse mechanism. The displacements at the performance point in either direction is defined with consideration of the displacements allowed by the joints. The coordinates of the elastic limit (d*, a*), the joint capacity (d_s) and coordinates of the performance points Px and Py in either direction are reported in Table 2.

Table.2 Performance points data

	d^* [m]	d_s [m]	d_p [m]	a^* [g]
P_x	0,019	0,040	0,059	0,119
P_y	0,021	0,060	0,081	0,083

Figure 7 shows that in both directions' scenario B occurs and therefore it is necessary to introduce isolation devices with inherent damping capability.

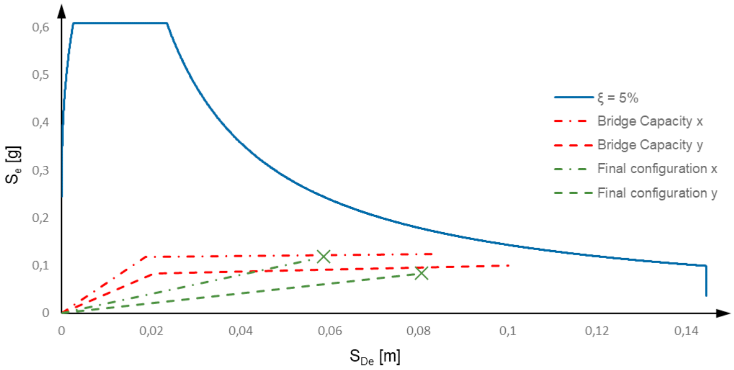

Figure 7. Bilinear capacity curves and final configurations

Table 3 summarizes the results from the procedure, while Figure 8 shows the performance of the retrofitted bridge.

Table 3. Design characteristics of the isolation system

	$k_{is,th}$ [kN/m]	$\xi_{is,th}$ [%]	d_s [m]
Isolation system - longitudinal	27182,82	10,56	0,040
Isolation system - traversal	12685,10	11,36	0,060

$k_{is,th}$, $\xi_{is,th}$ and d_s represent the nominal properties of the isolation system obtained from the design procedure. The next step is to select, from the portfolios of the manufacturers, commercial devices which match these properties. In particular, $k_{is,th}$ defines the maximum stiffness, $\xi_{is,th}$ the minimum damping, and d_s the minimum design displacement of the isolation system for the Life Safety Limit State.

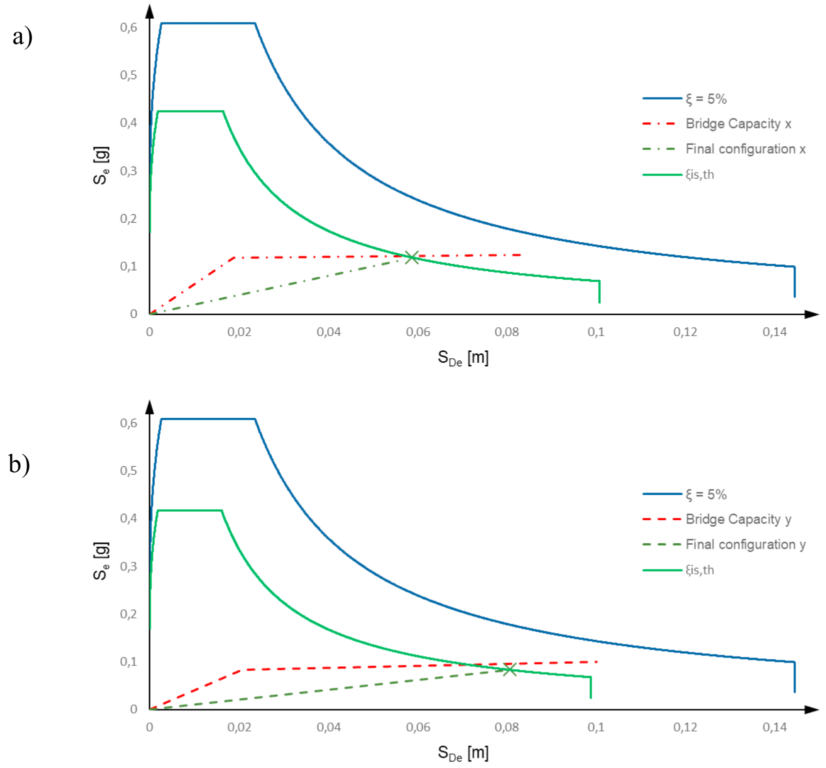

Figure 8. Demand curves and capacity curves in x (a) and y (b) directions

4.2. NLTHA validation

The validation of the design procedure was eventually carried out by performing nonlinear dynamic analysis using the nominal values of the properties of the isolation system (Table 3). During the validation, the behavior of the substructures was checked and verified that they do not enter the plastic field or undergo brittle mechanisms, to verify that after retrofitting the substructures are in the elastic field.

Table 4 shows the results in terms of the base reactions of the two piers, both in the As-Built and in the isolated configuration, obtained by averaging the maxima of the results for each of the seven accelerograms.

Base reactions show a decrease between 20% and 30% after retrofitting with the isolation system: by comparing the maximum shear forces and bending moment to the elastic limits, which count V_{RD}=3151 kN and M_y=11700 kNm respectively, it is concluded that the requirement of elastic behavior has been met.

Table 4. Reactions calculated from NTHA

		As Built configuration				Isolated configuration			
		F_X	F_Y	M_X	M_Y	F_X	F_Y	M_X	M_Y
		kN	kN	kNm	kNm	kN	kN	kNm	kNm
Pier 1	min	1272	1295	14276	13733	982	1021	10109	10301
	max	1237	1316	13913	13222	918	946	11050	9753
Pier 2	min	1263	1289	14280	13661	984	1021	10111	10327
	max	1230	1313	13849	13100	926	945	11069	9781

5. Conclusions

The paper presents a fast procedure for the retrofit of bridges by application of seismic isolation. Specifically, the procedure aims at performing the preliminary sizing of the isolation system, accounting for the resources of the bridge to retrofit without substructure stiffening.

The field of application of the procedure is related to the simply supported bridges or bridges with continuous decks on multiple supports, which are the most common layouts in the Italian infrastructure stock and are suitable for the replacement of existing bearings with isolation devices.

This procedure is applied in this paper to a case study, showing an excellent result in terms of reliability, as the optimal isolation system was defined in a direct step without iterations.

References

Ambraseys, N.; Smit, P.; Sigbjornsson, R.; Suhadolc, P.; Margaris, B. Internet-Site for European Strong-Motion Data, European Commission, Research-Directorate General, Environment and Climate Programme (2002). Available online: http://www.isesd.cv.ic.ac.uk/ESD/ (accessed on 20 December 2022).

Cardone D., Dolce M., Palermo G. "Direct displacement-based design of seismically isolated bridges". Bull Earthquake Eng (2009) 7:391–410 DOI 10.1007/s10518-008-9069-2

Cardone D., Palermo G., Dolce M. "Direct Displacement-Based Design of Buildings with Different Seismic Isolation Systems" Journal of Earthquake Engineering, 14:163–191, 2010. DOI: 10.1080/13632460903086036

CEN European Committee for Standardization: Brussels, Belgium, 2004. EN 1998-1 Eurocode 8: Design of Structures for Earthquake Resistance—Part 1: General Rules, Seismic Actions and Rules for Buildings.

CEN European Committee for Standardization: Brussels, Belgium, 2004. EN 1998-2 Eurocode 8: Design of Structures for Earthquake Resistance—Part 2: Bridges.

Circolare 21 gennaio 2019, n. 7 C.S.LL.PP. Istruzioni per l'applicazione dell'«Aggiornamento delle "Norme tecniche per le costruzioni"» di cui al decreto ministeriale 17 gennaio 2018, Roma; (in Italian)

Chopra, A.K.; Goel, R.K. A modal pushover procedure to estimate seismic demands of buildings. Earthq. Eng. Struct. Dyn. 2002, 31, 561–582.

Chopra, A.K.; Goel, R.K. A modal pushover analysis procedure to estimate seismic demands for unsymmetric-plan buildings. Earthq. Eng. Str. Dyn. 2004, 33, 903–927.

Delgado et al, 2009. Shear effects on hollow section piers under seismic actions: Experimental and numerical analysis. Bulletin of Earthquake Engineering, Volume 7, Issue 2, Pages 377 – 389, 10.1007/s10518-008-9098-x

Dolce M., Cardone D., Palermo G. "Seismic isolation of bridges using isolation systems based on flat sliding bearings" Bull Earthquake Eng (2007) 5:491–509. DOI 10.1007/s10518-007-9044-3

Furinghetti, M. Definition and Validation of Fast Design Procedures for Seismic Isolation Systems. Vibration 2022, 5, 290–305. https://doi.org/10.3390/vibration5020017

Iervolino, I.; Galasso, C.; Cosenza, E. REXEL: Computer aided record selection for code-based seismic structural analysis. Bull. Earthq. Eng. 2010, 8, 339–362, http://dx.doi.org/10.1007/s10518-009-9146-1.

Italian Building Code. Technical Recommendations for Buildings—D.M. 17/02/2018. Italian Building Code: Rome, Italy, 2018. (In Italian)

Kun Ye, Yan Xiao, Liang Hu "A direct displacement-based design procedure for base-isolated building structures with lead rubber bearings (LRBs)" Engineering Structures 197 (2019) 109402 https://doi.org/10.1016/j.engstruct.2019.109402

Paraskeva, T.S., Kappos, A.J.; Sextos, A.G. Extension of modal pushover analysis to seismic assessment of bridges. Earthq. Eng. Struct. Dyn. 2006, 35, 1269–1293.

Paraskeva, T.S.; Kappos, A.J. Further development of a multimodal pushover analysis procedure for seismic assessment of bridges. Earthq. Eng. Struct. Dyn. 2009, 39, 211–222.

Pettorruso C., Quaglini V. 2023. Assessment of the seismic vulnerability and modelling of existing bridge with different levels of accuracy: strengths and weaknesses. 9th International Conference on Computational Methods in Structural Dynamics and Earthquake Engineering. DOI: 10.7712/120123.10675.20183.

Pinto et al, 2003. Cyclic tests on large-scale models of existing bridge piers with rectangular hollow cross-section. Earthquake Engineering and Structural Dynamics, Volume 32, Issue 13, Pages 1995 – 2012, 10.1002/eqe.311

SAP2000 Analysis Reference, Volume 1; Computer and Structures Inc.: Berkeley, CA, USA, 1997.