8th Canadian Conference on Earthquake Engineering / 8ième Conférence canadienne sur le génie paraséismique
Vancouver – 1999

Modeling inelastic seismic response of RC viaducts

Fischinger, M.[1], Isaković, T.[2], Križaj, S.[3]

ABSTRACT

Analytical results are compared with the experimental results for two large-scale single column bent viaducts which were pseudo-dynamically tested in the European Laboratory of the Structural Assessment in Italy. Two typical inelastic element models (beam element with lumped plasticity and fiber element model) are used in the inelastic time history analysis. Relatively simple beam element with Takeda hysteretic rules has proved to be quite successful in modeling inelastic response of the viaducts with the exception of a short column behavior. The response of the fiber element was difficult to control and a lot of tuning was needed to obtain good correlation with the experimental results.

INTRODUCTION

Reinforced concrete, single-column bent viaducts are frequently used in Europe. Since their structural concept is strictly related to functionality, they give the impression of being rather simple structures, whose seismic response could be easily predicted. In accordance to this, rather simple seismic design methods are currently used in practice. They are predominantly elastic with only implicit considerations of the inelastic response. However, recent research has shown that certain structural characteristics may yield highly irregular and even unexpected response in transverse direction of such viaducts even in the elastic range (Fischinger et. al. 1997). It has been also recognized that inelastic seismic analysis is needed in some cases.

Although several inelastic analytical methods and computational models are available, little is known about their applicability in practice. Accordingly, the objective of the work presented in this paper has been to assess the merits and shortcomings of some most common models, as well as to estimate their applicability in the inelastic seismic analysis of the chosen type of bridge structures.

Two inelastic models (beam element model with lumped plasticity and fiber element model) are tested in the frame of the chosen procedure (inelastic time-history analysis). The analytical results are compared with experimental results obtained on idealized single-column bent viaducts. One symmetric and one asymmetric viaduct are analyzed to address the problem of "regularity". These viaducts were tested in the European Laboratory of the Structural Assessment (ELSA) at Ispra, Italy (Pinto et. al. 1996) in support of the new European standards for seismic design of bridges - Eurocode 8/2 (1994). Tests were performed pseudo-dynamically on large-scale (1:2.5) specimens.

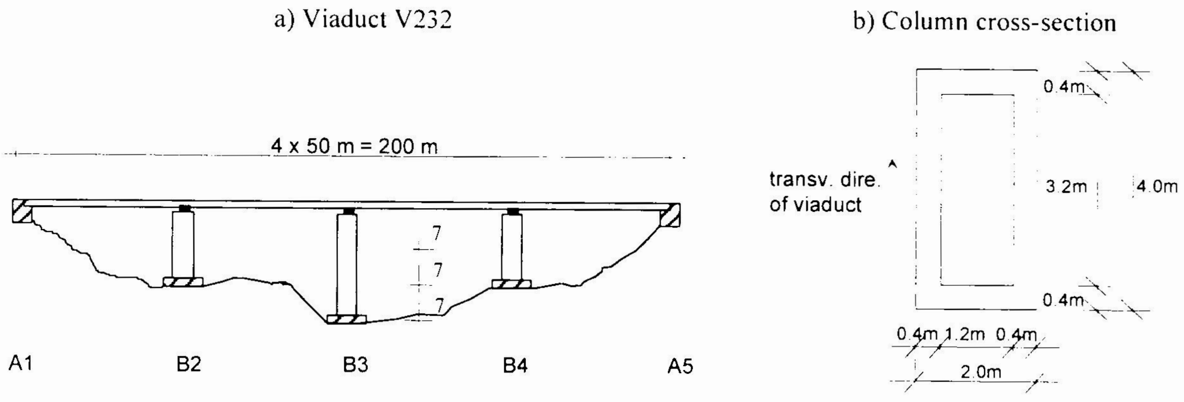
ANALYSED VIADUCTS

Description of the viaducts

Two large-scale (1:2.5) specimens called V232 and V213 were analyzed in the transverse direction. Full-scale structures consisted of a 200-meter deck and three single column bents (see Fig. 1). The deck is pinned at the abutments. The numbers in the viaducts' name refer to the column heights in terms of unit lengths of 7 meters. For example, in V232 the first column has a height of 14 meters, the second column 21 meters, and the third column 14 meters.

---

[1] Professor, [2] Research Assistant, [3] former Ms.D. Student,
Institute of Structural Engineering, Earthquake Engineering and Construction IT, Faculty of Civil and Geodetic Engineering, University of Ljubljana, SI-1001 Ljubljana, Jamova 2, P.O. Box 3422, Slovenia


a) Viaduct V232

b) Column cross-section

Figure 1. Analyzed viaducts

Earthquake load

Artificial accelerogram, used in the experiment as the design earthquake, was applied first. This record was generated to be compatible with the spectrum defined in the Eurocode 8/1 (1994) standard. The accelerogram was properly scaled, since it was applied to the specimens. The full-scale record has the maximum acceleration of $a = 3.72$ m s^{2} and duration of 10 s. After the design earthquake had been applied, tests (and analyses) were repeated with the "high level" earthquake. Accelerations were multiplied by factor 2.0 in the case of V232 viaduct.

ANALYSIS VERSUS EXPERIMENTAL RESULTS

Inelastic time history analysis was used to simulate pseudo-dynamic experiment. Since seventies, DRAIN family programs have been widely used by the engineering community for this purpose. Many versions of the program and variety of element models have been used. The element models can be categorized into two main groups. First group comprises simple models consisting essentially of elastic beam elements with lumped plasticity in the end plastic hinges. The moment-rotation hysteretic relationship is typically monitored in these hinges. The second group includes more sophisticated elements monitoring stress-strain relationships (e.g. fiber elements). Representatives of both groups were used in this study. Standard fiber element (type No.15) was used in the frame of DRAIN 3DX (Parkash et.al.1993). Beam element with plastic hinges using Takeda hysteretic rules was incorporated into the program for comparison.

Lumped plasticity beam element model

Beam elements with two non-linear rotational springs at the two ends have been extensively used by the earthquake engineering community. Several elements of this type were developed for DRAIN program. The variation of the element used in this study was developed at the University of Ljubljana (e.g. Fajfar and Fischinger, 1987). It is based on tri-linear Takeda hysteretic rules to simulate the behavior of RC elements. Important advantage of this type of elements is that they are controlled by only few parameters (yield force, yield displacement, hardening parameter, unloading parameter) with clear phisical meaning.

It is important to emphasize that in the very first model of the regular V232 viaduct (referred as the "initial model" in the figures) no "tuning" of the element parameters were done. All properties (including hardening parameter) were calculated from the first principles and the usual value of the unloading parameter in the Takeda rules ($\alpha = 0.5$) was used. However, material and damping (1.6%) properties were based on the test results.

The correlation between analytical displacement time history response, obtained by the initial model, and experimentally obtained displacements is good in the case of the design earthquake (Figures 2) and even better for the high level earthquake (Figure 6). However, the modeling of enery absorbtion is good for high level earthquake, only (Figure 7). In the case of the design earthquake, the initial model failed to predict actual stiffness degradation on the unloading branch (Figure 3).

To account for stiffness degradation, unloading pararameter $\alpha = 1.0$ was used in the modified model. Hysteretic (Figure 4) as well as displacement time history response (Figure 5) improves in the case of the design earthquake. However, the response is much worse for the high level earthquake (Figure 6), indicating that the energy absorbtion of the modified element is too small in the case of larger plastic excursions.

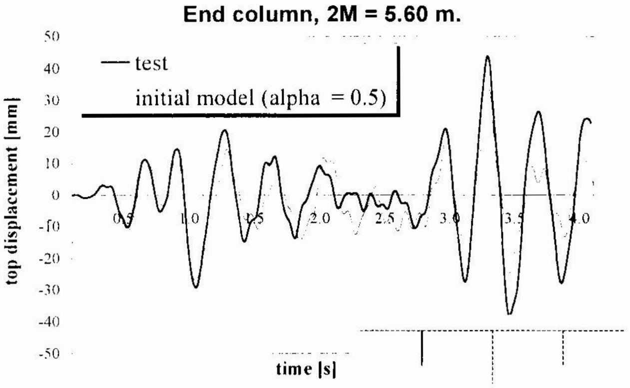


Figure 2. Displacement time-history
(V232 - design earthquake - initial model)

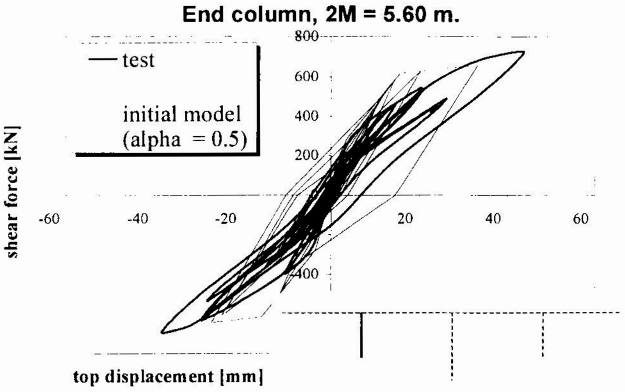


Figure 3. Shear force-displacement diagram
(V232 - design earthquake - initial model)

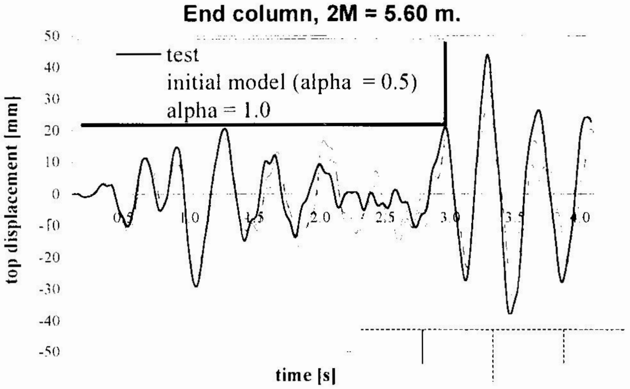


Figure 4. Displacement time-history
(V232 - design earthquake - modified model)

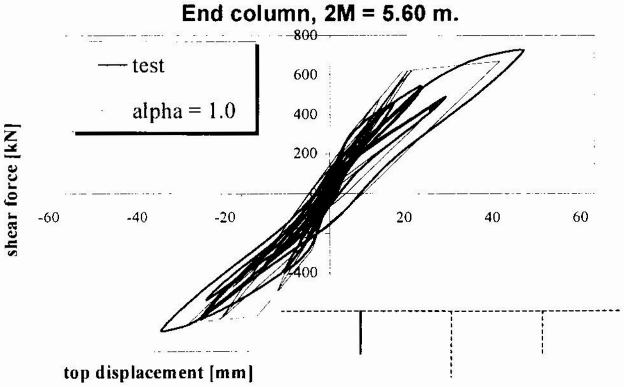


Figure 5. Shear force-displacement diagram
(V232 - design earthquake - modified model)

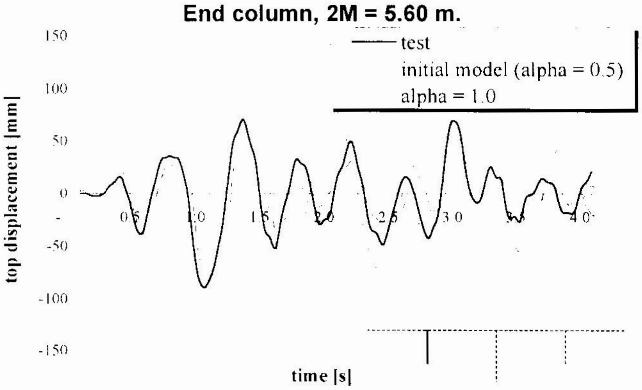


Figure 6. Displacement time-history
(V232 - high level earthquake)

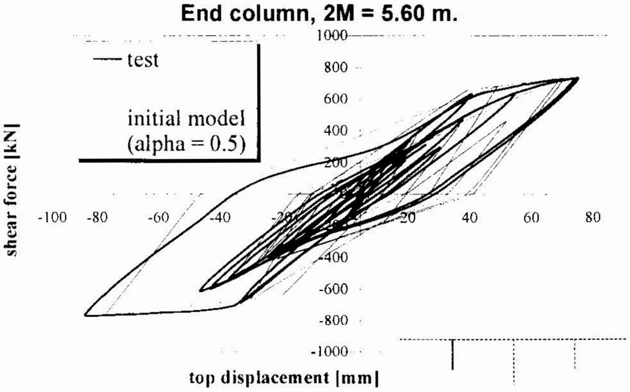


Figure 7. Shear force-displacement diagram
(V232 - high level earthquake)

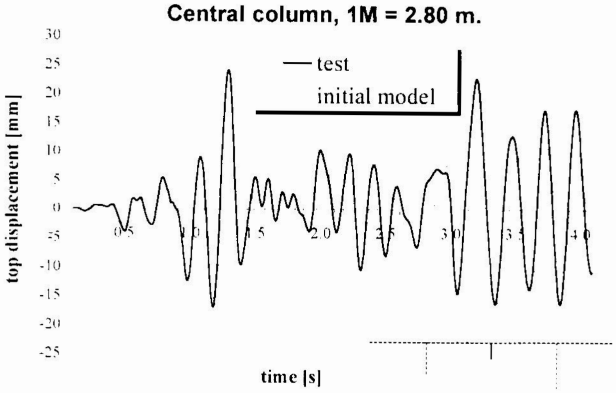


Figure 8. Displacement time-history
(V213 - design earthquake)

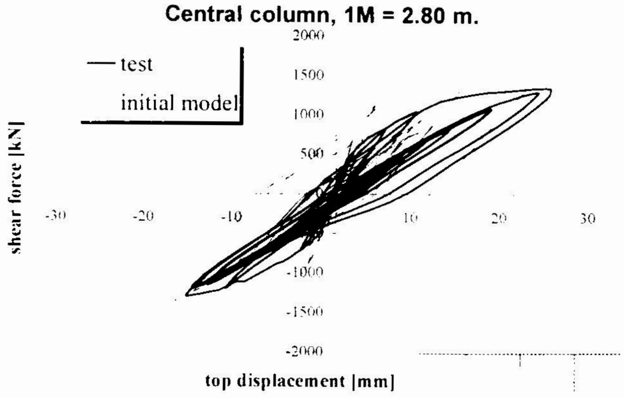


Figure 9. Shear force-displacement diagram
(V213 - design earthquake - short column)

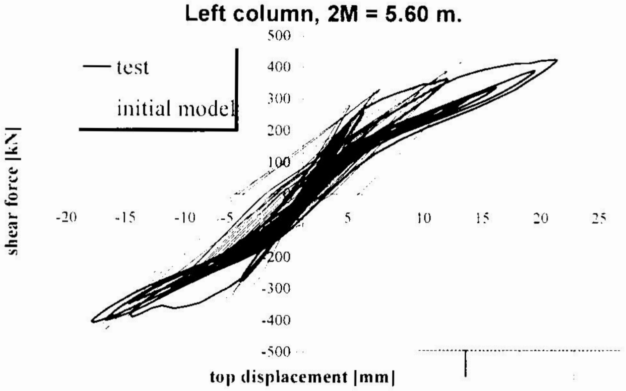


Figure 10. Shear force-displacement diagram
(V213 - design earthquake)

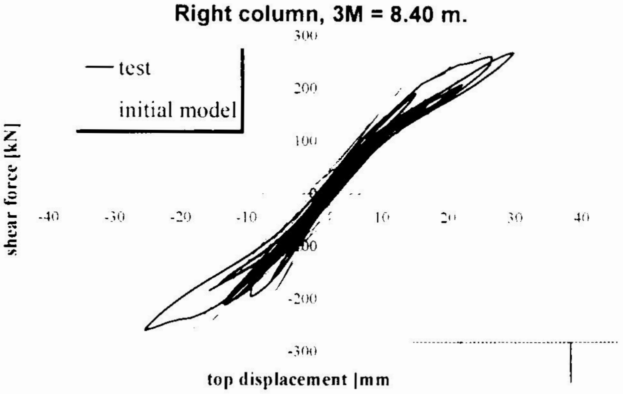


Figure 11. Shear force-displacement diagram
(V213 - design earthquake)

There was a doubt that this simple element is able to simulate the response of the irregular viaduct V213 and in particular the behavior of the short central column. To certain surprise the prediction of the displacement time history is as good as in the case of the regular structure (Figure 8). The same is true for the shear force – displacement diagrams of longer columns. However, the correlation in the hysteresis of the short column is indeed quite poor. Stiffness degradation and pinching in the experimental results for this short column could be attributed to either shear cracking or/and pull out of the reinforcement. However, we were not able to model neither of these phenomena appropriately.

Fiber element model

When modeling columns with fiber elements, columns are divided into a number of segments. The cross-section of each segment is further divided into certain number of fibers. Stress-strain relationship is monitored for each fiber. This straightforward approach appears to be natural and simple. However, in practice, this element proves to be complex and very difficult to control. In the case of the element in DRAIN-3DX, results are very sensitive to the number and length of the segments, in particular in the plastic hinge zone.

This was proved in the analysis of the viaduct V232. The initial models completely failed to predict the experimental response (Isaković et. al., 1998). Substantial tuning of input data was needed to obtain good results. Correlation between the analytical and experimental results was the best (Figures 12 to 15) when columns were modeled with two segments of different lengths. Both, the plastic hinge zone of each column as well as the rest of the column were modeled with one fiber segment, each. The length of the plastic hinge observed in the experiment was considered. This length was 0.5 m in the short columns (B2 and B4) and 0.28 m in the column B3, which would be difficult to predict in advance to the test.

The global response obtained with this model is relatively good. The maximum values of displacements and shear forces are similar to those obtained with the experiment. The displacement time history is also satisfying (Figure 12). However, the force-displacement relationship significantly differs from experimental results (Figure 13). The differences are especially large after maximum displacements at the top of the columns are reached and columns are in the phase of unloading. Fiber element was not able to simulate the significant decrease of stiffness in this phase. This observation is studied and explained in detail in the report (Isaković et. al., 1998).

Analytical response considerably improves (Figures 14 and 15) when the pull-out properties of the column-to-footing connections are also considered. However, the properties of the connection hinges are difficult to define. Therefore, only the qualitative analysis of the bond slip was performed.

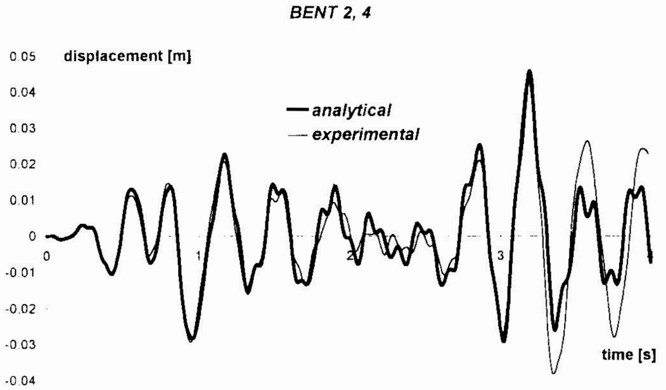


Figure 12. Displacement time-history
(V232 - design earthquake - without bond slip)

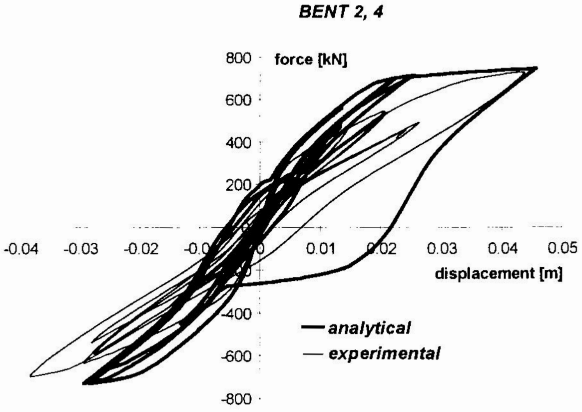


Figure 13. Shear force-displacement diagram
(V232 - design earthquake - without bond slip)

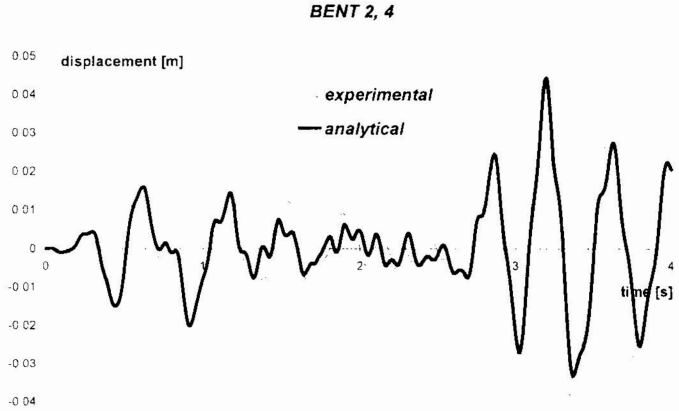


Figure 14. Displacement time-history
(V232 - design earthquake - with bond slip)

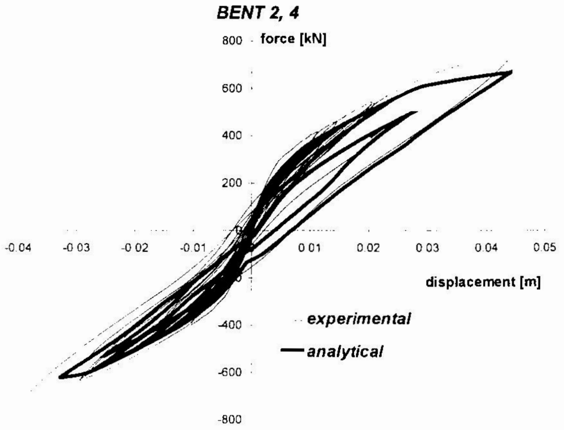


Figure 15. Shear force-displacement diagram
(V232 - design earthquake - with bond slip)

CONCLUSIONS

Analytical versus experimental results

One can never expect perfect correlation between analytical and test results. Specifically in the presented study, the pseudo-dynamic test on the reduced (although large) scale viaducts was modeled by dynamic response of full scale structures. It was also not possible to model the reported initial damage of the structure during the construction phase of the specimens. Furthermore, the same specimens were used in several tests, etc. Taking all these facts into account, we can conclude that acceptable or even good correlation between analytical and experimental results was obtained.

Beam element with lumped plasticity versus fiber elements

It is important to emphasize that the simple beam element was able to yield good results with no "tuning" of the element parameters. These parameters have a clear physical meaning and a direct influence on the results. Therefore, they are easy to control. Although the fiber element, monitoring stress-strain relationships appears to be "exact" and even easier to control, one never knows what the end result would be. In fact, the fiber element requires exact modelling and input data which are usually difficult to estimate. In the presented study a lot of tuning of input parameters was necessary to obtain good results.

Specific conclusions for the beam element with lumped plasticity

In general this relatively simple element was able to model the response of the regular and even irregular viaduct. Standard procedure of calculating element data from first principles and assuming the unloading parameter in the Takeda rules $\alpha = 0.5$ was successful. However, as expected, the model was able to model the flexural behavior only. With some modifications (not reported in the paper), it was possible to include also the shear behavior and pull-out of the reinforcement. Nevertheless, it is considered that these arbitrary modifications have no general validity at the present.

Specific conclusions for the fiber element

The fiber element presently incorporated into DRAIN-3DX (element type No.15) assumes constant stiffness over the entire length of the segment. Therefore a precise modeling of the plastic zone (whose length and bond slip is not known in advance) is necessary. Results strongly depend on the number and length of the segments. Due to this and relative complexity as well as some errors in the computer code, it was decided not to use this element until some major modifications are made.

ACKNOWLEDGEMENTS

The support of the Ministry of Science and Technology of the Republic of Slovenia and the U.S. National Science Foundation in cooperation with the University of Nevada, Reno is gratefully acknowledged.

REFERENCES

Eurocode 8 (1994). Design provisions for earthquake resistance of structures, European pre-standard ENV 1998, CEN, Brussels, Belgium.

Fajfar, P., and Fischinger, M. 1987. Non-linear seismic analysis of RC buildings: Implications of a case study. European Earthquake Engineering, Vol. 1, pp. 31-43.

Fischinger, M., Isaković, T., and Fajfar, P. 1997. Seismic analysis of viaduct structures - Which method to choose? Proc. Workshop on Seismic Design Methodologies for The Next Generation of Codes (Fajfar, P., and Krawinkler, H., ed.). Bled, Slovenia, Balkema, Rotterdam, pp 347-358.

Isaković, T., and Fischinger, M. 1998. Application of fiber beam-column element in DRAIN-3DX (type 15). IKPIR Report EE – 2/98. University of Ljubljana, Faculty of Civil and Geodetic Engineering.

Parkash, V., Powell, G.H., and Filippou, F.C. 1993. DRAIN-3DX: Base program user guide. Department of Civil Engineering, University of California, Berkeley, USA.

Pinto, A. V., Verzeletti, G., Pegon, P., Magonette, G., Negro, P., and Guedes, J. 1996. Pseudo-dynamic testing of large-scale R/C bridges. Report EUR 16378, European Laboratory for Structural Assessment, Ispra, Italy.