SEISMIC VULNERABILITY OF AN ISOLATED BRIDGE IN MEXICO

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ABSTRACT :

The 525 meters long Infiernillo II bridge crosses the Balsas river and it is the first isolated bridge built in Mexico. The bridge is part of a highway that connects central cities of the country to the Pacific Coast. Reinforced concrete slab deck on camel back steel trusses compose the superstructure of the five simple supported spans. The substructure consists of reinforced concrete bents and abutments. An analytical model of the structure aimed at determining the bridge capacity was created by the use of the SAP2000 program. The bridge demands were assessed using several strong motion movements recorded close to the Pacific Coast in Mexico by the national seismic instrumentation network in the country and by the results of a hazard analysis in the in the site. The study started calibrating the analytical model proposed with the results obtained with ambient vibration measurements. The bridge irregularity is also analyzed and the importance of the dynamic characteristics of the isolators employed was remarked. Finally, probability density functions of the bridge capacity and demand were assessed and fragility curves were proposed aimed at determining the expected behavior of the bridge as function of peak ground acceleration of the typical strong motions recorded in Mexico.

KEYWORDS: Bridges, Base isolation, Seismic Vulnerability.

1. INTRODUCTION

Earthquake occurrences are very frequent in Mexico. The country is located in a high seismicity zone and most of the strong earthquakes have epicenters in a zone of the Pacific Coast situated at the boundary of the Pacific and North-American Plates. Dynamic characteristics of the seismic records near to the Pacific Coast of Mexico show high-energy contents of high frequencies, making attractive the use of isolation systems to reduce the seismic response of bridges in this region. Moreover the close location of many urban areas and highways to the seismic events originated in this source is an additional issue to consider in the use of these devices to enhance structural safety against natural hazards.

Base Isolation systems reduce the seismic response of bridges by uncoupling a structure from damaging effects of earthquakes. Typical isolation devices include frictional/sliding bearings, elastomeric bearings and lead rubber bearings. Several of these systems are combined with passive energy devices by a need to control isolator displacements. Various experimental studies have shown the feasibility of the use of metallic yielding devices to enhance the energy dissipation capacity of structures with stable hysteretic behavior. The use of base isolation systems in bridge structures are described in Jangid, 2004, Shen et al., 2004 among others. Reviews of experimental and analytical studies are provided in Kunde and Jangid, 2003, Buckle, 2000, Soong and Spencer, 2002 and Jara and Casas, 2002.

2. BRIDGE GEOMETRY

The Infiernillo II Bridge crosses the Balsas River and is part of one of the highways that connect central cities of Mexico to the Pacific Coast. It is located in the kilometer 933+940 and about 100 km from the subduction faults. The bridge superstructure is a five simple supported 105 meters long span with a total length of 525 m. Each span of the bridge is divided in 17 panels with a length of 6m each, approximately. The 12 m width deck has been made of light-gage steel deck cover with a concrete slab depth of 18 cm. The slab is supported on girders, spaced of 1.5 m, which off-loads to floor beams with triangular cross-sections and spaced of 6 m. The girders are connected to two Camel Back type steel trusses braced at the top, with a maximum height of 6.5 m.

Figure 1 shows a lateral view of the 102 m long truss, showing also the deck of the bridge. Figure 2 shows two pictures of the bridge with its location in a red box on the left photograph.

Two non-prismatic abutments and four wall type reinforced concrete piers support the superstructure (figure 3). Piers are hollow box shape sections with plan dimensions of 8.5 x 3.5 m, 15 m height and thickness of 40 and 60 cm in longitudinal and transversal direction respectively. A hammerhead cap with the dimensions shown in figure 4 is used. Piers are supported on two reinforced concrete hollow cylinders (diameter of 8.5 to 10 m). In both ends of the cylinders a solid reinforced concrete cap was built to make possible the connection between them and the foundation piles in the bottom, and with the bridge piers on the top. The cylinders height is in the range of 21 m to 46 m.

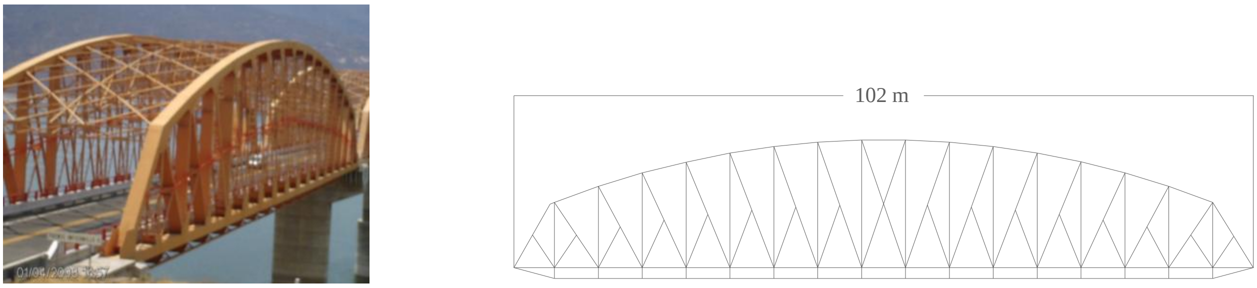

Figure 1. Superstructure steel truss of the Infiernillo II Bridge

Figure 2. Longitudinal and front view of the Infiernillo II Bridge

2.1. Isolation System

The bridge was projected with isolators of sliding multirotational bearings type (figure 5). There are two devices over each pier and each abutment of the bridge. Previous test analysis conducted by the manufacturers, displayed a bearing with stable hysteretic and non-degradation behavior (Muñoz, 2003). According to these results, the isolation system was modeled using a bi-linear hysteretic behavior as shown in figure 6.

The elastic stiffness, yield strength, yield displacement and post-yielding strength, are also shown in figure 6. It should be noted the high elastic stiffness exhibited by the device and the small post-yielding stiffness value (about 1% of the elastic stiffness).

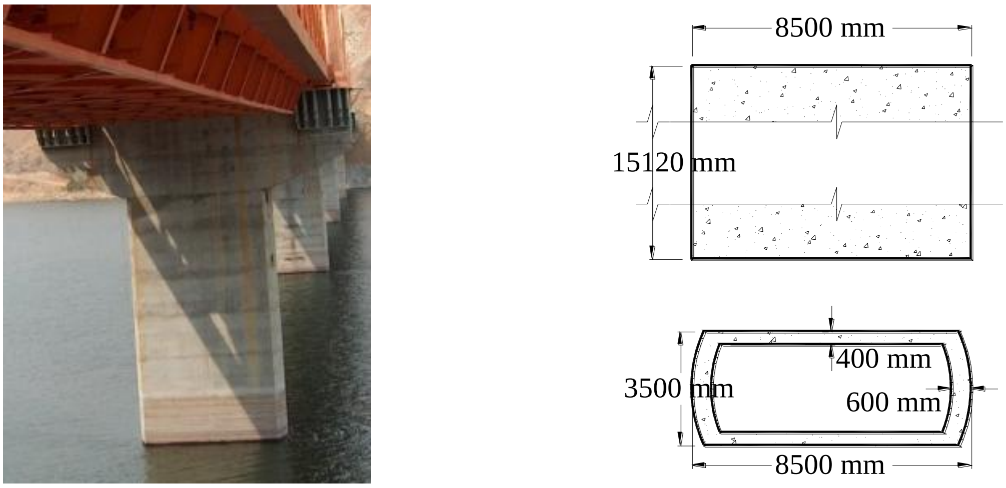

Figure 3. Wall type reinforced concrete piers of the Infiernillo II Bridge

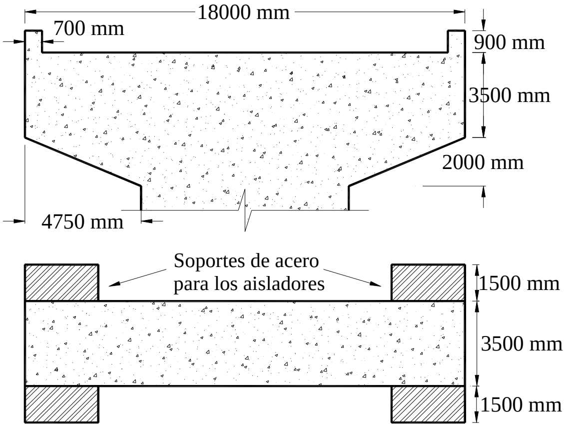

Figure 4. Bent cap of the Infiernillo II Bridge

The relatively close location of the bridge to the strongest seismic source of the country and the stiffness irregularity product of the different bent lengths of the bridge, made desirable the use of an isolation system to improve the expected behavior of the structure when subjected to strong motion movements.

Figure 5. Isolation system used in the Infiernillo II Bridge

3. DYNAMIC PROPERTIES OF INFRASTRUCTURE

Ambient and forced vibration measurements of the infrastructure of the bridge are reported by Muñoz (2003). An analytical model of these elements was proposed using a mesh of finite elements with the SAP2000 program. In this model, the added mass water effect was considered according to the Eurocode regulations. The results of the dynamic properties obtained are summarized in table 1.

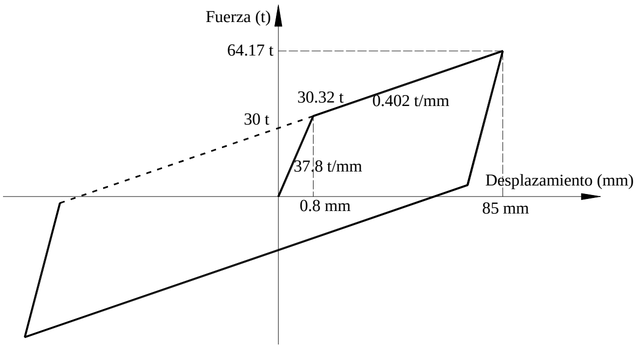

Figure 6. Hysteretic behavior model of the isolation system

Table 1. cylinder dynamic properties

Cylinder	Period (s)		
	Ambient vibration	Forced vibration	Analytical model
2	0.357	0.329	0.367
3	0.584	0.503	0.607
4	0.598	0.570	0.643
5	0.250	0.254	0.219

4. ANALYTICAL MODEL OF THE BRIDGE

Several structural models of the bridge with different levels of complexity were analyzed. All of them were created using the SAP2000 program using linear and non-linear elements (figure 7). In all cases, the truss elements were modeled using frame type elements with geometrical properties obtained from the structural project and drawings of the bridge. The isolation system was represented by link elements with bilinear hysteretic properties (rubber isolator type) with coupled plasticity properties for shear deformations and linear effective stiffness properties for the remaining four deformations.

4.1. Seismic Excitation

A collection of 116 seismic records of subduction type and 43 seismic records of intraplate type earthquakes were selected for the non linear time history analysis of the bridge. In the first case, all the records selected belong to earthquakes with a minimum magnitude of 7.0 and in the second case to earthquakes with a minimum magnitude of 6.5. In both cases the seismic stations are always situated in a range of 50km to 150 km to the earthquake epicenter.

A seismic hazard assessment in the site of the bridge location was carried aimed at determining the expected peak ground acceleration for different return periods of earthquakes. There were considered in this analysis all the seismic faults in Mexico with contribution to the seismic hazard in the place. The results obtained are summarized in table 2.

All the seismic records used in time history analyses were scaled to the values showed in table 2 for the seismic vulnerability assessment of the bridge.

Table 2. Expected PGA at the bridge location

PGA (gals)	Return periods (years)
152	50
198	100
347	500
420	1000

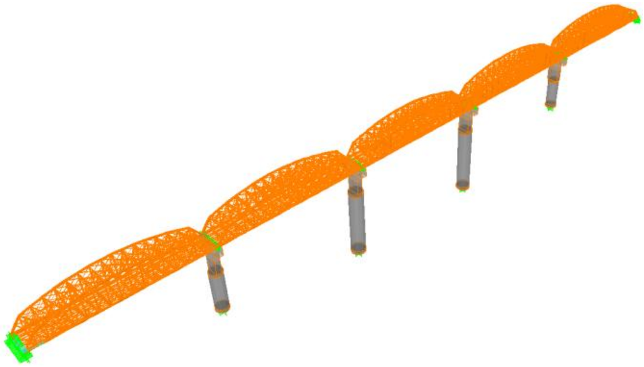

Figure 7. Analytical model of the Infiernillo II bridge

4.2. Dynamic Properties of the Bridge

The steel elements of the bridge have a elasticity modulus of Es=2.1E6 kg/cm^2, and the reinforced concrete elements of Ec=221,000 kg/cm^2. Using these material properties and the analytical model created, the first ten vibration periods of the bridge were obtained. Table 3 shows the periods of the bridge for the case of elastic behavior of the isolation system and the case of inelastic behavior of the device. It is remarkable the small period change between these two states of behavior. The fundamental period of the bridge is of translation movement in transverse direction and the second period is translation in longitudinal direction.

Table 3. Vibration periods of the Infiernillo II Bridge

Mode number	Period (sec)	
	Elastic behavior range of isolators	Inelastic behavior range of isolators
1	2.5159	2.9810
2	2.4167	2.8985
3	2.3147	2.8267
4	2.1510	2.7105
5	2.1203	2.6560
6	2.0675	2.6470
7	2.0067	2.6094
8	1.9172	2.4755
9	1.7962	2.3545
10	1.7352	2.2862

4.3. Seismic Demands

The expected spectral seudoacceleration and displacement demands of the bridge were determined as the average value of the spectral ordinate for the bridge fundamental period obtained with the collection of scaled seismic records. Table 4 shows the expected seudoacceleration and displacement values grouped according to the earthquake source, for different return periods.

Table 4. Seudoacceleration and displacement demands

Subduction earthquakes			
PGA (gales)	Tr (años)	Sa (cm/sec^2)	D (cm)
152	50	139	22
198	100	181	29
347	500	318	51
420	1000	384	62
Intraplate earthquakes			
Amáx (gales)	Tr (años)	Sa media T puente/g	D medio T puente (mm)
152	50	85	14
198	100	111	18
347	500	195	31
420	1000	236	38

4.4. Seismic Vulnerability of the Infiernillo II Bridge

The capacity of the bridge was determined based on moment curvature curves of the cylinder elements of the bridge. Figure 8 shows the two analytical models of the cylinders used.

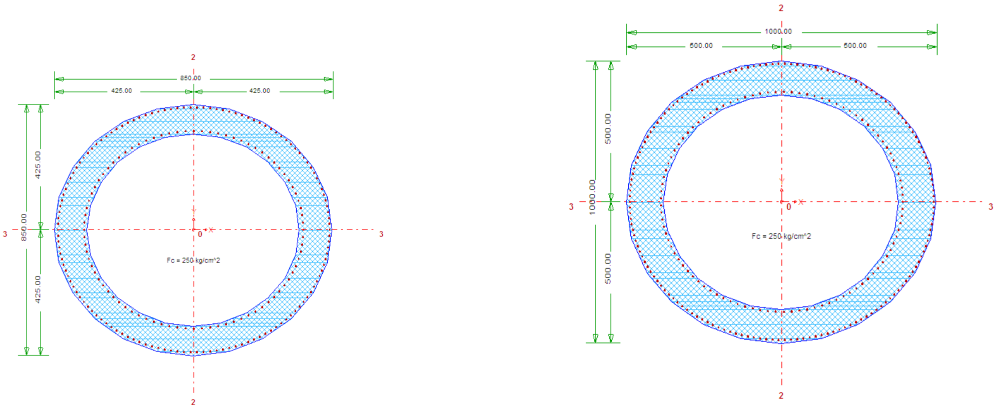

Figure 8. Analytical model of cylinders

Considering the reinforcement bar distribution in the base of the elements, and two steel behavior models, the moment curvature curves shown in figure 9 were obtained.

As expected, the cylinders with comparable length (two external and two internal) have similar behavior. Based on these curves the rotation ductility of the cylinders was estimated. The values found are in the range of 5.9 to 6.5. Once determined the analytical moment curvature curves, a tri-linear idealized curves were proposed for the subsequent analyses of the bridge.

The seismic vulnerability of the bridge was performed determining the capacity using a push-over analysis. The shape pattern of the lateral loads applied was determined subjecting the bridge to the collection of the seismic records previously mentioned. The average value of the maximum lateral deformations in different sections of the bridge height was used to select the shape pattern of the loads applied in the push-over analysis. The shape pattern obtained was different in each direction of analysis. In transverse direction, the flexibility of the bridge deck was evident in these analyses.

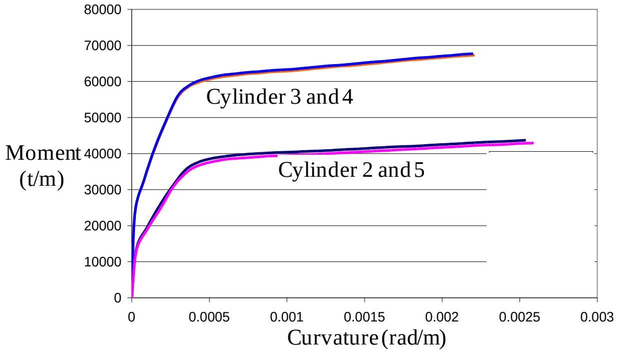

Figure 9. Moment curvature curves of the cylinder elements

The push-over curves with the shape load patterns of the subduction and intraplate type earthquakes applied in transverse direction of the bridge are shown in figure 10.

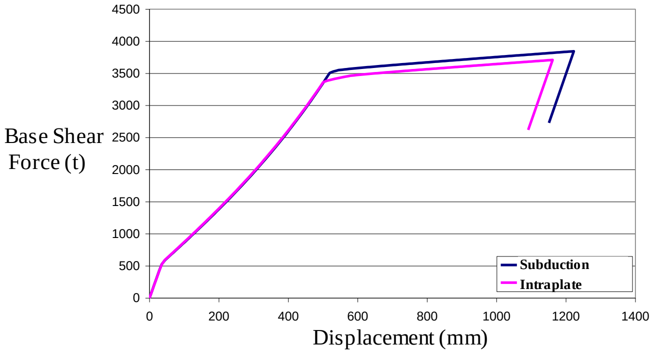

Figure 10. Push-over curves in transverse direction of the Infiernillo II Bridge

Several limit states were defined to the seismic vulnerability assessment of the bridge. Table 5 shows the selected limits based on curvature ductility values (Nielson, 2005).

Table 5. Curvatura ductility values for limit states of bent behavior

	Light damage	Moderate damage	Extense damage	Colapse
Ductility μ_ϕ	1	1.58	3.22	6.84

The ADRS curves generated for each limit state are presented in figure 11. The displacement demand and capacity of the bridge for the four states of damage can be seen in this figure.

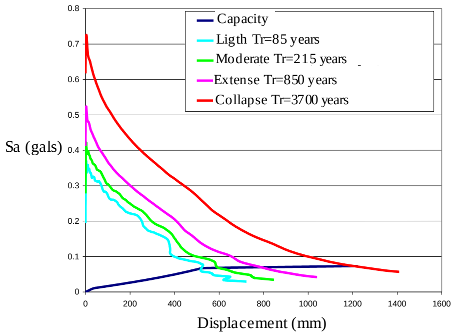

Figure 11. Displacement demand and capacity in transverse direction of the Infiernillo II Bridge

Fragility curves were determined for each limit state of behavior and for several standard deviation of the bridge demand and capacity. As one example of these results, figure 12 displays the fragility curves of PGA of the joint demand-capacity density function for a standard deviation of 0.6.

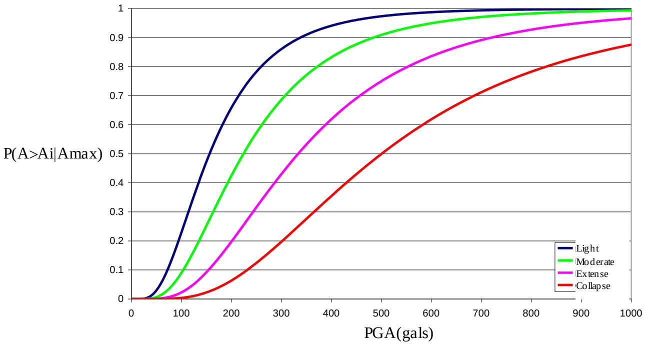

Figure 12. Fragility curve of the Infiernillo II Bridge

4. CONCLUSIONS

The important differences among the displacement demands on piers reflected their irregularity that is directly associated with differences in height of the substructure and the larger stiffness of the initial and final span of the bridge. The piers had out of phase movements when the bridge was subjected to the action of the seismic records in the transverse direction that did not occur in the longitudinal direction. In spite of that, the bridge deck did not have out of phase movements due to the beneficial effect of the isolation system.

The vulnerability analysis showed that a light damage of bridge is expected for a return period of 85 years and the collapse of the structure is associated to a large return period of 3700 years. At the same time, it could be observed that the design displacement of the isolation system is related to a relative small return period of earthquakes, showing that these elements should have been designed for a larger design displacement for a better expected behavior of the bridge.

REFERENCES

AASHTO, (2002), ”Standard Specification For Highway Bridges”, American Association of State Highway and Transportation Officials, Washington, D.C., 17th edition.
Beskos, D.E., and Anagnostopoulos, S.A., (1997), Computer Analysis and Design of Earthquake Resistant Structures: A Handbook, Chapter 12 Bridges, Computational Mechanics Publications.
Buckle, I.., (2000), "Passive control of structures for seismic loads", presented at the Twelve World Conference on Earthquake Engineering, New Zealand, pp 209-221.
Jangid, R.S., (2004), “Seismic response of isolated bridges”, Journal of Structural Engineering, Vol. 9, No. 2, pp. 156-166.
Jara M. y Casas J.R., (2002), “Vibration control in bridges. A state of the art and state of the practice” (in Spanish), Monografía CIMNE IS-48, Centro Internacional de Métodos Numéricos en Ingeniería, Barcelona, España.
Kunde M.C. and Jangid R.S., (2003), “Seismic behaviour of isolated bridges: A state-of-the-art review”, Electronic Journal of Structural Engineering, Australia, Vol. 3, pp. 140-170.
Nielson (2005), “Analytical fragility curves for Highway Bridges in Moderate Seismic Zones”, PhD Thesis, School of Civil and Environmental Engineering, Georgia Institute of Technology.
Shen J., Tsai M.H., Chang K.C. and Lee J.C., (2004), “Performance of a seismically isolated bridge under near-fault earthquake ground motions”, Journal of Structural Engineering, Vol. 130, No. 6, pp. 861-868.
Spencer J.R., (2002), "Supplemental energy dissipation: state-of-the-art and state-of-the-practice", Engineering Structures, Vol. 24, pp 243-259.