16th World Conference on Earthquake, 16WCEE 2017

Santiago Chile, January 9th to 13th 2017

Paper N° 958 (Abstract ID: 958)

Registration Code: S-U1464366936

NONLINEAR RESPONSE ANALYSIS OF A CURVED CONCRETE BRIDGE PLACED SEISMIC ZONES

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Abstract

Geometric constraints of highways or urban roads currently often raise the need for projecting bridges with a horizontal curved configuration. At the present the use of box girders has been gaining popularity in bridge engineering due to its greater stability, serviceability, economy, aesthetics and structural efficiency. So this research focuses on the study of behavior and structural response, of concrete bridges with curved box-girders subjected to seismic actions to determine by numerical modeling, the nonlinear and seismic response taking into account nonlinear material behavior. This study investigates the potential damage that it could suffer the bridge during earthquakes, 3D numerical models with beam and solid element were developed by using of the FEM of an existing bridge and were carried out analysis step by step and nonlinear. The structure is composed of concrete frame in longitudinal direction, which is formed by rectangular columns of variable section, the requirements of AASHTO, IMT-SCT and CFE-2008 were used. Finally, it is observed from the 4 models that as the radius of curvature of the structure in plan, is more noticeable, the concentration of cracking and crushing of concrete is located in the central segments and piers, respect to the time analysis, the displacement histories are more evident in straight bridge.

Keywords: Horizontally curved bridges; Concrete box-girder bridges; Seismic behavior; Numerical modeling; Nonlinear response analysis.

1. Introduction

In the past, bridges on curved alignments were rare; however, modern highway bridges and traffic separation structures are commonly built on a horizontal curve. This change has come about because of higher traffic volumes and speeds, the geometric constraints of the urban environment, and improved structural forms that lend themselves to curved construction. Geometric constraints of highways, roads and urban roads force to project and to design bridge structures with curved geometries in plan. So, at the present the use of box girders has been gaining popularity in bridge engineering due to its greater stability, to resist torsion effect, as well as, serviceability, economy, aesthetics and structural efficiency.

So, the construction in México as well as in the world of curved box-girder bridges in inter-changes of modern highway systems has become increasingly popular for economic and aesthetic reasons. Box-girder cross sections may take the form of single cell (one box), or multi-cell box girder (separate boxes), with a common bottom flange (contiguous boxes or cellular shape).

1.1 Problem statement

Generally, the design codes of bridges recommend limited analytical methods for the analysis of certain types of straight box-girder bridges as well as load distribution factors, for longitudinal moment and shear. However, for other types of structuration such as curved box-girder bridges the analytical methods are scarce.

After mentioning the need to design horizontally curved concrete box-girder bridge, silvering the problem about the limitations that exist in the standards and regulations and bridge design and construction codes. However, experience in the design and construction of such bridges alert us care that must be taken in each of its stages, both in the design phase and its construction phase in order to have a structure that meets the requirements of security, functionality and aesthetics that are raised from the project. So, the structural behavior of box girders is complex, so it is not easy to analyze their actual service conditions by conventional methods. The diversity of ways in design is increasing more and more. It represents a challenge for engineers, to propose new structural forms and materials. Analytical methods have developed rapidly in the same way, particularly with the use of computerized methods, such as the FEM.

1.2 Aim and justification

So this research focuses on the study of dynamical behavior and nonlinear response, of concrete unicellular decks curved of bridges subjected to seismic actions to determine by numerical modeling, the structural and seismic response taking into account nonlinear material behavior.

This study investigates the potential damage of the different possible scenarios that they could suffer the bridge during strong motions. So, to know the inelastic behavior and its response of the structure the ANSYS program [2] was used for these analysis. The structures were analyzed by static and step-by-step methods. The requirements of AASHTO [1], IMT-SCT [6] and CFE-2008 [5] codes and manuals were used for the analysis.

For this purpose, we have developed 3D numerical models, using beam and solid elements by FEM. Thus, the aim of numerical modeling and seismic analysis of bridges, is to provide a mathematical formulation of the behavior of a bridge that will satisfy a request for review to determine its nonlinear response. To take into a count the mechanical behavior of material was chosen a finite element to carrying out modeling and three-dimensional (3D) analysis of structures without concrete reinforcing bars. The constitutive law for this item is the William and Warnke model [2, 13], which allows the solid element fails by cracking tension and crushing compression as well as Scott, Kent, Park model use for step by step analysis [12].

1.3 Scope

Develop tridimensional numerical models (3D) by FEM of the bridge with the use of beam and solid elements, and then through the numerical results to know and study their dynamic and seismic behavior. As well as, to observe if the structure goes into the non-linear range of material. Likewise, a constitutive law of concrete material is introduced (Willian-Warnke model), reflecting the cracking concrete in tension and crushing when the concrete in compression fail.

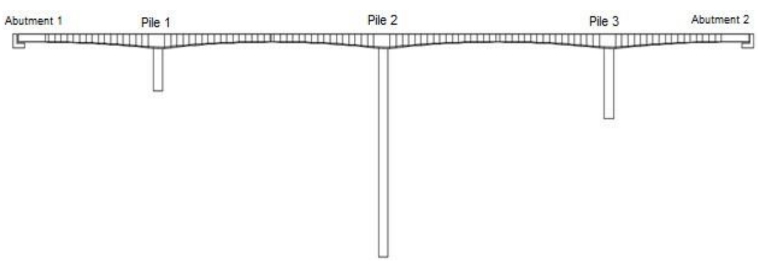
2. Structure studied and numerical model

2.1 Structure studied

The bridge studied, is located on the stretch of bifurcation of Xalapa in Veracruz state. The viaduct is a prestressed concrete structure with a superstructure to four lanes, with a design speed of 110 km/hr, it has a length of 470 m. and a width of 17.90 m (see figure 1). The structure is composed of concrete frames in longitudinal direction, which are formed by hollow rectangular columns of variable section (see figure 2, 3.1 and 3.2). The beams are formed by hollow box girders with a variable section has a curvature in plan with a radius of 572.96 m.

Fig. 1 – Bridge studied

2.2 Characteristics of structural elements



The piers are of reinforced concrete, cast in situ, they are hollow rectangular elements of variable section. The columns have three types of section each with different height: column 1, h1 = 23 m, column 2, h2 = 113 m and column 3, h = 38.00m (see figs. 2, 3.1, 3.2, 4.1, 4.2).

Fig. 2.1 - Lateral view of the bridge and location of columns

Columns sections

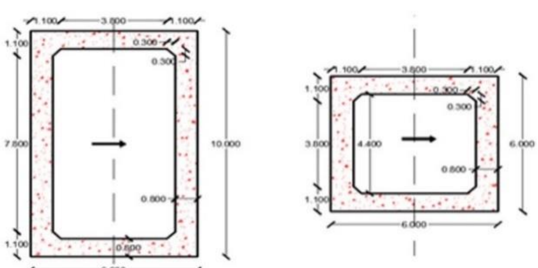


Fig. 3.1 – Cross sections of columns 1 and 3

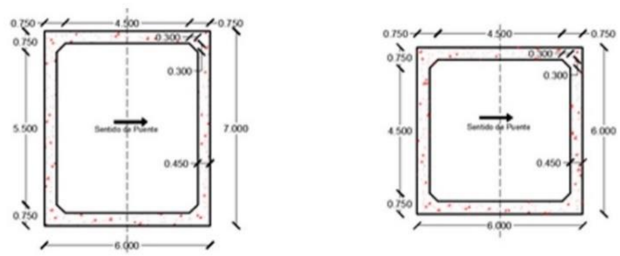


Fig. 3.2 – Cross sections of column 2

The box-girder sections are hollow prestressed concrete elements of variable section box (see figs. 4.1, 4.2). Concrete box-girder sections

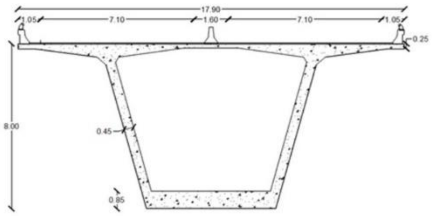


Fig. 4.1 - Box-Girder Sections

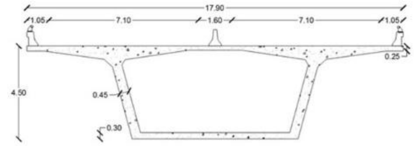


Fig. 4.2 - Box-Girder Sections at midspan

2.3 Mechanical properties of materials

For the main structural elements "concrete class 1" was used, which was considered volumetric weight of 23.544 N/mm^3 and a modulus of elasticity E_c, quality stone aggregates for hydraulic concrete regulations for Transport Infrastructure IMT-SCT [6]. For steel reinforcement steel structural elements grade 42 it was used with a yield stress of 412.17 Mpa. For steel prestressing wires called strands, laid wires compound helical shape with the following characteristics were used, see table 1.

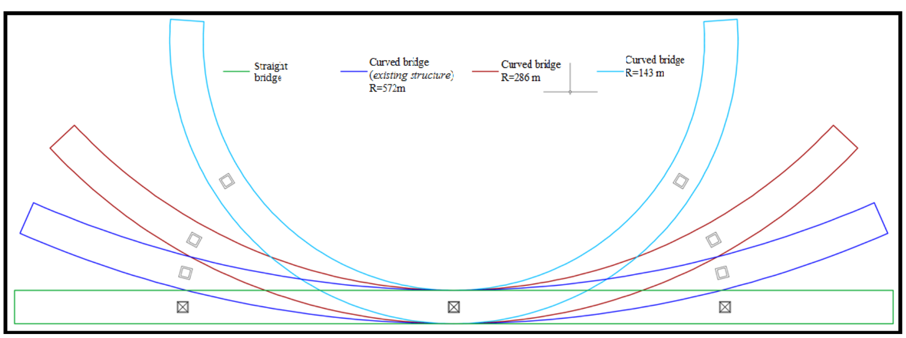
Table 1 – Mechanical properties of materials

Mechanical Properties of Materials				
Material	**Description**	**Strength**		**Units**
Concrete	Piers	f´c=	34.35	Mpa
	Box girdes	f´c=	39.25	Mpa
	Footings	f´c=	29.44	Mpa
	Young modulus in piers	Ec=	25703.24	Mpa
	Young modulus in beams	Ec=	27477.92	Mpa
	Young modulus foundation	Ec=	23796.58	Mpa
	Volumetric weight	γ	23.544	N/mm3
	Poisson's ratio	ν	0.2	

Mechanical Properties of Materials				
Material	**Descripción**	**Resistencia**		**Unidad**
Reinforcing steel	Yield stress	f´y=	412.17	Mpa
	Young modulus	f´c=	206084.4	Mpa
	Poisson's ratio		0.3	
Prestresse d steel	Tensile Strength		1490.00	Mpa
	Yield stress	fpu=	1860.00	Mpa
	Young modulus		197,000	Mpa

3. Numerical modeling and dynamical analysis

The concrete highway bridge has a curved geometry of the deck plan, is modeled by FEM. The bridge is modeled three-dimensionally (3D), with a length of 470 m, a width of 17.90 m and a height of 113 m, structured by a deck with a box section, supported by three rectangular hollow columns and the abutments are simply supported (see fig. 5.2). Likewise, they are carried out the nonlinear and step in time-step analysis, using real (SCT-85), ground motions earthquake.



The bridge is curved horizontal alignment with a radius of curvature of 572 m, so this geometry is compared with numerical results of a straight type and two models of smaller radius of curvature (see fig. 5.1).

Fig. 5.1 - Plan view of the four bridges studied

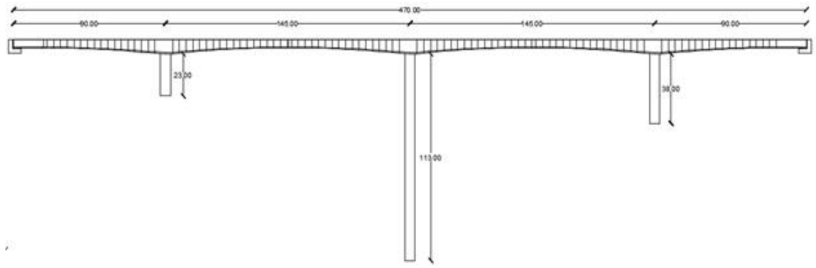
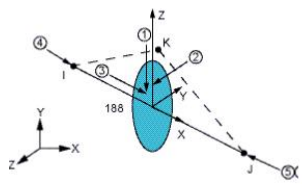


Fig. 5.2 - Lateral view of the bridge

3.1 Single-lines three-dimensionally model 3D

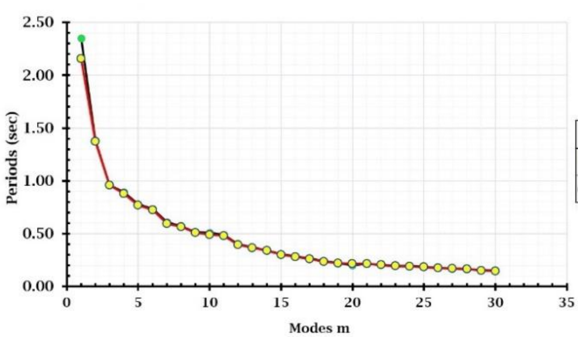
The development of 3D numerical model was performed using the ANSYS v.15.0 program, which beam type elements were used BEAM188 to describe the characteristics of the physical behavior of the elements, this element is appropriate to analyze moderately slender or thin structures based Timoshenko theory for beams. The BEAM188 element is a 3-D linear or quadratic (2 or 3 nodes, being the 3rd intended to guide the element) with 6 degrees of freedom at each node translations in the X, Y, Z and rotations about directions X, Y, Z. [2].



For modeling of beams, the beam elements (beam188) is discretized in the same number of segments containing the bridge, see fig. 6. Calculating for each of the 111 dowels their geometrical properties model consists of 4,487 nodes and 202 beam elements.

Fig. 6 – Beam188 element [2]

3.1.1 Modal Dynamic Analysis



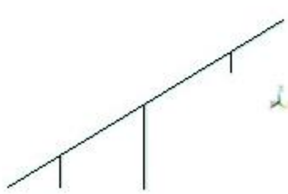
Modal Shape
Single-line model with beam element 188

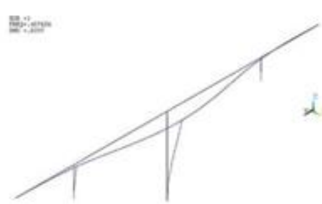
MODE	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Straight bridge	2.35	1.39	0.96	0.89	0.78	0.74	0.61	0.57	0.52	0.51	0.49	0.40	0.37	0.34	0.31
C bridge R=572	2.16	1.37	0.96	0.88	0.77	0.72	0.60	0.57	0.51	0.49	0.48	0.40	0.37	0.34	0.30

Fig. 7 – Vibration periods **T** (secs) of straight and curve models studied

In order to study the influence of the curvature of the deck in plant, 3D numerical models were made, considering the same sections real-curved bridge, the first was a straight bridge and the second the actual curved bridge. The goal was to see through the dynamic characteristics such as: (periods **T**, frequencies **f** and mode shapes **Φ**), the bridge response based on their curvature, in figures 7 and 8 are showing the comparison of the numerical results of vibration periods obtained of two models studied.

3.1.1 Modal configuration of straight bridge model 1





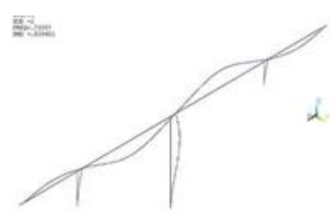


Fig. 8.1 – Straight bridge, isometric view. Fig. 8.2 – Mode 1 Fig. 8.3 – Mode 2

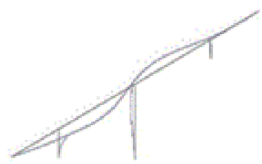


Fig. 8.4 – Mode 3

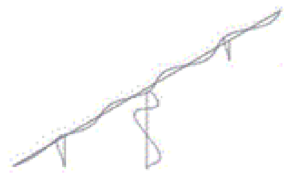


Fig. 8.5 – Mode 30

3.1.2 Modal configuration of curved bridge isometric view

Fig. 9.1 – Curved bridge, isometric view

Fig. 9.2 – Mode 1

Fig. 9.3 – Mode 2

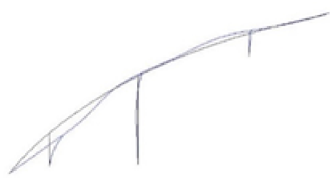


Fig. 9.4 – Mode 3

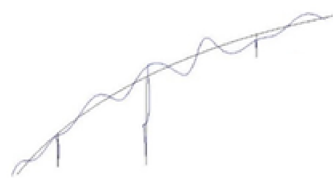


Fig. 9.5 – Mode 30

3.2 Three-dimensional numerical model 3D with solid elements

In this section three-dimensional numerical models constituted by solid elements are presented.

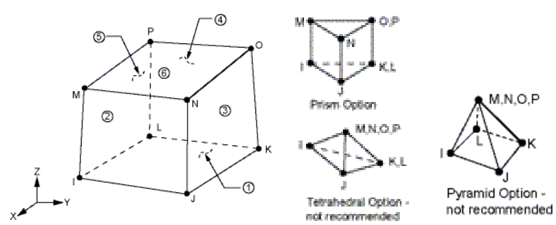
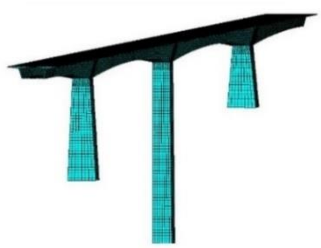


Fig. 10 – Solid element 185 [2]

The FEM models consisted of solid element, in the ANSYS [2] library the solid element 185 is chosen for linear and non-liner analysis, this element is defined for eight nodes each then with three degree of freedom translation in x, y, z, also the element takes into account the plasticity, creep, large deflections and large deformations (see fig. 10).

3.2.1 Meshing of the structures and boundary conditions

Through using techniques based on the discretization by FEM, 3D models were developed to study the structural behavior of curved bridges based on box girders using solid elements. Then four numerical models are shown in figures 11, which were developed to study behavior under the influence of the curvature in plan, the bridge. The restriction of movement was based on physical considerations of the actual structure, columns (1, 2 and 3) considered as supports embedded, i.e. restricting the displacements and rotations, for the abutments (1 and 2) were considered only **U*y*** and **U*z*** restricted the movement.



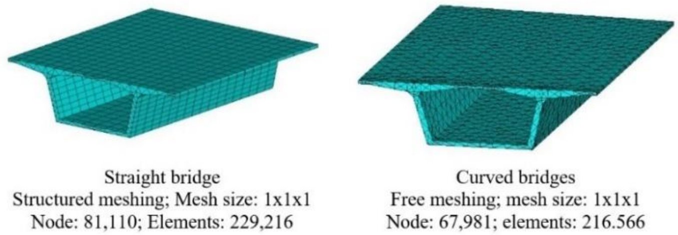


Fig. 11.1 – Straight bridge 3D view

Fig. 11.2 – Deck (box girder sections)

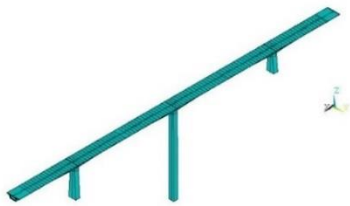


Fig. 11.3 – Straight bridge (model 1)

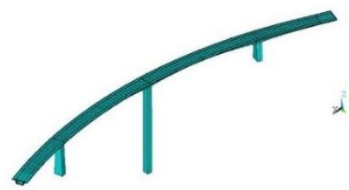


Fig. 11.4 – Curved bridge R=572m (model 2) (*existing structure*).

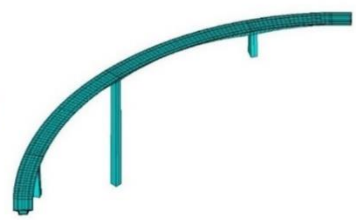


Fig. 11.5 – Curved bridge R=286 m (model 3)

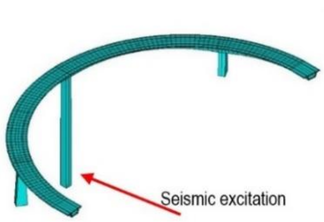


Fig. 11.6 – Curved Bridge R = 143 m (model 4)

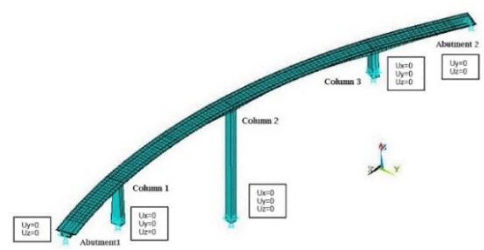
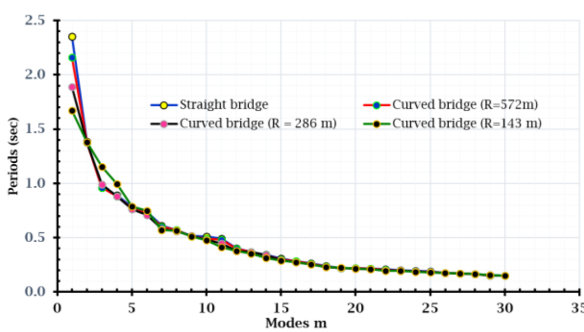


Fig. 11.7 – Boundary conditions of bridge R = 572 m

3.2.2 Numerical results of modal dynamic analysis

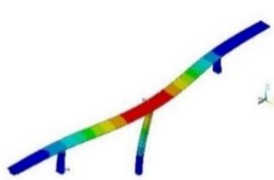


Modal Shape and periods
3D model with solid element 185

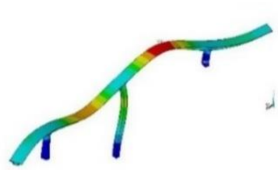
MODE	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Straight bridge	2.35	1.38	0.96	0.89	0.78	0.74	0.61	0.57	0.52	0.51	0.49	0.40	0.37	0.34	0.31
C bridge R=572	2.16	1.37	0.96	0.88	0.77	0.72	0.60	0.57	0.51	0.49	0.48	0.40	0.37	0.34	0.30
C bridge R=286	1.89	1.37	0.99	0.88	0.76	0.71	0.58	0.56	0.51	0.48	0.45	0.38	0.37	0.34	0.29
C bridge R=143	1.67	1.38	1.15	1.00	0.79	0.75	0.57	0.57	0.51	0.48	0.41	0.38	0.35	0.31	0.29

Fig. 12. Comparison of the first 30 periods of vibration of the four models "3D" studied

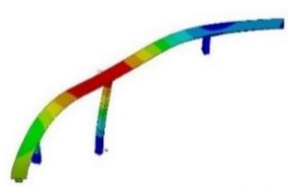
In figures 12 and 13 are shown the three first modal configuration of the four models studied.



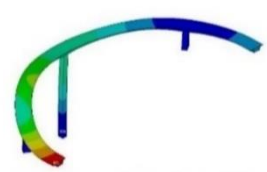
Straight bridge



Curved bridge, R=572 m (*existing structure*)

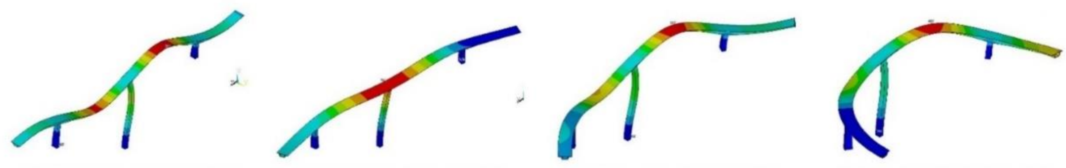


Curved bridge, R=286 m



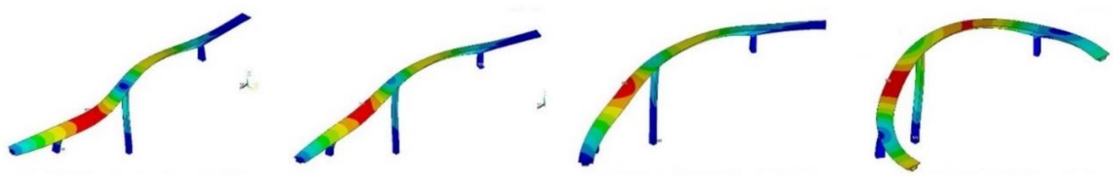
Curved bridge, R=143 m

Fig. 13.1 – Modal configuration m=1



Straight bridge | Curved bridge, R=572 m (*existing structure*) | Curved bridge, R=286 m | Curved bridge, R=143 m

Fig. 13.2 – Modal configuration m=2



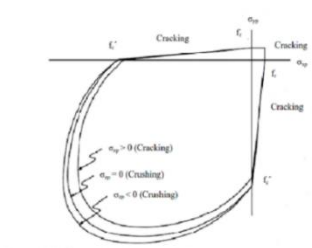
Straight bridge | Curved bridge, R=572 m (*existing structure*) | Curved bridge, R=286 m | Curved bridge, R=143 m

Fig. 13.3 – Modal configuration m=3

3.2.3 Constitutive model

The failure criterion chosen for its characteristics was the failure criteria developed in 1975 by William & Warnke [2, 13], predicts the surface of concrete failure unconfined compression and tension in the principal stress field, assuming an isotropic behavior, (fig. 14). The failure criterion is expressed as:

$$\frac{F}{f_c'} - S \geq 0 \tag{1}$$



were:

F = Function dependent on the state of major stresses $(\sigma_1 + \sigma_2 + \sigma_3)$

S= Failure surface defined from five parameters (f_t, f'_c, f_{cb}, f_1, f_2,)

f'_c = Ultimate compressive stress

f_t = Ultimate resistance to uniaxial tension

f_{cb} = Ultimate biaxial compression resistance.

f_1 = Ultimate biaxial compression strength under a state of hydrostatic stresses σ_h

f_2 = Ultimate uniaxial compression strength under a state of hydrostatic stresses σ_h

Fig. 14 – Failure surface of William and Warnke [2]

4. Numerical Results

The bridge presents a curved horizontal alignment with a radius of curvature of 572 m, which is compared with numerical results of a straight type and two models of smaller radius of curvature. To do so, they are carried out static and step by step nonlinear analysis no-linear analysis in time-step using real ground motions earthquakes.

4.1 Numerical results by static no-linear analysis

4.1.1 Model 1 "straight bridge" under gravity loads.

In this part, it is presented the stress state due to the most unfavorable combination of gravity loads (dead load and vehicular live load, T3-S2-R4 [6]), see fig. 15.

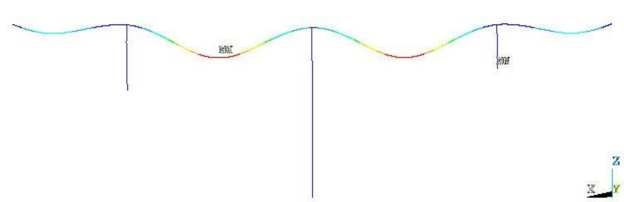


Fig. 15 Deformed structure representation under gravity loads

In this image (fig. 16.1) it is observed that due to changes in rigidity showing the bridge, by the stiffness variation at each of its columns, cracking starts in column 1, in the transition zone, girder-column (fig. 16.2) and cracking and crushing the bridge are shown in fig. 16.3.

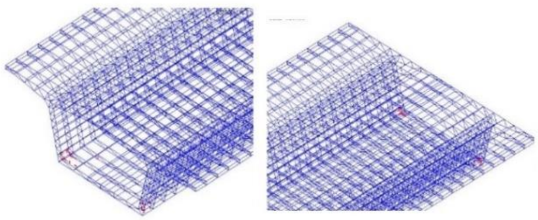


Fig. 16.1 Cracking the material support of the dowels at the abutments 1 and 2

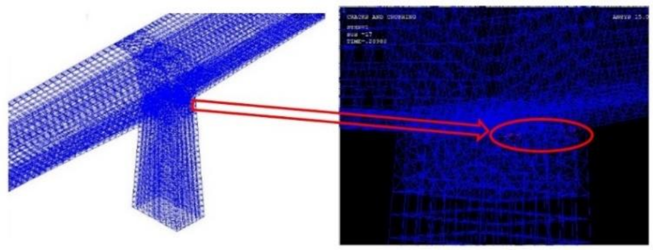
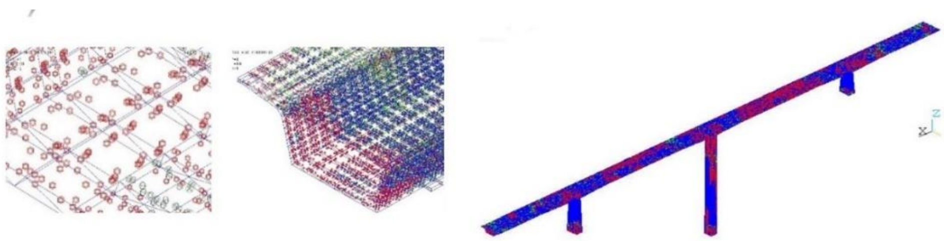


Fig. 16.2 Cracking in the transition dowel-column 1



Cracking and crushing at the abutments 1 Model 1 "straight bridge”

Fig. 16.3 Cracking and crushing the material in the box-girders, piers and support in the abutment

4.1.2 Model 2 curved bridge (existing bridge)

Figure 17 shown a state of cracking it occurs on the support zone of the abutment due to stress generated in the area. Following the same pattern of behavior of model 1 cracking progresses significantly in the segments of the abutment due to the concentration of tensile stresses, which arise being the last step of charging.

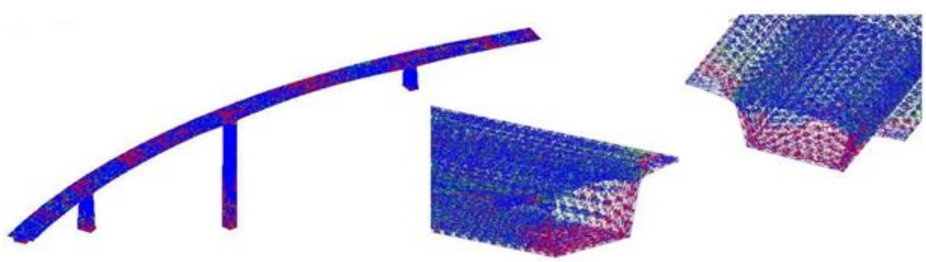
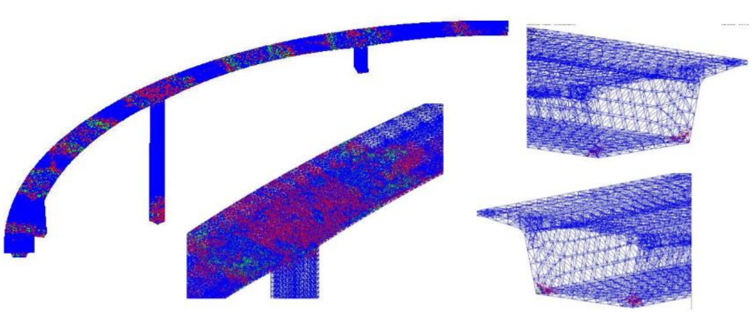


Fig. 17. Cracking and crushing of different areas of model 2, curved bridge (existing bridge).

4.1.3 Model 3 curved bridge (R=286 m)

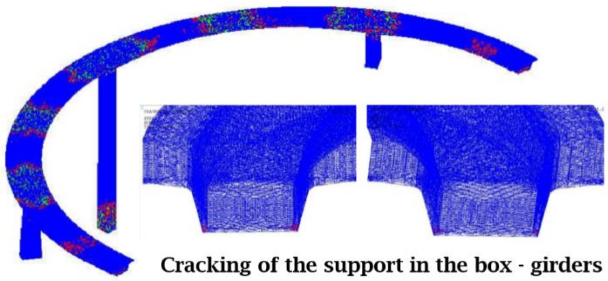


Also in figure 18 are shown the state of cracking occurs on the support zone of the abutment and the transition of deck - pier.

Fig. 18.3 Cracking and crushing of different areas of model 3, curved bridge (R=286m).

4.1.4 Model 4, curved bridge (radius = 143 m)

In the area of support of the box-girders at the abutments (figs. 19), cracking it occurs on the support zone of the abutment and the corners of the segments box girders.



In this case, wherein the radius of curvature is greater (R=143m) the concentration of cracking and crushing of the elements is located on the piers and in the central segments of each of the three spans.

For the case where the curvature radius is larger than the other, i.e. R=143 m, the concentration of cracking and crushing of the elements is placed in piles and central segments of the clearings.

Fig. 19. Cracking and crushing pattern in different areas of model 4.

4.2 Numerical results by nonlinear seismic analysis

Finally, it was performed the non-linear seismic analysis, (time-history) by three-dimensional (3D) models of the bridges, to evaluate the seismic response of the system and the individual components.

4.2.1 Constitutive model

The mechanical characterization of the material was performed using a constitutive model proposed by Scott et. al. (1982) [12], the model considers a simple concrete. Thus, the nonlinear behavior is taken into account by the numerical models of stress-strain relationship, for which a nonlinear MISO model, ANSYS [2], characterized by a curve with 30 points was used with a maximum strain ratio ε_c=0.004 and f'_c=39.25 Mpa.

4.2.2 Seismic records

The non-linear analysis, step-by-step were carried out employing seismic records at Mexico City and Union obtained of the earthquake originated at the Subduction zone of Mexican Pacific Coast in 1985 and, their elastic response spectrums with 5% of critical damping are shown in Figures 20.a, 20.b.

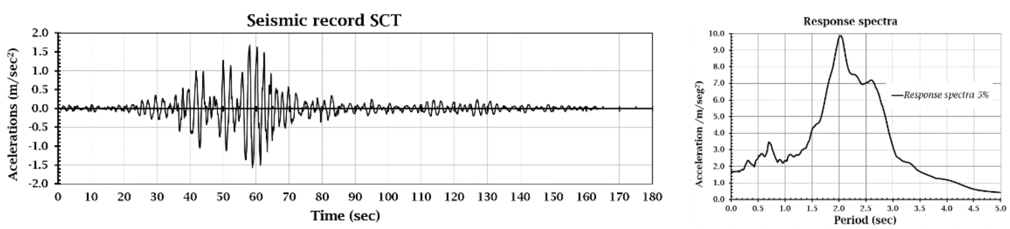


Fig. 20.a Horizontal ground acceleration record, SCT-85 and response spectra, Mexico City

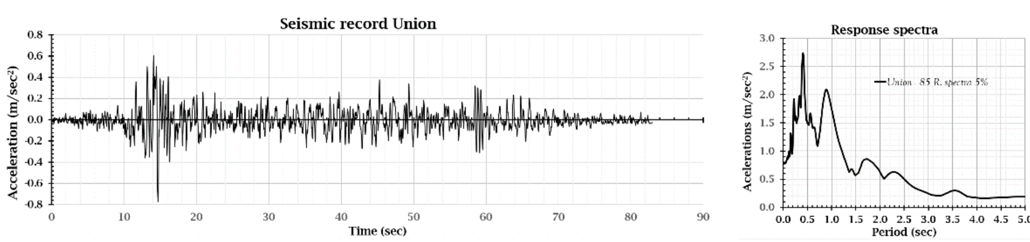


Fig. 20.b Horizontal ground acceleration record, Union-85 and response spectra, Acapulco Gro.

4.3 Time-History analysis results

Seismic records SCT and UNION were used to perform the analyzes time-history for the 4 structures studied (*straight bridge, existing curved bridge, curved bridge R=286m and curved bridge R=143m*), these signals were applied at the base of columns, in the transverse direction of each of the four bridges (see figure 11.6), to observe their seismic behavior in that direction, because its rigidity has increased susceptibility to be demand, the figure 21 shows the location of the four structures in seismic response spectra of the two signals, SCT and UNION, with different dynamic characteristics. The Step by step time-analysis were carried out in the 4 bridge models with the purpose to know the influence of horizontal curvature of the bridges in the seismic response.

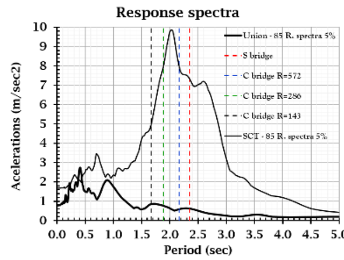
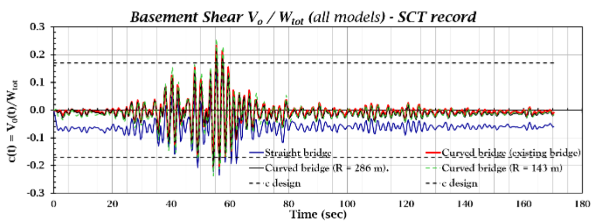


Fig. 21. Four structures placed in seismic response spectra of the two signals, SCT and UNION.



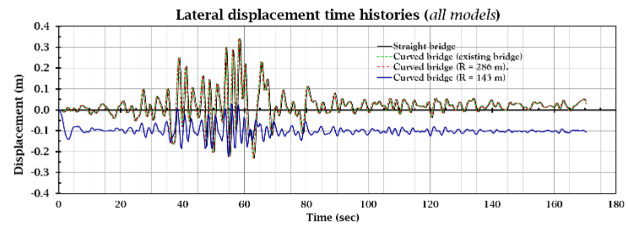


Fig. 22.1 Comparison of the V_0 basement shear time-histories. Fig. 22.2 Lateral displacements time-histories (*all models*) with SCT record.

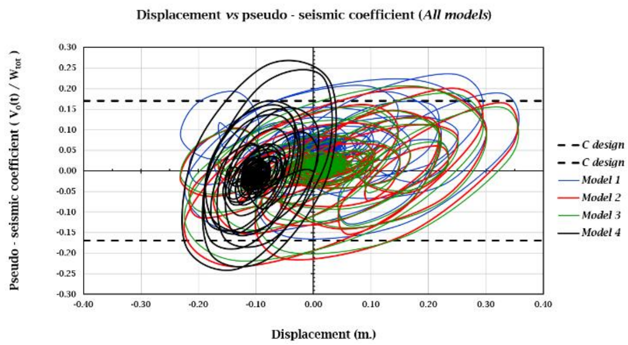
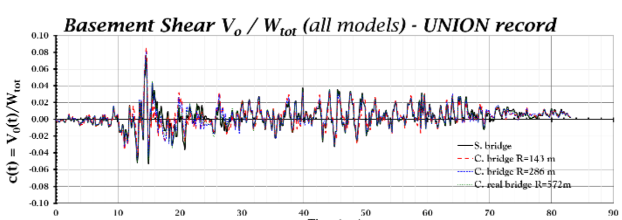


Fig. 23 **c(t)** *vs* lateral displacement hysteresis loops with SCT signal, all models

The results of SCT signal, time history of basement shear ($c(t)=V_o(t)/W_{tot}$ *vs time*), of central column (pile 2), are shown in figures 21.1, 21.2, it can see that the structures go in the nonlinear range ($c(t)>0.17$). Conversely, the numerical results with the UNION signal show a decreased seismic response in 4 structures analyzed, remaining in the linear range ($c\ (14.6) = 0.0812 < 0.17$) in straight bridge, however, the maximum displacements of the pile 2 are of the order 20 cm in straight bridge, 17cm for existing straight bridge, and the minimum values are presented in the curved bridge R=143 m, as shown in figures 23.1, 23.2. The hysteresis loops of numerical results ($c\ (55.42) = V_o\ (55.42)/W_{tot} = 0.26 > 0.147$ *vs displacement*) obtained from seismic analysis step by step with the SCT record, the 4 models (*straight b., existing c. b., c. b R = 286m and c. b. R = 143m*), are shown in figures 23, and which is observed the nonlinear behavior of the structures and energy dissipation through stable cycles.



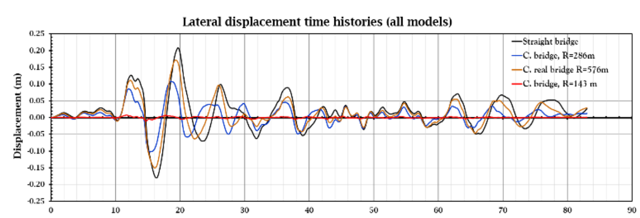


Fig. 24.1 Comparison of the V_0 basement shear time-histories. Fig. 24.2 Lateral displacements time-histories (*all models*) with UNION record.

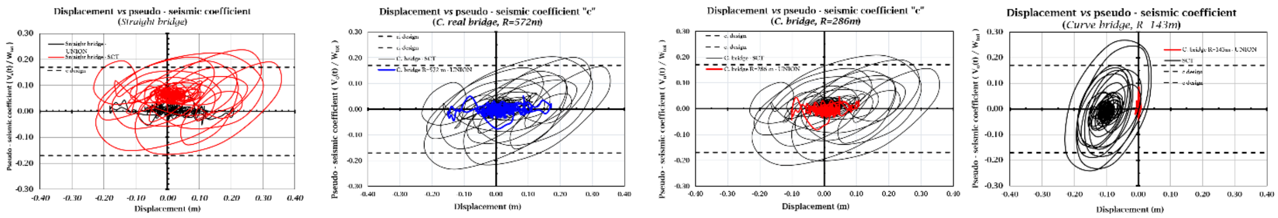


Fig. 23 Comparison between SCT and UNION hysteresis loops (**c(t)** *vs* lateral displacement), all models.

Figure 24 shows the comparison between, the loops hysteresis, (*c(t) vs lateral displacement*), related to the SCT and UNION signals, it is observing a clear difference in the response of the 4 structures, so the major response, in which the structures go in into the nonlinear interval, is produced by SCT, while the second remains in the elastic range. The figures 25 shown the maximum lateral displacements of 3 models (straight b., existing curved b. R=572m, curved b. R=286m), produced by the UNION record.

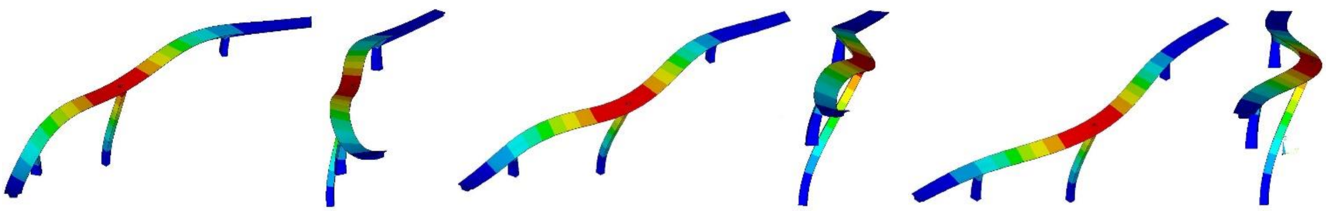


Fig. 25 Maximum lateral displacements of 3 models (*straight b., existing curved b. R=572m, curved b. R=286m*) produced by the UNION record.

Conclusions

Since, being a structure with a very irregular variation in rigidity, this generates, large variations in distortion and stress concentration in certain structural elements. So, it proceeded to study the structure using two types of numerical modeling developed by using the FEM: the first with beam elements and the second with solid elements, very similar results were obtained for the case of dynamic analysis which served later to validate the models with solid elements that were with which it finally performed nonlinear analysis over time.

It was observed that as they the radius of curvature of the models is more pronounced the displacements are increased, whereas the stress response, is distributed more uniformly due to lateral displacements of the central column are present, which they help avoid stress concentrations at a given point. Likewise, about the numerical results by static nonlinear analysis, it is observed that the first traces of concrete cracking are shown in the areas of dowels of box sections supported on the columns, this is due to a concentration of tensional stresses and compression in these regions.

From the 3D numerical results by nonlinear seismic analysis, for the 4 structures studied, employing the seismic records at Mexico City and Union obtained to the earthquake at the subduction zone of Mexican Pacific, with different dynamic properties, as can be seen (fig. 20), to know the influence of horizontal curvature of the bridges in the seismic response. We can see that, the results obtained with SCT signal, the time-history of the basement shear $V_o(t)$ (*c(t) vs time*), of central column (pile 2), the four bridge models go into the nonlinear range, since the seismic demand is greater than the design capacity by 53% ($c(t)>0.17$). Conversely, the numerical results with the UNION signal show a decreased seismic response in 4 structures analyzed, remaining in the linear range ($c(t)<0.17$).

Regarding the hysteresis loops obtained to the numerical results (*c(t) vs lateral displacement*), from of step by step seismic analysis with the SCT record, it found that the 4 models (*straight bridge., existing bridge, c. b R=286m and c. b. R=143m*), shown a nonlinear behavior and their energy dissipation through of cycles is stable.

Additionally, concerning the lateral displacement produced by both SCT and UNION records, it is observed that there is not a great difference on two of the four bridges (*straight and existing bridges*), since its horizontal curvature is not very evident, show a lower lateral stiffness in transversal direction, however, in most of the models, the torsion occurs on the box girders.

4. Acknowledgements

This research was conducted at SEPI, ESIA-UZ, of the Instituto Politécnico Nacional in collaboration with the Mexican Petroleum Institute and is related to the thesis of Master of A. Aguilar, fellow of CONACyT, 2015.

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