Probabilistic Approach for Structural Evaluation of Common Bridges Exceeding Service Life

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Abstract. The Mexican bridge inventory has 7580 bridges, with almost 61% built before 1980 and more than 40% that have exceeded their service life. For these, the design criteria considered traffic and load conditions that have been exceeded significantly. Moreover, in most cases, there is little information, including drawings, design calculation or rehabilitation reports. As a consequence, calculation of the structural capacity or residual life is not an easy task, not to mention that fatigue, corrosion, damage or any other deterioration mechanism might be present. To address this problem, in 2011, the Mexican Transport Institute proposed the creation of the Monitoring Centre for Bridges and Intelligent Structures that not only is going to monitor the most important bridges in Mexico, but also monitoring some of the most common bridges (type bridges). The goal is to develop parametric models of the type bridges, which could provide information of their structural condition based on field data (static and dynamic) obtained from simplified experimental procedures; at the same time, from adequate deterioration models, to calculate the residual life considering actual and close future conditions. To present, 6 bridges have been instrumented and monitoring is being carried out and deterioration models have been proposed for short span reinforced concrete, and short and mid-span steel bridges.

Introduction

In the past 10 years, structural health monitoring for bridges has become a common approach for structural conservation and maintenance, particularly for special or important bridges [1-3]. Recent technological developments allow, more and more, larger number of sensors, sophisticated and reliable monitoring systems, and complex analysis strategies. Although the cost of sensors and instrumentation is decreasing, a full scale monitoring system is still only possible for large and important structures.

In the case of smaller or less significant bridge structures, which are the most common in many worldwide bridge inventories, are not regarded as feasible candidates for

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permanent or remote structural health monitoring, from an economical point of view. As a consequence, different alternatives for monitoring must be considered, not only because these smaller bridges could represent a high percentage of the whole bridge catalogue, but also, because they are more sensitive to vehicle's loads and ambient conditions.

Several problems arise when considering these more common and less important structures; the first, that they could have ages that range from more than 40 years; and for that, it is very probable that the design codes and specifications, have been exceeded by present traffic and load conditions. The second problem is the large variety of designs, material's characteristics, and dimensions; which are difficult to synthesize in a general model to evaluate structural capacity or for prognosis.

In this work, based on the characteristics of the Mexican bridge inventory, some basic ideas have been proposed to build up few probabilistic parametric models for the most common types of bridges in Mexico. From these parametric models, structural capacity or residual should be calculated from basic experimental data obtained from a simple load test and an impact-response test. The first, to get the flexural displacement from, and the second, to measure the first transversal and torsional natural frequencies; and finally, from these build an index related with the structural condition [4].

1. Mexican Bridge Inventory

Since 1990, Mexico has been using a bridge management system identified as SIPUMEX, to keep a complete database of the bridge inventory in the Federal Highway network to evaluate their structural condition and to plan the yearly maintenance programs. In the SIPUMEX, there is a complete description of the almost 7585 bridges, including sub-structure and super-structure characteristics; geometrical features; few design data, and a standard structural condition index that rates the global state of the bridges [5].

1.1 Present Condition

One primary characteristic of the Mexican bridge inventory is that almost 46% of the bridges have more than 40 years and were designed considering loads according to HS-15 or HS-20 AASHTO code (figure 1).

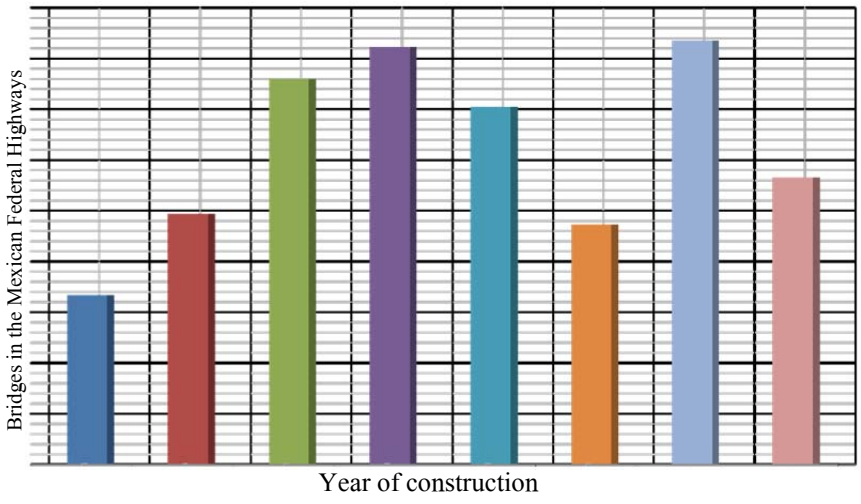

Figure 1. Bridge age distribution according to SIPUMEX

To present and according to the SIPUMEX data, the most common bridges are reinforced concrete, prestressed concrete, and concrete-steel (figure 2). The average structural condition is 1.44, but bridges with ages between 30 to 70 years have a higher value for the structural condition index (figure 4).

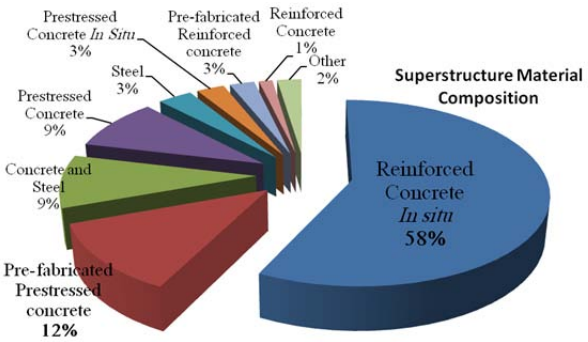

Figure 3. Composition of the Mexican bridge inventory according to SIPUMEX

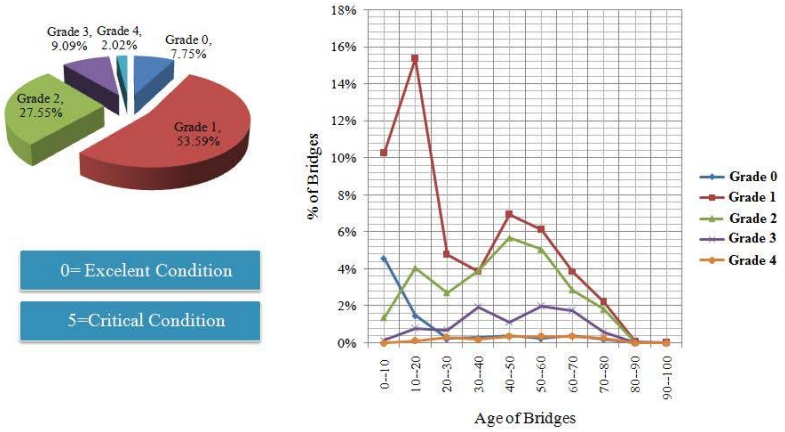

Figure 4. Structural condition index of the bridge Mexican inventory

Although the SIPUMEX is powerful tool for bridge management, it has some important aspects that need improvement. The first is the structural rating, which is based on visual inspections; the second, it does not evaluates the structural capacity or residual life of bridges; and finally, an economical modulus to estimate rehabilitation costs.

As for the first, it has been proposed to use a simple load test to measure the static structural flexure, and from that, to estimate the structural stiffness of the bridge. At the same time, a dynamic test is been proposed to measure the first flexural and torsional frequencies. It is possible to define standard tests and establish a stiffness rating index I_k from the following relation [4]:

$$I_k = c_{type} \frac{f^2}{\delta}$$

Where f is the frequency, δ is the maximum flexure displacement, and c_{type} is a constant related to the bridge type and to the bridge design code when constructed.

As for the second improvement, the structural capacity of a bridge is estimated from the previous stiffness rating index, bridge type, age, dimensions and design code; the residual life is evaluated from a deterioration model. As it can be seen, the best approach to this problem is using statistical data from the bridges and load conditions, and through a probabilistic analysis.

1.2 The Monitoring Centre for Bridges and Intelligent Structures

In Mexico, to develop a comprehensive information database and to build the statistical information needed to calculate the structural capacity and residual life of bridges, it has been created the Monitoring Centre for Bridges and Intelligent Structures. This Centre is planned to have remote monitoring of the most important bridges in Mexico (figure 5).

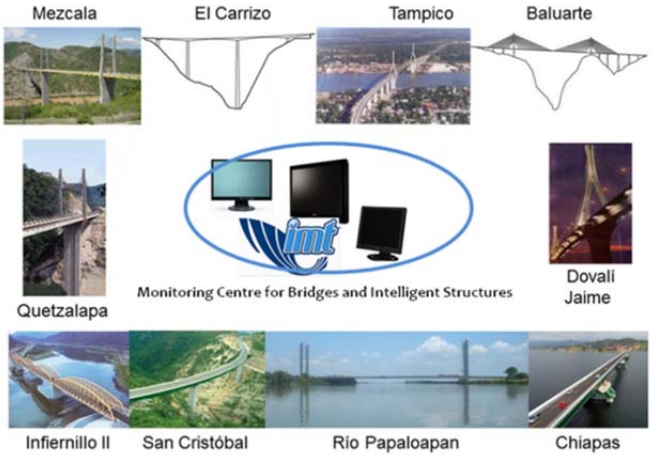

Figure 5. The first 10 bridges considered for remote permanent monitoring in Mexico

From the complete infrastructure of the Monitoring Centre for Bridges and Intelligent Structures, it was decided to include 6 common or "Type Bridges" for remote monitoring for a period of at least 5 years. In this case, 2 bridges of each type: prestressed concrete, reinforced concrete and concrete-steel, were selected (figure 6). The main idea of this monitoring is to have an initial sample of the short term structural performance of these bridges, and from that, calibrate the "Type Bridges" models.

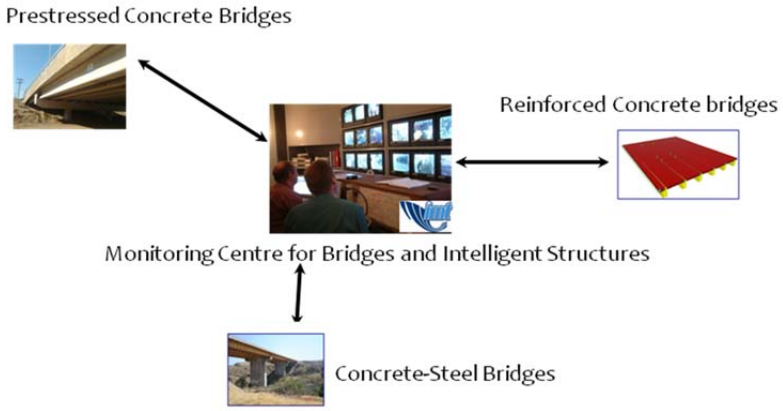

Figure 6. The "Type bridges" approach for the Monitoring Centre in Mexico

2. Structural Evaluation of "Type Bridges"

2.1 Structural Characteristics of "Type Bridges"

To show an example of how it is intended to evaluate the structural condition of the "Type Bridges", a reinforced bridge was analysed. In this case, a 1 span bridge with 13.5 meters of

span length and 11 m width (figure 7a), was chosen as it is a representative according to statistical data from the SIPUMEX bridge inventory (figure 7b).

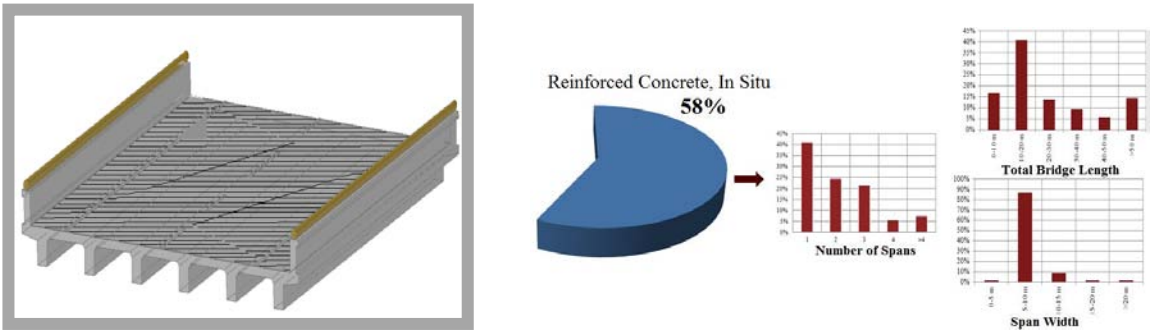

Figure 7. Model of the reinforced concrete bridge selected for this analysis

2.2 Design Code Dilemma

Evaluation of the "Type Bridges" is not an easy task. One of the main aspects is to have a reference of the code used when the bridge was designed; especially for bridges with ages more than 40 years, since it is not clear indication on which standard was used when designed and there are no drawings or specifications available in most cases. Figure 8 shows the statistical distribution in percentage, of the different design vehicles used for different reinforced concrete bridges in the SIPUMEX bridge management system.

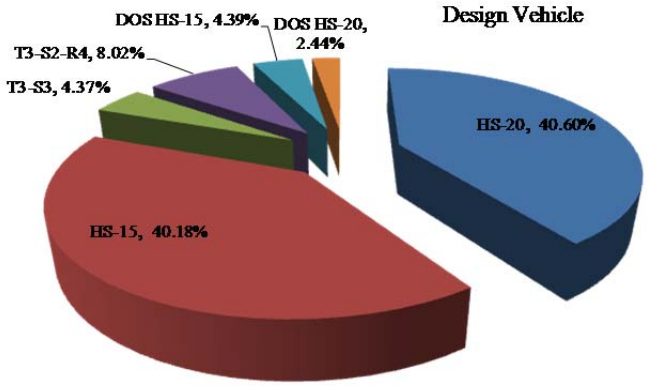

Figure 8. Percentage statistical distribution of design vehicles used for reinforced concrete bridges

2.3 The Parametric Model Approach for load capacity

The parametric model approach is based on a probabilistic model and the Monte Carlo simulation. Figure 8 shows a flow diagram of how the analysis is been proposed. In this case, it is assumed that statistical data of traffic, vehicles type composition and gross vehicles weights are known. At the same time, the parametric model, built from the corresponding design code of the bridge and calibrated to the experimental static and dynamic evaluation, is used to its evaluate structural performance (structural reliability and load capacity).

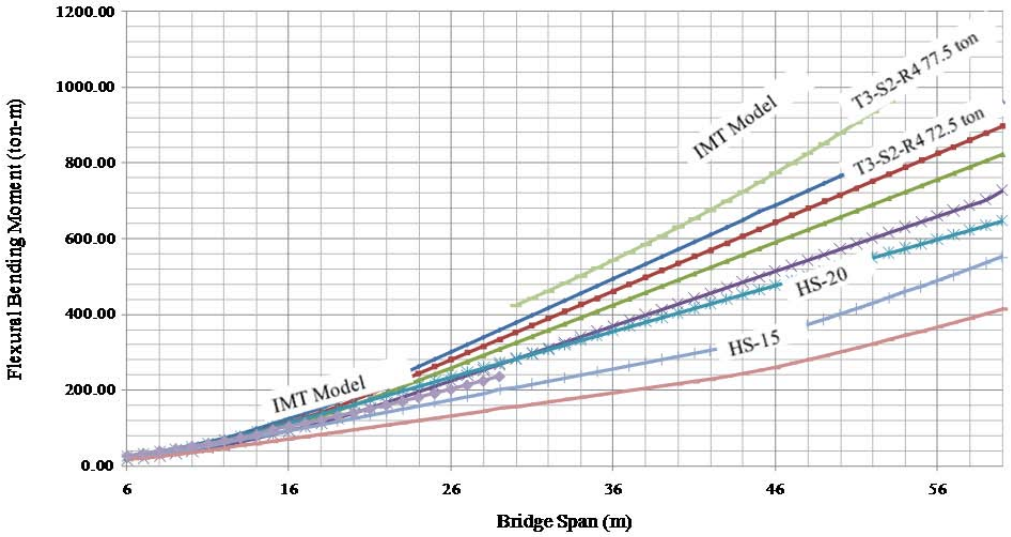

Figure 9. Moments calculated with different design vehicles for reinforced concrete bridges

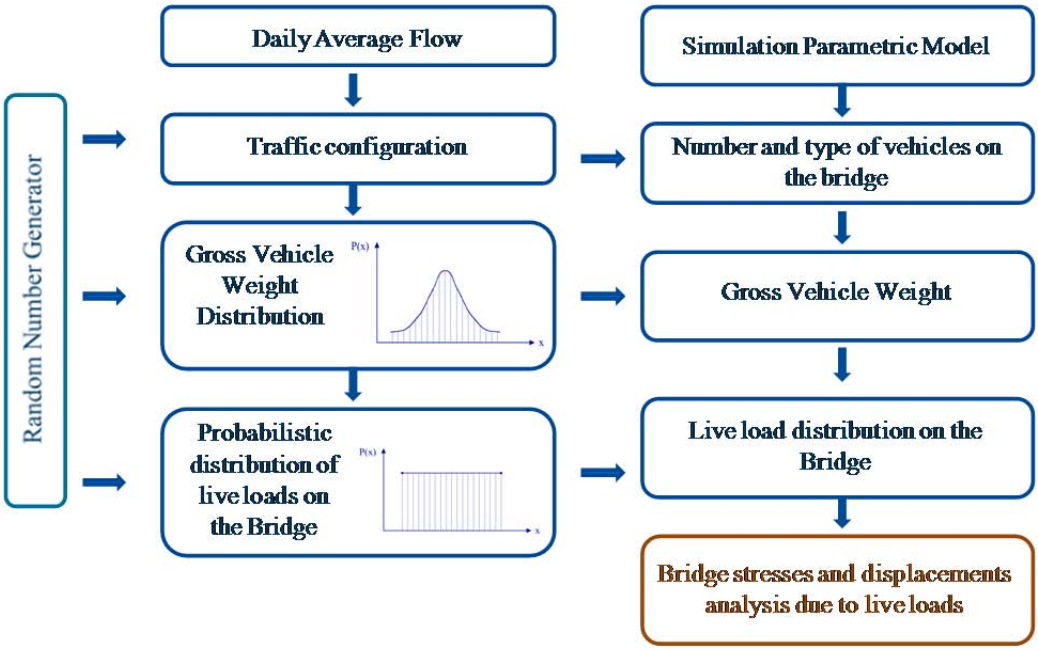

Figure 8. Flow diagram for Monte Carlo simulation with one parametric model

3. Structural Prognosis

Calculation of the structural capacity of a given bridge is not easy but it can be determined from experimental data and a reference model. If the reference model is a probabilistic parametric model, additional statistical data is required for the analysis, as it is the case for the "Type Bridges". At any rate, prognosis is more complicated since it is necessary to have a deterioration or damage model to predict how the bridge will behave under given conditions. Predictive models are not simple as these should consider all different deterioration mechanisms such as corrosion, fatigue, overloading, and scouring, among the most common ones.

3.1 Deterioration Mechanisms

An example of a fatigue deterioration model is shown in figure 9. In this case, it was considered for reinforced concrete and it only considers cracking due to fatigue until a crack grows to reach the reinforcing steel bars. If a more complete model is it going to be built, it should include corrosion.

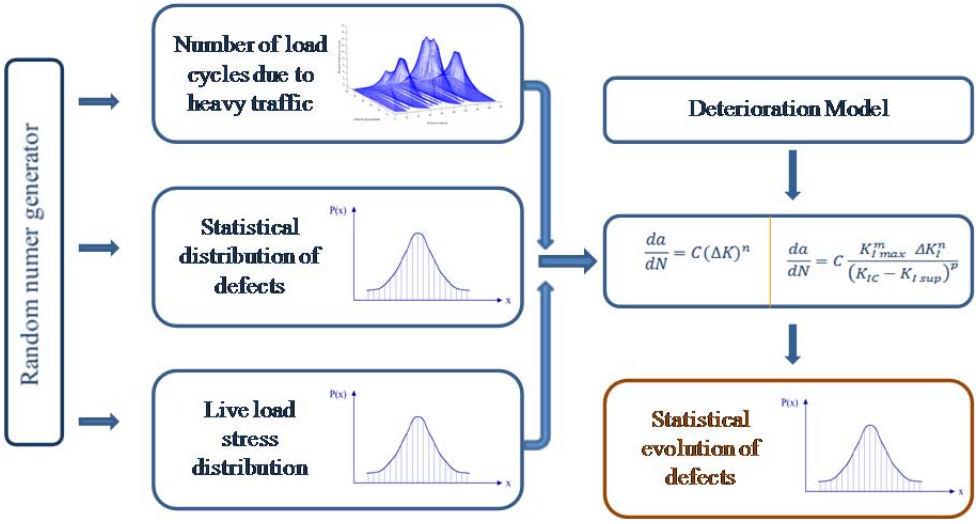

Figure 9. Fatigue deterioration probabilistic model for reinforced concrete

3.2 Fatigue Analysis

For a statistical analysis of fatigue, it is necessary to have full information of live load conditions acting on the bridge, including wind, earthquakes, traffic, or any other that might affect the bridge. In the case of traffic, daily traffic flow, statistical gross vehicle weight, statistical vehicle size, lane distribution traffic, etc., are necessary to calculate the statistical stresses and displacements in a bridge. Table 1 presents the statistical load conditions for the most common heavy vehicles on Mexican highways. It should be noted that each condition is represented by a load probability distribution, and in some cases, more than one, as it is the case for the T3-S2-R4 double-trailer, where overloading has to be represented by two distributions.

Table 1. Statistical traffic configuration in Mexican Highways

Heavy Vehicle Type		Empty	Loaded	Overloaded
C2		34.50 %	65.12 %	0.37 %
C3		19.65 %	75.13 %	4.82 %
T3-S2		22.86 %	50.83 %	22.86 %
T3-S3		35.35%	24.84 %	35.35 %
T3-S2-R4		30.51%	35.05 %	30.51 %

Following the fatigue analysis flow chart in figure 9, statistical distributions for defects (size of cracks), were calculated for a 30 years scenario. Figure 10 shows an example of these results for 4% traffic grow rate. Little difference is noted in this case, but it can be seen that the density distributions for large cracks increases noticeable as time goes by. Key aspect in this analysis is the crack propagation model and the appropriate value for the model parameters.

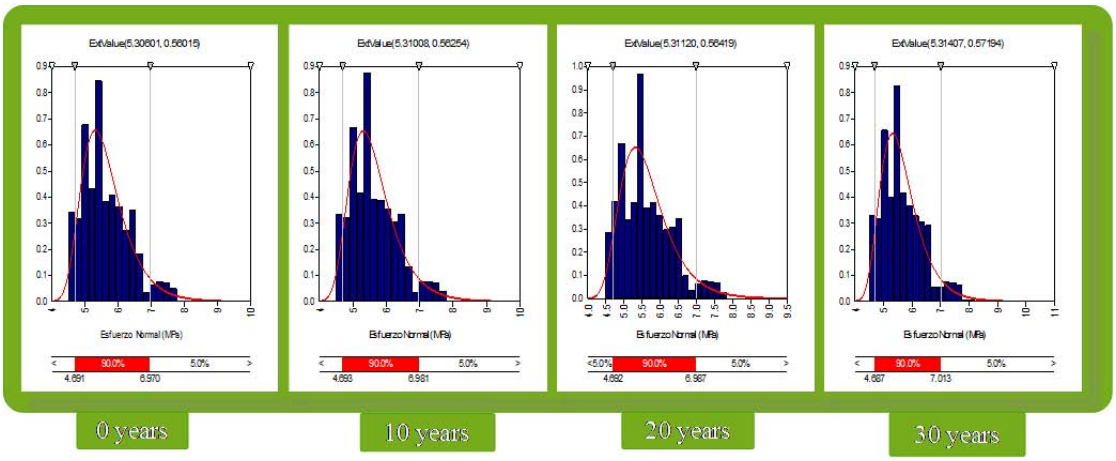

Figure 10. Evolution of the statistical distributions of defects due to traffic fatigue

4. Conclusions

From the previous analysis, it is possible to build parametric models for "Type Bridges" to calculate their structural capacity. Residual life estimation is more complex, as it is related to several deterioration mechanisms and basic models must be considered for all of them. In the example considered in this work, fatigue was the only damage model and yet, for a well known model, the parameters used to describe the material's behaviour are key aspect for an appropriate representation.

More comprehensive and extensive research is needed to develop simple parametric models of "Type Bridges", and the idea of remote permanent monitoring of some sample bridges might bring out an important insight in this matter.

The probabilistic approach proposed in this work, is feasible, as it can handle the range of variation of the parameters needed for the models, but the range of uncertainty still is also large.

References

[1] J. M. Ko, and Y. Q. Ni, "Technology Developments in Structural Health Monitoring of Large-Scale Bridges", *Engineering Structures*, **27**(12), pp. 1715–1725, 2005.

[2] F. N. Catbas, M. Susoy, and D. M. Frangopol, "Structural Health Monitoring and Reliability Estimation: Long Span Truss Bridge Application with Environmental Monitoring Data", *Engineering Structures*, **30**(9), pp. 2347–2359, 2008.

[3] S. Jang. H. Jo, S. Cho, K. Mechitov, J. A. Rice, S.-H. Sim, H.-J. Jung, Ch.-B. Yun, B. F. Spencer, Jr., and G. Agha, "Structural health monitoring of a cable-stayed bridge using smart sensor technology: deployment and evaluation", *Smart Structures and Systems*, **6**(5-6), pp. 439-459, 2010.

[4] C. W. Bert, "Relationship between Fundamental Natural Frequency and Maximum Static Deflection for Various Linear Vibratory Systems", *Journal of Sound and Vibration*, **162**(3), pp. 547-557, 1993.

[5] SCT, "SIPUMEX: El Sistema de Administración de Puentes Mexicanos", *Dirección General de Conservación de Carreteras*, Secretaría de Comunicaciones y Transportes, México, D.F., 1992 (in Spanish).

[6] "Manual Estadístico del Sector Transporte 2011", *Instituto Mexicano del Transporte*, Sanfandila, Qro., 2011 (In Spanish).