Probabilistic model for bridge structural evaluation using nondestructive inspection data

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ABSTRACT

A bridge management system developed for the Mexican toll highway network applies a probabilistic-reliability model to estimate load capacity and structural residual life. Basic inputs for the system are the global inspection data (visual inspections and vibration testing), and the information from the environment conditions (weather, traffic, loads, earthquakes); although, the model takes account for additional non-destructive testing or permanent monitoring data. Main outputs are the periodic maintenance, rehabilitation and replacement program, and the updated inspection program. Both programs are custom-made to available funds and scheduled according to a priority assignation criterion. The probabilistic model, tailored to typical bridges, accounts for the size, age, material and structure type. Special bridges in size or type may be included, while in these cases finite element deterministic models are also possible. Key feature is that structural qualification is given in terms of the probability of failure, calculated considering fundamental degradation mechanisms and from actual direct observations and measurements, such as crack distribution and size, materials properties, bridge dimensions, load deflections, and parameters for corrosion evaluation. Vibration measurements are basically used to infer structural resistance and to monitor long term degradation.

Keywords: Structural evaluation, health monitoring, bridge management systems, probabilistic reliability.

1. INTRODUCTION

In Mexico, the first bridge administration system was designed basically to handle the information from the whole bridge inventory of the national highway network system. At initial stages, visual inspections were used to evaluate different parts and elements of the bridges to give a structural condition index calculated from the average of the individual qualifications weighted according to their structural importance[1]. At first, the main result from this administration system was a global picture and classification of the 6500 bridges[2] along with their type (figure 1), size, condition, location, etc. At that moment, overall information was available as the age (figure 2) and the structural condition (figure 3) of the bridges.

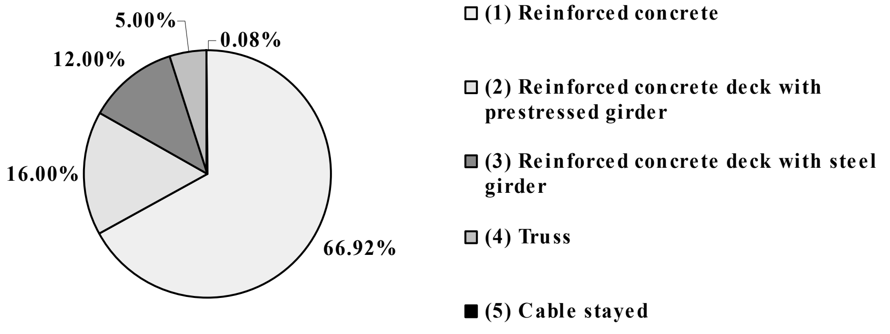

Figure 1. Bridge type distribution for the federal highway system in Mexico

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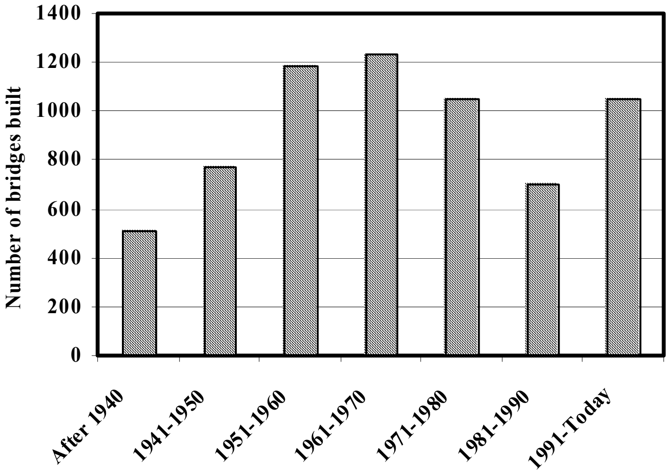

Figure 2. Bridge construction history in Mexico

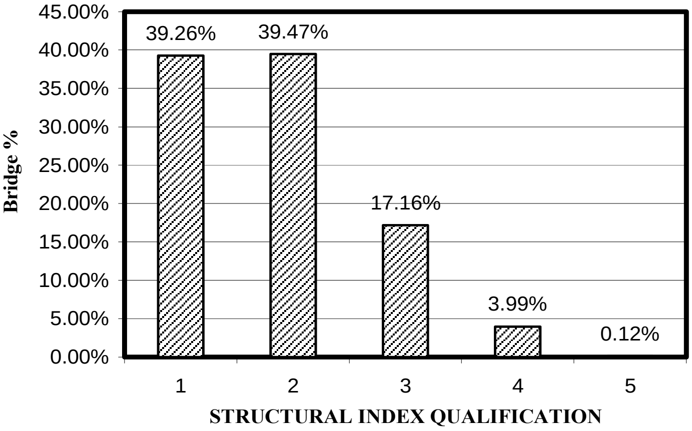

Figure 3. Structural evaluation of the Mexican bridge inventory in 1995. Lower index is for good condition and high index for critical condition.

Later, although all the previous information was very valuable, it was realized that it was not sufficient, while a more precise structural evaluation was necessary to estimate the cost of maintenance in a short and a middle term. At the same time, since in most cases the available budget is not sufficient, it is necessary to elaborate a maintenance program where the bridges are classified in different priority levels as to their structural condition and life prediction. By the mid 90's, the Instituto Mexicano del Transporte (IMT) developed the SIAP[3], a bridge administration system that included a more complete structural evaluation from dynamic tests and a complete data base that included design project specifications and drawings, history of inspections and maintenance, and photographic files. The Global Positioning Systems (GPS) with a Geographic Information Systems (GIS) opened up multiple applications for the SIAP, not only for the data recording, but also for the analysis and the correlation to geographic and environmental information. By the late 90's, the application for the SIAP was given in the toll highway system administration (CAPUFE) which has more than 2000 bridges and it is responsible for the most important ones in Mexico.

Despite of all the information and the computational technology available nowadays, it is recognized that a bridge administration system is only useful if the input data is accurate and reliable, which comes from the field inspections. A good method and an appropriate program for the bridge inspections are the key for a good system, where sufficient information is needed to evaluate the structural capacity and life prediction; as well as the cost for rehabilitation. Based on this, since 2004, the IMT initiated the development of the SIAPC-II, a new version of the SIAP-CAPUFE that will consider three different levels of inspection (including corrosion damage inspection), structural analysis geographically correlated, a structural capacity and life prediction model, and a maintenance budget model. This new concept for the bridge administration system is under the SIGET[4] global concept, the Transport Geographic Information System, which is intended not only for the maintenance of the transport infrastructure (highway, railway and airports), but also for planning and operation considering all the modes and the engineering, political, social and economic factors involved in the transport process.

2. THE SIAPC-II CONCEPT

The basic concept of the SIAPC-II is fairly simple; it considers as input the field data from inspections and the main output are programs for special inspections and maintenance (figure 4). In the same way as the SIGET, the SIAPC-II is being developed on the ArcGIS[5] platform; where all the information is geographically referenced and includes operational data, highway type and significance in the communications network, and environmental data. Analysis is according to the inspection level, and in particular, the general structural analysis is designed to calculate a structural index, as early versions of the SIAP, but including corrosion damage parameters. Structural capacity and life prediction are estimated from a special module to assign a priority level for rehabilitation. A maintenance cost estimation module is applied to associate priority to the overall maintenance cost, and at the final stage, the user inputs the approved budget and, if necessary, redefines the priority scale to obtain the final maintenance program.

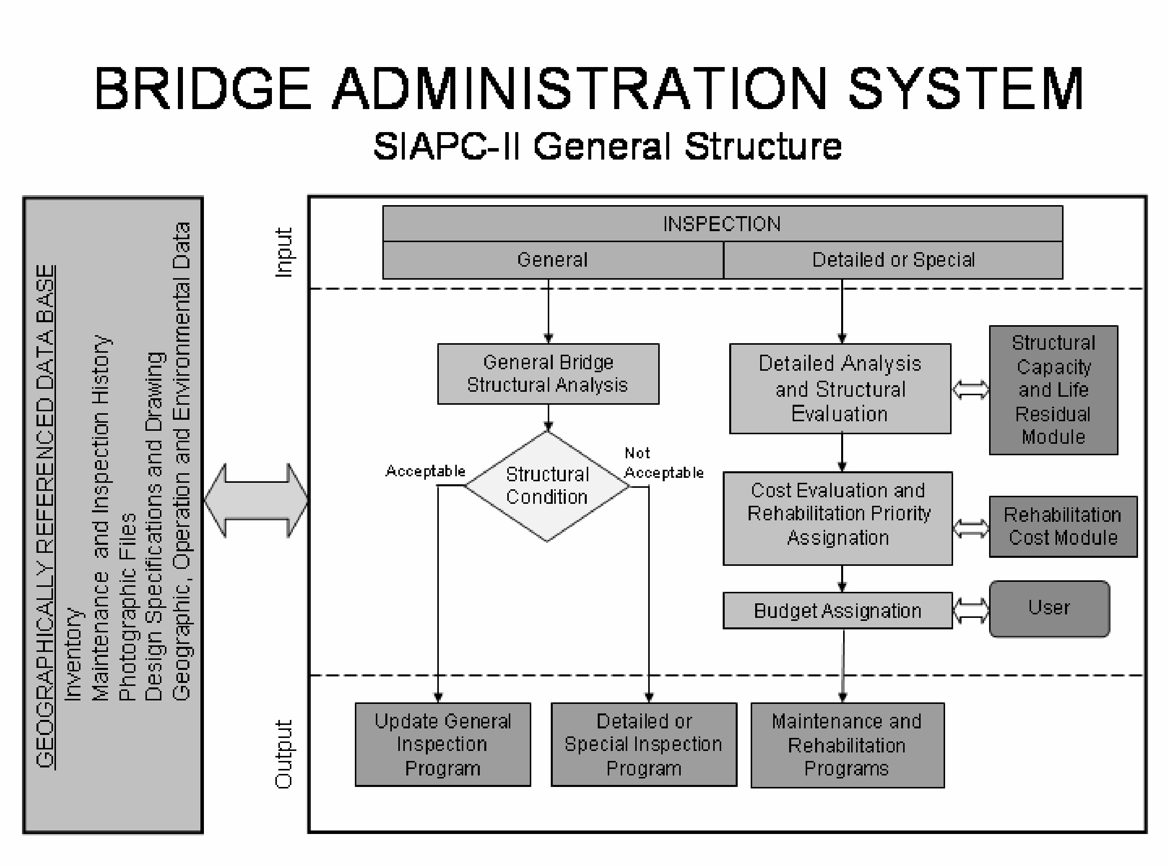

Figure 4. Blocked general structure for the SIAPC-II

3. THE NON-DESTRUCTIVE INSPECTION STRATEGY

Three different levels for inspection are considered for the SIAPC-II, according to the following table:

Table 1. Scope for the different inspection levels in the SIAPC-II

Inspection Level	Inspection Technique	Analysis criteria
General	Visual	Structural index
Detailed	Dynamic testing, static and semi-static load testing, and corrosion evaluation	Structural evaluation and life prediction
Special	As needed	Structural evaluation and life prediction

The general bridge structural analysis, which is intended for all bridges, correlates the structural index from the visual inspections with the environmental data and the maintenance and inspection histories. If a bridge condition is classified as not acceptable, the detailed inspection may be required, but in some particular cases, only a special inspection is sufficient. The detailed inspection includes dynamic testing, static and semi-static load tests and potential and resistivity measurements[6]. A mobile laboratory has been designed to accommodate the sensors and instrumentation needed for the inspections and an impact device is considered to run the dynamic tests under controlled conditions. Dynamic responses could be measured using accelerometers and FBG extensometers and, at least, the two first vibration modes are considered for evaluation. A truck with known weight is used for the load tests, where the deck deflections are measured with FBG or laser extensometers. Potential and resistivity concrete measurements are used to evaluate the corrosion damage in the reinforcement steel. Under this basic concept, it is considered for future development that some bridges will allow permanent instrumentation, so that, dynamic tests and load test could be part of the general evaluation.

All the information from a detailed inspection is registered into a computer with a GIS, and loaded to the SIAPC-II electronically so that all information is updated automatically into the system. While all the information is geographically correlated to the bridges, no further processing is needed. Analysis of the detailed inspections is carried out into several stages to evaluate the results of each test and to provide the updated input information for the structural capacity and life prediction model. Any additional data is also useful, for example, corrosion damage evaluation is improved through the investigation of the DURACON Program[7], which is an Iberoamerican Program to elaborate a map of the environmental aggressiveness of concrete reinforced structures.

A typical screenshot for the SIAPC-II is shown in figure 5, where the bridges with different levels of corrosion damage are shown on a map and all the specific data of each can be investigated by selecting the bridge (P in a box) and using all the options available from ArcGIS.

4. THE PROBABILISTIC MODEL FOR STRUCTRAL EVALUATION

Reliability is the ability of a bridge to perform structurally adequate for its useful life and under the operational conditions for what it was designed. In this case, bridge reliability is the probability of failure, which is a combination of the individual reliabilities of the structural components of the bridge. Due to complexity, two components are used in the calculation of reliability of bridges: resistance and capacity. If resistance (demand) is greater than capacity (supply), the bridge will fail (figure 6). Probability of failure depends on some reasonable assumptions and on the inspection data[8,9].

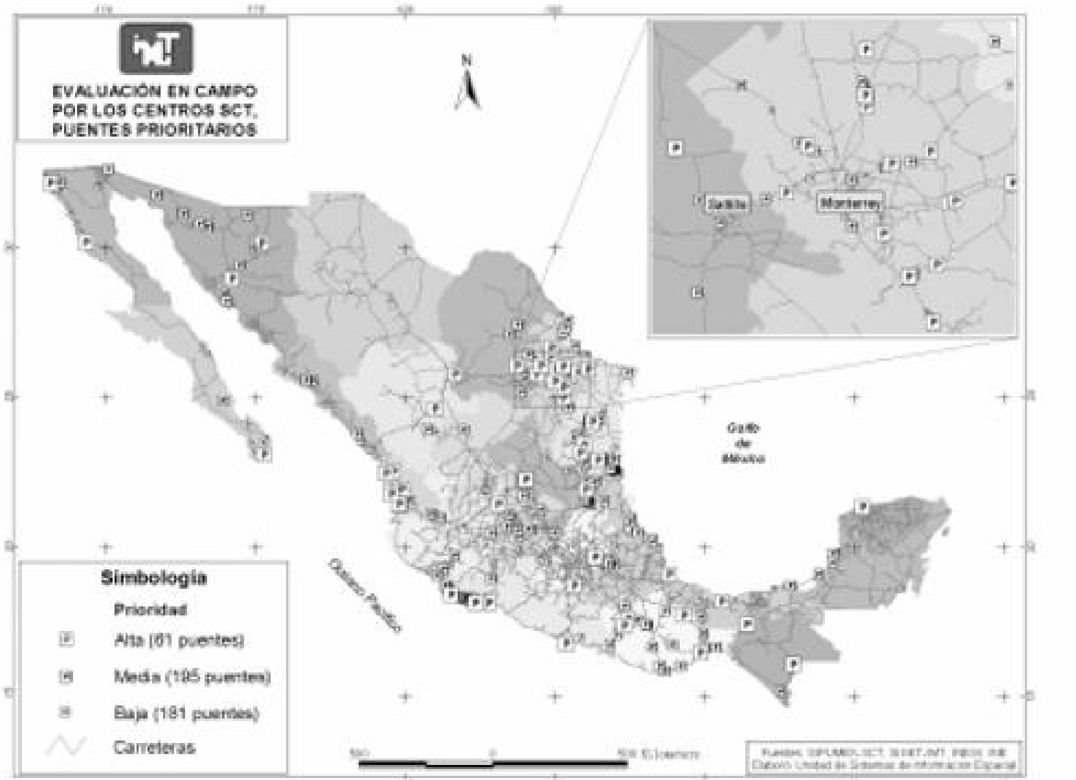

Figure 5. Screenshot from SIGET showing bridges with low (Baja), medium (Media) and high (Alta) priority for maintenance due to corrosion damage

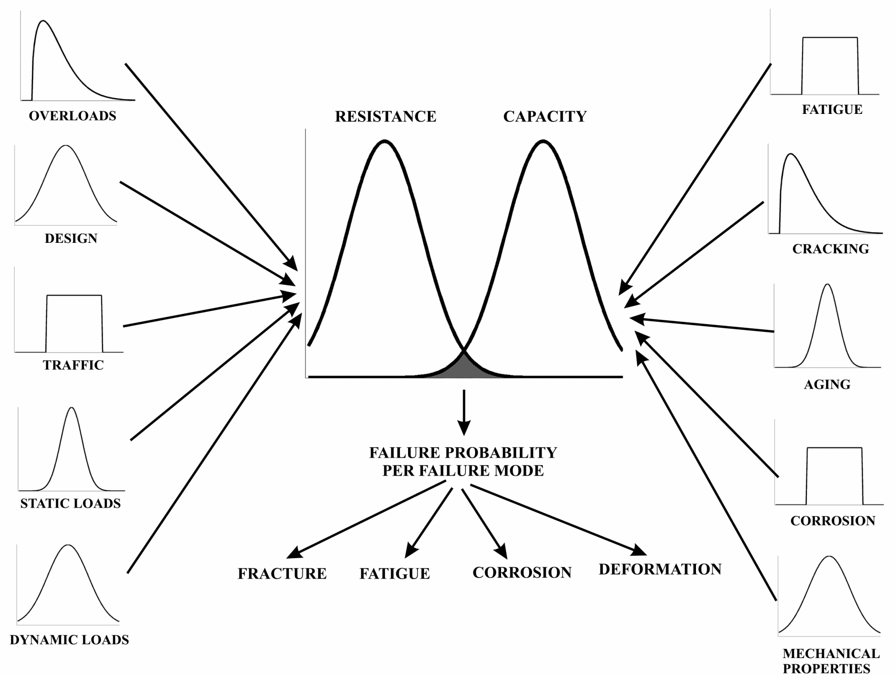

Figure 6. General description of the probabilistic model

Reliability of a bridge, **R**, is defined as:

$$\mathbf{R} = 1 - \mathbf{P_f} \tag{1}$$

Where $\mathbf{P_f}$ is the probability of failure. For discrete events,

$$\mathbf{P_f} = \mathbf{P(A < B)} = \sum \mathbf{P(A < B / B = b)P(B = b)} \tag{2}$$

Where **A** is the capacity (supply), **B** is the resistance or demand, and **b** is the resistance at a given instance.

Most parameters involved are random variables with a particular distribution (normal, uniform, exponential, etc.). To calculate reliability, the characteristics (mean and variance for normal distribution) are estimated. For complex structures, both, capacity and resistance may be function of several variables, but for simplicity, consider a simple case of a normal distribution where the two first moments are considered. In this case suppose that the capacity **A** is the total load effect on the bridge and depends on **D**, the dead load, **L**, the live load, and **I**, the impact load, which are all random variables. Then:

$$\mathbf{A} = \mathbf{D} + \mathbf{L} + \mathbf{I} \tag{3}$$

Failure will occur if the load **A**, exceeds the bridge resistance **R**; then, the probability of failure is given by the probability of having a value of **R** less than **A**, or:

$$\mathbf{P_f} = \mathbf{P(R < A)} \tag{4}$$

It is assumed that the mean (**m**) is the difference between the resistance and the capacity, that is:

$$\mathbf{m} = \mathbf{R} - \mathbf{A} \tag{5}$$

And the variance ($\boldsymbol{\sigma}_\mathbf{m}$) is the difference between the variance of the resistance and capacity, that is:

$$(\sigma_\mathbf{m})^2 = (\sigma_\mathbf{R})^2 - (\sigma_\mathbf{A})^2 \tag{6}$$

The failure probability is in the region where m<0, mathematically for discrete events, $\mathbf{P_f = \Sigma\ P[m = m_i]}$, for values where $\mathbf{m_i < 0}$. The safety index ($\boldsymbol{\beta}$) is defined as the ratio of the mean and the variance:

$$\beta = \frac{\mathbf{m}}{\sigma_\mathbf{m}} \tag{7}$$

While the failure probability is the sum of probabilities over a range where the safety index is negative, it is possible to express the failure probability in terms of a function of this index[8], that is:

$$\mathbf{Pf} = \Phi(\beta) \tag{8}$$

Typical relation of probability of failure and safety index is shown in figure 7.

To obtain the bridge structural condition from detailed inspections, two main approaches are considered. For most of the bridges, the probabilistic approach, and for special large bridges, a deterministic FE calibrated model. The probabilistic model, tailored to the general types of bridges in figure 1, includes two types of variables: the deterministic and the probabilistic. Within the deterministic data are the type, size, age and identified damage of the bridge. For the probabilistic data, the material properties, aging, fatigue, external loads and the not identified damage are considered. A particularity of the probabilistic model is that it can be improved as more inspections and data are recorded into the system. Within the probabilistic model, to calculate the reliability of a bridge and considering statistical data for several variables, a Monte Carlo simulation process is suggested[10]. Main outputs of this model are the structural capacity (based on the probability of failure) and the residual life (based on the probability of failure on time prognostic).

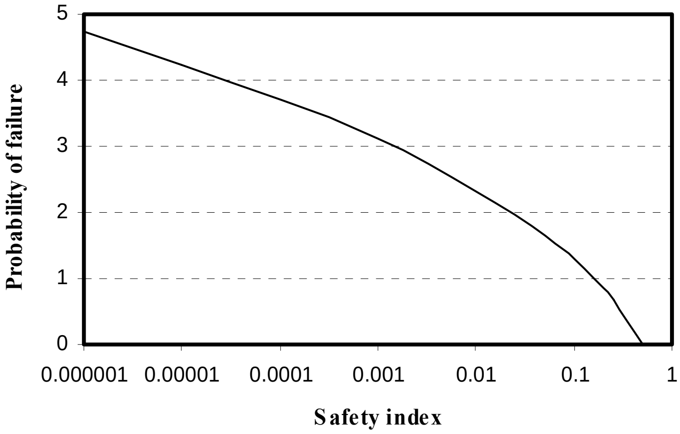

Figure 7. Relationship between probability of failure $\mathbf{P_f}$ and the safety index $\boldsymbol{\beta}$

5. CONCLUSIONS

In the past 10 years, Mexico has evolved from a basic bridge administration system, to a more complex system that involves geographically referenced and operational data. Although this model requires more information, the present software and hardware technologies make possible appropriate communication and administration of this system. The SIAPC-II, an updated version of the bridge administration system of the toll highway infrastructure is being developed on a simple concept where the main input comes from the bridge inspection and the output are the inspection and maintenance programs. To assure a good result from the administration system, it is necessary to have appropriate inspection methods and procedures; in this case, three levels of inspections are considered, visual for a general inspection; corrosion, dynamic, static and semi-static testing for detailed inspection; and special inspection for particular cases. For the bridge load capacity and life prediction, a probabilistic model is used for most bridges and a FE deterministic model for special large bridges. The system includes a module to estimate the rehabilitation cost and to assign a initial priority level, while the user, at the end, inputs the approved budget and updates the priority level to consider external elements not seen by the system.

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