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Autor: Sobrino, Juan A.

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Structural Evaluation of a Prestressed Concrete Bridge

Évaluation structurale d'un vieux pont en béton précontraint

Konstruktionsuntersuchung einer vorgespannten Betonbrücke

Juan A. SOBRINO
Dr. Eng.
Technical University of Catalunya
Barcelona, Spain

J.A. Sobrino received his Ph.D. in the Civil Engineering School of UPC in 1994. At present, he is working at the Department of Applied Mathematics of the UPC as Assistant Professor and as a bridge consulting engineer.

SUMMARY

The paper presents a procedure for the structural evaluation of an existing prestressed concrete bridge. The method is based on probabilistic analysis for the calculation of the safety margin of the Serviceability and Ultimate Limit States. Bayesian techniques to update the statistical parameters of the resistance and load variables are introduced. The assessment of a continuous prestressed concrete voided slab bridge is presented to describe the general procedure and the structural performance under traffic load, including real data. The bridge was recently demolished because of planning reasons and before its demolition a large number of experiments were performed.

RÉSUMÉ

L'article présente une méthode d'évaluation structurale de ponts existants en béton armé ou précontraint. La méthode est basée sur l'utilisation d'études probabilistes pour le calcul du niveau de sécurité des états limites de service et ultimes. On introduit les techniques bayésiennes pour l'actualisation des paramètres de résistance ou de charge. On présente l'évaluation structurale du tablier d'un pont en béton précontraint pour la description du procédé général et pour obtenir le niveau de sécurité du pont pour les charges du trafic routier, en utilisant des données réelles. Avant que le pont ne soit démoli, pour des raisons urbanistiques, des essais furent réalisés.

ZUSAMMENFASSUNG

Ziel dieses Artikels ist, einen Ablauf zur Konstruktionsuntersuchung einer existierenden vorgespannten Betonbrücke vorzustellen. Die Methode beruht auf der Wahrscheinlichkeitsanalyse und der Berechnung einer Sicherheitsspanne für die Gebrauchstauglichkeit und den Grenzzustand. Die Aufbereitung der Wahrscheinlichkeitsparameter für Widerstand und Belastungsvariablen erfolgt durch Bayes'sche Methoden. Die Beurteilung einer ständig vorgespannten Betonbrücke in Leichtbauweise wird vorgestellt, um den allgemei-nen Ablauf und das Verhalten unter Verkehrslast zu beschreiben. Dabei werden realitäts-treue Daten verwendet. Bevor die Brücke zerstört wurde, wurde eine grosse Anzahl von Versuchen durchgeführt.

1. INTRODUCTION

The structural capacity evaluation of existing prestressed concrete bridges requires more accurate methods than those provided by the design Codes. The use of load and resistance models and safety factors of the Codes, that have been calibrated for structural design, is not a rational method to obtain the load carrying capacity or the structural performance of existing bridges. The main reason is that reliability methods have been used in the calibration of Design Codes considering global uncertainties and data coming from different sources. In the other hand, an important part of the concrete bridge stock in developed countries have been designed using different structural verification criteria, safety factors, nominal loads, materials, etc. Most of these bridges will be calified as deficient using current Standards.

The direct application of **reliability methods** provides a consistent procedure for this purpose taking into account the geometrical, material and load uncertainties for each case of study. The more relevant parameters can be updated using data coming from experimental test (load test, concrete cores, steel bars specimens), traffic measurements, etc. These data reduce the uncertainties in the evaluation. As a consequence, more efficient and realistic structural evaluation can be performed.

2. STRUCTURAL EVALUATION PROCEDURE

Reliability method provides tools to obtain a rational measure of the safety level in existing structures. The more accepted safety measure is the Reliability Index (β) that is generally defined as a function of the probability of failure (P_f) [1]:

$$\beta = \Phi^{-1} (P_f) \qquad (1)$$

Φ^{-1} = Inverse Standard Normal probability density function.

The reliability level accepted in the evaluation should be the same as the accepted values for the design of new bridges. Current Codes in developed countries have been calibrated considering a maximum probability of failure between 10^{-4} and 10^{-6} in the lifetime [1][2]. These values are equivalent to a Reliability Index between β=3,8 and 5.

2.1 General Procedure

The structural capacity is evaluated based on Ultimate Limit State formulation. The failure function is formulated as the following expression:

$$R - S = 0 \qquad (2)$$

Where: R = Structural Response (Resistance)
S = Load Effects

R and S are modelled as random variables to obtain the Reliability Index, using data coming from inspections, tests, traffic measurements, etc. (Figure 1) [3].

If semiprobabilistic methods are used, design values of these variables (R_d and S_d) are compared. In that cases, design values are obtained with the nominal values and safety factors specified in the Codes [1] [4].

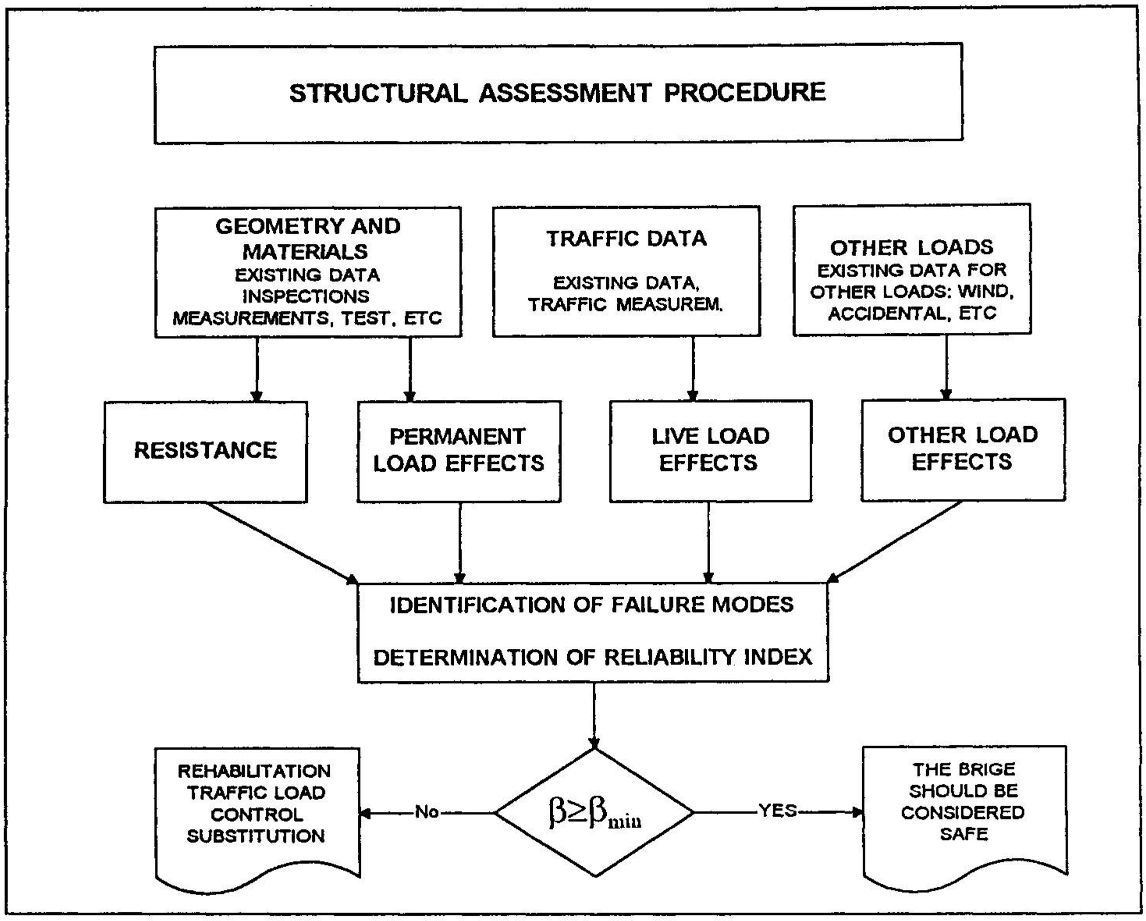

Figure 1.- General Assessment procedure

3. APPLICATION EXAMPLE

The presented structural evaluation procedure is applied for the assessment of a prestressed concrete continuous curved bridge [3]. The bridge was built in 1969 and was demolished in 1993 because of urbanistic reasons. The bridge deck has 4 spans of 17 + 21.3 + 26.6 + 21.3 m long and the radius of curvature in plant is practically constant and equal to R= 120 m. The deck is simply supported in piers, with one circular column per support axis, and two bearings in the abutments. The typical cross-section is a voided slab (Figure 2). The voids are eliminated at supports.

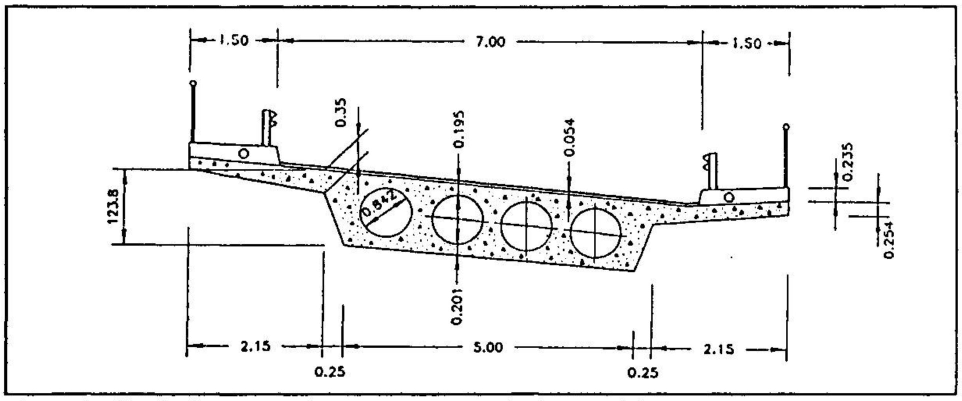

Figure 2.- Typical cross-section. The geometry is drawn with mean values.

In this paper, the ultimate flexural capacity of the bridge deck is evaluated. In the followings' steps the evaluation procedure is summarized.

3.1 Existing data, Inspection, Experimental Test. Updating Information

The more relevant information for the geometrical and material property's identification has been collected coming from existing drawings, results of the quality control during construction, inspections before and during demolition and some experimental test just before demolition. A complete statistical analysis was performed for the more important data. In some cases, general uncertainties were assumed coming from previous studies [3]. Finally, the statistical parameters were updated using bayesian techniques.

Geometrical parameters. The more significant results are the followings [3]:

1.- Values of the total depth of the deck are higher than those specified in drawings (H_{nom} = 1.20 m). The statistical parameters were: H_{mean} = 1.236 m and the Coefficient of Variation V_{HF} = 1,7%.
2.- The nominal diameter of voids was D_{nom}= 850 mm. The statistical parameters were: D_{mean}= 842 mm and the Coefficient of Variation V_D = 3,8%
3.- Higher covers of the top steel bars were measured. The nominal cover was R_{nom} = 30 mm. The statistical parameters were: R_{mean} among 80 and 132 mm, and the Standard deviation σ_R=15mm.
4.- Higher covers of the bottom steel bars were measured. The nominal cover was R_{nom} = 30 mm. The statistical parameters were: R_{mean} 37,3 mm, and the Standard deviation σ_R =12 mm
5.- The position of the prestressing steel was practically coincident with the expected value in the critical sections. The Standard deviation was σ_{dp} =16 mm.

Mechanical properties. The more significant results are the followings:

1.- The compressive resistance of the concrete was measured by testing 21 cores. The specified value was f_{ck} = 35 MPa and the updated parameters were: $f_{c,\,mean}$= 45,1 MPa and the Coefficient of Variation V_{fc} = 11,2%.
2.- The resistance of the reinforcing bars was measured in 8 tests. The specified value of the yield stress was f_{yk} = 400 MPa and the updated statistical parameters were: $f_{y,\,mean}$= 438 MPa and the Coefficient of Variation V_{fy} = 5,2%.
3.- The resistance of the prestressing steel was measured in 4 tests. The specified value of the yield stress was f_{ypk} = 1500 MPa and the updated statistical parameters were: $f_{yp,\,mean}$= 1459 MPa and the Coefficient of Variation V_{fyp} = 2,4 %.

The updated values were obtained using bayesian techniques and assuming usual values of uncertainties observed in a large data bank collected in Spain [3].

3.2 Cross-Sectional response

The ultimate flexural capacity (M_u) of the critical cross-sections has been evaluated in a probabilistic manner using updated geometrical and mechanical properties data. The responses have been obtained using Monte-Carlo techniques including the uncertainties in geometry of the cross-section (depths, voids, widths, etc.), position of reinforcing bars and prestressing steel, uncertainties in resistance of concrete and steels and, finally, including the model uncertainty (Figure 3). The method to obtain the flexural response takes into account the non-linear behaviour of materials and is according to Model Code of the CEB recommendations [4]. The partial results are not included due to the lack of space.

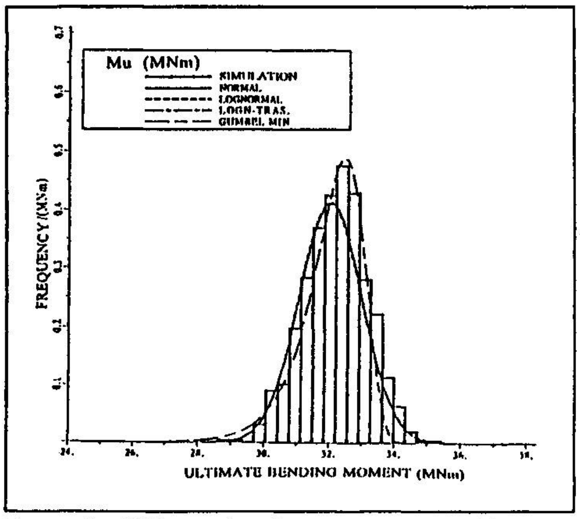

Figure 3.- Ultimate bending moment at mid-span 3 obtained by simulation.

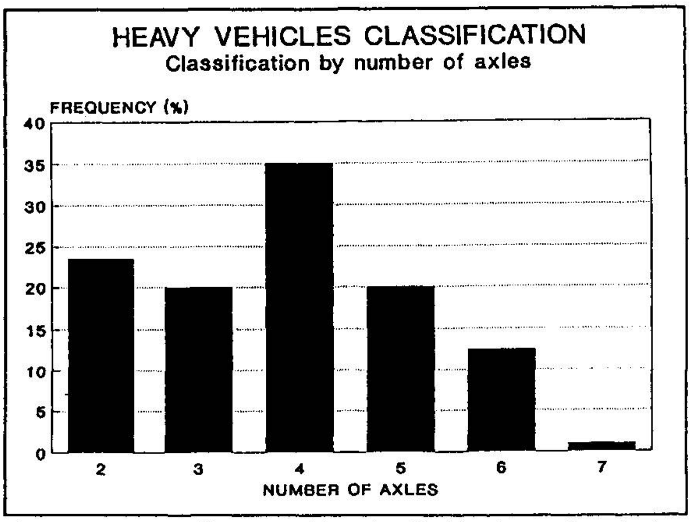

Figure 4.- Heavy traffic composition classified by the number of axles.

3.3 Load effects evaluation

The load effects due to permanent actions have been obtained considering real geometry and depth of pavement. The statistical parameters have been calculated using Monte-Carlo techniques. On the same way, using traffic load data of some highways in Spain and simulation techniques has been possible to obtain the live load effects in different traffic situations (fluid traffic and traffic jams). The simulation program developed for this purpose has been checked with the results of other authors and similar traffic situations [3]. In that case, the traffic configuration is according to Figure 4. With the obtained results has been possible to develop a simplified load model (equivalent uniform and axle tandem loads) that have been used in the non-linear analysis of the structure until failure. Due to the lack of space the partial results are not presented.

3.4 Failure mode identification. Global Structural Analysis.

The safety of the bridge deck has been evaluated for 5 different failure modes that are illustrated in Figure 5. In addition, the ultimate flexural capacity of the bridge deck has been evaluated for 3 different structural analysis (elastic, plastic and non-linear). The failure functions and the mathematical procedure for the three different structural analyses were presented in [3] [5].

3.5 Reliability analysis

The safety level is expressed in terms of the Reliability Index, as defined in section 1. The value of β, using Hasofer-Lind definition, has been obtained with the FORM method [1]. The more relevant results are summarized in Table 1 for a time reference period of 50 years.

FAILURE MODE	β ELASTIC ANALYSIS	β PLASTIC ANALYSIS	β NON-LINEAR ANALYSIS
MODE 1	8.9	10.4	8.4
MODE 2	7.2	7.9	7.8
MODE 3	7.9	9.1	8.6
MODE 4	9.5	10.9	8.4
MODE 5	9.4	10.9	9.1

Table 1.- Reliability Index for different modes of failure and the 3 structural analysis for a reference period of 50 years.

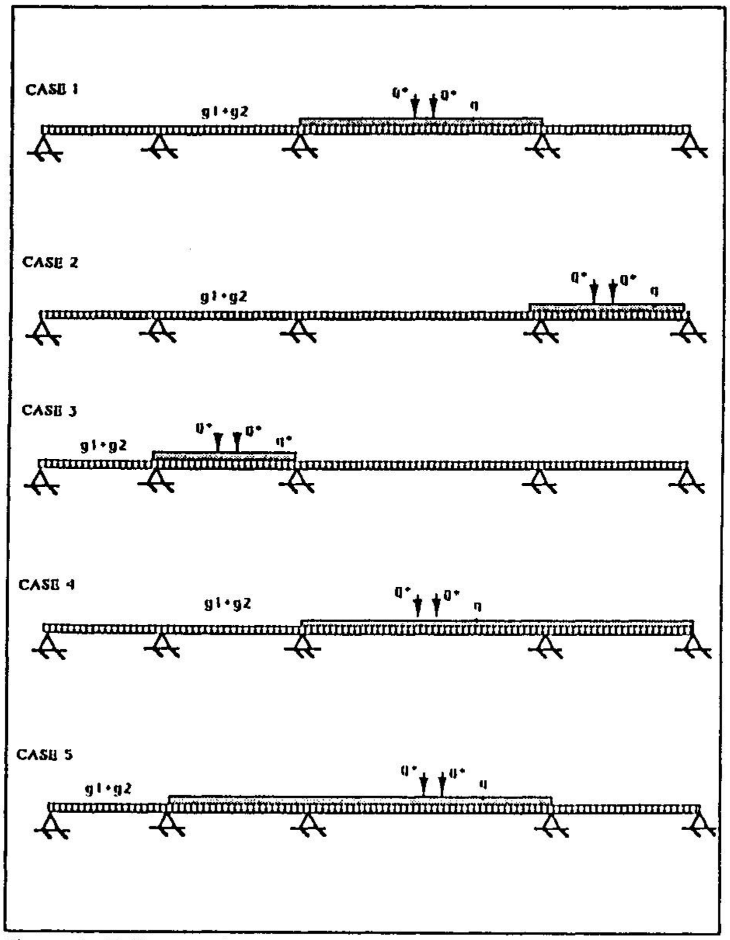
Figure 5.- Failure modes considered in the assessment of the deck

In the evaluation of both the load effects and the structural response model uncertainties have been included using models accepted in the calibration of some modern Codes. As a conclusion, the Reliability Index is depending on the structural analysis and, in some cases, the elastic analysis is not conservative because it can not predict the real critical cross-section or the exact mode of failure. The bridge deck should be calified safe (β=7.8) for the traffic loads in the considered period of time.

4. CONCLUSIONS

The Reliability Index is the more convenient measure of the safety of existing bridges. This parameter can be obtained using data coming from inspections, test, traffic measurements, etc. In some cases general uncertainties can be considered if data is not available. The paper presents some real data that can be useful in other similar cases.

5. ACKNOWLEDGEMENTS

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