PONT ARRABIDA - AUSCULTATION ET EVALUATION

ARRABIDA BRIDGE - INSPECTION AND ASSESSMENT

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Résumé: Le pont Arrabida, qui a été terminé en 1963, est un pont en arc avec une portée de 278.40 m sur le Douro à Porto, près de la mer. Ce travail présente les principaux résultats de l'inspection effectuée en 1997 et l'évaluation structurelle du pont pour préparer sa réhabilitation.

Abstract: The Arrabida bridge, finished in 1963, is an arch bridge with 278.40 m span over the River Douro at Oporto, near the sea coast. This paper presents the main results of the inspection carried out in 1997 and the structure assessment of the bridge, in order to promote its general rehabilitation.

1. INTRODUCTION

The Arrabida Bridge has a total length of 493.20 m with an arch of 278.40 m span and 52.00 m height. The deck with 21.20 m spans has a total width of 25.00 m with 12 beams. The beams have a variable depth from 1.80 m to 1.10 m and the slab between beams has a thickness of 0.18 m and a span of 2.00 m. The deck is supported through transverse beams in 4 rectangular columns 1.20 m x 1.20 m, in each support alignment. Over the river two twin arches 8.00 m wide with a double box section support the columns.

The structure is full continuous between abutments.

Because the bridge has had no significant inspection or maintenance during its service life the Road Authority decided to promote a special detailed inspection and a detailed structure safety assessment according to the new codes and new service conditions, since the number of lanes were increased from 4 to 6.

2. INSPECTION

2.1. Collecting data

This bridge is very well documented. The design, by Edgar Cardoso and dated from 1955, is complete, very well presented and detailed (Cardoso, 1955). Documents from construction exist, namely the studies and performance of the concrete used in the bridge (C40 was specified but higher values were achieved since the contractor had a prize for each kg/cm² of characteristic cube strength in excess of 400 kg/cm². A w/c ratio of 0.32 was used and plasticers introduced). The steel used was of class S235.

Due to the aggressiveness of the environment a concrete surface painting was adopted. Concrete cover is not explicitly indicated. From the drawings and calculations we assume that 3 cm was used for the deck and 4 cm for the arch and columns.

A preliminary visual inspection was carried out in order to establish the objectives, to plan the inspection and define the type, number and location of the tests. (Fig. 1). The selected zones for testing include areas in the upstream and downstream sections and in the various types of structure elements: beam and slab deck, columns and arches.
2.2. Visual inspection
One main observation was the extensive delamination, spalling and reinforcement exposure in many beams over the arch mainly concentrated in the soft corners or near construction joints. Other areas with low cover or concrete defects showed progressive corrosion of the reinforcement. The surface paint almost disappeared over the river, the most exposed surfaces of the bridge. Figure 2 shows a deterioration mapping and some photos illustrating some of the visible defects.

2.3. Testing
Testing is needed to access the deterioration process which is in general a two phase process with an initiation stage where no defects are visible and a propagation phase, usually much shorter than the initiation one, which leads to visible defects.
Basic testing included the hammering for delamination detection, the bar location and cover measurement, and the measurement of the depth of carbonation and chloride penetration.
The variability of the concrete properties, cover and penetration processes are very important to understand the deterioration. Figure 3 shows the variability of the cover measurements in the main girders of Arrabida Bridge.
The tolerance or error of the test procedure has also to be considered and investigated.
The technique used to obtain the carbonation depth or chloride content at different levels has also different accuracy according to the test procedure.
The scope of the detailed inspection of this outstanding bridge included other tests with the objectif of fully characterising the stage of the deterioration.
DECK

Deterioration Mapping
Cracking
Delamination or exposed bars

Exposed bars in construction joints and low cover regions
Cracking in transverse beams
Plastic hinge in short columns
Cracking in the pier transverse beams
Water accumulation inside the arches

Figure 2: Visual inspection. Main pathologies

Figure 3: Variation of cover in the main girders
Sixteen concrete cores were taken, a macroanalysis done for each one and samples obtained to perform the following tests:
- Petrographic analysis and scanning electron microscopy observation with the main objective of assessing the concrete chemical deterioration.
- Concrete quality, expressed by the absorption, porosity and diffusion coefficients
- Concrete mechanical properties (strength and deformability modulus)
  Since depassivation of reinforcement occurs the rate of corrosion was assessed measuring the electrical potential, concrete resistivity and polarisation resistance in 6 selected areas.
  Steel characteristics were also obtained by 6 samples in tensile tests.

2.4. Assessment of the deterioration process
The objective of assessment is to understand the causes and effects of the mechanisms of deterioration or structure distress or to assess the structure safety levels.

The assessment of the initial phase for a chloride penetration problem is illustrated in Fig. 4a, where the chloride concentration at different levels is presented (basic testing) for the Arrabida Bridge. These results were obtained after 35 years of service and from samples taken in the construction joints, the location where deterioration is more relevant. It is also important to stress the fact that this results will vary from element to element due to the heterogeneity of concrete, eventual use of different mixes, different compaction and curing, different exposure conditions, ...

From these results and assuming a diffusion of chlorides governed by the modified Fick’s law and considering the variation in time of the diffusion parameters it is possible to obtain an interpretation of the penetration process and a prediction of its evolution. In Fig. 4b the relation between depth and time needed for the chloride content to achieve a level of 0.05 % by weight of concrete is presented. The envelope between the two curves reflects the variability of the chloride penetration.

From these curves it is possible to understand that for the average cover depth in the girders of 27 mm the time needed for the critical chloride content to be reached varies between 20 and 70 years. Then depassivation occurs, corrosion may start and the corrosion rate variation can be assessed.

It is important to refer that in areas other than those of the construction joints or concreting defects, the chloride contamination was still not relevant due to the good quality of the concrete. This is thus an example of the importance of good execution for durability of concrete structures.

3. STRUCTURE SAFETY ASSESSMENT
The assessment of the safety of this structure was based in the following studies:
3.1. Collecting data and evaluating the models of the original design

The codes used at the time of the design dated from 1935 and safety criteria for reinforced concrete were based in stress allowable limits for steel and concrete which were compared with acting stresses for service loads calculated in the cracked state, when appropriate.

Due to the relevance of this bridge, the Designer and Road Authority decided to adopt live loads much higher than those of the existing codes (similar to those of the future EC 1). Even the earthquake action was considered ($a = 0.5 \text{ m/s}^2$) although Oporto, at the time, was not considered in the codes a region with seismic risks.

Analytical models and experimental tests in scaled models were performed for this high hyperstatic structure with a complex geometry. At that time the elastic analysis of the full 3D structure would not be an easy (or possible) task, the scaled models were very accurate (in the elastic regime) and Prof. Edgar Cardoso was an expert in this area. However, very detailed analytical models were done for the deck (influence surfaces for the slab and influence lines for the beams). The results from analytical and experimental models were compared and adopted for dimensioning the most unfavourable ones. The construction sequence and the arch analysis were also studied in great detail in the design.

3.2. In situ tests and measurements

The levelling of the deck, the geometry of the arch and the verticality of the columns were obtained by very rigorous topographic means. These results were compared with the available information from the time of the construction and the long-term observation reports, leading to the conclusion that the structure has not suffered relevant deformations since 1968.

In order to access the dynamic response of the bridge and to have a control of the full 3D models, the traffic and wind induced vibrations in the bridge were measured in 10 different locations with 6 triaxial acceleration transducers. From these registrations, the modes of vibration and frequencies were obtained (Rodrigues, 1998) and compared with those obtained with the 3D analytical model showing a very good agreement. (Fig. 5)

3.3. Analytical studies for the assessment of the structure

In this study and rehabilitation design the following models were done;
- 3D model with bar elements and 3D model with slab elements in the deck; (Fig. 5)
- Local slab and bar detailed model for 3 deck spans;
- Models for the systems of construction of the execution to access the effects of dead load.

The comparison between the design results and those of this study were remarkably similar. (Appleton, 1997)

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Figure 5
From this study it was concluded that the actual safety requirements are complied with. The single remark refers to the forces obtained in the short columns over the arch, which in the design were not properly assessed.

In fact, full continuity between these columns, the deck and arch was introduced in the construction. However, in a 3D model the effect of the arch deformability generates (even in an elastic model) high bending moments in these columns, as shown in Fig. 6:

![Figure 6: Columns over the arch](image)

In fact, on site, plastic hinges were generated in these columns as shown in Fig. 2. It should be referred that both the scaled experimental model and the substructure models of the original design did not include this effect.

4. LESSONS FROM THE DESIGN, CONSTRUCTION AND USED OF THIS BRIDGE

4.1. Durability of concrete structures

A good or very good durability of concrete structures in a marine environment can be achieved with a very good concrete mix and a very good execution. In this bridge good concrete was applied but many concreting defects (mainly construction joints) led to a significant deterioration.

In situ control of cover should have the same relevance as the strength of concrete (and its quality), since the variability of concrete cover in concrete construction leading to areas with low cover and corresponding premature deterioration it is still enormous.

4.2. Structure design

Reliable 3D models are important for a correct assessment of the behaviour of a complex structure, although intuition and simple and substructure models continue to play an important role in structural design.

5. REFERENCES

