DYNAMIC MONITORING OF AN OLD LONG CONCRETE BRIDGE

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ABSTRACT: This paper presents the dynamic monitoring carried out on a 458 m long, 38 m high, Papagaios Bridge, State of Paraná. This is a concrete arch bridge built over 60 years ago, which needed repairs. The dynamic monitoring was designed to carry out a structural integrity assessment and to calibrate a numerical model to be used for the structural rehabilitation design. Vibration measurements were carried out on the bridge in selected locations. This paper addresses data analysis, the impact measurements when a train enters the bridge and modal analysis. An important aspect was the measurements taken at the entrance to the bridge before and after emergency repairs, allowing analysis of the coefficient of impact before and after the repairs. In addition, the analysis of the frequency calibrated numerical model led to conclusions about the necessary structural reinforcement, that is, the need for reinforcement in the deck and pillars. The decks were reinforced using carbon fibre. Ballast had to be removed and reinforcement applied. Reinforcing the pillars was much simpler than originally expected. The analysis clearly showed that the pillars lacked structural stiffness. This was achieved simply by reinforcing at many positions along their heights, surrounding them with welded steel L sections.

KEYWORDS: Dynamic tests; old concrete bridge; vibrations; accelerometers, modal analysis

RESUMO: Este artigo apresenta os resultados de monitoramento dinâmico realizado na Ponte dos Papagaios, no Paraná, antiga estrutura de concreto armado com 458 m de extensão e uma

altura máxima de 38 m. Essa obra foi construída há mais de 60 anos e as inspeções visuais claramente indicavam a necessidade de recuperação estrutural. O trabalho constou de medições de vibrações realizadas com acelerômetros ultra-sensíveis em posições selecionadas sobre a ponte. Este artigo abrange a análise dos dados, antes e depois de reparos, bem como resultados da análise modal global da estrutura. Um aspecto importante foi as medições realizadas na entrada da ponte antes e depois de reparos emergenciais, permitindo análise de coeficiente de impacto antes e depois dos reparos. Além disso, a análise do modelo numérico calibrado na frequência, levou à conclusões sobre o reforço estrutural necessário, ou seja, necessidade de reforco no tabuleiro e nos pilares. O reforco dos tabuleiros constou de aplicação de fibra de carbono. O lastro teve que ser retirado e o reforço aplicado. O reforço dos pilares foi muito mais simples que o esperado originalmente. As análises mostraram claramente que os pilares apresentavam falta de rigidez estrutural. Isso foi conseguido simplesmente reforçando em muitas posições ao longo da suas alturas, envolvendo-os com cantoneiras soldadas.
PALAVRAS-CHAVE: Ensaios dinâmicos; ponte antiga de concreto; vibrações; acelerômetros; análise modal

INTRODUCTION

Papagaios Bridge (Figure 1, Figure 2) is an old concrete structure, built in the late 50s, located in the State of Paraná, Brazil. The bridge is 458 m long and has a maximum height of 36 m. The centre arch is 90 m long, sided by 35 m long smaller arches. The client decided to carry out studies for the integrity assessment of the structure followed by a repair design. This paper summarises the results of the dynamic measurements programme carried out in 2020. The Authors carried out an Operation Modal Analysis (OMA) and a Dynamic Amplification Factor (DAF) analysis to evaluate the stiffness of the bridge and the impact factors at its abutments. The results yielded the vibration level of the bridge under operation.

Figure 1 Papagaios Bridge

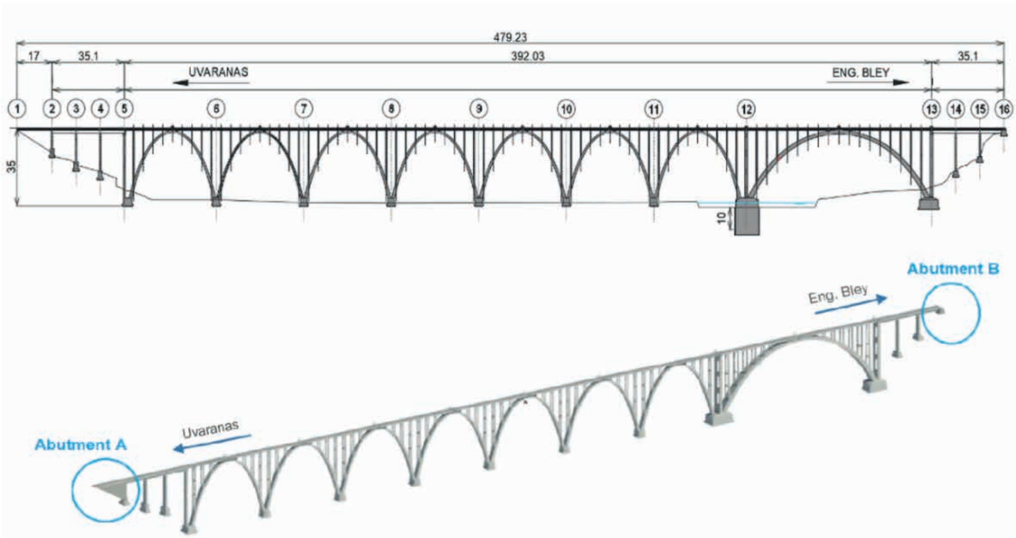

Figure 2 Papagaios Bridge main dimensions and abutments A and B

BRIDGE INSPECTION

The Authors carried out a visual inspection to detect structural pathologies. Figure 3 and Figure 4 present a few examples. Bridge abutment B showed the most important structural damage including steel reinforcement corrosion, concrete spalling and – most important – a large shear crack at the bridge's shallow foundation under abutment B.

Figure 3 Substructure pathologies: concrete cracking, vegetation, concrete efflorescence

Figure 4 Superstructure pathologies: torsion cracks, steel corrosion, shear crack at Abutment B

DYNAMIC TESTS

Dynamic monitoring (DM) of large structures presents the advantage of minimal disturbance to its operation (Brinker et al, 2015, Fryba et al,2001) . Real-time monitoring, damage detection, structural evaluation or the possibility of obtaining a calibrated numerical model (Magalhães et al, 2012, Altunisik et al, 2016, Turker et al, 2014) have led the client to select DM for this project.

OPERATION MODAL ANALYSIS (OMA)

The Operational Modal Analysis (OMA) is a technique for obtaining modal parameters such as natural frequencies, damping and vibration modes. It consists of measuring vibrations under the structure's normal operation conditions, *i.e.*, under traffic and wind excitations (Rainieri et al, 2014).

The DM consists of vibration measurements on selected locations using very sensitive accelerometers and recorders. In this case, two very accurate 24-bit vibration recorders were used. Their characteristics are 3D accelerometers range ± 1g, 100 Hz sampling rate, very low noise ≤ 10^{10} g^2 /Hz (narrowband analysis), and dynamic range ^{3} 110 dB.

A preliminary and undamaged numerical model of the structure enabled the selection of 28 measurement positions (**Error! Reference source not found.**) where the model indicated large amplitudes.

The measurements were carried out by two recorders on the bridge slabs and the top of the pillars. One recorder was placed in a fixed position, while the other recorded vibration on the previous measurement location. This led to a double measurement on each location and synchronization between all measurement locations.

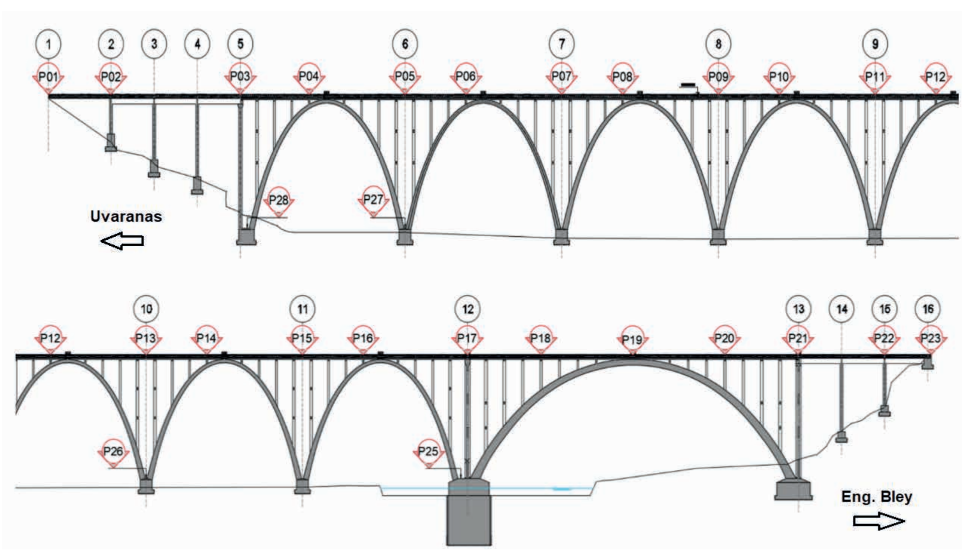

Figure 5 Measurement locations

An enormous amount of data was analysed to obtain the dynamic signature of the structure, followed by modal analysis in which a numerical finite element model in the frequency domain was calibrated to represent the measured behaviour.

The modal test scope is to determine the so-called *modal parameters*, *i.e.*, natural frequencies, damping, and vibration modes (Brandt, 2011). These parameters inform the structural behaviour or the structure dynamic signature. These frequencies (f_r) are directly proportional to the structural stiffness, according to the following equation:

$$f_r = \frac{1}{2\pi}\sqrt{\frac{K}{m}}$$

Where: *K* is the stiffness and *m is* the corresponding mass. Damping is related to the energy dissipation rate. Vibration modes inform the shapes in which a structure vibrates. Each resonance or natural frequency is related to a damping value and a modal shape (Clough & Penzien, 2003).

Data processing included the following techniques: zero filtering, and decimation, followed by FDD (frequency domain decomposition) (Brinker & Ventura, 2015, Rainieri & Fabroccino, 2014, Brandt, 2011), through different software packages.

DYNAMIC AMPLIFICATION FACTOR (DAF)

Trains exert dynamic forces on bridges, generating dynamic responses. These responses are in general large close to expansion joints, especially when the train enters the bridge. This leads to an impact due to the sudden change of vertical stiffness between the railway pavement before and at the bridge. These responses are considered through an amplification factor (1+*DAF*) which is multiplicated by the static response *R(static)* resulting in the dynamic response *R(dynamic)* according to:

$$R(dynamic) = (1+DAF) \times R(static)$$

The structural response to dynamic loads is fundamental for analysing its behaviour and integrity. The dynamic response is analysed by comparing their values with structural design standards (Ataei et al, 2018, Liu et al, 2018).

Impact factors measurements were taken with a recorder on a fixed position on one sleeper (Figure 6), while the other, or the *traveller*, was positioned on various sleepers. These locations were previously selected (Figure 6) based on the preliminary numerical model which indicated locations of large vertical response when a train enters the bridge.

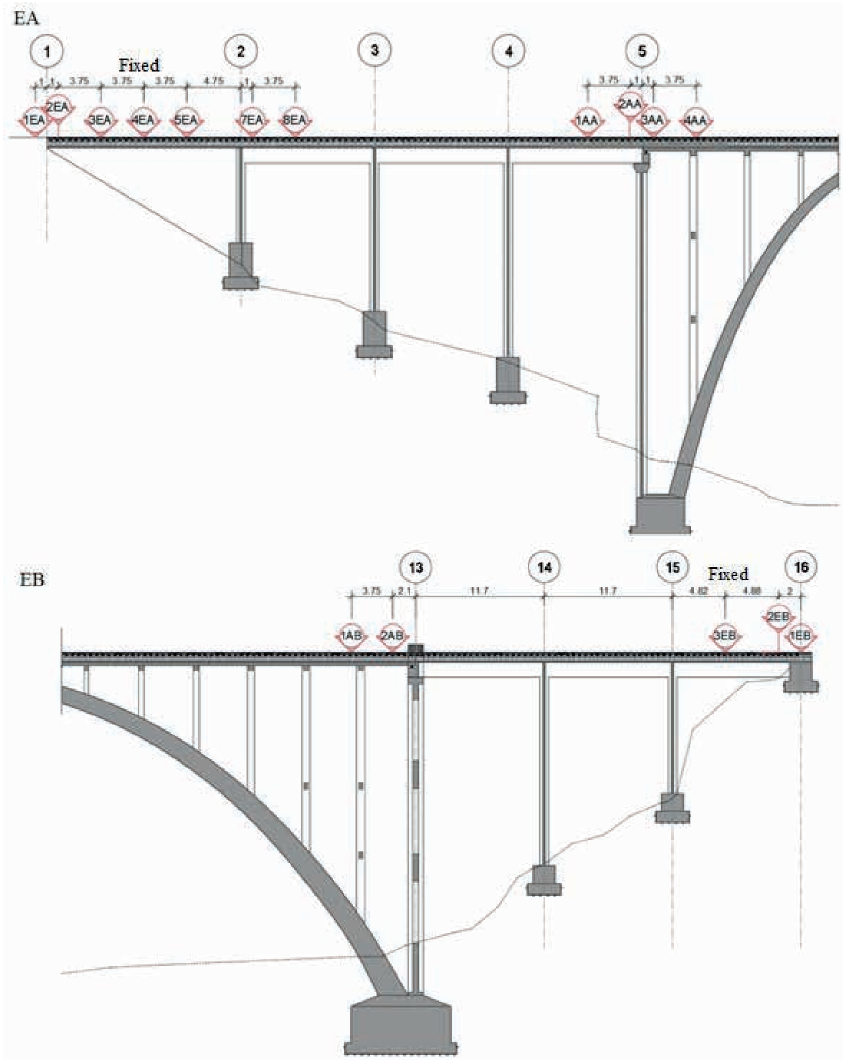

Figure 6 Measurement locations at the abutments A (top) and B (bottom)

The impact factor (φ) is the ratio between *R(dynamic)* and *R(static)*. To obtain the responses, a double integration of the acceleration versus time was carried out followed by normalization relative to the fixed position measurement.

Pfeil (1985) proposed the following equation for estimating φ, where ℓ is the span length of a bridge:

$$\varphi = 0.1\% \, (1600 - 60\sqrt{\ell} + 2{,}25l) > 1{,}2$$

Pfeil (1985) recommended φ minimum and maximum values of 1.2 and 1.6, respectively. Further to these recommendations, the Brazilian standard for concrete bridges (Magalhães et al, 2011) adopted these concepts.

REPAIR WORK AT THE ABUTMENT B

The client carried out emergency repairs at abutment B (Figure 7) which consisted of demolishing the damaged areas, using rock bolts and new rebars and additional concrete.

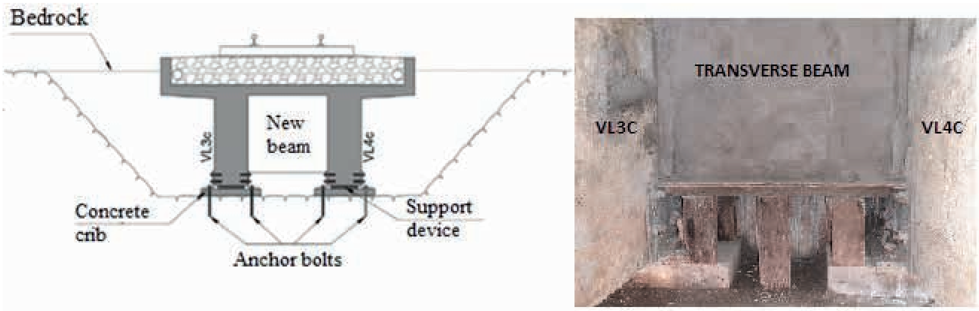

Figure 7 Emergency repair works at abutment B

MEASUREMENTS AFTER THE REPAIRS

After completing the repairs, a second measurement campaign took place at Abutment B and extended to points P20 to P23 (Figure 6).

RESULTS

The modal parameters were extracted utilizing the Frequency Domain Decomposition (FDD) technique using ARTeMis 6.0 software (ARTeMIS, 2022). The FDD technique extracts vibration modes and corresponding natural frequencies and damping (Magalhães et al, 2011). Table 1 presents the results.

Mode order	Frequency (Hz)	Damping (%)
f 1	0.635	0.884
f 2	0.673	1.359
f 5	0.928	0.429
f 75	4.525	6.076
f 78	4.785	0.703
f 264	11.832	1.029
f 311	15.038	0.228
f 312	15.136	0.241

Table 1 Extracted modal parameters through FDD

A preliminary numerical model yielded a first frequency equal to 0.55 Hz when using concrete Young's modulus of E =29 GPa. This modulus value was estimated for a concrete unconfined strength of 22 MPa, as used during the construction period.

The measured fundamental frequency of 0.635 Hz and the other of the table were obtained by processing the data and statistical analyses. To calibrate the numerical model with the first frequency it was necessary to increase Young's modulus to 40 GPa, which agrees with values found in the literature (Altunisik et al, 2016, Turker et al, 2014). Figure 8 shows the calibrated model.

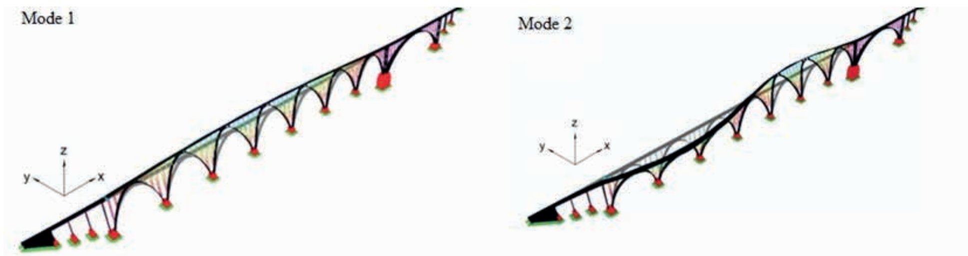

Figure 8 Numerical vibration modes

MODAL ANALYSIS BEFORE AND AFTER REPAIR WORKS

Point P23 of abutment B was selected for comparing results before and after repairs. It returned the same number of frequencies between campaigns in a frequency close to 5.5 Hz. Figure 13 presents measured frequencies before and after repair. The vertical colour scale indicates the change in frequency. Blue points indicate no significant frequency change, while the red ones indicate change.

The larger frequencies in Figure 13 correspond to 5.423 Hz and 5.499 Hz, in which the difference is so small that cannot be used to indicate any significant change in stiffness. Also, the transverse modes cannot be used to indicate a change of stiffness, therefore the OMA cannot indicate damage in this bridge.

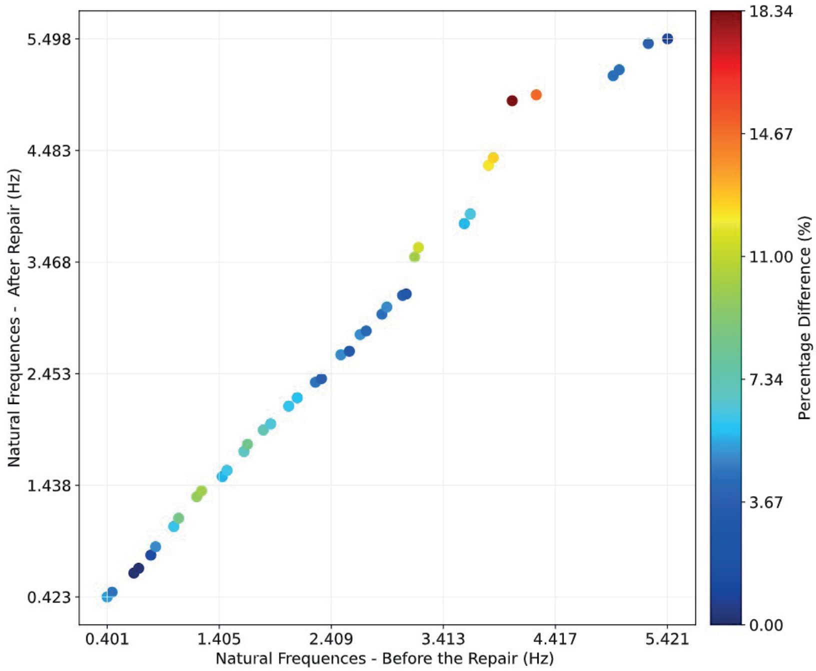

Figure 9 Comparative between natural frequencies after and before repairs.

AMPLIFICATION FACTORS RESULTS

The vertical response of the bridge is given by the integration of measured accelerations and normalized to the fixed position measurement. Figure 10 presents the results for abutment A, showing low values below 1.2, therefore acceptable impact values (ABNT NBR 7187). On the other hand, Figure 11 presents results from abutment B, showing high values up to 2.6 before repairs and how much they decreased after the repair works.

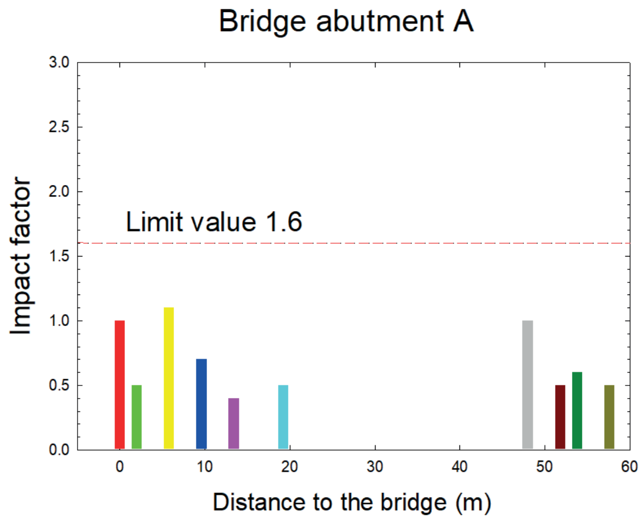

Figure 10. Dynamic Amplification Factors DAF– Abutment A (no repairs)

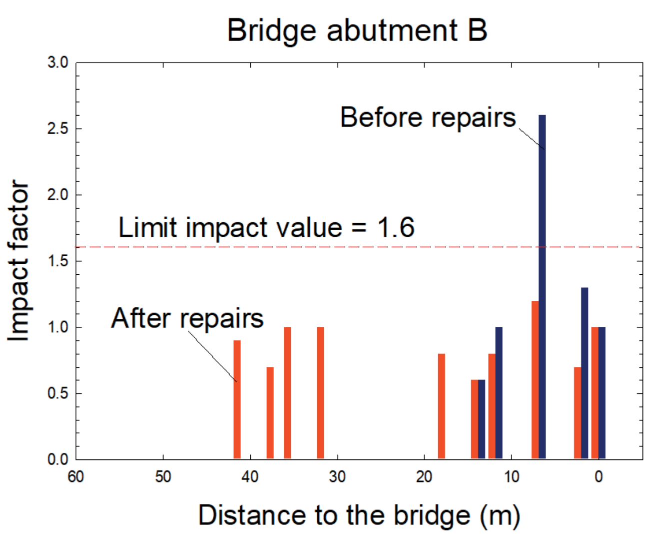

Figure 11. Dynamic Amplification Factors DAF– Abutment B, before and after repairs

CONCLUSIONS

The present work evaluated the structural condition of a reinforced concrete arch railway bridge through dynamic tests before and after the repair at one abutment. The Operational Modal Analysis leads to the structure's fundamental frequency of 0.635 Hz.

Experimental frequencies obtained through OMA before and after the repairs at the abutment did not provide any insight into the damage state conditions. This was due to uncertainties in the association with the experimental vibration modes shapes.

The good performance of abutment A was confirmed by the assessment of impact factors, or DAF. At abutment B, however, measurements before repairs showed high impact factors, up to 2.6, but reduced values, below 1.2, once the repairs were made.

Despite the limitations, it can be concluded that OMA is capable of inferring the global stiffness of the structure, while the DAF values can be used to assess whether or not the abutment structure elements are susceptible to acceptable amplification values.

This project demonstrates the effectiveness of dynamic tests as a complementary tool in the structural assessment of reinforced concrete bridges, analysis of train impacts and contributing to sustainable maintenance management of civil infrastructures.

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