Vibration tests on dismounted bridge beams and effects of deterioration

A. Quattrone1,2, E. Matta1, L. Zanotti Fragonara1, R. Ceravolo1 & A. De Stefano1

1 Department of Structural, Geotechnical and Building Engineering, Politecnico di Torino, corso Duca degli Abruzzi 24 – 10129 Turin, Italy

2 E-mail: antonino.quattrone@polito.it

Abstract. This paper aims at describing the tests campaign carried out on five precast bonded post-tensioned concrete bridge beams, recently dismounted after a service life of 50 years. The girders were part of the deck of a recently dismounted viaduct of an Italian motorway. The beams showed different deterioration levels, mainly due to the different exposure to corrosive agents. The test campaign were designed for evaluating the residual load bearing capacity of the members. Dynamic measurements were acquired before and after the static tests by using different excitation sources. This experimental research highlights that the natural frequencies of the beams can be used as a predictor of the ultimate bending moment of an existing structure.

1. Introduction

The network of infrastructures of a nation constitutes an asset of strategic importance to the life of the community. Its management requires periodic monitoring, through both short-term and long-term programs. In particular, the actual serviceability conditions, the assessment of the safety conditions and the vulnerability to natural catastrophic events must be checked, also resorting to experimental techniques. A thorough knowledge of the effective operational conditions and the residual safety margins of an infrastructure, achievable implementing a monitoring system, may lead to a rational scheduling of the interventions, and hence to an optimal management of economic resources.

The reduction of structural safety during the service life is a widely debated issue [1 - 5]. Several factors, such as corrosion, rheological effects, increasing of service loads, cracking propagation due to cyclic loads, may act simultaneously on a structure over its lifetime and lead to a substantial reduction in its capability to meet the required performances.

On this light, performing experimental campaigns on real structures with different deterioration levels should represent a great source of information to be used in developing predictive models and calibrating monitoring techniques.

Structural diagnostics is often associated to the analysis of vibration measurements, since modal quantities reflects the global behavior of the monitored object. The variation of these quantities can be used as indicator of occurring damages.

In this paper, the experimental vibration tests performed on five beams dismounted after 50 years of service life are illustrated and the results of the dynamic identifications and their evolution as a function of the ultimate bearing capacity are presented. Experimental modal analysis was performed and the results are presented and compared. In particular, the connection between the deterioration
levels (expressed in terms of ultimate bearing moment) and the identified modal parameters is highlighted.

2. Description of the tests
The experimental testing campaign was commissioned by the Italian motorway company ATS autostrada TO-SV S.p.A., at the aim of evaluating the residual strength of a set of bridge beams removed from Pesio viaduct after fifty years of service life during the modernization works of A6 Torino-Savona motorway.

The tested beams had all the same geometrical characteristics and presented different degradation levels. Each deck of the viaduct was constituted by five 35 m long simply supported beams. The section of the beams had a trapezoidal shape with linearly varying height from 1.55 m at the supports to 2.95 m at the midspan. The beams were constituted by a bottom precast part completed by a 0.1 m thick, cast-in-place slab. The post-tensioning reinforcement consisted of 5+5 six-strand tendons, placed in the two sloping lateral walls. The design characteristics of the employed materials were:

- Post-tensioning tendons steel - ultimate tensile strength: 1600 MPa;
- Concrete – cube compressive strength: 45 MPa;

Figure 1. A view of the Pesio Viaduct deck (a), the midspan cross section (b) and a beam placed on the test bench (c)
The tested beams presented different deterioration levels, mainly related to the position occupied in the deck. The health state of the tested beams was classified in three levels (good, intermediate and bad condition) on the basis of a visual inspection (see Table 1, second column). The estimated ultimate bending moment $M_{d,u}$ is 23950 kNm.

**Table 1.** Visual inspection rating and ultimate bending moments in midspan section

| Beam | Condition Rating | Midspan ultimate moment $M_u$ [kNm] | Percentage ratio $M_u / M_{d,u}$ | Tests               |
|------|------------------|-------------------------------------|----------------------------------|---------------------|
| B01  | Bad              | 11172                               | 46.7%                            | Static              |
| B02  | Intermediate     | 22581                               | 94.3%                            | Static + Dynamic    |
| B03  | Good             | 20142                               | 84.1%                            | Static + Dynamic    |
| B04  | Good             | 18336                               | 76.6%                            | Static + Dynamic    |
| B05  | Intermediate     | 19321                               | 80.7%                            | Static + Dynamic    |
| B06  | Bad              | 12087                               | 50.5%                            | Static              |
| B07  | Bad              | 11242                               | 46.9%                            | Static + Dynamic    |
| B08  | Good             | 14960                               | 62.5%                            | Static              |
| B09  | Good             | 14924                               | 62.3%                            | Static              |

2.1. **Static tests**

A four-point static bending test was chosen to determine the ultimate load capacity. The forces, applied by means of four hydraulic jacks, were progressively incremented performing loading and unloading cycles until reaching the ultimate load. The static tests have been designed in order to investigate the whole behavior of the post-tensioned beams, determining both the decompression moments and the ultimate bending strengths. Table 1 lists the condition rating of the beams and their ultimate bending moments, Figure 2 shows the test configuration.

![Dynamic tests configuration](image)

**Figure 2.** The dynamic tests configuration
2.2. Dynamic tests
The beams were tested after the dismantlement and, in three cases, after the execution of the static tests (Table 1).

A set of 18 unidirectional capacitive accelerometers was used to acquire the vibration response under both ambient noise and impact hammer excitations (Figure 2). Furthermore the beams B04, B05 and B07 have been tested by using an electro-mechanical vibrodyne placed on the upper slab. A sine sweep excitation with frequency varying in the range of the first two flexural modes have been applied. The vibrodyne has been positioned to maximize the number of excitable modes in its operative range. Thus it was possible to excite a range of frequencies including the first two flexural modes and the first torsional mode of the beams.

The accelerometers have been placed along the longitudinal axis of the beam on the slab, with a closer spacing in the middle part of the span, in order to get an adequate spatial resolution of the vertical flexural modes. Three accelerometers were placed along transversal axis to discriminate among torsional and transversal bending modes.

The acceleration signals were acquired at a 400 Hz sampling frequency for both ambient noise and impact hammer excitations. The impact tests were carried out by hitting the beams along the slab with a sledge hammer both in vertical and transversal directions.

3. Experimental modal analysis
Among all the available methods which can be employed to identify the modal parameters, it was decided to adopt two techniques working in the time domain. The Eigenvalue Realization Algorithm (ERA) was used to analyse the free decay responses [7], whilst ambient vibration signals called for a Stochastic Subspace Identification (SSI) [8].

After a preliminary analysis of the spectral content, the signals acquired were pretreated by filtering out of the bandwidth [0 - 50 Hz], removing the trends and reducing sampling frequency to 200 Hz. Several modal identification sessions were performed. Some tolerance criteria were adopted to discard computational modes, based on modal shape assurance coherence criterion (MAC) and fixing a maximum value of damping ratio. The chosen parameters are:

- MAC > 85%
- 0 ≤ ζ ≤ 10%

A data cleansing process was further introduced in order to neglect those results which differed from the mean values of identified frequencies more than the computed standard deviation.

4. Discussion of the experimental results
The following graphs show the variation of the first four bending modes as a function of the ultimate bending moments in the midspan section.

The results of the analysis, reported in Figure 4, highlight a correlation between the dynamic characteristics of the beams and the ultimate bending strengths. Both static and dynamic tests showed the different evolution in time of the beams after 50 years in service, the former in terms of residual load-bearing capacity, the latter in terms of changes in modal frequencies.

The ultimate bending strength and the modal parameters are both influenced by the different levels of deterioration of the beams. These differences can be correlated mainly with the different position occupied in the deck. The edge beams are usually more exposed to weather, chemical attacks of chlorides contained in de-icing salts and pollutants emitted by vehicle traffic. Moreover, they typically undergo higher stress levels, resulting in the years in wider cracking patterns.

This phenomenon is pointed out by the behavior of beam B07. In this particular case, an important role was played by the lack of care in the design of the non-structural details, as it is possible to notice in Figure 5. The residual bending strength has been possibly affected by the localized damage induced
in the section next to the drainpipes (Figure 5), as partially highlighted by the different failure behavior. The beams B02 and B04 showed mostly brittle failure due to the crushing of the upper slabs, whilst in the case of the beam B07 has been caused by the rupture of the corroded reinforcement.

Figure 4. The bending modal frequencies identified in ambient vibration tests

Figure 5. Beam B07: corrosion of the post-tensioned tendons and ordinary reinforcement. The deterioration is particularly advanced in the sections next to the drainpipes.
On the other hand, the ultimate bending moment of the interior beams (i.e. B02) is comparable to the ultimate bending moment $M_{d,u}$ calculated on the basis of the mean values of materials properties and the geometrical measures reported in the original design documentation.

5. Conclusions
This paper presents the experimental campaign carried out at the purpose of evaluating the residual strength of nine bridge beams with different levels of degradation, recently dismounted after 50 years of service life.

Dynamic tests were carried out on five beams and the modal parameters were identified. The evolution of the dynamic characteristics as a function of the ultimate flexural strength has been highlighted.

The identified modal parameters, in particular the natural frequencies, showed to be sensitive features of the strength reduction. This capability makes them suitable symptoms to be monitored in order to estimate the reliability of the structure.

6. References
[1] Enright MP and Frangopol DM 1998 Service-life prediction of deteriorating concrete bridges Journal of Structural Engineering ASCE 3 124 309-317
[2] Thoft-Christensen P 1998 November Assessment of the reliability profiles for concrete bridges Engineering Structures 20 11 1004-1009
[3] Stewart MG and RosowskY DV 1998 Structural safety and serviceability of concrete bridges subject to corrosion ASCE Journal of Infrastructure Systems 4 146-155.
[4] Nowak, A. S., Collins, K. R., 2000. Reliability of Structures. Mc Graw Hill International Editions
[5] Ceravolo R, Pescatore M and De Stefano A 2009 Symptom based reliability and generalized repairing cost in monitored bridges Reliability Engineering & System Safety 94 (8) 1331-1339
[6] Ewins DJ. Modal testing: Research Studies Press Ltd; 2000.
[7] Juang JN and Pappa RS 1984 An eigensystem realisation algorithm (ERA) for modal parameter identification and modal reduction NASA/JPL Workshop on identification and control of flexible space structures
[8] Van Overschee P and De Moor B. Subspace Identification for Linear Systems: Theory and Implementation - Applications: Kluwer Academic Press Dordrecht; 1996.
[9] Friswell MI 2007 Damage identification using inverse methods Philosophical Transaction of the Royal Society A 365 393-410
[10] Peeters B and DeRoeck G 1999 Reference-based stochastic subspace identification for output-only modal analysis Mechanical Systems and Signal Processing 13 855-878
[11] Doebbling SW, Farrar CR, Prime MB and Shevitz DW 1996 Damage Identification and Health Monitoring of Structural and Mechanical Systems from Changes in Their Vibration Characteristics: A Literature Review Technical Report LA-13070-MS Los Alamos National Laboratory, Los Alamos, NM.