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Static load testing with temperature compensation for structural health monitoring of bridges

Viet Ha Nguyen [a,*], Sebastian Schommer [a], Stefan Maas [a], Arno Zürbes [b]

[a] University of Luxembourg, Faculty of Science, Technology and Communication, Research Unit Engineering Sciences, Rue Coudenhove-Kalergi 6, L-1359, Luxembourg
[b] Fachhochschule Bingen, Fachbereich 2 - Technik, Informatik und Wirtschaft, Germany

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ABSTRACT

The paper presents a series of repeated static loading tests on a prestressed concrete beam, which was originally part of a real bridge and then subjected to stepwise artificial damage. The tests were done during a one-month period that four levels of damage were introduced by cutting tendons until visible cracking occurred. The deflection line was measured by means of several displacement sensors and the retrieved information is used in different ways for damage detection.

At first, the sensor spacing requirement is analyzed with respect to measurement accuracy as well as necessary resolution for the numerical derivations of the deflection line to obtain the rotational angle and the curvature of the beam. These derived quantities may be used as damage indicators in addition to the deflection.

Damage of concrete goes very often along with non-linear phenomena like cracking of concrete and plastic strain of reinforcement steel. These effects are discussed and their influence on the repeated loading tests as well the test procedure for condition monitoring is deployed. Progressive damage goes along with progressive sagging of the bridge due to gravity, which can also be used as damage indicator.

Finally, the effect of varying outdoor temperatures are discussed and assessed. Though these effects can be reduced by choosing cloudy days without high temperature changes and without high solar irradiation, the outdoor temperature is never constant. Hence, a compensation algorithm is proposed which reflects the measured data according to a reference temperature. This compensation visibly improved the regularity of data.

1. Introduction

Damage detection of bridges based on dynamic characteristics, i.e. modal parameters like eigenfrequencies, mode-shapes or damping ratios has been studied a lot in the last decades. For example, damage can be uncovered by reduction of eigenfrequencies or change of mode-shapes. The modal features are also used for subsequent procedures like finite-element model updating as illustrated on the Z-24 Bridge (Switzerland) [1] and the Gaertnerplatz Bridge (Germany) [2]. These parameters allow assessing experimentally stiffness/flexibility, as for instance reported for real bridges in Luxembourg [3,4]. Damage in the I-40 Bridge in New Mexico was localized by a sensitivity analysis [5]. Further to detection and localization, assessment of damage can be realized [1,4,6,7] and even a prediction of remaining lifetime is targeted [8,9].

On the other hand, static load tests have a long tradition in civil engineering, provide important information on deformation, displacement, rotation and strain [10,18]. They have been since ever an appropriate alternative and an amendment to visual and dynamic inspections as deflection or strain measurements are relative easy. Static load testing within the service load limits have been used to validate new bridges and to verify the actual capacity of existing bridges. For example, before the opening to traffic in 10-2013, a new bridge in Grevenmacher (Luxembourg) connected to Wellen (Germany) over the Mosel River was undergone static load testing by six full charged trucks to archive the deflection line. For old bridges, this kind of test is very useful to check their present condition. In Florida [11], two prestressed concrete bridges were subjected to full-scale static tests where load testing vehicles delivered the ultimate live load. The results showed consistently that structures have greater residual strength than indicated by analysis or design. After 23 years of service, the real structural behaviour of the cable-stayed “Antonio Dovali Jaime” Bridge in Mexico was assessed [12]; after the load test campaign, residual deformations

* Corresponding author.
E-mail address: vietha.nguyen@uni.lu (V.H. Nguyen).

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Table 1
Material properties of tested concrete specimens.

Specimen no.	Length [mm]	Diameter [mm]	Mass [kg]	Density [kg/ m^3]	Young's Modulus [MPa]	Poisson's ratio	Compression strength [MPa]	Splitting tensile strength [MPa]
1	200	104	4.14	2439	42,670	0.12	91	–
2	203	104	4.18	2426	–	–	–	5.9
3	204	104	4.23	2445				
4	202	104	4.19	2438				
5	204	104	4.17	2408	37,130	0.14	67	–
6	202	104	4.16	2431	39,180	–	69	–
7	203	104	4.29	2483	–	–	–	4.0
8	203	104	4.17	2423				
9	203	104	4.27	2474	43,290	0.13	75	–
10	204	104	4.16	2399	–	–	–	5.8
11	198	104	4.10	2443				
12	202	104	4.10	2392				
Mean value				**2433**	**40,568**	**0.13**	**76**	**5.2**
Variance				733	8,524,692	0.00	113	1.1
Standard deviation				27	2920	0.01	11	1.0

were not observed. A concrete arch bridge in Turkey, dates back to mid-to-late 19th century and has approximately 8600 km of track length was checked by both dynamic and static load testing [13]. The static load test was performed by two diesel locomotive of DE24000 type and the load rating procedure proved the considerably safety of the bridge. Marefat [14,15] studied the remaining load carrying capacity of two plain 60-year-old concrete arch bridges in Iran. By overloading compared to the expected service load, these bridges proved their satisfactory performance. However, the high load testing may provoke additional cracks and is hence not always appropriate.

Moreover, it is known that ambient temperature can change the stiffness of asphalt and bearings (pads, soil) and hence the static test results. Therefore, a temperature compensation procedure is discussed, used and evaluated below.

We got recently the chance to perform static and dynamic testing of a real prestressed concrete bridge prior to its demolishment. Increasing artificial damage was introduced in four successive steps and its effect on the static load testing within the service load limits is subsequently analyzed here, while the dynamic testing methods will be published in a companion paper. The relation between damage, static deflection, rotational angle, curvature and sagging together with unavoidable outdoor temperature variations are investigated.

2. Description of the structure

The tested structure was a part of the bridge, which was built between 1953 and 1955 and which crossed Mosel River between Grevenmacher (Luxembourg) and Wellen (Germany). It was demolished in 2013 and replaced by a new steel bridge. Some material tests were performed to verify the static strength of concrete and tendons for the bridge after 60-year service life.

2.1. Material properties of the concrete

Twelve cylindrical specimens of the concrete were taken in total and seven underwent so far compression or tension testing. The results are given in Table 1.

2.2. Prestressed tendons

The concrete beam was prestressed by 19 steel tendons along the longitudinal direction of the beam, as shown in Fig. 1 for a half of the symmetric beam.

As shown in Fig. 2, each tendon was composed of 12 steel wires of 7 mm diameter; they surrounded a spring that runs along the axis of the tendon. The whole tendon laid in a sheathing. During the construction of the bridge, the tendons were prestressed and

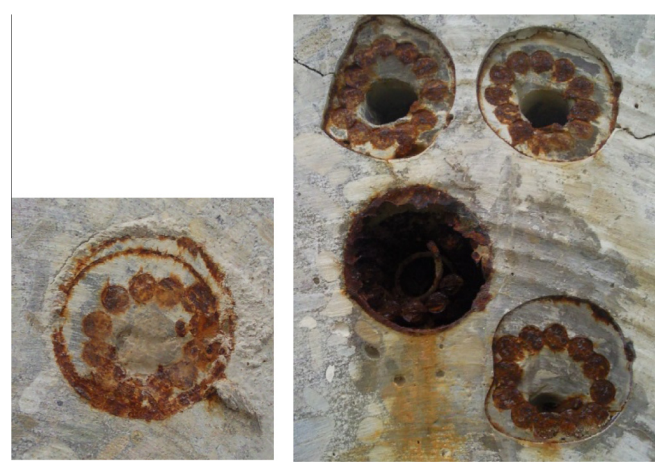

Fig. 2. Anchor heads of post-tensioned concrete beams.

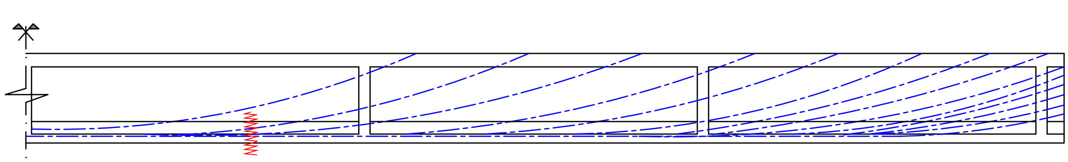

Fig. 1. Positioning of tendons along the beam's length, shown for a half of the beam.