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Experimental analysis of the effective pre-stress in large-span bridge box girders after 40 years of service life

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ABSTRACT

The rheological properties of concrete and pre-stressing steel have a significant influence on the deformation and pre-stress losses of p.c. members and thus affect their long-term deflection and service behaviour. Long-span concrete bridge girders can be particularly sensitive to pre-stress losses as the dead load is large compared to the total load. Some observations of excessive long-term deflections have been made of long-span pre-stressed concrete box girder bridges over the last few years. This has led some researchers to question the reliability of the available theoretical models to provide correct long-term predictions. The main results of experimental tests conducted on 9 concrete bridge box-girders with a span of 35 m are presented in this work. The girders, which were part of an Italian motorway bridge dismantled after 40 years of service life, were tested up to failure with a specially built test frame. The mean deformation measured over five zones of each beam allowed the effective stress in the pre-stressing tendons to be evaluated for a total of 45 zones. Finally, the experimental data have been compared with theoretical predictions obtained by applying both the rules of an international standard (Eurocode 2) and a refined analytical model that takes into account the presence of two types of concrete with different properties as well as the various stages of the construction and pre-stressing.

1. Introduction

The rheological properties of concrete and the relaxation of pre-stressing steel have a significant influence on both the deformation and the pre-stress losses of concrete bridge girders and therefore affect their long-term deflection and service behaviour. Long-span concrete bridge girders can be particularly sensitive to pre-stress losses, as the dead load is large compared to the total load [1,2]. The long-term increase in displacements is of great importance for serviceability, durability and reliability reasons. Several bridges have been closed or have needed repairs, due to excessive deflection before the end of their initially assumed service life and the cost of a reduced service life can be particularly severe for societies, owners and users. For this reason, the theoretical evaluation of the effects of long-term creep and the shrinkage of concrete and relaxation of pre-stressing steel is a very important aspect in the design process, in order to guarantee proper service behaviour of the structure. Some observations of excessive long-term deflections have been made on long-span pre-stressed concrete box girder bridges over the last few years [1–5]. This has led some researchers to question the reliability of the available theoretical models to provide correct long-term predictions [4–6]. The collection of experimental data that are able to establish the effective long-term behaviour of structures and verify the calibration of theoretical models is particularly complex, but certainly valuable. Some authors have recently proposed applying a statistical analysis on bridge deflection data in order to improve the concrete creep model [4]: a collected database of multi-decade bridge deflection has thus been exploited, through inverse analysis in order to recalibrate the theoretical creep model. The main advantage of this approach is that it offers the possibility of collecting a large amount of deflection data which, generally, constitute the most available deformation parameter in practical cases, and of performing statistical analysis of the phenomenon. However, deflection is affected not only by time-dependent phenomena and their interactions, but also by a series of other aspects, such as stiffness variations due to cracking propagation and the consequent redistribution of the bending moment (undetermined structures), the behaviour of D-regions, the non-uniform mechanical properties of materials along the structure and, in the case of existing structures, the effects of deterioration. In this context, an inverse analysis of deflection involves greater uncertainties than a method that considers

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Nomenclature

A_c	concrete area
A_p	prestressing steel area
e_c	distance of the resultant tendon from the centroid of the section
f_{ctm}	mean value of the axial tensile strength of concrete
$f_{ct,res}$	residual tensile strength of concrete
$f_{0,2k}$	characteristic 0.2% proof-stress of pre-stressing steel
f_{ptk}	characteristic tensile strength of pre-stressing steel
f_{tk}	characteristic tensile strength of ordinary reinforcement
h	overall depth of a cross-section
h_0	notional size of the section
J_c	second moment of inertia of the section
M_{cr}	cracking bending moment
M_{dec}	decompression moment
M_{sw}	bending moment due to the self-weight
P_u	experimental failure load
R_{ck}	characteristic compressive cube strength of concrete at 28 days
y_i	distance of the neutral axis from the bottom fibre
u	perimeter of the concrete cross-section
z	vertical distance between the measured strains at the two chords
χ	ageing coefficient
$\Delta\varphi$	variation in the creep coefficient
$\Delta\varepsilon_{sh}$	variation in the shrinkage strain
$\varepsilon_{exp,bottom}$	measured mean strain in the bottom chord
$\varepsilon_{exp,top}$	measured mean strain in the top chord
$\sigma_{p,eff}$	effective residual stress in the pre-stressing steel
φ_∞	final value of the creep coefficient

the local deformation of a part of the structure (mean deformation of a beam block).

The main results of experimental tests conducted on 9 concrete bridge box-girders with a span of 35 m are presented in this work. The girders, which were part of an Italian motorway bridge dismantled after 40 years of service life, were tested up to failure with a purpose-built test frame. Owing to the different positions in the bridge and the various environmental attack levels, the girders were characterized according to their different deterioration conditions.

The effective stress in the pre-stressing tendons is here evaluated on the basis of the mean deformation measured on five zones of each beam, over 45 zones.

Both provides a rich source of information on the examined structure:

- an estimation of the pre-stressing losses in its present condition after a few decades of service life, on the basis of detailed experimental determination of the mean deformation of a part of the structure and of related actions;
- a comparison of the actual pre-stressing losses with different beams built at the same time and subjected to the same macro-environmental conditions;
- a comparison of the experimental observations with a theoretical analysis based on international standards (Eurocode 2).

2. Experimental programme

The experimental testing campaign was commissioned by the ATS Autostrada TO-SV S.p.A. Italian motorway company, in order to evaluate the residual strength of a set of bridge beams removed from the Pesio viaduct (Piedmont, Italy) after forty years of service life during the modernization works of the A6 Torino-Savona motorway.

The Pesio viaduct was built in 1965 and dismantled in 2005 (Fig. 1). Nine beams from the viaduct were stored in an in situ test area for the experimental campaign, which was carried out in 2011.

The viaduct had 26 spans, each of which was constituted by five 35 m long simply supported beams connected by transversal RC beams.

2.1. Beams

The cross-section of the beams was a trapezoidal shaped box-section; the height of the section varied linearly from 1.55 m at the supports to 2.95 m at the midspan. The beams were constituted by a lower precast part, which was completed with a 100 mm thick, cast-in-place slab (Fig. 2). The post-tensioning reinforcement consisted of 5 + 5 six-strand tendons, placed in the two inclined lateral walls. The tendons were positioned parallel to the bottom chord along almost the whole length of the element. Six strands were anchored to the support section, and the other four strands were anchored to the upper side of a carriageway slab, close to the support (see Fig. 3).

The original design documents of the bridge were available and they offered a detailed description of the design characteristics of the material, the geometry and the different construction and pre-stressing phases. The beams were built according to the following sequence:

- Construction of the bottom part of the section.
- Pre-stressing of the first series of tendons (series 1, see Fig. 3).
- In situ casting of the top slab.
- Pre-stressing of the second series of tendons (series 2, see Fig. 3).

The initial pre-stressing stresses, in the design documents, were calculated for the different sections, taking into account losses due to friction. Table 1 shows the initial pre-stressing stresses, indicated by the designer, for the five beam sections that were instrumented during the tests. The design values of the bending moments due to permanent and variable loads are shown in the same table.

The design properties of the employed materials, which were checked experimentally, are:

- Pre-stressing steel – non-stabilized strands: characteristic 0.2% proof-stress $f_{0,2k} = 1600\ \text{N/mm}^2$ and characteristic tensile strength $f_{ptk} = 1800\ \text{N/mm}^2$.
- Ordinary reinforcement: characteristic yielding stress $f_{yk} = 440\ \text{N/mm}^2$.
- Precast section concrete (concrete 1) – characteristic cube compressive strength $R_{ck} = 45\ \text{N/mm}^2$.
- Top slab concrete (concrete 2) – characteristic cube compressive strength $R_{ck} = 25\ \text{N/mm}^2$.

All the tested beams had the same geometrical and material characteristics but, due to their different positions on the bridge and the different environmental attack levels, they presented different degradation levels. On the basis of a simple visual inspection,