Engineering Structures 117 (2016) 358–371

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Time-dependent reliability of strengthened PSC box-girder bridge using phased and incremental static analyses

Tong Guo [a,*], Zheheng Chen [a], Tie Liu [a], Dazhang Han [b]

[a] *Key Laboratory of Concrete and Prestressed Concrete Structure, Ministry of Education, School of Civil Engineering, Southeast University, Nanjing, PR China*
[b] *Jiangsu Transport Planning & Design Institute Ltd., Nanjing, PR China*

ARTICLE INFO

Article history:
Received 30 June 2014
Revised 3 March 2016
Accepted 7 March 2016
Available online 23 March 2016

Keywords:
Time-dependent reliability
Strengthened bridge
Prestressed concrete
Box girder
Finite element method

ABSTRACT

Prestressed concrete (PSC) box-girder bridges are extensively used in highway and railway construction. Excessive long-term deflection and unexpected cracks however are often observed. To achieve deflection control and/or to restore the bearing capacity of bridges, structural strengthening measures are frequently adopted. This paper proposes an approach based on probabilistic finite element analyses to evaluate the time-dependent reliabilities of strengthened PSC box-girder bridges. The time-dependent behaviour of the girders is simulated considering concrete shrinkage, creep and cracking, corrosion and stress relaxation of steel, etc. In particular, phased analysis is adopted to account for the existing damage and stress conditions prior to strengthening, and the incremental static analysis method is used to calculate the structural reliabilities. Application is made to the time-dependent reliability assessment of a PSC box-girder bridge, and the effectiveness of three strengthening methods including externally bonded steel plates, fibre reinforced polymer (FRP) composites and external post-tensioning is compared. The presented study provides references to reliability-based design and optimization of strengthening strategies for PSC box-girder bridges.

1. Introduction

Prestressed concrete (PSC) box-girders are widely used in highway and railway bridges due to their large bending and torsional stiffness, aesthetic shape, relatively low material costs and easy maintenance. However, excessive long-term (i.e. ten years or more) deflection and cracks have been observed in past decades [1], which undermines the bridge serviceability and may even trigger structural collapse [2]. Such unexpected damage demonstrates the needs for accurately predicting time-dependent behaviour of PSC box-girder bridges, which is influenced by a number of factors. First, the box-girder has a closed section, and the shear lag effect [3], the torsion and distortional warping make the analysis more complex than regular rectangular beams. According to the analysis by Kristek and Bazant [4], the long-term deformation of box-girder may be underestimated by about 20% using the classical theory of beam bending. Besides, the highly uncertain concrete creep and shrinkage bring additional difficulties to the accurate prediction of time-dependent behaviour [5]. Other factors include the complex segmental construction procedure and the corresponding influence on bridge deflections [6,7], etc. For bridges in a chloride environment, the deterioration process of the bridge may also be accelerated due to corrosion of prestressed tendons (PTs) and reinforcing bars [8].

To make an accurate prediction on behaviour of PSC box-girder bridges, extensive studies have been conducted for years. For example, both experimental and analytical studies were conducted to evaluate the shear lag effect on box-sections [3,4]. Bazant et al. [9] further indicated that the thickness difference among the webs and the top and bottom slabs also has a certain influence on the time varying response of concrete structures. For creep and shrinkage analyses, a number of models have been developed, and some of which were adopted in design codes [10]; however, most of these models are based on explicit equations, while creep, shrinkage and stress relaxation are complex deterioration processes and may have interactive influence on each other; therefore, the necessity of using three-dimensional (3D) FE models with embedded material models should be highlighted. Previously, Sousa et al. [11] developed a two-dimensional beam element FE model, where creep and shrinkage were taken into account, and the actual sequence of construction was also simulated. Guo et al. [12] further proposed a 3D shell element model in which the corrosion model was also implemented, so that the influence of corrosion on long-term performance is also included.

---

* Corresponding author. Tel./fax: +86 25 83790923.
E-mail address: guotong77@gmail.com (T. Guo).

http://dx.doi.org/10.1016/j.engstruct.2016.03.011
0141-0296/

When the uncertainties in long-term behaviour are to be considered, these FE models can be used in reliability or probabilistic analyses. However, computational-efficiency problem may arise when using traditional Monte Carlo simulation, due to that a large number of sampling are often needed. Therefore, some improvements by using the importance sampling or adaptive importance sampling, the response surface, etc., were made [12–14]. In addition to the simulation-based approaches, some finite-difference-based methods, such as the Perturbation Method, First/second-Order Reliability Methods and the Spectral Stochastic Finite Element, have been developed and evaluated [14]; though they are relatively more efficient, the accuracy of structural response prediction at the ultimate limit state requires further validation.

Despite of these great research efforts, many existing PSC box-girder bridges are designed based on previous codes rather than such complicated analyses, and consequently many bridges show different degrees of premature damage. To maintain the required serviceability and load-bearing capacity, various strengthening measures are often used, including externally bonded steel plates or fibre reinforced polymer (FRP) composites [15,16] and external post-tensioning [17], etc. Effectiveness of these strengthening measures were experimentally validated, though most of them were on scaled specimens [18,19], which may have the size effect. Therefore, field tests were further conducted to evaluate the in-situ performance of strengthened bridges [20–22]; however, most tests focused on the short-term behaviour, while the study on long-term behaviour (i.e. deflection, etc.) of full-scale strengthened bridges was very limited. In addition, most analytical studies regarding strengthened structures did not take the existing damage (i.e. deformation and cracking, etc.) into account, which should not be neglected; therefore, a simplied method was proposed to calculate long-term deflections in FRP-strengthened reinforced concrete beams [23].

Based on previous research efforts, this paper focuses on the time-dependent reliability assessment of PSC box-girder bridges after strengthening. To accurately simulate the behaviour of PSC box-girder bridges associated with uncertainties, a probabilistic finite element (FE) approach is adopted in which nonlinear stress–strain relationship, the shrinkage and creep model, the smeared crack model of concrete as well as the stress relaxation model of steel are integrated. As a result, the influence of prestress loss, loss of cross-sectional area due to corrosion, and load history on creep and shrinkage behaviour is included and updated from time to time. Moreover, to account for the effect of damage prior to the strengthening (i.e., cracks, deflection, etc.), the phased analysis technique is used in this study. An incremental static analysis method is adopted to keep a balance between the accuracy and efficiency of reliability analyses with small failure probabilities.

2. Simulation of time-dependent deterioration of PSC box-girder

2.1. Composite degenerated shell element

In this study, an eight-node composite degenerated shell element in the FE software DIANA [25] is used to simulate the thin-walled box-girder. This shell element is capable of modelling pre- and post-cracking behaviour of thin-walled reinforced concrete (RC) structures and enables easy modelling of distributed reinforcements as well as prestressed tendons [12]. In this shell element, a series of embedded reinforcement grids are defined to simulate the non-prestressed reinforcements, as shown in Fig. 1a–d. Prestressed tendons are easily modelled using an automatic tendon generation scheme included in DIANA [25], based on a few predefined location points and the shape functions, as shown in Fig. 1e.

2.2. Creep and shrinkage

During the past decades, quite a few shrinkage and creep models have been proposed, of which the widely used ones include the CEB-FIP series model, the ACI series model, the BP series model and the GL2000 model [25,26], etc. According to the evaluation by Al-Manaseer and Lam [27,28], the B3 and GL2000 models are better for predicting the shrinkage strain, in which the B3 model slightly underestimates the shrinkage strain, while the GL2000 model overestimates it. The CEB-FIP90, B3 and GL2000 models can well predict the creep deformation, and when combined with the FE analysis, the integrated CEB-FIP model can simulate the creep and shrinkage behaviour with acceptable accuracy [12]; therefore it is adopted in this study.

The creep function in the CEB-FIP model, $J(t,t_0)$, is shown in the following Eq. (1).

$$J(t,t_0)=\frac{1}{E_c(t_0)}+\frac{\varphi(t,t_0)}{E_{c28}} \tag{1}$$

where $E_c(t_0)$ is the modulus of elasticity at the concrete age of t_0, and E_{c28} corresponds to the value at the age of 28 days. $\varphi(t,t_0)$ is the creep coefficient, which is determined from the following hyperbolic power function:

$$\varphi(t,t_0)=\left[1+\frac{1-RH/RH_0}{0.46(h/100)^{1/3}}\right]\left(\frac{5.3}{\sqrt{0.1f_{cm28}}}\right)\left(\frac{1}{0.1+t_0^{1/5}}\right)\left[\frac{t-t_0}{\beta_H+(t-t_0)}\right]^{0.3} \tag{2}$$

where RH is the relative environmental humidity; RH_0 equals to 100%; and h is the nominal size of the concrete member (mm) which is defined as $2A_c/u$; A_c is the cross-sectional area and u is the perimeter in contact with the atmosphere. f_{cm28} stands for the mean compressive strength at the age of 28 days, and β_H is defined as $150(1+(1.2RH)^{18})h/100+250\leqslant 1500$.

The change of concrete strength with time is predicted as

$$f_{cm}(t)=\beta_{cc}(t)f_{cm28} \tag{3a}$$

$$\beta_{cc}(t)=\exp\left(s\left(1-\sqrt{28/t_{eq}}\right)\right) \tag{3b}$$

where $\beta_{cc}(t)$ is a time-dependent coefficient and s takes the value of 0.20, 0.25 and 0.38 for rapid hardening high strength cement, normal and rapid hardening cement, and slowly hardening cement, respectively. The equivalent age of concrete t_{eq} is defined as

$$t_{eq}=\int_0^t 4000(1/273-1/T(\tau))d\tau \tag{3c}$$

where $T(\tau)$ is the temperature of concrete at τ days.

The modulus of elasticity of concrete at t days can be estimated as

$$E_c(t)=\beta_{cc}(t)E_{c28} \tag{4}$$

The shrinkage strains $\varepsilon_s(t,t_s)$ at an age of t days is

$$\varepsilon_s(t,t_s)=(160+10\beta_c(9-0.1f_{cm28}))\times 10^{-6}\beta_{RH}\times\sqrt{\frac{t-t_s}{350(h/100)^2+(t-t_s)}} \tag{5a}$$

where β_c is a shrinkage coefficient dependent on cement type, t_s is the age of concrete at the beginning of shrinkage (day), and β_{RH} is related to the environmental humidity RH as follows