Engineering Structures 57 (2013) 502–511

Contents lists available at ScienceDirect

Engineering Structures

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

Capturing the long-term dynamic properties of concrete cable-stayed bridges

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ARTICLE INFO

Article history:
Received 18 September 2012
Revised 4 October 2013
Accepted 6 October 2013
Available online 8 November 2013

Keywords:
Concrete cable-stayed bridges
Concrete creep
Concrete shrinkage
Steel relaxation
Time-dependent behaviour

ABSTRACT

A cable-stayed bridge can be analysed by finite element method with the bridge deck and pylons modelled as beam elements taking into account geometric nonlinearities, and the stay cables as truss elements with equivalent Ernst moduli to account for cable sag. The long-term dynamic properties of concrete cable-stayed bridges are governed by the time-dependent material behaviour, including ageing, creep and shrinkage of concrete, and steel relaxation. A design code can be regarded as a summary of experience and local material properties of a certain country or geographical location. Results of analyses using five design codes show that, although different codes give different long-term material properties, the trend of long-term dynamic characteristics is largely independent of the code adopted. An empirical formula with undetermined coefficients is hence proposed to model the long-term development of structural frequencies, which will be useful to engineers conducting structural health monitoring of concrete cable-stayed bridges irrespective of the geographical locations. Moreover, an experiment has been conducted to monitor the long-term development of dynamic properties of post-tensioned concrete beams for verification. The combined effects of time-dependent behaviour and structural damage on the structural frequencies are also investigated.

1. Introduction

Structural health monitoring systems have been used to ensure structural serviceability and provide early warnings of any structural damage. Central to these systems is to detect possible shift of structural properties from the undamaged state. However, the long-term time-dependent behaviour of structural materials also induces changes in structural properties. So it is desirable to investigate the effect of time-dependent behaviour on the long-term variations of dynamic properties and damage detection [1].

Creep and shrinkage affect the performance of concrete structures, causing additional deflections, stress redistribution as well as degeneration of flexural stiffness [2]. So it is important to accurately predict and assess their effects on the long-term structural performance [3]. The time integration method in conjunction with finite element method serves as a reliable tool for time-dependent analysis of concrete structures [4–6]. In this method, concrete components are usually represented as beam, plate or shell elements [6–9]. In order to account for the interaction among concrete creep, concrete shrinkage and cable relaxation accurately, an equivalent creep model for tendons has been proposed by Au and Si [6]. Based on this model, the long-term performance of concrete structures can be predicted accurately taking into account the time-dependent behaviour of concrete and steel tendons.

Although progress has been made in the research on time-dependent behaviour of concrete structures and long-term monitoring has been implemented in some projects [10], the effects of time-dependent behaviour on the dynamic performance of concrete structures have received little attention. The age-adjusted elasticity modulus (AAEM) as a time-dependent tangential modulus was adopted by Sapountzakis and Katsikadelis [11] to investigate the creep and shrinkage effect on dynamic analysis of reinforced concrete slab-and-beam structures, showing that natural frequencies decreased with time. In the long-term observation of dynamic responses of old reinforced concrete structures, Pirner et al. [12] found the downtrend of the fundamental natural frequency of an old chimney probably because of increase of weight due to the increase of moisture or flying ash deposit, and reduction of stiffness as a result of degradation of concrete, concrete creep and cross section weakening by cracking. The study of Esfahani and Behnam [13] showed that the dynamic characteristics of reinforced concrete beams decreased with age of specimen in hot and dry conditions. Xia et al. [14] also showed that the natural frequencies decreased with an increase of in temperature and humidity based on the observation of a laboratory reinforced concrete slab. The authors [1,15] have proposed two systematic methods

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http://dx.doi.org/10.1016/j.engstruct.2013.10.007

to investigate the long-term variations of dynamic properties of cable-stayed bridges considering the effects of concrete ageing, creep and shrinkage, and cable relaxation. Concrete ageing which manifests as increase in elastic modulus plays an important role in the long-term dynamic properties of structures according to these findings. However it should be pointed out that the present analysis does not take into consideration the effects of damage, deterioration and changes of mass due to corrosion, etc. as they are based on totally different mechanisms.

There are several models for creep and shrinkage of concrete around the world, such as CEB-FIP Model Code 1990 (MC 90) [16], British Standard BS 5400 [17], American Code ACI 209 [18], Eurocode BS EN 1992 [19], Chinese Code JTG 2004 [20], etc. They are mainly proposed on the basis of properties of local materials of their respective geographical locations, and hence they may give different estimates of long-term structural performance. This paper aims to develop an empirical model with undetermined coefficients that can cater for different code models for time-dependent behaviour of structural properties. The first part introduces the procedures to investigate the long-term dynamic properties, which include the time integration method for evaluation of the long-term variation of internal forces and the choice of parameters for dynamic analysis. Then various code models are introduced for the subsequent investigations of long-term variations of dynamic properties, which is followed by a detailed numerical study. To verify the trends of variation identified by the numerical study, the long-term dynamic properties of two prestressed concrete beam specimens are presented. Then an empirical formula is proposed and verified using the numerical and experimental results. Finally, the influence of time-dependent behaviour on damage identification is explored by examining a hypothetical damage scenario.

In order to simplify the analysis and focus on the long-term time-dependent behaviour of structural materials, the following assumptions are made:

(a) Mean values of temperature, live load and ambient relative humidity are used.
(b) The instantaneous elastic moduli of cables remain constant.
(c) There is no overloading in the period considered.

2. Time integration method for long-term dynamic characteristics

2.1. Properties of structural components

A reliable time integration method has been developed in conjunction with finite element method to consider the creep and shrinkage development of concrete and the relaxation of prestressing cables [5,6]. The concrete members are usually represented by beam elements and the tendons are idealized as a series of truss elements. Hypothetical rigid arm connections are provided between the beam and truss elements to ensure compatibility. Following the finite element method and neglecting body forces, the incremental load vector of a general spatial concrete beam element $\{\Delta q^e\}_c = [\Delta q_1 \Delta q_2 \ldots \Delta q_{12}]_c^{\mathrm{T}}$ can be obtained as

$$\{\Delta q^e\}_c = [\bar{k}]_c\{\Delta u\}_c + \{\Delta q\}_{\varphi c} + \{\Delta q\}_{cs} \tag{1}$$

in terms of beam stiffness matrix $[\bar{k}]_c$, incremental displacement vector $\{\Delta u\}_c$, incremental load vectors $\{\Delta q\}_{\varphi c}$ and $\{\Delta q\}_{cs}$ due to concrete creep and shrinkage respectively. Using the conventional finite element formulation, the stiffness matrix and the incremental load vectors due to creep and shrinkage can be formulated in terms of the mean modulus of elasticity $\bar{E}_c$ and the corresponding modulus of rigidity of concrete $\bar{G}_c$ taken respectively as

$$\bar{E}_c(t) = \frac{[E_c(t) + E_c(t+\Delta t)]/2}{1 + \varphi_c(t+\Delta t, t)/2} \tag{2}$$

$$\bar{G}_c(t) = \frac{\bar{E}_c(t)}{2(1+\nu_c)} \tag{3}$$

where $E_c(t)$ is the instantaneous modulus of elasticity at time t, Δt is the time interval, $\varphi_c(t + \Delta t, t)$ is the creep coefficient at time $(t + \Delta t)$ for concrete loaded at time t, and ν_c is the Poisson's ratio of concrete.

When a tendon is stretched with the strain kept constant thereafter, the intrinsic relaxation loss depends on the initial prestress σ_{pi} and the stress ratio with respect to the "yield" strength f_{py} or the characteristic strength f_{pk} of the tendon. The loss $\Delta\sigma_{pr}$ can be given either in logarithmic form [21] as

$$\frac{\Delta\sigma_{pr}(t)}{\sigma_{pi}} = -\frac{\log(C_l t)}{B_l}(\mu_l - 0.55) \tag{4}$$

or in exponential form [19] as

$$\frac{\Delta\sigma_{pr}(t)}{\sigma_{pi}} = -C_e \rho_{1000} e^{B_e \mu_e}\left(\frac{t}{1000}\right)^{0.75(1-\mu_e)} \tag{5}$$

where B_l, B_e, C_l and C_e are coefficients related to the tendon types in terms of stress relaxation; $\mu_l = \sigma_{pi}/f_{py}$ and $\mu_e = \sigma_{pi}/f_{pk}$ are stress ratios; and ρ_{1000} is the value of relaxation loss in % at 1000 h after tensioning at a mean temperature of 20 °C. Based on the stress relaxation function above, an equivalent creep model of tendons is developed by Au and Si [6] and the creep coefficients $\bar{\varphi}_s$ at uniform time intervals can be obtained by a step-by-step procedure as

$$\bar{\varphi}_s(\Delta t) = \frac{-\Delta\sigma_{pr}(t_0)}{\sigma_{pi} + \Delta\sigma_{pr}(t_0)/2} \tag{6a}$$

$$\begin{aligned}\bar{\varphi}_s[(k+1)\Delta t] = {} & \frac{\sigma_{pi}\bar{\varphi}_s(k\Delta t)}{\sigma_{pi} + \Delta\sigma_{pr}(t_0)/2} \\ & - \frac{\Delta\sigma_{pr}(t_0 + k\Delta t)[1 + \bar{\varphi}_s(\Delta t)/2] - \Delta\sigma_{pr}(t_0)\bar{\varphi}_s[(k-1)\Delta t]/2}{\sigma_{pi} + \Delta\sigma_{pr}(t_0)/2} \\ & - \frac{\sum_{i=2}^{n} \frac{\Delta\sigma_{pr}[t_0 + (i-1)\Delta t]}{2}\{\bar{\varphi}_s[(k-i+2)\Delta t] - \bar{\varphi}_s[(n-i)\Delta t]\}}{\sigma_{pi} + \Delta\sigma_{pr}(t_0)/2} \\ & (k = 1, 2 \ldots n)\end{aligned} \tag{6b}$$

Based on the equivalent creep model of tendons and following the conventional finite element formulation, the incremental nodal force vector $\{\Delta q^e\}_s = [\Delta q_1 \Delta q_2]_s^{\mathrm{T}}$ of a tendon element for the time interval from t to $(t + \Delta t)$ can be derived as

$$\{\Delta q^e\}_s = [\bar{k}]_s\{\Delta u\}_s + \{\Delta q\}_{\varphi s} \tag{7}$$

in terms of the stiffness matrix $[\bar{k}]_s$, incremental displacement vector $\{\Delta u\}_s$ and incremental load vector due to tendon creep $\{\Delta q\}_{\varphi s}$. Note that the variable t has been omitted for brevity hereafter. The stiffness matrix $[\bar{k}]_s$ is given by

$$[\bar{k}]_s = \frac{\bar{E}_s(\Delta t)A_s}{l_s}\begin{bmatrix} 1 & -1 \\ -1 & 1 \end{bmatrix} \tag{8}$$

where A_s is cross sectional area, l_s is the length of tendon element, and $\bar{E}_s(\Delta t)$ is the mean modulus of elasticity over the time interval Δt taking into account stress relaxation, which can be expressed in terms of the modulus of elasticity of the steel tendon E_s as

$$\bar{E}_s(\Delta t) = \frac{E_s}{1 + \bar{\varphi}_s(\Delta t)} \tag{9}$$