Composites Part B 86 (2016) 261–272

Contents lists available at ScienceDirect

Composites Part B

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

Structural behaviour evolution of composite steel-concrete curved structure with uncertain creep and shrinkage effects

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ARTICLE INFO

Article history:
Received 4 June 2015
Received in revised form
13 August 2015
Accepted 6 October 2015
Available online 21 October 2015

Keywords:
A. Hybrid
B. Creep
B. Physical properties
C. Finite element analysis (FEA)
Time-dependent uncertainty analysis

ABSTRACT

This paper presents a new computational scheme to robustly determine the structural behaviour (both serviceability and strength) of composite concrete-filled steel tubular (CFST) arch with consideration of uncertain creep and shrinkage effects. The focused uncertainties in this study originate from the intrinsic viscoelastic effects of concrete, which inevitably affect the structural performance of CFST arch through its service life. Due to the diverse variations and intricate nature of creep and shrinkage observed in engineering practices, it is advisable that the two mercurial parameters are modelled as uncertain-but-bounded variables. The effects of uncertain creep and shrinkage on the long-term structural behaviour are investigated such that the worst and best scenarios of structural responses at each specific loading time can be precisely calculated. The proposed computational method competently determines the bounded structural responses at any specific loading time such that, evolutions of structural behaviours of CFST arch can be quantitatively constructed for the purpose of safety assessment. Numbers of often encountered engineering examples are investigated to illustrate the capability, credibility and efficiency of the proposed approach.

1. Introduction

Concrete-filled steel tubular (CFST) arch is a type of modern composite steel-concrete curved structures which has been extensively implemented in contemporary bridge engineering [1–3]. The stimulation of high demand of such composite structure comes from the remarkable advantages such as, high strength with relatively light weight, excellent compressive strength with enhanced ductility and flexural properties, efficient construction without additional steel frameworks, and economical friendly with complimentary appearance [4,5]. Therefore, the successful implementation of composite CFST arch has once again illustrated the widespread applications and innovative technologies of composite materials.

However, alike many other composite materials, side-effects do occur in the employment of such materials in engineering applications, whose influences could be very dramatic and situational dependent. This also includes the CFST arch. Due to the intrinsic properties of concrete, viscoelastic effects, in particular creep and shrinkage, constantly deteriorate the mechanical performance of concrete involved engineering structures through designed service lives [6–11]. Consequently, such time-dependent, inevitable, and intricate phenomenon motivates the continuous development of structural deformation and stress when the structure is subjected to sustained loadings [12–16]. By inspecting both previous experimental and analytical works, the impacts of the inherent creep and shrinkage on the overall structural performance are arbitrarily severe [6–11], and failure in assessing such effects of uncertainties could jeopardise the safety of engineering structures [17–21] by compromising the structural performance [22–26].

Regarding to the uncertainty analysis on creep and shrinkage of various composite materials, extensive amount of research works have been conducted to investigate the mercurial and unfavourable effects on the mechanical performance of various engineering structures. Madsen and Bažant [6] have identified some noticeable uncertainties related to creep and shrinkage process, and then proposed a practical probabilistic approach for analysing the effects of uncertain creep and shrinkage acting on various structural elements. The Latin Hypercube sampling method has been adopted by Xi and Bažant [27] to statistically evaluate the creep and shrinkage responses of structures, as well as the uncertain impacts of these time-dependent variables on the structural deflection and stress.

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http://dx.doi.org/10.1016/j.compositesb.2015.10.004
1359-8368/

Also, Li [28] proposed both simulation and analytical approach to predict the time-dependent serviceability of simple reinforced concrete beams involving probabilistic creep and shrinkage effects subjected to random loadings. Moreover, Stewart [29] proposed a probabilistic method to calculate the deflections of reinforced concrete structures with the consideration of random creep and shrinkage effects. Furthermore, Choi et al. [30] presented a Monte-Carlo Simulation based sampling technique to calculate the immediate and long-term deflections of reinforced concrete beams and slabs with random creep and shrinkage effects. Yang [31] adopted the Bayesian statistical inference approach to investigate the uncertain creep and shrinkage effects for the prestressed concrete box girder bridges. Ma and Wang [32] implemented the Monte-Carlo and Latin Hypercube sampling methods to investigate the reliability of CFST arch bridge accounting the random creep effects. In addition to the acknowledgement of uncertain creep and shrinkage effects in the composite steel-concrete structures, such uncertain viscoelastic effects have also been investigated in other composite materials [33]. For that reason, the impacts of such uncertain viscoelastic effects of composite CFST structures must be accommodated and thoroughly investigated in real-life engineering applications.

Even though considerable amount of work has been conducted to investigate the uncertain viscoelastic effects on general concrete structures, robust life-time performance assessments of CFST structures with consideration of uncertain time-dependent creep and shrinkage effects still need thorough exploration. In this paper, a novel computation-orientated scheme is developed for assessing the long-term serviceability and strength of composite CFST arch with accommodation of uncertain time-dependent creep and shrinkage effects. Due to the insufficiency of experimental data, as well as the large arbitrariness and inconsistency observed in the reported experimental works [34–36], it will be extremely challenging to accurately model the uncertain parameters in a probabilistic format for reliable and un-biased statistical analysis. Hence, the uncertainties of creep and shrinkage of the concrete core are modelled by the interval approach instead. Unlike the probabilistic approaches, the implemented uncertainty model merely requires the boundary information (i.e., upper and lower bounds) of the uncertain parameters. Such relaxation on the data requirement for uncertainty analysis has provided flexibility on uncertainty modelling, but at the same time, stimulated the possibility of valid uncertainty analysis. Consequently, the proposed time-dependent uncertain structural behaviour analysis is capable to assess the serviceability and strength of composite CFST arch by calculating the deformation and internal forces at any loading time during the service life. The developed scheme has the ability to rigorously establish long-term structural behaviour evolutions, which rigorously outline the predictions on the structural serviceability and strength, for CFST arch implicated by uncertain time-dependent viscoelastic effects.

This paper is organized as follows. Section 2 concentrates on the investigation of long-term structural serviceability analysis of CFST arch involving uncertain creep and shrinkage effects. The adopted models for such uncertain viscoelastic effects are introduced in prior such that the structural serviceability and strength analysis with uncertain creep and shrinkage are developed within the scheme of finite element method. After that, an alternative finite element (FE) formulation of linear analysis for CFST arch considering the impact of uncertain creep and shrinkage is presented. Moreover, detailed formulations of the proposed computational approach are presented in the final part of Section 2. Numbers of practically motivated examples are presented in Section 3 to illustrate the accuracy, computational efficiency, as well as the applicability of the proposed computational scheme. Furthermore, the Monte-Carlo Simulation (MCS), as a global search method, is implemented to verify the accuracy of the proposed methods into certain extent. Finally, some concluding remarks are summarized in Section 4.

2. Uncertain time-dependent structural serviceability and strength analysis of CFST arch

2.1. Uncertain time-dependent creep and shrinkage effects via interval approach

Among diverse well-established material models for analysing creep and shrinkage effects, the adopted model for this paper is the one suggested in both ACI Committee 209 [37] and Australian design standards AS3600 [38].

The deterministic material model in ACI Committee 209 and AS3600 specifies the deterministic creep coefficient $\tilde{\phi}$ as:

$$\tilde{\phi}(t,t_0) = \left[\frac{(t-t_0)^{0.6}}{10+(t-t_0)^{0.6}}\right]\tilde{\phi}_u \tag{1}$$

where t is the loading time measured in days; t_0 is the age of concrete at first loading (days); $\tilde{\phi}_u$ is the deterministic final creep coefficient when $t \to \infty$. Regarding to this study, a $t_0 = 15$ days is adopted. By further implementing the relationship on $\tilde{\phi}_u$, which was suggested in ACI Committee 209 [37] and Gilbert [39], the deterministic final creep coefficient $\tilde{\phi}_u$ can be alternatively expressed as:

$$\tilde{\phi}_u = 1.25 t_0^{-0.118}\tilde{\phi}_{\infty,7} \tag{2}$$

where $\tilde{\phi}_{\infty,7}$ is the deterministic final creep coefficient when the concrete is firstly loaded in the 7*th* day.

Therefore, by substituting Eq. (2) into Eq. (1), the nominal creep coefficient at any time t can be expressed as:

$$\tilde{\phi}(t,t_0) = 1.25 t_0^{-0.118}\left[\frac{(t-t_0)^{0.6}}{10+(t-t_0)^{0.6}}\right]\tilde{\phi}_{\infty,7} \tag{3}$$

On the other hand, the deterministic shrinkage strain, $\tilde{\varepsilon}_{sh}$, of the concrete is formulated as [37,39]:

$$\tilde{\varepsilon}_{sh}(t) = \left(\frac{t}{t+d_0}\right)\tilde{\varepsilon}^*_{sh} \tag{4}$$

where $\tilde{\varepsilon}^*_{sh}$ is the nominal final shrinkage strain and $d_0 = 35$ days for moist cured concrete.

It is assumed in this study that the uncertainties of creep coefficient and final shrinkage strain are independent for each element of CFST arch, and also there is no correlation between the uncertain creep coefficient and final shrinkage strain for the same CFST element. Therefore, for a CFST arch consisting of n elements, the uncertain creep coefficient and final shrinkage strain vectors are expressed respectively as:

$$\boldsymbol{\varphi}_{\infty,7} \in \boldsymbol{\Phi}_{\infty,7} = \left\{\boldsymbol{\varphi}_{\infty,7} \in \Re^n \middle| \underline{\phi^i_{\infty,7}} \le \phi^i_{\infty,7} \le \overline{\phi^i_{\infty,7}}, \quad i = 1\ldots n\right\} \tag{5}$$

$$\boldsymbol{\varepsilon}^*_{sh} \in \boldsymbol{\Psi}_{sh} = \left\{\boldsymbol{\varepsilon}^*_{sh} \in \Re^n \middle| \underline{\varepsilon^{*i}_{sh}} \le \varepsilon^{*i}_{sh} \le \overline{\varepsilon^{*i}_{sh}}, \quad i = 1\ldots n\right\} \tag{6}$$

where $\boldsymbol{\varphi}_{\infty,7}$ and $\boldsymbol{\varepsilon}^*_{sh}$ denote the uncertain creep coefficient and final shrinkage strain vectors respectively; $\boldsymbol{\Phi}_{\infty,7}$ and $\boldsymbol{\Psi}_{sh}$ denote the