Engineering Structures 100 (2015) 308–325

Contents lists available at ScienceDirect

Engineering Structures

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

Strength and ductility performance of concrete-filled steel tubular columns after long-term service loading

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ARTICLE INFO

Article history:
Received 6 February 2015
Revised 23 April 2015
Accepted 12 June 2015
Available online 25 June 2015

Keywords:
Concrete-filled steel tubular columns
Long-term service loading
Creep
Stress–strain relationship
Strength
Ductility

ABSTRACT

Concrete-filled steel tubular (CFST) columns are widely used in infrastructure applications and thus usually are subject to long-term service loading. However, understanding the influence of sustained loading on the ultimate performance of these structural members is still lacking. The objective of this work is to develop a constitutive model to account for strength and ductility change of CFST columns under sustained loading, validated by experimental data reported in the literature.

In this framework, a simplified analytical method equipped with a monolithic iterative scheme is developed to efficiently estimate the creep deformation of these composite columns at any designated target time. Based on the calculated creep status, an analytical stress–strain curve is proposed to characterize the post-creep mechanical behavior of steel-confined concrete. This stress–strain behavior incorporates the combined effects of enhanced compressive strength of plain concrete and reduced confining strength provided by steel tube, both of which are caused by sustained load. Finite element based numerical study together with the available test database are used to validate the mechanical analysis and to assess the performance of the proposed constitutive model. The predicted post-creep response is found to be in good agreement with the experimental results for CFST columns with circular and square cross-sections. Finally, an extensive parametric study based on a pushover analysis is conducted to examine the influence of individual critical design parameters on structural ultimate strength and ductility due to long-term service loading.

1. Introduction

During the past few decades, concrete-filled steel tubular (CFST) columns have been increasingly used in a wide variety of structural engineering applications, particularly in bridges and high-rise buildings. The popularity of CFST columns can be attributed to their superior structural properties (e.g. high strength and ductility, good fire resistance, and large energy absorption capacity), resulting from the combined action of the composite constituent materials (steel and concrete). The steel tube serves as longitudinal and transverse reinforcement offering confining pressure to the concrete infill. On the other hand, the concrete core can stabilize and stiffen the surrounding steel tube in the sense that the local buckling of the steel tube is prevented or at least delayed. Furthermore, this type of structural member has proven to reduce the labor and material cost during the construction process since external steel tubes can act as integral and permanent formworks. The behavior of CFST columns under short-term loading has been investigated in depth and well addressed by existing design codes. The related studies include Furlong [1], Neogi et al. [2], Knowles and Park [3], Ghosh [4], Rangan and Joyce [5], Ge and Usami [6], Fujinaga et al. [7], Schneider [8], Han et al. [9], Huang et al. [10], Sakino et al. [11], Elremaily and Azizinamini [12], and Wheeler and Bridge [13], to name just a few.

In permanent structures and facilities, CFST columns are usually subjected to long-term service loads before ultimate failure is experienced. Compared with the short-term deformation of CFST columns, the creep and shrinkage of concrete core and its interaction with the surrounding steel tube produce great uncertainties on the ultimate response of CFST columns with long-term service loading applied. A few investigations, including both theoretical and experimental ones, were carried out in order to study the creep and shrinkage behavior of CFST columns, e.g. Morino et al. [14], Uy [15], Naguib and Mirmiran [16], Ma and Wang [17], Gunnarsson et al. [18]. It was found that shrinkage strain in CFST columns was very small or totally eliminated due to the prevention of moisture egress in a sealed environment [19,20]. In addition, the stress

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http://dx.doi.org/10.1016/j.engstruct.2015.06.024
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redistribution between the concrete core and steel tube could reduce the creep strain of concrete to some extent [21].

Compared with the research on the time-dependent creep and shrinkage behavior of CFST columns, models that describe the ultimate mechanical performance of CFST columns after long-term service load remain relatively undeveloped. According to the pioneering experimental study conducted by Han et al. [9] and Wang et al. [22], the circular and square CFST column specimens under sustained load showed increase of up to 20% in load-bearing capacities when compared with their companion load-free specimens. However, an opposite trend, i.e. reduction in load-carrying capacity, has also been reported by other researchers, e.g. Wang et al. [23]. It is still an open question [24] to explain such divergent changes in structural strength. Aside from the unclear mechanism, the lack of understanding of the potential influence of long-term service loading on structural deformation capacity (i.e. ductility) also underlines the necessity to conduct further research on this important, but generally neglected topic.

This paper is devoted to exploring the mechanism underlying the experimentally observed strength and ductility change of CFST columns after long-term service loading. The remainder of the paper is organized as follows. In Section 2, we establish a framework for efficient evaluation of creep strain of CFST columns at any designated target time, imperative for the long-term failure analysis of CFST columns. In this framework, the efficiency of creep analysis is considerably enhanced by a monolithic iterative scheme. In Section 3, we show that the post-creep mechanical behavior of CFST columns depends on the combined action of enhanced compressive strength of plain concrete and residual creep deformation. A uniaxial constitutive model, incorporating the aforementioned effects brought about by long-term service load, is proposed for steel-confined concrete core with both circular and square cross-sections. Section 4 reports a finite element based numerical study on the effect of creep deformation on the confining strength, which serves to validate the mechanical analysis presented in Section 3. In Section 5, we further apply the proposed stress–strain relation to fiber element analysis where the nonlinear behavior of CFST columns under compression is investigated. By comparison with the available experimental data, our model is found to perform well for both the circular and square CFST members. In Section 6, the validated post-creep constitutive model is used for pushover analysis of CFST columns with long-term service load applied. A parametric study is conducted to examine the influence of critical design parameters on the post-creep ultimate strength and ductility of CFST column members subjected to combined compression and bending loads. Final concluding remarks are given in Section 7.

2. Creep analysis of CFST columns

The creep deformation analysis of CFST columns includes two main ingredients, i.e. the initial short-term elastic analysis and the subsequent long-term creep analysis. The focus in this paper is on perfectly bonded composite columns, in which the concrete core and steel tube sustain the axial load together. The combined effects of concrete creep, lateral confinement provided by the steel tube, and stress redistribution induced by geometric compatibility (see Fig. 1) make the deformation of CFST columns under sustained load a complex time-dependent process. Following the framework proposed by Naguib and Mirmiran [16], we establish hereinafter a predictive model with all aforementioned effects considered for the efficient assessment of creep deformation of CFST columns at any designated target time. However, and in contrast to the previously proposed framework [16], the creep strain of CFST columns at any target time can be conveniently obtained through a simplified design method without repeating the complicated iterative algorithm for each loading increment of the whole duration. In other words, only one iterative process is needed for predicting the final status of creep. Another novel contribution of our model is that a monolithic iterative scheme is developed instead of the staggered one used in [16] to achieve better convergence of creep iterations.

2.1. Creep model for confined concrete

The mechanical behavior of confined concrete is considerably different from that of plain concrete, due to the sealed wrapping, variable stress history, and multi-axial stress status caused by the steel tube confinement. Without loss of generality, we adopt the B3 model, developed by Bažant and Baweja [25], in the creep analysis of confined concrete, considering that the B3 model is simple yet well justified. Any other creep model, such as the CEB model [26], the ACI 209 model [27] or the B4 model [28,29] introduced very recently, can equally be employed in our framework. Although full details of the B3 model can be found in Bažant and Baweja [25], a brief description with the relevant equations is provided for clarity.

Since the moisture migration of the concrete core is prevented by the surrounding steel tube [30], we neglect the drying creep and shrinkage strain of the concrete infill in our study. Furthermore, the concrete creep together with the deformation compatibility can change the stress distribution between the concrete core and the steel tube of CFST columns even though a fixed load is applied. Thus the varying stress history in concrete should be taken into account.

The total strain $\varepsilon(t)$ of a concrete member subjected to a uniaxial stress $\sigma(t)$ can be calculated as follows:

$$\varepsilon(t) = \int_0^t J(t, t_0)\, d\sigma(t_0) \tag{1}$$

with the creep compliance function $J(t, t_0)$ representing the total strain at target time t due to a unit constant stress applied at age t_0. According to the B3 model, the compliance function $J(t, t_0)$ can be expressed as

$$J(t, t_0) = q_1 + C_0(t, t_0) + C_d(t, t_0, t_d) \tag{2}$$

where q_1 is the instantaneous elastic strain due to the unit stress and $C_0(t, t_0)$ the basic creep compliance. $C_d(t, t_0, t_d)$ denotes the additional compliance function for drying creep which started at age t_d and has been neglected as stated above. Then the compliance function can be further expanded as

$$J(t, t_0) = q_1 + q_2 Q(t, t_0) + q_3 \ln\left[1 + (t - t_0)^n\right] + q_4 \ln\left(\frac{t}{t_0}\right) \tag{3}$$

where q_2, q_3, and q_4 are empirical constitutive parameters; $Q(t, t_0)$ can be easily obtained either from an approximate explicit formula or by numerical integration, such as those given in [25]; n is an empirical parameter whose value can be taken as 0.1 for all normal concrete types.

In practice, the total integrated strain given in Eq. (1) can be approximated by a sum of strains caused by small stress increments applied at all time intervals, that is

$$\varepsilon(t_n) \approx \sum_{i=1}^{n} \frac{1}{2}[J(t_n, t_i) + J(t_n, t_{i-1})]\Delta\sigma(t_i) \tag{4}$$

where the subscripts n and i denote total and individual time steps, respectively.

In Eqs. (1) and (4), the salient feature of confined concrete, namely the status of triaxial stresses, is not reflected. According to the study of Gopalakrishnan et al. [31], creep strains of concrete