Composites Part B 157 (2019) 173–181

Contents lists available at ScienceDirect

Composites Part B

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

Effect of concrete creep on dynamic stability behavior of slender concrete-filled steel tubular column

Y.Q. Huang[a], J.Y. Fu[a,*], A.R. Liu[a], Y.L. Pi[a,b], D. Wu[a,b], W. Gao[a]

[a] Centre for Engineering Structure Disaster Prevention and Control, Guangzhou University, Guangzhou 510006, China

[b] Centre for Infrastructure Engineering and Safety (CIES), School of Civil and Environmental Engineering, The University of New South Wales Sydney, NSW 2052, Australia

ARTICLE INFO

Keywords:
Slender concrete-filled steel tube column
Dynamic stability
Time analysis
Age-adjusted effective modulus method
Bolotin's method

ABSTRACT

An analytical procedure for dynamic stability of CFST column accounting for the creep of concrete core is proposed. The long-term effect of creep of concrete core is formulated based on the creep model by the ACI 209 committee and the age-adjusted effective modulus method (AEMM). The equations of boundary frequencies accounting for the effects of concrete creep are derived by the Bolotin's theory and solved as a quadratic eigenvalue problem. The effectiveness of the proposed method and the characteristics of time-varying distribution of instability regions are numerically surveyed. It is shown that the CFST column becomes dynamically unstable even when the sum of the sustained static load and the amplitude of the dynamic excitation is much lower than the static instability load. It is also found that due to the time effects of concrete creep under the sustained static load, the same excitation, that cannot induce dynamic instability in the early stage of sustained loading, can induce the dynamic instability in a few days later. The critical amplitude and frequency of the dynamic excitation can decrease by 6% and 3% in 5 days, and 11% and 6% in 100 days.

1. Introduction

Steel hollow sections are very efficient in resisting compression forces, and filling these sections with concrete greatly enhances the load-carrying capacity [1,2]. The concrete-filled steel tubular (CFST) structure possesses many mechanic benefits, such as high strength and fire resistances, favorable ductility and large energy absorption capacities, so the CFST members are widely used in modern structures [3]. Moreover, with the advancement in the strength resistance and construction techniques of CFST column, slender CFST columns are frequently adopted to support the roofs of industrial plants, the decks of railways and the floors of multistory buildings [4].

It is known when a slender column is subject to an axial compression, it could fail owing to lateral instability [5]. The instability of slender CFST columns under axial static compression has been experimentally and numerically studied by many researchers [4,6–8]. These studies have shown that slender CFST columns are prone to global buckling under static loading. In addition to the static loading, the service loads of slender CFST members also involve the dynamic loading. For example, the slender CFST piers in modern bridges are subject to the dynamic vehicle loading, and the high CFST pillars supporting large span roofs are loaded by dynamic wind loading. The behavior of CFST columns subjected to cycles of compressive loading has also been reported by many researchers [9–11]. Under a sustained centric axial static load, the concrete core of a CFST column creeps with the time and the creep of the concrete core may change the lateral stiffness and the lateral natural frequency of the CFST column significantly. If the column under the sustained load is further excited by an axial dynamic excitation at some stage, the column may suddenly lose its stability laterally due to dynamic resonance when certain relationships between the frequency of excitation and the natural frequency of the column are satisfied and the amplitudes of the excitation are sufficiently high. Because the creep of the concrete core develops with the time and changes the lateral natural frequency, the relationships between the frequency of the excitation and the natural frequency of the column and the required amplitude of the excitation inducing the dynamic instability of the CFST column may change greatly with the time. Such dynamic instability may occur even when the sum of the amplitude of the excitation and the sustained static load is much smaller than the static instability load of the column.

Meanwhile, the engineering structures are commonly subject to sustained static loads and sudden dynamic excitations [12,13]. Since the mechanical property of the concrete core is time-dependent due to creep when it is under a sustained load, the dynamic stability of a CFST

* Corresponding author.
E-mail address: jiyangfu@gzhu.edu.cn (J.Y. Fu).

https://doi.org/10.1016/j.compositesb.2018.08.117
Received 1 July 2018; Accepted 23 August 2018
Available online 27 August 2018
1359-8368/

column under dynamic excitation would be affected by the loading time difference between the first static loading and the dynamic excitation. However, there is no knowledge about how the creep of the concrete core influences the dynamic stability of a CFST column available in the literature hitherto. To ensure that CFST columns under sustained static loads and sudden dynamic excitations do not suddenly lost their stability, it is much needed to investigate the effects of the creep of the concrete core on the dynamic stability of CFST columns.

This study, therefore, is devoted to establishing an analytical procedure for the time-dependent dynamic stability analysis of slender CFST columns accounting for the creep of the concrete core. The column under a sustained static load and suddenly subjected to a dynamic excitation is considered. The age-adjusted effective modulus method (AEMM) is used to describe the effect of the creep on the effective modulus of the concrete and the time-dependent model of concrete creep of the ACI committee 209 [14] is adopted in the investigation. Based on these, the differential equation of lateral motion of the CFST column under the dynamic excitation is derived. The equations of boundary frequencies are then established by the Bolotin's method and they are solved to determine the boundaries of regions of dynamic instability. Finally, the effectiveness of the proposed method and the characteristics of time-dependent dynamic stability of CFST columns accounting for the creep of the concrete core are discussed by elaborate numerical examinations.

2. Creep of concrete core under sustained static load

The aging property of the concrete was firstly noticed about 110 years ago, and a large amount of literature have been concentrated on this subject, such as the books by Bazant [5], Neville [15] and Gilbert [16]. The final total strain of the concrete at time infinity could be several times the initially instantaneous strain, so the analysis overlooking the time effect might extraordinarily underestimate the load effect in the concrete or concrete-composite structures [17–19]. The gradual development of strains in the sustained loaded concrete is due to the creep and shrinkage of the concrete [16]. The creep and shrinkage strains of CFST columns with various cross-sectional shapes and concrete types were widely tested [20–22] and numerically computed [23–25]. It was found that the shrinkage of the concrete in CFST columns is very small and negligible owing to the prevention of moisture egress in a seated environment [25,26].

This study assumes that the CFST column is under a centric axial sustained static load for some time and then is suddenly subjected to a centric axial dynamic excitation for a short period. Under the sustained axial load, the effective modulus of the concrete changes with the time due to the creep of the concrete core. The age-adjusted effective modulus method [27] is adopted in this investigation. According to the method, the effective modulus of concrete E_{ec} at the time t_1 is given by

$$E_{ec}(t_1, \tau_0) = \frac{E_c(\tau_0)}{1 + \chi(t_1, \tau_0)\varphi(t_1, \tau_0)} \tag{1}$$

where $E_c(\tau_0)$ represents the elastic modulus of concrete at the time τ_0 of first loading; $\varphi(t_1,\tau_0)$ is the creep coefficient and $\chi(t_1,\tau_0)$ is the aging coefficient.

The time-related creep coefficient $\varphi(t_1,\tau_0)$ can be determined according to the long-term model proposed by the ACI committee 209 [14].

$$\varphi(t_1, \tau_0) = \frac{(t_1 - \tau_0)^{0.6}}{10 + (t_1 - \tau_0)^{0.6}}\varphi^*(\tau_0) \tag{2}$$

where $(t_1\text{-}\tau_0)$ denotes the duration of loading (in days); $\varphi^*(\tau_0)$ is the final creep coefficient. According to the existing creep test results [21,28], the final creep coefficient $\varphi^* = 2.29$ is used here.

Additionally, the aging coefficient $\chi(t_1,\tau_0)$ can be computed by the empirical expression [16,29].

$$\chi\left(t_1, \tau_0\right) = 1 - \frac{(1 - \chi^*)(t_1 - \tau_0)}{20 + t_1 - \tau_0} \tag{3}$$

where χ^* is the final aging coefficient

$$\chi^* = \frac{k_1\tau_0}{k_2 + \tau_0} \tag{4}$$

with

$$k_1 = 0.78 + 0.4e^{-1.33\varphi^*(\tau_0)} \text{ and } k_2 = 0.16 + 0.8e^{-1.33\varphi^*(\tau_0)} \tag{5}$$

Therefore, for a CFST column under sustained static loading from the time τ_0, when the column is dynamically excited at the time t_1, the effective modulus of concrete at time t_1 can be computed by Eqs. (1)–(5) for the dynamic stability analysis of the CFST column under a dynamic excitation starting at the time t_1.

3. Dynamic stability analysis accounting for creep of concrete core

3.1. Governing equation of dynamic stability

A simply-supported CFST column is initially subjected to a sustained axial concentric static load P_0 from the time τ_0 and then subjected to an additional dynamical excitation from a time t_1 ($t_1 > \tau_0$), as shown in Fig. 1. Without loss of generality, the dynamic excitation is considered as a harmonic type excitation $P(t) = P_0 + P_t \cos\theta t$ with the period $T = 2\pi/\theta$, where P_0 is the sustained static load, and P_t and θ denote the amplitude and circular frequency of dynamic excitations.

For a straight column subject to an axial excitation, it would vibrate in the axial direction. However, when certain relationships between the frequency and amplitude of the excitation and the lateral natural frequency of the column are satisfied, the column may suddenly vibrate laterally and lose its stability in a dynamic resonance instability mode [30–34]. The initial and deformed configurations of CFST column during dynamic instability is shown in Fig. 1a. The length of column is L, and the lateral displacement of column is represented by $u(x,t)$, where t is the time and x is the coordinate along the length of column. The cross section of column consisted of a steel tube and a concrete core is shown in Fig. 1b.

Forces acting on the infinitesimal element dx in the deformed position of the column are shown in Fig. 1c. These forces include the inertia force $m_e\partial^2u/\partial t^2$ and the viscous damping force $c(x)\partial u/\partial t$, where m_e is the equivalent mass per unit length of the column and $c(x)$ is a damping constant; the axial force N, the shear force V and the moment M at the bottom of the element; and the axial force $N+(\partial N/\partial x)\mathrm{d}x$, the shear force $V+(\partial V/\partial x)\mathrm{d}x$, and the moment $M+(\partial M/\partial x)\mathrm{d}x$ on the top of the element. The inertial moment caused by the angular acceleration of the element is neglected.

The following assumptions are adopted for the dynamic stability analysis of CFST columns [28,35,36]: (1) the size of the cross section of the CFST column is much smaller than the length of the column such that the column is sufficiently slender; (2) oscillation of CFST column is small and the deformation is linearly elastic, which satisfies the Euler-Bernoulli hypothesis on that the cross section remains plane and perpendicular to the column axis during deformation; (3) the concrete core and the steel tube of the CFST column are fully bonded; and (4) the flexural stiffness of the CFST column is regarded as constant along the CFST column. Because the axial rigidity of the CFST column is much higher than its lateral rigidity, the influence of the axial vibration on the lateral vibration is negligible and the internal axial force is equal to the sum of the sustained static load and the external axial excitation.

Based on the assumptions, considering the forces acting on the infinitesimal element shown in Fig. 1, the equation of motion for the column be derived as