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Creep effects on dynamic behavior of concrete filled steel tube arch bridge

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Abstract. Long-term properties of concrete affect structures in many respects, not excepting dynamic behaviors. This paper investigates the influence of concrete creep on the dynamic behaviors of concrete filled steel tube (CFT) arch bridges, by means of combining the analytical method for the creep of axially compressed CFT members, which is based on Model B3 for concrete creep, with the finite element model of CFT arch bridges. By this approach, the changes of the stress and strain of each element in the bridge with time can be obtained and then transformed into damping and stiffness matrices in the dynamic equation involved in the finite element model at different times. A numerical example of a long-span half-through CFT arch bridge shows that creep influences the natural vibration characteristics and seismic responses of the bridge considerably, especially in the early age. In addition, parameter analysis demonstrates that concrete composition, compressive strength and steel ratio have an obvious effect on the seismic response of the CFT arch bridge.

Keywords: creep; dynamic analysis; concrete filled steel tube; arch bridge; finite element model.

1. Introduction

With competitive advantages of favorable mechanical properties, construction efficiency, aesthetic shapes as well as good adaptability to various spans, concrete filled steel tube (CFT) arch bridges have gotten a wide application in many countries (Zhong 2003). During the past two decades, more than three hundred CFT arch bridges have been built or are under construction in China (Chen 2007). Thus, particular attention has been paid to their dynamic behaviors, including the natural vibration characteristics and seismic responses of CFT arch bridges under longitudinal and transverse earthquake waves, as reviewed by Wen and Wang (2006), as well as their dynamic responses under automobile loads (Wang and Xu 2001). For a large span bridge, its dynamic response analysis should be carried out based on the configuration under static loads. However, most of the existing dynamic studies only consider the short-term effects of static loads, ignoring the long-term effects such as creep.

In fact, creep has considerable influences on statically indeterminate concrete structures (Neville 2002) and composite structures (Zhong 2003). As regards the influence of creep on structural dynamic behaviors, Sapountzakis and Katsikadelis (2003) have demonstrated that the

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eigenfrequencies of reinforced concrete slab-and-beam structures are decreased with time, and that the maximum deflections at the center of a stiffened plate under forced vibrations at the age of 1000 days is 2.05 times greater than that at the age of 30 days. The similar predominant actions of creep have also been verified for reinforced concrete slabs stiffened by steel beams with deformable connections by Sapountzakis (2004).

For CFT arch bridges, creep will cause additional deflections as well as redistributions of internal force and rigidity (Wang *et al.* 2007, Starossek *et al.* 2010), therefore, affect the dynamic properties and structural responses under seismic loads. As creep effects of CFT arch bridges with long span are obvious to such an extent that the deflection at mid-span could increase by 36.7% after one year, the moment at mid-span of ribs could increase by about 25% and creep could raise the stress in steel tubes by about 5-27%, while decrease that in concrete cores by about 20-52% generally (Wang *et al*. 2008), the influence of creep on the dynamic response of CFT arch bridges should be considered reasonably. At present, only Zhou and Wang (2006) analyzed the dynamic behavior of CFT arch bridge considering the creep effect of concrete, demonstrating the creep behavior has an obvious influence on its dynamic responses. However, their model can not analyze the effect of concrete composition and compressive strength on the dynamic behavior, which affect the concrete creep significantly.

In this paper, the dynamic behavior of CFT arch bridges under the earthquake waves, taking the creep effect into account, is investigated by combining the analytical method for the creep of axially compressed CFT members, which is based on Model B3 for concrete creep, with the finite element model of CFT arch bridges to obtain the changes of the stress and strain of each element in CFT bridges with time, and transforming the changes into damping and stiffness matrices in the dynamic equation involved in the finite element model of bridges at different times. The solution to the seismic response considering creep effect of a half-through long-span CFT arch bridge is presented as a practical application. The influences of water/cement ratio (w/c), aggregate/cement ratio (a/c) and compressive strength (f_c) of concrete and steel ratio (α), which affect the creep of CFT members, on the seismic response of this bridge are also analyzed.

2. Dynamic analysis of CFT arch bridges considering creep effect

2.1 Creep model for concrete

For predicting the concrete creep, Model B3 (Bazant 1995a), taking various parameters such as composition and compressive strength of concrete and environmental relative humility into account, has gotten wide applications. An important advantage of Model B3 is that all the free parameters for creep with elastic deformation are contained in the formulas linearly. Therefore, linear regression based on the least-square method can be used to identify these parameters from test data, so as to minimize the coefficient of variation of the deviations of the model from available data (Bazant 1995b). The accuracy of Model B3 has been verified by comparing its predicted results against the RILEM data bank and the results calculated by ACI 209 model, CEB 90 model and GL 2000 model (Lam 2002, Rajeev *et al*. 2007).

For CFT members, the concrete core only has basic creep, which can be calculated by Model B3 as

$$C_0(t,t') = q_2 Q(t,t') + q_3 \ln[1+(t-t')^n] + q_4 \ln\left(\frac{t}{t'}\right) \quad (1)$$

where $C_0(t, t')$ = compliance function for basic creep (10^{-6}/MPa); q_2, q_3, and q_4 = aging viscoelastic compliance, non-aging viscoelastic compliance, and flow compliance concerning the composition and strength of concrete respectively, as deduced from the solidification theory; $Q(t,t')$ = a function concerning the age at loading; t = target time, representing the age of concrete (d); t' = age at loading (d); n = empirical parameter.

2.2 Creep analysis of axially compressed CFT members

Stress redistribution occurs on the cross-sections of CFT members even under the constant axial loads during the creep process. As there is no additional external force, the increments of axial force in the concrete core and steel tube of a CFT member satisfy the following formula (Han and Wang 2001, 2004, Wang and Han 1999, Wang 2006)

$$N_c^c + N_s^c = 0 \quad (2)$$

where N_c^c, N_s^c = increments of axial forces in the concrete core and steel tube due to creep respectively. Neglecting the radial and hoop stresses in the concrete core and steel tube, Eq. (2) can be written as

$$\sigma_c^c A_c + \sigma_s^c A_s = 0 \quad (3)$$

where σ_c^c, σ_s^c = axial stress increments of the concrete core and steel tube due to creep respectively; A_c, A_s = sectional areas of the concrete core and steel tube respectively. Note that

$$\varepsilon_s^c = \frac{\sigma_s^c}{E_s} \quad (4)$$

where ε_s^c = axial strain increment of the steel tube due to creep; and E_s = elastic modulus of the steel. Therefore, the axial stress increment of the concrete core can be calculated as

$$\sigma_c^c = -\alpha\sigma_s^c = -\alpha E_s \varepsilon_s^c \quad (5)$$

in which

$$\alpha = A_s/A_c \quad (6)$$

Creep is assumed to be dependent linearly on stress as the arch rib is within the service stress range. For a small time interval $t' - t$, the stress increment in the concrete core $\sigma_c^c(t,t')$ can be considered to be constant, which means the creep strain of the concrete core at age t is

$$\varepsilon_c^c(t,t') = [\sigma_c^0(t') + \sigma_c^c(t,t')]C_0(t,t') \quad (7)$$

where $\sigma_c^0(t')$ = initial axial stress in the concrete core at the age of loading t'.

The geometric compatibility which the creep model for CFT members must follow is the axial strain increments of the concrete core and steel tube due to the creep are equal to each other. According to the geometric compatibility and Eqs. (5) and (7), the creep strain of an axially compressed CFT member, which equals to the strain increment of the steel tube due to the creep, can be obtained as

$$\varepsilon_{sc}^{c}(t,t') = \varepsilon_{s}^{c}(t,t') = \frac{\sigma_c^0(t')C_0(t,t')}{1+\alpha E_s C_0(t,t')} \tag{8}$$

where $\varepsilon_{sc}^{c}(t,t')$ = creep strain of the axially compressed CFT members. Therefore, the total strain of an axially compressed CFT member is

$$\varepsilon_{sc}(t,t') = \varepsilon_{sc}^{0}(t') + \varepsilon_{sc}^{c}(t,t') \tag{9}$$

where $\varepsilon_{sc}^{0}(t')$ = initial axial strain in the concrete core at the age of loading t'. Meanwhile, the stresses in the concrete core can be obtained according to Eqs. (5) and (8) as

$$\sigma_c(t,t') = \sigma_c^0(t') + \sigma_c^c(t,t') = \frac{\sigma_c^0(t')}{1+\alpha E_s C_0(t,t')} \tag{10}$$

2.3 Creep analysis of CFT arch bridges

Assuming that CFT is a single material, the material elastic modulus is given as (Zhong 2003)

$$E_{sc} = f_{sc}^{p}/\varepsilon_{sc}^{p} \tag{11}$$

in which

$$f_{sc}^{p} = (0.172 f_y/235 + 0.488) f_{sc}^{y} \tag{12a}$$

$$\varepsilon_{sc}^{p} = 0.67 f_y/E_s \tag{12b}$$

$$f_{sc}^{y} = (1.213\zeta + B\zeta + C\zeta^2) f_{ck} \tag{12c}$$

$$\zeta = A_s f_y / A_c f_{ck} \tag{12d}$$

For axially compressed circular CFT columns

$$B = 0.1759(f_y/235) + 0.974 \tag{13a}$$

$$C = -0.1038(f_{ck}/20) + 0.0309 \tag{13b}$$

where f_y = yield strength of steel tube, f_{ck} = standard concrete strength.

The internal forces and stresses in the concrete core and steel tube of CFT arch bridges vary constantly with time since the creep effect. Therefore, the whole creep process is divided into small time steps, which makes it possible to deal with the stress of the concrete core as a constant and to model the creep development of CFT arch bridges by the reduction of the elastic modulus within each time step. At any target time t, the reduced elastic modulus of the CFT material $E_{sc}(t,t')$ is given as

$$E_{sc}(t,t') = \frac{N(t')}{A_{sc}\varepsilon_{sc}(t,t')} \tag{14}$$

where $N(t')$ = axial force in CFT members loaded at age t'; A_{sc} = cross-sectional area of CFT members, $A_{sc} = A_s + A_c$.

2.4 Dynamic analysis of CFT arch bridges

Dynamic analysis of CFT arch bridges considering the creep effect leads to the typical equation of motion involving the reduced elastic modulus of CFT material as

$$[\mathbf{M}]\{\ddot{\mathbf{x}}(t)\}+[\mathbf{C}_t]\{\dot{\mathbf{x}}(t)\}+[\mathbf{K}_t]\{\mathbf{x}(t)\} = -[\mathbf{M}][\mathbf{R}]\{\ddot{\mathbf{x}}_g(t)\} \tag{15}$$

where [**M**] = mass matrix of the bridge; $[\mathbf{C}_t], [\mathbf{K}_t]$ = damping and stiffness matrices respectively, which include the creep effect and vary with time; $\mathbf{x}(t)$ = displacements vector; $\ddot{\mathbf{x}}_g(t)$ = ground acceleration vector; [**R**] = earthquake influence coefficient matrix.

3. Creep effect on the dynamic behaviors of CFT arch bridges

3.1 Description of the bridge and finite element modeling

A half-through CFT arch bridge is studied as a practical application, whose span is 76 m + 360 m + 76 m long. The calculated span, rise and rise span ratio of main arch are 344 m, 76.45 m and 1/4.5 respectively. The coefficients of the arch axis are $m = 2$ and $k = 1.317$. Each arch rib, whose typical cross section is shown in Fig. 1, is a CFT truss consisting of six CFT chords connected by web members. Concrete C50 is used in the chords and horizontal webs, whereas there is no concrete within the web members and steel tubes of transverse braces. The height of the cross section of the main arch rib is variable along the span. The distances between the top and bottom chords at the arch foot and arch crown are 8.039 m and 4.000 m respectively. The distance between the two arch ribs is 35.95 m. A total of eight transverse braces are set between the two ribs.

A three dimensional finite element model of the CFT arch bridge was developed for this investigation, with the general finite element software ANSYS. A total of three types of elements are used in the finite element model. The main arch ribs, side arch ribs, web members, transverse braces, spandrel columns, beams and stringers under the bridge deck, tie beams, piers, pile caps and pile foundations were all modeled by a two-node 3D beam element; the hangers and horizontal cables were modeled by a 3D spar element; and the soil is modeled by a 3D spring-damper element, whose stiffness is calculated by the 'm' method (Lee *et al.* 2001). The finite element

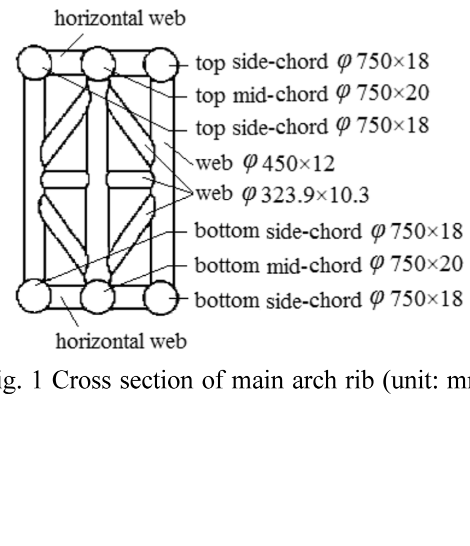

Fig. 1 Cross section of main arch rib (unit: mm)

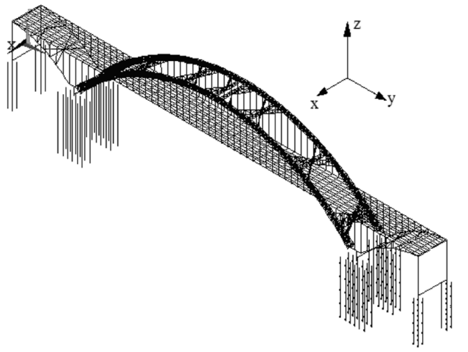

Fig. 2 Finite element model

model for this bridge consists of 4660 nodes and 9383 elements, as illustrated in Fig. 2. The self weight, which contributes to creep, is assumed to be applied at the age of 28 days permanently. Creep is not considered during the construction period.

3.2 Analytical results of creep effects on CFT arch bridge

Figs. 3 and 4 show the axial forces in the concrete core and steel tube respectively. Axial force in the concrete core decreases over time, while that in the steel tube increases. The axial forces in the concrete core at arch foot, 1/4 span and arch crown decrease by 20.5%, 19.1% and 19.8% respectively after one year, and axial forces in the steel tube at arch foot, 1/4 span and arch crown increase by 26.4%, 28.2% and 27.2% respectively.

The first three calculated eigenfrequencies of the bridge for different ages are presented in Fig. 5. The eigenfrequency decreases with time, meaning that the dynamic properties of the bridge are influenced by the creep behavior of concrete. As expected, this influence is more significant in the early ages. With the model developed in this paper, the first three eigenfrequencies decrease by 3.02%, 5.38% and 1.29% for one year respectively.

The forced vibration of this bridge has been investigated under different seismic excitations. Figs. 6 through 8 present the displacements at middle span of this bridge under the effect of El-Centro wave, whose peak acceleration is chosen to be 0.15g. It can be seen from these figures that

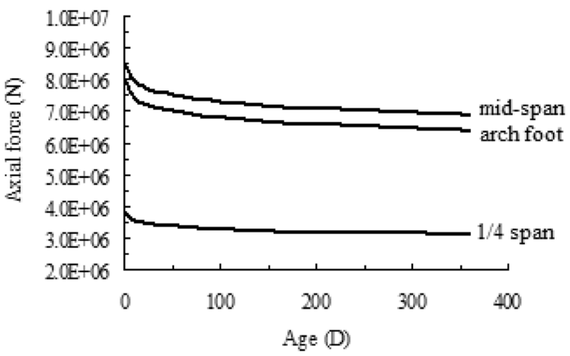

Fig. 3 Axial force of concrete in the main arch ribs

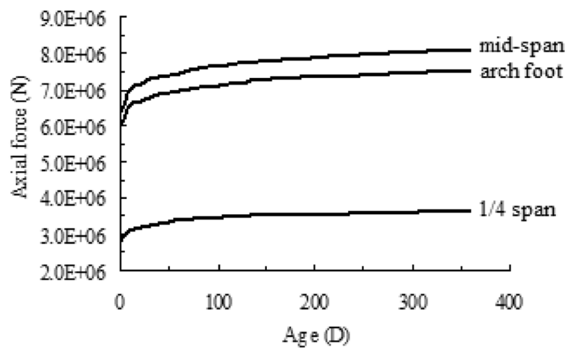

Fig. 4 Axial force of steel tube in the main arch ribs

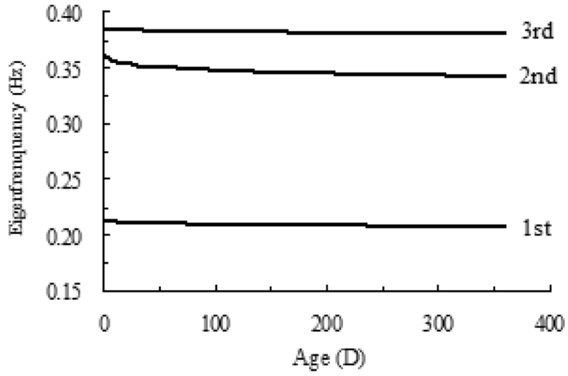

Fig. 5 Time-dependent eigenfrequencies

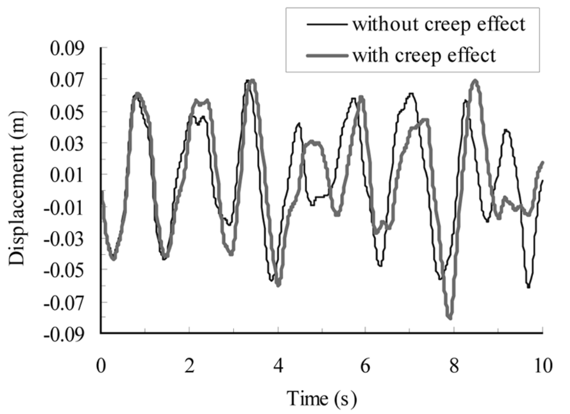

Fig. 6 Displacement at mid-span under excitation along *x*-axis

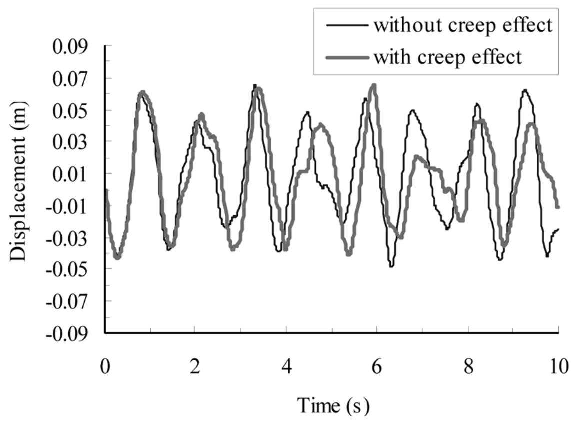

Fig. 7 Displacement at mid-span under excitation along *y*-axis

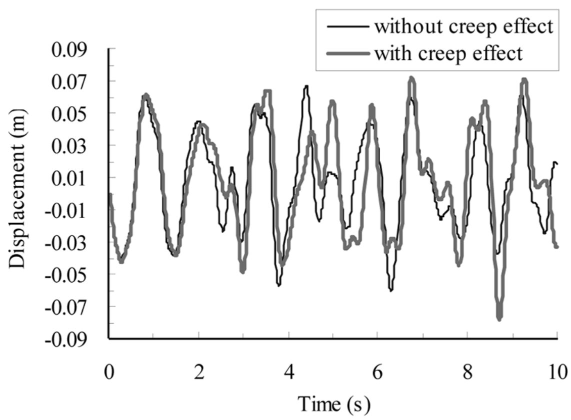

Fig. 8 Displacement at mid-span under excitation along *z*-axis

the creep effect has magnified the maximum values of the displacement. The maximum displacements at middle span involving the creep effect after one year, under the excitations along x-axis, y-axis and z-axis, are 15.33%, 0.86% and 17.75% greater than those calculated without the creep effect respectively.

4. Parameter analysis

Creep effect on the dynamic responses of CFT arch bridges are further studied with the focus on parameters that affect the creep behaviours of concrete and CFT members.

Figs. 9 through 11 show the displacements at middle span under the effect of z-axis excitation with different w/c, a/c and f_c of the concrete core after 360 days. According to these figures, it can be concluded that the time histories of the bridge displacement, considering the creep effect of the concrete, change considerably due to the composition and compressive strength of concrete.

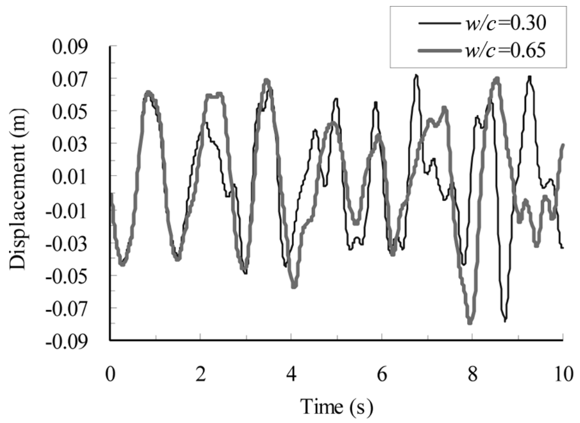

Fig. 9 Displacements at middle span with different w/c

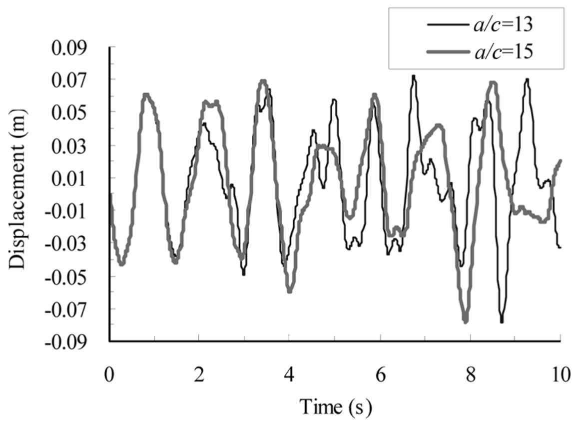

Fig. 10 Displacements at middle span with different a/c

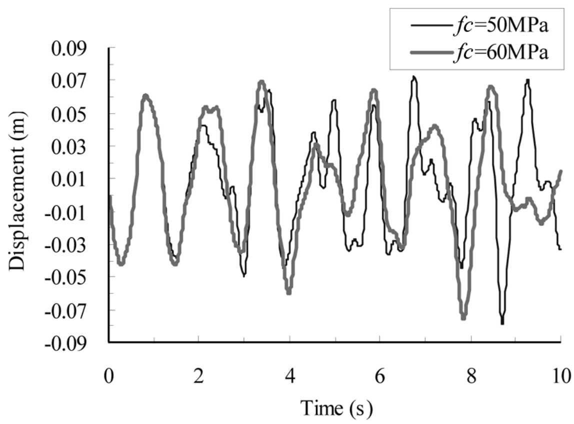

Fig. 11 Displacements at middle span with different f_c

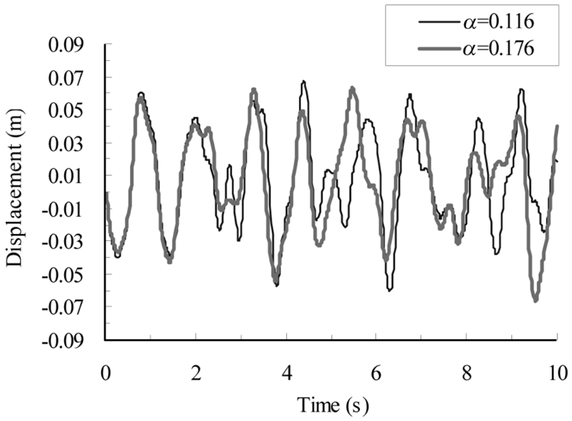

Fig. 12 Displacements at middle span with different α, without creep effect

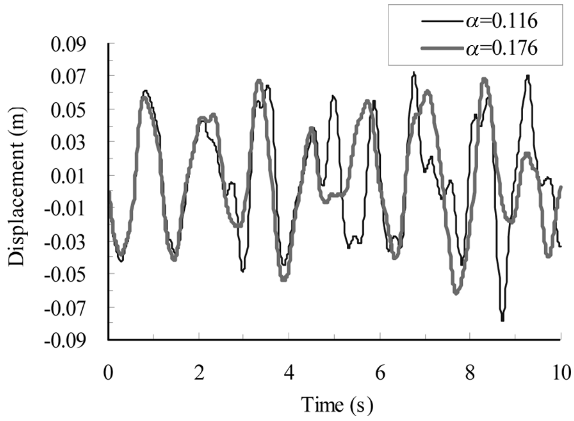

Fig. 13 Displacements at middle span with different α, with creep effect

Steel ratio, unlike concrete composition and compressive strength investigated above, is not the factor influencing the concrete creep. However, the variation of steel ratio results in the change of the bridge stiffness and the change of the creep behaviour of CFT members, as well as seismic responses correspondingly. The effect of steel ratio on the dynamic behaviour of this bridge has been revealed in Figs. 12 and 13. Fig. 12 presents its effect without considering creep behaviour, which is used to observe its effect due to its contribution to the change of the bridge stiffness; while Fig. 13 presents the effect considering creep behaviour, which involves its contribution to the change of the bridge stiffness and the change of the creep behaviour of CFT members as well.

It can be seen that the displacement time histories change greatly with the change of steel ratio. With the increase of the steel ratio α from 0.116 to 0.176, the maximum values of the displacements at the middle span, without and with considering the creep effect respectively, decrease by 0.72% and 12.8%. This result demonstrates that the effect of the steel ratio on the dynamic behaviour of CFT arch bridges is mainly dependent on its contribution to the change of the creep behaviour of CFT members and bridge.

5. Conclusions

This paper proposed an analytical method for the seismic behaviors of CFT arch bridges, considering the creep effect. The following conclusions can be drawn with a half-through long-span CFT arch bridge as a practical application.

(1) Creep effect changes the natural vibration characteristics of CFT arch bridges. The calculated eigenfrequency decreases with the age of the bridge, especially in the early age.

(2) The creep of concrete has an obvious influence on the seismic responses of CFT arch bridges. The maximum values of displacement along the rib excited by different excitations can be magnified by the creep effect.

(3) The composition and compressive strength of concrete, which influence the concrete creep, have an obvious effect on the dynamic responses of CFT arch bridges when the creep effect is considered. On the other hand, the change of steel ratio, by changing the creep behaviour of CFT

members and bridges, also affects the dynamic behaviours of CFT arch bridges involving creep effect prominently.

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References

Bazant, Z.P. and Baweja, S. (1995a), "Creep and shrinkage prediction model for analysis and design of concrete structures-model B3", *Mater. Struct.*, **28**, 357-365.

Bazant, Z.P. and Baweja, S. (1995b), "Justification and refinements of model B3 for concrete creep and shrinkage. 2. Updating and theoretical basis", *Mater. Struct.*, **28**, 488-495.

Chen, B.C. (2007), *Design and Construction of CFT Arch Bridges*, People Jiaotong Press, Beijing, China. (in Chinese)

Han, B. and Wang, Y.F. (2001), "Creep analysis of small eccentrically compressed CFT members", *Eng. Mech.*, **18**(6), 110-116. (in Chinese)

Han, B. and Wang, Y.F. (2004), "Long term load-carrying capacity of axially compressed concrete filled steel tubular short columns", *Proceedings of '04 ISCC*, Changsha, China.

Lam, J.P. (2002), "Evaluation of concrete shrinkage and creep prediction models", MS thesis, Civil and Environmental Engineering Dept., San Jose State University, San Jose State.

Lee, C.F., Lau, C.K., Ng, C.W.W., Kwong, A.K.L., Pang, P.L.R., Yin, J.H. and Yue, Z. Q. (2001), *Soft Soil Engineering*, Swets & Zeitlinger B.V., Lisse, The Netherlands.

Neville, A.M. (2002), "Creep of concrete and behavior of structures. Part I: problems", *Concrete Int.,* **24**(5), 59-66.

Rajeev, G., Ram, K. and Paul, D.K. (2007), "Comparative study of various creep and shrinkage prediction models for concrete", *J. Mater. Civil Eng.*, **19**(3), 249-260.

Sapountzakis, E.J. and Katsikadelis, J.T. (2003), "Creep and shrinkage effect on the dynamic analysis of reinforced concrete slab-and-beam structures", *J. Sound Vib.*, **260**(3), 403-416.

Sapountzakis, E.J. (2004), "Dynamic analysis of composite steel-concrete structures with deformable connection", *Comput. Struct.*, **82**(9-10), 717-729.

Starossek, U., Falah, N. and Lohning, T. (2010), "Numerical analyses of the force transfer in concrete-filled steel tube columns", *Struc. Eng. Mech.*, **35**(2), 2651-2666.

Wang, Y.F. and Han, B. (1999), "Creep analysis of axially compressed concrete filled steel tubular members", *Proceedings of EPMESC VII*, Macao.

Wang, Y.F. and Xu, S.J. (2001), "Study on dynamic response of concrete filled steel tubular arch-bridge under moving vehicles", *Proceedings of International Symposium on Traffic Induced Vibrations & Controls*, Beijing, China.

Wang, Y.F. (2006), *Creep of Concrete Filled Steel Tube*, Science Press, Beijing, China. (in Chinese)

Wang, Y.F., Han, B. and Zhang, D.J. (2008), "Advances in creep of concrete filled steel tube members and structures", *Proceedings of '8 Concreep Conference*, Ise-Shima, Japan.

Wang, Y.F., Han, B., Du, J.S. and Liu, K.W. (2007), "Creep analysis of concrete filled steel tube arch bridges", *Struct. Eng. Mech.*, **27**(6), 639-650.

Wen, J. and Wang, Y.F. (2006), "Advances in study on dynamic behavior of creep of concrete filled steel tube", *Proceedings of 8th ASCCS,* Harbin, China.

Zhong, S.T. (2003), *Concrete Filled Steel Tubular structures*, Tsinghua University Press, Beijing, China. (in Chinese)

Zhou, Y. and Wang, Y.F. (2006), "Creep effect on the dynamic analysis of concrete filled steel tubular arch bridge", *J. Dalian Univ. of Tech.*, **46**(1), 82-87. (in Chinese)