Engineering Structures 99 (2015) 1–8

Contents lists available at ScienceDirect

Engineering Structures

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

Creep influence on structural dynamic reliability

Y.S. Ma [a,b], Y.F. Wang [a,*]

[a] School of Civil Engineering, Beijing Jiaotong University, Beijing, China
[b] Center of Science and Technology of Construction, Ministry of Housing and Urban-Rural Development, Beijing, China

ARTICLE INFO

Article history:
Received 14 July 2014
Revised 6 April 2015
Accepted 11 April 2015
Available online 15 May 2015

Keywords:
Creep
Dynamic reliability
Stochastic seismic analysis
Arch bridges

ABSTRACT

Creep brings forth considerable influences on both static and dynamic behaviours of concrete structures. This paper intends to deepen the investigation on the creep influence on structural dynamic performance, evaluating their relationship from the view of reliability. The influencing mechanism of concrete creep on structural dynamic behaviour is first stated. Integration of the structural creep analysis by the Model B3 and the age-adjusted effective modulus method with the stochastic seismic analysis by the pseudo-excitation method is then proposed. Based on the creep-influenced structural static and stochastic seismic behaviours, formulations for the dynamic reliability with the consideration of creep effect are derived using the first-passage failure criterion and Poisson crossing assumption. A systematic numerical simulation is conducted on a long-span concrete filled steel tube arch bridge, considering (1) the creep influence on concrete mechanical properties and structural configuration and internal forces; (2) the dimensionality, wave passage effect and incoherence effect of random ground motions; and (3) the uncertainties existing in the structure and creep behaviour. Critical conclusions are drawn and it is recommended to consider the long-term effect of dead loads in seismic design to ensure structural seismic safety.

1. Introduction

Creep has a considerable influence on the behaviour of concrete structures [1–3] and composite structures [4,5]. Deflections due to the long-term effect can be large, normally significantly larger than the short-term or elastic deflections. By altering the long-term stress state, creep can also cause a change in the stress maxima for superimposed live loads, and can even change the safety margin of a structure under short-time overloads [6].

Beyond the conventional creep effect analysis, researchers also took notice of the creep influence on structures in dynamic field [7–9]. Ma [10] analysed in detail the relationships between sustained loading and instantaneous loading, and between a long-term effect and an instantaneous response, drawing the conclusions that structural natural frequencies increase when creep effect is taken into account, and that the creep influence on the displacement and internal force responses under an earthquake effect is not negligible, otherwise responses of some sections will be greatly underestimated.

As an external disturbance to structures, earthquake is featured not only by obvious dynamic nature but also strong randomness [11], which determines that random vibration analysis [12,13] and the measure of dynamic reliability [14] play an increasingly important role in modern engineering. The investigations about probabilistic seismic performance and dynamic reliability estimation, paying special attention to damaged structures [15] and stochastic structures [16,17], have been conducted for bridges [18–21], frames [22–24], offshore structures [25], underground structures [26] and towers [27] under stationary or non-stationary random excitations in recent years, with a great effort for the computational efficiency [28–30]. Nevertheless, even allowing for such various engineering applications, it would appear that so far no dynamic reliability analysis has taken note of the realistic long-term effect occurring anterior to the random excitations, in spite that concrete is aging viscoelastic in nature and the time-dependent property exerts a considerable influence on structural behaviours in practice as stated above.

For these many reasons, an additional argument in favour of creep influence on the dynamic behaviour of structures is to be advanced in this paper from the perspective of reliability. Precisely, this paper relates the ageing viscoelastic property and time-dependent constitutive relation of concrete to the random vibration behaviour of structures under multi-directional spatial

---

* Corresponding author at: School of Civil Engineering, Beijing Jiaotong University, No. 3 Shangyuancun Road, Haidian District, Beijing 100044, China. Tel.: +86 010 5168 8091.

E-mail address: cyfwang@bjtu.edu.cn (Y.F. Wang).

http://dx.doi.org/10.1016/j.engstruct.2015.04.018

seismic motions, revealing the creep influence on structural seismic responses in the sense of statistics. The assessment method of dynamic reliability, with the consideration of creep effects on both seismic response and threshold, was also presented. A long-span concrete filled steel tube (CFST) arch bridge, which has found a wide application in China [31,32], was evaluated in this paper as a numerical example. Previous works have firmly demonstrated that creep could cause an approximate 35% increase in the mid-span deflection of CFST arch bridges after one year, and raise the stress in the steel tube of arch rib of the bridges by about 5–27%, while decrease that in the concrete core by about 20–52% [33,34]. This paper intends to observe the creep effect on stochastic seismic behaviour and dynamic reliability of CFST arch bridges, and to reflect the significant influence of concrete creep on structural dynamic behaviour finally.

2. Influence of creep on dynamic behaviour

As would usually be the case in practice, earthquake occurs years after the completion of a structure during its working life. From a more essential viewpoint, the creep influence on structural dynamic behaviour is originated from the influence of a sustained loading on a structure, which is twofold: structural deformation and internal forces vary with time; and an increase in the concrete elastic modulus happens after a period of sustained loading [35,36]. In this paper, the structural configuration and internal forces after a period of concrete creep are considered to be the initial condition for the subsequent random vibration and dynamic reliability analyses; and the concrete elastic modulus reckoning in sustained loading effect $E_{c,sus}(t, t_0)$ is introduced as

$$E_{c,sus}(t,t_0) = \beta_{c,sus}(t,t_0)\beta_E(t)E_{c,28} \quad (1)$$

to substitute the traditional 28-day one $E_{c,28}$ to perform the dynamic analysis, where the item $\beta_E(t)E_{c,28}$ expresses the development of elastic modulus due to aging of a load-free concrete at an age of t as recommended by CEB-FIP Model Code 2010 [37]; $\beta_E(t)$ is a coefficient which depends on the age of concrete; and $\beta_{c,sus}(t, t_0)$ is the ratio between the elastic modulus of the concrete after a period of sustained loading and the elastic modulus of an identical concrete with the same age but not previously loaded. From four groups of tests [10,38–40], in which the concrete compressive strength f_{cm} ranges from 10.6 to 45.9 MPa and the loading duration $t - t_0$ ranges from 30 to 3860 days, a regressive formula of $\beta_{c,sus}(t, t_0)$ can be gained as

$$\beta_{c,sus}(t,t_0) = 0.147 f_{cm}^{-0.03} \ln(3051 + t - t_0) \quad (2)$$

where f_{cm} is the 28-day cylindrical compressive strength of concrete (MPa); and t_0 is the age at loading (d). The deviation of the regression from the test data is 2.03% in average.

Detailed interpretation of the influencing mechanism and derivation of Eqs. (1) and (2) are given in [10].

3. Structural creep effect

A structural creep analysis should precede the random vibration and dynamic reliability analyses, to generate an actual state of the structural deformation and internal forces when a ground motion acts. Given that the sealing action provided by the steel tube protects the concrete from the migration and loss of moisture, and considerably reduces shrinkage and drying creep of the concrete, we lay emphasis only on basic creep in this paper [41,42]. The structural creep effect was analysed by the age-adjusted effective modulus method [6,43], with the combination of the Model B3 [44] for concrete creep, which characterizes basic creep as

$$C_0(t,t_0) = q_2 Q(t,t_0) + q_3 \ln[1 + (t - t_0)^n] + q_4 \ln\left(\frac{t}{t_0}\right) \quad (3)$$

where $C_0(t, t_0)$ is the 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; $Q(t, t_0)$ = a function concerning the age at loading; and n = empirical parameter.

Detailed computational method and validation against in-site measurements were given in a previous work [34].

4. Computation of random responses considering creep effect

4.1. Equations of motion after creep

Assume that the structural creep behaviour begins at time t_0, and an earthquake excitation acts on the structure at time t. In the case of considering creep effect, the equation of motion of a multi-degree-of-freedom system at time t is

$$[M]\{\ddot{u}\} + [C]\{\dot{u}\} + [K^c]\{u\} = [P] \quad (4)$$

where $[M]$ and $[C]$ are the mass and damping matrices respectively; $\{u\}$ is the random displacement response vector; $[P]$ represents the random excitation vector; $[K^c]$ is the stiffness matrix of the structure at time t considering creep effect; and superscript c denotes creep effect. As stated above, $[K^c]$ reflects two aspects of the creep influence at the same time: the variation in structural configuration and internal forces accumulated during creep; and the variation in concrete elastic modulus caused by creep. The updated parameters at time t were used to assemble the structural stiffness matrix $[K^c]$, which ensures the embodiment of the creep influence in the random vibration analysis.

Consider a bridge with m non-supporting nodes (subscript a) and n supporting nodes (subscript b), and decompose the absolute displacement vector $\{u\}$ into a quasi-static displacement vector (superscript s) and a dynamic relative displacement vector (superscript d), a general form of the equation of random vibration considering creep effect is expressed as

$$[M_a]\{\ddot{u}_a^d\} + [C_a]\{\dot{u}_a^d\} + [K_a^c]\{u_a^d\} = -[M_a][B]\{\ddot{u}_b^s\} \quad (5)$$

$$[B] = -[K_a^c]^{-1}[K_{ab}^c] \quad (6)$$

4.2. Computation of random responses

Because the maximum value of a time-varying mean square response under a non-stationary excitation approximates the stationary mean square response [45], in view of the most interest on the maximum response in engineering, the seismic ground motion is assumed to be a Gaussian stationary random process in this paper. With consideration of the variability in space, the power spectral density matrix of the ground acceleration can be expressed as [19]

$$[S(\omega)] = [e^{-i\omega T}]^* [S_{\ddot{X}}][R][S_{\ddot{X}}][e^{-i\omega T}] \quad (7)$$

where $[e^{-i\omega T}]$, $[R]$ and $[S_{\ddot{X}}]$ represent wave passage effect, incoherence effect and local site effect respectively; and superscript * indicates complex conjugate. $[R]$ is an n-dimensional positive or semi-positive definite real symmetric matrix. Let the rank of $[R]$ be r, through LDLT decomposition method, $[R]$ can be written as the product of an $n \times r$ real matrix $[Q]$ and its transpose. Thus,

$$[S(\omega)] = [e^{-i\omega T}]^* [S_{\ddot{X}}][Q][Q]^T [S_{\ddot{X}}][e^{-i\omega T}] = [F]^*[F]^T \quad (8)$$

in which