Creep modeling for concrete-filled steel tubes

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Received 21 January 2003; received in revised form 12 May 2003; accepted 4 June 2003

Abstract

Using the rate of flow method and the double power law function for basic creep of concrete, an algorithm is developed for the time-dependent behavior of concrete-filled steel tube (CFT), with or without the interface bond. The model adheres to geometric compatibility and static equilibrium, and considers the effects of sealed concrete, multi-axial state of stresses, creep Poisson’s ratio, stress redistribution, variable creep stress history, and creep failure of the column. The model is verified against previous creep tests for bonded and unbonded specimens. A study is then carried out on the practical design parameters that may affect creep of CFT columns under service loads, or lead to their creep rupture at high levels of sustained load. The study indicates that creep of CFT columns should be considered in the design, however, with creep coefficients much lower than those prescribed in the current ACI. Creep of CFT is shown to be a function of concrete mix, column geometry, and interface bond. Therefore, a single ultimate creep coefficient cannot be used for all concrete mixes, column geometries, and construction types. Bonded tubes curtail creep of concrete much more than the equivalent unbonded ones, mainly because of the stress relaxation phenomenon, which is more pronounced for smaller diameter-to-thickness ratios. For diameter-to-thickness ratios of 40 or less, bonded tubes are more durable in creep rupture than the equivalent unbonded ones. Creep rupture life of 75 years is quite feasible in bonded CFT, with diameter-to-thickness ratio of 40 or less, for sustained loads as high as 65% of the static capacity of the column.

Keywords: Bond; Columns; Concrete-filled steel tube; Time-dependent behavior

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0143-974X/$ - see front matter © 2003 Elsevier Ltd. All rights reserved. doi:10.1016/S0143-974X(03)00085-3
## Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha$</td>
<td>load distribution factor, or creep parameter for concrete</td>
</tr>
<tr>
<td>$A_c, A_s$</td>
<td>cross-sectional areas of concrete core and steel tube</td>
</tr>
<tr>
<td>$B$</td>
<td>column width</td>
</tr>
<tr>
<td>$D$</td>
<td>concrete core diameter</td>
</tr>
<tr>
<td>$\Delta\sigma$</td>
<td>stress increment</td>
</tr>
<tr>
<td>$\Delta t$</td>
<td>time step</td>
</tr>
<tr>
<td>$\varepsilon(t)$</td>
<td>total strain</td>
</tr>
<tr>
<td>$E(t_0)$</td>
<td>initial elastic secant mouldus</td>
</tr>
<tr>
<td>$E_c, E_s$</td>
<td>modulus of elasticity of concrete core and steel tube</td>
</tr>
<tr>
<td>$\varepsilon_{ca}, \varepsilon_{sa}$</td>
<td>axial strains in concrete core and steel tube</td>
</tr>
<tr>
<td>$\varepsilon_{ca-uniaxial}$</td>
<td>uniaxial creep strain in concrete core</td>
</tr>
<tr>
<td>$\varepsilon_{cr}$</td>
<td>radial strain in concrete core</td>
</tr>
<tr>
<td>$E_d$</td>
<td>dynamic modulus</td>
</tr>
<tr>
<td>$E_{\text{effective}}$</td>
<td>effective modulus of elasticity</td>
</tr>
<tr>
<td>$E_o$</td>
<td>asymptotic modulus for short duration of loading</td>
</tr>
<tr>
<td>$\varepsilon_{s1}, \varepsilon_{s2}$</td>
<td>axial and hoop strains in steel tube</td>
</tr>
<tr>
<td>$\varepsilon_{sa}, \varepsilon_{sh}$</td>
<td>axial and hoop strains in steel tube</td>
</tr>
<tr>
<td>$\varepsilon_{shr}$</td>
<td>shrinkage strain</td>
</tr>
<tr>
<td>$\varepsilon_{sy}$</td>
<td>yield strain of steel tube</td>
</tr>
<tr>
<td>$f_r$</td>
<td>lateral confining pressure</td>
</tr>
<tr>
<td>$f_{sa}, f_{sh}$</td>
<td>axial and hoop stresses in steel tube</td>
</tr>
<tr>
<td>$h$</td>
<td>column height</td>
</tr>
<tr>
<td>$J$</td>
<td>creep compliance function or creep strain per unit stress</td>
</tr>
<tr>
<td>$L$</td>
<td>loading span</td>
</tr>
<tr>
<td>$m, n$</td>
<td>creep parameters for concrete</td>
</tr>
<tr>
<td>$\nu_c, \nu_{EPR}$</td>
<td>static and effective Poisson’s ratio of concrete</td>
</tr>
<tr>
<td>$\nu_s$</td>
<td>Poisson’s ratio of steel</td>
</tr>
<tr>
<td>$P$</td>
<td>total sustained axial load;</td>
</tr>
<tr>
<td>$P_c, P_s$</td>
<td>axial load on concrete core and steel tube</td>
</tr>
<tr>
<td>$P_{\text{Static}}$</td>
<td>static capacity of the column</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>applied stress</td>
</tr>
<tr>
<td>$t$</td>
<td>tube thickness</td>
</tr>
<tr>
<td>$t_o$</td>
<td>age at loading</td>
</tr>
<tr>
<td>$\phi$</td>
<td>(total) creep coefficient</td>
</tr>
<tr>
<td>$\phi_d$</td>
<td>recoverable delayed elastic creep coefficient</td>
</tr>
<tr>
<td>$\phi_r$</td>
<td>creep parameter for concrete</td>
</tr>
<tr>
<td>$\phi_f$</td>
<td>creep flow</td>
</tr>
<tr>
<td>$\phi_u$</td>
<td>ultimate creep coefficient</td>
</tr>
</tbody>
</table>
1. Introduction

Concrete-filled steel tube (CFT) combines the benefits of two materials to provide high strength and ductility. Two types of construction are feasible: bonded (BCFT) or unbonded (UCFT). In BCFT, the tube and the concrete core both share the axial load, either by direct loading of the tube and concrete together, or through friction bond between the two. In UCFT, anti-friction material may be applied to the inner surface of the tube to eliminate any composite action under axial or lateral loads. The tube then provides only confining pressure for concrete.

Some researchers, such as Orito et al. [1], have advocated that the tube in UCFT would be more resistant to outward buckling, and therefore, its confining effect may be utilized more efficiently. While significant work has been carried out on the short-term static or dynamic behavior of CFT, less emphasis has been placed on its time-dependent response. Creep effects have been accounted for by reducing either the strength or the initial elastic modulus of concrete [2,3]. Error in prediction of creep strains may lead to differential axial shortening, cracking, creep rupture, and creep buckling, all of which are of great concern in high-rise buildings [3,4]. The absolute amount of cumulative column shortening influences the design of cladding details and the detailing of elevator rails, and vertical pipes, whereas the differential shortening between adjacent columns and walls may cause distortion of slabs [5].

Time-dependent behavior of CFT columns is markedly different from ordinary concrete columns in several aspects, as follows:

1. Concrete core is essentially sealed from migration of any moisture due to presence of the tube, and therefore, drying creep and shrinkage strains are considerably lower in CFT.
2. Confinement of concrete by the tube offers resistance to the lateral expansion of concrete. This multi-axial stress effect does not allow concrete to freely creep in the axial direction.
3. Stress transfer between concrete core and steel tube is possible in BCFT, resulting in stress relaxation of concrete, and further reducing its creep.
4. As a result of stress relaxation in concrete, even though the total axial load on the column may be constant, stresses in each component (steel and concrete) may vary significantly over time. This variation must be accounted for in the creep analysis.

This paper evaluates the effect of these issues on creep modeling of CFT columns. It verifies the proposed model against experimental data, and provides results of a parametric study on creep of CFT columns under service loads, as well as creep rupture of CFT columns at high levels of sustained load.

2. Literature review

Terrey et al. [3] considered time-dependent behavior of concrete encased in a steel section as an area that requires further exploration. Most recently, Ichinose et al.

Experiments by Terrey et al. [3] showed the moisture egress from encased concrete to be very small or totally eliminated. As such, shrinkage of concrete core may be safely neglected, and creep coefficients may be 50–60% of those in ordinary concrete. Ichinose et al. [4] also reported a series of tests to obtain creep coefficients in composite steel-concrete columns. Uy and Das [6] studied creep and shrinkage of concrete in a fabricated steel box column typically used in tall buildings. They used an age-adjusted effective modulus method (AEMM) to simulate the construction of individual floor levels in a building.

Morino et al. [7] reported on creep tests of square CFT columns, including six concentrically loaded stubs with width-to-thickness $B/t$ ratios from 23 to 47 and height-to-width $h/B$ ratios from 2:1 to 12:1; one beam with a $B/t$ ratio of 33 and span-to-depth $L/B$ ratio of 26; and two eccentrically loaded columns both with $B/t$ ratio of 33 and $h/B$ ratio of 8:1. Although they did not make a conclusive statement regarding the length effect on creep behavior of CFT columns, they noted a clear reduction in the creep coefficient of concrete core, due mainly to the stress redistribution between concrete and steel. They further questioned whether creep coefficient is a function of the loading condition, and emphasized the need to develop a uniform method for time-dependent analysis of CFT columns.

Bradford and Wright [8] developed a model to study the long-term behavior of lightweight concrete core in thin steel sheeting typical of that encountered in a composite profiled wall. Under sustained loads, concrete creeps and shrinks, producing compressive stresses in steel that increase over time, and may eventually be large enough to precipitate its local buckling.

3. Analytical modeling

3.1. Creep model for concrete

Of the number of creep models available for concrete [9], the effective modulus method (EMM) is the simplest and the oldest, consisting only of a single linear elastic solution, as

$$E_{\text{Effective}} = \frac{1}{J(t,t_o)} = \frac{E(t_o)}{1 + \phi(t,t_o)}$$

(1)

where $J$ is the creep compliance function, i.e. creep strain per unit stress, $t_o$ is the age at loading, $E(t_o)$ is the initial modulus of elasticity, and $\phi$ is the creep coefficient. Total strain in concrete at any time can then be calculated as

$$\varepsilon(t) = \int_{t_o}^{t} J(t,t_o) d\sigma(t_o) + \varepsilon_{\text{Shr}}$$

(2)

where $\sigma(t_o)$ is the applied stress and $\varepsilon_{\text{Shr}}$ is the shrinkage strain. To account for aging
effects and stress variations, an age-adjusted effective modulus method (AEMM) was introduced, which also follows a single linear elastic solution. The rate of creep method (RCM), on the other hand, is based on a first-order differential equation, and accounts for any stress history. However, it results in parallel creep curves and overestimating of the creep recovery, because rate of creep is considered independent of the loading age. The rate of flow method (RFM) by Bazant and Wittmann [9] and England and Illston [10] addresses most of these deficiencies by combining the EMM and RCM, using a two-part creep compliance function as

\[ J(t,t_o) = \frac{1 + \phi(t,t_o)}{E(t_o)} = \frac{1}{E_d} + \frac{\phi(t) - \phi(t_o)}{E(t_o)} \]  

(3)

where the total creep coefficient \( \phi \) consists of an irrecoverable creep flow \( \phi_f \) and a recoverable delayed elastic component \( \phi_d \), as

\[ \phi(t,t_o) = E(t_o)J(t,t_o) - 1 = \phi_f(t) + \phi_d. \]  

(4)

The delayed elastic component, which is independent of the loading age, is represented by a fictitious effective modulus, also termed as dynamic modulus \( E_d \), given by

\[ E_d = \frac{E(t_o)}{1 + \phi_d}. \]  

(5)

Previous research has shown that the delayed creep strains are identical for different concrete mixes [11]. Nielson [12] suggested a value of 0.333 for \( \phi_d \). The assumption of a constant \( \phi_d \) simplifies the integration process, but leads to a kink in the early phase of the creep curve. Use of the double power law function, as will be discussed later, for the creep flow \( \phi_f \) at the early ages in RFM alleviates the problem and results in a smooth creep curve. Once the value of \( \phi_f \) exceeds zero, the RFM can proceed with the constant \( \phi_d \) of 0.333. The initial elastic modulus \( E(t_o) \) is the secant modulus calculated shortly after applying the load based on a short-term stress–strain model for concrete. In the present study, confinement model of Ahmad and Shah [13] is used, which suggests an incremental-iterative process for the passive confinement developed by the steel tube.

3.2. Effect of sealed concrete

Creep of concrete consists of two components: basic and drying. The drying creep is related to the moisture egress from concrete. Neville [14] showed that concrete, while still drying, creeps more than both the wet (fresh) concrete and the already dry (old) concrete, since in the latter two cases the drying component of creep does not take place. The pores of sealed concrete are either coated with epoxy or encased in a tube, thus preventing or significantly reducing its shrinkage and drying creep. Russell and Corely [15] showed that creep of sealed concrete might be half as much as that of the exposed concrete, under the same sustained loads and when loaded at the same age.
3.3. Double power law for basic creep of concrete

The RFM requires a creep prediction curve for the specific mix of concrete [9]. The double power law describes the basic creep of sealed or encased concrete, for which the drying creep component could be neglected [16]. The creep compliance function $J(t, t_0)$ is expressed as

$$J(t, t_0) = \frac{1}{E_o} + \frac{\phi_f}{E_o}(\alpha + t_0^{-m})(t-t_0)^n$$

where $E_o$ is the asymptotic modulus for short duration of loading, and $\phi_f, \alpha, m,$ and $n$ are all functions of concrete mix proportions and the 28-day compressive strength of concrete. Effect of different concrete mixes on creep parameter $n$ is shown in Table 1 after Freudenthal and Roll [17]. The various mixes shown in the table are used later in the model validation and the parametric study.

3.4. Effect of multi-axial stresses and creep Poisson’s ratio

Net creep strain of concrete under multi-axial stresses is less than that under uniaxial stress of the same magnitude [18]. Gopalakrishnan et al. [18] and Jordaan and Illston [19] have shown that despite anisotropy and creep nonlinearity, creep strain in concrete conforms to the principle of superposition by adding creep strain in each direction caused by each stress component acting separately. Gopalakrishnan et al. [18] defined three Poisson’s ratios: static or elastic $\varepsilon_{\text{elastic lateral}}/\varepsilon_{\text{elastic axial}}$, creep Poisson’s ratio or CPR $\varepsilon_{\text{creep lateral}}/\varepsilon_{\text{creep axial}}$, and effective Poisson’s ratio or EPR $\varepsilon_{\text{total lateral}}/\varepsilon_{\text{total axial}}$.

Under triaxial loading with unequal principal stresses, creep Poisson’s ratio is largest in the direction of the smallest stress. Gopalkrishnan et al. [18] showed the

<table>
<thead>
<tr>
<th>Mix number</th>
<th>Mix ratio (cement to aggregates)</th>
<th>Mix proportion by weight</th>
<th>Compressive strength MPa</th>
<th>Creep parameter ($n$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1: 2.5</td>
<td>1.0</td>
<td>0.450</td>
<td>1.0</td>
</tr>
<tr>
<td>2</td>
<td>1: 4</td>
<td>1.0</td>
<td>0.500</td>
<td>1.6</td>
</tr>
<tr>
<td>3</td>
<td>1: 4</td>
<td>1.0</td>
<td>0.490</td>
<td>1.6</td>
</tr>
<tr>
<td>4</td>
<td>1: 4.5</td>
<td>1.0</td>
<td>0.500</td>
<td>2.4</td>
</tr>
<tr>
<td>5</td>
<td>1: 4.5</td>
<td>1.0</td>
<td>0.375</td>
<td>1.8</td>
</tr>
<tr>
<td>6</td>
<td>1: 6</td>
<td>1.0</td>
<td>0.525</td>
<td>2.4</td>
</tr>
<tr>
<td>7</td>
<td>1: 7</td>
<td>1.0</td>
<td>0.500</td>
<td>3.5</td>
</tr>
</tbody>
</table>
effective Poisson’s ratio to be constant over time for both biaxial and triaxial loadings, with its value ranging from 0.09 to 0.17, somewhat less than the case of uniaxial loading, which is in the range of 0.17–0.22.

Jordaan and Illston [19] also studied time-dependent effects on the Poisson’s ratio for sealed concrete under variable multi-axial state of stresses, and concluded that the effective Poisson’s ratio remains approximately constant over time and is equal to its static value. The differences and variations observed in other tests, they argued, are not so great as to exclude the possibility of forming a suitable method for calculating creep in most engineering applications. Therefore, the normal constitutive relations for concrete under multi-axial state of stresses can be adopted for the elastic strains, and creep strains in any direction can be computed using the principle of superposition and a creep constitutive equation similar to those for elastic strain. The axial creep strain in a laterally confined concrete can be written as

$$\varepsilon_{ca} = \varepsilon_{ca\text{-uniaxial}} - 2\nu_c J(t, t_0)f_r$$

(7)

where $\varepsilon_{ca\text{-uniaxial}}$ is the creep strain from the uniaxial RFM, $\nu_c$ is the static Poisson’s ratio, as discussed above, and $f_r$ is the lateral confining pressure on concrete. The radial creep strain in concrete can be calculated using the effective Poisson’s ratio, $\nu_{EPR}$ as

$$\varepsilon_{cr} = \nu_{EPR}\varepsilon_{ca}$$

(8)

3.5. Effect of stress relaxation and redistribution

Stress redistribution in hybrid systems results in stress relaxation for the component with higher creep potential. In order to account for the variable creep stresses in concrete with no significant drying creep, Boltzmann principle of superposition may be used [9]. Accordingly, strain due to any stress history may be obtained by integrating the response to small stress increments ($\Delta\sigma$) applied at small time intervals ($\Delta t$), as

$$\varepsilon(t) = \sum_{q=1}^{r} \frac{1}{2}[J(t, t_q) + J(t, t_{q-1})] \Delta\sigma(t_q) + \varepsilon_{shr}$$

(9)

where subscripts $r$ and $q$ refer to small time steps for the numerical integration.

3.6. Failure criterion

Failure of CFTs under short-term (static) or long-term (creep) loading occurs when strains in the tube exceed the yielding strain of steel. Long-term failure, termed here as creep rupture, is based on total creep strains in the tube. In UCFT, the tube is only subjected to hoop strains, and therefore, a uniaxial failure criterion suffices, as given by

$$\varepsilon_{s2} < \varepsilon_{sy}$$

(10)
where \( \varepsilon_{s2} \) is the hoop strain in the tube, and \( \varepsilon_{sy} \) is the yield strain of steel tube. The tube in BCFT is subjected to biaxial stresses, for which von Mises yielding criterion is considered, as given by

\[
\left( \frac{\varepsilon_{s1}}{\varepsilon_{sy}} \right)^2 + \left( \frac{\varepsilon_{s2}}{\varepsilon_{sy}} \right)^2 + \frac{\varepsilon_{s1}\varepsilon_{s2}}{\varepsilon_{sy}^2} < 1
\]  

(11)

where \( \varepsilon_{s1} \) is the axial strain in the tube.

3.7. Modeling requirements

Two major requirements for creep modeling of CFT are as follows (see Fig. 1):

(a) Static equilibrium: In UCFT, only the equilibrium in the hoop direction needs to be satisfied, as

\[
f_r = \frac{2f_t}{D}
\]

(12)

where \( f_r \) is the hoop stress in the tube, \( t \) is the tube thickness, and \( D \) is the core diameter. In BCFT, equilibrium in the axial direction must also be satisfied at each time step, as

\[
P = P_c + P_s
\]

(13)

where \( P \) is the total sustained axial load on the section, and \( P_c \) and \( P_s \) are the contributions from the concrete core and steel tube, respectively. Therefore, axial stress in concrete remains constant in UCFT, whereas in BCFT it changes over time.

(b) Strain compatibility: In UCFT, the only condition is that hoop strain in the tube must be equal to the radial strain in the concrete core, or else a gap will be developed between the two materials. In BCFT, one needs to also satisfy the axial strain compatibility, assuming perfect bond between the tube and the concrete core in the axial direction.

3.8. Creep algorithm

Based on the above discussion, an algorithm was developed for the time-dependent analysis of both BCFT and UCFT. The following steps are used in the analysis:

1. Short-term (static) strains and stresses are determined at time \( t_o \) based on the above conditions. In UCFT, concrete takes the entire axial load. On the other hand, in BCFT, a load distribution factor (\( \alpha \)) is assumed such that

\[
P_c = \alpha P, \text{ and } P_s = P - P_c
\]

(14)

where an initial estimate of \( \alpha \) can be simply based on the stiffness ratio of the section, as
Fig. 1. Creep mechanism in UCFT and BCFT columns.

\[ \alpha = \frac{E_c A_c}{E_c A_c + E_s A_s} \]  

(15)

where \( E \) and \( A \) designate the modulus of elasticity and cross-sectional area, respectively, and subscripts \( c \) and \( s \) denote concrete and steel, respectively. Once
the axial load is known (or assumed) in concrete, using the iterative procedure of Ahmad and Shah [13], the hoop stress in the tube is calculated such that it satisfies static equilibrium and strain compatibility in the hoop direction. It should be noted that the assumption of strain compatibility in the hoop direction may be questionable in UCFT due to the higher Poisson’s ratio of steel in its elastic range. However, due to the load redistribution algorithm of the model the difference is expected to be negligible. The axial strain in the tube $\varepsilon_{sa}$ can then be calculated as

$$\varepsilon_{sa} = \frac{f_{sa}}{E_s} - \nu_s \frac{f_{sh}}{E_s}$$

(16)

where $f_{sa}$ and $f_{sh}$ are the axial and hoop stresses in the tube, respectively, and $\nu_s$ is the Poisson’s ratio of steel. Note that $f_{sa}$ in UCFT is zero, and tensile hoop strain is considered negative. While this essentially concludes short-term analysis of UCFT, for BCFT another level of iteration must be carried out for $\alpha$, until the difference between the axial strains in steel and concrete falls within the preset tolerance. Once convergence is achieved, the effective Poisson’s ratio of concrete $\nu_{EPR}$ is taken as the ratio of radial to axial strain in concrete core, and is kept constant throughout the time-dependent analysis.

2. The time step is incremented by a preset value of $\Delta t$.

3. Using the RFM and the double power law, the uniaxial creep strain ‘potential’ of concrete is estimated based on the current level of axial stress in concrete. In BCFT, it is necessary to account for the varying stresses in concrete by the principle of superposition. In UCFT, however, axial stress in concrete remains constant.

4. Axial creep strain in concrete is modified for the effect of multi-axial stresses using Eq. (7).

5. Radial creep strain in concrete is calculated using $\nu_{EPR}$ and Eq. (8).

6. Axial and lateral strains in the steel tube are calculated independently from concrete, taking into account the Poisson’s ratio of steel.

7. In BCFT, axial strains in concrete $\varepsilon_{ca}$ and steel $\varepsilon_{sa}$ are compared, and if the difference is larger than the preset tolerance, the axial stress in the tube is adjusted to maintain static equilibrium, taking into account the biaxial state of stress in the tube. In essence, a stress relaxation takes place, whereby concrete is relieved from part of its axial stress. Previous experiments by Morino et al. [7] have shown that the axial stress variation in the tube may be in the order of 10–20% of the initial stress, whereas stresses in concrete may vary about 5–10%. Steps 4 to 7 are repeated until convergence is achieved.

8. In both BCFT and UCFT, radial strain in concrete $\varepsilon_{cr}$ is compared with the hoop strain in steel $\varepsilon_{sh}$, and if the difference is greater than the preset tolerance, hoop strain in the tube is adjusted and a new confinement pressure $f_c$ is calculated. Steps 4 to 8 are then repeated until convergence is achieved. Upon convergence, failure of the tube is examined, according to Eq. (10) for uniaxial stresses in UCFT and Eq. (11) for biaxial stresses in BCFT. If failure has occurred, the procedure would stop. Otherwise, steps 2 to 9 will be repeated for the duration of sustained loads. Before embarking on a new time step, the varying creep stress
in concrete $\Delta f_{co}$ is determined to allow for time integral of creep strains based on the principle of superposition.

More details on the analytical procedure can be found in Naguib [20].

4. Model validation

The proposed model was validated against the experimental data of Terrey et al. [3] for a BCFT and a UCFT specimen, both of which with 600 mm height and 196 mm inside diameter, and a concrete core of 45.2 MPa. The tube thickness in BCFT and UCFT specimens was 1.5 and 1 mm, respectively, representing a $D/t$ ratio of 130 and 196, respectively. The inside surface of the UCFT was greased to prevent any friction bond between steel and concrete. Both specimens were loaded 18 days after casting with a sustained load of 350 kN for approximately 100 days. Based on the information on the mix and strength of concrete, a creep parameter $n$ of 0.147 was assumed for modeling of concrete.

Fig. 2 shows comparison between the experiment and the model for the total strains in concrete and steel in the UCFT specimen. The predicted strains in the tube were adjusted for the temperature variation of 10 °C during the creep tests. The analytical curves are parallel to the experimental ones. The model slightly overestimates strains in concrete, while underestimating those in the tube. This may be attributed to (a) some stress transfer between steel and concrete, as perfect debonding may not exist at the interface, and (b) difference in prediction of elastic strains using the confinement model of Ahmad and Shah [13]. Fig. 3 shows a comparison between the creep coefficients calculated for the test data and the proposed model. The creep coefficient is defined as the ratio of the net creep strain to the elastic strain, as

![Graph showing creep strains for UCFT specimen—comparison of model and experiments.](image-url)
\[ \phi = \frac{\varepsilon_{\text{Total}} - \varepsilon_{\text{Elastic}}}{\varepsilon_{\text{Elastic}}} \]  \hspace{1cm} (17)

The figure also shows creep curves of ACI 209 [21] for two different ultimate creep coefficients \( \phi_u \) of 1.2 and 1.45. The ACI 209 creep model follows a power law function, as

\[ \varphi(t,t_o) = \phi_u(t_o)\left(\frac{(t-t_o)^{0.6}}{10 + (t-t_o)^{0.6}}\right) \]  \hspace{1cm} (18)

where ACI 209 suggests \( \phi_u \) in the range of 1.3 to 4.15, with a typical value of 2.35 for ordinary concrete. The figure shows that creep of UCFT is much less than that of conventional concrete. The difference between the coefficient of 1.2 that matches the experiments and the coefficient of 1.45 that matches the model is considerably less than the usual range of variations for creep coefficients in concrete. The difference is due mainly to the difference in the elastic strain of concrete, which is slightly underestimated by the confinement model of Ahmad and Shah [13]. Although the model of Ahmad and Shah [13] was calibrated using a number of tests including small-scale CFTs, most of its applications are in conventional reinforced concrete columns.

Fig. 4 shows the total creep strains for the BFCT specimen along with the predicted strains from the proposed model. Also shown in the figure is the total creep strains calculated using the AEMM by Terrey et al. [3]. A good agreement is noted in the trend of the creep curve. The difference is again in predicting the initial elastic strain. Fig. 5 shows a comparison between the creep coefficients calculated for the test data and the proposed model. In the figure, creep curves of ACI 209 [21] are also shown for two different ultimate creep coefficients of 1.2 and 1.0, of which the former matches the test data and the latter matches the model. The difference in the creep coefficient is again due to the initial elastic strain in concrete [13], as described.
above. Otherwise, the net creep strains appear to be in good correlation with the experiments, as the creep curves in Fig. 4 are parallel to each other.

Nakai et al. [22] also tested three specimens with 1 m height, outside diameter of 165.2 mm and tube thickness of 0.0 (i.e. with no tube), 4.5, 5.0 mm, respectively. The specimens were filled with 29.4 MPa concrete, and tested for 6 months under a sustained stress of 7.85 MPa. Their suggested creep coefficient of 1.44–1.60 for CFT is compared with the proposed model in the next section.

5. Parametric study

Using the above model, a parametric study was carried out on the practical design factors that may affect long-term behavior of CFT for creep under service loads and for creep rupture.
5.1. Creep under service loads

The equivalent ultimate creep coefficient $\phi_u$ for CFT is calculated using Eq. (18) with the least square method, such that the ACI 209 [21] creep curve provides the best fit to the predicted creep. Figs. 6 and 7 show the ultimate creep coefficients for UCFT and BCFT, respectively, for different concrete mixes and column cross-sections. The mix is identified by creep parameter $n$, which is varied between 0.12 and 0.178 (see Table 1). The larger the $n$ value, the greater is the creep of concrete. The cross-section of the column is identified by $D/t$ ratio. The figures also show the suggested creep coefficients of Terrey et al. [3] and Nakai et al. [22] at their respective $D/t$ ratios. The following observations can be made:

- For the same concrete mix and creep parameter $n$, regardless of the interface bond
or lack of it, creep coefficient increases as $D/t$ ratio increases. Creep of CFT is asymptotically bounded by $\phi_{n,\text{Sealed}}$ for a sealed concrete of the same mix with no steel jacket ($D/t\to\infty$), and zero for an all steel column ($D/t\to0$).

- For the same concrete mix and creep parameter $n$ and column geometry $D/t$, BCFT curtails creep of concrete much more than UCFT.
- Effect of $D/t$ ratio is much more pronounced in BCFT, where stress redistribution can relieve concrete from some of its creep stresses. On the other hand, the tube in UCFT can only confine lateral expansion of concrete, while creep stresses in concrete remain constant.
- The proposed model is in general agreement with the suggested creep coefficients of previous studies [3,22]. However, the notion that a single creep coefficient can be applied to any concrete mix, column geometry, and interface bond is not appropriate.

5.2. Creep rupture

Creep rupture life of CFT is defined as the service life (time in years) that it takes for the column to develop yielding in the tube under sustained loads. As discussed earlier, failure in UCFT is uniaxial, whereas it follows the von Mises criterion in BCFT. Figs. 8 and 9 show the estimated creep rupture life of UCFT and BCFT, respectively, for one concrete mix No. 2 ($n = 0.14$), grade 60 steel tube (414 MPa yield), and different $D/t$ ratios, as function of $P/P_{\text{Static}}$, where $P$ is the sustained load and $P_{\text{Static}}$ is static capacity of the column. Following observations can be made:

- UCFT columns with thicker tubes are much less durable for creep rupture, because their static capacity is increased, without any stress redistribution that can relieve concrete from its creep stress. Creep rupture life of 75 years at 50% of static capacity is not feasible for UCFT with $D/t$ ratios of less than 80.

Fig. 8. Estimated creep rupture life of UCFT columns.
BCFT columns with thicker tubes are much more durable for creep rupture. This is due to the larger stress relaxation that can occur in concrete. Creep rupture life of 75 years is quite feasible for $D/t$ ratios of 40 or less, at even 65% of static capacity.

A comparison of estimated creep rupture life for UCFT and BCFT is shown in Fig. 10, as function of absolute value of sustained load, normalized as $P/f_c^2 A_c$, where $f_c$ is the 28-day compressive strength of concrete and $A_c$ is the area of concrete core. The figure shows that for $D/t$ ratios of less than 40, BCFT is much more durable than its equivalent UCFT. Moreover, creep rupture life of both types of column generally increases for smaller $D/t$ ratios.
6. Conclusions

Using the rate of flow method and the double power law creep function, an algorithm is developed for the creep of CFT columns by adhering to the strain compatibility and static equilibrium. The proposed model shows good agreement with previous creep tests on bonded and unbonded CFT. The study indicates that creep of CFT columns should be considered in the design, however, with creep coefficients much lower than those prescribed in the current ACI 209 [21]. A study on the effect of practical design parameters revealed the following:

- Creep of CFT is a function of concrete mix, column geometry, and interface bond. The notion that a single creep coefficient can be used for all concrete mixes and column geometries and types of construction is not appropriate.
- Creep of CFT is asymptotically bounded by $\phi_{u-Sealed}$ for a sealed concrete of the same mix with no steel jacket ($D/t \rightarrow \infty$), and zero for an all steel column ($D/t \rightarrow 0$).
- BCFT curtails creep of concrete much more than UCFT. This is due to the stress relaxation of concrete, which is more pronounced for smaller $D/t$ ratios.
- For the same magnitude of sustained loads, BCFT is much more durable for creep rupture than its equivalent UCFT for $D/t$ ratios of 40 or less.

Acknowledgements

This study is an extension of the first author’s dissertation on long-term behavior of concrete-filled fiber reinforced polymer (FRP) tubes, which was supported by the National Science Foundation CAREER award to the second author. Findings and opinions expressed here are those of the authors alone and not necessarily those of the sponsoring agency.

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