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CREEP ANALYSIS OF CONCRETE COLUMNS BY USING FINITE ELEMENT METHOD[#]

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Abstract. The authors have carried out studies on long term behavior of concrete-filled steel tubular (CFST) column by numerical methods based on experimental data that is described by a visco-elastic model, and the age-adjusted effective modulus (AAEM) method is adopted to modelling creep behavior of the concrete core, which is evaluated by the Finite Element Method (FEM) combined Prony's series interpolation by using ANSYS software. The CFST column with circular sections under long term sustained loading are performed, ensuring the ultimate load bearing capacity of the members is limited to cause cracks. In the material modelling, the confining effect of the concrete was taken into account while the steel was modelled as a bilinear kinematic hardening model with perfect bond between concrete and steel. The scope of applicability, advantages over other methods and limitations are discussed in detail.

Keywords: creep, viscoelastic, CFST, Prony series, AEMM.

Classification numbers: 2.9.4, 5.4.3.

1. INTRODUCTION

Concrete-filled steel tubular (CFST) column is a composite structure that possesses many mechanical benefits that best leverage the mechanical properties of the materials such as high strength and fire resistances compared to traditional concrete columns, so the CFST members are widely used in modern structures. In addition to the common mechanical behavior in concrete columns, the creep behavior is further considered. Creep in concrete, play a critical role in estimating the reduction of durability of materials. Structures that operate over a long period of time will be taken into consideration for stability or structures are affected by the surrounding environment by chemical factors, which work under constant load or high temperature will be affected by the factors that damage them and must consider creep phenomenon.

Many researchers have focused on long term experimental tests on the time-dependent response of concrete-filled steel tubular (CFST) members, conducted test on circular and square columns [1-4] modelled in the format of the ACI-209 model [5]. In order to take into account the

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time effects, the age adjusted effective modulus (AAEM) method is used [6]. For CFST members, The temperature and humidity are assumed to be almost constant during the whole year, so that the influence of temperature gradient could be kept to minimum values, only basic creep and autogenous shrinkage occur as the concrete as sealed inside the steel tube and cannot or limited to exchange moisture with the air [7-10]. Besides considering the effect of time, confining concrete to limit its exposure to the surrounding environment, it is also necessary to consider the bearing capacity to avoid causing damage such as cracks. In the load bearing process to limit factors that cause damage such as cracking, considering the ultimate load bearing capacity is necessary, previous researchers have evaluated the possibility of cracks and proposed suggestions [11-12]. Friction is an important parameter in considering the interaction between the two materials, in other words, friction factor represents the impact of reciprocal stress between steel and concrete. Therefore, simplified analysis can bring about many errors, because that core concrete is always in a multi axial stress state [13]. So to describe the interaction between steel and concrete is perfect and limit errors, the time-varying stress function is added. Finally, from the conclusions of the previous study, the authors attempt to evaluate the long term behavior of CFST columns based on empirical data [1], viscoelastic model [14-15] is used to predict the creep strain of the CFST columns quickly at any time by using the Prony series method [16], the accuracy is quite high, considering the ultimate load bearing capacity so that the cracks are neglected.

This paper proposes a viscoelastic model to calculate creep for CFST column by using Prony series, which is described by the Generalized Maxwell model characterized by elastic and viscous components, which are modelled as linear combinations of springs and damping. The prediction of the creep behavior was based on creep coefficient in ACI-209 model. Most importantly, FEM and support tools in the ANSYS software were employed to create 3D models for the nonlinear analysis of CFST columns. The process of calculating creep of CFST column is implemented in 365 days with different solutions, all using interpolation Prony for the creep problem of CFST column with stress values varying at a given time and remain constant for a corresponding period of time. The computed numerical results are then compared with analytical solutions based on discrete experimental data.

2. A BRIEF OF THE THEORY AND METHODS

2.1. Creep on CFST columns

The delayed creep behaviour of CFST is influenced by several factors such as concrete mixture, age of concrete, shape and size of the specimen, properties of aggregates, in which aggregates play an important role in creep. It is also known as the modulus of elasticity of the aggregate. For the conventional structure, creep phenomenon seems to occur when the structure is subjected to constant load for a while. For the CFST column structure, the stress value seems to change with the loading time. This means that when the CFST structure is loaded with constant load during the survey process, but actually the stress value acting on steel and concrete will change due to interaction between these two surfaces as well as the bearing characteristics of the concrete core. During the load-bearing process, there is a time when the stress will be constant, at which time the strain – time curve is proposed with three stages consisting of initial strain and creep strain, the shrinkage strain is ignored according to discussed above. The total strain axial of CFST column, or concrete strain in the steel tube is as follows:

$$\varepsilon(t)=\varepsilon_0+\varepsilon_{cr} \tag{1}$$

where, ε_0 is instantaneous strain, ε_{cr} is creep strain of steel tube due to concrete creep which means that the creep strain of concrete will decrease due to stress change in steel tube. When the stress varies with time, the total strain at time t may be expressed as the sum of the strains produced by σ_c^0 and the strains produced by the change in stress $\sigma_{c1}^c(t)=\sigma_c^c(t)-\sigma_c^0(t_0)$, calculated equations as expressed as indicators:

$$\varepsilon_c^c(t)=\varepsilon_c^0+\varepsilon_{sc}^c=\varepsilon_c^0+\varepsilon_{cc}^c+\varepsilon_{c1}^c \tag{2}$$

$$\varepsilon_c^c(t)=\frac{\sigma_c^0(t_0)}{E_c(t_0)}+\frac{\sigma_c^0(t_0)}{E_c(t_0)}\varphi(t,t_0)+\frac{\sigma_c^c(t)-\sigma_c^0(t_0)}{E_\varphi} \tag{3}$$

The axial creep strain of the CFST column can be expressed as:

$$\varepsilon_{sc}^c=\varepsilon_{cc}^c+\varepsilon_{c1}^c \tag{4}$$

where, ε_{cc}^c is creep strain of concrete with no steel confinement, ε_{c1}^c is the reduced strain of the concrete considering the steel tube confinement, which means the axial creep strain of CFST column ε_{sc}^c is equal to strain of steel tube due to creep ε_{s1}^c. In other words, actually the strain increment of the steel tube is the concrete creep. The strain when loaded at t_0 days of steel tube and concrete ε_s^0, ε_c^0, respectively. Hence:

$$\varepsilon_{sc}^c=\varepsilon_{s1}^c \quad ; \quad \varepsilon_s^0=\varepsilon_c^0 \tag{5}$$

The time dependent analysis of composite material sections is based on the following fundamental conditions: Static equilibrium and geometric compatibility. When the stress redistribution occurs during creep, internal force change of steel tube is N_s and concrete core is N_c. The stress change of steel tube and concrete are σ_{s1}^c, σ_{c1}^c, respectively. Therefore:

$$N_s+N_c=\sigma_{s1}^c A_s+\sigma_{c1}^c A_c=0 \tag{6}$$

Due to the characteristic of geometry, the area ratio of steel with respect to concrete is $\alpha = A_s/A_c$, Eq. (6), can be rewritten as:

$$\varepsilon_{s1}^c=-\frac{\varepsilon_{c1}^c}{\alpha E_s} \tag{7}$$

and equation (4), (5) becomes:

$$\frac{\sigma_c^0(t_0)}{E_c(t_0)}\left[1+\varphi(t,t_0)\right]+\frac{\left[1+\chi\varphi(t,t_0)\right]\sigma_{c1}^c}{E_c(t_0)}=-\frac{\sigma_{c1}^c}{\alpha E_s} \tag{8}$$

Letting $n = E_s/E_c(t_0)$ in Eq. (8), the change in stress on concrete and steel tube because of the concrete creep is expressed as follows:

$$\sigma_{c1}^c=\frac{\alpha n\sigma_c^0\varphi(t,t_0)}{1+\alpha n\left[1+\chi(t,t_0)\varphi(t,t_0)\right]} \quad ; \quad \sigma_{s1}^c=\frac{n\sigma_c^0\varphi(t,t_0)}{1+\alpha n\left[1+\chi(t,t_0)\varphi(t,t_0)\right]} \tag{9}$$

Finally, the total creep strain ε_{sc}^c of the CFST column is obtained as follows:

$$\varepsilon_{sc}^{c}=\frac{\varepsilon_{sc}^{0}\varphi\left(t,t_0\right)}{1+\alpha n\left[1+\chi\left(t,t_0\right)\varphi\left(t,t_0\right)\right]}\ with:\ \varepsilon_{sc}^{0}=\varepsilon_{c}^{0}\ at\ time\ t_0 \tag{10}$$

2.2. Age Adjusted Effective Modulus (AAEM)

During the long term load of the CFST column, creep behavior of concrete is characterized by time factor and stress transfer between steel and concrete, one of the most successful approaches to the creep analysis of concrete in the age-adjusted effective modulus method (AAEM) further developed by Bazant. The AEMM method for conventional concrete [16, 17] shown in Eq. (11), is used to compute the creep strain on concrete induced by loads varying with time. When the stress is applied gradually to the concrete, creep coefficient is different for each changes of stress, a reduced creep coefficient $\varphi(t,\tau)\,\chi(t,\tau)$ is introduced:

$$E_{\varphi}=\frac{E_c\left(t_0\right)}{1+\chi\varphi(t,t_0)} \tag{11}$$

The creep coefficient $\varphi(t,\tau)$ can be proposed by the ACI 209:

$$\varphi\left(t,t_0\right)=\frac{\left(t-t_0\right)^{\psi}}{d+\left(t-t_0\right)^{\psi}}\varphi_u \tag{12}$$

$$\varphi_u=2.35\gamma_{c,to}\gamma_{c,RH}\gamma_{c,\psi}\gamma_{c,s}\gamma_{c,\lambda}\gamma_{sh,a} \tag{13}$$

where: d (in days) and ψ are considered constants for a given member shape and size that define the time-ratio part; (t – to) is the time since application of load, and φ_u is the ultimate creep coefficient. For the standard conditions, the ultimate creep coefficient φ_u = 2.35. Additionally, the aging coefficient χ can be computed by the empirical expression:

$$\chi\left(t,t_0\right)=\frac{1}{1-e^{-\varphi\left(t,t_0\right)}}-\frac{1}{\varphi\left(t,t_0\right)} \tag{14}$$

This equation will be used to enter equation 11 to describe the decrease in elastic modulus of the material and then combine with equation 15 to infer the predicted curve.

2.3. Analysis creep behavior by using Generalized Maxwell model

To verify the creep of concrete by FEM, the viscoelastic model is used by the author. In this paper, use the physical models described for viscoelastic materials. This behavior is considered based on one of the best models describe the visco-elastic behavior of materials [14], the Generalized Maxwell Model is described by using the Prony series, which is a powerful method for modelling the behavior of the viscoelastic material. The model consists of n + 1 elements in parallel, which are n the Maxwell model and a spring, expressed as follows:

$$E(t)=E_0^E\left(\alpha_{\infty}^{E}\sum_{i=1}^{n}\alpha_i^E exp\left(-t/\tau_i\right)\right) \tag{15}$$

$$\alpha_i^E=\frac{E_i}{E_0}\quad;\quad\alpha_{\infty}^{E}=\frac{E_{\infty}}{E_0}\quad;\quad\alpha_{\infty}^{E}+\sum_{i=1}^{n}\alpha_i^E\le 1 \tag{16}$$

where, E_0 is the elastic material constant according to Hooke, E_i is the elastic material constant of the Maxwell's element, E_∞ is the equilibrium module. The viscosity coefficient is η_i which can be expressed over the time $\eta_i = \tau_i \times E_i$. Prony series was then proposed by the following formulas (17) relating shear and bulk modulus over the time:

$$G(t) = G_0\left(\alpha_\infty^G + \sum_{i=1}^{n}\alpha_i^G exp\left(-t/\tau_i\right)\right) \quad ; \quad K(t) = K_0\left(\alpha_\infty^K + \sum_{i=1}^{n}\alpha_i^K exp\left(-t/\tau_i\right)\right) \tag{17}$$

where, G_0, K_0 are initial shear and bulk modulus, respectively. G_i, K_i are shear and bulk modulus of *i-th* terms, no dimension. α_∞ could be simply calculated by t equal to zero.

Based on discrete experimental data for the reduction of the durability of concrete over the time, presented and calculated using the Prony series method, this set of data is obtained the terms i (α_i, τ_i) of the Prony series, with the curve fitting.

3. SIMULATION

3.1. Geometry model and material properties

According to [1], the columns are loaded with a force by an axial pressure $P = 5$ Mpa was implemented over the entire top surface of the CFST model, see the scheme in Fig.1. Boundary conditions that applied to the CFST columns where at the bottom surface the column is fixed at the three direction which three degrees of freedom at each node, translations in the nodal x, y and z directions. The analysis of the CFST columns was made of an eight-node solid element SOLID 185 type of element in ANSYS was used for modelling to both model of concrete and steel. The bilinear kinematic hardening model is adopted for the steel, with tangent modulus being 0.05 of the elastic modulus of steel 2.06e5 Mpa, Poisson ratio $\upsilon_s = 0.3$ is assumed. Elastic modulus of concrete at 28-day age $E_{cm} = 35.905$ GPa, Poisson ratio $\upsilon_c = 0.15$ is assumed. The ultimate creep coefficient $\varphi_u = 2.12$. The detailed geometry parameters are given in Table 1

Table 1. Axially compressed short columns.

Number	D× T× L (m)	f_y (MPa)	f_{ck} (MPa)	A_s (m^2)	A_c (m^2)	α	N_k	N_{ut}
1	1× 0.012× 3	345	40.7	0.037	0.748	0.0498	12.850	55.775
2	1× 0.018× 3	345	40.7	0.056	0.730	0.0761	19.158	64.732
3	1× 0.024× 3	345	40.7	0.074	0.712	0.1034	25.388	71.494
4	1× 0.03× 3	345	40.7	0.091	0.694	0.1317	31.540	77.432

The long term services load test was carried out under permissible limits, in order to limit the possibility of cracks and errors in the calculation process. Therefore, the ultimate load bearing capacity of the CFST column is based on equation [1] with $N_k = A_s f_y$; N_{u28} is the load bearing capacity when the concrete age is equal to 28 days as follows:

$$N_{ut} = N_k + \frac{\left(N_{u28} - N_k\right)t}{1.243 + 0.977t} \tag{18}$$

The maximum dead load of the CFST columns is taken from 30-40 % of the ultimate load.

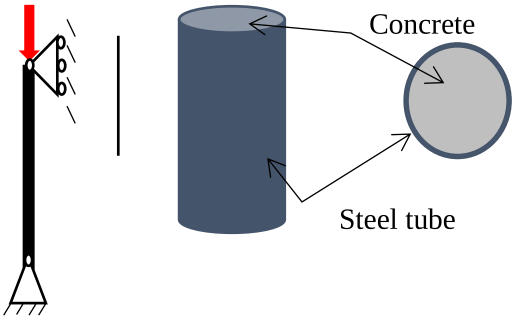

Figure 1. CFST column.

3.2. Creep calculation of concrete column with time-varying stress value

Table 2. Creep coefficient and elasticity modulus at time t_i.

Age (day)	Age (second)	φ(t,t0) (-)	χ (t,t0) (-)	G (Mpa)	K (Mpa)
28	0	0	0.5	15610.87	17097.62
60	2764800	0.9422	0.5774	10110.53	13358.7
90	5356800	1.1518	0.5939	9609.099	12028.79
120	7948800	1.2746	0.6034	9269.546	11441.25
150	10540800	1.3590	0.6099	8948.989	11073.44
180	13132800	1.4221	0.6147	8824.076	10524.25
240	18316800	1.5122	0.6215	8666.591	10152.36
365	29116800	1.6253	0.6298	7714.197	9801.274

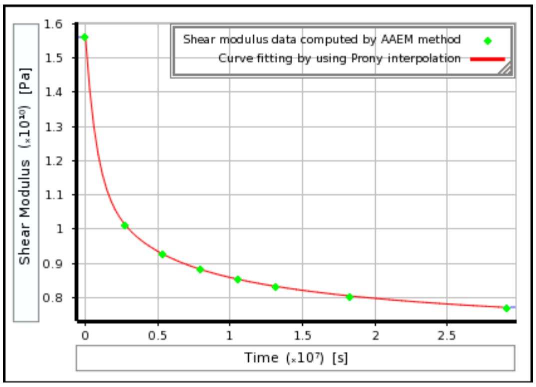

Figure 2. Shear Modulus Curve Fitting.

A detailed analysis of the creep coefficient was calculated from time t_0 = 28 days to t = 365 days. The durability values of concrete decreases over time for the COLUMN model are shown in Table 2, with the data computed using the ACI-209 and AAEM method. The creep curve of the material is determined by Prony's series interpolation, using the curve fitting tool in ANSYS.

Data points used to set curves listed in Table 2 are values G, K corresponding to the concrete age (second). The Prony interpolation from discrete data presented in Fig. 2.

Table 3. Creep parameters obtained by using interpolation of Prony series.

Index	Relative Moduli G, K	Relaxation Time G, K, (s)
1	0.263205	742988
2	0.133754	3342944
3	0.131522	16538227

The parameters used in the interpolation process are: Number of Terms *i-th* are used to improve model accuracy, which are mutually supportive. By using 3-th terms of Prony's series, the creep curve is defined, inference the parameters Relative Moduli and Time Relaxation of G, K. Creep parameters obtained by using interpolation of Prony series, are listed in Table 3.

3.3. Creep calculation of CFST columns

The total strain – time curves of 4 specimens are shown in Fig. 3. By the comparison between the analytical and numerical results, we can draw comments as follows: The use of Prony interpolation method with visco-elastic model is capable of predicting the creep behavior of CFST columns.

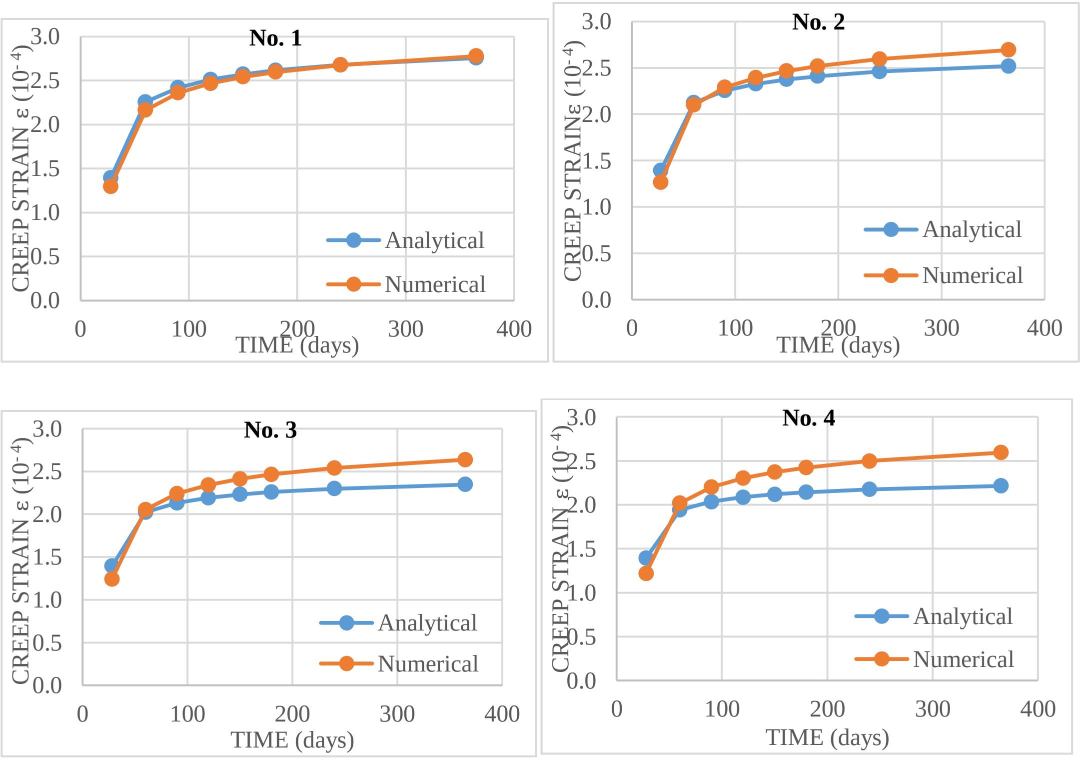

Figure 3. Strain – time curves of specimens No.1; No.2; No.3; No.4.

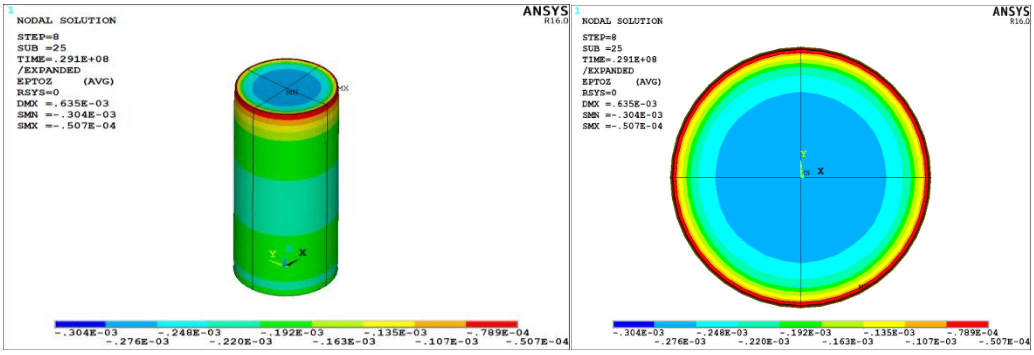

Figure 4. Axial deformation of CFST column No.1 at 365 days by using FEM.

The equation (10) shows that the results depend on the ratio between the two materials steel and concrete. Moreover, in ANSYS software the equation (15) is converted into the system of equations (17) to describe the change of the Poisson ratio which will change as the steel thickness increases. The mesh convergence and geometry compatibility as well as boundary conditions were briefly evaluated according to [1].

4. CONCLUSION

The analysis and calculation results presented in this paper are summarized as follows: From a plenty of strain – time or creep curves, creep strain still trends upwards. The effect of stress on the steel tube thickness of the CFST column is more horizontal deformation than vertical deformation. For short CFST column, the column length does not significantly affect the time dependent behavior. The evaluation of the problem with the Generalized Maxwell viscoelastic model and using Prony series with 3 pairs of parameters give high precision prediction results. In addition to assessing steel tube thickness, it is necessary to rely on other parameters such as load bearing capacity, composite material interaction. The difference between analytical and numerical results is due to the fact that the Prony numerical method or the Generalized Maxwell model only determines the behavior of concrete material. For CFST column structures when working in high temperature environments such as fires or environments with low humidity due to environmental factors such as rain, the CFST structures will limit the effects of creep phenomenon where traditional columns are limited due to the absence of steel layer to avoid moisture exchange with the environment.

The aim of this paper is using the numerical method described by the Prony string physical model to predict the long-term behavior of CFST column structure for a long time such as 1 year when experimental research is limited. In the future, the behavior of the CFST column will be analyzed by other methods such as the superposition principle or the nonlinear viscoelastic behavior of concrete as well as the plastic behavior of steel.

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