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Compressive behavior of concrete filled steel tubular columns subjected to long-term loading

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A B S T R A C T

Despite many successes in concrete creep studies, its effect on the mechanical behavior of concrete members is far from a thorough understanding. For the members subjected to a long-term loading, the classical stress–strain models for the short-term behavior of confined or uniaxially loaded concrete are not suitable. An experiment procedure was designed to investigate the effect of long-term loading on the compressive strength, modulus of elasticity, and stress strain of confined concrete. Eight concrete filled steel tubular (CFT) columns were prepared, four of which were subjected to constant compressive loadings for 411 days then unloaded, and the other four were companion load-free specimens. After two weeks of creep recovery, the specimens were axially loaded in compression up to failure. Based on the microprestress solidification theory for concrete creep and a plasticity model for concrete, an analytical model was presented to predict the behavior of CFT columns after creep. The comparison between the model predictions and the experimental results shows a good agreement. Both the experimental and theoretical results indicate that after creep the elastic modulus of CFT columns increased, while the compressive strength slightly decreases.

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1. Introduction

When subjected to sustained load the strength of concrete decreases with time under load [1,2]. The mechanical deterioration performance of concrete caused by creep requires the design concrete strength to be reduced with an increase in service lifetime. Therefore, when analyzing concrete members or structures, it is very important to investigate mechanical properties and behavior of concrete of the day, which are different from those of the concrete at 28-day age.

It is generally accepted that the mechanical behavior of a concrete filled steel tubular (CFT) member under load depends on the stress strain relationship of the constituent materials (i.e. steel and concrete). The stress–strain relationship of concrete under load is time-dependent and affected by the factors including ambient condition, creep, damage (at high stress level) etc. Therefore, the creep of concrete core will considerably affect the mechanical behavior of CFT. Unlike ambient condition (durability) and damage, the effect of creep on the stress strain relationship of concrete is considered in few studies.

The creep effect on the mechanical properties of other engineering materials, such as ceramic, metal and so on, was experimentally and theoretically investigated [3,4]. Although the creep mechanisms of these materials are pretty different from that of concrete, these researches indicated that the effect of long–term loading on the mechanical properties of these materials should be considered. Washa and Fluck [5] presented the experimental results which shown the effect of the 10.5-year loading period on the compressive strength and the modulus of elasticity of concrete. The results indicated that the modulus of elasticity values determined from tests of cylinders that had been loaded for 10.5 years were 20% higher than those for the companion unloaded cylinders, while the compressive strength was 5% lower. Cook and Chindaprasirt [6] gave partly different conclusions through their test data. The sustained load history marginally increases the compressive strength of concrete, but increase of the modulus of elasticity is more significant. Ozbolt and Reinhardt [2] studied the effect of sustained load on the compressive strength of concrete member, and concluded that the strength is only 70% of the instantaneous strength after creep. The decrease of strength due to creep was also considered by introducing a coefficient which depended on the time under load in CEB-FIP code [1]. Intending to investigate the influence of long-term loading on concrete columns, Choo et al. [7] provided a realistic long-term concrete stress strain model that includes the effects of creep and shrinkage. Although meaningful in practical applications of concrete structures, strictly speaking, the model could not be reckoned as a solution of the creep-effect problem because the branch of stress strain curve after the long-term service load was increased quickly was an identical copy of the counterpart of

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the short-term stress strain curve, moreover, the model was not validated through comparison with experimental data.

CFT column system has become increasingly popular in structural applications in the last few decades. To predict the strength and behavior of this system, many analytical models have been proposed. Hajjar and Gourley [8] presented a polynomial equation to represent the three-dimensional cross-section strength of square or rectangular CFT columns. Hu et al. [9] proposed proper material constitutive models for CFT columns, and verified them by the nonlinear finite element program ABAQUS against experimental data. Sakino et al. [10] attempted to derive methods to characterize the load–deformation relationship of CFT columns. Lakshmi and Shanmugam [11] proposed an analytical method to predict the inelastic and ultimate load behavior and to compute the ultimate strength of CFT columns.

In recent years, the creep of CFT attracted researchers' attention and a few experimental and theoretical studies were reported [12–15]. Yet for all that, the sustained load influence was not taken into account in the aforementioned models for predicting the stress strain behavior of CFT.

The purpose of this paper is to study the effect of sustained load on stress strain relationship of CFT columns with circular cross section. In this paper CFT is assumed as a special material, although it consists of two materials. The stress in the stress–strain curve denotes the average stress of the cross section, and the strain is the actual strain of the concrete and steel tube. Moreover, modulus of elasticity of CFT columns can be seen as a kind of generalized elastic modulus.

Creep tests were first performed, and after 411 days of creep and two weeks of creep recovery, compression tests were implemented on the creep specimens and the companion load-free specimens. A creep-plasticity constitutive model for CFT under uniaxial compression is presented to investigate the long-term loading effect. The creep strain of concrete core is modeled based on the triaxial generalization of the microprestress–solidification theory [16,17]. For the short-term stress strain behavior of CFT columns in compression, a plasticity approach for confined concrete based on the plasticity theory was adopted. The sum of plastic strain (irrecoverable strain) caused by sustained stress can be treated as the initial value of the effective plastic strain when analyzing the stress strain response in compression.

2. Experimental program

2.1. Specimen design

Eight cylindrical CFT columns are 150 mm × 150 mm in cross section and 450 mm in height. The wall thickness of steel tube is 5 mm. These specimens were divided into four groups and each group has one loaded creep specimen and one companion load-free shrinkage specimen, as shown in Table 1. The letters A and B in the names of specimens indicate the specimens are made from two different concrete mixtures, which would be described in details in Section 2.2.

2.2. Material properties

Two concrete mixtures were used, labeled A and B with the designed cubic compressive strengths at 28 days 60 MPa and 80 MPa, respectively. The corresponding measured cubic compressive strengths at 28 days are 63.0 MPa and 76.2 MPa. The proportion of mixtures is shown in Table 2. The average compressive and tensile strength of the steel tube are 351 MPa.

Table 1
Details of specimens.

Group	Specimen	Test objective
1	A1	Creep
	A2	Shrinkage
2	A3	Creep
	A4	Shrinkage
3	B1	Creep
	B2	Shrinkage
4	B3	Creep
	B4	Shrinkage

Table 2
Mix proportions of concrete A and B.

Mix proportions		Concrete A	Concrete B
Aggregate (kg/m^3)	Coarse	929.43	964.30
	Sand	760.44	727.45
Cement (kg/m^3)		451.61	470.50
Water (kg/m^3)		170	155
Additives (kg/m^3)		79.69	83.04
Water:cement (w/c)		0.46	0.43

2.3. Specimen preparation

The CFT columns were prepared in a material laboratory. The concrete ingredients were batched accurately, and then mixed thoroughly in a mixer into uniform concrete mixtures, which were poured into the steel tubes with pre-installed vibrating string strain gauges. A vibration table was used to achieve the compaction of concrete. Then, the specimens were cured in a standard curing room with a constant temperature of 20 °C and a relative humidity of more than 95% for 28 days. Meanwhile, three 150 mm standard cubes were prepared for each type of concrete mixtures to determine the 28-day cubic concrete compressive strength by standard uniaxial compression tests.

2.4. Instrumentation

The creep tests were conducted using a computer controlled stress relaxation testing machine, as shown in Fig. 1, which has 10-data acquisition channels and a maximum load capacity of 1000 kN. The axial load applied to the columns was kept constant by automatically compensating the stress relaxation caused by creep. The axial creep strain of specimens was recorded by an automatic data acquisition system which was connected to the pre-installed vibrating string strain gauges.

The compression tests were conducted using an electro-hydraulic servo-controlled test machine, as shown in Fig. 2. During the test, the axial stress and strain were recorded by an automatic acquisition system. The vibrating string strain gauges in the specimens are also used to measure the vertical strain.

2.5. Test procedure

In the creep test, the specimen was placed on the platen of the stress relaxation testing machine, and first compressed to 30% of the theoretical ultimate load, then remained constant. The stress relaxation problem in this test was addressed by manually resizing the load imposed by the test machine. The theoretical ultimate load of CFT columns can be calculated by an empirical formula in creep experiment design, written as

$$N_u = (1.212 + B\xi + C\xi^2) f_c A_{sc} \tag{1}$$

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