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Time-dependent behaviour of expansive concrete-filled steel tubular columns

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ABSTRACT

Expansive concrete-filled steel tubes (ECFST) are commonly used in modern building and bridge applications. Despite their popularity, limited attention has been devoted to investigate the time-dependent behaviour of such elements. This paper intends to provide new experimental data for the benchmarking of numerical models. Particular attention is devoted to ECFST elements first loaded at quite early concrete ages, e.g. 5 days after concrete casting, to reflect the construction site practice. Eleven ECFST short columns were subjected to different levels of sustained axial loads applied at different concrete ages. Seven columns were then tested to failure to evaluate the long-term effects on their ultimate capacity. The accuracy of four currently available concrete models, EC2, MC90, AFREM and B3, in predicting the long-term response of ECFST elements was investigated based on the related experimental results. Investigation shows that the assumption of linear creep can apply to ECFST elements with initial concrete compressive stresses up to approximately 80% of the concrete strength, rather than the normally accepted upper limit of 40%–50%. During the service life, confinement does not affect the performance of ECFST elements. Model EC2 is adequate to predict the time-dependent response of ECFST elements.

1. Introduction

In modern concrete-filled steel tubular (CFST) structures, expansive additive are commonly added in the concrete mix to reduce the tendency of the concrete to separate from the steel tubes. CFST members prepared with expansive concrete are usually referred to as expansive concrete-filled steel tubes (ECFST). Due to the extensive use of ECFST members in modern high-rise buildings and large-span bridges, it is necessary to have a comprehensive understanding of the time-dependent behaviour of such members.

Most research carried out to date on CFST members has dealt principally with normal concrete. In 1980s Tan and Qi [1] carried out 40 long-term tests on circular CFST specimens subjected to both axial and eccentric loads. These samples were loaded at different ages of concrete varying from 28 days to 13 months. One decade later, Terry et al. [2] conducted similar experiments on circular CFST samples axially loaded at an earlier age of the concrete, i.e. 18 days. Kwon et al. [3] reported other long-term tests on circular columns loaded at 28 days after the casting of the concrete. The effect of decaying sustained loads on the overall long-term response was investigated experimentally by Ichinose [4]. The first tests on square CFST specimens were performed by Morino [5]. This test series included six concentrically loaded columns, two eccentrically loaded columns and one flexural member. In all cases the load was applied at 28 days after the concrete pour. Similar cross-sections were tested by Uy [6] and Kwon [7] applying axial loading at 14 and 28 days of age of the concrete respectively. In the experiments of Morino [5], Uy [6] and Kwon [7], the stress level in the core concrete remained within 0.4 of the mean cylinder compression strength $f_{cm}(t)$. Higher sustained loads were reported by Han [8,9] on square and rectangular CFST specimens reaching stress levels in the core concrete higher than $0.7f_{cm}(28)$.

Wang [10] reported the first long-term tests on six ECFST short columns with identical material and geometric properties. The columns were loaded at 28 days after concrete casting at different levels of sustained axial forces maintained for a period of 100 days. The expansive additive used in his specimens weighed 20% of the weight of cement. Following Wang's work, Yao et al. [11] tested nine ECFST stubs with a lower amount of expansive additive (12.5% of the weight of cement). Different levels of axial loads were applied at 28 days after concrete casting and maintained for seven months.

In summary, only very limited research has focused on the time effects in ECFST applications, and the currently available experimental results on ECFST columns are obtained from tests with sustained loads applied at 28 days from concrete casting, despite the fact that current construction practice tends to load ECFST specimens at a concrete age much earlier than 28 days due to stringent construction requirements.

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This paper intends to provide new experimental data describing the time-dependent behaviour of ECFST circular short columns subjected to sustained axial loads first applied at early concrete ages ($t_0 \leq 28$ days, where t_0 is the time of first loading). The long-term deformation of eleven ECFST specimens was monitored over five months to study the influence of t_0 and of the applied stress level on their time-dependent behaviour. After five months under sustained loads, some of these specimens were tested to failure while the remaining ones were kept under sustained loads for a longer duration. The measured ultimate capacities of those specimens under sustained loading were compared against the one from the companion specimen (prepared with the same concrete mix at the same casting day) which was kept unloaded for the whole duration of the long-term tests to gain insight into the possible influence of time effects on the ultimate behaviour of ECFST specimens. Investigations on the confinement effect on long-term behaviour of ECFST specimens in service conditions are then provided based on the longitudinal and circumferential deformations measured on the steel tubes during the failure tests. Finally, the feasibility of available concrete models to predict the time-dependent response of expansive concrete in composite applications is evaluated. Four concrete models, EC2 [12], MC 90 [13], AFREM [14] and B3 [15], are considered in this study.

2. Experimental programme

2.1. Preparation of specimens

Eleven ECFST short columns were prepared for testing. For clarity these specimens have been subdivided into eight groups numbered from I to VIII.

The details of specimens are listed in Table 1. Some main test results are also included in Table 1, which will be illustrated later in the paper. Tabulated values include the outer diameter D, the thickness of the steel tube t_s, the length of the specimen L, the ratio of steel area over concrete area $\alpha = A_s/A_c$, the sustained axial force N_L, the concrete age at first loading t_0, the ratio of the sustained load over the cross-sectional ultimate capacity n_L (where $n_L = N_L/N_u$ and the ultimate capacity N_u is calculated at 28 days after the concrete casting), the initial stress level in the concrete $n_c(t_0) = \sigma_c(t_0)/f_{cm}(t_0)$ (where $\sigma_c(t_0)$ denotes the initial concrete stress of the time of first loading; $f_{cm}(t_0)$ defines the corresponding mean cylinder compression strength), the tested ultimate failure load N_{ul}, and the ratio K_f of the ultimate failure load observed for specimens tested under sustained load (i.e. specimens I, III, IV, and VII) over the ultimate capacity of the specimen kept unloaded during the long-term tests (i.e. specimen VIII). The ratio K_f provides an overview of the effect of creep on the ultimate capacity of the ECFST specimens. The adopted ultimate capacity N_u has been calculated according to reference [16]:

$$N_u = A_{sc} \cdot (1.212 + B\xi + C\xi^2) f_{ck} \qquad (1)$$

where A_{sc} $(=A_s + A_c)$ is the total area of the cross-section of the specimen; f_{ck} denotes the characteristic compression strength of 150 mm × 150 mm × 300 mm concrete prisms tested at 28 days from concrete casting which can be converted to an equivalent cylinder concrete strength (f_{cm28}) as recommended in Chinese code 'Code for design of concrete structures GB 50010 2002' [17]; $\xi = \alpha f_y/f_{ck}$ is defined as the confinement effect coefficient, in which f_y is the yield strength of the steel tube; $B = 0.1759 f_y/235 + 0.974$, in which f_y is in terms of MPa, and $C = -0.1038 f_{ck}/20 + 0.0309$, where f_{ck} is also in terms of MPa.

Eq. (1) well predicts the ultimate capacity of concrete-filled tubes with the ratio α in a range of 0.04–0.2, and with the concrete strength f_{cm28} varying between 20 MPa and 70 MPa as specified in the Chinese code 'Code for design of steel–concrete composite structure DL/T 5085-1999' [18].

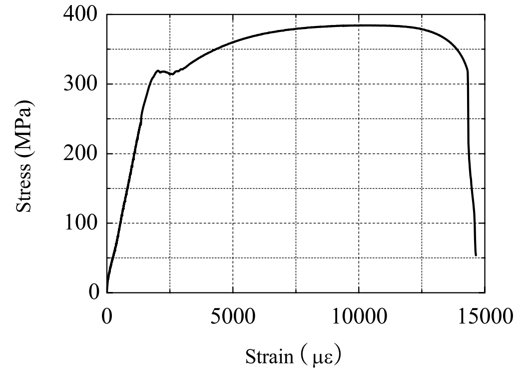

Fig. 1. Typical stress–strain curve for the steel tube.

Chen [19] reported that out of the 62 standing CFST arch bridges possessing a main span longer than 150 m, 44 bridges have arch ribs with the ratio α in the range of 0.06–0.1. In this context, $\alpha = 0.08$ was adopted in the design of the specimens to reflect common construction practice. All specimens had a length-over-diameter ratio (L/D) of 3 to reduce end effects and to prevent slenderness effects on test results.

The hollow steel tubes used for the eleven specimens were cut from one single 6 m long cold rolled circular tube with an outer diameter of 140 mm and a wall thickness of 2.6 mm. A 160 × 160 mm steel plate of 10 mm thick was welded to the bottom end of each stub. During casting, the specimens were kept in a vertical position and the steel tubes were kept ungreased to reflect the common site practice. All the specimens were cast on the same day in two batches. The concrete core was cast slightly higher than the steel tube to avoid the presence of gaps between the concrete core and the top steep plate before the top steel plates were welded. Immediately after the concrete pouring, the top surfaces of the specimens were tightly wrapped with plastic films to reflect the real situation in which the concrete core remains sealed during construction and in service. The plastic films were removed in 1 day and the top surfaces of the CFST specimens were ground plane and smooth. A 160 × 160 mm steel plate of 10 mm thick was then welded to the top of the steel tube to seal the concrete right after the smoothing operation was completed.

2.2. Material properties

2.2.1. Steel coupon tests

Standard tensile tests were carried out on AG-250kNI tensile testing apparatus, Shimadzu Co., Japan, to obtain the material properties of the steel tube. The sample preparation, the measurement of the geometrical properties of the coupons, and the testing speed have been carried out in accordance with Australian Code 'Metallic materials-Tensile testing at ambient temperature AS 1391 2007' [20]. During the test, the deformation of the coupons was measured by strain gauges located in the middle of the coupons on both sides. A representative stress–strain curve recorded during these tests is presented in Fig. 1 and the measured mechanical properties were: mean yield strength of 315 MPa, elastic modulus of 1.79×10^5 MPa and Poisson's ratio equal to 0.265.

2.2.2. Concrete cube tests

The concrete mix adopted for the specimens is outlined in Table 2. Its content reflects common specifications adopted in real CFST arch bridge applications and used an amount of expansive additive corresponding to 12% of the weight of the cement.