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Thermal creep and relaxation of prestressing steel

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HIGHLIGHTS

- Thermal creep and relaxation tests of prestressing steel are used for validation.
- Harmathy's creep model is enhanced by inclusion of tertiary creep.
- Parameters of the enhanced creep model are determined.
- Thermal creep and relaxation can be accurately predicted.
- Proper choice of thermal creep parameters is important to accurate prediction.

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ABSTRACT

The thermal creep and relaxation of prestressing steel are crucial to the permanent loss of prestress in post-tensioned concrete structures after fire. Harmathy's creep model is widely used to account for the irrecoverable thermal creep strain. In view of advances in steel manufacture, it is desirable to determine the relevant parameters of Harmathy's creep model for common prestressing steel being used. Recently, Gales et al. found that the creep parameters obtained by Harmathy and Stanzak in the 1970s were out of date as the use of these parameters could not give accurate numerical results. They further identified the parameters through testing of prestressing steel to ASTM A417. This study further extended the work of Gales et al. Based on the steady state thermal creep and relaxation tests of prestressing steel to GB/T 5224 (Grade 1860) and BS 5896 (Grade 1860) over wide stress ranges, the parameters of Harmathy's thermal creep model were identified and calibrated. Using the approach of Maljaars et al., the lower limit of tertiary creep was estimated and the creep model was further fine-tuned to incorporate tertiary creep. Numerical studies were conducted to examine the thermal creep and relaxation of prestressing steel at elevated temperatures using the enhanced creep model. The numerical predictions were found to agree well with the test results in respect of thermal creep and relaxation. In particular, predictions using the enhanced creep model with different sets of thermal creep parameters were compared with results of the thermal relaxation test conducted by MacLean, indicating different thermal creep resistance.

1. Introduction

Prestressing steel tendons in the form of strands or wires are important components in post-tensioned (PT) concrete structures, which enable the structures to achieve high load-carrying capacities and large span to depth ratios. In particular, the use of PT concrete slabs in buildings is becoming popular. However in view of the relatively small concrete covers provided to the tendons in slabs as compared to those in beams, once such slabs are subjected to fire, the steel tendons carrying high stresses are quite sensitive to the ensuing elevated temperatures causing their stresses to decrease because of the thermal elongation, mechanical degradation, and thermal creep and relaxation, which further reduce their load-carrying capacities. The mechanical properties of prestressing steel at elevated temperatures have been investigated by tests, mainly covering the elastic modulus, yield strength and ultimate strength [1–6]. It is well known that the mechanical properties degrade with increasing temperature. The thermal relaxation of prestressing steel has been investigated with emphasis on the permanent loss of stress [3,7–10].

The thermal creep of structural steel was addressed by Harmathy [11] in predicting the deformation of steel structures in fire. To solve the problem, a comprehensive creep model was proposed

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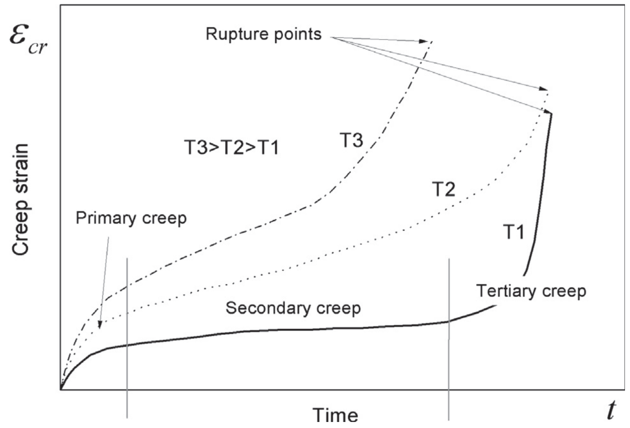
based on Dorn's creep theory [11]. Moreover, a series of thermal creep tests were conducted by Harmathy and Stanzak [12] to identify the parameters of the creep model, in which prestressing steel to ASTM A421 (Grade 1725) was investigated and its thermal creep parameters were identified as well. Recently, based on the creep model and thermal creep parameters of prestressing steel to ASTM A421 (Grade 1725), MacLean [3], Gales [7] and Gales et al. [8,10] proposed a method for prediction of the thermal relaxation of prestressing steel strands with validation against their thermal relaxation tests. However, comparison with the test results indicates the predictions have overestimated the thermal relaxation, which suggests that the thermal creep parameters need updating. Afterwards, steady state and transient thermal tensile tests of prestressing steel to ASTM A416 (Grade 1860) and BS 5896 (Grade 1860) were conducted to identify the thermal creep parameters of Harmathy's creep model by Gales et al. [13,14]. Besides, the thermal creep of prestressing steel to GB/T 5224 (Grade 1770) was investigated by Zhang and Zheng by steady state tests, proposing an empirical formula for estimating thermal creep strain [15]. However, in the determination of thermal creep parameters, Gales et al. [13,14] assumed the same value of thermal creep activation energy obtained by Harmathy and Stanzak [12] for prestressing steel to ASTM A421 (Grade 1725), and hence the results might need further refinement. The empirical formula proposed by Zhang and Zheng may also be improved by the development of a proper theoretical model. Besides, the prestressing steel made in Mainland China to GB/T 5224 (Grade 1860) [16] and that to BS 5896 (Grade 1860) [17] widely used in many places including Hong Kong are in need of a thorough investigation of thermal creep and relaxation properties. Therefore, such investigations will be desirable for providing accurate numerical predictions.

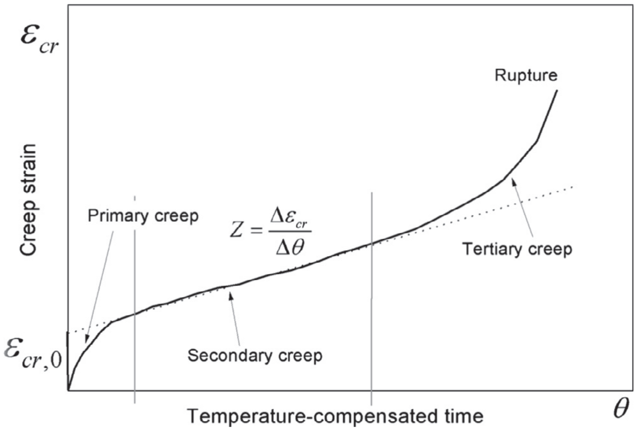
The present study further extended the work by Gales et al. [8–10]. Steady state thermal creep and relaxation tests of prestressing steel to GB/T 5224 (Grade 1860) and BS 5896 (Grade 1860) were conducted. Based on Harmathy's creep model, the thermal creep parameters were identified using the test results. As Harmathy's creep model cannot account for tertiary creep, the model has been further modified in order that tertiary creep can be explicitly incorporated. This will help structural designers to better understand and model the performance of prestressing strands at elevated temperatures.

2. Creep theory and existing model

Creep is the time-dependent plastic strain under constant stress and temperature. Prestressing steel invariably contains some defects of microstructure, which may cause movement of lattice dislocations under high stresses or diffusion under elevated temperatures. Thermal creep deformation can take two forms, namely solid state diffusion dominated creep, and glide or sliding dominated creep [18]. The former mechanism occurs at lower stress but higher temperature, and the creep strain is governed by the rate of solid state diffusion in the bulk of crystal grains or along grain boundaries, or by extensive diffusion-assisted dislocation climb for larger grain sizes. The latter mechanism occurs at higher stress but lower temperature, and the creep strain is governed by dislocation motion assisted by vacancy diffusion, dislocation slip over crystallographic planes which prevail at room temperature, with individual grains sliding over each other under the conditions of higher stress and temperature [18].



(a) Variation of creep strain with time



(b) Variation of creep strain with temperature-compensated time

Fig. 1. Creep strain at constant stress and temperature [19].

The three stages of creep [19] are shown in Fig. 1(a). The first stage or primary creep develops rapidly but at decreasing strain rate. The second stage known as secondary creep or steady-state creep develops linearly at a strain rate that remains nearly constant. The third stage or tertiary creep is characterized by accelerated strain rate until rupture. Secondary creep is better understood among various stages at elevated temperatures, and the creep rate obeys Arrhenius's Law given by

$$\frac{\partial \varepsilon_{cr}}{\partial t} \propto \exp\left(-\frac{Q_c}{R\bar{T}}\right) \qquad \frac{d\sigma}{dt} = 0 \tag{1}$$

where ε_{cr} is the creep strain; t is time; Q_c is the activation energy for thermal creep, which is approximately the activation energy for lattice self-diffusion when it is above half of the melting temperature (in Kelvin); R is the gas constant; $\bar{T}$ is the temperature in Kelvin; and σ is the creep stress in MPa.

The temperature-compensated time θ according to Dorn's creep theory as presented by Harmathy [11] is

$$\theta = \int_0^t \exp\left(-\frac{Q_c}{R\bar{T}}\right) dt \tag{2}$$

Differentiating Eq. (2) with respect to time t, and substituting into Eq. (1) give

$$\frac{\partial \varepsilon_{cr}}{\partial \theta} = \frac{\partial \varepsilon_{cr}}{\partial t} \exp\left(\frac{Q_c}{R\bar{T}}\right) \equiv Z \tag{3}$$

where Z is the Zener-Hollomon parameter [20] as shown in Fig. 1(b), which is taken as a function of stress and independent of temperature. The dimensionless parameter $\varepsilon_{cr,0}$ in Fig. 1(b) can be obtained by extending the straight line for secondary creep to the vertical axis, which is uniquely determined by stress and also independent of temperature.