Verification of Steel Constitutive Models in Japanese and European Fire-Resistant Design Codes

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Simulations are conducted using constitutive models of structural steel at elevated temperatures described in Eurocode 3 and the AIJ Recommendation, and the analytical results are compared with existing column test data. Based on the calculated results using s-e curves in the AIJ Recommendation, we obtained somewhat conservative failure times, which are, thus, on the safe side. In addition, the calculated behavior with the s-e curves in Eurocode 3 seemed to reproduce the experimental values accurately except that the calculated displacement was slightly larger than the experimental displacement.

Key words: High temperature, σ–ε curve, Eurocode 3, AIJ Recommendation , Steel column, Fire-resistant design

1. INTRODUCTION

It is a well-known fact that the material behavior model used for structural analysis has validity as a predictor of fire behavior.

It can be safely assumed that fire behavior models of steel have three main components: thermal strain, instantaneous stress-related strain, and creep strain. However, for practical considerations in fire conditions, the time when a steel structure is exposed to high temperature is short so that the creep strain is small. Therefore, it is often assumed that the creep of steel is incorporated in the stress-strain relationship at different temperatures in a simplified manner as that used in Eurocode 3 and the AIJ Recommendation.

With a focus on steel columns, this paper illustrates the differences in behavior that may be obtained depending on the material models chosen.

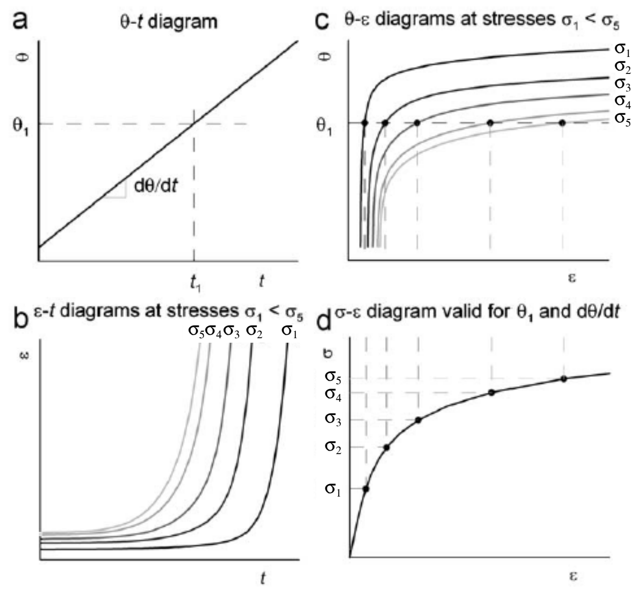

Fig.1 Transient tests and constructed σ–ε curve [3]

2. CONSTITUTIVE MODELS IN FIRE-RESISTANT DESIGNS

2.1 Stress-Strain curves in Eurocode 3

2.1.1 Simplified model for design purposes

In Eurocode 3, a simplified model is used in practice, in which an approximate value of the creep strain is incorporated into the stress-strain relationship. The model is solely based on transient-state tests and the procedure to construct the σ–ε relationship is as follows.

Figure 1 contains an explanation of how these σ–ε curves are derived. The material is heated at a certain heating rate *dθ/dt* (Fig. 1a) and subjected to a stress level which is kept constant in time. The mechanical strain that develops with time depends on the stress level (Fig. 1b).

The mechanical strains determined in Fig. 1b are plotted as a function of the temperature in Fig. 1c. The σ–ε curve is obtained by plotting the stress levels as a function of the strains developed at a certain temperature (Fig. 1d). The so-called transient state σ–ε curve of Fig. 1d is valid for a certain temperature θ_1 and heating rate *dθ/dt*. By applying this method, the influence of high-temperature creep is incorporated into the σ–ε relationship.

It is noteworthy that the σ–ε curves resulting from steady-state tests at elevated temperature and transient-state tests may

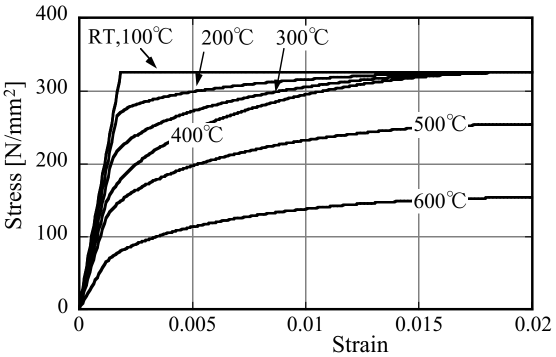

Fig.2 Stress-strain curves (Eurocode 3)

Valid only for heating rates: 2-50 K/min

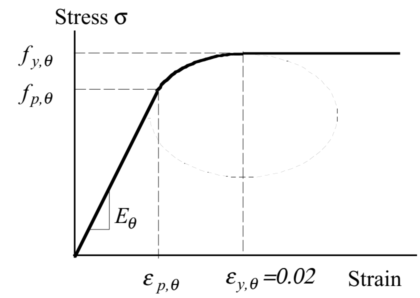

Fig.3 Key parameters of a stress-strain curve(Eurocode 3)

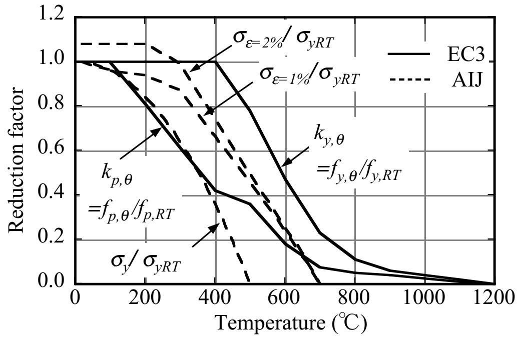

Fig.4 Redction factors (Eurocode 3)

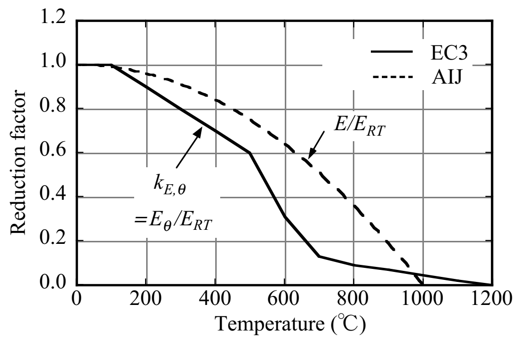

Fig.5 Redction factors (Eurocode 3)

differ for structural steels, a fact which is attributed to the influence of creep. This difference is also dependent on the heating rate in the transient test. Frequently, when using constructed σ–ε curves for design, somewhat conservative values are obtained, which are on the safe side.

2.1.2 σ–ε curves in Eurocode 3

The stress-strain curves described in Eurocode 3 are shown in Fig. 2. In Eurocode 3 , the σ–ε curves of structural steel consist of a straight line for the initial response followed by an elliptical branch and then a plateau. Figure 3 provides an illustration of this model and shows the same parameters to be used in the mathematical model[2].

To use this model, the reduced strength and stiffness of steel at elevated temperatures are required as input data. The parameters are exclusively dependent on the temperature level.

Graphic representations of the parameters are shown in Figs. 4 and 5. The parameters are expressed as the ratio of the value at elevated temperature to that at ambient temperature. These ratios are often referred to as reduction factors. Reduction factors for proportional limit $k_{p,\theta}$, yield strength $k_{y,\theta}$, and elastic modulus $k_{E,\theta}$ for structural steel are derived from the test data collected by Kirby and Preston[4].

Referring to Figs. 3 and 4, at 600 C, the yield strength decreases to about half its ambient temperature value, while the elastic modulus and proportional limit decrease more rapidly to about 30% and 20%, respectively, of their ambient values. Referring back to Fig.2, the bilinear elastic plastic relationship, which is commonly assumed in idealized stress-strain models at ambient temperature, disappears as the material becomes more inelastic under elevated temperatures.

2.2 Stress-Strain curves in the AIJ Recommendation

The σ–ε curves of steel in the AIJ Recommendation are determined on the basis of the result of the steady-state tensile tests under constant high temperatures with a strain rate of dε/dt=0.3%/min. In Fig. 5, the stress values at 1% strain on the σ–ε curves obtained by the steady-state tensile tests are plotted and jointed by straight lines to show the same materials. The lower bound of all the stress values at 1% strain is estimated and shown by a thick straight line.

The stress-strain curves in the AIJ Recommendation are shown in Fig. 7. To represent mathematically the characteristics of σ–ε curves at different temperatures, three equations in Fig. 8 are adopted.

The elastic part and the flat yield plateau are described by two linear lines defined individually by the modulus of elasticity E and yield stress σy. The strain-hardening branch in the tri-linear σ–ε curves and the round-house type σ–ε curves at high temperature is described by a curved line

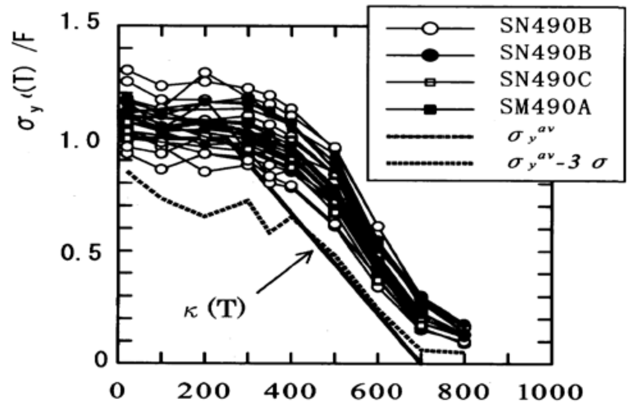

Fig.6 Effective yield strength to 1 % strain(AIJ[1])

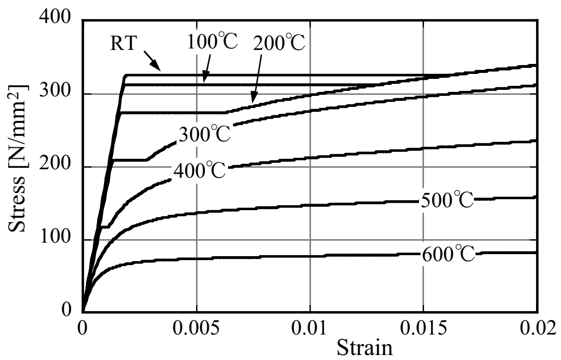

Fig.7 Stress-strain relation(AIJ[1])

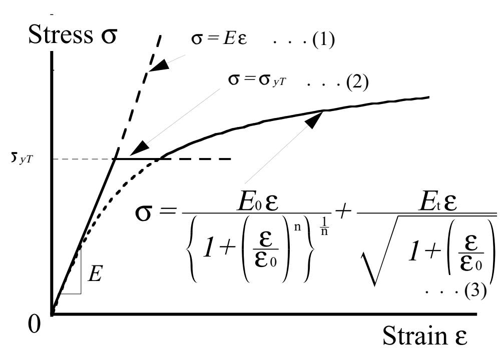

Fig.8 Stress-strain relationship(AIJ[1])

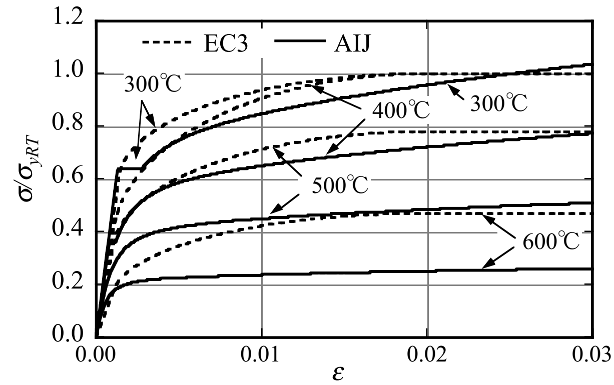

Fig.9 Comparison of σ-ε curves in EC3 and AIJ(300-600℃)

equation with the initial modulus of elasticity E.

The stress values at 1% strain of the σ–ε curves in the AIJ Recommendation (Fig. 7) are determined so that they agree with the lower bound of the experimental values (Fig. 6). Therefore, the σ–ε curves in the AIJ Recommendation are somewhat lower than the experimental ones in general.

The graphic representations of the yield stress, stress at 1% strain, stress at 2% strain and elastic modulus are shown in Figs.4 and 5.

2.3 Comparison of σ–ε curves in EC3 and AIJ

In Fig. 9, the σ–ε curves in Eurocode 3 and the AIJ Recommendation, from 300 to 600 C are compared. In this figure, the solid lines are the σ–ε curves in Eurocode 3, and the dotted lines are the AIJ Recommendation σ–ε curves.

At 300 C, the shape of the σ–ε curve in Eurocode 3 is the round-house type, but the σ–ε curve in the AIJ Recommendation have a flat yield plateau. From 400 C to 600 C, the difference between the curves in Eurocode 3 and the AIJ Recommendation is very large, and the ultimate strength of the AIJ Recommendation is considerably smaller than that of Eurocode 3.

3. SIMULATION OF COLUMN FIRE TEST

Simulations are conducted by a finite element method using σ–ε curves of steel at elevated temperatures described in Eurocode 3 and the AIJ Recommendation, and the analytical results are compared with existing column test data.

3.1 Steel Column Fire Test

A full-scale test on a steel column exposed to fire that was conducted by Kohno [6] has been simulated by the finite-element method on the basis of the beam theory. Two press-formed square steel columns, B-CS06 and B-CS10, were used for test specimens. Test columns were fabricated using SN490B grade steel, and the measured value of the steel yield strength was 363MPa. The sectional dimension of columns was □ -600x600x28, and the slenderness ratio was λ=0.23.

The existing load ratios to the sustained allowable load were 0.6 for B-CS06 and 1.0 for B-CS10. The steel column B-CS06 was heated by the ISO 834 standard fire temperature curve, and B-CS10 was heated by the hydrocarbon fire curve.

3.2 Analytical Results and Experimental Results

The experimental results and the results of the numerical analysis are shown in Figs. 10 and 11. The upper figures in Figs. 10 and 11 show the steel temperatures measured at points on specimens (experimental values), and the steel temperatures of B-CS06 and B-CS10 rose almost linearly with a temperature rise of 2.5 to 3.3 K per minute.

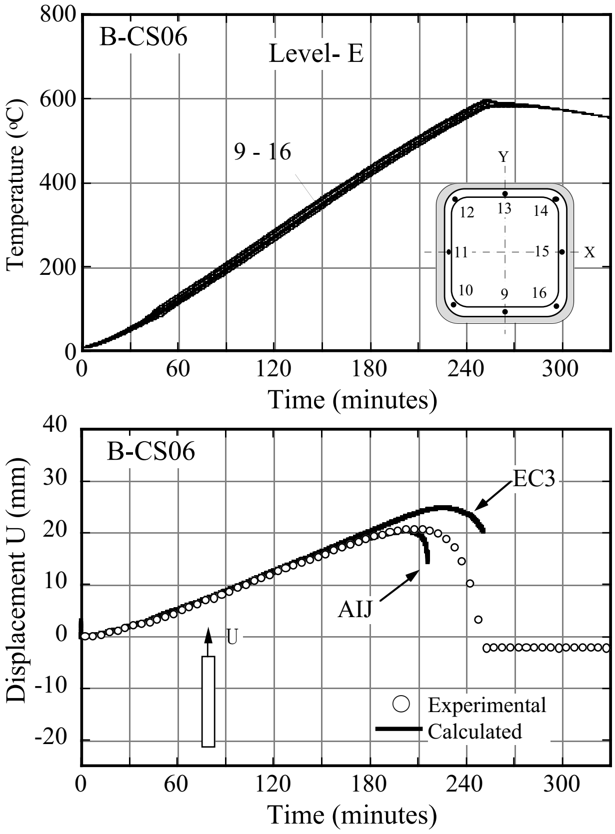

Fig.10 Measured and calculated results(B-CS06)

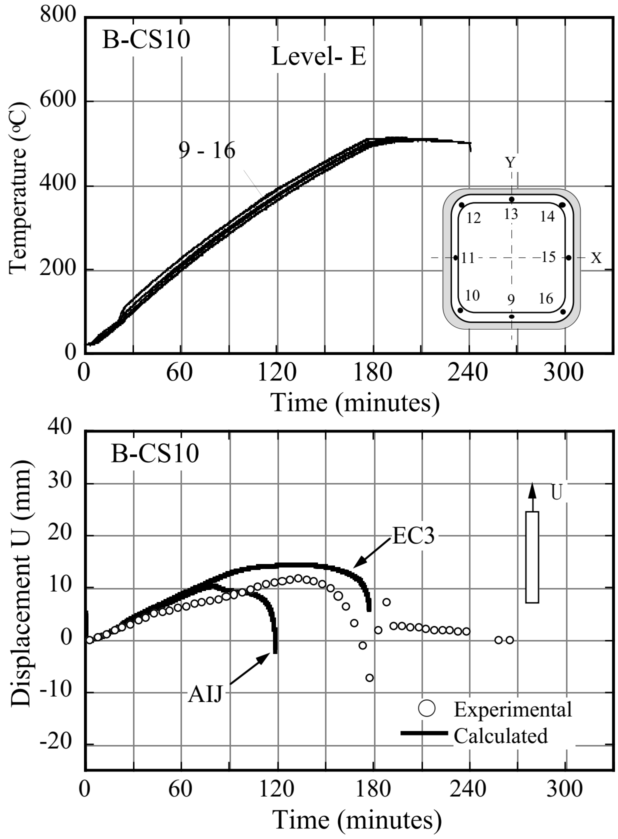

Fig.11Measured and calculated results(B-CS06)

The lower figures in Figs. 10 and 11 show the column elongations; open circles denote the experimental values, and solid lines denote the values calculated using the σ–ε curves described in Eurocode 3 and the AIJ Recommendation.

In Fig. 10, the calculated values for B-CS06 reproduced the experimental values very accurately up to 180 minutes. However, the failure time with the σ–ε curves of AIJ was somewhat conservative. On the other hand, the collapse time with Eurocode 3 agreed very well, but the calculated displacement *U* with Eurocode 3 (solid line) was slightly higher than the experimental displacement *U* (open circles).

In Fig. 11, the failure time by the σ–ε curves in the AIJ Recommendation was very conservative. The calculated behavior by the σ–ε curves in Eurocode 3 seemed to reproduce the experimental values accurately except that the calculated displacement *U* (solid line) was slightly larger than the experimental displacement *U*.

4. CONCLUSIONS

Based on the numerical analysis of the steel column tests under fire conditions, the following conclusions were obtained.

The σ–ε curves in the AIJ Recommendation for the buckling behavior of steel columns lead to a conservative failure time that is on the safe side.

The σ–ε curves in Eurocode 3 for the buckling behavior of steel columns reproduced the experimental values accurately except that the calculated displacement *U* was slightly larger than the experimental displacement *U*.

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