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TESTING THE ACCEPTABILITY OF DIFFERENT CREEP STRAIN CALCULATION MODELS IN STRUCTURAL FIRE ANALYSIS

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Abstract. *This paper investigates the accuracy of a selection of creep models in predicting the structural behaviour of steel under various heat rates and load ratios. Most of the commonly-used stress strain laws of steel for structural fire engineering have already implicitly considered the creep strain, however, these considerations cannot adequately capture the effects of the stress level, heat rate and strain rate on the creep strain of the steel. In this paper, several available creep models were implemented into the finite element code-Vulcan and the acceptability of these creep models was tested by the comparisons with published experimental results. In order to introduce an explicit creep model into the structural fire analysis, the substantial implicit creep should be removed from the initial material laws. A practical way to obtain the creep-free material curves from established material laws is proposed and it has been demonstrated that the combination of an creep-free stress strain curve with an explicit creep model can improve the accuracy of the prediction of the creep strain of steel in fire.*

1 INTRODUCTION

Creep strain is a temperature-, time- and stress-dependent variable in common structural fire analysis procedures, which is rarely included explicitly. Prediction of creep strains is rather complicated, compared to calculation of the other strain components in steel, because of the different physical phases of creep that occur in stressed steel during a fire. The influence of creep on structural behaviour is usually experienced through a reduction in fire resistance, and strong dependence of the behaviour on the temperature-time history. Generally, passive fire protection causes slow growth and decay of the structure temperatures in fire, and “natural” fire curves including a cooling phase may further slow heating rates in the protected steel members. In such cases the creep strains are likely to influence structural response of these members significantly. There are two ways of introducing the realistic creep strain into the structural fire analysis. One is to use the effective temperature-stress-strain curves extracted from the standard tests and the other is to use specific and proper creep model in the structural analysis. The first approach requests amount of data bases from the standard tests and may not be handy for the engineers' use, whereas the second approach is better for general engineering use but does request cautions when selecting the proper creep models. Recently the effects of creep strain of steel on the performance of buildings in fire, considered explicitly within the thermo-structural analysis rather than implicitly in equivalent stress-strain curves, has been attracting growing research interest. However, creep strain models suitable for adoption in performance-based structural fire engineering design and assessment practice still need to be explored and developed.

Although a steel temperature of 400°C is generally assumed to be the temperature above which creep strains can become significant within the time-scale of some building fires, the ranges within which creep strains should be taken into account in thermo-structural analysis are still vague. Further investigation of the influence of heating rates and stress levels on creep strain development is necessary to identify where creep strains need to be explicitly included.

As an initial investigation of the ways in which creep influences the behaviour of steel structures in fire, and the issues to be covered when embedding creep strain calculation into global modelling used in performance-based structural fire engineering design, this study attempts to combine different creep models with commonly used constitutive laws for steel, and to test the reliability of these combinations in structural fire analysis.

This paper presents the results of some recent enhancements of the *Vulcan* research code in conducting creep analysis, including verification against experimental data. Several types of explicit creep development models [1-3] are implemented for this purpose. Comparisons are made with results from published experimental studies [4-6]. The experimental studies were conducted on common contemporary structural steel, of grades S275 and S355. In order to investigate the influence of the basic stress-strain material model on the creep analysis, two such models (Eurocode 3 and Ramberg-Osgood) were used in the simulations.

Furthermore, the paper investigates practical ways of expressing constitutive laws for steel, to be used in fire engineering analysis, as a combination of a basic (creep-free) ambient-temperature stress-strain curve, temperature-dependent reduction factors on these, and a temperature-dependent creep law.

2 NUMERICAL MODELLING

2.1 Implemented creep models

Generally, there are two types of formulations to predict the creep in steel, i.e. time hardening formulation and strain hardening formulation. Time hardening rule is based on the assumption that the stress level during fire exposure is constant and that the creep strain rate is a function of stress and time. Strain hardening rule is based on the assumption that stress level changes during fire exposure and that the creep strain rate is function of previously accumulated creep strain and stress. Three widely-used creep strain models were implemented in *Vulcan* research code for this study. The details of these models are described as follow.

First implemented creep model (*Creep_model 1*) follows Harmathy's strain hardening rule [2], which can be expressed as:

$$\varepsilon_{cr} = Z \cdot exp\left(-\frac{\Delta H}{R \cdot T_{\mathrm{R}}}\right) \cdot coth^2\left(\frac{\varepsilon_{cr,c}}{\varepsilon_{\mathrm{cr},0}}\right)\Delta t \tag{1}$$

where T_R is the temperature (K), R is the universal gas constant (J/molK), ΔH is the creep activation energy (J/mol), Z is the Zener-Hollomon parameter (h^{-1}), $\varepsilon_{cr,0}$ is a dimensionless creep parameter, $\varepsilon_{cr,c}$ is previously accumulated creep strain and Δt is the time increment.

Second implemented creep model (*Creep_model 2*) follows Harmathy's a time hardening rule [1], which can be expressed as:

$$\varepsilon_{cr} = \frac{\varepsilon_{cr,0}}{\ln 2} \cdot cosh^{-1}\left(2^{\frac{Z\theta}{\varepsilon_{cr,0}}}\right) \qquad \left(\theta < \theta_0\right) \tag{2}$$

$$\varepsilon_{\mathrm{cr}} = \varepsilon_{\mathrm{cr},0} + Z\theta \qquad \left(\theta \geq \theta_0\right) \tag{3}$$

$$\theta_0 = \varepsilon_{\mathrm{cr},0} / Z \tag{4}$$

where θ is temperature compensated time θ [1].
Third implemented creep model (*Creep_model 3*) is Plem's strain hardening rule [3], which can be expressed as:

$$\varepsilon_{\mathrm{cr}} = \varepsilon_{\mathrm{cr},0}(2\sqrt{Z\theta / \varepsilon_{\mathrm{cr},0}}) \qquad (0 \le \theta < \theta_0) \tag{5}$$

$$\varepsilon_{\mathrm{cr}} = \varepsilon_{\mathrm{cr},0} + Z\theta \qquad (0 \le \theta < \theta_0) \tag{6}$$

where θ_0 is determined from Eqn (4). Temperature compensated time θ for Plem's model is calculated as:

$$\theta = \theta^0 + exp^{\frac{\Delta H}{RT_R}} \Delta t \tag{7}$$

where θ^0 represents shifted temperature-compensated time, which is a function of previously accumulated creep strain. Material parameters Z, ΔH, R and $\varepsilon_{\mathrm{cr},0}$ are taken from study [7] for steel A36, which is equivalent to Eurocode steel grade S275:

$$\varepsilon_{\mathrm{cr},0} = 1.03 \cdot 10^{-6} \sigma^{1.75} \tag{8}$$

$$Z = 3.75 \cdot 10^{8} \sigma^{4.7} \quad (\sigma \le 103 \text{ MPa}) \tag{9}$$

$$Z = 1.23 \times 10^{16} exp^{0.0435\sigma} \quad (103 < \sigma \le 310 \text{ MPa}) \tag{10}$$

$$\frac{\Delta H}{R} = 38900 \text{ K} \tag{11}$$

2.2 Experimental studies

The results of two different experimental studies were chosen to test the reliability of selected creep models.

A series of transient coupon tests at various heating rates and stress level were conducted by Wainman and Kirby [4]. The heat rates varied between 2.5°C/min to 20°C/min and the stress level ranged from 25 MPa to 350MPa. British standard steel grades 43A and 50B were tested in the study, which correspond to Eurocode 3 steel grades S275 and S355, respectively.

Boko *et al* [5] conducted a small series of transient coupon tests on a more recent alloy of steel grade S355 at various stress levels between 50-400 MPa. A single heating rate of 10°C/min was used in the transient tests.

Above experimental tests were selected since they focused on commonly used steel grades in engineering practice. The heat rate in the tests conducted by Wainman and Kirby [4] and Boko *et al* [5] are of interest for the development of creep-free material law, which will be described in detail in section 2.3.

The coupon tests mentioned above were modelled by three-noded beam elements with segmental cross section in *Vulcan*. The same boundary conditions and load levels as in the experimental tests were applied on the finite element models. The coupons were pre-loaded before the temperatures start to increase according to the heat rates in the experimental tests.

2.3 Creep-free material law

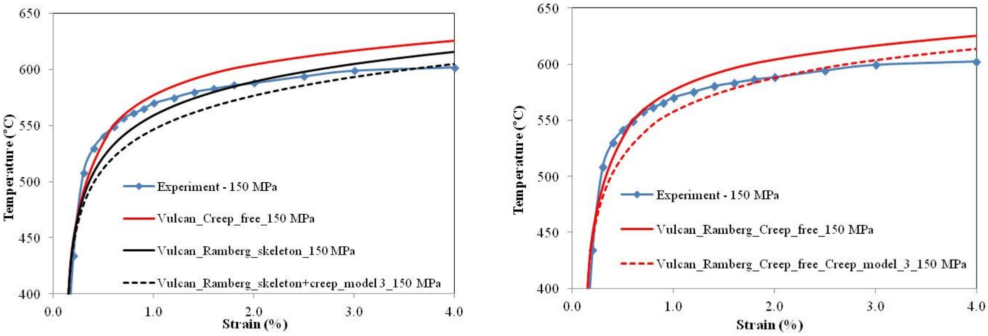
Eurocode 3 material stress-strain law [8] is very commonly used in structural fire design and analysis by scientists and structural engineers and it has implicit consideration of the creep strain. These considerations were on the basis of Kirby's tests [4] with heating rate of 10°C/min and only included the "likely" deformations due to creep during the time of exposure to the fire. Recent research [9-10] have shown that implicit creep contained in the Eurocode 3 curves cannot account for the effects of creep strains on structural response if prolonged temperature exposure over 400°C is present.

With the purpose to introduce proper creep models into the structural fire analysis, it is necessary to omit the implicit creep consideration in the mechanical stress-strain curve in order to avoid the over- or under-estimation of the creep strain. A practical procedure of excluding implicit creep from Eurocode stress-strain curves will be presented briefly in the paper.

A series of transient coupon tests at different stress levels are modelled in *Vulcan* in order to obtain corresponding temperature-creep strain curves. These curves can be used to construct a series of stress-creep strain curves, which are then used to subtract the initial material stress-strain curves. This procedure is basically a reverse of the methodology by which a stress-strain curve is constructed from a series of transient tests. The proposed methodology was applied to the Eurocode 3 and Ramberg-Osgood material curves to generate corresponding creep-free stress-strain laws.

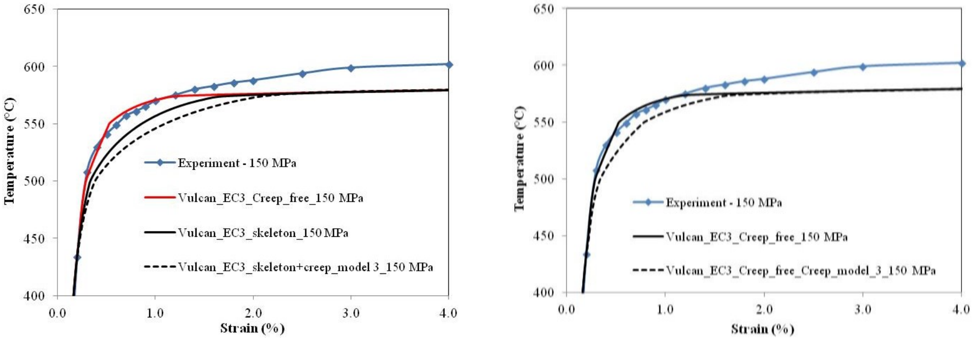
3 COMPARISON OF RESULTS

In this section a selection of study results is presented. Figure 1 presents the comparison of the results from Kirby's experimental tests [4] with stress level of 150MPa with the predictions from *Vulcan* using *Creep_model 3* .



(a) S275 10°C/min – Ramberg-Osgood curves

(b) S275 10°C/min – Ramberg-Osgood creep free curves

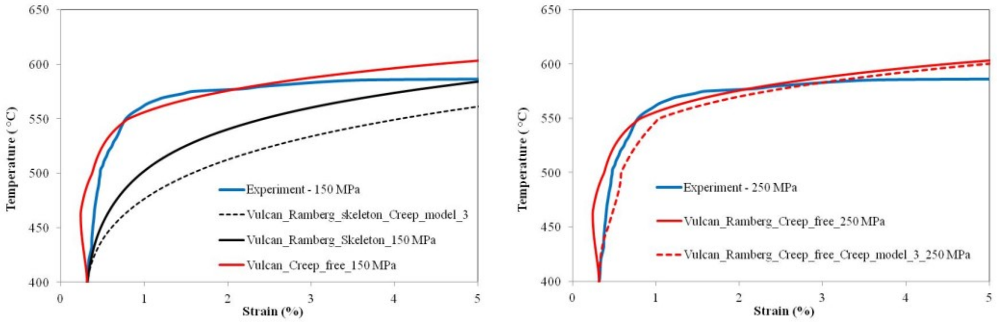


(c) S275 10°C/min – EC3 curves

(d) S275 10°C/min – EC3 creep free curves

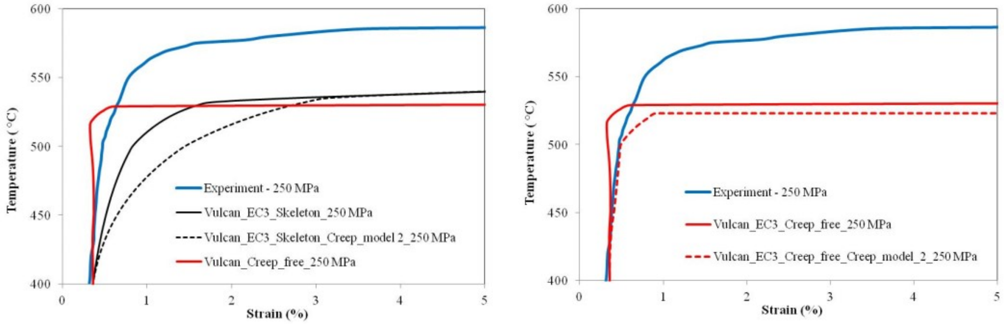
Figure 1. Comparison of results between *Vulcan* predictions and tests from study [4]

Figure 2. presents the comparison between Boko's experimental study [5] with stress level of 250 MPa and the *Vulcan* predictions using *Creep_model 2* and *Creep_model 3*.



(a) S355 10°C/min – Ramberg-Osgood curves

(b) S355 10°C/min – Ramberg-Osgood creep free curves



(c) S355 10°C/min – EC3 curves

(d) S355 10°C/min – EC3 creep free curves

Figure 2. Comparison of results between *Vulcan* predictions and tests from study [5]

Table 1 presents a comparison of results between simulations from Figure 1 conducted with creep-free curves in predicting creep strains and implicit creep.

Table 1. Accuracy of creep-free curves in predicting total strain from study [4] for steel grade S275 at 150 MPa.

Strain (%) / Temperature (°C)	Exp [4]	Ramberg_skeleton+Creep_model 3	EC3_skeleton +Creep_model 3	Ramberg_creep_free+Creep_model 3	EC3_creep_free+Creep_model 3
1.0	570	547	545.5	559	559
1.2	575	555	554	566.5	565
1.4	580	561.5	560.5	573.5	569.5
1.6	583	568	565	580	573
2.0	588	577	572.5	589	575.5

4 DISCUSSION

Comparisons of the results in Figure 1 indicate that both Eurocode 3 and Ramberg-Osgood implicit curves (marked as "skeleton") provide unrealistic predictions of total strain (creep+mechanical) of the experimental tests. The predictions become even more inaccurate if combining commonly-used stress-strain curves with explicit creep models. This is evident by the comparisons of the results of the numerical modelling and the experimental tests [4-5] for steel grades S275 and S355. However, better correlation with the experimental results can be achieved if combining creep-free stress-strain curves with the explicit creep model. This is particularly evident for Ramberg-Osgood material law which has excellent correlation with the experimental results. Simulations conducted with Eurocode 3 creep-free curves yield a better correlation only for steel grades from study [4]. Figures 1 and 2 provide a good illustration of the level of implicit creep strain which is present in Eurocode 3 and Ramberg-Osgood curves. These results indicate, firstly, that the conventional material laws in elevated temperature consist certain level of inaccuracy, and secondly, that the combination of the creep-free material laws and proper creep models can provide better prediction of the behaviour of steel in fire.

4.1 Creep free material laws

In light of the presented results, an optimal set of creep-free stress-strain curves is necessary in order to utilize the creep strain models in structural fire analysis. One of the approaches is to use the proposed "reverse-engineering" methodology to optimize the existing engineering curves, such as EC curves.

4.2 Effects of strain rate

Limited numbers of tests and research have been carried out to study the effects of the strain rate on the steel material in fire. The presented creep strain models cover the strain from a certain load but they do not reflect the stress due to the changing strain rate. Tests conducted by Renner [6] studied the influence of different strain rates on the stress-strain material law of steel grade S275 between 400-700°C. A total of 25 coupons were tested under three different displacement speeds (0.7-6.0 mm/min) per temperature level. It has revealed that the strain rate has significant impact on the stress-strain material law of steel under elevated temperature and should not be neglected.

The presented strain hardening creep model (*Creep_model 1*) was used to model these tests because the stress levels in the coupons changed during the displacement control tests. A displacement control solver was utilized to simulate the experiment process. Three displacement speeds (0.7 mm/min, 3.1 mm/min and 6.0 mm/min) were model on the Material B coupons with yield strength of 308 MPa. Figure 3 plots a typical comparison between the results from the numerical model and the test result. Table 2 shows the creep strains in the coupon for different displacement speeds.

Table 2 Creep strain predict by present creep model for different displacement speeds in Renner's tests [6] at 500 ºC

Strain (%)	0.7 mm/min	3.1 mm/min	6.0 mm/min
0.5	0.0112	0.0068	0.0053
1.0	0.0156	0.0092	0.0072
1.5	0.0185	0.0108	0.0084
2	0.0206	0.0121	0.0095

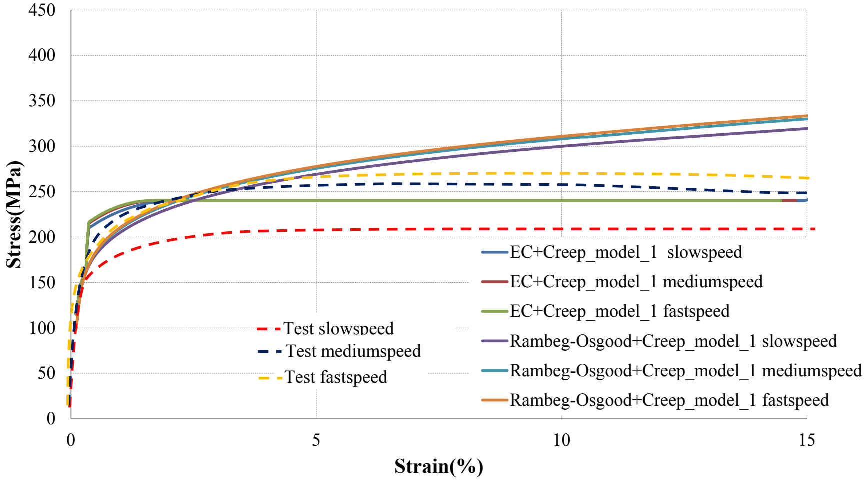


Figure 3. Comparison of results between *Vulcan* predictions and tests from Renner's tests [6]

It can be observed that the creep strains do contribute to the reduction of the strength of the steel as the displacement speeds decrease, however, the creep models is not adequately capable of tracking the strain rate effect on the material behaviour of steel under elevated temperature. This indicates that during the selection of the optimal creep-free stress strain curves, the strain rate effect should be taken into account. Ideally, there will be a group of creep-free stress strain curves for each strain rate.

5 CONCLUSION

Comparing the results of the simulations conducted using different creep and constitutive models with the coupon experiments have illustrated:

- Explicit creep analysis combined with implicit material curves yields imprecise predictions of creep strain in structural fire analysis;
- It is possible to exclude the influence of implicit creep from existing material stress-strain curves by creating creep-free curves;
- Accurate numerical prediction of transient coupon tests using explicit creep models cannot be achieved if the material's basic stress-strain law is determined from transient coupon tests conducted with heating rates of 10°C/min. This indicates that a suitable basic stress-strain constitutive model given by rapid (although not dynamic) testing at constant temperatures is as important as the nature of the creep model itself;
- As the displacement speed raises, the creep strain decrease as well as the ultimate strength of the steel under elevated temperature;
- The presented creep models have limited capacity of modelling the strain rate effect on the material properties of steel in fire. During the selection of the optimal creep-free basic stress-strain curves, the strain rate effect should be taken into account.

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