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Rheological modelling of high-temperature stationary creep tests of Grade S275JR steel

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Abstract

The paper presents a new validation study of a unified rheological model, in reproducing creep strains from a recent experimental study performed on grade S275JR coupons. The objective of this research is to further test the modelling capabilities of the proposed rheological model and its validity for application in general structural fire engineering analysis. The rheological model is composed of two serially connected Kelvin-Voight elements, used to represent the material's sensitivity to strain-rate-governed changes of yield strength, temperature and heating rate. The paper presents the performance of the model in stationary-creep conditions.

Keywords

Rheological model, steel, creep, fire, creep, S275JR, Kelvin-Voight

1 Introduction

The evolution of strain components in carbon steel during fire is greatly affected by the form of the temperature-time curves induced in key parts of the structure. In any steel member, this depends on the distance of the member from the fire, its fire protection thickness, its section factor and the fire severity. This is especially important to consider, since the evolution of creep strain can potentially not only reduce the fire resistance of individual structural members, but also accelerate the development of inherent progressive collapse mechanisms of the whole structure. The traditional approach to treating time-dependent strains in structural fire engineering is to use a temperature-dependent material model, which implicitly includes the creep strain generated in transient tests conducted at "realistic" heating rates. The Eurocode 3 material model [1] for steel at high temperature is the most representative type of implicit creep material model, which is widely used in structural fire analysis. The Eurocode 3 material model was developed on the basis of test studies [2-4] conducted on transient coupon tests conducted at a 10°C/min fire temperature rate.

The possible content of implicit creep within Eurocode 3 material model has previously been investigated in research conducted by Torić et al. [5, 6]. As an output of this research a creep-free Eurocode 3 material model was proposed, using the original strain equations but with a reduction of the yield strain value of steel to 1% instead of 2%. A follow-up of this research was a member study conducted by the Universities of Split and Sheffield [7] that investigated the inherent creep behaviour of Grade S275JR steel and EN6082AW T6 aluminium columns at constant temperature. The conclusions of the study showed very low creep resistance for load levels above 90% of column's load bearing capacity at prescribed temperatures, indicating that, even in cases of short-term constant temperature exposure, the possibility of column failure due to creep exists.

The research within this paper presents further examination of an existing rheological model [8] suitable for application in quasi-static (slow-time) structural FEM models, and capable of taking into account the influence of the temperature-time curves induced on the response of a steel structure exposed to fire. The aim of the development of this type of rheological model was to provide a reliable computational tool for estimating creep development in various thermo-mechanical conditions related to possible temperature-time curves in realistic fires.

2 Behaviour of steel in stationary-creep conditions

Creep in metallic materials represents a time-dependent process, which starts to evolve during the exposure of materials to an external load. Creep is especially pronounced when the material is exposed to high temperature, in comparison to ambient temperature (when it is usually considered negligible). During high temperature exposure, the atom movement in the crystal lattice becomes substantial, and this results in the development of creep. Dislocation climb, one of the observed types of deformation mechanism during creep development, presents the most important deformation mechanism by which creep manifests itself at high temperature [9].

As is well known, there are three main creep phases in steel during exposure to constant stress and temperature. The primary creep phase is characterised by an initial rapid increase of creep strain and a subsequent decrease. The secondary creep phase is characterised

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by a constant creep strain-rate. Within the tertiary creep phase, the creep strain-rate increases exponentially until rupture occurs. Due to the nature of creep development at higher temperature levels, there are no clear boundaries between the three stages, as is the case at lower temperature levels. Figure 1 presents the boundaries between each creep phase at different temperature levels.

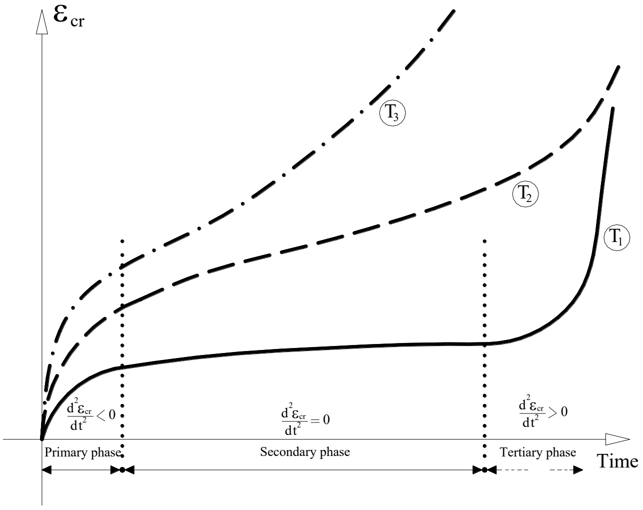

Figure 1. Creep phases ($T_1<T_2<T_3$)

This is the main reason why it is difficult to define a unique mathematical description for creep strain development at high temperatures. Because of this, only the primary and secondary creep phases are taken into account in most structural fire resistance analyses, in order to simplify the analysis that includes a quasi-static calculation.

3 The importance for development of a unified rheological model

Generally, steel is exposed to different types of heating curves in realistic fire. There are no general guidelines on when to use creep analysis and what kind of structure types are sensitive to time dependent deformation. Therefore, it is important to analyse structural behaviour by using a material model that provides a strain output that is sensitive on the type of thermal and mechanical exposure generally expected in fire. This should include cases when steel is exposed to temperatures over 400°C for prolonged time periods. A "universal" material behaviour model needs to be developed for this purpose. The proposal of the authors offers a strain- and heating-rate sensitive material model which requires only temperature-dependent yield strength and modulus of elasticity as an input for simulating the time-dependent behaviour of carbon steel.

4 A unified rheological model

The rheological model is composed of two components, each representing strain output of steel at very low and high strain rates (Figure 2).

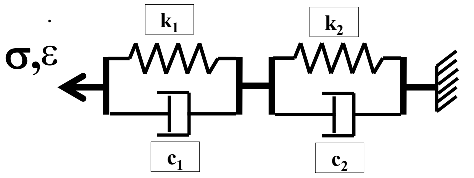

Figure 2. Unified rheological model

The first Kelvin-Voight (KV1) element represents strain output at high strain rates where an apparent yield strength increase occurs due to inertia effects. At normal strain rates, this strain component represents stress-related (mechanical) strain. The second KV element (KV2) represents strain output when low (creep) strain rates are imposed on the steel.

The strain components for steel at any temperature level [10] can be defined using the following equation:

$$\varepsilon_{tot} = \varepsilon_{th}(T) + \varepsilon_{\sigma}(\sigma, T) + \varepsilon_{cr}(\sigma, T, t) \tag{1}$$

in which ε_{tot} is the total strain, $\varepsilon_{th}(T)$ is the temperature-dependent thermal strain, $\varepsilon_{\sigma}(\sigma, T)$ is the stress-related strain, and $\varepsilon_{cr}(\sigma, T, t)$ is the creep strain. A unified rheological model does not take into account the development of thermal strain since this can be defined relatively easily.

A parallel connection between the elements of a single KV element divides the total stress into the two components σ_1 and σ_2:

$$\sigma = \sigma_1 + \sigma_2; \sigma_1 = k_1(\sigma, T)\varepsilon; \sigma_2 = c_1(\dot{\varepsilon} \tag{2}$$

where σ_1 represents the stress in the spring and σ_2 represents the stress in the damper. The damper values for c_1 and c_2 are determined using the nonlinear relationship:

$$c_i = \frac{\sigma_{d_i}}{\dot{\varepsilon}} \tag{3}$$

where σ_{d_i} represents damper stress and $\dot{\varepsilon}$ represents the strain rate. A set of temperature- and strain-rate-dependent curves which are used to determine the damper values c_1 and c_2 as well as the spring values k_1 and k_2 are documented in detail in references [5, 6, 8].

The differential equation describing the strain evolution for a series connection of KV elements can be defined as:

$$\frac{\sigma}{c_i} = \frac{k_i}{c_i}\varepsilon_i + \dot{\varepsilon} \quad \text{(i=1, 2)} \tag{4}$$

where $\dot{\varepsilon}$ =const= $\dot{\varepsilon}$ or $\sigma = \sigma_{el1} = \sigma_{el2}$

In Equation (4) $\dot{\varepsilon}_i$ represents the first strain derivative of the i-th KV, and k_i and c_i represent the spring and damper functions. Figure 3 presents a stress-strain model for spring k_1. This stress-strain model represents a 'creep free' model, and its development is well documented in studies [5, 6]. The constitutive model for spring k_2 is almost identical to that for spring k_i, the only difference being that the temperature-dependent yield strength $f_{y,\theta}$ of k_2 has been reduced to 80% of the original yield strength of k_i [8]. Figure 4 presents a stress-strain model for spring k_2.

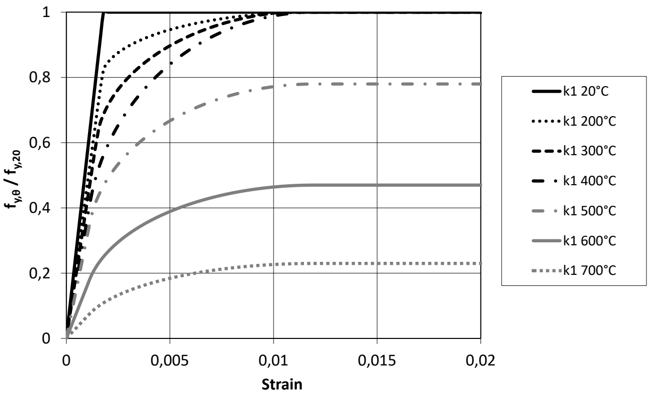

Figure 3. Constitutive stress-strain model for spring k_1 [8]

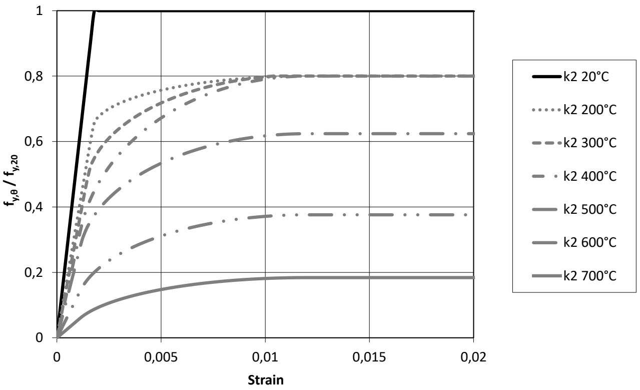

Figure 4. Constitutive stress-strain model for spring k_2 [8]

The stress-strain representation of the springs is given by the following equations [1, 8]:

$$\sigma = \varepsilon E_{\mathrm{a},\theta} \quad (\varepsilon \le \varepsilon_{\mathrm{p},\theta}) \tag{5}$$

$$\sigma = f_{\mathrm{p},\theta} - c + (b/a)\left[a^2 - (\varepsilon_{\mathrm{y},\theta} - \varepsilon)^2 \right]^{0.5}$$

$$(\varepsilon_{\mathrm{p},\theta} < \varepsilon < \varepsilon_{\mathrm{y},\theta}) \tag{6}$$

$$\sigma = f_{\mathrm{y},\theta} \quad (\varepsilon_{\mathrm{y},\theta} < \varepsilon < 0.04) \tag{7}$$

Parameters a^2, b^2 and c can be obtained from the following expressions:

$$a^2 = (\varepsilon_{\mathrm{y},\theta} - \varepsilon_{\mathrm{p},\theta})(\varepsilon_{\mathrm{y},\theta} - \varepsilon_{\mathrm{p},\theta} + c / E_{\mathrm{a},\theta})$$
$$b^2 = c(\varepsilon_{\mathrm{y},\theta} - \varepsilon_{\mathrm{p},\theta})E_{\mathrm{a},\theta} + c^2 \tag{8}$$
$$c = \frac{(f_{\mathrm{y},\theta} - f_{\mathrm{p},\theta})^2}{(\varepsilon_{\mathrm{y},\theta} - \varepsilon_{\mathrm{p},\theta})E_{\mathrm{a},\theta} - 2(f_{\mathrm{y},\theta} - f_{\mathrm{p},\theta})}$$

where: $\varepsilon_{\mathrm{p},\theta} = f_{\mathrm{p},\theta} / E_{\mathrm{a},\theta}$ and $\varepsilon_{\mathrm{y},\theta} = 0.01$. Parameters $f_{\mathrm{p},\theta}$, $f_{\mathrm{y},\theta}$, $E_{\mathrm{a},\theta}$ are respectively the proportional limit, yield strength and modulus of elasticity at temperature θ.

The nonlinear relationship for dashpot c_1 is presented in Figure 5.

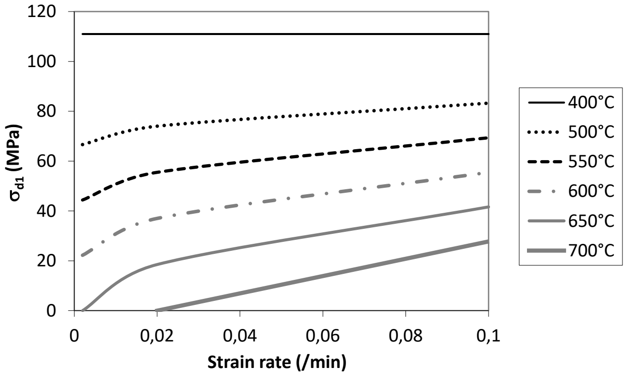

Figure 5. Constitutive nonlinear model for damper c_1 [8]

The nonlinear relationship for dashpot c_2 is presented in Figure 6. For intermediate temperature and stress values a linear interpolation is used for calculation of damper values c_1 and c_2.

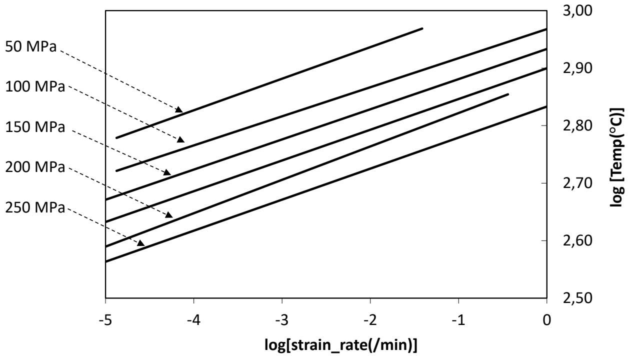

Figure 6. Constitutive model for damper c_2 [8]

Two differential equations for each KV element are integrated with respect to time, using small time increments (Euler integration). Depending on the type of loading scheme (stress-controlled or strain-rate-controlled), two types of solution are developed. Figure 7 presents a calculation scheme for a stress-controlled loading scheme.

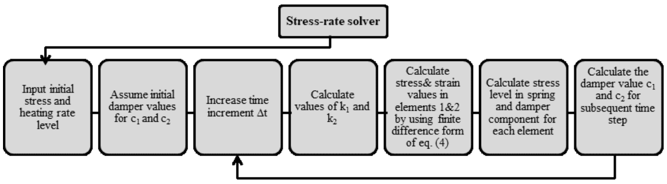

Figure 7. Principle of a stress-rate solver

5 Modelling of the stationary creep tests

Validation of the developed unified rheological model for stationary creep conditions was conducted on the results of a recent coupon study of the mechanical and creep properties of Grade S275JR at high temperature [11]. A total of 22 coupons were tested in the study. The test temperature range in the study was 400-600°C. As an input into the rheological model, temperature-dependent material properties for yield strength and modulus of elasticity from study [11] have been used for the presented comparisons. Figure 8 presents a plot of reduction factors up to 600°C.

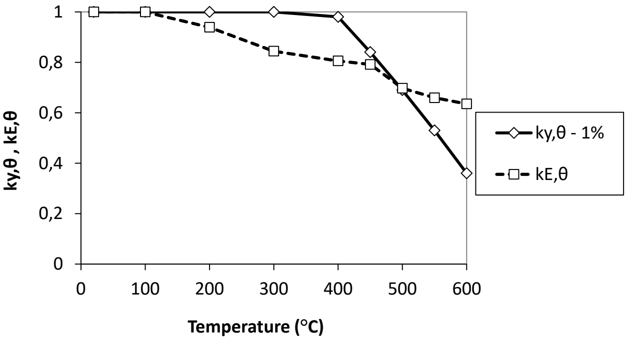

Figure 8. Temperature-dependent yield strength and modulus of elasticity

Table 1 presents the reduction values for temperature-dependent yield strength at 1% strain and modulus of elasticity, which are used as input for the unified rheological model. The experimental values of yield strength at 1% strain and modulus of elasticity at 20°C were: 287.5 MPa and 204.7 GPa respectively.

Table 1 Reduction factors for yield strength at 1% strain and modulus of elasticity

Temperature (°C)	$k_{y,\theta}= f_{y,\theta}/f_{y,20}$ - 1%	$k_{E,\theta}=E_{y,\theta}/E_{y,20}$
100	1.0	1.0
200	1.0	0.94
300	1.0	0.84
400	0.98	0.81
500	0.69	0.70
600	0.36	0.64

The results of the modelling study are presented in Figures 9-11, which show comparisons between the stationary creep tests and the rheological model at 400°C. The stress levels in the selected tests were 0.7 $f_{0.2,\theta}$, 0.8 $f_{0.2,\theta}$ and 0.9$f_{0.2,\theta}$, where $f_{0.2,\theta}$ represents the stress at 0.2% strain. The comparison of strain components includes the initial elastic (stress-related) strain and the creep strain.

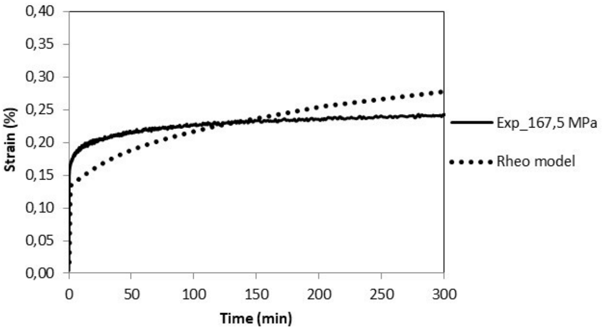

Figure 9. Comparison experiment-rheo model at stress level of 0.7 $f_{0.2,\theta}$

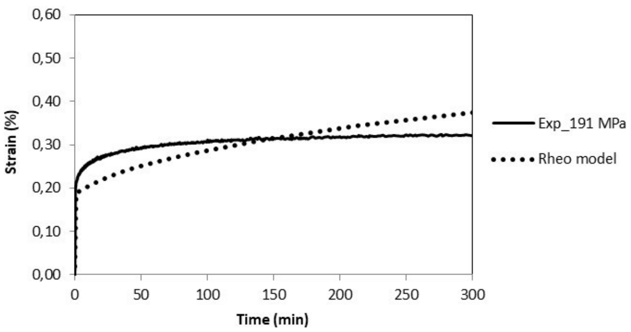

Figure 10. Comparison experiment-rheo model at stress level of 0.8 $f_{0.2,\theta}$

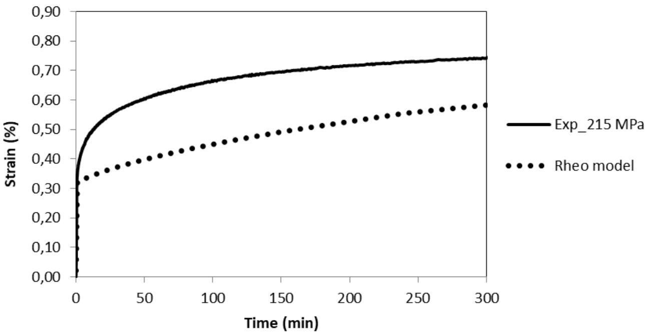

Figure 11. Comparison experiment-rheo model at stress level of 0.9 $f_{0.2,\theta}$

The comparisons presented in Figures 9-11 indicate that the unified rheological model can simulate the stationary creep behaviour of Grade S275JR steel for higher stress levels 0.7 $f_{0.2,\theta}$ and 0,8 $f_{0.2,\theta}$ with slight under prediction of the total strain in the first 100 minutes. At the stress level 0.9 $f_{0.2,\theta}$ the discrepancy is greater, as can be seen in Figure 11. This indicates that at stress levels very close to $f_{0.2,\theta}$ at 400°C the predictions of the rheological model cannot be considered as reliable due to their under prediction of total strain. Further testing of the performance of the rheological model is planned for the temperature intervals of 500°C and 600°C.

In order to demonstrate how creep strain is calculated by the rheological model a plot of stress values for spring and damper of the second Kelvin-Voight element is given in Figure 11. The results from Figure 12 are given for simulation of creep test at 400°C, stress level of 0.9 $f_{0.2,\theta}$.

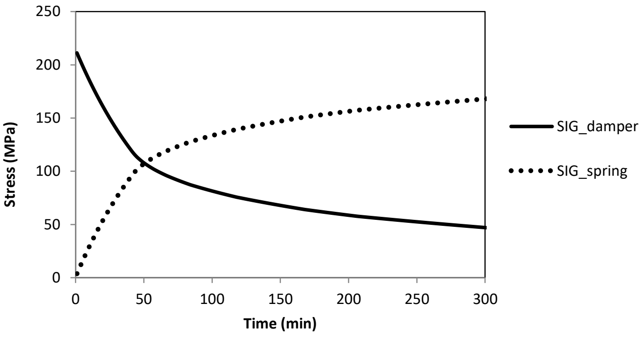

Figure 12. Stress values of the second Kelvin-Voight element: Simulation of creep test presented in Figure 10

6 Conclusion

Considering the comparisons presented between the unified rheological model and the stationary creep tests, it can be concluded that the rheological model generally provides satisfactory prediction of creep development for Grade S275JR. The exception to this is the creep strain development at the very high stress value of 0.9 $f_{0.2,\theta}$. These refer to the 240-minute interval, which is considered important in most countries for fire resistance of buildings higher than 18m. Further development and testing of the rheological model is planned for temperature values greater than 400°C.

Acknowledgement

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References

[1] *EN1993-1-2, Eurocode 3 - Design of Steel Structures: Part 1-2: General Rules - Structural Fire Design*, European Committee for Standardization, Brussels, Belgium, 2005.

[2] Kirby, B.R. and Preston, R.R., High Temperature Properties of Hot-Rolled, Structural Steels for Use in Fire Engineering Design Studies, *Fire Safety Journal*,13:27-37, 1988.

[3] Wainman D. E. and Kirby B. R., *Compendium of UK Standard Fire Test Data: Unprotected Structural Steel – 1 & 2*, British Steel Corporation, 1988.

[4] Rubert A., Schaumann P., Temperaturabhaengige Werkstoffeigenschaften von Baustahl bei Brandbeanspruchung, *Stahlbau*, 3,: 81-86, 1985.

[5] Torić, N., Sun R.-R., Burgess, I.W., Development of a creep-free stress-strain law for fire analysis of steel structures, *Fire and Materials*, 40(7):896-912, 2016.

[6] Torić, N., Sun R.R. and Burgess, I.W. Creep-free fire analysis of steel structures with Eurocode 3 material model, *Journal of Structural Fire Engineering*, 7(3): 234-248, 2016.

[7] Torić N., Boko I., Divić V., Burgess I.W., Behaviour of steel grade S275JR columns under the influence of high-temperature creep, *Metals*, 8 (11), paper no. 874, 2018.

[8] Torić N., Burgess I.W., A unified rheological model for modelling steel behavior in fire conditions, *Journal of constructional steel research*, 127: 221-230, 2016.

[9] Lee J., Gillie M., Numerical modelling of creep in structural steel exposed to fire, *7th International Conference on Structures in Fire*, Zurich, Switzerland, 449-458, 2012.

[10] Anderberg Y., Modelling Steel Behaviour, *Fire Safety Journal*, 13(1):17-26, 1988.

[11] Torić N., Brnić J., Boko I., Brčić M., Burgess I.W., Uzelac Glavinić I.: Development of a high temperature material model for grade S275JR steel, *Journal of constructional steel research*,137: 161-168, 2017.