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# CREEP-FREE FIRE ANALYSIS OF STEEL STRUCTURES WITH EUROCODE 3 MATERIAL MODEL

**Neno Torić [1*], Rui Rui Sun [2] and Ian W. Burgess [3]**

**Abstract:**

This paper proposes a methodology to remove inherent implicit creep from the Eurocode 3 material model for steel, and presents a creep-free analysis on simply supported steel members. Most of the available material models of steel are based on transient coupon tests which inherently include creep strain associated with particular heating rates and load ratios. The creep-free analysis aims to reveal the influence of implicit creep by investigating the behaviour of simply supported steel beams and columns exposed to various heating regimes. The paper further evaluates the implicit consideration of creep in the Eurocode 3 steel material model. Finally, a modified Eurocode 3 carbon steel material model for creep-free analysis is proposed for general structural fire engineering analysis.

**Keywords:**

Steel, creep, fire, beam, column, finite element, creep-free

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# 1. INTRODUCTION

The Eurocode 3 steel material model [1] is widely used for both design and research in performance-based structural fire engineering. The model itself was created on the basis of test results from a transient coupon study [2, 3] conducted with a heating rate of about 10°C/min. This type of testing methodology was chosen in order to obtain a material model which implicitly includes some creep strain. This is usually considered a very convenient way of taking the effect of high-temperature creep into account in structural fire analysis. Implicit creep contained within the material model effectively reduces the value of tangent modulus in the elliptic branch of the Eurocode 3 model. A reduced value of tangent modulus generally leads to a conservative prediction of buckling temperatures in the case of isolated columns, or deflection predictions in the case of isolated beams. In both cases the effects of implicit creep can be interpreted as conservative when estimating the fire resistance of a member. The Eurocode 3 material model may logically be considered as conservative for heating rates which are over 10°C/min. However, this does not apply for heating rates below 10°C/min, in which case more substantial creep is expected to occur [4-6]. Heating rates below 10°C/min for steel members are possible in cases of protected and unprotected steel members, depending on the heating rate of the fire itself. In both cases an explicit creep analysis is necessary in order to conduct an accurate representation of the structural behaviour in fire. Creep analysis is especially important in steel columns, where the columns' buckling resistance can be reduced due to the presence of creep [7]. If explicit creep analysis is necessary, then an implicit-creep material model can be considered as a false starting point, and so a creep-free material model is needed [8].

The main aim of this paper is to explore the level of conservatism of the Eurocode 3 material model for steel with respect to implicit creep, by conducting creep-free analyses of simply supported beams and columns. A further aim is to test its validity at lower heating rates by conducting structural analyses using heating rates lower than 10°C/min on beams and columns. A modified Eurocode 3 material model is proposed which can provide simulation results equivalent to a creep-free analysis procedure, and this is used in the paper to extract the implicit creep from the Eurocode 3 model. The creep-free material model is then utilized in a parametric study of the creep-free behaviour of stocky and slender columns. The analysis presented in the paper is conducted with the Vulcan research code, by combining it with three different creep models.

# 2. CREEP-FREE ANALYSIS

## 2.1 Methodology

The basic methodology of removing implicit creep from the Eurocode 3 material model revolves around finding postulated implicit creep curves derived from the specific transient coupon testing used to create the Eurocode 3 model. Since the test data published by Kirby and Preston [2] provided total strain (summing the stress-related and creep strains), a natural way of removing the creep strain is to apply existing creep models to determine the implicit creep value and to subtract it from the total strain. Therefore, it is necessary to select a suitable creep model and material parameters to calculate postulated implicit creep. An additional problem exists in finding suitable material parameters for the creep model, since creep strain at any stress level depends heavily on these input parameters [9]. In this study Harmathy's creep parameters were chosen, since they apply most closely to the steel alloys tested by Kirby and Preston.

Structural fire analysis normally involves transient heating scenarios, in which the strains and stresses change with temperature and time. Therefore, the postulated implicit creep relationship has to be a function of stress and temperature. Firstly, explicit creep analyses are conducted for a set of transient coupon simulations at different stress levels and a predefined heating rate. A distinct creep strain-temperature curve is extracted from each transient coupon simulation. The next step is to create a set of temperature-dependent stress-creep strain curves using these creep strain-temperature curves. These curves represent the postulated implicit creep functions which can then be used to subtract implicit creep from a structural fire analysis. The modified total strain equation for steel [10] for a creep-free analysis can be expressed as:

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

In which $\varepsilon_{tot}$ is the total strain, $\varepsilon_{th}(T)$ is the temperature-dependent thermal strain and $\varepsilon_{\sigma}(\sigma,T)$ is the stress-related strain (dependent upon applied stress $\sigma$ and temperature T). The strain $\varepsilon_{cr}(\sigma,T,t)$ is the stress-, temperature- and time-dependent creep strain, and $\varepsilon_{impl,cr}(\sigma,T)$ is the postulated implicit creep function. The material model used to represent stress-related strain in the subsequent analysis is the original Eurocode 3 material model [1].

The modified total strain equation has been implemented in the Vulcan research code in order to test the methodology in various fire settings. In this study, three different creep models were used in the analyses: Harmathy's strain-hardening model (denoted Cr_1) [11], Harmathy's time-hardening model (Cr_2) [12] and Plem's strain-hardening model (Cr_3) [13]. The details of the implementation of the creep models in the Vulcan code can be found in [8]. Fig. 1 presents the simulations of temperature-creep strain curves for S355 steel using creep models Cr_1 - Cr_3. Curves from Fig. 1 are used to create a set of stress-creep strain curves which represent the postulated implicit creep function. Fig. 2 presents simulation results for this creep function using models Cr_1 - Cr_3 on the basis of temperature-creep strain curves from Fig. 1.

## 2.2 Verification of the creep-free methodology

In this section a selection of results is shown in order to present the application of the methodology. A coupon specimen from Kirby and Preston [2] was modelled using two three-noded line elements in the Vulcan research code, with an 8x8 segmentation of a solid rectangular cross-section. Key modelling parameters for the model of the coupon are presented in Table 1. Engineering strain was determined as the ratio of the calculated extension to the gauge length of the coupon for each time step.

Fig. 3 presents a comparison of results using the creep-free methodology with test data from the study conducted by Kirby and Preston [2] for S355 steel at 10°C/min. Fig. 4 presents a similar comparison for S355 steel at 5°C/min. It can be seen from Figs. 3 and 4 that the Eurocode 3 material model significantly overestimates the total strain if combined with an explicit creep model, for both of the selected heating rates. However, when the creep-free methodology is used to obtain a stress-strain curve in terms simply of stress-related strain, the strain prediction is much better compared to the implicit Eurocode 3 material model. Figs. 3 and 4 clearly illustrate why a creep-free material model is required if it is necessary to conduct an accurate analysis of steel response in fire.

This is especially evident from the strain-temperature curves obtained by combining the Eurocode 3 implicit-creep material model with an explicit-creep model; this is sometimes used as a modelling strategy in structural fire analysis.

It is important to note that the creep-free curves presented in Figs. 3 and 4 were obtained using Cr_2 as a background creep model. This model provides a very smooth creep-free curve for steel S355, which is a very important aspect of the creep-free analysis when considering the physical behaviour of a steel coupon. Creep models Cr_1 and Cr_3 provide unrealistic creep-free curves for steel S355, and are disregarded in the subsequent analysis.

## 2.3 Modified Eurocode 3 material model

Results obtained from the proposed creep-free methodology were utilized to find a practical way of extracting implicit creep from the Eurocode 3 model. It was found that a practical way to obtain the closest match with the creep-free analysis results was to change the value of yield strain in the Eurocode 3 material model from 2% to 1%. A comparison between the modified Eurocode 3 material model and the original one is presented in Fig. 5, in which $f_{y,20}$ is the yield strength at normal temperature and $f_{y,\theta}$ is the yield strength at temperature $\theta$.

A comparison of results between the creep-free analysis of coupon tests from study [2] (S355 at 10°C/min) and the modified Eurocode 3 material model is presented in Fig. 6. In this particular comparison, model Cr_2 was used as a basis for obtaining the creep-free curve, since this model provides smooth results for the creep-free analysis (as stated previously in Section 2.2), without any abrupt changes in the total strain-temperature curves. It can be seen that the reduction of yield strain to 1% in the Eurocode 3 material model gives a close match between the creep-free analysis results and the modified Eurocode 3 model results. Additionally, it can be seen from Fig. 6 that, for the coupon tests conducted at 250 MPa, the modified Eurocode 3 model provides a better match with the test results than the creep-free analysis. This is because the creep-free analysis removes implicit creep above 400°C, which is a characteristic of the selected creep models. When the yield strain is adjusted to a value of 1%, the implicit creep is removed from the temperature region (100°C and beyond) in which the elliptic part of the model exists. This effect may prove beneficial for creep-free analysis, since the creep effects are known to occur below 400°C at higher stress and temperature levels [14].

# 3. APPLICATION OF CREEP-FREE ANALYSIS TO SINGLE BEAMS AND COLUMNS

This section summarizes the creep-free structural analysis of uniformly heated simply supported beams and columns under various heating rates and load levels. Heating rates adopted in the analysis are below 10°C/min, since the objective was to test the influence of implicit creep for heating rates lower than that on which the Eurocode 3 material model was originally based. A further reason for using linear "ramp" temperature curves is because heating rates below 10°C/min usually occur in fire-protected steel members. Therefore, the heating rates of 2.5°C/min and 5°C/min are adopted for studying the creep-free behaviour of isolated beam and column members in the following section. The initial yield strength and modulus of elasticity for the beam and column analyses were taken as 355 MPa and 210 GPa respectively.

## 3.1 Beam analysis

A creep-free analysis was carried out by simulating a simply supported steel beam of 5.0 m span. Mesh density, boundary conditions and the heating conditions of the simply supported beam are shown in Fig. 7. Three-noded line elements were used to model the beam [15]. Fig. 8 shows a comparison of modelling results from the creep-free analysis combined with the explicit creep model for this simply supported beam. Creep-free analysis has been conducted by using two different approaches: the approach using a postulated implicit creep function obtained from creep model Cr_2 (marked as creep-free methodology in Fig. 8) and the approach using the modified Eurocode 3 material model (marked as creep-free_modified EC3).

Two different load ratios, 46% and 63%, corresponding to vertical forces of 90 and 125 kN, were used in the analyses.

It can be seen from Fig. 8 that a significant difference in the deflection response exists between the creep-free analysis and the implicit Eurocode 3 model. However, the critical temperature of the beam remains unchanged, irrespective of whether the creep-free or implicit material model is used. The analyses using the implicit and explicit creep models show very different deflection predictions compared to those from creep-free analysis. In general, the Eurocode 3 material model does not appear to be conservative in predicting creep for heating rates lower than 10°C/min. Only the deflection response of the beam is affected by removing the implicit creep. Fortunately the deflection of an isolated beam is not generally considered an important factor for fire resistance, for which the beam's critical temperature is the only important factor. It can be concluded that the implicit-creep Eurocode 3 material model is not inherently conservative if the heating rate is less than 10°C/min, and structural fire engineering modelling should be conducted with an explicit creep model for such slow heating rates.

## 3.2 Column analysis

Fig. 9 shows the mesh density, boundary and the heating conditions for the structural analyses of simply supported columns. An HE240M structural section was adopted for these analyses. The modified Eurocode 3 material model, described in section 2.3, was adopted as the creep-free stress-strain model. The column analyses were conducted under two different heating rates below 10°C/min. The slendernesses of the columns involved in this study ranged from 60 to 100, which covers the typical mid-range between stocky and slender columns. Two creep models (Cr_2 and Cr_3) were utilized to provide a basis for comparison in explicit creep analysis of the columns. The columns were loaded with vertical axial compressive force V, corresponding to load selected in the range 20%-70% of the column's load capacity at ambient temperature (marked as $N_{b,y,Rd}$ in Table 2), A lateral force H, equivalent to V/400, was applied to each column to provide a small geometrical imperfection. The geometry and loading conditions of the column are defined in Table 2.

Figs. 10-12 present comparisons of the critical temperatures of the columns, calculated using the implicit and creep-free Eurocode 3 models. It can be seen that the application of the modified Eurocode 3 material model results in a slight increase of the columns' critical temperatures, ranging up to 10% for the stockier columns and 3% for the more slender columns. This indicates that the implicit Eurocode 3 model has a relatively mild inherent conservativeness in the effect of its prediction of the creep in steel in fire.

The results of the creep analyses using the implicit and modified (explicit) Eurocode 3 material models are also listed in Tables 3 and 4 respectively. The creep analysis using the implicit Eurocode 3 model leads to up to 7% lower column critical temperatures for a stocky column and almost identical critical temperatures for both material models for a slender column.

Overall, the analysis shows that the implicit Eurocode 3 material model does not provide sufficient conservativeness in predicting the high-temperature creep in steel, and thus the critical temperatures of the columns are almost identical in the creep-free and implicit creep analyses. The implicit creep content in the Eurocode 3 material model does not provide a significant level of safety when analysing columns of moderate and high slenderness. Furthermore, the results shown in Figs. 10-12 also indicate that creep strain tends to reduce the critical temperature of columns in fire, and that the magnitude of the reduction depends directly on the amount of creep strain given by the creep model. Since the critical temperature is the most important criterion of fire resistance of columns, an explicit creep consideration is clearly required for the structural fire analysis of columns if heating rates lower than 10°C/min are expected to occur during the course of a fire.

# 4. CONCLUSIONS

A creep-free methodology which attempts to extract the implicit creep strain content from the original Eurocode 3 material model has been presented. This methodology has been used to predict the creep-free response of steel coupons, tested by Kirby and Preston

[2]. The modification of the Eurocode 3 model leads to a creep-free Eurocode 3 model. The modified Eurocode 3 model has been verified by comparing results based on the creep-free coupon analysis. It has been demonstrated that a suitable creep-free Eurocode 3 model can be created by changing the nominal high-temperature yield strain of steel to 1%. The modified creep-free model was used to explore the level of conservativeness of the implicit Eurocode 3 model, by analysing the response of simply supported beams and columns.

It is concluded that the implicit creep content in the Eurocode 3 material model is not sufficiently conservative to cover all typical cases. The implicit Eurocode 3 material model provides larger deflections in beams than creep-free analysis, without influencing the critical temperatures. For the simply supported columns, the critical temperatures from the explicit creep analyses are almost identical, regardless of the material model adopted. Therefore, it is imperative not to rely on the conservativeness of the implicit Eurocode 3 material model with respect to creep.


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**Figure Captions**

Figure 1: Temperature-creep strain curves for S355 using creep model Cr_1, Cr_2 and Cr_3

Figure 2: Postulated implicit creep function for S355 using creep model Cr_1, Cr_2 and Cr_3

Figure 3: Simulated total strain-temperature curves for S355 using; Eurocode 3 material model with creep models Cr_1 – Cr_3 at 10°C/min.

Figure 4: Simulated total strain-temperature curves for S355 using; Eurocode 3 material model with creep models Cr_1 – Cr_3 at 5°C/min.

Figure 5: Comparison between the modified Eurocode 3 material model and the original one

Figure 6: Comparison of results between the coupon creep-free analysis and the modified Eurocode 3 material model analysis for study [2] - S355 at 10°C/min

Figure 7: Finite element mesh and heating conditions for a simply supported beam

Figure 8: Creep-free analysis results for a simply supported beam using; Eurocode 3 material model with creep model Cr_2 at 2.5 and 5°C/min.

Figure 9: Finite element mesh and heating conditions for a simply supported column

Figure 10: Comparison of results using modified and implicit Eurocode 3 material model – slenderness 60

Figure 11: Comparison of results using modified and implicit Eurocode 3 material model – slenderness 80

Figure 12: Comparison of results using modified and implicit Eurocode 3 material model – slenderness 100

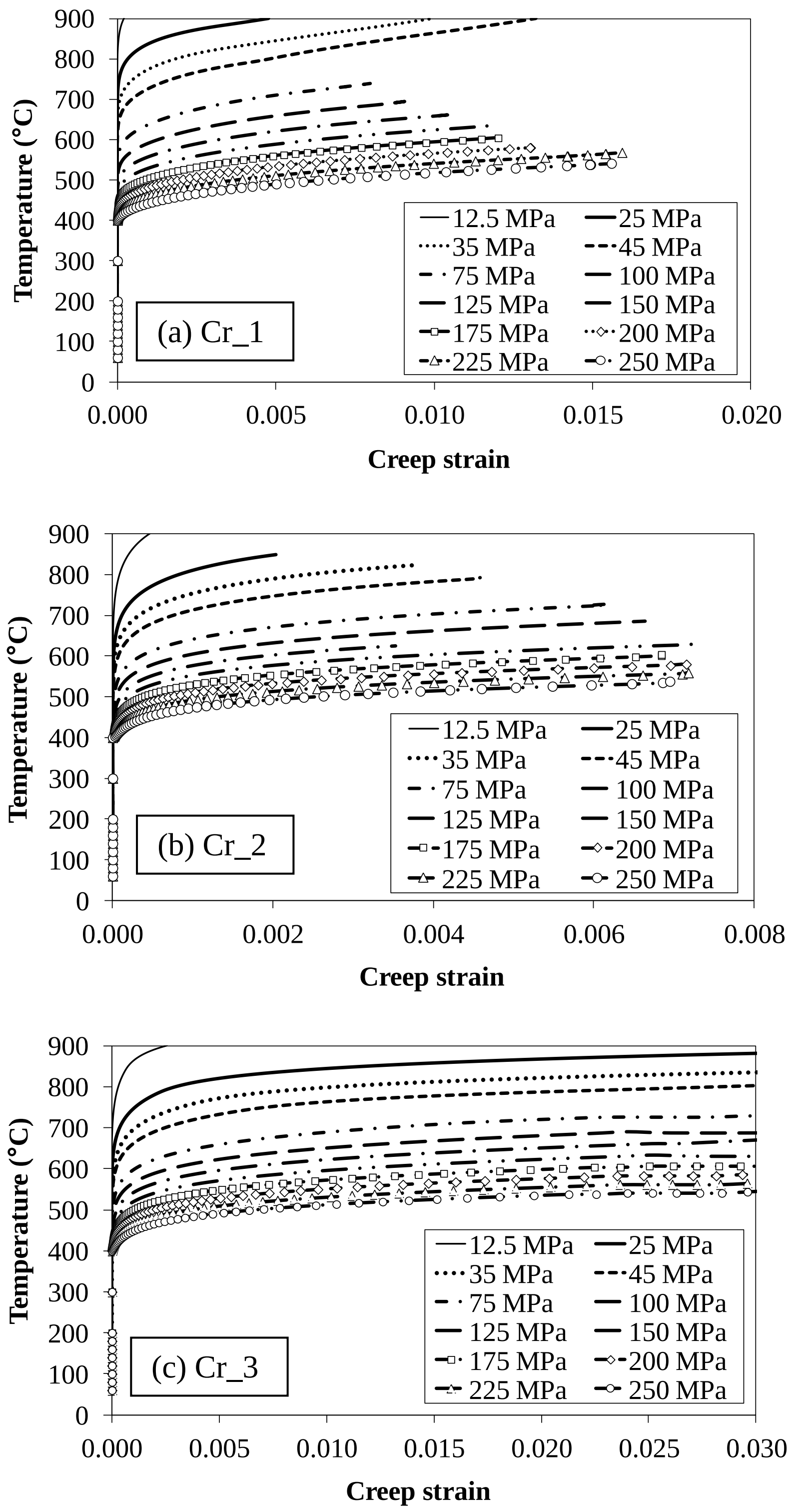
**Table Captions**

Table 1: Input parameters for the numerical analysis of the coupons.

Table 2: Geometrical and load parameters for the column analysis

Table 3: *Columns' critical temperature using implicit Eurocode 3 material model* – slenderness 60

Table 4: *Columns' critical temperature* using modified Eurocode 3 material model – slenderness 60



Temperature (°C)
Creep strain
12.5 MPa
25 MPa
35 MPa
45 MPa
75 MPa
100 MPa
125 MPa
150 MPa
175 MPa
200 MPa
225 MPa
250 MPa
(a) Cr_1
(b) Cr_2
(c) Cr_3


Figure 1

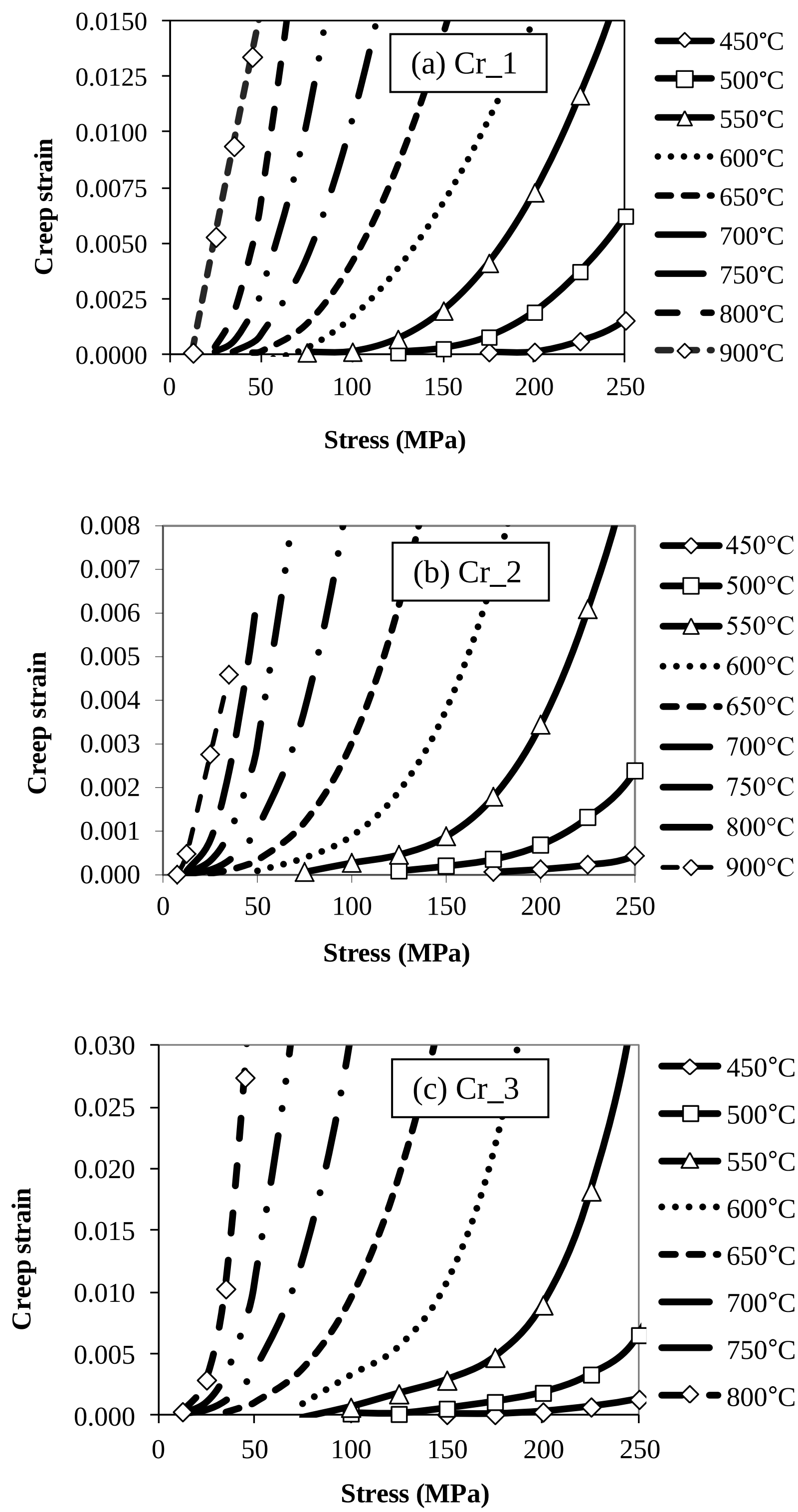
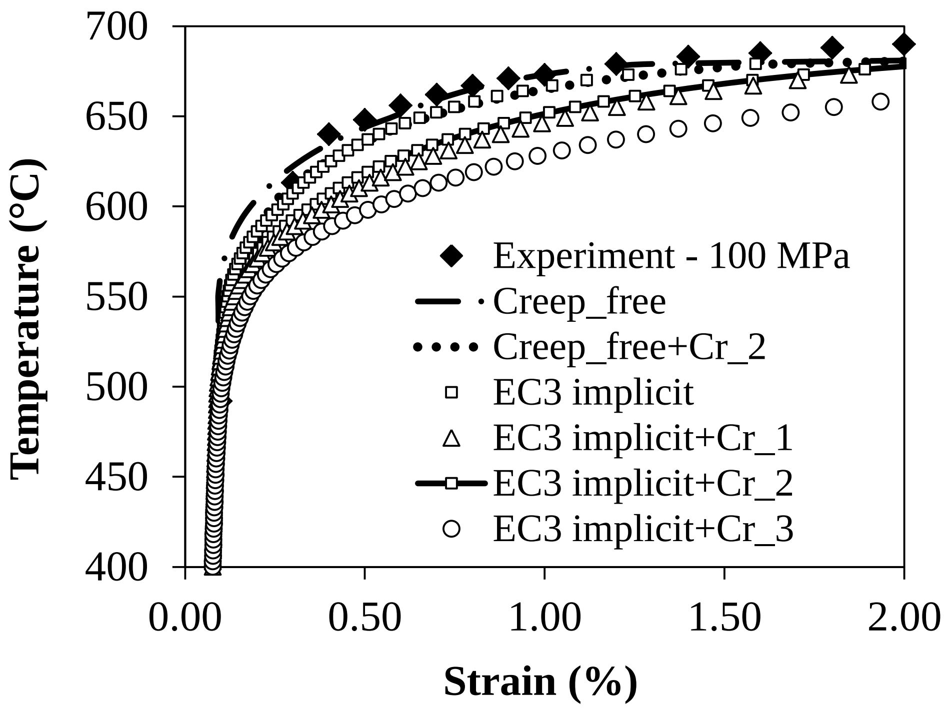
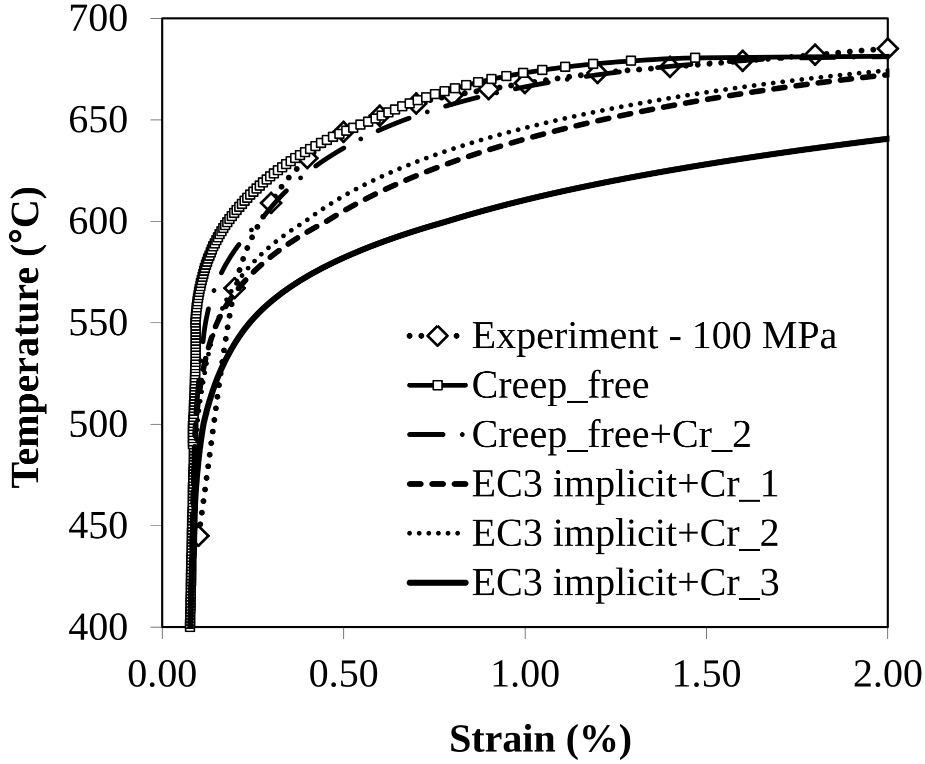

(a) Cr_1
Creep strain
Stress (MPa)
0.0000
0.0025
0.0050
0.0075
0.0100
0.0125
0.0150
0
50
100
150
200
250
450°C
500°C
550°C
600°C
650°C
700°C
750°C
800°C
900°C
(b) Cr_2
Creep strain
Stress (MPa)
0.000
0.001
0.002
0.003
0.004
0.005
0.006
0.007
0.008
0
50
100
150
200
250
450°C
500°C
550°C
600°C
650°C
700°C
750°C
800°C
900°C
(c) Cr_3
Creep strain
Stress (MPa)
0.000
0.005
0.010
0.015
0.020
0.025
0.030
0
50
100
150
200
250
450°C
500°C
550°C
600°C
650°C
700°C
750°C
800°C

Figure 2



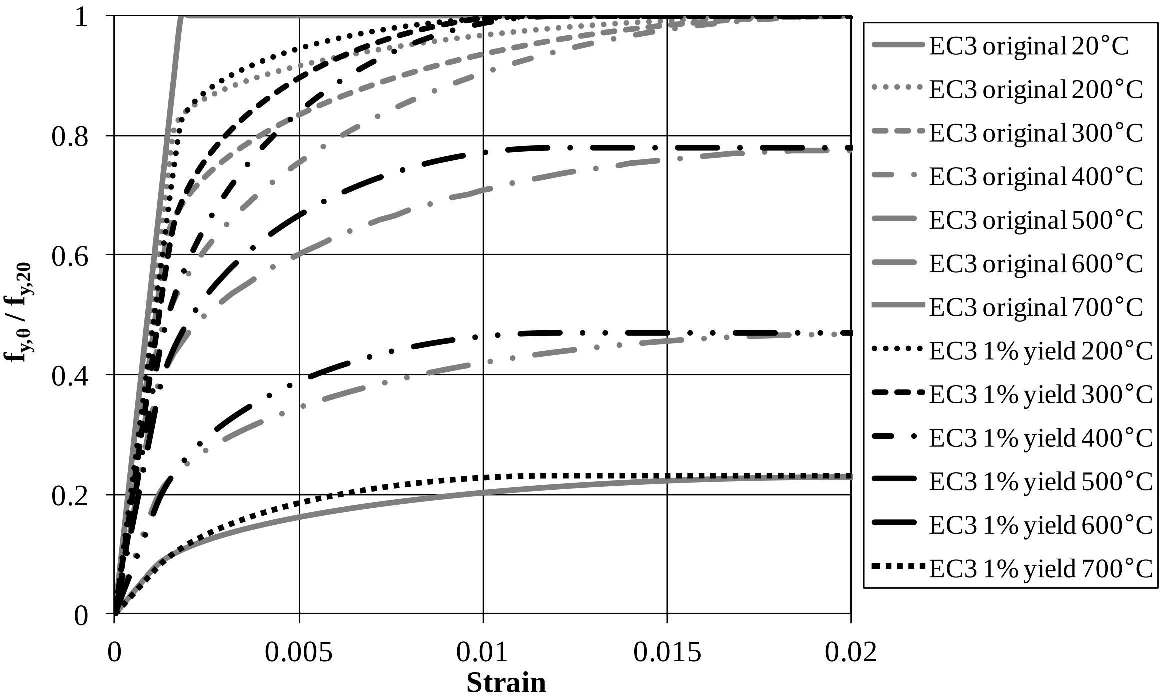
700
650
600
550
500
450
400
0.00
0.50
1.00
1.50
2.00
Temperature (°C)
Strain (%)
Experiment - 100 MPa
Creep_free
Creep_free+Cr_2
EC3 implicit
EC3 implicit+Cr_1
EC3 implicit+Cr_2
EC3 implicit+Cr_3


Figure 3



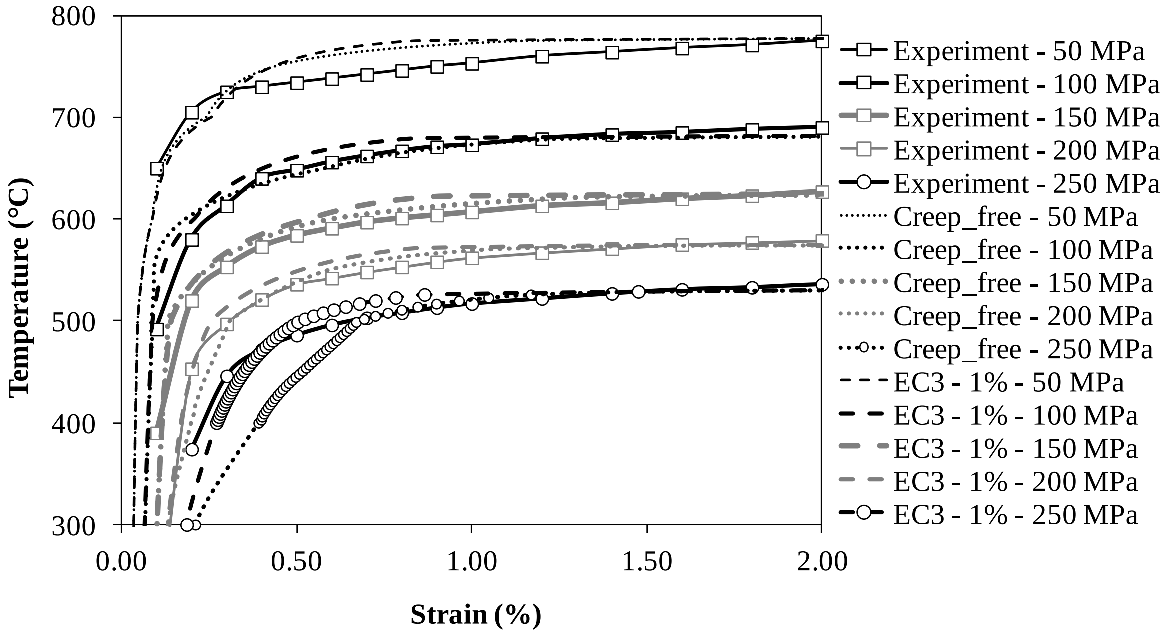
700
650
600
550
500
450
400
Temperature (°C)
0.00
0.50
1.00
1.50
2.00
Strain (%)
Experiment - 100 MPa
Creep_free
Creep_free+Cr_2
EC3 implicit+Cr_1
EC3 implicit+Cr_2
EC3 implicit+Cr_3


Figure 4



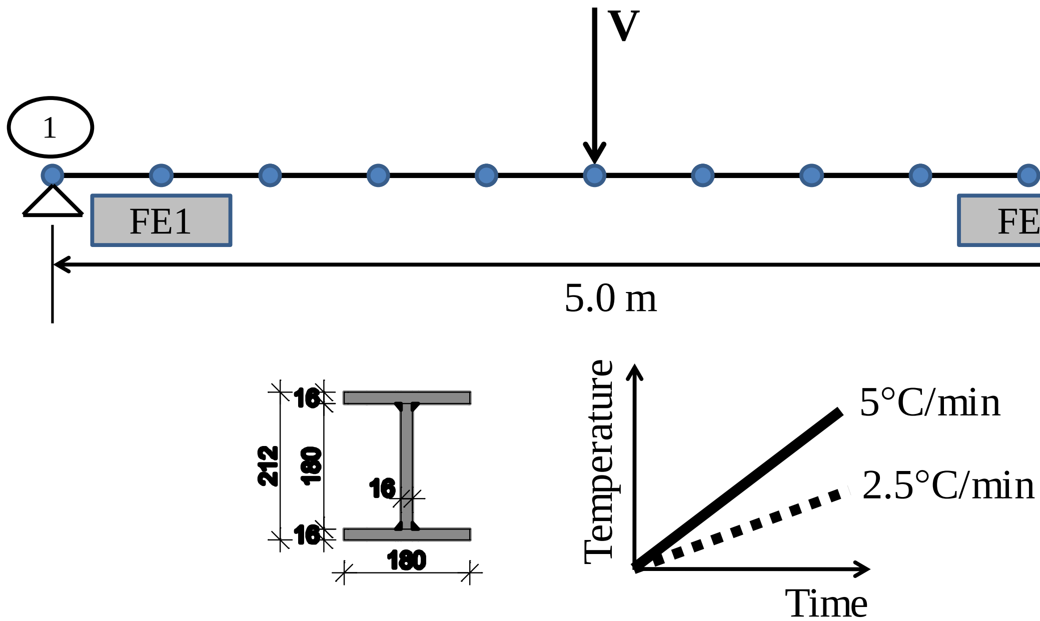
1
0.8
0.6
0.4
0.2
0
0
0.005
0.01
0.015
0.02
Strain
f y,θ / f y,20
EC3 original 20°C
EC3 original 200°C
EC3 original 300°C
EC3 original 400°C
EC3 original 500°C
EC3 original 600°C
EC3 original 700°C
EC3 1% yield 200°C
EC3 1% yield 300°C
EC3 1% yield 400°C
EC3 1% yield 500°C
EC3 1% yield 600°C
EC3 1% yield 700°C


Figure 5



800
700
600
500
400
300
Temperature (°C)
0.00
0.50
1.00
1.50
2.00
Strain (%)
Experiment - 50 MPa
Experiment - 100 MPa
Experiment - 150 MPa
Experiment - 200 MPa
Experiment - 250 MPa
Creep_free - 50 MPa
Creep_free - 100 MPa
Creep_free - 150 MPa
Creep_free - 200 MPa
Creep_free - 250 MPa
EC3 - 1% - 50 MPa
EC3 - 1% - 100 MPa
EC3 - 1% - 150 MPa
EC3 - 1% - 200 MPa
EC3 - 1% - 250 MPa


Figure 6



V
1
11
FE1
FE5
5.0 m
16
212
180
16
16
180
Temperature
Time
5°C/min
2.5°C/min


Figure 7

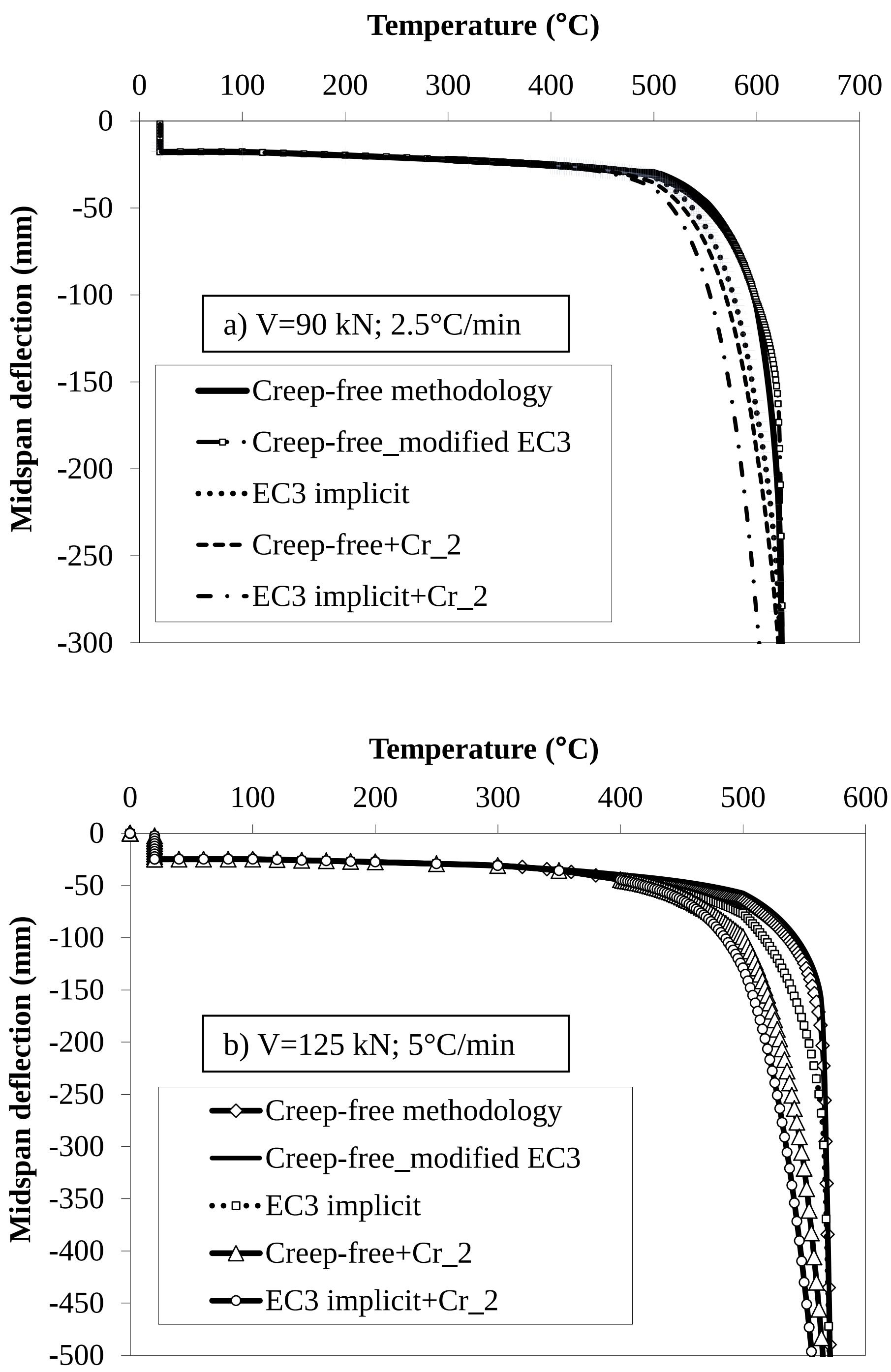

Temperature (°C)
0
100
200
300
400
500
600
700
0
-50
-100
-150
-200
-250
-300
Midspan deflection (mm)
a) V=90 kN; 2.5°C/min
Creep-free methodology
Creep-free_modified EC3
EC3 implicit
Creep-free+Cr_2
EC3 implicit+Cr_2
Temperature (°C)
0
100
200
300
400
500
600
0
-50
-100
-150
-200
-250
-300
-350
-400
-450
-500
Midspan deflection (mm)
b) V=125 kN; 5°C/min
Creep-free methodology
Creep-free_modified EC3
EC3 implicit
Creep-free+Cr_2
EC3 implicit+Cr_2

Figure 8

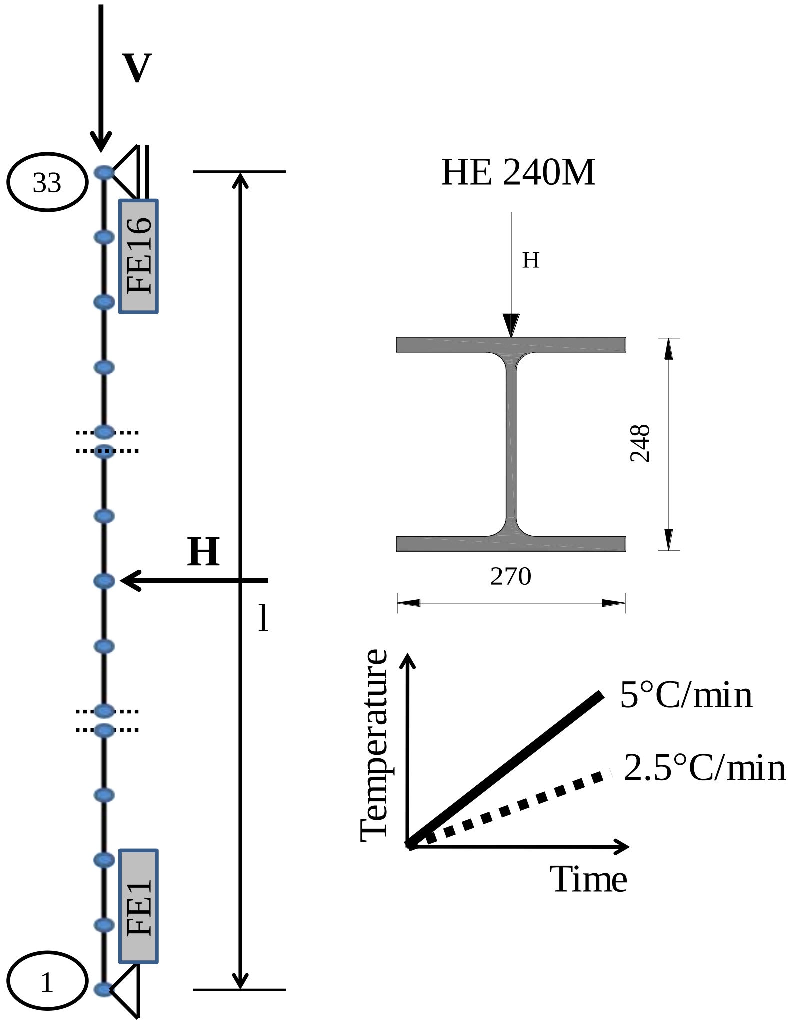

V
33
FE16
H
l
FE1
1
HE 240M
H
248
270
Temperature
5°C/min
2.5°C/min
Time

Figure 9

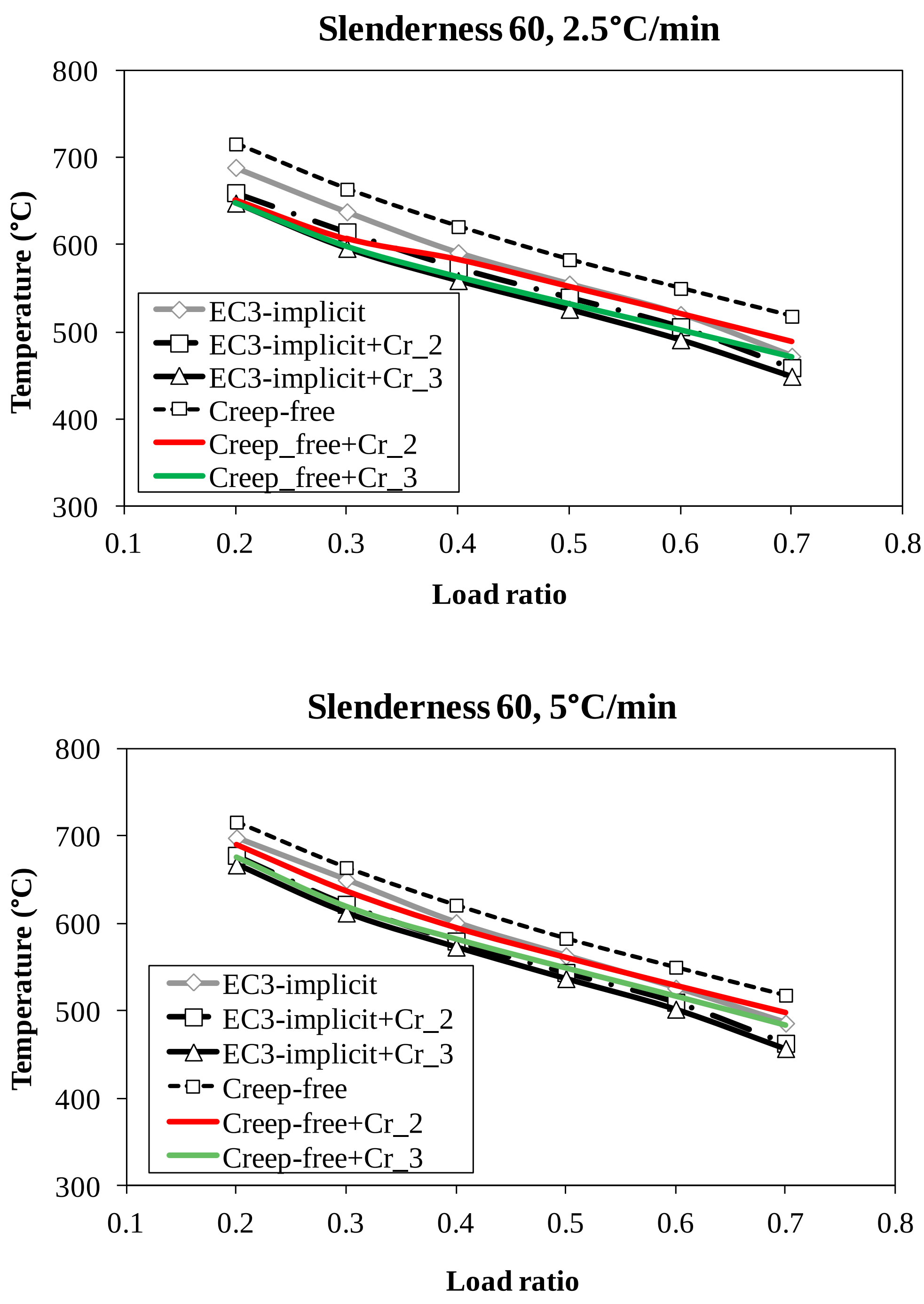

Slenderness 60, 2.5°C/min
800
700
600
500
400
300
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
Temperature (°C)
Load ratio
EC3-implicit
EC3-implicit+Cr_2
EC3-implicit+Cr_3
Creep-free
Creep_free+Cr_2
Creep_free+Cr_3
Slenderness 60, 5°C/min
800
700
600
500
400
300
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
Temperature (°C)
Load ratio
EC3-implicit
EC3-implicit+Cr_2
EC3-implicit+Cr_3
Creep-free
Creep-free+Cr_2
Creep-free+Cr_3

Figure 10

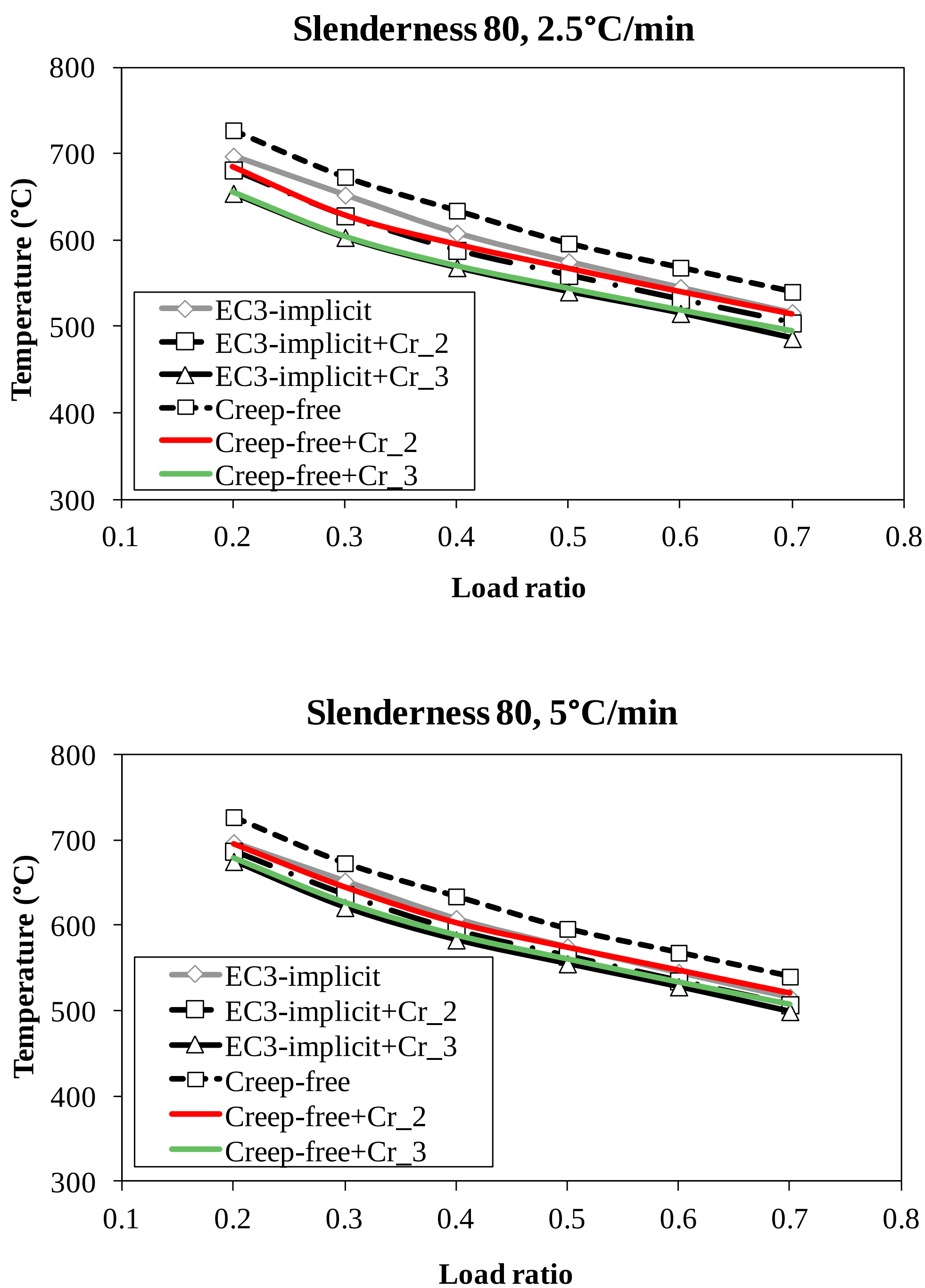

Slenderness 80, 2.5°C/min
800
700
600
500
400
300
Temperature (°C)
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
Load ratio
EC3-implicit
EC3-implicit+Cr_2
EC3-implicit+Cr_3
Creep-free
Creep-free+Cr_2
Creep-free+Cr_3
Slenderness 80, 5°C/min
800
700
600
500
400
300
Temperature (°C)
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
Load ratio
EC3-implicit
EC3-implicit+Cr_2
EC3-implicit+Cr_3
Creep-free
Creep-free+Cr_2
Creep-free+Cr_3

Figure 11

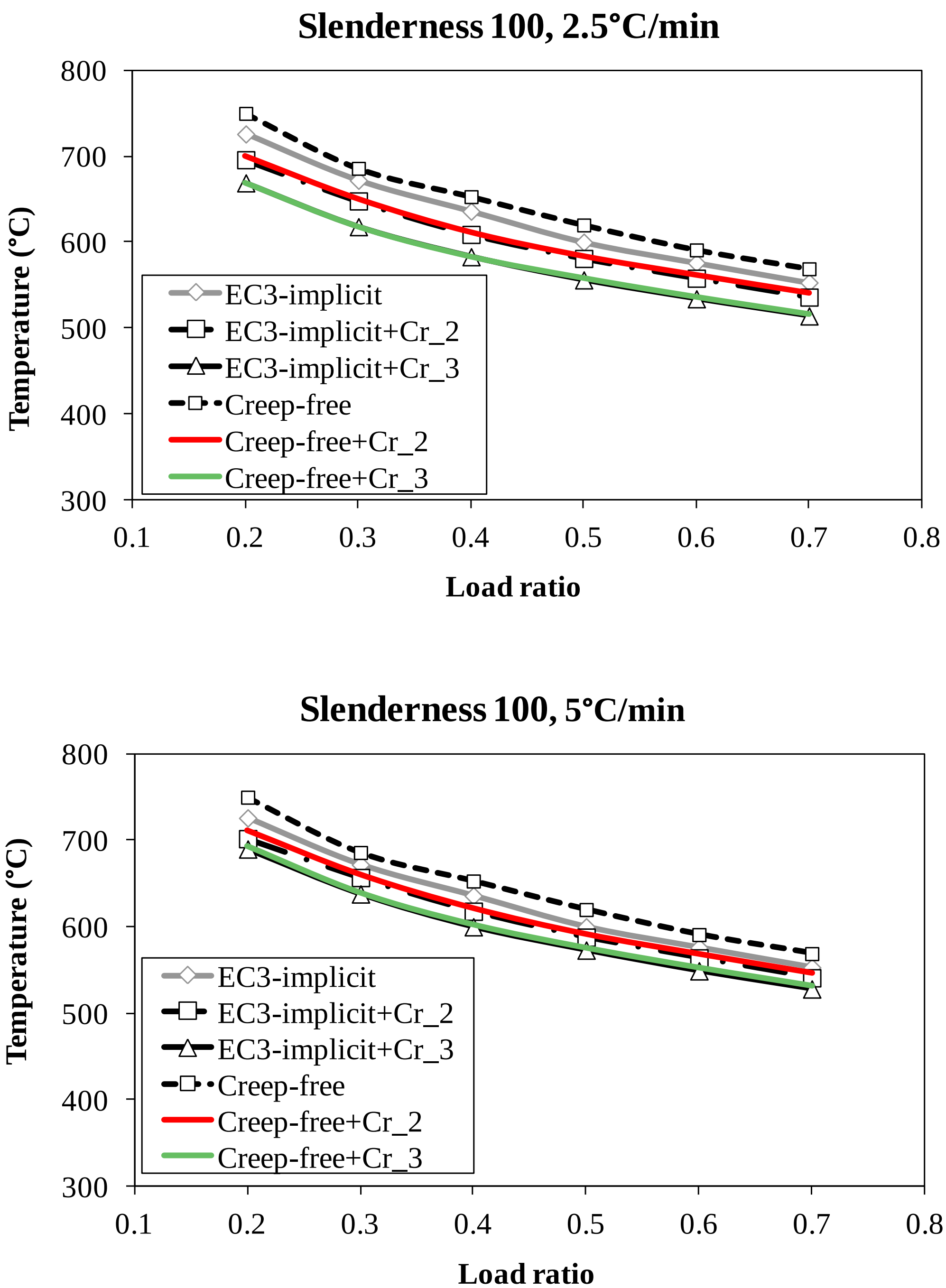

Slenderness 100, 2.5°C/min
Temperature (°C)
800
700
600
500
400
300
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
Load ratio
EC3-implicit
EC3-implicit+Cr_2
EC3-implicit+Cr_3
Creep-free
Creep-free+Cr_2
Creep-free+Cr_3
Slenderness 100, 5°C/min
Temperature (°C)
800
700
600
500
400
300
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
Load ratio
EC3-implicit
EC3-implicit+Cr_2
EC3-implicit+Cr_3
Creep-free
Creep-free+Cr_2
Creep-free+Cr_3

Figure 12

Table 1

| Steel grade from study [2] | Yield strength - 20°C (MPa) | Modulus of elasticity - 20°C (MPa) | Incremental time step **Δt** (min) | Gauge length **l** (mm) | Rectangular section length **a** (mm) |
|---|---|---|---|---|---|
| S355 | 357.0 | 185000.0 | 0.3 | 40 | 7.07 |

Table 2

| Length **l** (mm) | Slenderness | $N_{b,y,Rd}$ (N) | Load ratio | Axial force **V** (N) | Lateral force **H** (N) |
|---|---|---|---|---|---|
| 3834 | 60 | 5205135 | 0.2 | 1041027 | 2603 |
| | | | 0.3 | 1561541 | 3904 |
| | | | 0.4 | 2082054 | 5205 |
| | | | 0.5 | 2602568 | 6506 |
| | | | 0.6 | 3123081 | 7808 |
| | | | 0.7 | 3643595 | 9109 |
| 5112 | 80 | 4025562 | 0.2 | 805112 | 2013 |
| | | | 0.3 | 1207669 | 3019 |
| | | | 0.4 | 1610225 | 4026 |
| | | | 0.5 | 2012781 | 5032 |
| | | | 0.6 | 2415337 | 6038 |
| | | | 0.7 | 2817893 | 7045 |
| 6390 | 100 | 2997463 | 0.2 | 599493 | 1499 |
| | | | 0.3 | 899239 | 2248 |
| | | | 0.4 | 1198985 | 2997 |
| | | | 0.5 | 1498731 | 3747 |
| | | | 0.6 | 1798478 | 4496 |
| | | | 0.7 | 2098224 | 5246 |

Table 3

| | | 2.5°C/min | | 5°C/min | |
|---|---|---|---|---|---|
| | EC3-implicit | Cr_2 | Cr_3 | Cr_2 | Cr_3 |
| Load ratio | Temp (°C) | | | | |
| 0.2 | 689 | 660 | 648 | 678 | 667 |
| 0.3 | 638 | 615 | 596 | 622 | 612 |
| 0.4 | 591 | 574 | 559 | 580 | 573 |
| 0.5 | 555 | 540 | 526 | 544 | 537 |
| 0.6 | 520 | 506 | 491 | 510 | 502 |
| 0.7 | 472 | 459 | 449 | 463 | 457 |

Table 4

| | | 2.5°C/min | | 5°C/min | |
|---|---|---|---|---|---|
| | Modified EC3 | Cr_2 | Cr_3 | Cr_2 | Cr_3 |
| Load ratio | Temperature (°C) | | | | |
| 0.2 | 716 | 651 | 648 | 690 | 675 |
| 0.3 | 664 | 607 | 598 | 637 | 619 |
| 0.4 | 621 | 583 | 563 | 595 | 582 |
| 0.5 | 583 | 552 | 532 | 561 | 549 |
| 0.6 | 550 | 521 | 502 | 529 | 517 |
| 0.7 | 518 | 489 | 471 | 498 | 484 |