VERIFICATION OF THE RAMBERG-OSGOOD MATERIAL MODEL FOR THE FIRE DESIGN OF STEEL MEMBERS

Samer Nemer

Abstract

In this paper, the modified Ramberg-Osgood constitutive equations for calculating the stress-strain of steel at elevated temperatures using the parameters determined based on the transient state tensile test results achieved at the Helsinki University of Technology are verified. This is done by numerically comparing the global and local buckling capacities of I-shaped steel members incorporating the modified Ramberg-Osgood model along with the material model given in the fire section of Eurocode EN1993-1-2. For this purpose, a numerical model using the ABAQUS software was developed. Then, nonlinear analyses with imperfections (GMNIA) were performed to compare the buckling capacities of the steel columns and beams of four different hot-rolled cross-sections (IPE160, IPE180, HE100B, HE500B), made of steel grade S355, at three different temperatures (400°C, 500°C, 600°C). The results showed that adopting the modified Ramberg-Osgood model can lead to the same buckling capacities resulting when using the EN1993-1-2 material model for steel temperatures of less than 400°C. However, adopting this model for 600°C overestimates the buckling capacities in most cases.

Key words

- Ramberg-Osgood
- Fire design
- Structural steel
- Material model
- Elevated temperatures
- Nonlinear analysis.

1 INTRODUCTION

1.1 Literature study

Numerical modeling is considered nowadays to be an effective tool for investigating and proposing new design methods. An extremely important step to build a reliable numerical model, which is able to predict the actual buckling capacity of steel members at elevated temperatures, is the correct application of the accurate mechanical properties of the material/materials used. It is a well-known fact that when the temperature increases, the mechanical properties of steel, especially its strength and stiffness, reduce dramatically, and this considerably affects the structural response of steel members and may lead to structural instability in steel structures as a whole.

In the literature available, the material models of steel at elevated temperatures are usually given in the form of stress-strain curves. The mechanical properties of steel (e.g., the modulus of elasticity, yield stress and ultimate strength) can be obtained from these curves. These data are obtained from two types of tensile tests of steel at elevated temperatures, namely, steady state and transient state tests. In steady-state tests, the specimen is first heated to the required temperature before straining to failure. The specimen in transient-state tests is first subjected to the load, and then the temperature is increased until failure. Kirby and Preston (1988) reported that transient-state tests give lower values of strengths than the values obtained from steady-state tests on carbon steel for a temperature range of (400 – 800) °C. There are many material models available in the literature. For a practical design, EN 1993-1-2 (2005) adopts Rubert and Schau-
mamann’s model, which is derived from transient-state tests on beams (Rubert and Schaumann, 1986). In addition to the deterioration of strength and stiffness when the temperature increases, the clear yield point at a normal temperature disappears at elevated temperatures, and the yield strength becomes difficult to identify as the behavior becomes highly nonlinear with the rising temperature. For this reason, and because of large strains shown in steel members at elevated temperatures, it is more usual to consider the effective yield stress at a total strain within a range between 0.2% to 2.0% (ECCS, 1989; BS 5950, 2000). EN 1993-1-2 adopts an effective yield strength at a 2.0% total strain for classes 1, 2, 3 cross-sections. For class 4 cross-sections, the 0.2% proof strength should be used (EN 1993-1-2, 2005).

The material model investigated in this paper is that given by (Outinen et al., 1997) it was proposed using the calculating method developed by (Ramberg and Osgood, 1943); the mechanical properties of S355 steel at elevated temperatures are calculated using simple formulas based on transient state tensile test results carried out at the Laboratory of Steel Structures at the Helsinki University of Technology (SFS-EN 10 002-5, 1992; EN 10 002-2, 1992; EN 10 002-4, 1992). These formulae are proposed instead of the reduction factors given in EN1993-1-2. Wang et al. (2012) reported that the Ramberg-Osgood equations are capable of providing a convenient way to express stress-strain curves as a continuous function. Very important research was conducted by (Pauli et al., 2012), who carried out extensive experimental investigations on the material behavior of carbon steel at elevated temperatures and on structural stub and slender columns on fire. It was reported that the EN1993-1-2 material model for carbon steel has difficulties in describing the stress-strain relationships from tensile tests due to the fact that it overestimates the strain hardening for strains smaller than 2% and underestimates it for larger strains. Moreover, the shape of the modelled stress-strain curve of EN1993-1-2 cannot be adapted to the individual stress-strain relationships of the experimental results. On the other hand, adapting the one-stage Ramberg-Osgood model and its modification by Gardner-Nethercot (Gardner and Nethercot, 2004), has led to the better modelling of experimentally obtained individual stress-strain relationships of different steel grades and temperatures. Moreover, for high temperatures above 600 °C, it has been shown that the stress-strain relationship has an almost bilinear shape (Pauli, 2012). Another disadvantage of the Eurocode material model was reported by (Wang et al., 2012) who stated that the rate of change of the gradients (the tangent modulus) at the points between the limit of proportionality \( f_p \) and yield points \( f_y \) is not continuous, even though the values of the stress and tangent modulus are continuous. According to (Knobloch et al., 2010), the effect of the nonlinear stress-strain relationship of steel at elevated temperatures on the overall buckling strength is of high importance. In addition, it was concluded that adopting the temperature-dependent stress reached at a 2% strain leads to unreliable results for the cross-sectional capacity in pure compression. Moreover, the unsafe nature of the EN1993-1-2 curve was also reported by (Nemer and Papp, 2021).

1.2 The aim of the current research

Thorough knowledge and proper implementation of the behavior of materials at elevated temperatures is extremely important for developing accurate numerical models, which are able to predict the real behavior of steel members at elevated temperatures. Additionally, improving the accuracy of the material models incorporated in a fire design is also important with regard to the safety and economy of a steel structural design. Based on the available literature given above, it can be stated that there is a lack of certainty in and many disadvantages of the current EN1993-1-2 material model. Therefore, this paper aims at evaluating the applicability of the modified Ramberg-Osgood material model as an alternative material model for the fire design of steel members. The parameters for this fire design model were presented by (Outinen et al., 1997) based on an actual test that was not investigated or verified later by other researchers.

1.3 The content of the paper

In this paper, the EN1993-1-2 and the modified Ramberg-Osgood material models are first presented; then the numerical model is explained. Subsequently, the local buckling capacity of a steel beam studied by (Prachar et al., 2016) and the global buckling strengths of columns and beams are calculated by a geometrically and materially nonlinear analysis (GMNIA) incorporating the two material models.

2 MATERIAL MODELS AT ELEVATED TEMPERATURES

This section covers the description of two material models, which represent the material response of carbon steel at elevated temperatures, i.e., (1) the EN1993-1-2 material model and (2) the Ramberg-Osgood material model.

2.1 The EN1993-1-2 material model

The material model for carbon steel at elevated temperatures, as given in the fire section of Eurocode (EN1993-1-2, 2005), is presented in Fig. 1. The response of the material is divided into four stages as follows:

The first stage is linear-elastic up to the proportional limit point \( f_y \) (the end of the elastic stage), at which the stress is proportional to the strain. At this stage, only two basic material parameters are needed, i.e., the slope of the linear elastic range

Fig. 1 EN1993-1-2 material model for steel at elevated temperature θ [1]
for steel at elevated temperatures ($E_\theta$) and also the proportional limit for steel at elevated temperatures ($f_{p,\theta}$). Then, the linear elastic range is followed by an elliptical curve between the proportional limit $f_{p,\theta}$ to the effective yield strength of steel at an elevated temperature ($f_{y,\theta}$), which is defined as the strength at a 2% total strain. In the third stage, the stress remains constant between $\varepsilon_{y,\theta} = 2\%$ and the limiting strain for the yield strength, $\varepsilon_{t,\theta} = 15\%$. In the last stage the stress drops to zero at the ultimate strain $\varepsilon_{u,\theta} = 20\%$, which means a fracture.

Fig. 2 shows the stress-strain curve according to the fire section of Eurocode EN1993-1-2 for S355 steel at three different temperatures (400, 500, 600 °C).

In EN1993-1-2, the strength and stiffness degradation of steel at an elevated temperature is presented using reduction factors, where the property at an elevated temperature is normalized with respect to the equivalent property at an ambient temperature. Table 1 presents the reduction factors for the effective yield strength ($k_{y,\theta} = f_{y,\theta} / f_y$), proportional limit ($k_p,\theta = f_{p,\theta} / f_y$) and elastic modulus ($k_e = E_\theta / E$) at the three temperatures (400, 500, 600 °C) investigated, where $f_y$, $E$ are the yield strength and the modulus of elasticity of the normal temperature design, respectively.

The Modified Ramberg-Osgood model based on a real transient test

The equation for calculating the stress-strain curve of steel at elevated temperatures proposed by (Ramberg and Osgood, 1943), is the following:

$$\varepsilon_i = \frac{\sigma_i}{E_{a,\theta}} + \beta_i \left( \frac{f_{y,\theta}}{E_{a,\theta}} \right) \frac{\sigma_i}{f_{y,\theta}} n_i$$

(1)

$\sigma_i$, $\varepsilon_i$; represent the stress and corresponding strain, respectively, at temperature $\theta$

$n_i$; coefficient that enables the curvature to be adjusted; $\beta_i = 6/7$.

Outinen et al. (1997) proposed simple formulas to determine the parameters of the Ramberg-Osgood equation (2,3,4) based on the test results for steel grade S355, as follows:

For $200^\circ C \leq \theta \leq 700^\circ C$:

$$E_\theta = 263000 - 325 \theta$$

(2)

For $200^\circ C \leq \theta \leq 700^\circ C$:

$$f_{y,\theta} = 352 - 0.54(\theta - 200)$$

(3)

For $200^\circ C \leq \theta \leq 700^\circ C$:

$$n_i = 0.000231 \theta^2 - 0.231 \theta + 62.5$$

(4)

3 NUMERICAL MODEL

3.1 General

An advanced geometrically and materially nonlinear analysis with imperfections included (GMNIA) using ABAQUS software (ABAQUS 3DEXPERIENCE r2018x) was used for calculating the ultimate load capacity of the members studied. The validation of this program was published in (Hajdú and Papp, 2018) and (Hajdú, 2021). The members are modelled using the general purpose S4R shell elements.

3.2 Study program

Four sections were studied to recognize the effect of material models on steel members with different sections subjected to an axial force or a bending moment. The dimensions of these cross-sections are presented in Table 2.
3.3 Meshing size

The mesh size was determined to be 16 elements in the flange, and 16 elements in the web depth, while along the member’s length, the size of the elements was 20 mm, as shown in Fig. 4.

![Fig. 4 Meshing of the ABAQUS model](image)

3.4 Load and boundary conditions

For the sake of simplicity, the members investigated in this study were simply-supported; i.e., two reference points, one at each end, were coupled with the nodes of both end surfaces of the members using kinematic coupling restraints. Then, these reference points were restrained against all degrees of freedom except for the displacement in the direction of the load applied at the loaded end and the rotations about the axes of the buckling at both ends, as shown in Fig. 5.

![Fig. 5 ABAQUS model: Boundary conditions and load application](image)

3.5 Imperfections

The load was modelled by applying the distributed forces on the flanges and on the web of the loaded end using the modified RIKS tool, which is available in the ABAQUS library (ABAQUS, 2018).

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The residual stresses were taken into account by introducing the ECCS type model for hot-rolled cross-sections (ECCS, 1976) into the numerical model. The amplitude of the initial stress depends on the height-to-width ratio of the section investigated, as shown in Fig. 6.

The initial geometric imperfections of the members were taken into account by performing a linear buckling analysis (LBA) on the perfect prismatic member with the given boundary conditions; then the relevant normalized global buckling mode was extracted. Thus, the first global buckling mode shape derived from the linear buckling analysis was introduced into the non-linear finite element model (GMNIA), and multiplied by the amplitude of the initial geometrical imperfection. The nodal coordinates of the model were updated by adding the nodal imperfections established. The amplitude of the initial geometrical imperfection of the column is considered to be equal to L/1000, where L is the member length. The amplitude of the initial geometrical imperfection of the column is taken to be L/1000, which is widely used in the literature, and corresponds to 75% of the recommended tolerance value of L/750 for a steel column in Annex D of EN1090-2:2008 (BS EN 1090 2, 2008).

It is worthwhile mentioning that in the finite element models, the true stress and plastic strain were adopted instead of the engineering stress and strain. Therefore, the following equations were used to represent the relationship between the true stress and plastic strain:

\[
\sigma_{true} = \sigma_{nom}(1 + \varepsilon_{nom}) \quad (5)
\]

\[
\varepsilon_{true} = \ln (1 + \varepsilon_{nom}) \quad (6)
\]

\[
\varepsilon_{pl} = \ln (1 + \varepsilon_{nom}) - \frac{\sigma_{true}}{E} \quad (7)
\]

### Tab. 2 Characteristics of different sections investigated in this paper

<table>
<thead>
<tr>
<th>Cross-section</th>
<th>h</th>
<th>b</th>
<th>tf</th>
<th>tr</th>
<th>r</th>
</tr>
</thead>
<tbody>
<tr>
<td>IPE160</td>
<td>160</td>
<td>82</td>
<td>5.0</td>
<td>7.4</td>
<td>9</td>
</tr>
<tr>
<td>IPE180</td>
<td>180</td>
<td>91</td>
<td>5.3</td>
<td>8.0</td>
<td>9</td>
</tr>
<tr>
<td>HE100B</td>
<td>100</td>
<td>100</td>
<td>6.0</td>
<td>10.0</td>
<td>12</td>
</tr>
<tr>
<td>HE500B</td>
<td>500</td>
<td>300</td>
<td>14.5</td>
<td>28.0</td>
<td>27</td>
</tr>
</tbody>
</table>

![Fig. 6 Considered residual stress patterns for h/b<1.2 (left) and h/b>1.2 (right) [16]](image)
4 RESULTS

4.1 Comparison with the numerical simulation given by Prachar et al.

A number of class 4 (slender) welded steel beams were investigated numerically and experimentally at elevated temperatures by (Prachar et al., 2016). The two material models investigated in this paper were employed to simulate a heated Class 4 steel beam under lateral torsional buckling at 450 °C presented in (Pauli, 2012) as (TEST 6). It is worthwhile mentioning that in this model, the yield strength is based on the strain at 0.2% proof strength for both materials used. The dimensions of the cross-section of the beam along with the capacities calculated by Prachar et al., and by the numerical model described above incorporating the two material models are presented in Table 3.

Tab. 3 Numerical results using the two material models

<table>
<thead>
<tr>
<th>NO.</th>
<th>Cross-section (mm)</th>
<th>Load capacities (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>hw X t w</td>
<td>Prachar et al.</td>
</tr>
<tr>
<td>Test 6</td>
<td>446 X 4</td>
<td>150 X 7</td>
</tr>
</tbody>
</table>

The total load-displacement curves of the same numerical simulations are shown in Fig. 7. Based on the results presented in Table 3 and Fig. 7, it can be said that adopting the modified Ramberg-Osgood material model in the numerical model results in a capacity similar to that calculated using the EN1993-1-2. However, there is a clear difference in the deflection, which is due to the difference in the Young’s modulus value, as follows:

According to EN1993-1-2, the Young’s modulus at 450 °C is $E_0 = 136500$ N/mm²; while according to the test results given by (Outinen et al., 1997), $E_0 = 116750$ N/mm².

4.2 Comparative study of columns

Following the comparison of the lateral torsional buckling of the steel beam presented in the previous section, the two material stress-strain curves were incorporated in the ABAQUS model to calculate the capacities (N) of steel compressed members in a fire with varying member lengths (slenderness ratios) and under three different temperatures. Fig. 8 shows the results of the numerical models for the columns made of IPE160 and HE100B cross-sections at three different temperatures (400 °C, 500 °C, and 600 °C), where $N_{pl,Rd}$ is the plastic compressive resistance of the cross-section at elevated temperatures.

It can be seen that adopting the Ramberg-Osgood model can result in similar buckling capacities to those predicted by using the EN1993-1-2 material model for steel columns at 400 °C and 500 °C. However, for columns under 600 °C, the Ramberg-Osgood model overestimates the buckling capacities for various slenderness ratios and cross-sections.

4.3 Comparative study of beams

In this section, the two material models were used for calculating the buckling capacities of steel members under pure bending. The results of the comparison of the lateral torsional buckling capacities (M) for members made of IPE180 and HE500B cross-sections at three different temperatures 400 °C, 500 °C, and 600 °C are presented in Fig. 9, where $M_{pl,Rd}$ is the plastic.
moment resistance of the cross-section at elevated temperatures.

Again, it can be seen that the two material models lead to almost the same buckling resistances for steel beams at 400°C and 500°C. However, for the beams at 600°C, the Ramberg-Osgood material model overestimates the buckling capacities compared to the capacities calculated with the EN1993-1-2 material model mainly for short beams, while this difference reduces for long beams (1.5), where both material models lead to similar capacities.

5 CONCLUSION

This paper presents a numerical investigation of the verification of the Ramberg-Osgood material model with parameters calculated based on a transient test achieved at the Helsinki University of Technology. A finite element model was developed and verified; then three different cases were investigated, i.e., a Class 4 steel beam at 450°C, a comparative study on columns with different slenderness ratios and three different temperatures (400, 500, 600°C), and a similar study on beams. It can be concluded that the modified Ramberg-Osgood leads to buckling capacities that correspond to those given by adopting the EN1993-1-2 material model for beams and columns at 400°C and 500°C. However, at 600°C, the Ramberg-Osgood model overestimates the buckling capacities for most cases. Therefore, the parameters should be modified, and more conservative values should be adopted.

Acknowledgments

This research did not receive any specific grant funding from agencies in the public, commercial or not-for-profit sectors.

Disclosure statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Fig. 9 Comparison of the buckling capacities for columns made of IPE160 (Left) and HE100B (Right)
REFERENCES


