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Modified procedure for buckling of steel columns at elevated temperatures

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A B S T R A C T

Buckling capacity of axially loaded steel columns with hot-rolled I-sections, circular and rectangular hollow sections in fire is studied. The current Eurocode method for checking the stability at elevated temperatures has been derived on the same basis as in ambient conditions. Due to significant nonlinearities in the behaviour in fire the standard method appears to be not fully appropriate in certain ranges of parameters. In the present work the behaviour of columns is studied by comprehensive numerical simulation at a wide range of temperatures and slenderness values. Based on the results two alternative analytical procedures have been proposed and validated for evaluation of buckling strength. One of them needs numerical determination of a number of parameters beforehand. The other is based on the modification of the nonlinear material model and despite some limitations, it is convenient to use with common design procedures and applicable for an appreciable range of typical sections.

1. Introduction

Stability of a steel column at fire temperatures is a complex phenomenon, influenced by several features concerning geometry, fabrication method and modified material properties. Behaviour of axially loaded columns can be effectively simulated by advanced numerical methods, but convenient simplified methods are needed for practical design. The current Eurocode method for checking the buckling capacity of columns in fire conditions is based on the extensive numerical investigation, performed by Talamona et al. [1,2] and experimental results. Several authors like Knobloch et al. [3], Vila Real et al. [4], Toh et al. [5], Somaini et al. [6], have referred to certain discrepancy between the present Eurocode 3 design method [7] and the results of experiments and numerical models for buckling resistance of steel columns in fire. In order to better understand the behaviour of columns and improve the simplified methods several authors have studied the influence of the temperature distribution [8], axial constraints [9] heating rate [10] and initial stress [11] on the resistance of columns in fire. Several works have proposed alternative procedures, which usually are focused on specific section types like H-sections [5,6] or square hollow sections [12], applicable only with limited parameter ranges or tend to be quite complex and not inherent to the common standard based approach [6]. Therefore further investigation to develop appropriate design models is justified.

The objective of this work is to demonstrate the complexity of the behaviour of steel columns in fire conditions, which restricts accuracy of the present design procedure. The purpose is to reduce the level of simplification, caused by inappropriate representation of the nonlinear stress-strain relationship and characteristics of different section types. Two methods, using a unified formulation for a wide range of standard section types, are proposed for buckling evaluation of axially loaded columns in fire. The methods are conveniently applicable with current practical design procedures and the reliability has been validated by finite element based numerical results.

2. Principles of the present design method

The EC3 design method is only shortly outlined here to give the motivation and background for the development of the following methods. The present Eurocode design method for axially loaded columns in fire conditions uses in principle the same model as in normal temperature conditions. It is based on Ayrton-Perry formulation [13], which states that an initially curved axially compressed element becomes unstable, if stresses caused by compression and additional bending reach the yield stress limit in the middle section of the column. The simplicity of the criterion makes the EC3 design model very effective in normal temperature conditions, but according to numerical simulation the section plastification does emerge prior to column buckling and in fact the yield limit criterion is not valid. After the compression stress has reached the yield limit the decrease of the column stiffness starts and progresses rapidly. In normal temperature conditions the Ayrton-Perry approach and the non-linear FEM model practically coincide,

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because the ideal elasto-plastic material model is used for the strain-stress relationship. At elevated temperatures the stress-strain relationship of the steel material becomes more complicated, including a parabolic zone in the bilinear combination of curves.

The Ayrton-Perry approach itself is based on the solution of an initially curved elastic beam subject to axial compression. A number of solutions to this problem are available (i.e. by Euler, Timoshenko). The potential energy variation approach, following the scheme in Fig. 1 is considered hereby. The initial shape of the beam is presented in the form of a sinusoid wave (Eq. (2-1)), where $y_{0.mid}$ is the maximum initial imperfection in the middle of the column and is usually defined as a fraction of the length. The additional displacement due to compression of the column is defined as Eq. (2-2), where $y_{1.mid}$ is the maximum displacement in the middle of the column. P is the axial load, EI is the elastic bending stiffness, L is the initial length of the column. The deformation potential energy U is defined in Eq. (2-3). The column top displacement e due to bending is Eq. (2-4). The potential energy decrease due to the work of the external force can be defined using Eq. (2-5). According to the potential energy variation principle, regarding minor deviation from the equilibrium state the first variation of the total energy must be equal to zero (Eq. (2-6)). Then the column deformation results as Eq. (2-7). The limit load can be derived from the second variation of the total potential energy (Eq. (2-8)), reaching a well-known solution in Eq. (2-9). Combining the yield limit criterion, formulated as Eq. (2-10) with Eq. (2-7), a solution can be presented in the convenient EC3 form.

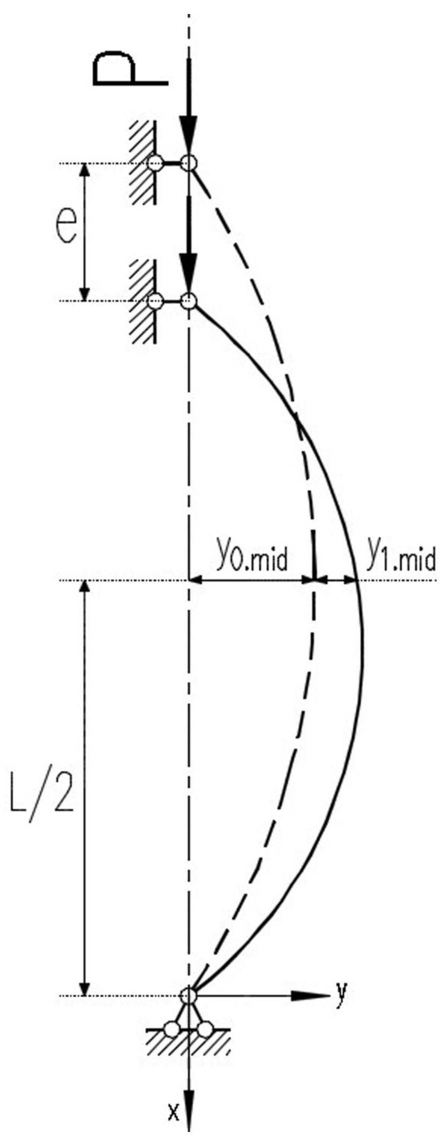

Fig. 1. Column with imperfection.

Obviously at elevated temperatures the behaviour of the element subject to compression becomes more complex and hereby it is reasonable to discuss the effect of temperature on the essential features of the above presented basic buckling formulation (Eq. (2-1)-(2-9)). Due to the stress-strain curve at elevated temperatures, the relationship between bending stiffness and stress state becomes highly non-linear as illustrated in Fig. 2, where one of the diagrams corresponds to ambient conditions and the other to 500 °C. Temperature 500 °C is chosen as an arbitrary example, as analogous non-linear relationship can be observed at all elevated temperatures starting from approximately 100 °C. In Fig. 2 M_{Sd} is the acting bending moment, $M_{pl.N.Rd.}$ is the plastic bending moment capacity corresponding to the acting axial load value, EI is the bending stiffness corresponding to the acting bending moment and axial load and EI_0 is the bending stiffness at zero stress state, EI_{fi} is the bending stiffness in fire accounting for the material properties at elevated temperature and the stress state, $EI_{fi.0}$ is the bending stiffness in fire accounting for the material properties at elevated temperature at zero stress state, $M_{sd.fi}$ is the acting bending moment, $M_{pl.N.rd.fi}$ is the bending moment capacity in fire conditions at specific axial load level, $\alpha = N_{sd.fi}/N_{pl.Rd.fi}$ is the axial load level, where $N_{sd.fi}$ is the acting axial load and $N_{pl.rd.fi}$ the axial load capacity in fire conditions. Reduced bending stiffness EI or EI_{fi}, can be calculated using section strains, which correspond to the external and internal force equilibrium conditions at respective temperature and stress state of the section. In case of ambient temperature the solution can be presented in analytical form. In case of elevated temperatures, analytical solution becomes complicated, but numerical methods can be effectively utilized. The following procedure was applied for composing diagrams of Fig. 2(b) at elevated temperatures. Axial force $N_{sd.fi}$ was expressed in a nondimensional form as a factor α; section's plastic bending moment capacity $M_{pl.N.rd.fi}$ corresponding to the axial force $N_{sd.fi}$ was calculated. For any given value of $M_{sd.fi}$ section strains fulfilling the external and internal forces equilibrium condition were determined according to the material model [7] and assuming plain section hypothesis, so that $N_{int} = N_{sd.fi}$, $M_{int} = M_{sd.fi.}$ Bending stiffness EI_{fi} of the section can be easily obtained from the strains using the stress-strain curve at the corresponding temperature. Then the bending stiffness EI_{fi} can be related to the bending stiffness $EI_{fi.0}$, which is a product of the section's second moment of inertia I and deformation modulus in the elastic range corresponding to a certain temperature (500 °C in Fig. 2(b)).

The following characteristic features, caused by the behaviour of the material model can be observed in Fig. 2, where 500 °C is applied as an example of elevated temperatures:

- at the temperature equal to 500 °C the influence of axial load level on the bending stiffness curves is of distinctly different nature compared to ambient conditions;
- at the temperature equal to 500 °C, for axial load level, corresponding to the stress level higher than the proportionality limit ($\alpha \geq 0.5$), dramatic reduction in bending stiffness can be observed even without any acting bending moment;
- at the temperature equal to 500 °C, for axial load level, corresponding to the stress level higher than the proportionality limit ($\alpha \geq 0.5$), the bending stiffness in certain range of moments increases with the increase of acting bending moment;
- in ambient conditions a common feature for all the sections is rapid reduction of bending stiffness after reaching the yield stress limit; at 500 °C the rapid drop in bending stiffness occurs close to the section's plastic bending capacity, while elsewhere the curves are relatively smooth.