Journal of Constructional Steel Research 96 (2014) 140–150

Contents lists available at ScienceDirect

Journal of Constructional Steel Research

Alternative approach to buckling of square hollow section steel columns in fire

Andrei Kervalishvili, Ivar Talvik *

Institute of Structural Design, Tallinn University of Technology, Ehitajate tee 5, Tallinn 19086, Estonia

ARTICLE INFO

Article history:
Received 10 April 2013
Accepted 23 November 2013
Available online 14 February 2014

Keywords:
Column
Buckling
Eurocode 3
Fire
Numerical analysis
Analytical model

ABSTRACT

Stability of axially loaded steel columns with square hollow sections at elevated temperatures is studied herein. At present the Eurocode model for checking buckling capacity of columns in fire has been developed on the similar basis as for ambient conditions. It is shown that due to the effect of complex non-linear behavior the standard design model is not always adequate and in certain situations prediction of buckling capacity of columns according to the common design formulas may even reach results on the unsafe side. The main focus of this work is the performance of an analytical model against advanced numerical methods. For this purpose extensive numerical study was performed using non-linear FE method. Based on the results obtained with advanced calculation models of column behavior at elevated temperatures an analytical model has been proposed and verified. The proposed model accounts for variable non-linear stiffness properties, which have significant effect on the buckling capacity of axially loaded columns in fire. The advantage of the method is the format, which is convenient for incorporation into common design algorithms.

1. Introduction

Failure of a steel column at elevated temperatures is a phenomenon of pronounced complexity, influenced by a number of aspects. Behavior of columns under compression can be effectively simulated with advanced numerical methods. Still it has been a general approach to search for simplified methods in order to reduce the effort in practical design work. Even losing in accuracy is acceptable, if the results are on safe side. In general case of beam-columns at elevated temperatures the proposed simplified methods tend to be rather complex or inaccurate.

The present Eurocode model is based on the comprehensive numerical studies, carried out by Talamona et al. [1,2] and experimental results. Certain deviations of the Eurocode 3 design method [3] from some advanced numerical models for axially loaded steel columns in fire have been demonstrated. For example, Somaini et al. [4] point out that at fire temperatures the proposed simplified models do not properly account for material non-linear stress–strain relationship. Vila Real et al. [5] also mention that in some cases numerical results highlight certain unconservative nature of the Eurocode design expressions. Eurocode 3 method is based on report [6], composed for hot-rolled H-section and only later the method has been extrapolated to other section types, including hollow sections.

Methods alternative to EC3 have been proposed. For example Toh et al. [7] use Rankine approach, while Somaini et al. [8] have proposed a method, based on non-linear stress–strain relationship and incremental curvature variation procedure. Various authors have contributed to investigation of different aspects, which have an effect on stability of steel columns. These are influences of axial restraints [9], temperature distribution [10], heating rate and thermal creep [11], and residual stress [12].

Somaini et al. [8] propose analytical model in the form which is completely different from EC tradition. The model performs well accounting for variable bending stiffness through moment–curvature relationship curve. It has to be noted, that even the simplified version of the model is still quite complicated.

The present work deals with practical design method for axially loaded column with rectangular hollow sections. The main objective is to demonstrate the complexity of the behavior of a column at elevated temperatures and propose an alternative practical design method. The method is based on numerous FEM simulations. The main focus is on the effect of non-linear stress–strain relationship on the buckling of columns with square hollow section, disregarding residual stresses and other abovementioned effects, which require separate consideration. Proposed approach can be further extended and applied to more sophisticated FEM models.

2. Basis of current design methods

Stability of an axially loaded column belongs to classical problems in structural mechanics and design. Many researchers (Euler, Engesser, Shanley, Timoshenko etc.) have dealt with the problem and proposed different solutions. Eurocode 3 uses the Ayrton–Perry approach [13], which itself is based on the Euler formulation of axially loaded column

* Corresponding author. Tel.: +372 5141204.
E-mail addresses: kervalisvili.andrei@gmail.com (A. Kervalishvili), ivar.talvik@ttu.ee (I. Talvik).

0143-974X/$ – see front matter
http://dx.doi.org/10.1016/j.jcsr.2013.11.018

with initial curvature. Consider a column, whose length is L and the flexural stiffness is EI, submitted to axial compression P. Corresponding deformed geometry $y(x)$ is shown in Fig. 1. y_0 is the initial imperfection caused by imperfection before application of the load, and a_0 is the maximum initial imperfection value at mid-height of the column. The derivation of buckling factor is covered in Eqs. (2-1) to (2-9), where y_{mid} is the deflection at mid-height, A is the area and $W_{el.min}$ is the elastic bending modulus of the cross section, λ is the slenderness of the bar, N_{cr} is the Euler critical load and M_{mid} is the bending moment at mid-height, and f_y is the yield stress of the steel material.

According to Ayrton–Perry approach, an initially curved column becomes unstable, if compression stresses at one side of the section approach the yield value (Eq. (2-2)). According to the same authors, sinusoidal shape is a good approximation to the initial curvature (Eq. (2-3)). Using Eq. (2-3) for the solution of Eq. (2-1), we can obtain Eq. (2-4). Further Eq. (2-2) can be expressed as Eq. (2-5), which is a simple second order equation regarding P. Ayrton and Perry present the solution to Eq. (2-5) in the form of buckling factor χ (Eq. (2-6)), which indicates the reduction of buckling resistance compared to compression resistance. Eqs. (2-6) and (2-7) for calculating buckling factor as a function of non-dimensional slenderness λ are familiar to Eurocode users with the exception of factor η (Eq. (2-9)), which is a calibration factor to match the model (Eq. (2-6)) with the test results.

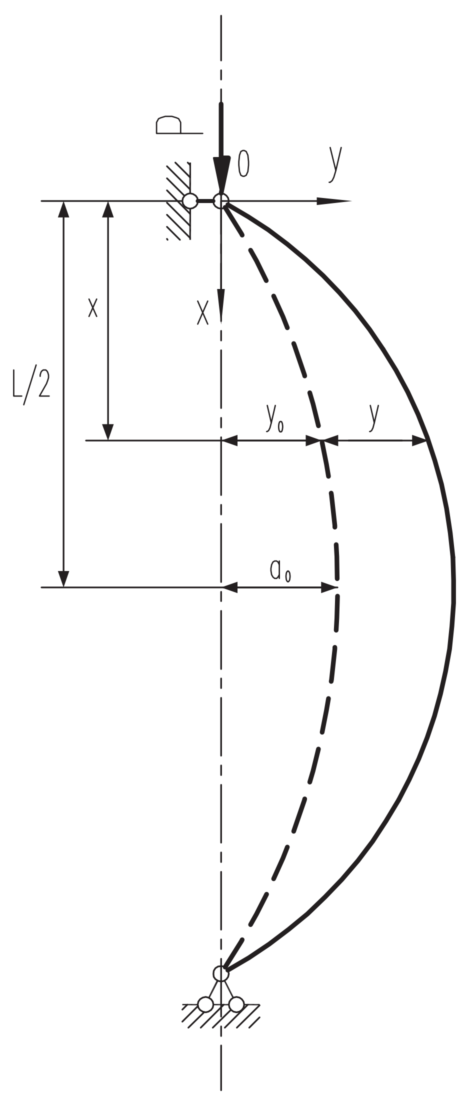

Fig. 1. Column with imperfection.

Eq. (2-1) serves as the basis of practical design models for stability. Essential feature of the model is bending stiffness EI, which is assumed to remain constant during the whole loading process. In reality this is not the case. Bending stiffness depends on the stress state or in terms of model (2-1) that bending stiffness is a function of P and y. Model (2-6) is sufficiently reliable in ambient temperatures, which has been validated by numerous experimental studies. This can be explained by involvement of the condition of Eq. (2-2) in the solution. In case Eq. (2-2) is not involved, the solution of Eq. (2-1) will be the Euler's critical load.

$$EIy'' = -P(y + y_0) \tag{2-1}$$

$$\frac{P}{A} + \frac{M_{mid}}{W_{el.min}} = f_y \tag{2-2}$$

$$y_0 = a_0 \sin(\pi x / L) \tag{2-3}$$

$$y_{mid} = \frac{a_0}{1 - \frac{P}{N_{cr}}} \tag{2-4}$$

$$\frac{P}{A} + \frac{a_0 P}{\left(1 - \frac{P}{N_{cr}}\right) W_{el}} = f_y \tag{2-5}$$

$$\chi = \frac{1}{\Phi + \sqrt{\Phi^2 - \lambda^2}} \tag{2-6}$$

$$\Phi = \frac{1}{2}\left(1 + \eta + \lambda^2\right) \tag{2-7}$$

$$\eta = \frac{Aa_0}{W_e} \tag{2-8}$$

$$\eta = \alpha(\lambda - 0,2) \tag{2-9}$$

Eurocode stress–strain curves are used in the current work for material modeling. There is one principal difference in the stress–strain curves at ambient temperature and temperatures higher than 200 °C. For ambient conditions ideal elasto-plastic material model is used, but at temperatures higher than 200 °C, a parabolic zone is included into the bilinear combination of curves. While stress–strain curve as the basic indication of material properties has been defined for different temperature conditions, not enough attention has been paid in EC methodology to bending stiffness as the integral property of a bar and its dependence on stress state both in ambient conditions and in high temperatures. Several researchers have reported about the significant effect of stress state on bending stiffness in ambient conditions, using different approaches — Engesser introduced tangent modulus formula, Considere and Von-Karman applied double module theory, and Shanley proposed inelastic column theory [14]. In the following section the influence of stress state on the bending stiffness of square hollow section elements in fire condition is studied.