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Equivalent geometric imperfection definition in steel structures sensitive to lateral torsional buckling due to bending moment

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ABSTRACT

The purpose of this paper is to present a proposal for the design of steel structures sensitive to lateral torsional buckling due to bending moment in order to fill the gaps in the current Standard EN 1993-1-1, guidelines for obtaining the magnitude of the imperfection. The proposal generalizes the approach provided in clause 5.3.2(11) of EN 1993-1-1 for steel structures sensitive to flexural buckling under compression.

1. Introduction

The design of steel beam and columns takes into consideration the effect of geometric imperfections, residual stresses, variation of the yield strength, etc. In particular, the EN 1993-1-1 (EC-3) [1] proposes two methods (see Fig. 1).

Method (A) Indirectly, performing a linear analysis and using interaction formulae at the member level as proposed by various authors (Greiner and Lindner [2], or Boissonade et al. [3]). This method includes geometric and material nonlinearity by means of buckling curves, obtaining the reduction factor χ and χ_{LT} Clause 6.3 of the EC-3, by default in this article the clauses and nomenclature refer to EC-3)) from the non-dimensional slenderness $\bar{\lambda}$ and $\bar{\lambda}_{LT}$.

The Work done by Marques et al. [4] extends the scope of the standard presenting a design model for the stability verification of tapered beams subject to linear bending moment distributions and to parabolic bending moment.

Method (B) Directly, including equivalent geometric imperfections in the nonlinear analysis.

This method has the following theoretical advantages compared to method (A):

– Buckling is considered at the section level as additional displacements and forces that verify the compatibility and equilibrium equations, instead of stability checks at the member level reducing the strength of the members.
– The buckling problem is understood as a global issue and is analyzed by considering the interaction of all members of the structure rather than only by the members under compression or bending, which means that secondary internal forces will also appear in the stabilizing beams or tension members.

These imperfections can be expressed as:

(B.1) Directly in structures sensitive to flexural buckling due to compression, including equivalent geometric imperfections in the structural analysis. This can be expressed in two ways:

(B.1.1) Based on initial global sway imperfections and local bow imperfections defined in 5.3.2 EC-3, or
(B.1.2) Based on a single imperfection, akin to the buckling mode (η_{cr}) of the structure (5.3.2(11)).

In Method (B.1.2), for structures sensitive to flexural buckling due to compression, the EC-3 proposes the imperfection (η_{init}) obtained by scaling the buckling mode, given by:

$$\eta_{init}(x) = \frac{e_0}{\bar{\lambda}^2} \frac{N_{RK}}{EI\left|\eta''_{cr}\right|_{\max}} \eta_{cr}(x)$$

where $e_0 = \alpha(\bar{\lambda} - 0.2)\frac{M_{Rk}}{N_{Rk}} \frac{1-\frac{\chi\bar{\lambda}^2}{\gamma_{M1}}}{1-\chi\bar{\lambda}^2}$, for $\bar{\lambda} \geqslant 0.2, \bar{\lambda} = \sqrt{\frac{\alpha_{ult,k}}{\alpha_{cr}}}$.

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Nomenclature

α is the imperfection factor (Tables 6.1 and 6.2 of EC-3) related to each buckling curve
α_{LT} is the imperfection factor (Table 6.3 of EC-3) for lateral torsional buckling
α_{cr} is the minimum force amplifier for the axial force configuration in members to reach the elastic critical buckling load
$\alpha_{ult,k}$ is the minimum force amplifier for the axial force configuration in members to reach the characteristic resistance N_{Rk} of the most axially stressed cross section without taking buckling into account
β is the correction factor for the lateral torsional buckling curves
γ_{M1} is the partial safety factor for the resistance of members to instability assessed by member checks
γ_{M0} is the partial safety factor for the resistance of cross sections whatever the class is
χ is the reduction factor for the relevant buckling curve
χ_{LT} is the reduction factor for lateral torsional buckling
$\bar{\lambda}$ is the nondimensional slenderness
$\bar{\lambda}_{LT}$ is the nondimensional slenderness for lateral torsional buckling
$\bar{\lambda}_{LT,0}$ is the plateau length of the lateral torsional buckling curves
$\{\eta_{init}\}$ is the vector of imperfections
η_{cr} is the shape of the elastic critical buckling mode
$(EI\eta''_{cr,\max})$ is the bending moment due to the buckling mode η_{cr} at the critical cross section
$\omega(y,z)$ is the warping function
θ_x is the torsional rotation
A is the cross sectional area
$B_{pl,Rd}$ is the plastic bimoment resistance
$\{d_{NL}\}$ is the vector of nonlinear displacements
e_{M} is the magnitude of the imperfection. E is the modulus of elasticity for steel
$\{F_{ext}\}$ is the vector of external forces
G is the shear modulus for steel
I_y, I_z are the second moment of area with respect to y, z axes
I_t is the torsional constant
I_w is the warping constant
KB is the generic element of the structure
$[K_L]$ is the linear stiffness matrix
$[K_G]$ is the geometric stiffness matrix taking into account bending moment
L is the total length of the structure
M_{Rk} is the characteristic moment resistance of the critical cross section($M_{el,Rk}$ in class 3, $M_{pl,Rk}$ in class 2)
M_0 is the reference bending moment ($My_{\mathrm{Ed},0}$ according to [1]), related to one section of the structure $M_{pl,y,Rd}, M_{pl,z,Rd}$ are the plastic moment resistance about y and z axes
M_y is the bending moment (My_{Ed} according to [1])
NB is the number of elements
t is the thickness of the flange/web
T is the torsional moment
T_t is the internal St. Venant torsional moment
T_w is the internal warping torsional moment
u is the displacement in direction x of the centroid
V_y, V_z are the shear forces in y and z directions
v, w are the displacements in the principal directions y and z of the shear center
W_z is the bending section modulus about z axis
W_y is the bending section modulus about y axis
W_ω is the bimoment section modulus
x is the axis of the member
y_{sc}, z_{sc} are the coordinates of the shear center
y, z are the coordinates of the check point
z_j is the mono-symmetry constant

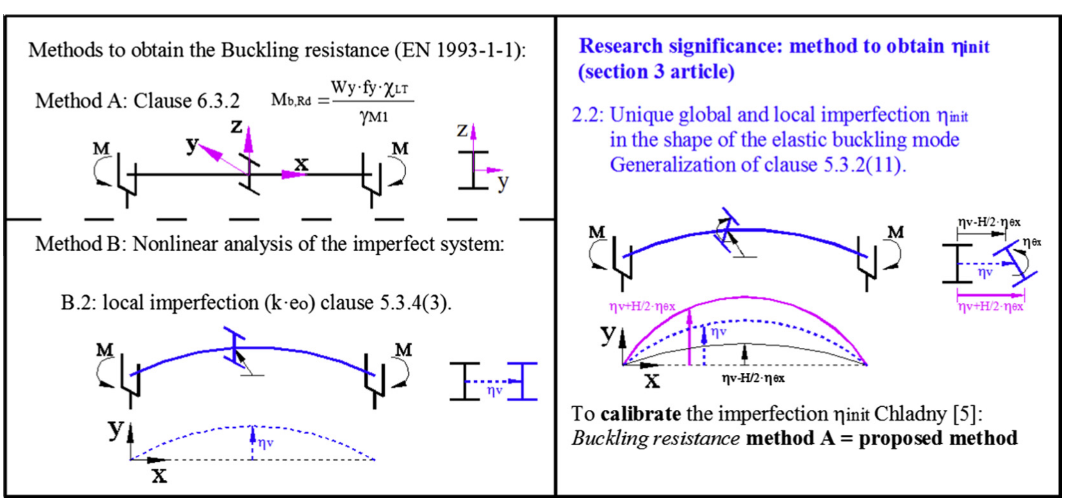

Fig. 1. Summary of the methods to obtain the buckling resistance and the scope of this research.

Chladný [5–7] proposed the proper arrangements in clause 5.3.2(11) to deal in structures sensitive to flexural buckling with tapered columns and/or non-uniform distribution of the compression force along their length and/or arch geometry.

(B.2) Directly in structures sensitive to lateral torsional buckling due to bending moment, including equivalent geometric imperfections in the structural analysis. According to clause 5.3.4(3) “taking account of lateral torsional buckling of a member in bending the