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An efficient geometrically exact beam element for composite columns and its application to concrete encased steel I-sections

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ABSTRACT

In this paper, a computationally efficient geometrically exact and materially non-linear 2D Euler–Bernoulli beam finite element is proposed, which is capable of accurately capturing the buckling behaviour of steel–concrete composite columns and complies with the principles of the general method of Eurocode 4 (EC4) (EN 1994-1-1:2004, 2004). The element is easy to implement and, due to the Euler–Bernoulli constraint, only requires uniaxial material laws for both steel and concrete. The element is subsequently employed to investigate the buckling behaviour of partially and fully concrete encased steel I-section uniformly compressed columns. In particular, the results of a parametric study are presented and discussed, aiming at assessing the influence of the equivalent member imperfections and the concrete material law, in order to provide recommendations concerning their use in non-linear analysis according to the general method of EC4.

1. Introduction

The European Standard EN 1994-1-1 part 1-1 [1] (EC4) prescribes two design methods for composite columns: (i) the "general method" (GM), which has a broad scope but requires performing a materially and geometrically non-linear analysis, and (ii) the "simplified method" (SM), which is based on second-order results and, necessarily, has a limited scope—e.g., it may only be applied to uniform members with doubly symmetrical cross-sections.

As pointed out in [2], advanced methods such as the GM generally lead to a more economic design, since simplified methods incorporate assumptions that invariably fall too much on the conservative side. In spite of this argument, studies concerning the application of the GM are very scarce.[1] The method was first outlined in [2] and a simple beam finite element was introduced, using a standard linearised geometric matrix to account for geometric non-linearity. More recently, the GM was discussed in [3] and, focusing on the implications of adopting constitutive laws based on mean values, as prescribed by the GM, an overall safety factor approach was proposed, which relates the cross-section resistances calculated using design and mean values. This method was subsequently employed in [4] to analyse high-strength concrete-filled tubes with inner core steel profiles. In this case, 3D solid finite element models were used, which require a significant computational effort.

This paper aims at contributing for a more widespread use of the GM. For this purpose, a simple and computationally efficient geometrically exact 2D Euler–Bernoulli beam finite element is proposed, specifically designed to comply with the principles of the method. A parametric study is then performed to assess the influence of key aspects, namely the influence of the equivalent member imperfections and the concrete material law, in order to make recommendations concerning their use in the context of the GM. In this study, only concrete encased steel I-section members are considered, simply supported and braced against torsion and either major or minor axis bending (axes y and z, respectively, see Fig. 1). Shrinkage and creep effects are not taken into consideration. Two arguments can be put forward to support these simplifications: (i) the buckling resistances may be directly calculated using the column buckling curves and thus employed for comparison purposes and (ii) they correspond to the standard benchmark case, for which e.g. the EC4 equivalent imperfections have been calibrated [3,5].

The outline of the paper is as follows. Section 2 presents a brief overview of the EC4 methods for uniformly compressed members. Section 3 is devoted to the formulation and validation of the geometrically exact beam finite element. Section 4 presents and discusses the results of the parametric studies carried out to assess

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[1] Note that this statement strictly refers to the application of the GM of EC4. There is a significant amount of research concerning the development and application of advanced non-linear analysis methods for steel–concrete composite beams and columns—see Section 3.

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the influence of member imperfections and the concrete material law. Finally, Section 5 presents the concluding remarks.

2. Overview of the EC4 methods

For completeness of the paper, the EC4 methods for column members are briefly outlined in this section. As previously mentioned, only isolated members, uniformly compressed and buckling in a uniaxial flexural mode, are dealt with.

For members in axial compression only, the SM allows calculating the buckling resistance using the European column buckling curves a, b, c—this method is herein designated as SM1. For the particular case of encased steel I-section columns, curve b applies for buckling about y, whereas curve c is employed for buckling about z. The member resistance is given by $\chi N_{pl,Rd}$, where $N_{pl,Rd}$ is the cross-section plastic resistance to compression and χ is the buckling reduction factor, which is obtained from the relevant buckling curve, as a function of the member relative slenderness

$$\bar{\lambda} = \sqrt{N_{pl,Rk}/N_{cr}}, \tag{1}$$

where $N_{pl,Rk}$ is the characteristic counterpart of $N_{pl,Rd}$ and N_{cr} is the critical force for the relevant buckling mode, calculated using an effective flexural stiffness $(EI)_{eff}$ where the concrete contribution is affected by a correction factor of 0.6.

The generic SM (herein designated SM2) involves a second-order elastic analysis including equivalent member imperfections and considering an effective flexural stiffness $(EI)_{eff,II}$, calculated using a concrete correction factor of 0.5 and further affecting all contributions by a calibration factor of 0.9 (thus $(EI)_{eff,II} < 0.9(EI)_{eff}$). For encased I-section columns, the imperfection amplitude equals $e_0 = L/200$ for buckling about y and $e_0 = L/150$ for buckling about z. The buckling check reads

$$\frac{M_{Ed}}{M_{pl,N,Rd}} \leqslant \alpha_M, \tag{2}$$

where M_{Ed} is the maximum bending moment in the member, $M_{pl,N,Rd}$ is the cross-section plastic bending resistance associated with the applied axial force N_{Ed} and α_M is a coefficient equal to 0.9 for steel grades S235 to S355 and 0.8 for S420 and S460.

For simply supported members, M_{Ed} may be obtained through

$$M_{Ed} = \frac{N_{Ed} e_0}{1 - N_{Ed}/N_{cr,II}}, \tag{3}$$

where $N_{cr,II}$ is calculated with $(EI)_{eff,II}$. This equation may be deemed "exact" for a single half-wave sinusoidal-shaped bow imperfection of amplitude e_0 (at mid-length). For other support conditions, the amplification factor $1/(1 - N_{Ed}/N_{cr,II})$ may still be applied if the imperfection shape corresponds to the critical buckling mode and the amplitude e_0 is appropriately adjusted—see [6] for a complete discussion of this subject.

The expression for e_0 that makes the SM2 match exactly the SM1 may be found by substituting (3) in (2) with $N_{Ed} = \chi N_{pl,Rd}$, which leads to

$$e_0 = \frac{\alpha_M M_{pl,N,Rd}}{\chi N_{pl,Rd}} \left(1 - \frac{\chi N_{pl,Rd}}{N_{cr,II}}\right), \tag{4}$$

where $M_{pl,N,Rd}$ is calculated for $N_{Ed} = \chi N_{pl,Rd}$. An expression which is equivalent to (4) was employed for the derivation of the equivalent imperfections for an earlier version of the German code [5]. The current imperfections in EC4 are slightly higher: $L/300$ for curve a, $L/200$ for curve b and $L/150$ for curve c.

The GM requires performing a physically and geometrically non-linear analysis of the member. Residual stresses and geometric imperfections may be accounted for through the equivalent initial bow imperfections, as for the SM2. Moreover, it may be assumed that plane sections remain plane and that full composite action exists. For structural steel, an elastic–perfectly plastic material law is prescribed, according to clause 5.4.3(4) of Eurocode 3 [7]. No practical difference exists between characteristic and design values, since the recommended partial factor is equal to 1. For reinforcing steel, reference is made to clause 3.2.7 of Eurocode 2 [8], where an elastoplastic material law is given, which may include hardening and is based on design values. Finally, for concrete, the tensile strength is discarded and, for compression, the stress–strain law is given in clause 3.1.5 of Eurocode 2, which is based on mean values.

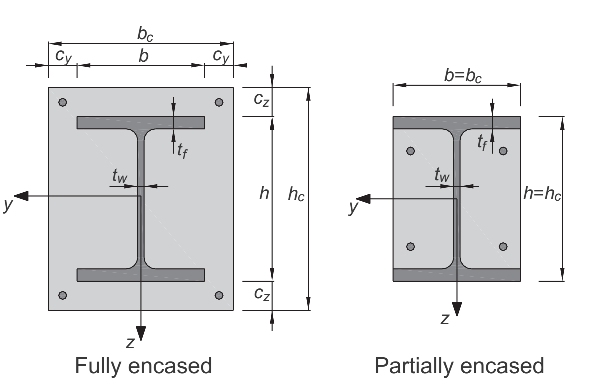

Fig. 1. Cross-section geometry and axes for concrete encased steel I-section columns.

3. Finite element formulation

3.1. Formulation

The proposed beam finite element employs a 2D total Lagrangian Euler–Bernoulli description, where the only unknown is the position vector of the beam axis, $\boldsymbol{r}$ (see Fig. 2). The geometrically exact concept introduced by Simo (e.g., [9–11]) is followed,

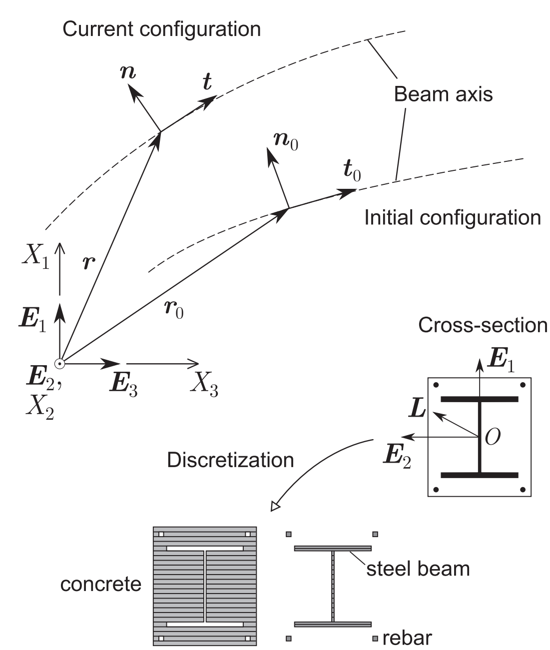

Fig. 2. Reference system, initial/current configurations of the beam axis and associated vectors $(\boldsymbol{r}, \boldsymbol{t}, \boldsymbol{n})$, reference cross-section orientation and cross-section discretization.