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Derivation of DSM-type resistance functions for in-plane global buckling of steel beam-columns

Andreas Taras

Bundeswehr University Munich, Germany

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ABSTRACT

This paper presents the derivation of a new design formulation for the representation of the buckling strength of steel beam-columns, which follows the format and basic principles of novel and increasingly popular international design methods, such as the *Direct Strength Method DSM* (Schafer, 2008)– used predominantly in North America for the design of cold-formed steel members – and the *General Method GM* – included in the Eurocode EN 1993-1-1 (EN 1993-1-1, 2005) section 6.3.4 as an alternative way of designing generic steel members and structural systems.

The paper focuses on the in-plane buckling strength of double-symmetric hot-rolled, tubular and welded sections, with compact sections; this focus on an otherwise well-understood problem allows for a clearer focus on the key aspects which need to be accounted for in a DSM/GM type representation of beam-column strength. In particular, a generalized definition of slenderness (in line with the DSM philosophy) and a generalized imperfection term, which accounts for the ratio between bending moments and axial forces in the beam column, are used to obtain an Ayrton-Perry (Ayrton and Perry, 1886; Rondal and Maquoi, 1979) type design formulation for beam-column in-plane global buckling.

In the paper, the key components that need addressing in a DSM – as well as any other – beam-column design approach are highlighted, namely: *i.* the influence of the relative ratio between bending and compression loading, *ii.* the effect of non-uniform bending moment diagrams, *iii.* the deterioration of the achievable plastic cross-sectional utilization due to loss of rigidity by yielding in slender members and *iv.* the interaction between buckling modes, in this case local and global buckling. The paper proposes a coherent, innovative design formulation which accounts for all of these effects and compares the outcome of the new strength predictions with numerical (non-linear FEM) and traditional Eurocode results.

1. Introduction and scope

In this paper, a new formulation for the design of beam-columns against in-plane buckling is presented. It makes use of a generalized slenderness definition and an "overall" formulation of the buckling reduction factor for combined load cases, following the basic precepts of comparatively novel and increasingly popular international design methods, such as the *Direct Strength Method DSM* [1]– used predominantly in North America for the design of cold-formed steel members – and the *General Method GM* – included in the Eurocode EN 1993-1-1 [2] Section 6.3.4 as an alternative way of designing generic steel members and structural systems. Due to its practicality, the DSM has received wide acceptance in the design of cold-formed members [5], and an increasing effort in expanding its applicability to welded and hot-rolled sections can be observed. However, the inclusion of beam-columns in its design approach is currently seen as one of the main challenges facing the DSM ([6,7,8]).

In the proposed formulation, great care is placed on accurately describing the specific behaviour of each studied cross-sectional type. The result is a DSM/GM-type formulation for hot-rolled members failing in in-plane buckling, which makes use of a "generalized slenderness" definition, and is simultaneously as accurate, safe and mechanically consistent as the familiar and thoroughly studied interaction-concept formulae.

The paper has the following scope and structure: *i.* It begins with a discussion of the main concepts for the design of beam-columns, the "interaction" and the "DSM/generalized slenderness" concept. Then, it proceeds with an introductory numerical study of the in-plane buckling behaviour of beam-columns. *iii.* After a discussion of the "interaction concept" design rules currently contained in Eurocode 3, *iv.* a new formulation for the in-plane buckling check of beam-columns is developed and presented. The formulation, which fits into the concept of DSM concepts for the design against global buckling, makes use of a "generalized slenderness" definition and of an overall, in-plane buckling reduction factor, formulated using an Ayrton-Perry type representation. *v.* The accuracy and efficiency of the proposed formulation is demonstrated by means of comparative numerical (GMNIA) calculations. *vi.* A discussion

E-mail address: andreas.taras@unibw.de.

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of further steps needed for an expansion of this DSM beam-column design proposal concludes the paper.

2. Concepts for beam-column design

Beam-columns are characterized by the simultaneous presence of compressive axial forces and bending moments. The resistance of a steel member against either one of these two sources of compressive stresses can be determined using the methods detailed therein. For a given level of the axial force N and the bending moment M, one can thus calculate the utilization of a steel member for *either* N *or* M by using e.g. the design formulae for columns and beams of Eurocode 3 [2]; these can be written as $n_{FB} = N/(\chi \cdot A \cdot f_y/\gamma_{M1})$ for flexural buckling of a member under axial load and $m_{LT} = M/(\chi_{LT} \cdot W \cdot f_y/\gamma_{M1})$ for LT-buckling of a member in bending.

Due to the non-linearity of both stresses and deformations with respect to the level of loading, the resistance against the combination of axial forces and bending moments cannot generally be calculated directly from a (linear) superposition of the utilizations for the single loading components. This obviously must be – and is - considered by design rules for beam columns.

In this context, two distinct concepts have come to be seen as the most advantageous ways of dealing with the beam-column buckling behaviour, see Fig. 1:

i. The first and (currently) most common is the so-called “interaction concept”. It directly makes use of the valuable information contained in the utilizations n_{FB} and m_{LT} by adding them together, and accounts for the mentioned effects of the simultaneous presence of N and M by an *interaction factor* k. As described in [9] and [10], different uses (multiplier or addend) and positions (before n_{FB} or m_{LT}) of k have been considered. For the Eurocode, a format where k is a multiplier of the bending term was finally chosen.
ii. In the second type of concepts, a generalized definition of the (normalized) slenderness is used; they encompass the Direct Strength Method - DSM and the General Method - GM mentioned above, as the “overall method” commonly used for the design of plates and shells (see e.g. [11]) and the so-called “general method” for the design of beam-columns of clause 6.3.4 of Eurocode 3 - EN 1993-1-1. These methods have in common that they do not explicitly consider the utilizations for the single components of a given loading condition, but rather consider total utilizations for the combined case as basis for design. As is illustrated in Fig. 1, these methods define the slenderness $\bar{\lambda}_{GS}$ in a generalized form as the square root of total load proportionality factors LPF:

$$\bar{\lambda}_{GS} = \sqrt{\frac{LPF_{MNA}}{LPF_{LBA}}} = \sqrt{\frac{R_{pl}}{R_{cr}}} \tag{1}$$

LPF_{MNA} is the maximum amplifier of a combined load case that can be reached in a (materially non-linear) analysis of the structure *without taking into account the effects of the studied buckling case.* In the “overall method” used for plate and shell buckling analysis, this load proportionality factor is calculated by omitting *all* stability effects, but taking into account the material non-linearity. This corresponds to the plastic resistance R_{pl} of the studied structure, defined as a linear amplification factor for a given load case.

LPF_{LBA} is the maximum amplifier of a combined load case until elastic bifurcation is reached for the studied buckling phenomenon. It can also be seen as the resistance R_{cr} against elastic buckling of the studied member for a linear amplification of (N + M).

Finally, in the design concepts that make use of this “generalized slenderness”, the buckling design check has the following format:

$$R_d = \frac{\chi_{GS} \cdot LPF_{MNA}}{\gamma_{M1}} \geq 1.0 \tag{2}$$

Thereby, R_d is the design resistance (in terms of a maximum load amplification factor) of the structure against the studied buckling phenomenon for a given load combination. Eq. (2) contains a buckling reduction factor χ_{GS}, which is a function of the generalized slenderness $\bar{\lambda}_{GS}$. As is indicated by the question mark in Fig. 1, the values to be adopted for χ_{GS} are not clear and still up for debate, with a common opinion being that they must be studied and calibrated by means of experimental *and/or* numerical GMNIA calculations, see e.g. [12].

In summary, the “interaction concept” and the “generalized slenderness” concepts (such as the DSM and the Eurocode 3 “general method”) use different formulations for the buckling resistance of members under combined loading. Clearly, the formulation for the buckling design check according to Eq. Eq. (2) can be said to be “consistent” in the sense that it is a generalized formulation that also implicitly contains the buckling checks used for single load cases of only N or only M. However, the formulation does not – by itself – contribute to a solution of the design problem of members under combined loading, since the buckling reduction factor χ_{GS} must account for the exact same effects as the interaction factor k. The two concepts are therefore best thought of as two different forms of representation of the same information, without attributing a (inexistent) higher degree of mechanical

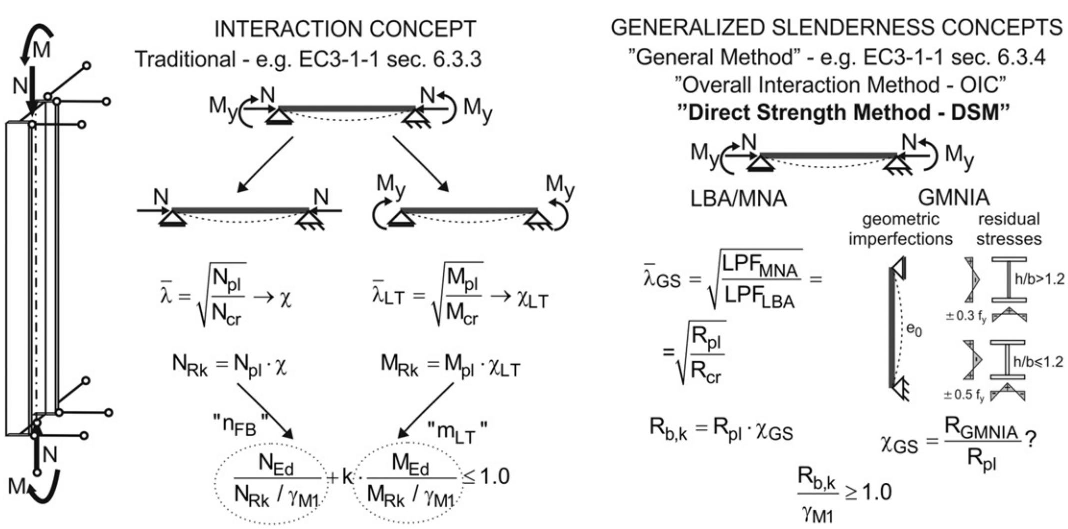

Fig. 1. Concepts for beam-column design; interaction concept versus generalized slenderness concepts.