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Comparison of the General Method with the Overall Method for the out-of-plane stability of members with lateral restraints

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ABSTRACT

The generalised slenderness concept has been gaining popularity recently. One of the methods that is based on this concept is the General Method, which was introduced in Part 1-1 of Eurocode 3 to enable the assessment of the out-of-plane stability of steel members that fall outside the scope of the buckling resistance of uniform members formulae. However, there is still uncertainty regarding the safety and accuracy of this method, namely when dealing with members that possess complex lateral restraints. The General Method resulted from an adaptation of a method present in Part 1-5 and Part 1-6 of Eurocode 3 that is commonly designated by the Overall Method, though it is not clear why this adaptation was performed. In this paper, a comparison between numerical results and results obtained by both methods, for members with different configurations of lateral restraints, is provided. The study shows that non-conservative results are obtained when applying the Overall Method to the more restrained cases, where the in-plane and out-of-plane buckling modes occur for almost the same load amplifier, while the General Method returns conservative results for the same cases. It is seen that when the in-plane buckling mode is the critical one, the assessment of the in-plane buckling resistance of the member would be sufficient to guarantee its safety. Additionally, this study provides insight into the problem of definition of imperfections when dealing with members with lateral restraints.

1. Introduction

The Part 1-1 of Eurocode 3 (EN 1993-1-1) [1] presents in its clause 6.3.4 the so-called General Method to assess the out-of-plane stability of steel members and plane frames. This method assumes a separation of the in-plane and out-of-plane behaviour, and the determination of a single generalised slenderness determined by the in-plane resistance and the critical load for the out-of-plane instability phenomenon. The overall resistance is then determined by applying a reduction factor to the in-plane resistance that accounts for out-of-plane buckling.

The General Method was first proposed in [2], and resulted from an adaptation of the MNA–LBA (Materially Non-linear Analysis/Linear Buckling Analysis) method found in Parts 1-5 and 1-6 of Eurocode 3, commonly designated in the literature and in the rest of this article by the Overall Method, for reasons that are not very clear and that were not fully comprehended by the authors, prior to this study. Some numerical and analytical studies have been performed and aimed at the validation of this method, which gave both satisfying [3] and unsatisfying [4] results, and have pointed out some inconsistencies [4,5] in the method. Therefore, there is still a lot of uncertainty regarding the safety and mechanical soundness of the General Method.

One of the main purposes of the method is to allow the stability verification of members not covered by the buckling resistance of uniform member expressions found in clauses 6.3.1, 6.3.2 and 6.3.3 of EN 1993-1-1, e.g. when the members are non-prismatic or when they possess complex lateral restraint conditions. Regarding the latter, there is still a lack of certainty about the applicability of the General Method to those members, namely whether the gain provided by the lateral restraints in the overall resistance is properly accounted for by the consideration of just a different slenderness value, if the same buckling curve as for the equivalent laterally unrestrained case is used.

The goal of this paper is to provide additional insight into these two methods related to the generalised slenderness concept applied to beam-columns, and to assess whether one or the other are better suited to be applied to the stability design of steel members with complex lateral support conditions. The already known aspects regarding the application of both methods are first exposed, and a numerical study on the behaviour of two cross-sections – one more slender I-section and one stockier H-section – is performed. Laterally unrestrained members are first analysed,

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and then the buckling designs of several lateral restrained setups are assessed and dissected by comparing the buckling curves to the numerical results for both methods.

It is seen that despite the stronger mechanical background of the Overall Method, the results given by this method together with the Eurocode buckling curves tend to be unsafe, namely when the out-of-plane resistance of a member gets closer to the in-plane resistance due to the addition of more lateral restraints. On the other hand, the General Method has given conservative results for these cases. To overcome this limitation, it is recommended to add a clause to the General Method, stating that in those situations only the in-plane resistance would have to be verified.

2. Background

2.1. Generalised slenderness concepts

The generalised slenderness concept first appeared in the Overall Method in Parts 1-5 and 1-6 of Eurocode 3, and later, in the final version of the EN1993-1-1 where the General Method was included. This concept differs from the interaction concept found in clauses 6.3.1 to 6.3.3, in which a certain member is studied by separately considering the column and beam behaviour and by relating them by interaction factors, since the member is considered as a whole and the buckling resistance is given as function of a single slenderness that leads to a single buckling reduction factor. A good additional explanation of the differences between these two concepts is given in [5].

The apparent simplicity of this concept in the design against different buckling phenomena of steel structures makes its use very attractive, even for the cases already covered by other formulae. For this reason, these and other generalised slenderness based methodologies have been receiving a lot of attention recently by the scientific community. One example of this growing popularity is a recent proposal made in [6], where a generalised slenderness concept is applied to the design against in-plane buckling of prismatic beam-columns. Other examples include the Direct Strength Method [7], used for the design of cold-formed steel structural members, or the Overall Interaction Concept [8,9], that aims to be "a straight-forward design check of the stability and resistance of steel members" [8].

2.2. The Overall Method and the General Method

Both the Overall Method and the General Method will be consistently applied throughout this paper, and hence the two methods are explained in the following paragraphs. Fig. 1 shows the formulae involved in both methodologies as well as an illustration of the physical meaning of the different amplification factors, plotted over the N-M interaction diagram of a beam-column subjected to a constant bending moment. The definition of the symbols there presented is given in the next sections.

A clarification should be given on the fact that by further mentioning in-plane and out-of-plane behaviour, one is referring to the plane of application of the loads, which in the current study corresponds to the direction of higher inertia of the profiles (see Fig. 2). This means that the displacements occurring in the direction of the z-axis of the profiles here analysed are taken as in-plane displacements, whereas the ones occurring in the y-axis are referred to out-of-plane ones.

2.2.1. Overall Method

The Overall Method is based on a Merchant-Rankine empirical expression for the interaction between the material strength of a member (plastic behaviour) and its vulnerability to buckling (elastic behaviour). A direct application of this methodology is used in Parts 1-5 and 1-6 of Eurocode 3 [10,11]. In this methodology, an overall slenderness $\bar{\lambda}_{ov}$ is determined according to the result of a Materially Non-linear Analysis (MNA) and the result of a Linear Buckling Analysis (LBA) – thus its designation of MNA/LBA approach – both expressed in the form of load amplification factors, respectively α_{pl} and $\alpha_{cr,ov}$. The overall resistance is obtained by reducing the plastic resistance by a proper factor, χ_{ov}, to account for the buckling instability of the member (see Fig. 1).

2.2.2. General Method

The General Method is a modified version of the Overall Method that was first proposed in [2] and was then implemented in Part 1-1 of EC3 in its clause 6.3.4, where α_{pl} was replaced by the load amplifier $\alpha_{ult,k}$ to account for all effects due to in plane geometrical deformation and imperfections (the so called second-order effects), which can be determined from an in-plane constrained Geometrically and Materially Non-linear Analysis with Imperfections ($GMNIA_{yy}$).

Similarly to the Overall Method, the General Method allows to assess the overall stability of steel members by ensuring that this in-plane load amplifier $\alpha_{ult,k}$, reduced by a factor χ_{op} that accounts for the out-of-plane instability, such as lateral or lateral-torsional buckling, is larger than the unit (see Fig. 1), i.e. that the effect of the acting loads do not surpass the resistance. According to the same clause 6.3.4, χ_{op} may be taken as the minimum of or by an interpolation between the values χ_z for out-of-plane flexural buckling and χ_{LT} for lateral-torsional buckling, both calculated for the slenderness $\bar{\lambda}_{op}$, as given in Fig. 1, where $\alpha_{cr,op}$ stands for the critical load amplifier for the out-of-plane direction.

An explanation to this adaptation is given in [12], where it is said about the Overall Method that "unconservative buckling checks may occur" if the common buckling curves are applied to members under simultaneous bending and compression, and that for this method to return satisfying results it "would require the determination of new specific buckling curves". These kind of unconservative results, illustrated by some examples in [12], may be the reason that led to the method being changed to become the General Method in Eurocode 3.

2.3. Prior research

Some studies have been performed regarding the accuracy and safety of the General Method. In [3] the aptitude of the method for the assessment of various stability problems in bar structures is investigated and advocated, whereas in [4,5] inconsistencies are shown when the methodology is applied for basic cases, suggesting that this methodology should be revised.

Besides the recognition of this lack of mechanical consistency, [13] points out that the application of the general methodology for tapered members results in a wide spread in the results, both on the safe and unsafe sides, and criticizes the way the interpolation between the reduction factors χ_z and χ_{LT} is made. Another negative aspect brought there to the discussion is that the determination of the in-plane load multiplier with imperfections may require long and complex calculations, and a variation of the General Method where the reference value is given by the cross-section capacity instead of the in-plane resistance is preliminary explored (which, in fact, is the same as applying the Overall Method to the out-of-plane stability case).

In [12,14] the point is highlighted that by using the Overall Method the problem of definition of imperfections by the designer is avoided in the determination of the in-plane resistance, and that this methodology is fully compatible with the existing rules for pure compression and pure bending – while the same is not true