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Slender steel columns: How they are affected by imperfections and bracing stiffness

Anders Klasson *, Roberto Crocetti, Eva Frühwald Hansson

Division of Structural Engineering, Lund University, Box 118, 22100 Lund, Sweden

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ABSTRACT

Finite-element programs can be used for designing columns and their bracing systems. It is well known, however, that the output obtained from such programs is highly dependent upon the input (such as imperfections and stiffness properties). In the present study, the effects of imperfections on the predicted strength and stiffness requirements of steel columns and of their bracing systems are investigated. Two different systems are analyzed: 1) a braced non-sway column and 2) a braced sway column. It was found that a poor choice of the shape of the initial imperfections can provide unrealistic results in terms of both the buckling load on the columns and the predicted reactions of the bracings. It was also found that superimposing different imperfection shapes can contribute to obtaining realistic and trustworthy results. Furthermore, it was shown that the shapes of the initial imperfections that lead to the lowest buckling load and those that result in the strongest bracing forces, are generally not the same.

1. Introduction

Structural imperfections are critical for determining the behavior of slender structural elements and their bracing systems. These imperfections include construction tolerances, geometrical deviations, residual stresses, load eccentricities and material deficiencies. The numerical modeling of some of the aforementioned imperfections can be cumbersome in design. For example, the modeling of residual stresses would likely require the use of either shell or solid elements (resulting in complex models). Moreover, the code does not specify a geometric imperfection to be used if the residual stresses were to be handled separately. Accordingly, the geometrical imperfections used in design are normally larger than the actual (measurable) geometrical deviations, so as to be able to account for the effect of all imperfections.

The important characteristics of a bracing system include its stiffness and its strength properties. Different in-plane bracing methods include discrete (as examined in this study), continuous, relative and lean on (as defined in Galambos et al. [1]), see Fig. 1.

In 1958, Winter [2] presented a simple yet powerful rigid link model employed for calculating the strength and stiffness requirements of bracings. This method can be used in particular for calculating the full-bracing (ideal stiffness) requirement. This requirement represents a conservative limit for the required bracing stiffness that is needed in order to achieve buckling between successive bracings. According to this model, a column can be braced at one or more points. Winter's rigid link model was later extended by Yura [3] to allow for cases in which less than full bracing is provided. The rigid link model can also account for initial imperfections, making the study of bracing forces and thus the strength requirements of the bracings possible. While simplified approaches such as the rigid link model are possible, analytical solutions can in some cases also be derived; see e.g. Timoshenko et al. [4] regarding the concept of buckling capacity when less than full bracing is provided. For derivation of the full bracing requirement of a sway prevented column with one intermediate bracing, see e.g. Galambos et al. [1]. The bracing force for a varying applied load, was derived by Trahair [5]. Even in simple cases, however, such as that of a column with only one intermediate bracing, closed-form solutions are rather involved and may not be as practical as ones based on a rigid link model. In the case of more complicated systems, closed-form solutions may not even exist. Since the rigid link model usually assumes equally spaced bracings, Plaut et al. [6–8] in several studies analyzed the implications of having unsymmetrically spaced bracings. It was found that no ideal stiffness could be defined if the bracings are spaced unsymmetrically. This was due to the fact that the displacements at the bracing points can be suppressed only if there is perfect symmetry, i.e. equal spans. Theoretically, this means that there will always be an additional elastic buckling capacity if the bracing stiffness would be increased (see for instance Mehri et al. [9] who thouroghly analyzed this case). Practically, however, a “full bracing requirement” can still be said to exist even for the unsymmetrical case; i.e. when the stiffness of the bracing tends to a value that generates a buckling capacity that would be obtained if infinitely rigid bracings were assumed.

* Corresponding author.
E-mail address: anders.klasson@kstr.lth.se (A. Klasson).

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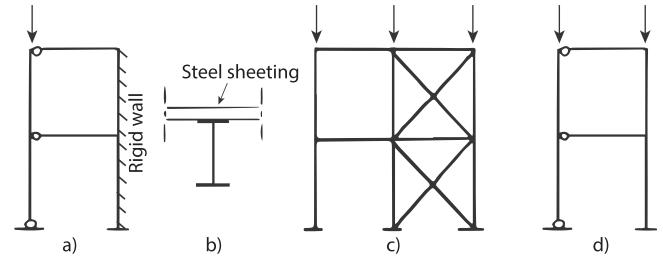

Fig. 1. a) Discrete bracing. b) Continuous bracing. c) Relative bracing. d) Lean on bracing.

In modern design, simplified methods such as those involving the use of rigid-link models for columns, are uncommon since most engineers have access to advanced finite element (FE) software. Such modeling may be comparatively easy and fast, even for users who lack an adequate physical understanding of the problem involved. It is well known, however, that the validity of results obtained using FE-modeling is strongly dependent upon the accuracy of the input and may completely misguide users who interpret it inaccurately [10]. Thus, as is also demonstrated in the present study, it is important that the effect of modeling assumptions, such as imperfections, are considered when design is based directly on FE -modeling.

For the design of columns aided by nonlinear incremental analysis, it has been shown in numerous studies that the choice of the imperfection shape strongly affects the results obtained. For instance, Wang et al. [11] clearly demonstrated how bracing forces can vary with different choices of the imperfection shape to employ. Giro Coelho et al. [12] studied a non-sway column (lacking intermediate support), and determined that the assumed imperfection shape affects the pre-buckling stiffness and thus the load-bearing capacity of the column. It should be mentioned that the most critical imperfection shape for the column did not always correspond to the first elastic buckling mode of the corresponding perfect (i.e. without imperfections) system.

The Eurocode 3 [13] design code states that the most unfavorable combination of initial imperfections should be used in design without clearly specifying what that combination is. In contrast to what was said in the previous paragraph the Eurocode tacitly suggests, according to the authors' interpretation, that imperfections related to buckling modes of the highest order, i.e. buckling between restraints (bracings) should be used, possibly in combination with the sway imperfections inherent in the structure (tolerances that the structure has). In addition, simplified requirements for bracings are specified by the Eurocode, e.g. a bracing stiffness requirement simply expressed in terms of the design load of the column. Overall, the approaches specified by the code do not adequately describe the true physical nature of the structure in an intuitive manner; something further being needed.

The output obtained in the FE-modeling of columns can be used in basically two different ways:

1. The FE-modeling is used simply for calculating the elastic critical load of a column, P_e. this value then determines the relative slenderness ratio, $\lambda = \sqrt{f_y A / P_e}$, and design with Eurocode 3 [13] for steel can be used. An FE-program can usually calculate the elastic critical load of a column either through an elastic buckling analysis of a perfect column, or by incremental analysis of an imperfect column (with an assumed minor imperfection).
2. Alternatively, an appropriate imperfection can be assigned to the column followed by an incremental non-linear (inelastic) analysis. Design is then based directly on these results.

The present study investigates, by means of nonlinear finite element analysis of discretely braced steel columns, what imperfection shapes to use in order to obtain an over all safe design (2nd alternative above). Attention is directed at the response of the column and of the entire bracing system (i.e. the bracing forces).

1.1. Aims

The specific aims of the present study are the following:

1. Determine the ideal stiffness of the bracing systems considered and the corresponding buckling modes of idealized/perfect columns (i.e. columns without imperfections). This will be mainly analyzed analytically, by means of the energy method, to be described more later on in the method section. The purpose of using the energy method is twofold: (1) to find suitable imperfections shapes (also linear buckling analysis could have been used here) for use in design based on FE-analysis and (2) to serve as a validation of the results from the incremental analysis.
2. Investigate the full bracing requirements, in terms of both the column strength and its elastic buckling limit, and the bracing forces involved when employing different imperfection shapes in an FE-analysis (i.e. a non-linear incremental analysis) of the columns in question.
3. Examine what the most unfavorable imperfection shapes would appear to be for the systems in question with respect to both column strength and the bracing forces.
4. Compare the column strength according to the code, Eurocode 3 chapter 6.3.1.2 [13] (using the relative slenderness ratio (λ)) with the strength predicted by the non-linear FE analysis for different imperfection shapes.
5. Investigate if there are any imperfection shapes that lead to unrealistic results in terms of FE-analysis and should thus be avoided in design.
6. Provide a reference aimed at aiding practicing engineers in the nonlinear design of columns.

1.2. Limitations

The current study is limited to the investigation of in-plane buckling of steel columns with symmetrical cross-sections (e.g. I-profiles) and two different statical systems, namely:

1. The first system, referred to as System A and shown in Fig. 2, is a non-sway column with a single intermediate mid-length bracing. Although such a system is uncommon among real structures, it appears to be the most common bracing system referred to in the literature such as in [14,3,5,15,9]. System A could, for example, be a scaffolding strut such as that shown in Fig. 2, which is attached at its top to a very rigid structure.
2. The second system, referred to as System B, is a sway column with two bracings of equal stiffness, placed at the top and at mid-length of the column. According to the authors' perception, this system is more commonly found among real structures than System A. It is hard to imagine many buildings where the top bracing would be stiffer than the lower, intermediate, ones. One example of the application to which System B can be put is shown in Fig. 3.

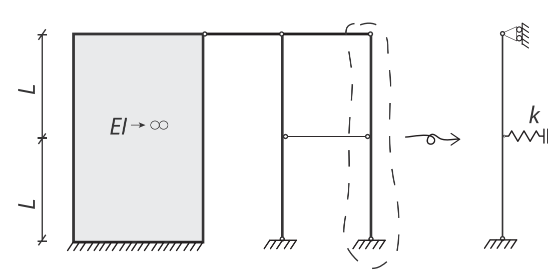

Fig. 2. System A. A column in which the top bracing can be considered to be rigid in relation to the middle bracing. It could be a scaffolding strut, connected at its top to the building.