Journal of Constructional Steel Research 136 (2017) 140–148

Contents lists available at ScienceDirect

Journal of Constructional Steel Research

journal homepage: www.elsevier.com/locate/jcsr

Influence of imperfections on the stability of beams with intermediate flexible supports

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ARTICLE INFO

Keywords:
Member buckling
Lateral torsional buckling
GMNIA-analyses

ABSTRACT

For the prediction of the ultimate load of beams and columns, respectively susceptible to lateral torsional buckling and flexural buckling, numerical FEM-calculations including geometric imperfections and residual stresses (so-called "GMNIA analyses"), are becoming more commonly employed and recognized. In these analyses, the shape of the geometric imperfections is often based on the 1st buckling mode, seen as the worst case for these members.

In this paper, the buckling behaviour of beams and columns with additional intermediate flexible supports is studied and illustrated, using additional spring elements with systematically varied stiffness.

As expected, a decrease of the spring stiffness always leads to a reduced elastic critical buckling load. Nevertheless, when assuming geometric imperfections based on the 1st buckling mode, this may lead to a higher ultimate load than for the system with rigid intermediate supports, when identical imperfection amplitudes are used. These interesting results are presented and analyzed for two simple cases, in order to clearly show the main effects. These cases are: 1.) Columns under compression with additional flexible support at midspan; 2.) Beams under bending with additional flexible supports of the compressed flange only. For the latter case, a parametric study was performed, varying the number of intermediate supports and stiffness of the lateral supports.

1. Introduction

The design rules in Eurocode 3, EN 1993-1-1 [1] for beams, columns and beam-columns susceptible to flexural or lateral torsional buckling (LTB) are based on comprehensive testing and numerical calculations, using the Finite Element Method (FEM), which include geometric imperfections and residual stresses; that is, on geometrical and material non-linear analyses with imperfections (GMNIA). For the shape of the geometric imperfections, the modal shapes resulting from a preceding linear buckling analysis (LBA) are used. During these calculations, primarily the standard cases of beams, columns and beam-columns were considered, taking into account individual members with simplified boundary conditions at the member ends (pinned ends with "end fork condition") and without additional intermediate flexible supports. For these simplified cases under pure compression or pure bending, geometric imperfections based on the first buckling mode of the LBA-analyses always lead to the lowest ultimate load.

This paper is limited to these simple load cases (columns under pure compression, beams under pure bending), in order to focus on the fundamental findings of the presented studies. It is well known that for beam-columns susceptible to LTB, two different buckling mode shapes must be considered. Depending on the ratio of compression to bending stresses, either the flexural buckling mode about the z-axis or the LTB-mode is decisive. Beam-columns are not treated here, meaning an interaction of buckling shapes of different buckling phenomena is excluded, while the pure cases (flexural buckling vs. LTB) are studied in detail.

Concerning the geometric imperfections, not only the imperfection shape along the member, but also the maximum amplitude e_0 is important. For the mentioned GMNIA-calculations, that were carried out in accordance with the background document to EN 1993-1-1 [2], an amplitude of $e_0 = L/1000$ was chosen (L being the member length) based on previously more stringent rules in national steelwork fabrication standards, now replaced, by the more lenient value L/750 in the European fabrication standard EN 1090-2. In the recent past, comprehensive research projects were carried out in order to develop procedures to obtain modified amplitudes $e_{0,mod}$ of equivalent geometric imperfections which scale the calculated 1st buckling shape - including for beam-columns with complex boundary conditions ([3–9]). This means that the equivalent geometric imperfections also

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http://dx.doi.org/10.1016/j.jcsr.2017.05.008
Received 26 September 2016; Received in revised form 27 April 2017; Accepted 10 May 2017

substitute the residual stresses and that global analysis and member checks alone, using 2nd order theory internal forces, lead to the same ultimate load as the design procedure of the Eurocode.

The LTB-behaviour of steel beams with additional flexible lateral restraints between the supports is also studied in [10], thereby considering residual stresses and geometric imperfections based on the 1st buckling mode.

The main focus of this paper is placed on the ultimate load capacity of beams under bending with intermediate flexible lateral supports of the compression flange only for different assumptions of geometric imperfections (shape and amplitude). The reference case is the system with rigid intermediate lateral supports. Based on LBA-analyses and an iterative process, the spring stiffness of the intermediate supports is chosen in such a way that the linear ideal buckling moment of the reference system is reduced to a specified value (e.g. 95% of M_{cr} leads to spring stiffness $C_{v,95}$).

In order to get a better understanding of the main findings of the LTB-behaviour of the beams, the rather simple flexural buckling behaviour of a compressed column with intermediate flexible support is shown first. The reason for that is the fact that the LTB-behaviour of a beam can be understood, in a simplified manner, as out-of-plane flexural buckling of the compressed flange.

It will be shown that both cases with intermediate flexible supports - flexural buckling of a column under compression and LTB of a beam under bending - behave in a similar manner.

2. Flexural buckling of a column in compression with intermediate flexible lateral support

In the following, a pin-ended column with an overall length of L = 8000 mm, with a squared hollow section 200/200/5 mm, material S 235 (f_{yk} = 235 N/mm^2) and with a single axial load N at the column top is analyzed.

The intermediate lateral support is situated at mid-span. For the reference case, shown in Fig. 1, a rigid lateral support is assumed ($C_{v,rigid}$) and therefore the buckling length of the column is equal to $L_{cr,0}$ = 4000 mm.

The critical buckling load $N_{cr,0}$ is given by the well-known Eq. (1).

$$N_{cr,0} = \frac{\pi^2 EI}{L^2{}_{cr,0}} = \frac{\pi^2 \cdot 21000 \cdot 2445}{400^2} = 3167\ kN \tag{1}$$

In contrast to Chapter 3, the global analysis was simplified here, following common practice in design offices:

- equivalent geometric imperfections with the shape of the first elastic buckling mode (stemming from preceding LBA-analyses) are chosen, including the effect of residual stresses,
- linear elastic material behaviour is assumed, and
- the determination of the ultimate load N_u is based on the section capacity (note: for the studied section, the plastic section capacity may be used) and on internal forces based on 2nd order theory.

These simplifications lead to nearly the same ultimate load N_u based on a "full" GMNIA-calculation procedure, because the amplitude $e_{0,mod}$ is based on EN 1993-1-1, clause 5.3.2 (11), which was itself derived from the column capacity given by the European buckling curves. For the assumed hot-finished section, buckling curve "a" must be used (imperfection factor α = 0.21) and $e_{0,mod}$ is based on Eq. (2) (note: the term η_{cr} of EN 1993-1-1 is omitted, because the buckling modes were previously scaled to a maximum value of η_{cr} = 1).

$$e_{0,mod} = e_{0,pinned} \cdot \frac{N_{cr}}{EI\ |\eta''_{cr,max}|} \tag{2}$$

$$e_{0,pinned} = \alpha \cdot (\bar{\lambda} - 0.2) \cdot \frac{M_{pl}}{N_{pl}} \tag{3}$$

(note: Eq. (3) implies γ_{M1} = 1.0).

For a pin-ended column with fixed supports, the 1st elastic buckling shape is sinusoidal and therefore $e_{0,mod} = e_{0,pinned}$. In the reference case this is also true.

Finally, based on Eq. (3), for the reference case the modified amplitude $e_{0,mod} = e_{0,pinned}$ gives:

$$e_{0,pinned} = 0.21 \cdot (0.536 - 0.2) \cdot \frac{6641}{910.2} = 0.515\ cm = 5.15\ mm \tag{4}$$

with:

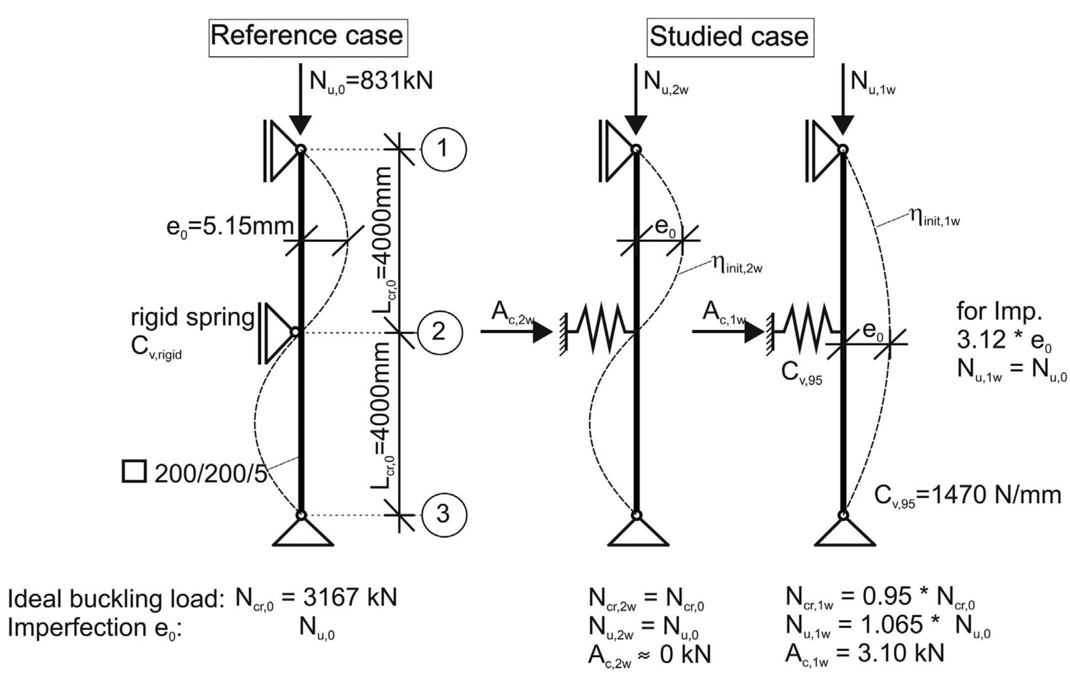

Fig. 1. Flexural buckling of a column with intermediate flexible support; system, loading, buckling modes and main results.